The GNU C++ Library Manual

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Chapter 1

Status

1.1 Implementation Status

1.1.1 C++ 1998/2003

1.1.1.1 Implementation Status

This status table is based on the table of contents of ISO/IEC 14882:2003.

This section describes the C++ support in mainline GCC, not in any particular release.

1.1.1.2 Implementation Specific Behavior

The ISO standard defines the following phrase:

> **`[1.3.5] implementation-defined behavior`** Behavior, for a well-formed program construct and correct data, that depends on the implementation *and that each implementation shall document*.

We do so here, for the C++ library only. Behavior of the compiler, linker, runtime loader, and other elements of "the implementation" are documented elsewhere. Everything listed in Annex B, Implementation Qualities, are also part of the compiler, not the library.

For each entry, we give the section number of the standard, when applicable. This list is probably incomplet and inkorrekt.

1.9 [intro.execution]/11 #3 If `isatty(3)` is true, then interactive stream support is implied.

17.4.4.5 [lib.reentrancy] Non-reentrant functions are probably best discussed in the various sections on multithreading (see above).

18.1 [lib.support.types]/4 The type of `NULL` is described under Support.

18.3 [lib.support.start.term]/8 Even though it's listed in the library sections, libstdc++ has zero control over what the cleanup code hands back to the runtime loader. Talk to the compiler people. :-)

18.4.2.1 [lib.bad.alloc]/5 (bad_alloc), *18.5.2 [lib.bad.cast]/5* (bad_cast), *18.5.3 [lib.bad.typeid]/5* (bad_typeid), *18.6.1 [lib.exception]/8* (exception), *18.6.2.1 [lib.bad.exception]/5* (bad_exception): The `what()` member function of class `std::exception`, and these other classes publicly derived from it, returns the name of the class, e.g. `"std::bad_alloc"`.

18.5.1 [lib.type.info]/7 The return value of `std::type_info::name()` is the mangled type name. You will need to call `c++filt` and pass the names as command-line parameters to demangle them, or call a runtime demangler function.

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18.2.1.4	`float_denorm_style`	Y	
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18.3	Start and termination	Y	
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18.5.3	Class bad_typeid	Y	
18.6	Exception handling		
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19	*Diagnostics*		
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20	*General utilities*		
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20.2.2	`pair`	Y	
20.3	Function objects		
20.3.1	Base	Y	
20.3.2	Arithmetic operation	Y	
20.3.3	Comparisons	Y	
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20.3.6	Binders	Y	
20.3.7	Adaptors for pointers to functions	Y	
20.3.8	Adaptors for pointers to members	Y	
20.4	Memory		
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20.4.2	Raw storage iterator	Y	
20.4.3	Temporary buffers	Y	
20.4.4	Specialized algorithms	Y	
20.4.4.1	`uninitialized_copy`	Y	
20.4.4.2	`uninitialized_fill`	Y	
20.4.4.3	`uninitialized_fill_n`	Y	
20.4.5	Class template `auto_ptr`	Y	
20.4.6	C library	Y	
21	*Strings*		
21.1	Character traits		
21.1.1	Character traits requirements	Y	
21.1.2	traits typedef	Y	
21.1.3	`char_traits`		

20.1.5 [lib.allocator.requirements]/5 "Implementors are encouraged to supply libraries that can accept allocators that encapsulate more general memory models and that support non-equal instances. In such implementations, any requirements imposed on allocators by containers beyond those requirements that appear in Table 32, and the semantics of containers and algorithms when allocator instances compare non-equal, are implementation-defined." There is experimental support for non-equal allocators in the standard containers in C++98 mode. There are no additional requirements on allocators. It is undefined behaviour to swap two containers if their allocators are not equal.

21.1.3.1 [lib.char.traits.specializations.char]/3,4, *21.1.3.2 [lib.char.traits.specializations.wchar.t]/2*, *21.3 [lib.basic.string]/6 basic_string::iterator, basic_string::const_iterator*, *23.* [lib.containers]'s foo::iterator*, *27.* [lib.input.output]'s foo::*_type*, *others...* Nope, these types are called implementation-defined because you shouldn't be taking advantage of their underlying types. Listing them here would defeat the purpose. :-)

21.1.3.1 [lib.char.traits.specializations.char]/5 I don't really know about the mbstate_t stuff... see the codecvt notes for what does exist.

22. [lib.localization]* Anything and everything we have on locale implementation will be described under Localization.

23. [lib.containers]* All of the containers in this clause define size_type as std::size_t and difference_type as std::ptrdiff_t.

26.2.8 [lib.complex.transcendentals/9 I have no idea what `complex<T>`'s `pow(0,0)` returns.

27.4.2.4 [lib.ios.members.static/2 Calling `std::ios_base::sync_with_stdio` after I/O has already been performed on the standard stream objects will flush the buffers, and destroy and recreate the underlying buffer instances. Whether or not the previously-written I/O is destroyed in this process depends mostly on the `--enable-libio` choice: for stdio, if the written data is already in the stdio buffer, the data may be completely safe!

27.6.1.1.2 [lib.istream::sentry], *27.6.2.3 [lib.ostream::sentry]* The I/O sentry ctor and dtor can perform additional work than the minimum required. We are not currently taking advantage of this yet.

27.7.1.3 [lib.stringbuf.virtuals]/16, *27.8.1.4 [lib.filebuf.virtuals]/10* The effects of `pubsetbuf/setbuf` are described in the Input and Output chapter.

27.8.1.4 [lib.filebuf.virtuals]/16 Calling `fstream::sync` when a get area exists will... whatever `fflush()` does, I think.

1.1.2 C++ 2011

This table is based on the table of contents of ISO/IEC JTC1 SC22 WG21 Doc No: N3290 Date: 2011-04-11 Final Draft International Standard, Standard for Programming Language C++

In this implementation the `-std=gnu++11` or `-std=c++11` flag must be used to enable language and library features. See dialect options. The pre-defined symbol `__cplusplus` is used to check for the presence of the required flag. GCC 5.1 was the first release with non-experimental C++11 support, so the API and ABI of features added in C++11 is only stable since that release.

This status table is based on the table of contents of ISO/IEC 14882:2011.

This section describes the C++11 support in mainline GCC, not in any particular release.

1.1.2.1 Implementation Specific Behavior

For behaviour which is also specified by the 1998 and 2003 standards, see C++ 1998/2003 Implementation Specific Behavior. This section only documents behaviour which is new in the 2011 standard.

17.6.5.12 [res.on.exception.handling] There are no implementation-defined exception classes, only standard exception classes (or classes derived from them) will be thrown.

17.6.5.14 [value.error.codes] The `error_category` for errors originating outside the OS, and the possible error code values for each error category, should be documented here.

18.6.2.2 [new.badlength] `what()` returns `"std::bad_array_new_length"`.

20.6.9.1 [allocator.member]/5 Over-aligned types are not supported by `std::allocator`.

20.7.2.2.1 [util.smartptr.shared.const] When a `shared_ptr` constructor fails `bad_alloc` (or types derived from it) will be thrown, or when an allocator is passed to the constructor then any exceptions thrown by the allocator.

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18.1	General		
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18.3	Implementation properties		
18.3.2	Numeric Limits		
18.3.2.3	Class template `numeric_limits`	Y	
18.3.2.4	`numeric_limits` members	Y	
18.3.2.5	`float_round_style`	N	
18.3.2.6	`float_denorm_style`	N	
18.3.2.7	`numeric_limits` specializations	Y	
18.3.3	C Library	Y	
18.4	Integer types		
18.4.1	Header `<cstdint>` synopsis	Y	
18.5	Start and termination	Partial	C library dependency for quick_exit, at_quick_exit
18.6	Dynamic memory management	Y	
18.7	Type identification		
18.7.1	Class type_info	Y	
18.7.2	Class bad_cast	Y	
18.7.3	Class bad_typeid	Y	
18.8	Exception handling		
18.8.1	Class exception	Y	
18.8.2	Class bad_exception	Y	
18.8.3	Abnormal termination	Y	
18.8.4	`uncaught_exception`	Y	
18.8.5	Exception Propagation	Y	
18.8.6	`nested_exception`	Y	
18.9	Initializer lists		
18.9.1	Initializer list constructors	Y	
18.9.2	Initializer list access	Y	
18.9.3	Initializer list range access	Y	
18.10	Other runtime support	Y	
19	*Diagnostics*		
19.1	General		
19.2	Exception classes	Y	
19.3	Assertions	Y	
19.4	Error numbers	Y	
19.5	System error support		
19.5.1	Class `error_category`	Y	
19.5.2	Class `error_code`	Y	
19.5.3	Class `error_condition`	Y	
19.5.4	Comparison operators	Y	
19.5.5	Class `system_error`	Y	
20	*General utilities*		
20.1	General		
20.2	Utility components		
20.2.1	Operators	Y	
20.2.2	swap	Y	
20.2.3	forward/move helpers	Y	
20.2.4	Function template `declval`	Y	
20.3	Pairs		
20.3.1	In general		
20.3.2	Class template `pair`	Y	
20.3.3	Specialized algorithms	Y	
20.3.4	Tuple-like access to `pair`	Y	
20.3.5	Piecewise construction	Y	

20.7.2.0 [util.smartptr.weakptr] what() returns "bad_weak_ptr".

20.8.11.1 [func.wrap.badcall] what() returns "bad_function_call".

20.8.9.1.3 [func.bind.place]/1 There are 29 placeholders defined and the placeholder types are CopyAssignable.

20.11.7.1 [time.clock.system]/3, /4 Time point values are truncated to time_t values. There is no loss of precision for conversions in the other direction.

20.15.7 [meta.trans]/2 aligned_storage does not support extended alignment.

21.2.3.2 [char.traits.specializations.char16_t], *21.2.3.3 [char.traits.specializations.char32_t]* The types u16streampos and u32streampos are both synonyms for fpos<mbstate_t>. The function eof returns int_type(-1). char_traits<char1 will transform the "noncharacter" U+FFFF to U+FFFD (REPLACEMENT CHARACTER). This is done to ensure that to_int_type never returns the same value as eof, which is U+FFFF.

22.3.1 [locale] There is one global locale for the whole program, not per-thread.

22.4.5.1.2 [locale.time.get.virtuals], *22.4.5.3.2 [locale.time.put.virtuals]* Additional supported formats should be documented here.

22.4.7.1.2 [locale.messages.virtuals] The mapping should be documented here.

23.3.2.1 [array.overview] array<T, N>::iterator is T* and array<T, N>::const_iterator is const T*.

23.5.4.2 [unord.map.cnstr], *23.5.5.2 [unord.multimap.cnstr]*, *23.5.6.2 [unord.set.cnstr]*, *23.5.7.2 [unord.multiset.cnstr]* The default minimal bucket count is 0 for the default constructors, range constructors and initializer-list constructors.

25.3.12 [alg.random.shuffle] The two-argument overload of random_shuffle uses rand as the source of randomness.

26.5.5 [rand.predef] The type default_random_engine is a synonym for minstd_rand0.

26.5.6 [rand.device] The token parameter of the random_device constructor can be used to select a specific source of random bytes. The valid token values are shown in the list below. The default constructor uses the token "default".

"default" Select the first available source from the other entries below. This is the only token that is always valid.

"rand_s" Use the MSVCRT rand_s function. This token is only valid for mingw-w64 targets.

"rdseed", "rdrand" or "rdrnd" Use the IA-32 RDSEED or RDRAND instruction to read from an on-chip hardware random number generator. These tokens are only valid for x86 and x86_64 targets when both the assembler and CPU support the corresponding instruction.

"darn" Use the Power ISA-3.0 DARN ("Deliver A Random Number") instruction to read from an on-chip hardware random number generator. This token is only valid for 64-bit powerpc targets when both the assembler and CPU support the corresponding instruction.

"hw", "hardware" Use any available CPU instruction to read from an on-chip hardware random number generator. This is equivalent to trying each of the following and using the first that is supported: "rdseed""rdrand""darn"

"arc4random", "getentropy" Use the named C library function, if available on the target.

"/dev/urandom", "/dev/random" Use the named character special file to read random bytes from. These tokens are only valid when the device files are present and readable by the current user.

"mt19937", seed value When no source of nondeterministic random numbers is available a mersenne_twister_engine will be used. An integer seed value can be used as the token and will be converted to an unsigned long using strtoul. These tokens are only valid when no other source of random bytes is available.

An exception of type runtime_error will be thrown if a random_device object is constructed with an invalid token, or if it cannot open or read from the source of random bytes.

26.5.8.1 [rand.dist.general] The algorithms used by the distributions should be documented here.

26.8 [c.math] Whether the rand function introduces data races depends on the C library as the function is not provided by libstdc++.

27.8.2.1 [stringbuf.cons] Whether the sequence pointers are copied by the `basic_stringbuf` move constructor should be documented here.

27.9.1.2 [filebuf.cons] Whether the sequence pointers are copied by the `basic_filebuf` move constructor should be documented here.

28.5.1 [re.synopt], *28.5.2 [re.matchflag]* , *28.5.3 [re.err]* `syntax_option_type`, `match_flag_type` and `error_type` are unscoped enumeration types.

28.7 [re.traits] The `blank` character class corresponds to the `ctype_base::blank` mask.

29.4 [atomics.lockfree] The values of the `ATOMIC_xxx_LOCK_FREE` macros depend on the target and cannot be listed here.

30.2.3 [thread.req.native]/1 `native_handle_type` and `native_handle` are provided. The handle types are defined in terms of the Gthreads abstraction layer, although this is subject to change at any time. Any use of `native_handle` is inherently non-portable and not guaranteed to work between major releases of GCC.

`thread` The native handle type is a typedef for `__gthread_t` i.e. `pthread_t` when GCC is configured with the `posix` thread model. The value of the native handle is undefined for a thread which is not joinable.

`mutex`, `timed_mutex` The native handle type is `__gthread_mutex_t*` i.e. `pthread_mutex_t*` for the `posix` thread model.

`recursive_mutex`, `recursive_timed_mutex` The native handle type is `__gthread_recursive_mutex_t*` i.e. `pthread_mutex_t*` for the `posix` thread model.

`condition_variable` The native handle type is `__gthread_cond_t*` i.e. `pthread_cond_t*` for the `posix` thread model.

30.6.1 [futures.overview]/2 `launch` is a scoped enumeration type with overloaded operators to support bitmask operations. There are no additional bitmask elements defined.

1.1.3 C++ 2014

In this implementation the `-std=gnu++14` or `-std=c++14` flag must be used to enable language and library features. See dialect options. The pre-defined symbol `__cplusplus` is used to check for the presence of the required flag. GCC 6.1 was the first release with non-experimental C++14 support, so the API and ABI of features added in C++14 is only stable since that release.

This status table is based on the table of contents of ISO/IEC 14882:2014. Some subclauses are not shown in the table where the content is unchanged since C++11 and the implementation is complete.

This section describes the C++14 and library TS support in mainline GCC, not in any particular release.

1.1.3.1 Implementation Specific Behavior

1.1.3.1.1 Filesystem TS

2.1 POSIX conformance [fs.conform.9945] The behavior of the filesystem library implementation will depend on the target operating system. Some features will not be supported on some targets. Symbolic links and file permissions are not supported on Windows.

15.30 Rename [fs.op.rename] On Windows, `experimental::filesystem::rename` is implemented by calling `MoveFileExW` and so does not meet the requirements of POSIX `rename` when one or both of the paths resolves to an existing directory. Specifically, it is possible to rename a directory so it replaces a non-directory (POSIX requires an error in that case), and it is not possible to rename a directory to replace another directory (POSIX requires that to work if the directory being replaced is empty).

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18.3.2.4	`numeric_limits` members	Y	
18.3.2.5	`float_round_style`	N	
18.3.2.6	`float_denorm_style`	N	
18.3.2.7	`numeric_limits` specializations	Y	
18.3.3	C Library	Y	
18.4	Integer types		
18.4.1	Header `<cstdint>` synopsis	Y	
18.5	Start and termination	Partial	C library dependency for quick_exit, at_quick_exit
18.6	Dynamic memory management	Y	
18.7	Type identification		
18.7.1	Class type_info	Y	
18.7.2	Class bad_cast	Y	
18.7.3	Class bad_typeid	Y	
18.8	Exception handling		
18.8.1	Class exception	Y	
18.8.2	Class bad_exception	Y	
18.8.3	Abnormal termination	Y	
18.8.4	`uncaught_exception`	Y	
18.8.5	Exception Propagation	Y	
18.8.6	`nested_exception`	Y	
18.9	Initializer lists		
18.9.1	Initializer list constructors	Y	
18.9.2	Initializer list access	Y	
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18.10	Other runtime support	Y	
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19.3	Assertions	Y	
19.4	Error numbers	Y	
19.5	System error support		
19.5.1	Class `error_category`	Y	
19.5.2	Class `error_code`	Y	
19.5.3	Class `error_condition`	Y	
19.5.4	Comparison operators	Y	
19.5.5	Class `system_error`	Y	
20	*General utilities*		
20.1	General		
20.2	Utility components		
20.2.1	Operators	Y	
20.2.2	swap	Y	
20.2.3	exchange	Y	
20.2.4	forward/move helpers	Y	
20.2.5	Function template `declval`	Y	
20.3	Pairs	Y	
20.4	Tuples	Y	
20.5	Compile-time integer sequences		
20.5.2	Class template	Y	

Paper	Title	Status	Comments
N3662	C++ Dynamic Arrays	N	Array Extensions TS
N3793	A proposal to add a utility class to represent optional objects	Y	Library Fundamentals TS
N3804	Any library proposal	Y	Library Fundamentals TS
N3866	Invocation type traits, but dropping function_call_operator.	N	Library Fundamentals TS
N3905	Faster string searching (Boyer-Moore et al.)	Y	Library Fundamentals TS
N3915	apply() call a function with arguments from a tuple	Y	Library Fundamentals TS
N3916	Polymorphic memory resources	Partial (missing pool resource and buffer resource classes)	Library Fundamentals TS
N3920	Extending shared_ptr to support arrays	Y	Library Fundamentals TS
N3921	`string_view`: a non-owning reference to a string	Y	Library Fundamentals TS
N3925	A sample proposal	Y	Library Fundamentals TS
N3932	Variable Templates For Type Traits	Y	Library Fundamentals TS
N4100	File System	Y	Link with -lstdc++fs

Table 1.4: C++ Technical Specifications Implementation Status

1.1.4 C++ 2017

In this implementation the `-std=gnu++17` or `-std=c++17` flag must be used to enable language and library features. See dialect options. The pre-defined symbol `__cplusplus` is used to check for the presence of the required flag. GCC 9.1 was the first release with non-experimental C++17 support, so the API and ABI of features added in C++17 is only stable since that release.

This section describes the C++17 and library TS support in mainline GCC, not in any particular release.

The following table lists new library features that are included in the C++17 standard. The "Proposal" column provides a link to the ISO C++ committee proposal that describes the feature, while the "Status" column indicates the first version of GCC that contains an implementation of this feature (if it has been implemented). The "SD-6 Feature Test" column shows the corresponding macro or header from SD-6: Feature-testing recommendations for C++.

Note 1: This feature is supported in GCC 7.1 and 7.2 but before GCC 7.3 the `__cpp_lib` macro is not defined, and compilation will fail if the header is included without using `-std` to enable C++17 support.

Note 2: This feature is supported in older releases but the `__cpp_lib` macro is not defined to the right value (or not defined at all) until the version shown in parentheses.

Note 3: The Parallel Algorithms have an external dependency on Intel TBB 2018 or later. If the `<execution>` header is included then `-ltbb` must be used to link to TBB.

Note 4: The mathematical special functions are enabled in C++17 mode from GCC 7.1 onwards. For GCC 6.x or for C++11/C++14 define `__STDCPP_WANT_MATH_SPEC_FUNCS__` to a non-zero value and test for `__STDCPP_MATH_SPEC_FUNCS__ >= 201003L`.

The following status table is based on the table of contents of ISO/IEC 14882:2017. Some subclauses are not shown in the table where the content is unchanged since C++14 and the implementation is complete.

Library Feature	Proposal	Status	SD-6 Feature Test
constexpr std::hardware_{constructive,destructive}_interference_size	P0154R1	12.1	__cpp_lib_hardware_interfe >= 201603
Core Issue 1776: Replacement of class objects containing reference members	P0137R1	7.1	__cpp_lib_launder >= 201606
Wording for std::uncaught_exceptions	N4259	6.1	__cpp_lib_uncaught_excepti >= 201411
C++17 should refer to C11 instead of C99	P0063R3	9.1	
Variant: a type-safe union for C++17	P0088R3	7.1	__has_include(<variant>), __cpp_lib_variant >= 201603 (since 7.3, see Note 1)
Library Fundamentals V1 TS Components: optional	P0220R1	7.1	__has_include(<optional>), __cpp_lib_optional >= 201603 (since 7.3, see Note 1)
Library Fundamentals V1 TS Components: any	P0220R1	7.1	__has_include(<any>), __cpp_lib_any >= 201603 (since 7.3, see Note 1)
Library Fundamentals V1 TS Components: string_view	P0220R1	7.1	__has_include(<string_view __cpp_lib_string_view >= 201603 (since 7.3, see Note 1)
Library Fundamentals V1 TS Components: memory_resource	P0220R1	9.1	__has_include(<memory_reso __cpp_lib_memory_resource >= 201603
Library Fundamentals V1 TS Components: apply	P0220R1	7.1	__cpp_lib_apply >= 201603
Library Fundamentals V1 TS Components: shared_ptr<T[]>	P0220R1	7.1	__cpp_lib_shared_ptr_array >= 201603
Library Fundamentals V1 TS Components: Searchers	P0220R1	7.1	__cpp_lib_boyer_moore_sear >= 201603
Library Fundamentals V1 TS Components: Sampling	P0220R1	7.1	__cpp_lib_sample >= 201603
Constant View: A proposal for a std::as_const helper function template	P0007R1	7.1	__cpp_lib_as_const >= 201510
Improving pair and tuple	N4387	6.1	N/A
make_from_tuple: apply for construction	P0209R2	7.1	__cpp_lib_make_from_tuple >= 201606
Removing auto_ptr, random_shuffle(), And Old <functional> Stuff	N4190	No (kept for backwards compatibility)	
Deprecating Vestigial Library Parts in C++17	P0174R2	12.1	
Making std::owner_less more flexible	P0074R0	7.1	__cpp_lib_transparent_oper >= 201510
std::addressof should be constexpr	LWG2296	7.1	__cpp_lib_addressof_conste >= 201603
Safe conversions in unique_ptr<T[]>	N4089	6	
LWG 2228: Missing SFINAE rule in unique_ptr templated assignment	N4366	6	
Re-enabling	[illegible]	[illegible]	__cpp_lib_enable_shared_fr

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21.1	General		
21.2	Common definitions		
21.3	Implementation properties		
21.3.1	General		
21.3.2	Header <limits> synopsis		
21.3.3	Floating-point type properties		
21.3.3.1	float_round_style	N	
21.3.3.2	float_denorm_style	N	
21.3.4	Class template numeric_limits	Y	
21.3.5	Header <climits> synopsis	Y	
21.3.6	Header <cfloat> synopsis	Y	
21.4	Integer types		
21.4.1	Header <cstdint> synopsis	Y	
21.5	Start and termination	Partial	C library dependency for quick_exit, at_quick_exit
21.6	Dynamic memory management		
21.6.1	Header <new> synopsis		
21.6.2	Storage allocation and deallocation	Y	
21.6.3	Storage allocation errors	Y	
21.6.4	Pointer optimization barrier	Y	
21.6.5	Hardware interference size	Y	
21.7	Type identification	Y	
21.8	Exception handling		
21.8.1	Header <exception> synopsis		
21.8.2	Class exception	Y	
21.8.3	Class bad_exception	Y	
21.8.4	Abnormal termination	Y	
21.8.5	uncaught_exceptions	Y	
21.8.6	Exception Propagation	Y	
21.8.7	nested_exception	Y	
21.9	Initializer lists	Y	
21.10	Other runtime support	Y	
22	*Diagnostics*		
22.1	General		
22.2	Exception classes	Y	
22.3	Assertions	Y	
22.4	Error numbers	Y	
22.5	System error support		
23	*General utilities*		
23.1	General		
23.2	Utility components		
23.2.1	Header <utility> synopsis		
23.2.2	Operators	Y	
23.2.3	swap	Y	
23.2.4	exchange	Y	
23.2.5	Forward/move helpers	Y	
23.2.6	Function template as_const	Y	
23.2.7	Function template declval	Y	
			Floating-point types up to 64-bit are formatted using

Paper	Title	Status	Comments
N4076	A generalized callable negator	Y	Library Fundamentals 2 TS
N4273	Uniform Container Erasure	Y	Library Fundamentals 2 TS
N4061	Greatest Common Divisor and Least Common Multiple	Y	Library Fundamentals 2 TS
N4066	Delimited iterators	Y	Library Fundamentals 2 TS
N4282	The World's Dumbest Smart Pointer	Y	Library Fundamentals 2 TS
N4388	Const-Propagating Wrapper	Y	Library Fundamentals 2 TS
N4391	make_array, revision 4	Y	Library Fundamentals 2 TS
N4502	Support for the C++ Detection Idiom, V2	Y	Library Fundamentals 2 TS
N4519	Source-Code Information Capture	Y	Library Fundamentals 2 TS
N4521	Merge Fundamentals V1 into V2	N (components from V1 are still in namespace fundamentals_v1)	Library Fundamentals 2 TS
P0013R1	Logical Operator Type Traits (revision 1)	Y	Library Fundamentals 2 TS
N4531	std::rand replacement, revision 3	Y	Library Fundamentals 2 TS
P0214R9	Data-Parallel Types	Y	Parallelism 2 TS

Table 1.7: C++ Technical Specifications Implementation Status

1.1.4.1 Implementation Specific Behavior

For behaviour which is also specified by previous standards, see C++ 1998/2003 Implementation Specific Behavior and C++ 2011 Implementation Specific Behavior. This section only documents behaviour which is new in the 2017 standard.

20.5.1.2 [headers] Whether names from Annex K are declared by C++ headers depends on whether the underlying C library supports Annex K and declares the names. For the GNU C library, there is no Annex K support and so none of its names are declared by C++ headers.

23.6.5 [optional.bad_optional_access] what() returns "bad optional access".

23.7.3 [variant.variant] variant supports over-aligned types.

23.7.10 [variant.bad.access] what() returns one of the strings "std::get: variant is valueless", "std::get: wrong index for variant", "std::visit: variant is valueless", or "std::visit<R>: variant is valueless".

23.8.2 [any.bad_any_cast] what() returns "bad any_cast".

23.12.5 [mem.res.pool.options], 23.12.5 [mem.res.pool.mem] Let S equal numeric_limits<size_t>::digits. The limit for maximum number of blocks in a chunk is given by 2^N-1, where N is min(19, 3 + S/2). The largest allocation size that will be allocated from a pool is 2^{22} when S > 20, otherwise 3072 when S > 16, otherwise 768.

23.12.6.1 [mem.res.monotonic.buffer.ctor] The default next_buffer_size is 128 * sizeof(void*). The default growth factor is 1.5.

23.15.4.3 [meta.unary.prop] The predicate condition for has_unique_object_representations is true for all scalar types except floating point types.

23.19.3 [execpol.type], 28.4.3 [algorithms.parallel.exec] There are no implementation-defined execution policies.

24.4.2 [string.view.template] basic_string_view<C, T>::iterator is C* and basic_string_view<C, T>::const_ is const C*.

28.4.3 [algorithms.parallel.exec] Threads of execution created by std::thread provide concurrent forward progress guarantees, so threads of execution implicitly created by the library will provide parallel forward progress guarantees.

29.4.1 [cfenv.syn] The effects of the <cfenv> functions depends on whether the FENV_ACCESS pragma is supported, and on the C library that provides the header.

29.6.9 [c.math.rand] Whether the rand function may introduce data races depends on the target C library that provides the function.

29.9.5 [sf.cmath] Calling the mathematical special functions with large inputs is supported but the results may be imprecise.

30.7.5.2.3 [ostream.inserters] NTCTS for nullptr_t is "nullptr".

30.10.2.1 [fs.conform.9945], *30.10.2.2 [fs.conform.os]* The behavior of the filesystem library implementation will depend on the target operating system. Some features will not be supported on some targets. Symbolic links and file permissions are not supported on Windows.

30.10.5 [fs.filesystem.syn] The clock used for file times is an unspecified type with a signed 64-bit representation, capable of representing timestamps with nanosecond resolution. The clock's epoch is unspecified, but is not the same as the system clock's epoch.

30.10.7.1 [fs.path.generic] dot-dot in the root-directory refers to the root-directory itself. On Windows, a drive specifier such as "C:" or "z:" is treated as a root-name. On Cygwin, a path that begins with two successive directory separators is a root-name. Otherwise (for POSIX-like systems other than Cygwin), the implementation-defined root-name is an unspecified string which does not appear in any pathnames.

30.10.10.1 [fs.enum.path.format] The character sequence is always interpreted in the native pathname format.

30.10.15.4 [fs.op.file_size] If !is_regular_file(p), an error is reported.

30.10.15.32 [fs.op.rename] On Windows, filesystem::rename is implemented by calling MoveFileExW and so does not meet the requirements of POSIX rename when one or both of the paths resolves to an existing directory. Specifically, it is not possible to rename a directory to replace another directory (POSIX requires that to work if the directory being replaced is empty).

30.10.29.2 [fs.enum.file_type], *30.10.34.3 [fs.op.copy]*, *30.10.34.35 [fs.op.status]* No additional file types are supported, and there are no implementation-defined enumerators in std::filesystem::file_type.

30.10.32 [fs.class.directory_iterator], *30.10.33 [fs.class.rec.dir.itr]* Any directory-like file types supported by opendir/readdir (or _wopendir/_wreaddir on Windows).

1.1.4.1.1 Parallelism 2 TS

9.3 [parallel.simd.abi] max_fixed_size<T> is 32, except when targetting AVX512BW and sizeof(T) is 1.

When targeting 32-bit x86, simd_abi::compatible<T> is an alias for simd_abi::scalar. When targeting 64-bit x86 (including x32) or Aarch64, simd_abi::compatible<T> is an alias for simd_abi::_VecBuiltin<16>, unless T is long double, in which case it is an alias for simd_abi::scalar. When targeting ARM (but not Aarch64) with NEON support, simd_abi::compatible<T> is an alias for simd_abi::_VecBuiltin<16>, unless sizeof(T) > 4, in which case it is an alias for simd_abi::scalar. Additionally, simd_abi::compatible<float> is an alias for simd_abi::scalar unless compiling with -ffast-math.

When targeting x86 (both 32-bit and 64-bit), simd_abi::native<T> is an alias for one of simd_abi::scalar, simd_abi::_ simd_abi::_VecBuiltin<32>, or simd_abi::_VecBltnBtmsk<64>, depending on T and the machine options the compiler was invoked with.

When targeting ARM/Aarch64 or POWER, simd_abi::native<T> is an alias for simd_abi::scalar or simd_abi::_VecB depending on T and the machine options the compiler was invoked with.

For any other targeted machine simd_abi::compatible<T> and simd_abi::native<T> are aliases for simd_abi::scala (subject to change)

The extended ABI tag types defined in the std::experimental::parallelism_v2::simd_abi namespace are: simd_abi::_VecBuiltin<Bytes>, and simd_abi::_VecBltnBtmsk<Bytes>.

simd_abi::deduce<T, N, Abis...>::type, with N > 1 is an alias for an extended ABI tag, if a supported extended ABI tag exists. Otherwise it is an alias for simd_abi::fixed_size<N>. The simd_abi::_VecBltnBtmsk ABI tag is preferred over simd_abi::_VecBuiltin.

9.4 [parallel.simd.traits] memory_alignment<T, U>::value is sizeof(U) * T::size() rounded up to the next power-of-two value.

9.6.1 [parallel.simd.overview] On ARM, simd<T, _VecBuiltin<Bytes>> is supported if __ARM_NEON is defined and sizeof(T) <= 4. Additionally, sizeof(T) == 8 with integral T is supported if __ARM_ARCH >= 8, and double is supported if __aarch64__ is defined. On POWER, simd<T, _VecBuiltin<Bytes>> is supported if __ALTIVEC__ is defined and sizeof(T) < 8. Additionally, double is supported if __VSX__ is defined, and any T with sizeof(T) <= 8 is supported if __POWER8_VECTOR__ is defined. On x86, given an extended ABI tag Abi, simd<T, Abi> is supported according to the following table:

ABI tag Abi	**value type T**	**values for Bytes**	**required machine option**
_VecBuiltin<Bytes>	float	8, 12, 16	"-msse"
		20, 24, 28, 32	"-mavx"
	double	16	"-msse2"
		24, 32	"-mavx"
	integral types other than bool	Bytes $\leq$ 16 and Bytes divisible by sizeof(T)	"-msse2"
		16 < Bytes $\leq$ 32 and Bytes divisible by sizeof(T)	"-mavx2"
_VecBuiltin<Bytes> and _VecBltnBtmsk<Bytes>	vectorizable types with sizeof(T) $\geq$ 4	32 < Bytes $\leq$ 64 and Bytes divisible by sizeof(T)	"-mavx512f"
	vectorizable types with sizeof(T) < 4		"-mavx512bw"
_VecBltnBtmsk<Bytes>	vectorizable types with sizeof(T) $\geq$ 4	Bytes $\leq$ 32 and Bytes divisible by sizeof(T)	"-mavx512vl"
	vectorizable types with sizeof(T) < 4		"-mavx512bw" and "-mavx512vl"

Table 1.8: Support for Extended ABI Tags

1.1.5 C++ 2020

In this implementation the -std=gnu++20 or -std=c++20 flag must be used to enable language and library features. See dialect options. The pre-defined symbol __cplusplus is used to check for the presence of the required flag.

This section describes the C++20 and library TS support in mainline GCC, not in any particular release.

The following table lists new library features that are included in the C++20 standard. The "Proposal" column provides a link to the ISO C++ committee proposal that describes the feature, while the "Status" column indicates the first version of GCC that contains an implementation of this feature (if it has been implemented). A dash (—) in the status column indicates that the changes in the proposal either do not affect the code in libstdc++, or the changes are not required for conformance. The "SD-6 Feature Test / Notes" column shows the corresponding macro or header from SD-6: Feature-testing recommendations for C++ (where applicable) or any notes about the implementation.

Note 1: This feature is supported in older releases but the __cpp_lib macro is not defined to the right value (or not defined at all) until the version shown in parentheses.

Note 2: The C++20 calendar types are supported since 11.1, time zones and UTC are supported since 13.1, and chrono::parse is supported since 14.1.

The following status table is based on the table of contents of ISO/IEC 14882:2020. Some subclauses are not shown in the table where the content is unchanged since C++17 and the implementation is complete.

Library Feature	Proposal	Status	SD-6 Feature Test / Notes
Compile-time programming			
Add constexpr modifiers to functions in <algorithm> and <utility> Headers	P0202R3	10.1	__cpp_lib_constexpr_algori >= 201703L
Constexpr for swap and swap related functions	P0879R0	10.1	__cpp_lib_constexpr_algori >= 201806L
Constexpr for std::complex	P0415R1	9.1	__cpp_lib_constexpr_comple >= 201711L (since 9.4, see Note 1)
std::is_constant_evaluated()	P0595R2	9.1	__cpp_lib_is_constant_eval >= 201811L
More constexpr containers	P0784R7	10.1	__cpp_lib_constexpr_dynami >= 201907L
Making std::string constexpr	P0980R1	12.1	__cpp_lib_constexpr_string >= 201907L
Making std::vector constexpr	P1004R2	12.1	__cpp_lib_constexpr_vector >= 201907L
Constexpr in std::pointer_traits	P1006R1	9.1	__cpp_lib_constexpr_memory >= 201811L (since 9.4, see Note 1)
constexpr for <numeric> algorithms	P1645R1	10.1	__cpp_lib_constexpr_numeri >= 201911L
Constexpr iterator requirements	P0858R0	9.1	__cpp_lib_array_constexpr >= 201803L __cpp_lib_string_view >= 201803L (both since 9.4, see Note 1)
constexpr comparison operators for std::array	P1023R0	10.1	__cpp_lib_array_constexpr >= 201806
Misc constexpr bits	P1032R1	10.1	__cpp_lib_array_constexpr >= 201811L __cpp_lib_constexpr_funct >= 201811L __cpp_lib_constexpr_itera >= 201811L __cpp_lib_constexpr_strin >= 201811L __cpp_lib_constexpr_tuple >= 201811L __cpp_lib_constexpr_utili >= 201811L
constexpr *INVOKE*	P1065R2	10.1	__cpp_lib_constexpr_functi >= 201907L
Transformation Trait remove_cvref	P0550R2	9.1	__cpp_lib_remove_cvref >= 201711L (since 9.4, see Note 1)
Implicit conversion traits and utility functions	P0758R1	9.1	__cpp_lib_is_nothrow_conve >= 201806L (since 9.4, see Note 1)
The identity metafunction	P0887R1	9.1	__cpp_lib_type_identity >= 201806L (since 9.4, see Note 1)
unwrap_ref_decay and unwrap_reference	P0318R1	9.1	__cpp_lib_unwrap_ref >= 201811L (since 9.4, see Note 1)
Improving Completeness Requirements for Type Traits	P1285R0	—	Most misuses are diagnosed, but not all.
Missing feature test macros	P1353R0	9.1	
Making			

Section	Description	Status	Comments
17	*Language support library*		
17.1	General		
17.2	Common definitions		
17.2.1	Header <cstddef> synopsis	Y	
17.2.2	Header <cstdlib> synopsis	Y	
17.2.3	Null pointers	Y	
17.2.4	Sizes, alignments, and offsets	Y	
17.2.5	byte type operations	Y	
17.3	Implementation properties		
17.3.1	General		
17.3.2	Header <version> synopsis	Y	
17.3.3	Header <limits> synopsis	Y	
17.3.4	Floating-point type properties		
17.3.4.1	Type float_round_style	N	
17.3.4.2	Type float_denorm_style	N	
17.3.5	Class template numeric_limits	Y	
17.3.6	Header <climits> synopsis	Y	
17.3.7	Header <cfloat> synopsis	Y	
17.4	Integer types		
17.4.1	General		
17.4.2	Header <cstdint> synopsis	Y	
17.5	Startup and termination	Partial	C library dependency for quick_exit, at_quick_exit
17.6	Dynamic memory management	Y	
17.7	Type identification	Y	
17.8	Source location		
17.8.1	Header <source_location> synopsis	Y	
17.8.2	Class source_location	Y	
17.9	Exception handling	Y	
17.10	Initializer lists	Y	
17.11	Comparisons		
17.11.1	Header <compare> synopsis	Y	
17.11.2	Comparison category types	Y	
17.11.3	Class template common_comparison_category	Y	
17.11.4	Concept three_way_comparable	Y	
17.11.5	Result of three-way comparison	Y	
17.11.6	Comparison algorithms	Y	
17.12	Coroutines		
17.12.1	General		
17.12.2	Header <coroutine> synopsis	Y	
17.12.3	Coroutine traits	Y	
17.12.4	Class template	Y	

1.1.5.1 Implementation Specific Behavior

For behaviour which is also specified by previous standards, see C++ 1998/2003 Implementation Specific Behavior, C++ 2011 Implementation Specific Behavior, and C++ 2017 Implementation Specific Behavior. This section only documents behaviour which is new in the 2020 standard.

16.4.2.4 [compliance] The implementation is freestanding if the `-ffreestanding` compiler flag is used, and hosted otherwise.

16.4.2.4 [compliance] The support for always lock-free integral atomic types and presence of `atomic_signed_lock_free` and `atomic_unsigned_lock_free` type aliases depends on the target.

27.5.11 [time.duration.io] The `"µs"` (`"\u00b5\u0073"`) is used for `std::micro Period::type` if the macro `_GLIBCXX_USE` is defined to a value other than zero before inclusion of the `chrono` header, `"us"` is used otherwise.

29.8.2.2 [stringbuf.cons] Sequence pointers are initialized to null pointers by the `basic_stringbuf(ios_base::openmode)` constructor.

31.7.1 [atomics.ref.generic.general], *31.7.3 [atomics.ref.int]*, *31.7.4 [atomics.ref.float]*, *31.7.5 [atomics.ref.pointer]* The values of `is_always_lock_free` members depend on the target and cannot be listed here.

31.7.1 [atomics.ref.generic.general] If `sizeof(T)` is equal to either `1`, `2`, `4`, `8`, or `16`, then the value of `required_alignment` member is equal to the maximum of `alignof(T)` and `sizeof(T)`. Otherwise `required_alignment` value is `alignof(T)`.

31.7.3 [atomics.ref.int] The value of `required_alignment` member is equal to the maximum of `alignof(value_type)` and `sizeof(value_type)`.

31.7.4 [atomics.ref.float], *31.7.5 [atomics.ref.pointer]* The value of `required_alignment` member is equal to `alignof(value_t`

32.7.3 [thread.sema.cnt] The value of default argument for the `least_max_value` parameter depends on the target operating system and platform, however the value of `counting_semaphore<>::max()` is greater than or equal to `numeric_limits<int`

1.1.6 C++ 2023

In this implementation the `-std=gnu++23` or `-std=c++23` flag must be used to enable language and library features. See dialect options. The pre-defined symbol `__cplusplus` is used to check for the presence of the required flag.

This section describes the C++23 and library TS support in mainline GCC, not in any particular release.

The following table lists new library features that have been accepted into the C++23 working draft. The "Proposal" column provides a link to the ISO C++ committee proposal that describes the feature, while the "Status" column indicates the first version of GCC that contains an implementation of this feature (if it has been implemented). A dash (—) in the status column indicates that the changes in the proposal either do not affect the code in libstdc++, or the changes are not required for conformance. The "SD-6 Feature Test / Notes" column shows the corresponding macro or header from SD-6: Feature-testing recommendations for C++ (where applicable) or any notes about the implementation.

1.1.7 C++ TR1

This table is based on the table of contents of ISO/IEC DTR 19768, Doc No: N1836=05-0096, Date: 2005-06-24, "Draft Technical Report on C++ Library Extensions".

In this implementation the header names are prefixed by `tr1/`, for instance `<tr1/functional>`, `<tr1/memory>`, and so on.

This page describes the TR1 support in mainline GCC, not in any particular release.

1.1.7.1 Implementation Specific Behavior

For behaviour which is specified by the 1998 and 2003 standards, see C++ 1998/2003 Implementation Specific Behavior. This section documents behaviour which is required by TR1.

3.6.4 [tr.func.bind.place]/1 There are 29 placeholders defined and the placeholder types are `Assignable`.

Library Feature	Proposal	Status	SD-6 Feature Test / Notes
Ranges and Views			
Range constructor for std::string_view	P1989R2	11.1	
`join_view` should join all views of ranges	P2328R1	11.2	
Clarifying range adaptor objects	P2281R1	11.1	
Views should not be required to be default constructible	P2325R3	11.3	`__cpp_lib_ranges >= 202106L`
Conditionally borrowed ranges	P2017R1	11.1	
Require `span` & `basic_string_view` to be Trivially Copyable	P2251R1	Yes	
Repairing input range adaptors and counted_iterator	P2259R1	12.1	
Superior String Splitting	P2210R2	12.1	
What is a `view`?	P2415R2	12.1	`__cpp_lib_ranges >= 202110L`
Fix istream_view	P2432R1	12.1	
`starts_with` and `ends_with`	P1659R3		`__cpp_lib_ranges_starts_en >= 202106L`
`zip`	P2321R2	13.1	`__cpp_lib_ranges_zip >= 202110L`
`views::repeat`	P2474R2	13.1	`__cpp_lib_ranges_repeat >= 202207L`
`views::enumerate`	P2164R9	13.1	`__cpp_lib_ranges_enumerate >= 202302L`
`views::join_with`	P2441R2	13.1	`__cpp_lib_ranges_join_with >= 202202L`
Windowing range adaptors: `views::chunk` and `views::slide`	P2442R1	13.1	`__cpp_lib_ranges_slide >= 202202L`
`views::chunk_by`	P2443R1	13.1	`__cpp_lib_ranges_chunk_by >= 202202L`
`views::stride`	P1899R3	13.1	`__cpp_lib_ranges_stride >= 202207L`
`views::cartesian_product`	P2374R4	13.1	`__cpp_lib_ranges_cartesian >= 202207L`
Empty Product for certain Views	P2540R1	13.1	`__cpp_lib_ranges_cartesian >= 202207L`
`views::as_rvalue`	P2446R2	13.1	`__cpp_lib_ranges_as_rvalue >= 202207L`
`cbegin` should always return a constant iterator	P2278R4	13.1	`__cpp_lib_ranges_as_const >= 202207L`
`ranges::to`	P1206R7	14.1 (`ranges::to` function) 15.1 (new members in containers)	`__cpp_lib_ranges_to_contai >= 202202L`, `__cpp_lib_containers_range >= 202202L`
Ranges iterators as inputs to non-Ranges algorithms	P2408R5		`__cpp_lib_algorithm_iterat >= 202207L`
Pipe support for user-defined range adaptors	P2387R3	13.1	`__cpp_lib_bind_pack >= 202202L`, `__cpp_lib_ranges >= 202202L`
`ranges::iota`, `ranges::shift_left`, and `ranges::shift_right`	P2440R1	13.1 (`ranges::iota`)	`__cpp_lib_ranges_iota >= 202202L`, `__cpp_lib_shift >= 202202L`
`ranges::find_last`	P1223R5	13.1	`__cpp_lib_ranges_find_last`

Section	Description	Status	Comments
2	*General Utilities*		
2.1	Reference wrappers		
2.1.1	Additions to header `<functional>` synopsis	Y	
2.1.2	Class template `reference_wrapper`		
2.1.2.1	`reference_wrapper` construct/copy/destroy	Y	
2.1.2.2	`reference_wrapper` assignment	Y	
2.1.2.3	`reference_wrapper` access	Y	
2.1.2.4	`reference_wrapper` invocation	Y	
2.1.2.5	`reference_wrapper` helper functions	Y	
2.2	Smart pointers		
2.2.1	Additions to header `<memory>` synopsis	Y	
2.2.2	Class `bad_weak_ptr`	Y	
2.2.3	Class template `shared_ptr`		Uses code from boost::shared_ptr.
2.2.3.1	`shared_ptr` constructors	Y	
2.2.3.2	`shared_ptr` destructor	Y	
2.2.3.3	`shared_ptr` assignment	Y	
2.2.3.4	`shared_ptr` modifiers	Y	
2.2.3.5	`shared_ptr` observers	Y	
2.2.3.6	`shared_ptr` comparison	Y	
2.2.3.7	`shared_ptr` I/O	Y	
2.2.3.8	`shared_ptr` specialized algorithms	Y	
2.2.3.9	`shared_ptr` casts	Y	
2.2.3.10	`get_deleter`	Y	
2.2.4	Class template `weak_ptr`		
2.2.4.1	`weak_ptr` constructors	Y	
2.2.4.2	`weak_ptr` destructor	Y	
2.2.4.3	`weak_ptr` assignment	Y	
2.2.4.4	`weak_ptr` modifiers	Y	
2.2.4.5	`weak_ptr` observers	Y	
2.2.4.6	`weak_ptr` comparison	Y	
2.2.4.7	`weak_ptr` specialized algorithms	Y	
2.2.5	Class template `enable_shared_from_this`	Y	
3	*Function Objects*		
3.1	Definitions	Y	
3.2	Additions to `<functional> synopsis`	Y	
3.3	Requirements	Y	
3.4	Function return types	Y	
3.5	Function template `mem_fn`	Y	
3.6	Function object binders		
3.6.1	Class template `is_bind_expression`	Y	
3.6.2	Class template `is_placeholder`	Y	
3.6.3	Function template `bind`	Y	
3.6.4	Placeholders	Y	
3.7	Polymorphic function wrappers		
3.7.1	Class	Y	

1.1.8 C++ TR 24733

This table is based on the table of contents of ISO/IEC TR 24733:2011, "Extensions for the programming language C++ to support decimal floating-point arithmetic".

This page describes the TR 24733 support in mainline GCC, not in any particular release.

1.1.9 C++ IS 29124

This table is based on the table of contents of ISO/IEC FDIS 29124, Doc No: N3060, Date: 2010-03-06, "Extensions to the C++ Library to support mathematical special functions".

Complete support for IS 29124 is in GCC 6.1 and later releases, when using at least C++11 (for older releases or C++98/C++03 use TR1 instead). For C++11 and C++14 the additions to the library are not declared by their respective headers unless `__STDCPP_WANT_MATH_SPEC_FUNCS__` is defined as a macro that expands to a non-zero integer constant. For C++17 the special functions are always declared (since GCC 7.1).

When the special functions are declared the macro `__STDCPP_MATH_SPEC_FUNCS__` is defined to `201003L`.

In addition to the special functions defined in IS 29124, for non-strict modes (i.e. `-std=gnu++NN` modes) the hypergeometric functions and confluent hypergeometric functions from TR1 are also provided, defined in namespace `__gnu_cxx`.

1.1.9.1 Implementation Specific Behavior

For behaviour which is specified by the 2011 standard, see C++ 2011 Implementation Specific Behavior. This section documents behaviour which is required by IS 29124.

7.2 [macro.user]/3 /4 The functions declared in Clause 8 are only declared when `__STDCPP_WANT_MATH_SPEC_FUNCS__ == 1` (or in C++17 mode, for GCC 7.1 and later).

8.1.1 [sf.cmath.Lnm]/1 The effect of calling these functions with `n >= 128` or `m >= 128` should be described here.

8.1.2 [sf.cmath.Plm]/3 The effect of calling these functions with `l >= 128` should be described here.

8.1.3 [sf.cmath.I]/3 The effect of calling these functions with `nu >= 128` should be described here.

8.1.8 [sf.cmath.J]/3 The effect of calling these functions with `nu >= 128` should be described here.

8.1.9 [sf.cmath.K]/3 The effect of calling these functions with `nu >= 128` should be described here.

8.1.10 [sf.cmath.N]/3 The effect of calling these functions with `nu >= 128` should be described here.

8.1.15 [sf.cmath.Hn]/3 The effect of calling these functions with `n >= 128` should be described here.

8.1.16 [sf.cmath.Ln]/3 The effect of calling these functions with `n >= 128` should be described here.

8.1.17 [sf.cmath.Pl]/3 The effect of calling these functions with `l >= 128` should be described here.

8.1.19 [sf.cmath.j]/3 The effect of calling these functions with `n >= 128` should be described here.

8.1.20 [sf.cmath.Ylm]/3 The effect of calling these functions with `l >= 128` should be described here.

8.1.21 [sf.cmath.n]/3 The effect of calling these functions with `n >= 128` should be described here.

1.2 License

There are two licenses affecting GNU libstdc++: one for the code, and one for the documentation.

There is a license section in the FAQ regarding common questions. If you have more questions, ask the FSF or the gcc mailing list.

Section	Description	Status	Comments
0	*Introduction*		
1	*Normative references*		
2	*Conventions*		
3	*Decimal floating-point types*		
3.1	Characteristics of decimal floating-point types		
3.2	Decimal Types		
3.2.1	Class `decimal` synopsis	Partial	Missing declarations for formatted input/output; non-conforming extension for functions converting to integral type
3.2.2	Class `decimal32`	Partial	Missing 3.2.2.5 conversion to integral type; conforming extension for conversion from scalar decimal floating-point
3.2.3	Class `decimal64`	Partial	Missing 3.2.3.5 conversion to integral type; conforming extension for conversion from scalar decimal floating-point
3.2.4	Class `decimal128`	Partial	Missing 3.2.4.5 conversion to integral type; conforming extension for conversion from scalar decimal floating-point
3.2.5	Initialization from coefficient and exponent	Y	
3.2.6	Conversion to generic floating-point type	Y	
3.2.7	Unary arithmetic operators	Y	
3.2.8	Binary arithmetic operators	Y	
3.2.9	Comparison operators	Y	
3.2.10	Formatted input	N	
3.2.11	Formatted output	N	
3.3	Additions to header `limits`	N	
3.4	Headers `cfloat` and `float.h`		
3.4.2	Additions to header `cfloat` synopsis	Y	
3.4.3	Additions to header `float.h` synopsis	N	
3.4.4	Maximum finite value	Y	
3.4.5	Epsilon	Y	
3.4.6	Minimum positive normal value	Y	
3.4.7	Minimum positive subnormal value	Y	
3.4.8	Evaluation format	Y	
3.5	Additions to `cfenv` and `fenv.h`	Outside the scope of GCC	
3.6	Additions to `cmath` and `math.h`	Outside the scope of GCC	
3.7	Additions to `cstdio` and `stdio.h`	Outside the scope of GCC	
3.8	Additions to `cstdlib` and `stdlib.h`	Outside the scope of GCC	
3.9	Additions to `cwchar` and `wchar.h`	Outside the scope of GCC	
3.10	Facets	N	
3.11	Type traits	N	

Section	Description	Status	Comments
7	Macro names	Partial	No diagnostic for inconsistent definitions of __STDCPP_WANT_MATH_SPEC_FU
8	Mathematical special functions	Y	
8.1	Additions to header <cmath> synopsis	Y	
8.1.1	associated Laguerre polynomials	Y	
8.1.2	associated Legendre functions	Y	
8.1.3	beta function	Y	
8.1.4	(complete) elliptic integral of the first kind	Y	
8.1.5	(complete) elliptic integral of the second kind	Y	
8.1.6	(complete) elliptic integral of the third kind	Y	
8.1.7	regular modified cylindrical Bessel functions	Y	
8.1.8	cylindrical Bessel functions (of the first kind)	Y	
8.1.9	irregular modified cylindrical Bessel functions	Y	
8.1.10	cylindrical Neumann functions	Y	
8.1.11	(incomplete) elliptic integral of the first kind	Y	
8.1.12	(incomplete) elliptic integral of the second kind	Y	
8.1.13	(incomplete) elliptic integral of the third kind	Y	
8.1.14	exponential integral	Y	
8.1.15	Hermite polynomials	Y	
8.1.16	Laguerre polynomials	Y	
8.1.17	Legendre polynomials	Y	
8.1.18	Riemann zeta function	Y	
8.1.19	spherical Bessel functions (of the first kind)	Y	
8.1.20	spherical associated Legendre functions	Y	
8.1.21	spherical Neumann functions	Y	
8.2	Additions to header <math.h>	Y	
8.3	The header <ctgmath>	Partial	Conflicts with C++ 2011 requirements.
8.4	The header <tgmath.h>	N	Conflicts with C++ 2011 requirements.

Table 1.14: C++ Special Functions Implementation Status

1.2.1 The Code: GPL

The source code is distributed under the GNU General Public License version 3, with the addition under section 7 of an exception described in the “GCC Runtime Library Exception, version 3.1” as follows (or see the file COPYING.RUNTIME):

```
GCC RUNTIME LIBRARY EXCEPTION

Version 3.1, 31 March 2009

Copyright (C) 2009 Free Software Foundation, Inc.

Everyone is permitted to copy and distribute verbatim copies of this
license document, but changing it is not allowed.

This GCC Runtime Library Exception ("Exception") is an additional
permission under section 7 of the GNU General Public License, version
3 ("GPLv3"). It applies to a given file (the "Runtime Library") that
bears a notice placed by the copyright holder of the file stating that
the file is governed by GPLv3 along with this Exception.

When you use GCC to compile a program, GCC may combine portions of
certain GCC header files and runtime libraries with the compiled
program. The purpose of this Exception is to allow compilation of
non-GPL (including proprietary) programs to use, in this way, the
header files and runtime libraries covered by this Exception.

0. Definitions.

A file is an "Independent Module" if it either requires the Runtime
Library for execution after a Compilation Process, or makes use of an
interface provided by the Runtime Library, but is not otherwise based
on the Runtime Library.

"GCC" means a version of the GNU Compiler Collection, with or without
modifications, governed by version 3 (or a specified later version) of
the GNU General Public License (GPL) with the option of using any
subsequent versions published by the FSF.

"GPL-compatible Software" is software whose conditions of propagation,
modification and use would permit combination with GCC in accord with
the license of GCC.

"Target Code" refers to output from any compiler for a real or virtual
target processor architecture, in executable form or suitable for
input to an assembler, loader, linker and/or execution
phase. Notwithstanding that, Target Code does not include data in any
format that is used as a compiler intermediate representation, or used
for producing a compiler intermediate representation.

The "Compilation Process" transforms code entirely represented in
non-intermediate languages designed for human-written code, and/or in
Java Virtual Machine byte code, into Target Code. Thus, for example,
use of source code generators and preprocessors need not be considered
part of the Compilation Process, since the Compilation Process can be
understood as starting with the output of the generators or
preprocessors.
```

```
A Compilation Process is "Eligible" if it is done using GCC, alone or
with other GPL-compatible software, or if it is done without using any
work based on GCC. For example, using non-GPL-compatible Software to
optimize any GCC intermediate representations would not qualify as an
Eligible Compilation Process.

1. Grant of Additional Permission.

You have permission to propagate a work of Target Code formed by
combining the Runtime Library with Independent Modules, even if such
propagation would otherwise violate the terms of GPLv3, provided that
all Target Code was generated by Eligible Compilation Processes. You
may then convey such a combination under terms of your choice,
consistent with the licensing of the Independent Modules.

2. No Weakening of GCC Copyleft.

The availability of this Exception does not imply any general
presumption that third-party software is unaffected by the copyleft
requirements of the license of GCC.
```

Hopefully that text is self-explanatory. If it isn't, you need to speak to your lawyer, or the Free Software Foundation.

1.2.2 The Documentation: GPL, FDL

The documentation shipped with the library and made available over the web, excluding the pages generated from source comments, are copyrighted by the Free Software Foundation, and placed under the GNU Free Documentation License version 1.3. There are no Front-Cover Texts, no Back-Cover Texts, and no Invariant Sections.

For documentation generated by doxygen or other automated tools via processing source code comments and markup, the original source code license applies to the generated files. Thus, the doxygen documents are licensed GPL.

If you plan on making copies of the documentation, please let us know. We can probably offer suggestions.

1.3 Bugs

1.3.1 Implementation Bugs

Information on known bugs, details on efforts to fix them, and fixed bugs are all available as part of the GCC bug tracking system, under the component "libstdc++".

1.3.2 Standard Bugs

Everybody's got issues. Even the C++ Standard Library.

The Library Working Group, or LWG, is the ISO subcommittee responsible for making changes to the library. They periodically publish an Issues List containing problems and possible solutions. As they reach a consensus on proposed solutions, we often incorporate the solution.

Here are the issues which have resulted in code changes to the library. The links are to the full version of the Issues List. You can read the full version online at the ISO C++ Committee homepage.

If a DR is not listed here, we may simply not have gotten to it yet; feel free to submit a patch. Search the `include` and `src` directories for appearances of `_GLIBCXX_RESOLVE_LIB_DEFECTS` for examples of style. Note that we usually do not make changes to the code until an issue has reached DR status.

5: string::compare specification questionable This should be two overloaded functions rather than a single function.

17: Bad bool parsing Apparently extracting Boolean values was messed up...

19: "Noconv" definition too vague If `codecvt::do_in` returns `noconv` there are no changes to the values in `[to, to_limit)`.

22: Member open vs flags Re-opening a file stream does *not* clear the state flags.

23: Num_get overflow result Implement the proposed resolution.

25: String operator<< uses width() value wrong Padding issues.

48: Use of non-existent exception constructor An instance of `ios_base::failure` is constructed instead.

49: Underspecification of ios_base::sync_with_stdio The return type is the *previous* state of synchronization.

50: Copy constructor and assignment operator of ios_base These members functions are declared `private` and are thus inaccessible. Specifying the correct semantics of "copying stream state" was deemed too complicated.

60: What is a formatted input function? This DR made many widespread changes to `basic_istream` and `basic_ostream` all of which have been implemented.

63: Exception-handling policy for unformatted output Make the policy consistent with that of formatted input, unformatted input, and formatted output.

68: Extractors for char* should store null at end And they do now. An editing glitch in the last item in the list of [27.6.1.2.3]/7.

74: Garbled text for codecvt::do_max_length The text of the standard was gibberish. Typos gone rampant.

75: Contradiction in codecvt::length's argument types Change the first parameter to `stateT&` and implement the new effects paragraph.

83: string::npos vs. string::max_size() Safety checks on the size of the string should test against `max_size()` rather than `npos`.

90: Incorrect description of operator>> for strings The effect contain `isspace(c,getloc())` which must be replaced by `isspace(c,is.getloc())`.

91: Description of operator>> and getline() for string<> might cause endless loop They behave as a formatted input function and as an unformatted input function, respectively (except that `getline` is not required to set `gcount`).

103: set::iterator is required to be modifiable, but this allows modification of keys. For associative containers where the value type is the same as the key type, both `iterator` and `const_iterator` are constant iterators.

109: Missing binders for non-const sequence elements The `binder1st` and `binder2nd` didn't have an `operator()` taking a non-const parameter.

110: istreambuf_iterator::equal not const This was not a const member function. Note that the DR says to replace the function with a const one; we have instead provided an overloaded version with identical contents.

117: basic_ostream uses nonexistent num_put member functions `num_put::put()` was overloaded on the wrong types.

118: basic_istream uses nonexistent num_get member functions Same as 117, but for `num_get::get()`.

129: Need error indication from seekp() and seekg() These functions set `failbit` on error now.

130: Return type of container::erase(iterator) differs for associative containers Make member `erase` return iterator for `set`, `multiset`, `map`, `multimap`.

136: seekp, seekg setting wrong streams? `seekp` should only set the output stream, and `seekg` should only set the input stream.

167: Improper use of traits_type::length() `op<<` with a `const char*` was calculating an incorrect number of characters to write.

169: Bad efficiency of overflow() mandated Grow efficiently the internal array object.

171: Strange seekpos() semantics due to joint position Quite complex to summarize...

181: make_pair() unintended behavior This function used to take its arguments as reference-to-const, now it copies them (pass by value).

195: Should basic_istream::sentry's constructor ever set eofbit? Yes, it can, specifically if EOF is reached while skipping whitespace.

206: `operator new(size_t, nothrow)` may become unlinked to ordinary `operator new` if ordinary version replaced The `nothrow` forms of new and delete were changed to call the throwing forms, handling any exception by catching it and returning a null pointer.

211: operator>>(istream&, string&) doesn't set failbit If nothing is extracted into the string, `op>>` now sets `failbit` (which can cause an exception, etc., etc.).

214: set::find() missing const overload Both `set` and `multiset` were missing overloaded find, lower_bound, upper_bound, and equal_range functions for const instances.

231: Precision in iostream? For conversion from a floating-point type, `str.precision()` is specified in the conversion specification.

233: Insertion hints in associative containers Implement N1780, first check before then check after, insert as close to hint as possible.

235: No specification of default ctor for reverse_iterator The declaration of `reverse_iterator` lists a default constructor. However, no specification is given what this constructor should do.

241: Does unique_copy() require CopyConstructible and Assignable? Add a helper for forward_iterator/output_iterator, fix the existing one for input_iterator/output_iterator to not rely on Assignability.

243: get and getline when sentry reports failure Store a null character only if the character array has a non-zero size.

251: basic_stringbuf missing allocator_type This nested typedef was originally not specified.

253: valarray helper functions are almost entirely useless Make the copy constructor and copy-assignment operator declarations public in gslice_array, indirect_array, mask_array, slice_array; provide definitions.

265: std::pair::pair() effects overly restrictive The default ctor would build its members from copies of temporaries; now it simply uses their respective default ctors.

266: bad_exception::~bad_exception() missing Effects clause The `bad_*` classes no longer have destructors (they are trivial), since no description of them was ever given.

271: basic_iostream missing typedefs The typedefs it inherits from its base classes can't be used, since (for example) `basic_iostr` is ambiguous.

275: Wrong type in num_get::get() overloads Similar to 118.

280: Comparison of reverse_iterator to const reverse_iterator Add global functions with two template parameters. (NB: not added for now a templated assignment operator)

292: Effects of a.copyfmt (a) If `(this == &rhs)` do nothing.

300: List::merge() specification incomplete If `(this == &x)` do nothing.

303: Bitset input operator underspecified Basically, compare the input character to `is.widen(0)` and `is.widen(1)`.

305: Default behavior of codecvt<wchar_t, char, mbstate_t>::length() Do not specify what `codecvt<wchar_t, char, mbstate_t>::do_length` must return.

328: Bad sprintf format modifier in money_put<>::do_put() Change the format string to "%.0Lf".

365: Lack of const-qualification in clause 27 Add const overloads of `is_open`.

387: std::complex over-encapsulated Add the `real(T)` and `imag(T)` members; in C++11 mode, also adjust the existing `real()` and `imag()` members and free functions.

389: Const overload of valarray::operator[] returns by value Change it to return a `const T&`.

396: what are characters zero and one Implement the proposed resolution.

402: Wrong new expression in [some_]allocator::construct Replace "new" with "::new".

408: Is vector<reverse_iterator<char*> > forbidden? Tweak the debug-mode checks in _Safe_iterator.

409: Closing an fstream should clear the error state Have `open` clear the error flags.

415: Behavior of std::ws Change it to be an unformatted input function (i.e. construct a sentry and catch exceptions).

431: Swapping containers with unequal allocators Implement Option 3, as per N1599.

432: stringbuf::overflow() makes only one write position available Implement the resolution, beyond DR 169.

434: bitset::to_string() hard to use Add three overloads, taking fewer template arguments.

438: Ambiguity in the "do the right thing" clause Implement the resolution, basically cast less.

445: iterator_traits::reference unspecified for some iterator categories Change `istreambuf_iterator::reference` in C++11 mode.

453: basic_stringbuf::seekoff need not always fail for an empty stream Don't fail if the next pointer is null and newoff is zero.

455: cerr::tie() and wcerr::tie() are overspecified Initialize cerr tied to cout and wcerr tied to wcout.

464: Suggestion for new member functions in standard containers Add `data()` to `std::vector` and `at(const key_type` to `std::map`.

467: char_traits::lt(), compare(), and memcmp() Change `lt`.

508: Bad parameters for ranlux64_base_01 Fix the parameters.

512: Seeding subtract_with_carry_01 from a single unsigned long Construct a `linear_congruential` engine and seed with it.

526: Is it undefined if a function in the standard changes in parameters? Use &value.

538: 241 again: Does unique_copy() require CopyConstructible and Assignable? In case of input_iterator/output_iterator rely on Assignability of input_iterator' value_type.

539: partial_sum and adjacent_difference should mention requirements We were almost doing the right thing, just use std::move in adjacent_difference.

541: shared_ptr template assignment and void Add an auto_ptr<void> specialization.

543: valarray slice default constructor Follow the straightforward proposed resolution.

550: What should the return type of pow(float,int) be? In C++11 mode, remove the pow(float,int), etc., signatures.

581: `flush()` not unformatted function Change it to be a unformatted output function (i.e. construct a sentry and catch exceptions).

586: string inserter not a formatted function Change it to be a formatted output function (i.e. catch exceptions).

596: 27.8.1.3 Table 112 omits "a+" and "a+b" modes Add the missing modes to fopen_mode.

630: arrays of valarray Implement the simple resolution.

660: Missing bitwise operations Add the missing operations.

691: const_local_iterator cbegin, cend missing from TR1 In C++11 mode add cbegin(size_type) and cend(size_type) to the unordered containers.

693: std::bitset::all() missing Add it, consistently with the discussion.

695: ctype<char>::classic_table() not accessible Make the member functions table and classic_table public.

696: istream::operator>>(int&) broken Implement the straightforward resolution.

761: unordered_map needs an at() member function In C++11 mode, add at() and at() const.

775: Tuple indexing should be unsigned? Implement the int -> size_t replacements.

776: Undescribed assign function of std::array In C++11 mode, remove assign, add fill.

781: std::complex should add missing C99 functions In C++11 mode, add std::proj.

809: std::swap should be overloaded for array types Add the overload.

853: to_string needs updating with zero and one Update / add the signatures.

865: More algorithms that throw away information The traditional HP / SGI return type and value is blessed by the resolution of the DR.

1203: More useful rvalue stream insertion Return the stream as its original type, not the base class.

1339: uninitialized_fill_n should return the end of its range Return the end of the filled range.

2021: Further incorrect uses of `result_of` Correctly decay types in signature of `std::async`.

2049: `is_destructible` underspecified Handle non-object types.

2056: future_errc enums start with value 0 (invalid value for broken_promise) Reorder enumerators.

2059: C++0x ambiguity problem with map::erase Add additional overloads.

2062: 2062. Effect contradictions w/o no-throw guarantee of `std::function` swaps Add `noexcept` to swap functions.

2063: Contradictory requirements for string move assignment Respect propagation trait for move assignment.

2064: More noexcept issues in basic_string Add noexcept to the comparison operators.

2067: packaged_task should have deleted copy c'tor with const parameter Fix signatures.

2101: Some transformation types can produce impossible types Use the referenceable type concept.

2106: move_iterator wrapping iterators returning prvalues Change the `reference` type.

2108: No way to identify allocator types that always compare equal Define and use `is_always_equal` even for C++11.

2118: `unique_ptr` for array does not support cv qualification conversion of actual argument Adjust constraints to allow safe conversions.

2127: Move-construction with `raw_storage_iterator` Add assignment operator taking an rvalue.

2132: `std::function` ambiguity Constrain the constructor to only accept callable types.

2141: `common_type` trait produces reference types Use `decay` for the result type.

2144: Missing `noexcept` specification in `type_index` Add `noexcept`

2145: `error_category` default constructor Declare a public constexpr constructor.

2162: `allocator_traits::max_size` missing `noexcept` Add `noexcept`.

2187: `vector<bool>` is missing `emplace` and `emplace_back` member functions Add `emplace` and `emplace_back` member functions.

2192: Validity and return type of `std::abs(0u)` is unclear Move all declarations to a common header and remove the generic `abs` which accepted unsigned arguments.

2196: Specification of `is_*[copy/move]_[constructible/assignable]` unclear for non-referencable types Use the referenceable type concept.

2212: `tuple_size` for `const pair` request `<tuple>` header The `tuple_size` and `tuple_element` partial specializations are defined in `<utility>` which is included by `<array>`.

2296: `std::addressof` should be constexpr Use `__builtin_addressof` and add `constexpr` to `addressof` for C++17 and later.

2306: `match_results::reference` should be `value_type&`, not `const value_type&` Change typedef.

2313: `tuple_size` should always derive from `integral_constant<size_t, N>` Update definitions of the partial specializations for const and volatile types.

2328: Rvalue stream extraction should use perfect forwarding Use perfect forwarding for right operand.

2329: `regex_match()/regex_search()` with `match_results` should forbid temporary strings Add deleted overloads for rvalue strings.

2332: `regex_iterator/regex_token_iterator` should forbid temporary regexes Add deleted constructors.

2332: Unnecessary copying when inserting into maps with braced-init syntax Add overloads of `insert` taking `value_type&&` rvalues.

2399: `shared_ptr`'s constructor from `unique_ptr` should be constrained Constrain the constructor to require convertibility.

2400: `shared_ptr`'s `get_deleter()` should use `addressof()` Use `addressof`.

2401: `std::function` needs more `noexcept` Add `noexcept` to the assignment and comparisons.

2407: `packaged_task(allocator_arg_t, const Allocator&, F&&)` should neither be constrained nor `explicit` Remove `explicit` from the constructor.

2408: SFINAE-friendly `common_type/iterator_traits` is missing in C++14 Make `iterator_traits` empty if any of the types is not present in the iterator. Make `common_type<>` empty.

2415: Inconsistency between `unique_ptr` and `shared_ptr` Create empty an `shared_ptr` from an empty `unique_ptr`.

2418: `apply` does not work with member pointers Use `mem_fn` for member pointers.

2440: `seed_seq::size()` should be `noexcept` Add `noexcept`.

2441: Exact-width atomic typedefs should be provided Define the typedefs.

2442: `call_once()` shouldn't `DECAY_COPY()` Remove indirection through call wrapper that made copies of arguments and forward arguments straight to `std::invoke`.

2454: Add `raw_storage_iterator::base()` member Add the `base()` member function.

2455: Allocator default construction should be allowed to throw Make `noexcept` specifications conditional.

2458: N3778 and new library deallocation signatures Remove unused overloads.

2459: `std::polar` should require a non-negative rho Add debug mode assertion.

2465: SFINAE-friendly `common_type` is nearly impossible to specialize correctly and regresses key functionality Detect whether `decay_t` changes either type and use the decayed types if so.

2466: `allocator_traits::max_size()` default behavior is incorrect Divide by the object type.

2484: `rethrow_if_nested()` is doubly unimplementable Avoid using `dynamic_cast` when it would be ill-formed.

2487: `bind()` should be `const`-overloaded not *cv*-overloaded Deprecate volatile-qualified `operator()` for C++17, make it ill-formed for C++20.

2499: `operator>>(basic_istream&, CharT*)` makes it hard to avoid buffer overflows Replace `operator>>(basic_` `CharT*)` and other overloads writing through pointers.

2537: Constructors for `priority_queue` taking allocators should call `make_heap` Call `make_heap`.

2566: Requirements on the first template parameter of container adaptors Add static assertions to enforce the requirement.

2583: There is no way to supply an allocator for `basic_string(str, pos)` Add new constructor.

2586: Wrong value category used in `scoped_allocator_adaptor::construct()` Change internal helper for uses-allocator construction to always check using const lvalue allocators.

2684: `priority_queue` lacking comparator typedef Define the `value_compare` typedef.

2735: `std::abs(short)`, `std::abs(signed char)` and others should return `int` instead of `double` in order to be comp Resolved by the changes for 2192.

2770: `tuple_size<const T>` specialization is not SFINAE compatible and breaks decomposition declarations Safely detect `tuple_size<T>::value` and only use it if valid.

2781: Contradictory requirements for `std::function` and `std::reference_wrapper` Remove special handling for `reference_wrapper` arguments and store them directly as the target object.

2802: Add noexcept to several `shared_ptr` related functions Add noexcept.

2873: `shared_ptr` constructor requirements for a deleter Use rvalues for deleters.

2921: `packaged_task` and type-erased allocators For C++17 mode, remove the constructors taking an allocator argument.

2942: LWG 2873's resolution missed `weak_ptr::owner_before` Add noexcept.

2996: Missing rvalue overloads for `shared_ptr` operations Add additional constructor and cast overloads.

2993: `reference_wrapper<T>` conversion from `T&&` Replaced the constructors with a constrained template, to prevent participation in overload resolution when not valid.

3074: Non-member functions for `valarray` should only deduce from the `valarray` Change scalar operands to be non-deduced context, so that they will allow conversions from other types to the value_type.

3076: `basic_string` CTAD ambiguity Change constructors to constrained templates.

3096: `path::lexically_relative` is confused by trailing slashes Implement the fix for trailing slashes.

3656: Inconsistent bit operations returning a count Changed `bit_width` to return `int`.

Chapter 2

Setup

Transforming libstdc++ sources into installed include files and properly built binaries useful for linking to other software is done as part of building GCC. Building libstdc++ separately from the rest of GCC is not supported.

The general outline of commands to build GCC is something like:

```
get gcc sources
extract into gccsrcdir
mkdir gccbuilddir
cd gccbuilddir
gccsrcdir/configure --prefix=destdir --other-opts...
make
make check
make install
```

Each step is described in more detail in the following sections.

2.1 Prerequisites

Because libstdc++ is part of GCC, the primary source for installation instructions is the GCC install page. In particular, list of prerequisite software needed to build the library starts with those requirements. The same pages also list the tools you will need if you wish to modify the source.

Additional data is given here only where it applies to libstdc++.

To take full advantage of useful space-saving features and bug-fixes you should use a recent binutils whenever possible. The configure process will automatically detect and use these features if the underlying support is present.

To generate the API documentation from the sources you will need Doxygen, see Documentation Hacking in the appendix for full details.

Finally, a few system-specific requirements:

linux The 'gnu' locale model makes use of `iconv` for character set conversions. The relevant functions are provided by Glibc and so are always available, however they can also be provided by the separate GNU libiconv library. If GNU libiconv is found when GCC is built (e.g., because its headers are installed in `/usr/local/include`) then the `libstdc++.so.6` library will have a run-time dependency on `libiconv.so.2`. If you do not want that run-time dependency then you should do one of the following:

- Uninstall the libiconv headers before building GCC. Glibc already provides `iconv` so you should not need libiconv anyway.
- Download the libiconv sources and extract them into the top level of the GCC source tree, e.g.,

```
wget https://ftp.gnu.org/pub/gnu/libiconv/libiconv-1.16.tar.gz
tar xf libiconv-1.16.tar.gz
ln -s libiconv-1.16 libiconv
```

This will build libiconv as part of building GCC and link to it statically, so there is no `libiconv.so.2` dependency.

- Configure GCC with `--with-libiconv-type=static`. This requires the static `libiconv.a` library, which is not installed by default. You might need to reinstall libiconv using the `--enable-static` configure option to get the static library.

If GCC 3.1.0 or later on is being used on GNU/Linux, an attempt will be made to use "C" library functionality necessary for C++ named locale support, e.g. the `newlocale` and `uselocale` functions. For GCC 4.6.0 and later, this means that glibc 2.3 or later is required.

If the 'gnu' locale model is being used, the following locales are used and tested in the libstdc++ testsuites. The first column is the name of the locale, the second is the character set it is expected to use.

```
de_DE               ISO-8859-1
de_DE@euro          ISO-8859-15
en_GB               ISO-8859-1
en_HK               ISO-8859-1
en_PH               ISO-8859-1
en_US               ISO-8859-1
en_US.ISO-8859-1    ISO-8859-1
en_US.ISO-8859-15   ISO-8859-15
en_US.UTF-8         UTF-8
es_ES               ISO-8859-1
es_MX               ISO-8859-1
fr_FR               ISO-8859-1
fr_FR@euro          ISO-8859-15
is_IS               UTF-8
it_IT               ISO-8859-1
ja_JP.eucjp         EUC-JP
ru_RU.ISO-8859-5    ISO-8859-5
ru_RU.UTF-8         UTF-8
se_NO.UTF-8         UTF-8
ta_IN               UTF-8
zh_TW               BIG5
```

Failure to have installed the underlying "C" library locale information for any of the above regions means that the corresponding C++ named locale will not work: because of this, the libstdc++ testsuite will skip named locale tests which need missing information. If this isn't an issue, don't worry about it. If a named locale is needed, the underlying locale information must be installed. Note that rebuilding libstdc++ after "C" locales are installed is not necessary.

To install support for locales, do only one of the following:

- install all locales, e.g., run `dnf install glibc-all-langpacks` for Fedora and related distributions.
- install just the necessary locales
  - with Debian GNU/Linux:
    Add the above list, as shown, to the file `/etc/locale.gen`
    run `/usr/sbin/locale-gen`
  - on most Unix-like operating systems:
    `localedef -i de_DE -f ISO-8859-1 de_DE`
    (repeat for each entry in the above list)
  - Instructions for other operating systems solicited.

Some tests for the `std::messages` facet require a message catalog created by the **msgfmt** utility. That is usually installed as part of the GNU gettext library. If **msgfmt** is not available, some tests under the `22_locale/messages` directory will fail.

2.2 Configure

When configuring libstdc++, you'll have to configure the entire *gccsrcdir* directory. Consider using the toplevel gcc configuration option `--enable-languages=c++`, which saves time by only building the C++ toolchain.

Here are all of the configure options specific to libstdc++. Keep in mind that they all have opposite forms as well (enable/disable and with/without). The defaults are for the *current development sources*, which may be different than those for released versions.

The canonical way to find out the configure options that are available for a given set of libstdc++ sources is to go to the source directory and then type: **./configure --help**.

`--enable-multilib`[default] This is part of the generic multilib support for building cross compilers. As such, targets like "powerpc-elf" will have libstdc++ built many different ways: "-msoft-float" and not, etc. A different libstdc++ will be built for each of the different multilib versions. This option is on by default.

`--enable-version-specific-runtime-libs` Specify that run-time libraries should be installed in the compiler-specific subdirectory (i.e., `${libdir}/gcc-lib/${target_alias}/${gcc_version}`) instead of `${libdir}`. This option is useful if you intend to use several versions of gcc in parallel. In addition, libstdc++'s include files will be installed in `${libdir}/gcc-lib/${target_alias}/${gcc_version}/include/g++`, unless you also specify `--with-gxx-include-dir=dirname` during configuration.

`--with-gxx-include-dir=<include-files dir>` Adds support for named libstdc++ include directory. For instance, the following puts all the libstdc++ headers into a directory called "4.4-20090404" instead of the usual "c++/(version)".

```
--with-gxx-include-dir=/foo/H-x86-gcc-3-c-gxx-inc/include/4.4-20090404
```

`--enable-cstdio` This is an abbreviated form of `'--enable-cstdio=stdio'` (described next).

`--enable-cstdio=OPTION` Select a target-specific I/O package. The choices are 'stdio' which is a generic abstraction using POSIX file I/O APIs (`read`, `write`, `lseek`, etc.), and 'stdio_pure' which is similar but only uses standard C file I/O APIs (`fread`, `fwrite`, `fseek`, etc.). The 'stdio_posix' choice is a synonym for 'stdio'. The default is 'stdio'. This option can change the library ABI.

`--enable-clocale` This is an abbreviated form of `'--enable-clocale=generic'` (described next).

`--enable-clocale=OPTION` Select a target-specific underlying locale package. The choices are 'ieee_1003.1-2001' to specify an X/Open, Standard Unix (IEEE Std. 1003.1-2001) model based on langinfo/iconv/catgets, 'gnu' to specify a model based on functionality from the GNU C library (langinfo/iconv/gettext) (from glibc, the GNU C library), 'generic' to use a generic "C" abstraction which consists of "C" locale info, 'newlib' to specify the Newlib C library model which only differs from the 'generic' model in the handling of ctype, or 'darwin' which omits the wchar_t specializations needed by the 'generic' model.

If not explicitly specified, the configure process tries to guess the most suitable package from the choices above. The default is 'generic'. On glibc-based systems of sufficient vintage (2.3 and newer), 'gnu' is automatically selected. On newlib-based systems (`'--with_newlib=yes'`) and OpenBSD, 'newlib' is automatically selected. On Mac OS X 'darwin' is automatically selected. This option can change the library ABI.

`--enable-libstdcxx-allocator` This is an abbreviated form of `'--enable-libstdcxx-allocator=auto'` (described next).

`--enable-libstdcxx-allocator=OPTION` Select a target-specific underlying std::allocator. The choices are 'new' to specify a wrapper for new, and 'malloc' to specify a wrapper for malloc. See Section 6.3.1.6 for more information. This option can change the library ABI.

`--enable-cheaders=OPTION` This allows the user to define the approach taken for C header compatibility with C++. Options are c, c_std, and c_global. These correspond to the source directory's include/c, include/c_std, and include/c_global, and may also include include/c_compatibility. The default is 'c_global'.

`--enable-threads` This is an abbreviated form of `'--enable-threads=yes'` (described next).

--enable-threads=OPTION Select a threading library. A full description is given in the general compiler configuration instructions. This option can change the library ABI.

--enable-libstdcxx-threads Enable C++11 threads support. If not explicitly specified, the configure process enables it if possible. This option can change the library ABI.

--enable-libstdcxx-time This is an abbreviated form of `'--enable-libstdcxx-time=yes'` (described next).

--enable-libstdcxx-time=OPTION Enables link-type checks for the availability of the `clock_gettime` clocks, used in the implementation of [time.clock], and of the `nanosleep` and `sched_yield` functions, used in the implementation of [thread.thread.this] of the 2011 ISO C++ standard. The choice OPTION=yes checks for the availability of the facilities in libc. OPTION=rt also checks in librt (and, if it's needed, links to it). Note that linking to librt is not always desirable because for glibc it requires linking to libpthread too, which causes all reference counting to use atomic operations, resulting in a potentially large overhead for single-threaded programs. OPTION=no skips the tests completely. The default is OPTION=auto, which skips the checks and enables the features only for targets known to support them. For Linux targets, if `clock_gettime` is not used then the [time.clock] implementation will use a system call to access the realtime and monotonic clocks, which is significantly slower than the C library's `clock_gettime` function.

--enable-libstdcxx-debug Build separate debug libraries in addition to what is normally built. By default, the debug libraries are compiled with `CXXFLAGS='-g3 -O0 -fno-inline'` , are installed in `${libdir}/debug`, and have the same names and versioning information as the non-debug libraries. This option is off by default.

Note this make command, executed in the build directory, will do much the same thing, without the configuration difference and without building everything twice: `make CXXFLAGS='-g3 -O0 -fno-inline' all`

--enable-libstdcxx-debug-flags=FLAGS This option is only valid when `--enable-libstdcxx-debug` is also specified, and applies to the debug builds only. With this option, you can pass a specific string of flags to the compiler to use when building the debug versions of libstdc++. FLAGS is a quoted string of options, like

```
--enable-libstdcxx-debug-flags='-g3 -O1 -fno-inline'
```

--enable-cxx-flags=FLAGS With this option, you can pass a string of -f (functionality) flags to the compiler to use when building libstdc++. This option can change the library ABI. FLAGS is a quoted string of options, like

```
--enable-cxx-flags='-fvtable-gc -fomit-frame-pointer -ansi'
```

Note that the flags don't necessarily have to all be -f flags, as shown, but usually those are the ones that will make sense for experimentation and configure-time overriding.

The advantage of --enable-cxx-flags over setting CXXFLAGS in the 'make' environment is that, if files are automatically rebuilt, the same flags will be used when compiling those files as well, so that everything matches.

Fun flags to try might include combinations of

```
-fstrict-aliasing
-fno-exceptions
-ffunction-sections
-fvtable-gc
```

and opposite forms (-fno-) of the same. Tell us (the libstdc++ mailing list) if you discover more!

--enable-c99 The long long type was introduced in C99, along with many other functions for wide characters, and math classification macros, etc. If enabled, all C99 functions not specified by the C++ standard will be put into `namespace __gnu_cxx`, and then all these names will be injected into namespace std, so that C99 functions can be used "as if" they were in the C++ standard (as they will eventually be in some future revision of the standard, without a doubt). By default, C99 support is on, assuming the configure probes find all the necessary functions and bits necessary. This option can change the library ABI.

--enable-wchar_t[default] Template specializations for the wchar_t type are required for wide character conversion support. Disabling wide character specializations may be expedient for initial porting efforts, but builds only a subset of what is required by ISO, and is not recommended. By default, this option is on. This option can change the library ABI.

--enable-long-long The long long type was introduced in C99. It is provided as a GNU extension to C++98 in g++. This flag builds support for "long long" into the library (specialized templates and the like for iostreams). This option is on by default: if enabled, users will have to either use the new-style "C" headers by default (i.e., <cmath> not <math.h>) or add appropriate compile-time flags to all compile lines to allow "C" visibility of this feature (on GNU/Linux, the flag is -D_ISOC99_SOURCE, which is added automatically via CPLUSPLUS_CPP_SPEC's addition of _GNU_SOURCE). This option can change the library ABI.

--enable-fully-dynamic-string This option enables a special version of basic_string avoiding the optimization that allocates empty objects in static memory. Mostly useful together with shared memory allocators, see PR libstdc++/16612 for details.

--enable-concept-checks This turns on additional compile-time checks for instantiated library templates, in the form of specialized templates described in the Concept Checking section. They can help users discover when they break the rules of the STL, before their programs run. These checks are based on C++03 rules and some of them are not compatible with correct C++11 code.

--enable-symvers[=style] In 3.1 and later, tries to turn on symbol versioning in the shared library (if a shared library has been requested). Values for 'style' that are currently supported are 'gnu', 'gnu-versioned-namespace', 'darwin', 'darwin-export', and 'sun'. Both gnu- options require that a recent version of the GNU linker be in use. Both darwin options are equivalent. With no style given, the configure script will try to guess correct defaults for the host system, probe to see if additional requirements are necessary and present for activation, and if so, will turn symbol versioning on. This option can change the library ABI.

--enable-libstdcxx-visibility In 4.2 and later, enables or disables visibility attributes. If enabled (as by default), and the compiler seems capable of passing the simple sanity checks thrown at it, adjusts items in namespace std, namespace std::tr1, namespace std::tr2, and namespace __gnu_cxx to have `visibility ("default")` so that -fvisibility options can be used without affecting the normal external-visibility of namespace std entities. Prior to 4.7 this option was spelled `--enable-visibility`.

--enable-libstdcxx-pch In 3.4 and later, tries to turn on the generation of stdc++.h.gch, a pre-compiled file including all the standard C++ includes. If enabled (as by default), and the compiler seems capable of passing the simple sanity checks thrown at it, try to build stdc++.h.gch as part of the make process. In addition, this generated file is used later on (by appending `-include bits/stdc++.h` to CXXFLAGS) when running the testsuite.

--enable-extern-template[default] Use extern template to pre-instantiate all required specializations for certain types defined in the standard libraries. These types include `string` and dependents like `char_traits`, the templatized IO classes, `allocator`, and others. Disabling means that implicit template generation will be used when compiling these types. By default, this option is on. This option can change the library ABI.

--disable-hosted-libstdcxx By default, a complete *hosted* C++ library is built. The C++ Standard also describes a *freestanding* environment, in which only a minimal set of headers are provided. This option builds such an environment. Note that a hosted library installs headers that still can be used in non hosted environments, as the library checks for `__STDC_HOSTED__`, however, a library configured with `--disable-hosted-libstdcxx` will not install unusable headers.

--disable-libstdcxx-hosted This is an alias for `--disable-hosted-libstdcxx`.

--disable-libstdcxx-verbose By default, the library is configured to write descriptive messages to standard error for certain events such as calling a pure virtual function or the invocation of the standard terminate handler. Those messages cause the library to depend on the demangler and standard I/O facilities, which might be undesirable in a low-memory environment or when standard error is not available. This option disables those messages. This option does not change the library ABI.

--disable-libstdcxx-dual-abi Disable support for the new, C++11-conforming implementations of `std::string`, `std::list` etc. so that the library only provides definitions of types using the old ABI (see Dual ABI). This option changes the library ABI.

--with-default-libstdcxx-abi=*OPTION* Set the default value for the _GLIBCXX_USE_CXX11_ABI macro (see Macros). The default is `OPTION=new` which sets the macro to `1`, use `OPTION=gcc4-compatible` to set it to `0`. This option does not change the library ABI.

--with-libstdcxx-lock-policy=OPTION Sets the lock policy that controls how `shared_ptr` reference counting is synchronized. The choice OPTION=atomic enables use of atomics for updates to `shared_ptr` reference counts. The choice OPTION=mutex enables use of a mutex to synchronize updates to `shared_ptr` reference counts. If the compiler's thread model is "single" then this option has no effect, as no synchronization is used for the reference counts. The default is OPTION=auto, which checks for the availability of compiler built-ins for 2-byte and 4-byte atomic compare-and-swap, and uses OPTION=atomic if they're available, OPTION=mutex otherwise. This option can change the library ABI. If the library is configured to use atomics and user programs are compiled using a target that doesn't natively support the atomic operations (e.g. the library is configured for armv7 and then code is compiled with `-march=armv5t`) then the program might rely on support in libgcc to provide the atomics.

--enable-vtable-verify Use `-fvtable-verify=std` to compile the C++ runtime with instrumentation for vtable verification. All virtual functions in the standard library will be verified at runtime. Types impacted include `locale` and `iostream`, and others. Disabling means that the C++ runtime is compiled without support for vtable verification. By default, this option is off.

--enable-libstdcxx-filesystem-ts[default] Build `libstdc++fs.a` as well as the usual libstdc++ and libsupc++ libraries. This is enabled by default on select POSIX targets where it is known to work and disabled otherwise.

--enable-libstdcxx-static-eh-pool Use a fixed-size static buffer for the emergency exception handling pool (see Memory allocation for exceptions). The default is to allocate the pool on program startup using `malloc`. With this option, a static buffer will be provided by libstdc++ instead. This does not change the library ABI.

--with-libstdcxx-eh-pool-obj-count=NUM Set the size of the emergency exception handling pool. NUM is the number of simultaneous allocated exceptions to support. This does not change the library ABI.

--with-libstdcxx-zoneinfo=OPTION Choose how `std::chrono::tzdb` will obtain the time zone info. The library requires a copy of the `tzdata.zi` and `leapseconds` files from the IANA Time Zone Database. The choice OPTION=static will embed a copy of the files into the library, and use that static data when time zone information is required. The choice OPTION=dir will use the files `dir/tzdata.zi` and `dir/leapseconds` (which must exist when a program tries to access time zone information). The choice OPTION=dir,static will try to use files in `dir` but if they are not available the embedded static data will be used instead. The default choice is OPTION=yes. This is equivalent to OPTION=dir,static with a system-specific default directory (if a suitable default for the target is known). The choice OPTION=no will disable all code for loading time zone info from file or from the embedded static data, which means that only the "UTC" and "GMT" time zones are defined. Using OPTION=no results in a smaller library, so is suitable for systems that will never need to query the time zone database. This does not change the library ABI.

2.3 Make

If you have never done this before, you should read the basic GCC Installation Instructions first. Read *all of them*. *Twice.*

Then type: **make**, and congratulations, you've started to build.

Chapter 3

Using

3.1 Command Options

The set of features available in the GNU C++ library is shaped by several GCC Command Options. Options that impact libstdc++ are enumerated and detailed in the table below.

The standard library conforms to the dialect of C++ specified by the `-std` option passed to the compiler. By default, **g++** is equivalent to **g++ -std=gnu++17** since GCC 11, and **g++ -std=gnu++14** in GCC 6, 7, 8, 9, and 10, and **g++ -std=gnu++98** for older releases.

3.2 Headers

3.2.1 Header Files

The C++ standard specifies the entire set of header files that must be available to all hosted implementations. Actually, the word "files" is a misnomer, since the contents of the headers don't necessarily have to be in any kind of external file. The only rule is that when one `#include`s a header, the contents of that header become available, no matter how.

That said, in practice files are used.

There are two main types of include files: header files related to a specific version of the ISO C++ standard (called Standard Headers), and all others (TS, TR1, C++ ABI, and Extensions).

Multiple dialects of standard headers are supported, corresponding to the 1998 standard as updated for 2003, the 2011 standard, the 2014 standard, and so on.

Table 3.2 and Table 3.3 and Table 3.4 show the C++98/03 include files. These are available in the C++98 compilation mode, i.e. `-std=c++98` or `-std=gnu++98`. Unless specified otherwise below, they are also available in later modes (C++11, C++14 etc).

The following header is deprecated and might be removed from a future C++ standard.

Table 3.5 and Table 3.6 show the C++11 include files. These are available in C++11 compilation mode, i.e. `-std=c++11` or `-std=gnu++11`. Including these headers in C++98/03 mode may result in compilation errors. Unless specified otherwise below, they are also available in later modes (C++14 etc).

Table 3.7 shows the C++14 include file. This is available in C++14 compilation mode, i.e. `-std=c++14` or `-std=gnu++14`. Including this header in C++98/03 mode or C++11 will not result in compilation errors, but will not define anything. Unless specified otherwise below, it is also available in later modes (C++17 etc).

Table 3.8 shows the C++17 include files. These are available in C++17 compilation mode, i.e. `-std=c++17` or `-std=gnu++17`. Including these headers in earlier modes will not result in compilation errors, but will not define anything. Unless specified otherwise below, they are also available in later modes (C++20 etc).

Option Flags	Description
-std	Select the C++ standard, and whether to use the base standard or GNU dialect.
-fno-exceptions	See exception-free dialect
-fno-rtti	As above, but RTTI-free dialect.
-pthread	For ISO C++11 <thread>, <future>, <mutex>, or <condition_variable>.
-latomic	Linking to libatomic is required for some uses of ISO C++11 <atomic>.
-lstdc++exp	Linking to libstdc++exp.a is required for use of experimental C++ library features. This currently provides support for the C++23 types defined in the <stacktrace> header, the Filesystem library extensions defined in the <experimental/filesystem> header, and the Contracts extensions enabled by -fcontracts.
-lstdc++fs	Linking to libstdc++fs.a is another way to use the Filesystem library extensions defined in the <experimental/filesystem> header. The libstdc++exp.a library also provides all the symbols contained in this library.
-fopenmp	For parallel mode.
-ltbb	Linking to tbb (Thread Building Blocks) is required for use of the Parallel Standard Algorithms and execution policies in <execution>.
-ffreestanding	Limits the library to its freestanding subset. Headers that are not supported in freestanding will emit a "This header is not available in freestanding mode" error. Headers that are in the freestanding subset partially will not expose functionality that is not part of the freestanding subset.

Table 3.1: C++ Command Options

algorithm	bitset	complex	deque	exception
fstream	functional	iomanip	ios	iosfwd
iostream	istream	iterator	limits	list
locale	map	memory	new	numeric
ostream	queue	set	sstream	stack
stdexcept	streambuf	string	utility	typeinfo
valarray	vector			

Table 3.2: C++ 1998 Library Headers

cassert	cerrno	cctype	cfloat	ciso646
climits	clocale	cmath	csetjmp	csignal
cstdarg	cstddef	cstdio	cstdlib	cstring
ctime	cwchar	cwctype		

Table 3.3: C++ 1998 Library Headers for C Library Facilities

strstream

Table 3.4: C++ 1998 Deprecated Library Header

array	atomic	chrono	codecvt	condition_ variable
forward_list	future	initalizer_ list	mutex	random
ratio	regex	scoped_ allocator	system_error	thread
tuple	typeindex	type_traits	unordered_map	unordered_set

Table 3.5: C++ 2011 Library Headers

ccomplex	cfenv	cinttypes	cstdalign	cstdbool
cstdint	ctgmath	cuchar		

Table 3.6: C++ 2011 Library Headers for C Library Facilities

shared_mutex

Table 3.7: C++ 2014 Library Header

any	charconv	execution	filesystem	memory_ resource
optional	string_view	variant		

Table 3.8: C++ 2017 Library Headers

barrier	bit	charconv	compare	concepts
coroutine	format	latch	numbers	ranges
semaphore	source_ location	span	stop_token	syncstream
version				

Table 3.9: C++ 2020 Library Headers

Table 3.9 shows the C++20 include files. These are available in C++20 compilation mode, i.e. `-std=c++20` or `-std=gnu++20`. Including these headers in earlier modes will not result in compilation errors, but will not define anything.

The following headers have been removed in the C++20 standard. They are still available when using this implementation, but in future they might start to produce warnings or errors when included in C++20 mode. Programs that intend to be portable should not include them.

ccomplex	ciso646	cstdalign	cstdbool	ctgmath

Table 3.10: C++ 2020 Obsolete Headers

Table 3.11 shows the C++23 include files. These are available in C++23 compilation mode, i.e. `-std=c++23` or `-std=gnu++23`. Including these headers in earlier modes will not result in compilation errors, but will not define anything.

expected	generator	print	spanstream	stacktrace
stdatomic.h	stdfloat			

Table 3.11: C++ 2023 Library Headers

Table 3.12 shows the C++26 include files. These are available in C++26 compilation mode, i.e. `-std=c++26` or `-std=gnu++26`. Including these headers in earlier modes will not result in compilation errors, but will not define anything.

text_encoding

Table 3.12: C++ 2026 Library Headers

Table 3.13, shows the additional include file define by the File System Technical Specification, ISO/IEC TS 18822:2015. This is available in C++11 and later compilation modes. Including this header in earlier modes will not result in compilation errors, but will not define anything.

Table 3.14, shows the additional include files define by the C++ Extensions for Library Fundamentals Technical Specification, ISO/IEC TS 19568:2015, ISO/IEC TS 19568:2017, and ISO/IEC TS 19568:2024. These are available in C++14 and later compilation modes, except for `<experimental/scope>` which is available in C++20 and later compilation modes. Including these headers in earlier modes will not result in compilation errors, but will not define anything.

Table 3.15, shows the additional include files define by the Networking Technical Specification, ISO/IEC TS 19216:2018. These are available in C++14 and later compilation modes. Including these headers in earlier modes will not result in compilation errors, but will not define anything.

In addition, TR1 includes as:

Decimal floating-point arithmetic is available if the C++ compiler supports scalar decimal floating-point types defined via `__attribute__((mode(SD|DD|LD)))`.

Also included are files for the C++ ABI interface:

And a large variety of extensions.

3.2.2 Mixing Headers

A few simple rules.

First, mixing different dialects of the standard headers is not possible. It's an all-or-nothing affair. Thus, code like

```
#include <array>
#include <functional>
```

Implies C++11 mode. To use the entities in <array>, the C++11 compilation mode must be used, which implies the C++11 functionality (and deprecations) in <functional> will be present.

experimental/filesystem

Table 3.13: File System TS Header

experimental/algorithm	experimental/any	experimental/array	experimental/chrono	experimental/deque
experimental/forward_list	experimental/functional	experimental/iterator	experimental/list	experimental/map
experimental/memory	experimental/memory_resource	experimental/numeric	experimental/optional	experimental/propagate_const
experimental/random	experimental/ratio	experimental/regex	experimental/scope	experimental/set
experimental/source_location	experimental/string	experimental/string_view	experimental/system_error	experimental/tuple
experimental/type_traits	experimental/unordered_map	experimental/unordered_set	experimental/utility	experimental/vector

Table 3.14: Library Fundamentals TS Headers

experimental/buffer	experimental/executor	experimental/internet	experimental/io_context
experimental/net	experimental/netfwd	experimental/socket	experimental/timer

Table 3.15: Networking TS Headers

tr1/array	tr1/complex	tr1/memory	tr1/functional	tr1/random
tr1/regex	tr1/tuple	tr1/type_traits	tr1/unordered_map	tr1/unordered_set
tr1/utility				

Table 3.16: C++ TR 1 Library Headers

tr1/ccomplex	tr1/cfenv	tr1/cfloat	tr1/cmath	tr1/cinttypes
tr1/climits	tr1/cstdarg	tr1/cstdbool	tr1/cstdint	tr1/cstdio
tr1/cstdlib	tr1/ctgmath	tr1/ctime	tr1/cwchar	tr1/cwctype

Table 3.17: C++ TR 1 Library Headers for C Library Facilities

decimal/decimal

Table 3.18: C++ TR 24733 Decimal Floating-Point Header

cxxabi.h	cxxabi_forced.h

Table 3.19: C++ ABI Headers

ext/algorithm	ext/atomicity.h	ext/bitmap_allocator.h	ext/cast.h	
ext/codecvt_specializations.h	ext/concurrence.h	ext/debug_allocator.h	ext/enc_filebuf.h	ext/extptr_allocator.h
ext/functional	ext/iterator	ext/malloc_allocator.h	ext/memory	ext/mt_allocator.h
ext/new_allocator.h	ext/numeric	ext/numeric_traits.h	ext/pb_ds/assoc_container.h	ext/pb_ds/priority_queue.h
ext/pod_char_traits.h	ext/pool_allocator.h	ext/rb_tree	ext/rope	ext/slist
ext/stdio_filebuf.h	ext/stdio_sync_filebuf.h	ext/throw_allocator.h	ext/typelist.h	ext/type_traits.h
ext/vstring.h				

Table 3.20: Extension Headers

debug/array	debug/bitset	debug/deque	debug/forward_list	debug/list
debug/map	debug/set	debug/string	debug/unordered_map	debug/unordered_set
debug/vector				

Table 3.21: Extension Debug Headers

parallel/algorithm	parallel/numeric

Table 3.22: Extension Parallel Headers

Second, the other headers can be included with either dialect of the standard headers, although features and types specific to C++11 are still only enabled when in C++11 compilation mode. So, to use rvalue references with `__gnu_cxx::vstring`, or to use the debug-mode versions of `std::unordered_map`, one must use the `std=gnu++11` compiler flag. (Or `std=c++11`, of course.)

A special case of the second rule is the mixing of TR1 and C++11 facilities. It is possible (although not especially prudent) to include both the TR1 version and the C++11 version of header in the same translation unit:

```
#include <tr1/type_traits>
#include <type_traits>
```

Several parts of C++11 diverge quite substantially from TR1 predecessors.

3.2.3 The C Headers and `namespace std`

The standard specifies that if one includes the C-style header (<math.h> in this case), the symbols will be available in the global namespace and perhaps in namespace `std::` (but this is no longer a firm requirement.) On the other hand, including the C++-style header (<cmath>) guarantees that the entities will be found in namespace std and perhaps in the global namespace.

Usage of C++-style headers is recommended, as then C-linkage names can be disambiguated by explicit qualification, such as by `std::abort`. In addition, the C++-style headers can use function overloading to provide a simpler interface to certain families of C-functions. For instance in <cmath>, the function `std::sin` has overloads for all the builtin floating-point types. This means that `std::sin` can be used uniformly, instead of a combination of `std::sinf`, `std::sin`, and `std::sinl`.

3.2.4 Precompiled Headers

There are three base header files that are provided. They can be used to precompile the standard headers and extensions into binary files that may then be used to speed up compilations that use these headers.

- stdc++.h

  Includes all standard headers. Actual content varies depending on language dialect.

- stdtr1c++.h

  Includes all of <stdc++.h>, and adds all the TR1 headers.

- extc++.h

  Includes all of <stdc++.h>, and adds all the Extension headers (and in C++98 mode also adds all the TR1 headers by including all of <stdtr1c++.h>).

To construct a .gch file from one of these base header files, first find the include directory for the compiler. One way to do this is:

```
g++ -v hello.cc

#include <...> search starts here:
 /mnt/share/bld/H-x86-gcc.20071201/include/c++/4.3.0
...
End of search list.
```

Then, create a precompiled header file with the same flags that will be used to compile other projects.

```
g++ -Winvalid-pch -x c++-header -g -O2 -o ./stdc++.h.gch /mnt/share/bld/H-x86-gcc.20071201/ ↩
    include/c++/4.3.0/x86_64-unknown-linux-gnu/bits/stdc++.h
```

The resulting file will be quite large: the current size is around thirty megabytes.

How to use the resulting file.

```
g++ -I. -include stdc++.h  -H -g -O2 hello.cc
```

Verification that the PCH file is being used is easy:

```
g++ -Winvalid-pch -I. -include stdc++.h -H -g -O2 hello.cc -o test.exe
! ./stdc++.h.gch
. /mnt/share/bld/H-x86-gcc.20071201/include/c++/4.3.0/iostream
. /mnt/share/bld/H-x86-gcc.20071201include/c++/4.3.0/string
```

The exclamation point to the left of the `stdc++.h.gch` listing means that the generated PCH file was used.

Detailed information about creating precompiled header files can be found in the GCC documentation.

3.3 Macros

All library macros begin with `_GLIBCXX_`.

Furthermore, all pre-processor macros, switches, and configuration options are gathered in the file `c++config.h`, which is generated during the libstdc++ configuration and build process. This file is then included when needed by files part of the public libstdc++ API, like `<ios>`. Most of these macros should not be used by consumers of libstdc++, and are reserved for internal implementation use. *These macros cannot be redefined*.

A select handful of macros control libstdc++ extensions and extra features, or provide versioning information for the API. Only those macros listed below are offered for consideration by the general public.

Below are the macros which users may check for library version information.

`_GLIBCXX_RELEASE` The major release number for libstdc++. This macro is defined to the GCC major version that the libstdc++ headers belong to, as an integer constant. When compiling with GCC it has the same value as GCC's pre-defined macro __GNUC__. This macro can be used when libstdc++ is used with a non-GNU compiler where __GNUC__ is not defined, or has a different value that doesn't correspond to the libstdc++ version. This macro first appeared in the GCC 7.1 release and is not defined for GCC 6.x or older releases.

`__GLIBCXX__` The revision date of the libstdc++ source code, in compressed ISO date format, as an unsigned long. For notes about using this macro and details on the value of this macro for a particular release, please consult the ABI History appendix.

Below are the macros which users may change with #define/#undef or with -D/-U compiler flags. The default state of the symbol is listed.

"Configurable" (or "Not configurable") means that the symbol is initially chosen (or not) based on --enable/--disable options at library build and configure time (documented in Configure), with the various --enable/--disable choices being translated to #define/#undef).

ABI-changing means that changing from the default value may mean changing the ABI of compiled code. In other words, these choices control code which has already been compiled (i.e., in a binary such as libstdc++.a/.so). If you explicitly #define or #undef these macros, the *headers* may see different code paths, but the *libraries* which you link against will not. Experimenting with different values with the expectation of consistent linkage requires changing the config headers before building/installing the library.

`_GLIBCXX_USE_DEPRECATED` Defined to the value `1` by default. Not configurable. ABI-changing. Turning this off removes older ARM-style iostreams code, and other anachronisms from the API. This macro is dependent on the version of the standard being tracked, and as a result may give different results for different `-std` options. This may be useful in updating old C++ code which no longer meet the requirements of the language, or for checking current code against new language standards.

`_GLIBCXX_USE_CXX11_ABI` Defined to the value `1` by default. Configurable via `--disable-libstdcxx-dual-abi` and/or `--with-default-libstdcxx-abi`. ABI-changing. When defined to a non-zero value the library headers will use the new C++11-conforming ABI introduced in GCC 5, rather than the older ABI introduced in GCC 3.4. This changes the definition of several class templates, including `std:string`, `std::list` and some locale facets. For more details see Dual ABI.

_GLIBCXX_CONCEPT_CHECKS Undefined by default. Configurable via `--enable-concept-checks`. When defined, performs compile-time checking on certain template instantiations to detect violations of the requirements of the standard. This macro has no effect for freestanding implementations. This is described in more detail in Compile Time Checks.

_GLIBCXX_ASSERTIONS Defined by default when compiling with no optimization, undefined by default when compiling with optimization. When defined, enables extra error checking in the form of precondition assertions, such as bounds checking in strings and null pointer checks when dereferencing smart pointers.

_GLIBCXX_NO_ASSERTIONS Undefined by default. When defined, prevents the implicit definition of `_GLIBCXX_ASSERTIONS` when compiling with no optimization.

_GLIBCXX_DEBUG Undefined by default. When defined, compiles user code using the debug mode. When defined, `_GLIBCXX_ASSE` is defined automatically, so all the assertions enabled by that macro are also enabled in debug mode.

_GLIBCXX_DEBUG_PEDANTIC Undefined by default. When defined while compiling with the debug mode, makes the debug mode extremely picky by making the use of libstdc++ extensions and libstdc++-specific behavior into errors.

_GLIBCXX_DEBUG_BACKTRACE Undefined by default. Considered only if libstdc++ has been configured with `--enable-libstc` and if `_GLIBCXX_DEBUG` is defined. When defined display backtraces on debug mode assertions.

_GLIBCXX_PARALLEL Undefined by default. When defined, compiles user code using the parallel mode.

_GLIBCXX_PARALLEL_ASSERTIONS Undefined by default, but when any parallel mode header is included this macro will be defined to a non-zero value if `_GLIBCXX_ASSERTIONS` has a non-zero value, otherwise to zero. When defined to a non-zero value, it enables extra error checking and assertions in the parallel mode.

__STDCPP_WANT_MATH_SPEC_FUNCS__ Undefined by default. When defined to a non-zero integer constant, enables support for ISO/IEC 29124 Special Math Functions.

_GLIBCXX_SANITIZE_VECTOR Undefined by default. When defined, `std::vector` operations will be annotated so that AddressSanitizer can detect invalid accesses to the unused capacity of a `std::vector`. These annotations are only enabled for `std::vector<T, std::allocator<T>>` and only when `std::allocator` is derived from new_allocator or malloc_allocator. The annotations must be present on all vector operations or none, so this macro must be defined to the same value for all translation units that create, destroy, or modify vectors.

_GLIBCXX_NO_FREESTANDING_CHRONO Undefined by default. When defined, the `<chrono>` header cannot be used with `-ffreestanding`. When not defined, durations, time points, and calendar types are available for freestanding, but the standard clocks and the time zone database are not (because they require OS support).

3.4 Dual ABI

In the GCC 5.1 release libstdc++ introduced a new library ABI that includes new implementations of `std::string` and `std::list`. These changes were necessary to conform to the 2011 C++ standard which forbids Copy-On-Write strings and requires lists to keep track of their size.

In order to maintain backwards compatibility for existing code linked to libstdc++ the library's soname has not changed and the old implementations are still supported in parallel with the new ones. This is achieved by defining the new implementations in an inline namespace so they have different names for linkage purposes, e.g. the new version of `std::list<int>` is actually defined as `std::__cxx11::list<int>`. Because the symbols for the new implementations have different names the definitions for both versions can be present in the same library.

The _GLIBCXX_USE_CXX11_ABI macro (see Macros) controls whether the declarations in the library headers use the old or new ABI. So the decision of which ABI to use can be made separately for each source file being compiled. Using the default configuration options for GCC the default value of the macro is `1` which causes the new ABI to be active, so to use the old ABI you must explicitly define the macro to `0` before including any library headers. (Be aware that some GNU/Linux distributions configured GCC 5 differently so that the default value of the macro is `0` and users must define it to `1` to enable the new ABI.)

Although the changes were made for C++11 conformance, the choice of ABI to use is independent of the `-std` option used to compile your code, i.e. for a given GCC build the default value of the _GLIBCXX_USE_CXX11_ABI macro is the same for all dialects. This ensures that the -std does not change the ABI, so that it is straightforward to link C++03 and C++11 code together.

Because std::string is used extensively throughout the library a number of other types are also defined twice, including the stringstream classes and several facets used by std::locale. The standard facets which are always installed in a locale may be present twice, with both ABIs, to ensure that code like std::use_facet<std::time_get<char>>(locale); will work correctly for both std::time_get and std::__cxx11::time_get (even if a user-defined facet that derives from one or other version of time_get is installed in the locale).

Although the standard exception types defined in <stdexcept> use strings, most are not defined twice, so that a std::out_of_ran exception thrown in one file can always be caught by a suitable handler in another file, even if the two files are compiled with different ABIs.

One exception type does change when using the new ABI, namely std::ios_base::failure. This is necessary because the 2011 standard changed its base class from std::exception to std::system_error, which causes its layout to change. Exceptions due to iostream errors are thrown by a function inside libstdc++.so, so whether the thrown exception uses the old std::ios_base::failure type or the new one depends on the ABI that was active when libstdc++.so was built, *not* the ABI active in the user code that is using iostreams. This means that for a given build of GCC the type thrown is fixed. In current releases the library throws a special type that can be caught by handlers for either the old or new type, but for GCC 7.1, 7.2 and 7.3 the library throws the new std::ios_base::failure type, and for GCC 5.x and 6.x the library throws the old type. Catch handlers of type std::ios_base::failure will only catch the exceptions if using a newer release, or if the handler is compiled with the same ABI as the type thrown by the library. Handlers for std::exception will always catch iostreams exceptions, because the old and new type both inherit from std::exception.

Some features are not supported when using the old ABI, including:

- Using std::string::const_iterator for positional arguments to member functions such as std::string::erase.
- Allocator propagation in std::string.
- Using std::string at compile-time in constexpr functions.
- Class std::chrono::time_zone and all related APIs.
- The <syncstream> header.

3.4.1 Troubleshooting

If you get linker errors about undefined references to symbols that involve types in the std::__cxx11 namespace or the tag [abi:cxx11] then it probably indicates that you are trying to link together object files that were compiled with different values for the _GLIBCXX_USE_CXX11_ABI macro. This commonly happens when linking to a third-party library that was compiled with an older version of GCC. If the third-party library cannot be rebuilt with the new ABI then you will need to recompile your code with the old ABI.

Not all uses of the new ABI will cause changes in symbol names, for example a class with a std::string member variable will have the same mangled name whether compiled with the old or new ABI. In order to detect such problems the new types and functions are annotated with the abi_tag attribute, allowing the compiler to warn about potential ABI incompatibilities in code using them. Those warnings can be enabled with the -Wabi-tag option.

3.5 Namespaces

3.5.1 Available Namespaces

There are three main namespaces.

- std

  The ISO C++ standards specify that "all library entities are defined within namespace std." This includes namespaces nested within namespace std, such as namespace std::chrono.

- abi

  Specified by the C++ ABI. This ABI specifies a number of type and function APIs supplemental to those required by the ISO C++ Standard, but necessary for interoperability.

- __gnu_

  Indicating one of several GNU extensions. Choices include `__gnu_cxx`, `__gnu_debug`, `__gnu_parallel`, and `__gnu_pbds`.

The library uses a number of inline namespaces as implementation details that are not intended for users to refer to directly, these include `std::__detail`, `std::__cxx11` and `std::_V2`.

A complete list of implementation namespaces (including namespace contents) is available in the generated source documentation.

3.5.2 namespace std

One standard requirement is that the library components are defined in `namespace std::`. Thus, in order to use these types or functions, one must do one of two things:

- put a kind of *using-declaration* in your source (either `using namespace std;` or i.e. `using std::string;`) This approach works well for individual source files, but should not be used in a global context, like header files.
- use a *fully qualified name* for each library symbol (i.e. `std::string`, `std::cout`) Always can be used, and usually enhanced, by strategic use of typedefs. (In the cases where the qualified verbiage becomes unwieldy.)

3.5.3 Using Namespace Composition

Best practice in programming suggests sequestering new data or functionality in a sanely-named, unique namespace whenever possible. This is considered an advantage over dumping everything in the global namespace, as then name look-up can be explicitly enabled or disabled as above, symbols are consistently mangled without repetitive naming prefixes or macros, etc.

For instance, consider a project that defines most of its classes in `namespace gtk`. It is possible to adapt `namespace gtk` to `namespace std` by using a C++-feature called *namespace composition*. This is what happens if a *using*-declaration is put into a namespace-definition: the imported symbol(s) gets imported into the currently active namespace(s). For example:

```
namespace gtk
{
  using std::string;
  using std::tr1::array;

  class Window { ... };
}
```

In this example, `std::string` gets imported into `namespace gtk`. The result is that use of `std::string` inside namespace gtk can just use `string`, without the explicit qualification. As an added bonus, `std::string` does not get imported into the global namespace. Additionally, a more elaborate arrangement can be made for backwards compatibility and portability, whereby the `using`-declarations can wrapped in macros that are set based on autoconf-tests to either "" or i.e. `using std::string;` (depending on whether the system has libstdc++ in `std::` or not). (ideas from Llewelly and Karl Nelson)

3.6 Linking

3.6.1 Almost Nothing

Or as close as it gets: freestanding. This is a minimal configuration, with only partial support for the standard library. Assume only the following header files can be used:

- `cstdarg`
- `cstddef`
- `cstdlib`
- `exception`
- `limits`
- `new`
- `exception`
- `typeinfo`

In addition, throw in

- `cxxabi.h`.

In the C++11 dialect add

- `initializer_list`
- `type_traits`

As of GCC 13, libstdc++ implements P1642, which brings in many more headers, as well a quite a few ones not covered by the paper. In general, if a feature does not require traditionally libc-provided facilities, or dynamic memory allocation, it's enabled in the freestanding subset. In addition, if only a subset of a header requires such features, it is partially included. Some examples include:

- `string_view`
- `tuple`
- `bitset`

Currently, this subset includes all of the iterator APIs (including the ranges APIs) that do not involve streams, the entire C++ algorithms library, excluding parallel algorithms, and a large part of the utilities library. This is on top of the headers included in the lists above.

If you're using a libstdc++ configured for hosted environments, and would like to not involve the libraries libstdc++ would depend on in your programs, you will need to use **gcc** to link your application with only `libsupc++.a`, like so:

gcc -ffreestanding foo.cc -lsupc++

If you configured libstdc++ with `--disable-hosted-libstdcxx`, however, you can use the normal **g++** command to link, as this configuration provides a (nearly) empty `libstdc++.a`.

3.6.2 Finding Dynamic or Shared Libraries

If the only library built is the static library (`libstdc++.a`), or if specifying static linking, this section is can be skipped. But if building or using a shared library (`libstdc++.so`), then additional location information will need to be provided.

But how?

A quick read of the relevant part of the GCC manual, Compiling C++ Programs, specifies linking against a C++ library. More details from the GCC FAQ, which states *GCC does not, by default, specify a location so that the dynamic linker can find dynamic libraries at runtime.*

Users will have to provide this information.

Methods vary for different platforms and different styles, and are printed to the screen during installation. To summarize:

- At runtime set `LD_LIBRARY_PATH` in your environment correctly, so that the shared library for libstdc++ can be found and loaded. Be certain that you understand all of the other implications and behavior of `LD_LIBRARY_PATH` first.
- Compile the path to find the library at runtime into the program. This can be done by passing certain options to **g++**, which will in turn pass them on to the linker. The exact format of the options is dependent on which linker you use:
  - GNU ld (default on GNU/Linux): `-Wl,-rpath,destdir/lib`
  - Solaris ld: `-Wl,-Rdestdir/lib`
- Some linkers allow you to specify the path to the library by setting `LD_RUN_PATH` in your environment when linking.
- On some platforms the system administrator can configure the dynamic linker to always look for libraries in `destdir/lib`, for example by using the **ldconfig** utility on GNU/Linux or the **crle** utility on Solaris. This is a system-wide change which can make the system unusable so if you are unsure then use one of the other methods described above.

Use the **ldd** utility on the linked executable to show which `libstdc++.so` library the system will get at runtime.

A `libstdc++.la` file is also installed, for use with Libtool. If you use Libtool to create your executables, these details are taken care of for you.

3.6.3 Experimental Library Extensions

GCC 5.3 includes an implementation of the Filesystem library defined by the technical specification ISO/IEC TS 18822:2015. Because this is an experimental library extension, not part of the C++ standard, it is implemented in a separate library, `libstdc++fs.a`, and there is no shared library for it. To use the library you should include `<experimental/filesystem>` and link with `-lstdc++fs`. The library implementation is incomplete on non-POSIX platforms, specifically Windows is only partially supported. Since GCC 14, `libstdc++exp.a` also contains the definitions for this library, so `-lstdc++exp` can be used instead of `-lstdc++fs`.

GCC 13 includes an implementation of the C++ Contracts library defined by P1429R3. Because this is an experimental extension, not part of the C++ standard, it is implemented in a separate library, `libstdc++exp.a`, and there is no shared library for it. To use the library you should include `<experimental/contract>` and link with `-lstdc++exp`.

Due to the experimental nature of these libraries the usual guarantees about ABI stability and backwards compatibility do not apply to them. There is no guarantee that the components in any `<experimental/xxx>` header will remain compatible between different GCC releases.

3.7 Concurrency

This section discusses issues surrounding the proper compilation of multithreaded applications which use the Standard C++ library. This information is GCC-specific since the C++ standard does not address matters of multithreaded applications.

3.7.1 Prerequisites

All normal disclaimers aside, multithreaded C++ application are only supported when libstdc++ and all user code was built with compilers which report (via `gcc/g++ -v`) the same thread model and that model is not *single*. As long as your final application is actually single-threaded, then it should be safe to mix user code built with a thread model of *single* with a libstdc++ and other C++ libraries built with another thread model useful on the platform. Other mixes may or may not work but are not considered supported. (Thus, if you distribute a shared C++ library in binary form only, it may be best to compile it with a GCC configured with --enable-threads for maximal interchangeability and usefulness with a user population that may have built GCC with either --enable-threads or --disable-threads.)

When you link a multithreaded application, you will probably need to add a library or flag to g++. This is a very non-standardized area of GCC across ports. Some ports support a special flag (the spelling isn't even standardized yet) to add all required macros to a compilation (if any such flags are required then you must provide the flag for all compilations not just linking) and link-library additions and/or replacements at link time. The documentation is weak. On several targets (including GNU/Linux, Solaris and various BSDs) -pthread is honored. Some other ports use other switches. This is not well documented anywhere other than in "gcc -dumpspecs" (look at the 'lib' and 'cpp' entries).

Some uses of `std::atomic` also require linking to `libatomic`.

3.7.2 Thread Safety

In the terms of the 2011 C++ standard a thread-safe program is one which does not perform any conflicting non-atomic operations on memory locations and so does not contain any data races. The standard places requirements on the library to ensure that no data races are caused by the library itself or by programs which use the library correctly (as described below). The C++11 memory model and library requirements are a more formal version of the SGI STL definition of thread safety, which the library used prior to the 2011 standard.

The library strives to be thread-safe when all of the following conditions are met:

- The system's libc is itself thread-safe,
- The compiler in use reports a thread model other than 'single'. This can be tested via output from `gcc -v`. Multi-thread capable versions of gcc output something like this:

  ```
  %gcc -v
  Using built-in specs.
  ...
  Thread model: posix
  gcc version 4.1.2 20070925 (Red Hat 4.1.2-33)
  ```

  Look for "Thread model" lines that aren't equal to "single."
- Requisite command-line flags are used for atomic operations and threading. Examples of this include `-pthread` and `-march=native`, although specifics vary depending on the host environment. See Command Options and Machine Dependent Options.
- An implementation of the `atomicity.h` functions exists for the architecture in question. See the internals documentation for more details.

The user code must guard against concurrent function calls which access any particular library object's state when one or more of those accesses modifies the state. An object will be modified by invoking a non-const member function on it or passing it as a non-const argument to a library function. An object will not be modified by invoking a const member function on it or passing it to a function as a pointer- or reference-to-const. Typically, the application programmer may infer what object locks must be held based on the objects referenced in a function call and whether the objects are accessed as const or non-const. Without getting into great detail, here is an example which requires user-level locks:

```
    library_class_a shared_object_a;

    void thread_main () {
      library_class_b *object_b = new library_class_b;
      shared_object_a.add_b (object_b);   // must hold lock for shared_object_a
      shared_object_a.mutate ();          // must hold lock for shared_object_a
    }

    // Multiple copies of thread_main() are started in independent threads.
```

Under the assumption that object_a and object_b are never exposed to another thread, here is an example that does not require any user-level locks:

```
    void thread_main () {
      library_class_a object_a;
      library_class_b *object_b = new library_class_b;
      object_a.add_b (object_b);
      object_a.mutate ();
    }
```

All library types are safe to use in a multithreaded program if objects are not shared between threads or as long each thread carefully locks out access by any other thread while it modifies any object visible to another thread. Unless otherwise documented, the only exceptions to these rules are atomic operations on the types in `<atomic>` and lock/unlock operations on the standard mutex types in `<mutex>`. These atomic operations allow concurrent accesses to the same object without introducing data races.

The following member functions of standard containers can be considered to be const for the purposes of avoiding data races: `begin`, `end`, `rbegin`, `rend`, `front`, `back`, `data`, `find`, `lower_bound`, `upper_bound`, `equal_range`, `at` and, except in associative or unordered associative containers, `operator[]`. In other words, although they are non-const so that they can return mutable iterators, those member functions will not modify the container. Accessing an iterator might cause a non-modifying access to the container the iterator refers to (for example incrementing a list iterator must access the pointers between nodes, which are part of the container and so conflict with other accesses to the container).

The Copy-On-Write `std::string` implementation used before GCC 5 (and with _GLIBCXX_USE_CXX11_ABI=0) is not a standard container and does not conform to the data race avoidance rules described above. For the Copy-On-Write `std::string`, non-const member functions such as `begin()` are considered to be modifying accesses and so must not be used concurrently with any other accesses to the same object.

Programs which follow the rules above will not encounter data races in library code, even when using library types which share state between distinct objects. In the example below the `shared_ptr` objects share a reference count, but because the code does not perform any non-const operations on the globally-visible object, the library ensures that the reference count updates are atomic and do not introduce data races:

```
std::shared_ptr<int> global_sp;

void thread_main() {
  auto local_sp = global_sp;  // OK, copy constructor's parameter is reference-to-const

  int i = *global_sp;         // OK, operator* is const
  int j = *local_sp;          // OK, does not operate on global_sp

  // *global_sp = 2;          // NOT OK, modifies int visible to other threads
  // *local_sp = 2;           // NOT OK, modifies int visible to other threads

  // global_sp.reset();       // NOT OK, reset is non-const
  local_sp.reset();           // OK, does not operate on global_sp
}

int main() {
  global_sp.reset(new int(1));
  std::thread t1(thread_main);
  std::thread t2(thread_main);
  t1.join();
  t2.join();
}
```

For further details of the C++11 memory model see Hans-J. Boehm's Threads and memory model for C++ pages, particularly the introduction and FAQ.

3.7.3 Atomics

3.7.4 IO

This gets a bit tricky. Please read carefully, and bear with me.

3.7.4.1 Structure

A wrapper type called `__basic_file` provides our abstraction layer for the `std::filebuf` classes. Nearly all decisions dealing with actual input and output must be made in `__basic_file`.

A generic locking mechanism is somewhat in place at the filebuf layer, but is not used in the current code. Providing locking at any higher level is akin to providing locking within containers, and is not done for the same reasons (see the links above).

3.7.4.2 Defaults

The __basic_file type is simply a collection of small wrappers around the C stdio layer (again, see the link under Structure). We do no locking ourselves, but simply pass through to calls to `fopen`, `fwrite`, and so forth.

So, for 3.0, the question of "is multithreading safe for I/O" must be answered with, "is your platform's C library threadsafe for I/O?" Some are by default, some are not; many offer multiple implementations of the C library with varying tradeoffs of threadsafety and efficiency. You, the programmer, are always required to take care with multiple threads.

(As an example, the POSIX standard requires that C stdio `FILE*` operations are atomic. POSIX-conforming C libraries (e.g, on Solaris and GNU/Linux) have an internal mutex to serialize operations on `FILE*`s. However, you still need to not do stupid things like calling `fclose(fs)` in one thread followed by an access of `fs` in another.)

So, if your platform's C library is threadsafe, then your `fstream` I/O operations will be threadsafe at the lowest level. For higher-level operations, such as manipulating the data contained in the stream formatting classes (e.g., setting up callbacks inside an `std::ofstream`), you need to guard such accesses like any other critical shared resource.

3.7.4.3 Future

A second choice may be available for I/O implementations: libio. This is disabled by default, and in fact will not currently work due to other issues. It will be revisited, however.

The libio code is a subset of the guts of the GNU libc (glibc) I/O implementation. When libio is in use, the `__basic_file` type is basically derived from FILE. (The real situation is more complex than that... it's derived from an internal type used to implement FILE. See libio/libioP.h to see scary things done with vtbls.) The result is that there is no "layer" of C stdio to go through; the filebuf makes calls directly into the same functions used to implement `fread`, `fwrite`, and so forth, using internal data structures. (And when I say "makes calls directly," I mean the function is literally replaced by a jump into an internal function. Fast but frightening. *grin*)

Also, the libio internal locks are used. This requires pulling in large chunks of glibc, such as a pthreads implementation, and is one of the issues preventing widespread use of libio as the libstdc++ cstdio implementation.

But we plan to make this work, at least as an option if not a future default. Platforms running a copy of glibc with a recent-enough version will see calls from libstdc++ directly into the glibc already installed. For other platforms, a copy of the libio subsection will be built and included in libstdc++.

3.7.4.4 Alternatives

Don't forget that other cstdio implementations are possible. You could easily write one to perform your own forms of locking, to solve your "interesting" problems.

3.7.5 Containers

This section discusses issues surrounding the design of multithreaded applications which use Standard C++ containers. All information in this section is current as of the gcc 3.0 release and all later point releases. Although earlier gcc releases had a different approach to threading configuration and proper compilation, the basic code design rules presented here were similar. For information on all other aspects of multithreading as it relates to libstdc++, including details on the proper compilation of threaded code (and compatibility between threaded and non-threaded code), see Chapter 17.

Two excellent pages to read when working with the Standard C++ containers and threads are SGI's https://web.archive.org/-web/20171221154911/http://www.sgi.com/tech/stl/thread_safety.html and SGI's https://web.archive.org/web/20171108142526/-http://www.sgi.com/tech/stl/Allocators.html.

However, please ignore all discussions about the user-level configuration of the lock implementation inside the STL container-memory allocator on those pages. For the sake of this discussion, libstdc++ configures the SGI STL implementation, not you. This is quite different from how gcc pre-3.0 worked. In particular, past advice was for people using g++ to explicitly define _PTHREADS or other macros or port-specific compilation options on the command line to get a thread-safe STL. This is no longer required for any port and should no longer be done unless you really know what you are doing and assume all responsibility.

Since the container implementation of libstdc++ uses the SGI code, we use the same definition of thread safety as SGI when discussing design. A key point that beginners may miss is the fourth major paragraph of the first page mentioned above (*For most clients...*), which points out that locking must nearly always be done outside the container, by client code (that'd be you, not us). There is a notable exceptions to this rule. Allocators called while a container or element is constructed uses an internal lock obtained and released solely within libstdc++ code (in fact, this is the reason STL requires any knowledge of the thread configuration).

For implementing a container which does its own locking, it is trivial to provide a wrapper class which obtains the lock (as SGI suggests), performs the container operation, and then releases the lock. This could be templatized *to a certain extent*, on the underlying container and/or a locking mechanism. Trying to provide a catch-all general template solution would probably be more trouble than it's worth.

The library implementation may be configured to use the high-speed caching memory allocator, which complicates thread safety issues. For all details about how to globally override this at application run-time see here. Also useful are details on allocator options and capabilities.

3.8 Exceptions

The C++ language provides language support for stack unwinding with `try` and `catch` blocks and the `throw` keyword.

These are very powerful constructs, and require some thought when applied to the standard library in order to yield components that work efficiently while cleaning up resources when unexpectedly killed via exceptional circumstances.

Two general topics of discussion follow: exception neutrality and exception safety.

3.8.1 Exception Safety

What is exception-safe code?

Will define this as reasonable and well-defined behavior by classes and functions from the standard library when used by user-defined classes and functions that are themselves exception safe.

Please note that using exceptions in combination with templates imposes an additional requirement for exception safety. Instantiating types are required to have destructors that do no throw.

Using the layered approach from Abrahams, can classify library components as providing set levels of safety. These will be called exception guarantees, and can be divided into three categories.

- One. Don't throw.

  As specified in 23.2.1 general container requirements. Applicable to container and string classes.

  Member functions `erase`, `pop_back`, `pop_front`, `swap`, `clear`. And iterator copy constructor and assignment operator.

- Two. Don't leak resources when exceptions are thrown. This is also referred to as the "basic" exception safety guarantee.

  This applicable throughout the standard library.

- Three. Commit-or-rollback semantics. This is referred to as "strong" exception safety guarantee.

  As specified in 23.2.1 general container requirements. Applicable to container and string classes.

  Member functions `insert` of a single element, `push_back`, `push_front`, and `rehash`.

3.8.2 Exception Neutrality

Simply put, once thrown an exception object should continue in flight unless handled explicitly. In practice, this means propagating exceptions should not be swallowed in gratuitous `catch(...)` blocks. Instead, matching `try` and `catch` blocks should have specific catch handlers and allow un-handed exception objects to propagate. If a terminating `catch(...)` blocks exist then it should end with a `throw` to re-throw the current exception.

Why do this?

By allowing exception objects to propagate, a more flexible approach to error handling is made possible (although not required.) Instead of dealing with an error immediately, one can allow the exception to propagate up until sufficient context is available and the choice of exiting or retrying can be made in an informed manner.

Unfortunately, this tends to be more of a guideline than a strict rule as applied to the standard library. As such, the following is a list of known problem areas where exceptions are not propagated.

- Input/Output

  The destructor `ios_base::Init::~Init()` swallows all exceptions from `flush` called on all open streams at termination.

  All formatted input in `basic_istream` or formatted output in `basic_ostream` can be configured to swallow exceptions when `exceptions` is set to ignore ios_base::badbit.

  Functions that have been registered with `ios_base::register_callback` swallow all exceptions when called as part of a callback event.

  When closing the underlying file, `basic_filebuf::close` will swallow (non-cancellation) exceptions thrown and return `NULL`.

- Thread

  The constructors of `thread` that take a callable function argument swallow all exceptions resulting from executing the function argument.

3.8.3 Memory allocation

When the program throws an exception the runtime will obtain storage for a `__cxa_exception` header and the thrown object itself. Libstdc++ will try to use `malloc` to obtain storage, but provides an emergency buffer to be used if malloc fails, as described by the Itanium exception handling ABI.

Contrary to the ABI, the libstdc++ emergency buffer is not always 64kB, and does not always allocate 1kB chunks. The buffer is used as a pool for variable-sized allocations, so that it doesn't waste space for smaller exception objects such as `std::bad_alloc`. The total size of the buffer is scaled appropriately for the target. Specifically it depends on `sizeof(void*)`, so that a 64-bit system uses a larger pool than a 32-bit system. This is done because for 32-bit systems the exception objects (and the exception header) require less space, and core counts and thread counts are typically lower as well.

By default, libstdc++ will use `malloc` to allocate the buffer on program startup. Configuring libstdc++ with the `--enable-libstdc` option will make it use a static buffer instead of using `malloc`.

The buffer size is chosen automatically, but can be overridden by configuring with `--with-libstdcxx-eh-pool-obj-count=NU` where `NUM` is the number of simultaneous allocations that should be supported. The size of the pool will be sufficient for `NUM` exceptions of `6 * sizeof(void*)` bytes, plus another `NUM` exceptions captured in `std::exception_ptr` and rethrown using `std::rethrow_exception`. The buffer size determined by the obj-count value applies whether the buffer is reserved as static storage or is allocated dynamically. Setting obj-count to zero will disable the pool, so that no emergency buffer is present.

For a dynamic buffer, the default size can also be changed at runtime, per-process, via the `GLIBCXX_TUNABLES` environment variable. The `GLIBCXX_TUNABLES` environment variable should be a string of colon-separated *name=value* pairs. The following names will be recognized, with the specified semantics:

`glibcxx.eh_pool.obj_count` The number of exception objects to provide space for in the pool. The value must be a non-negative integer and has the same meaning as the `--with-libstdcxx-eh-pool-obj-count` option for `configure`.

`glibcxx.eh_pool.obj_size` The expected size of exception objects that the pool might get used for. The value must be a positive integer, and is measured in units of `sizeof(void*)`. The default value is `6` which is large enough to store any exception type thrown by libstdc++. Exceptions larger than this can still be allocated from the pool, but larger exceptions will exhaust the pool more rapidly.

3.8.4 Doing without

C++ is a language that strives to be as efficient as is possible in delivering features. As such, considerable care is used by both language implementer and designers to make sure unused features do not impose hidden or unexpected costs. The GNU system tries to be as flexible and as configurable as possible. So, it should come as no surprise that GNU C++ provides an optional language extension, spelled `-fno-exceptions`, as a way to excise the implicitly generated magic necessary to support `try` and `catch` blocks and thrown objects. (Language support for `-fno-exceptions` is documented in the GCC manual.)

Before detailing the library support for `-fno-exceptions`, first a passing note on the things lost when this flag is used: it will break exceptions trying to pass through code compiled with `-fno-exceptions` whether or not that code has any `try` or `catch` constructs. If you might have some code that throws, you shouldn't use `-fno-exceptions`. If you have some code that uses `try` or `catch`, you shouldn't use `-fno-exceptions`.

And what is to be gained, tinkering in the back alleys with a language like this? Exception handling overhead can be measured in the size of the executable binary, and varies with the capabilities of the underlying operating system and specific configuration of the C++ compiler. On recent hardware with GNU system software of the same age, the combined code and data size overhead for enabling exception handling is around 7%. Of course, if code size is of singular concern than using the appropriate optimizer setting with exception handling enabled (ie, `-Os -fexceptions`) may save up to twice that, and preserve error checking.

So. Hell bent, we race down the slippery track, knowing the brakes are a little soft and that the right front wheel has a tendency to wobble at speed. Go on: detail the standard library support for `-fno-exceptions`.

In sum, valid C++ code with exception handling is transformed into a dialect without exception handling. In detailed steps: all use of the C++ keywords `try`, `catch`, and `throw` in the standard library have been permanently replaced with the pre-processor controlled equivalents spelled `__try`, `__catch`, and `__throw_exception_again`. They are defined as follows.

```
#if __cpp_exceptions
# define __try      try
# define __catch(X) catch(X)
# define __throw_exception_again throw
#else
# define __try      if (true)
# define __catch(X) if (false)
# define __throw_exception_again
#endif
```

In addition, for most of the classes derived from class `exception`, there exists a corresponding function with C language linkage. An example:

```
#if __cpp_exceptions
  void __throw_bad_exception()
  { throw bad_exception(); }
#else
  void __throw_bad_exception()
  { abort(); }
#endif
```

The last language feature needing to be transformed by `-fno-exceptions` is treatment of exception specifications on member functions. Fortunately, the compiler deals with this by ignoring exception specifications and so no alternate source markup is needed.

By using this combination of language re-specification by the compiler, and the pre-processor tricks and the functional indirection layer for thrown exception objects by the library, libstdc++ files can be compiled with `-fno-exceptions`.

User code that uses C++ keywords like `throw`, `try`, and `catch` will produce errors even if the user code has included libstdc++ headers and is using constructs like `basic_iostream`. Even though the standard library has been transformed, user code may need modification. User code that attempts or expects to do error checking on standard library components compiled with exception handling disabled should be evaluated and potentially made conditional.

Some issues remain with this approach (see bugzilla entry 25191). Code paths are not equivalent, in particular `catch` blocks are not evaluated. Also problematic are `throw` expressions expecting a user-defined throw handler. Known problem areas in the standard library include using an instance of `basic_istream` with `exceptions` set to specific ios_base::iostate conditions, or cascading `catch` blocks that dispatch error handling or recovery efforts based on the type of exception object thrown.

Oh, and by the way: none of this hackery is at all special. (Although perhaps well-deserving of a raised eyebrow.) Support continues to evolve and may change in the future. Similar and even additional techniques are used in other C++ libraries and compilers.

C++ hackers with a bent for language and control-flow purity have been successfully consoled by grizzled C veterans lamenting the substitution of the C language keyword `const` with the uglified doppelganger `__const`.

3.8.5 Compatibility

3.8.5.1 With C

C language code that is expecting to interoperate with C++ should be compiled with `-fexceptions`. This will make debugging a C language function called as part of C++-induced stack unwinding possible.

In particular, unwinding into a frame with no exception handling data will cause a runtime abort. If the unwinder runs out of unwind info before it finds a handler, `std::terminate()` is called.

Please note that most development environments should take care of getting these details right. For GNU systems, all appropriate parts of the GNU C library are already compiled with `-fexceptions`.

3.8.5.2 With POSIX thread cancellation

GNU systems re-use some of the exception handling mechanisms to track control flow for `POSIX` thread cancellation.

Cancellation points are functions defined by POSIX as worthy of special treatment. The standard library may use some of these functions to implement parts of the ISO C++ standard or depend on them for extensions.

Of note:

`nanosleep`, `read`, `write`, `open`, `close`, and `wait`.

The parts of libstdc++ that use C library functions marked as cancellation points should take pains to be exception neutral. Failing this, `catch` blocks have been augmented to show that the POSIX cancellation object is in flight.

This augmentation adds a `catch` block for `__cxxabiv1::__forced_unwind`, which is the object representing the POSIX cancellation object. Like so:

```
catch(const __cxxabiv1::__forced_unwind&)
{
  this->_M_setstate(ios_base::badbit);
  throw;
}
catch(...)
{ this->_M_setstate(ios_base::badbit); }
```

3.8.6 Bibliography

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3.9 Debugging Support

There are numerous things that can be done to improve the ease with which C++ binaries are debugged when using the GNU tool chain. Here are some of them.

3.9.1 Using g++

Compiler flags determine how debug information is transmitted between compilation and debug or analysis tools.

The default optimizations and debug flags for a libstdc++ build are `-g -O2`. However, both debug and optimization flags can be varied to change debugging characteristics. For instance, turning off all optimization via the `-g -O0 -fno-inline` flags will disable inlining and optimizations, and include debugging information, so that stepping through all functions, (including inlined constructors and destructors) is possible. In addition, `-fno-eliminate-unused-debug-types` can be used when additional debug information, such as nested class info, is desired.

Or, the debug format that the compiler and debugger use to communicate information about source constructs can be changed via `-gdwarf-2` or `-gstabs` flags: some debugging formats permit more expressive type and scope information to be shown in GDB. Expressiveness can be enhanced by flags like `-g3`. The default debug information for a particular platform can be identified via the value set by the PREFERRED_DEBUGGING_TYPE macro in the GCC sources.

Many other options are available: please see "Options for Debugging Your Program" in Using the GNU Compiler Collection (GCC) for a complete list.

3.9.2 Debug Mode

The Debug Mode has compile and run-time checks for many containers.

There are also lightweight assertions for checking function preconditions, such as checking for out-of-bounds indices when accessing a `std::vector`. These can be enabled without using the full Debug Mode, by using `-D_GLIBCXX_ASSERTIONS` (see Macros).

3.9.3 Tracking uncaught exceptions

The verbose termination handler gives information about uncaught exceptions which kill the program.

3.9.4 Memory Leak Hunting

On many targets GCC supports AddressSanitizer, a fast memory error detector, which is enabled by the `-fsanitize=address` option.

The `std::vector` implementation has additional instrumentation to work with AddressSanitizer, but this has to be enabled explicitly by using `-D_GLIBCXX_SANITIZE_VECTOR` (see Macros).

There are also various third party memory tracing and debug utilities that can be used to provide detailed memory allocation information about C++ code. An exhaustive list of tools is not going to be attempted, but includes `mtrace`, `valgrind`, `mudflap` (no longer supported since GCC 4.9.0), ElectricFence, and the non-free commercial product `purify`. In addition, `libcwd`, jemalloc and TCMalloc have replacements for the global `new` and `delete` operators that can track memory allocation and deallocation and provide useful memory statistics.

For valgrind, there are some specific items to keep in mind. First of all, use a version of valgrind that will work with current GNU C++ tools: the first that can do this is valgrind 1.0.4, but later versions should work better. Second, using an unoptimized build might avoid confusing valgrind.

Third, it may be necessary to force deallocation in other libraries as well, namely the "C" library. On GNU/Linux, this can be accomplished with the appropriate use of the `__cxa_atexit` or `atexit` functions.

```
#include <cstdlib>

extern "C" void __libc_freeres(void);

void do_something() { }

int main()
{
  atexit(__libc_freeres);
  do_something();
  return 0;
}
```

or, using `__cxa_atexit`:

```
extern "C" void __libc_freeres(void);
extern "C" int __cxa_atexit(void (*func) (void *), void *arg, void *d);

void do_something() { }

int main()
{
   extern void* __dso_handle __attribute__ ((__weak__));
   __cxa_atexit((void (*) (void *)) __libc_freeres, NULL,
    &__dso_handle ? __dso_handle : NULL);
   do_test();
   return 0;
}
```

Suggested valgrind flags, given the suggestions above about setting up the runtime environment, library, and test file, might be:

```
valgrind -v --num-callers=20 --leak-check=yes --leak-resolution=high --show-reachable= ↩
    yes a.out
```

3.9.4.1 Non-memory leaks in Pool and MT allocators

There are different kinds of allocation schemes that can be used by `std::allocator`. Prior to GCC 3.4.0 the default was to use a pooling allocator, `pool_allocator`, which is still available as the optional `__pool_alloc` extension. Another optional extension, `__mt_alloc`, is a high-performance pool allocator.

In a suspect executable these pooling allocators can give the mistaken impression that memory is being leaked, when in reality the memory "leak" is a pool being used by the library's allocator and is reclaimed after program termination.

If you're using memory debugging tools on a program that uses one of these pooling allocators, you can set the environment variable `GLIBCXX_FORCE_NEW` to keep extraneous pool allocation noise from cluttering debug information. For more details, see the mt allocator documentation and look specifically for `GLIBCXX_FORCE_NEW`.

3.9.5 Data Race Hunting

All synchronization primitives used in the library internals need to be understood by race detectors so that they do not produce false reports.

Two annotation macros are used to explain low-level synchronization to race detectors: `_GLIBCXX_SYNCHRONIZATION_HAPPENS_` and `_GLIBCXX_SYNCHRONIZATION_HAPPENS_AFTER()`. By default, these macros are defined empty -- anyone who wants to use a race detector needs to redefine them to call an appropriate API. Since these macros are empty by default when the library is built, redefining them will only affect inline functions and template instantiations which are compiled in user code. This allows annotation of templates such as `shared_ptr`, but not code which is only instantiated in the library. Code which is only instantiated in the library needs to be recompiled with the annotation macros defined. That can be done by rebuilding the entire libstdc++.so file but a simpler alternative exists for ELF platforms such as GNU/Linux, because ELF symbol interposition allows symbols defined in the shared library to be overridden by symbols with the same name that appear earlier in the runtime search path. This means you only need to recompile the functions that are affected by the annotation macros, which can be done by recompiling individual files. Annotating std::string and std::wstring reference counting can be done by disabling extern templates (by defining _GLIBCXX_EXTERN_TEMPLATE=-1) or by rebuilding the src/string-inst.cc file. Annotating the remaining atomic operations (at the time of writing these are in ios_base::Init::~Init, locale::_Impl, locale::facet and thread::_M_start_thread) requires rebuilding the relevant source files.

The approach described above is known to work with the following race detection tools: DRD, Helgrind, and ThreadSanitizer (this refers to ThreadSanitizer v1, not the new "tsan" feature built-in to GCC itself).

With DRD, Helgrind and ThreadSanitizer you will need to define the macros like this:

```
#define _GLIBCXX_SYNCHRONIZATION_HAPPENS_BEFORE(A) ANNOTATE_HAPPENS_BEFORE(A)
#define _GLIBCXX_SYNCHRONIZATION_HAPPENS_AFTER(A)  ANNOTATE_HAPPENS_AFTER(A)
```

Refer to the documentation of each particular tool for details.

3.9.6 Using gdb

Many options are available for GDB itself: please see "GDB features for C++" in the GDB documentation. Also recommended: the other parts of this manual.

These settings can either be switched on in at the GDB command line, or put into a .gdbinit file to establish default debugging characteristics, like so:

```
set print pretty on
set print object on
set print static-members on
set print vtbl on
set print demangle on
set demangle-style gnu-v3
```

Starting with version 7.0, GDB includes support for writing pretty-printers in Python. Pretty printers for containers and other classes are distributed with GCC from version 4.5.0 and should be installed alongside the libstdc++ shared library files and found automatically by GDB.

Depending where libstdc++ is installed, GDB might refuse to auto-load the python printers and print a warning instead. If this happens the python printers can be enabled by following the instructions GDB gives for setting your auto-load safe-path in your .gdbinit configuration file.

Once loaded, standard library classes that the printers support should print in a more human-readable format. To print the classes in the old style, use the **/r** (raw) switch in the print command (i.e., **print /r foo**). This will print the classes as if the Python pretty-printers were not loaded.

For additional information on STL support and GDB please visit: "GDB Support for STL" in the GDB wiki. Additionally, in-depth documentation and discussion of the pretty printing feature can be found in "Pretty Printing" node in the GDB manual. You can find on-line versions of the GDB user manual in GDB's homepage, at "GDB: The GNU Project Debugger" .

3.9.7 Debug Versions of Library Binary Files

As described above, libstdc++ is built with debug symbols enabled by default, but because it's also built with optimizations the code can be hard to follow when stepping into the library in a debugger.

If you would like to debug libstdc++.so itself, there are two ways to build an unoptimized libstdc++ with debug flags. The first is to create a separate debug build by running make from the top-level of a tree freshly-configured with

```
--enable-libstdcxx-debug
```

and perhaps

```
--enable-libstdcxx-debug-flags='...'
```

Both the normal build and the debug build will persist, without having to specify CXXFLAGS, and the debug library will be installed in a separate directory tree, in (prefix)/lib/debug. For more information, look at the configuration section.

A second approach is to use the configuration flags

```
make CXXFLAGS='-g3 -fno-inline -O0' all
```

3.9.8 Compile Time Checking

The Compile-Time Checks extension has compile-time checks for many algorithms. These checks were designed for C++98 and have not been updated to work with C++11 and later standards. They might be removed at a future date.

Part II

Standard Contents

Chapter 4

Support

This part deals with the functions called and objects created automatically during the course of a program's existence.

While we can't reproduce the contents of the Standard here (you need to get your own copy from your nation's member body; see our homepage for help), we can mention a couple of changes in what kind of support a C++ program gets from the Standard Library.

4.1 Types

4.1.1 Fundamental Types

C++ has the following builtin types:

- char
- signed char
- unsigned char
- signed short
- signed int
- signed long
- unsigned short
- unsigned int
- unsigned long
- bool
- wchar_t
- float
- double
- long double

These fundamental types are always available, without having to include a header file. These types are exactly the same in either C++ or in C.

Specializing parts of the library on these types is prohibited: instead, use a POD.

4.1.2 Numeric Properties

The header `<limits>` defines traits classes to give access to various implementation defined-aspects of the fundamental types. The traits classes -- fourteen in total -- are all specializations of the class template `numeric_limits` and defined as follows:

```
template<typename T>
  struct class
  {
    static const bool is_specialized;
    static T max() throw();
    static T min() throw();

    static const int digits;
    static const int digits10;
    static const bool is_signed;
    static const bool is_integer;
    static const bool is_exact;
    static const int radix;
    static T epsilon() throw();
    static T round_error() throw();

    static const int min_exponent;
    static const int min_exponent10;
    static const int max_exponent;
    static const int max_exponent10;

    static const bool has_infinity;
    static const bool has_quiet_NaN;
    static const bool has_signaling_NaN;
    static const float_denorm_style has_denorm;
    static const bool has_denorm_loss;
    static T infinity() throw();
    static T quiet_NaN() throw();
    static T denorm_min() throw();

    static const bool is_iec559;
    static const bool is_bounded;
    static const bool is_modulo;

    static const bool traps;
    static const bool tinyness_before;
    static const float_round_style round_style;
  };
```

4.1.3 NULL

The only change that might affect people is the type of `NULL`: while it is required to be a macro, the definition of that macro is *not* allowed to be an expression with pointer type such as `(void*)0`, which is often used in C.

For **g++**, `NULL` is `#define`'d to be `__null`, a magic keyword extension of **g++** that is slightly safer than a plain integer.

The biggest problem of #defining `NULL` to be something like "0L" is that the compiler will view that as a long integer before it views it as a pointer, so overloading won't do what you expect. It might not even have the same size as a pointer, so passing `NULL` to a varargs function where a pointer is expected might not even work correctly if `sizeof(NULL) < sizeof(void*)`. The G++ `__null` extension is defined so that `sizeof(__null) == sizeof(void*)` to avoid this problem.

Scott Meyers explains this in more detail in his book *Effective Modern C++* and as a guideline to solve this problem recommends to not overload on pointer-vs-integer types to begin with.

The C++ 2011 standard added the `nullptr` keyword, which is a null pointer constant of a special type, `std::nullptr_t`. Values of this type can be implicitly converted to *any* pointer type, and cannot convert to integer types or be deduced as an integer type. Unless you need to be compatible with C++98/C++03 or C you should prefer to use `nullptr` instead of `NULL`.

4.2 Dynamic Memory

In C++98 there are six flavors each of `operator new` and `operator delete`, so make certain that you're using the right ones. Here are quickie descriptions of `operator new`:

`void* operator new(std::size_t);` Single object form. Throws `std::bad_alloc` on error. This is what most people are used to using.

`void* operator new(std::size_t, std::nothrow_t) noexcept;` Single object "nothrow" form. Calls `operator new(std::size_t)` but if that throws, returns a null pointer instead.

`void* operator new[](std::size_t);` Array `new`. Calls `operator new(std::size_t)` and so throws `std::bad_` on error.

`void* operator new[](std::size_t, std::nothrow_t) noexcept;` Array "nothrow"`new`. Calls `operator new[](std::size_t)` but if that throws, returns a null pointer instead.

`void* operator new(std::size_t, void*) noexcept;` Non-allocating, "placement" single-object `new`, which does nothing except return its argument. This function cannot be replaced.

`void* operator new[](std::size_t, void*) noexcept;` Non-allocating, "placement" array `new`, which also does nothing except return its argument. This function cannot be replaced.

They are distinguished by the arguments that you pass to them, like any other overloaded function. The six flavors of `operator delete` are distinguished the same way, but none of them are allowed to throw an exception under any circumstances anyhow. (The overloads match up with the ones above, for completeness' sake.)

The C++ 2014 revision of the standard added two additional overloads of `operator delete` for "sized deallocation", allowing the compiler to provide the size of the storage being freed.

The C++ 2017 standard added even more overloads of both `operator new` and `operator delete` for allocating and deallocating storage for overaligned types. These overloads correspond to each of the allocating forms of `operator new` and `operator delete` but with an additional parameter of type std::align_val_t. These new overloads are not interchangeable with the versions without an aligment parameter, so if memory was allocated by an overload of `operator new` taking an alignment parameter, then it must be decallocated by the corresponding overload of `operator delete` that takes an alignment parameter.

Apart from the non-allocating forms, the default versions of the array and nothrow `operator new` functions will all result in a call to either `operator new(std::size_t)` or `operator new(std::size_t, std::align_val_t)`, and similarly the default versions of the array and nothrow `operator delete` functions will result in a call to either `operator delete(void*)` or `operator delete(void*, std::align_val_t)` (or the sized versions of those).

Apart from the non-allocating forms, any of these functions can be replaced by defining a function with the same signature in your program. Replacement versions must preserve certain guarantees, such as memory obtained from a nothrow `operator new` being free-able by the normal (non-nothrow) `operator delete`, and the sized and unsized forms of `operator delete` being interchangeable (because it's unspecified whether the compiler calls the sized delete instead of the normal one). The simplest way to meet the guarantees is to only replace the ordinary `operator new(size_t)` and `operator delete(void*)` and `operator delete(void*, std::size_t)` functions, and the replaced versions will be used by all of `operator new(size_t, nothrow_t)`, `operator new[](size_t)` and `operator new[](size_t, nothrow_t)` and the corresponding `operator delete` functions. To support types with extended alignment you may also need to replace `operator new(size_t, align_val_t)` and `operator delete(void*, align_val_t)` `operator delete(void*, size_t, align_val_t)` (which will then be used by the nothrow and array forms for extended alignments). If you do need to replace other forms (e.g. to define the nothrow `operator new` to allocate memory directly, so it works with exceptions disabled) then make sure the memory it allocates can still be freed by the non-nothrow forms of `operator delete`.

If the default versions of `operator new(std::size_t)` and `operator new(size_t, std::align_val_t)` can't allocate the memory requested, they usually throw an exception object of type `std::bad_alloc` (or some class derived from that). However, the program can influence that behavior by registering a "new-handler", because what `operator new` actually does is something like:

```
  while (true)
  {
    if (void* p = /* try to allocate memory */)
      return p;
    else if (std::new_handler h = std::get_new_handler ())
      h ();
    else
      throw bad_alloc{};
  }
```

This means you can influence what happens on allocation failure by writing your own new-handler and then registering it with `std::set_new_handler`:

```
typedef void (*PFV)();

static char*  safety;
static PFV    old_handler;

void my_new_handler ()
{
    delete[] safety;
    safety = nullptr;
    popup_window ("Dude, you are running low on heap memory.  You"
      " should, like, close some windows, or something."
      " The next time you run out, we're gonna burn!");
    set_new_handler (old_handler);
    return;
}

int main ()
{
    safety = new char[500000];
    old_handler = set_new_handler (&my_new_handler);
    ...
}
```

4.2.1 Additional Notes

Remember that it is perfectly okay to `delete` a null pointer! Nothing happens, by definition. That is not the same thing as deleting a pointer twice.

`std::bad_alloc` is derived from the base `std::exception` class, see Exceptions.

4.3 Termination

4.3.1 Termination Handlers

Not many changes here to `<cstdlib>`. You should note that the `abort()` function does not call the destructors of automatic nor static objects, so if you're depending on those to do cleanup, it isn't going to happen. (The functions registered with `atexit()` don't get called either, so you can forget about that possibility, too.)

The good old `exit()` function can be a bit funky, too, until you look closer. Basically, three points to remember are:

1. Static objects are destroyed in reverse order of their creation.
2. Functions registered with `atexit()` are called in reverse order of registration, once per registration call. (This isn't actually new.)

3. The previous two actions are “interleaved,” that is, given this pseudocode:

```
extern "C or C++" void f1 ();
extern "C or C++" void f2 ();

static Thing obj1;
atexit(f1);
static Thing obj2;
atexit(f2);
```

then at a call of `exit()`, `f2` will be called, then `obj2` will be destroyed, then `f1` will be called, and finally `obj1` will be destroyed. If `f1` or `f2` allow an exception to propagate out of them, Bad Things happen.

Note also that `atexit()` is only required to store 32 functions, and the compiler/library might already be using some of those slots. If you think you may run out, we recommend using the `xatexit`/`xexit` combination from `libiberty`, which has no such limit.

4.3.2 Verbose Terminate Handler

If you are having difficulty with uncaught exceptions and want a little bit of help debugging the causes of the core dumps, you can make use of a GNU extension, the verbose terminate handler.

The verbose terminate handler is only available for hosted environments (see Configuring) and will be used by default unless the library is built with `--disable-libstdcxx-verbose` or with exceptions disabled. If you need to enable it explicitly you can do so by calling the `std::set_terminate` function.

```
#include <exception>

int main()
{
  std::set_terminate(__gnu_cxx::__verbose_terminate_handler);
  ...

  throw anything;
}
```

The `__verbose_terminate_handler` function obtains the name of the current exception, attempts to demangle it, and prints it to `stderr`. If the exception is derived from `std::exception` then the output from `what()` will be included.

Any replacement termination function is required to kill the program without returning; this one calls `std::abort`.

For example:

```
#include <exception>
#include <stdexcept>

struct argument_error : public std::runtime_error
{
  argument_error(const std::string& s): std::runtime_error(s) { }
};

int main(int argc)
{
  std::set_terminate(__gnu_cxx::__verbose_terminate_handler);
  if (argc > 5)
    throw argument_error("argc is greater than 5!");
  else
    throw argc;
}
```

With the verbose terminate handler active, this gives:

```
% ./a.out
terminate called after throwing a 'int'
Aborted
% ./a.out f f f f f f f f f f f
terminate called after throwing an instance of 'argument_error'
what(): argc is greater than 5!
Aborted
```

The 'Aborted' line is printed by the shell after the process exits by calling `abort()`.

As this is the default termination handler, nothing need be done to use it. To go back to the previous "silent death" method, simply include `<exception>` and `<cstdlib>`, and call

```
std::set_terminate(std::abort);
```

After this, all calls to `terminate` will use `abort` as the terminate handler.

Note: the verbose terminate handler will attempt to write to `stderr`. If your application closes `stderr` or redirects it to an inappropriate location, `__verbose_terminate_handler` will behave in an unspecified manner.

Chapter 5

Diagnostics

5.1 Exceptions

5.1.1 API Reference

Most exception classes are defined in one of the standard headers `<exception>`, `<stdexcept>`, `<new>`, and `<typeinfo>`. The C++ 2011 revision of the standard added more exception types in the headers `<functional>`, `<future>`, `<regex>`, and `<system_error>`. The C++ 2017 revision of the standard added more exception types in the headers `<any>`, `<filesystem>`, `<optional>`, and `<variant>`.

All exceptions thrown by the library have a base class of type `std::exception`, defined in `<exception>`. This type has no `std::string` member.

Derived from this are several classes that may have a `std::string` member. A full hierarchy can be found in the source documentation.

5.1.2 Adding Data to `exception`

The standard exception classes carry with them a single string as data (usually describing what went wrong or where the 'throw' took place). It's good to remember that you can add your own data to these exceptions when extending the hierarchy:

```
struct My_Exception : public std::runtime_error
{
  public:
    My_Exception (const string& whatarg)
  : std::runtime_error(whatarg), e(errno), id(GetDataBaseID()) { }
    int  errno_at_time_of_throw() const { return e; }
    DBID id_of_thing_that_threw() const { return id; }
  protected:
    int    e;
    DBID   id;     // some user-defined type
};
```

5.2 Use of errno by the library

The C and POSIX standards guarantee that `errno` is never set to zero by any library function. The C++ standard has less to say about when `errno` is or isn't set, but libstdc++ follows the same rule and never sets it to zero.

On the other hand, there are few guarantees about when the C++ library sets `errno` on error, beyond what is specified for functions that come from the C library. For example, when `std::stoi` throws an exception of type `std::out_of_range`, `errno` may or may not have been set to `ERANGE`.

Parts of the C++ library may be implemented in terms of C library functions, which may result in `errno` being set with no explicit call to a C function. For example, on a target where `operator new` uses `malloc` a failed memory allocation with `operator new` might set `errno` to `ENOMEM`. Which C++ library functions can set `errno` in this way is unspecified because it may vary between platforms and between releases.

5.3 Concept Checking

In 1999, SGI added “concept checkers” to their implementation of the STL: code which checked the template parameters of instantiated pieces of the STL, in order to insure that the parameters being used met the requirements of the standard. For example, the Standard requires that types passed as template parameters to `vector` be "Assignable" (which means what you think it means). The checking was done during compilation, and none of the code was executed at runtime.

Unfortunately, the size of the compiler files grew significantly as a result. The checking code itself was cumbersome. And bugs were found in it on more than one occasion.

The primary author of the checking code, Jeremy Siek, had already started work on a replacement implementation. The new code was formally reviewed and accepted into the Boost libraries, and we are pleased to incorporate it into the GNU C++ library.

The new version imposes a much smaller space overhead on the generated object file. The checks are also cleaner and easier to read and understand.

They are off by default for all versions of GCC. They can be enabled at configure time with --enable-concept-checks. You can enable them on a per-translation-unit basis with `-D_GLIBCXX_CONCEPT_CHECKS`.

Please note that the checks are based on the requirements in the original C++ standard, many of which were relaxed in the C++11 standard and so valid C++11 code may be incorrectly rejected by the concept checks. Additionally, some correct C++03 code might be rejected by the concept checks, for example template argument types may need to be complete when used in a template definition, rather than at the point of instantiation. There are no plans to address these shortcomings.

Chapter 6

Utilities

6.1 Functors

If you don't know what functors are, you're not alone. Many people get slightly the wrong idea. In the interest of not reinventing the wheel, we will refer you to the introduction to the functor concept written by SGI as part of their STL, in their https://web.archive.org/web/20171209002754/http://www.sgi.com/tech/stl/functors.html.

6.2 Pairs

The `pair<T1,T2>` is a simple and handy way to carry around a pair of objects. One is of type T1, and another of type T2; they may be the same type, but you don't get anything extra if they are. The two members can be accessed directly, as `.first` and `.second`.

Construction is simple. The default ctor initializes each member with its respective default ctor. The other simple ctor,

```
pair (const T1& x, const T2& y);
```

does what you think it does, `first` getting `x` and `second` getting `y`.

There is a constructor template for copying pairs of other types:

```
template <class U, class V> pair (const pair<U,V>& p);
```

The compiler will convert as necessary from U to T1 and from V to T2 in order to perform the respective initializations.

The comparison operators are done for you. Equality of two `pair<T1,T2>`s is defined as both `first` members comparing equal and both `second` members comparing equal; this simply delegates responsibility to the respective `operator==` functions (for types like MyClass) or builtin comparisons (for types like int, char, etc).

The less-than operator is a bit odd the first time you see it. It is defined as evaluating to:

```
    x.first  <  y.first  ||
  ( !(y.first  <  x.first)  &&  x.second  <  y.second )
```

The other operators are not defined using the `rel_ops` functions above, but their semantics are the same.

Finally, there is a template function called `make_pair` that takes two references-to-const objects and returns an instance of a pair instantiated on their respective types:

```
pair<int,MyClass> p = make_pair(4,myobject);
```

6.3 Memory

Memory contains three general areas. First, function and operator calls via `new` and `delete` operator or member function calls. Second, allocation via `allocator`. And finally, smart pointer and intelligent pointer abstractions.

6.3.1 Allocators

Memory management for Standard Library entities is encapsulated in a class template called `allocator`. The `allocator` abstraction is used throughout the library in `string`, container classes, algorithms, and parts of iostreams. This class, and base classes of it, are the superset of available free store ("heap") management classes.

6.3.1.1 Requirements

The C++ standard only gives a few directives in this area:

- When you add elements to a container, and the container must allocate more memory to hold them, the container makes the request via its Allocator template parameter, which is usually aliased to allocator_type. This includes adding chars to the string class, which acts as a regular STL container in this respect.
- The default Allocator argument of every container-of-T is `allocator<T>`.
- The interface of the `allocator<T>` class is extremely simple. It has about 20 public declarations (nested typedefs, member functions, etc), but the two which concern us most are:

```
T*    allocate   (size_type n, const void* hint = 0);
void  deallocate (T* p, size_type n);
```

  The `n` arguments in both those functions is a *count* of the number of T's to allocate space for, *not their total size*. (This is a simplification; the real signatures use nested typedefs.)
- The storage is obtained by calling `::operator new`, but it is unspecified when or how often this function is called. The use of the `hint` is unspecified, but intended as an aid to locality if an implementation so desires. `[20.4.1.1]/6`

Complete details can be found in the C++ standard, look in `[20.4 Memory]`.

6.3.1.2 Design Issues

The easiest way of fulfilling the requirements is to call `operator new` each time a container needs memory, and to call `operator delete` each time the container releases memory. This method may be slower than caching the allocations and re-using previously-allocated memory, but has the advantage of working correctly across a wide variety of hardware and operating systems, including large clusters. The `__gnu_cxx::new_allocator` implements the simple operator new and operator delete semantics, while `__gnu_cxx::malloc_allocator` implements much the same thing, only with the C language functions `std::malloc` and `std::free`.

Another approach is to use intelligence within the allocator class to cache allocations. This extra machinery can take a variety of forms: a bitmap index, an index into an exponentially increasing power-of-two-sized buckets, or simpler fixed-size pooling cache. The cache is shared among all the containers in the program: when your program's `std::vector<int>` gets cut in half and frees a bunch of its storage, that memory can be reused by the private `std::list<WonkyWidget>` brought in from a KDE library that you linked against. And operators `new` and `delete` are not always called to pass the memory on, either, which is a speed bonus. Examples of allocators that use these techniques are `__gnu_cxx::bitmap_allocator`, `__gnu_cxx::pool_allocator`, and `__gnu_cxx::__mt_alloc`.

Depending on the implementation techniques used, the underlying operating system, and compilation environment, scaling caching allocators can be tricky. In particular, order-of-destruction and order-of-creation for memory pools may be difficult to pin down with certainty, which may create problems when used with plugins or loading and unloading shared objects in memory. As such, using caching allocators on systems that do not support `abi::__cxa_atexit` is not recommended.

6.3.1.3 Implementation

6.3.1.3.1 Interface Design

The only allocator interface that is supported is the standard C++ interface. As such, all STL containers have been adjusted, and all external allocators have been modified to support this change.

The class `allocator` just has typedef, constructor, and rebind members. It inherits from one of the high-speed extension allocators, covered below. Thus, all allocation and deallocation depends on the base class.

The choice of base class that `allocator` is derived from is fixed at the time when GCC is built, and the different choices are not ABI compatible.

6.3.1.3.2 Selecting Default Allocation Policy

It's difficult to pick an allocation strategy that will provide maximum utility, without excessively penalizing some behavior. In fact, it's difficult just deciding which typical actions to measure for speed.

Three synthetic benchmarks have been created that provide data that is used to compare different C++ allocators. These tests are:

1. Insertion.

   Over multiple iterations, various STL container objects have elements inserted to some maximum amount. A variety of allocators are tested. Test source for sequence and associative containers.

2. Insertion and erasure in a multi-threaded environment.

   This test shows the ability of the allocator to reclaim memory on a per-thread basis, as well as measuring thread contention for memory resources. Test source here.

3. A threaded producer/consumer model.

   Test source for sequence and associative containers.

Since GCC 12 the default choice for `allocator` is `std::__new_allocator`. Before GCC 12 it was the `__gnu_cxx::new_al`
extension (which has identical behaviour).

6.3.1.3.3 Disabling Memory Caching

In use, `allocator` may allocate and deallocate using implementation-specific strategies and heuristics. Because of this, a given call to an allocator object's `allocate` member function may not actually call the global `operator new` and a given call to to the `deallocate` member function may not call `operator delete`.

This can be confusing.

In particular, this can make debugging memory errors more difficult, especially when using third-party tools like valgrind or debug versions of `new`.

There are various ways to solve this problem. One would be to use a custom allocator that just called operators `new` and `delete` directly, for every allocation. (See the default allocator, `include/ext/new_allocator.h`, for instance.) However, that option may involve changing source code to use a non-default allocator. Another option is to force the default allocator to remove caching and pools, and to directly allocate with every call of `allocate` and directly deallocate with every call of `deallocate`, regardless of efficiency. As it turns out, this last option is also available.

To globally disable memory caching within the library for some of the optional non-default allocators, merely set `GLIBCXX_FORCE_NE`
(with any value) in the system's environment before running the program. If your program crashes with `GLIBCXX_FORCE_NEW` in the environment, it likely means that you linked against objects built against the older library (objects which might still using the cached allocations...).

6.3.1.4 Using a Specific Allocator

You can specify different memory management schemes on a per-container basis, by overriding the default Allocator template parameter. For example, an easy (but non-portable) method of specifying that only `malloc` or `free` should be used instead of the default node allocator is:

```
std::list <int, __gnu_cxx::malloc_allocator<int> >  malloc_list;
```

Likewise, a debugging form of whichever allocator is currently in use:

```
std::deque <int, __gnu_cxx::debug_allocator<std::allocator<int> > >  debug_deque;
```

6.3.1.5 Custom Allocators

Writing a portable C++ allocator would dictate that the interface would look much like the one specified for `allocator`. Additional member functions, but not subtractions, would be permissible.

Probably the best place to start would be to copy one of the extension allocators: say a simple one like `new_allocator`.

Since C++11 the minimal interface require for an allocator is much smaller, as `std::allocator_traits` can provide default for much of the interface.

6.3.1.6 Extension Allocators

Several other allocators are provided as part of this implementation. The location of the extension allocators and their names have changed, but in all cases, functionality is equivalent. Starting with gcc-3.4, all extension allocators are standard style. Before this point, SGI style was the norm. Because of this, the number of template arguments also changed. Table B.6 tracks the changes.

More details on each of these extension allocators follows.

1. `new_allocator`

   Simply wraps `::operator new` and `::operator delete`.

2. `malloc_allocator`

   Simply wraps `malloc` and `free`. There is also a hook for an out-of-memory handler (for `new`/`delete` this is taken care of elsewhere).

3. `debug_allocator`

   A wrapper around an arbitrary allocator `A`. It passes on slightly increased size requests to `A`, and uses the extra memory to store size information. When a pointer is passed to `deallocate()`, the stored size is checked, and `assert()` is used to guarantee they match.

4. `throw_allocator`

   Includes memory tracking and marking abilities as well as hooks for throwing exceptions at configurable intervals (including random, all, none).

5. `__pool_alloc`

   A high-performance, single pool allocator. The reusable memory is shared among identical instantiations of this type. It calls through `::operator new` to obtain new memory when its lists run out. If a client container requests a block larger than a certain threshold size, then the pool is bypassed, and the allocate/deallocate request is passed to `::operator new` directly.

   For thread-enabled configurations, the pool is locked with a single big lock. In some situations, this implementation detail may result in severe performance degradation.

   (Note that the GCC thread abstraction layer allows us to provide safe zero-overhead stubs for the threading routines, if threads were disabled at configuration time.)

6. `__mt_alloc`

   A high-performance fixed-size allocator with exponentially-increasing allocations. It has its own chapter in the documentation.

7. `bitmap_allocator`

   A high-performance allocator that uses a bit-map to keep track of the used and unused memory locations. It has its own chapter in the documentation.

6.3.1.7 Bibliography

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6.3.2 auto_ptr

6.3.2.1 Limitations

Explaining all of the fun and delicious things that can happen with misuse of the `auto_ptr` class template (called AP here) would take some time. Suffice it to say that the use of AP safely in the presence of copying has some subtleties.

The AP class is a really nifty idea for a smart pointer, but it is one of the dumbest of all the smart pointers -- and that's fine.

AP is not meant to be a supersmart solution to all resource leaks everywhere. Neither is it meant to be an effective form of garbage collection (although it can help, a little bit). And it can *not*be used for arrays!

AP is meant to prevent nasty leaks in the presence of exceptions. That's *all*. This code is AP-friendly:

```
  // Not a recommend naming scheme, but good for web-based FAQs.
  typedef std::auto_ptr<MyClass>  APMC;

  extern function_taking_MyClass_pointer (MyClass*);
  extern some_throwable_function ();

  void func (int data)
  {
APMC  ap (new MyClass(data));

some_throwable_function();   // this will throw an exception

function_taking_MyClass_pointer (ap.get());
  }
```

When an exception gets thrown, the instance of MyClass that's been created on the heap will be `delete`'d as the stack is unwound past `func()`.

Changing that code as follows is not AP-friendly:

```
APMC  ap (new MyClass[22]);
```

You will get the same problems as you would without the use of AP:

```
char*  array = new char[10];       // array new...
...
delete array;                      // ...but single-object delete
```

AP cannot tell whether the pointer you've passed at creation points to one or many things. If it points to many things, you are about to die. AP is trivial to write, however, so you could write your own `auto_array_ptr` for that situation (in fact, this has been done many times; check the mailing lists, Usenet, Boost, etc).

6.3.2.2 Use in Containers

All of the containers described in the standard library require their contained types to have, among other things, a copy constructor like this:

```
  struct My_Type
  {
My_Type (My_Type const&);
  };
```

Note the const keyword; the object being copied shouldn't change. The template class `auto_ptr` (called AP here) does not meet this requirement. Creating a new AP by copying an existing one transfers ownership of the pointed-to object, which means that the AP being copied must change, which in turn means that the copy ctors of AP do not take const objects.

The resulting rule is simple: *Never ever use a container of auto_ptr objects*. The standard says that "undefined" behavior is the result, but it is guaranteed to be messy.

To prevent you from doing this to yourself, the concept checks built in to this implementation will issue an error if you try to compile code like this:

```
  #include <vector>
  #include <memory>

  void f()
  {
std::vector< std::auto_ptr<int> >   vec_ap_int;
  }
```

Should you try this with the checks enabled, you will see an error.

6.3.3 shared_ptr

The shared_ptr class template stores a pointer, usually obtained via new, and implements shared ownership semantics.

6.3.3.1 Requirements

The standard deliberately doesn't require a reference-counted implementation, allowing other techniques such as a circular-linked-list.

6.3.3.2 Design Issues

The `shared_ptr` code is kindly donated to GCC by the Boost project and the original authors of the code. The basic design and algorithms are from Boost, the notes below describe details specific to the GCC implementation. Names have been uglified in this implementation, but the design should be recognisable to anyone familiar with the Boost 1.32 shared_ptr.

The basic design is an abstract base class, `_Sp_counted_base` that does the reference-counting and calls virtual functions when the count drops to zero. Derived classes override those functions to destroy resources in a context where the correct dynamic type is known. This is an application of the technique known as type erasure.

6.3.3.3 Implementation

6.3.3.3.1 Class Hierarchy

A `shared_ptr<T>` contains a pointer of type T* and an object of type `__shared_count`. The shared_count contains a pointer of type _Sp_counted_base* which points to the object that maintains the reference-counts and destroys the managed resource.

`_Sp_counted_base<Lp>` The base of the hierarchy is parameterized on the lock policy (see below.) _Sp_counted_base doesn't depend on the type of pointer being managed, it only maintains the reference counts and calls virtual functions when the counts drop to zero. The managed object is destroyed when the last strong reference is dropped, but the _Sp_counted_base itself must exist until the last weak reference is dropped.

`_Sp_counted_base_impl<Ptr, Deleter, Lp>` Inherits from _Sp_counted_base and stores a pointer of type `Ptr` and a deleter of type `Deleter`. `_Sp_deleter` is used when the user doesn't supply a custom deleter. Unlike Boost's, this default deleter is not "checked" because GCC already issues a warning if `delete` is used with an incomplete type. This is the only derived type used by `tr1::shared_ptr<Ptr>` and it is never used by `std::shared_ptr`, which uses one of the following types, depending on how the shared_ptr is constructed.

`_Sp_counted_ptr<Ptr, Lp>` Inherits from _Sp_counted_base and stores a pointer of type Ptr, which is passed to `delete` when the last reference is dropped. This is the simplest form and is used when there is no custom deleter or allocator.

`_Sp_counted_deleter<Ptr, Deleter, Alloc>` Inherits from _Sp_counted_ptr and adds support for custom deleter and allocator. Empty Base Optimization is used for the allocator. This class is used even when the user only provides a custom deleter, in which case `allocator` is used as the allocator.

`_Sp_counted_ptr_inplace<Tp, Alloc, Lp>` Used by `allocate_shared` and `make_shared`. Contains aligned storage to hold an object of type Tp, which is constructed in-place with placement `new`. Has a variadic template constructor allowing any number of arguments to be forwarded to Tp's constructor. Unlike the other `_Sp_counted_*` classes, this one is parameterized on the type of object, not the type of pointer; this is purely a convenience that simplifies the implementation slightly.

C++11-only features are: rvalue-ref/move support, allocator support, aliasing constructor, make_shared & allocate_shared. Additionally, the constructors taking `auto_ptr` parameters are deprecated in C++11 mode.

6.3.3.3.2 Thread Safety

The Thread Safety section of the Boost shared_ptr documentation says "shared_ptr objects offer the same level of thread safety as built-in types." The implementation must ensure that concurrent updates to separate shared_ptr instances are correct even when those instances share a reference count e.g.

```
shared_ptr<A> a(new A);
shared_ptr<A> b(a);

// Thread 1     // Thread 2
   a.reset();      b.reset();
```

The dynamically-allocated object must be destroyed by exactly one of the threads. Weak references make things even more interesting. The shared state used to implement shared_ptr must be transparent to the user and invariants must be preserved at all times. The key pieces of shared state are the strong and weak reference counts. Updates to these need to be atomic and visible to all threads to ensure correct cleanup of the managed resource (which is, after all, shared_ptr's job!) On multi-processor systems memory synchronisation may be needed so that reference-count updates and the destruction of the managed resource are race-free.

The function `_Sp_counted_base::_M_add_ref_lock()`, called when obtaining a shared_ptr from a weak_ptr, has to test if the managed resource still exists and either increment the reference count or throw `bad_weak_ptr`. In a multi-threaded program there is a potential race condition if the last reference is dropped (and the managed resource destroyed) between testing the reference count and incrementing it, which could result in a shared_ptr pointing to invalid memory.

The Boost shared_ptr (as used in GCC) features a clever lock-free algorithm to avoid the race condition, but this relies on the processor supporting an atomic *Compare-And-Swap* instruction. For other platforms there are fall-backs using mutex locks. Boost (as of version 1.35) includes several different implementations and the preprocessor selects one based on the compiler, standard library, platform etc. For the version of shared_ptr in libstdc++ the compiler and library are fixed, which makes things much simpler: we have an atomic CAS or we don't, see Lock Policy below for details.

6.3.3.3.3 Selecting Lock Policy

There is a single `_Sp_counted_base` class, which is a template parameterized on the enum __gnu_cxx::_Lock_policy. The entire family of classes is parameterized on the lock policy, right up to `__shared_ptr`, `__weak_ptr` and `__enable_shared_fro` The actual `std::shared_ptr` class inherits from `__shared_ptr` with the lock policy parameter selected automatically based on the thread model and platform that libstdc++ is configured for, so that the best available template specialization will be used. This design is necessary because it would not be conforming for `shared_ptr` to have an extra template parameter, even if it had a default value. The available policies are:

1. `_S_atomic`

   Selected when GCC supports a builtin atomic compare-and-swap operation on the target processor (see Atomic Builtins.) The reference counts are maintained using a lock-free algorithm and GCC's atomic builtins, which provide the required memory synchronisation.

2. `_S_mutex`

   The _Sp_counted_base specialization for this policy contains a mutex, which is locked in add_ref_lock(). This policy is used when GCC's atomic builtins aren't available so explicit memory barriers are needed in places.

3. `_S_single`

   This policy uses a non-reentrant add_ref_lock() with no locking. It is used when libstdc++ is built without `--enable-threads`.

For all three policies, reference count increments and decrements are done via the functions in `ext/atomicity.h`, which detect if the program is multi-threaded. If only one thread of execution exists in the program then less expensive non-atomic operations are used.

6.3.3.3.4 Related functions and classes

`dynamic_pointer_cast`, `static_pointer_cast`, `const_pointer_cast` As noted in N2351, these functions can be implemented non-intrusively using the alias constructor. However the aliasing constructor is only available in C++11 mode, so in TR1 mode these casts rely on three non-standard constructors in shared_ptr and __shared_ptr. In C++11 mode these constructors and the related tag types are not needed.

`enable_shared_from_this` The clever overload to detect a base class of type `enable_shared_from_this` comes straight from Boost. There is an extra overload for `__enable_shared_from_this` to work smoothly with `__shared_ptr<Tp, Lp>` using any lock policy.

`make_shared`, `allocate_shared` `make_shared` simply forwards to `allocate_shared` with `std::allocator` as the allocator. Although these functions can be implemented non-intrusively using the alias constructor, if they have access to the implementation then it is possible to save storage and reduce the number of heap allocations. The newly constructed object and the _Sp_counted_* can be allocated in a single block and the standard says implementations are "encouraged, but not required," to do so. This implementation provides additional non-standard constructors (selected with the type `_Sp_make_shared_tag`) which create an object of type `_Sp_counted_ptr_inplace` to hold the new object. The returned `shared_ptr<A>` needs to know the address of the new `A` object embedded in the `_Sp_counted_ptr_inplace`, but it has no way to access it. This implementation uses a "covert channel" to return the address of the embedded object when `get_deleter<_Sp_make_shared_tag>()` is called. Users should not try to use this. As well as the extra constructors, this implementation also needs some members of _Sp_counted_deleter to be protected where they could otherwise be private.

6.3.3.4 Use

6.3.3.4.1 Examples

Examples of use can be found in the testsuite, under `testsuite/tr1/2_general_utilities/shared_ptr`, `testsuite/20_util/shared_ptr` and `testsuite/20_util/weak_ptr`.

6.3.3.4.2 Unresolved Issues

The `shared_ptr` *atomic access* clause in the C++11 standard is not implemented in GCC.

Unlike Boost, this implementation does not use separate classes for the pointer+deleter and pointer+deleter+allocator cases in C++11 mode, combining both into _Sp_counted_deleter and using `allocator` when the user doesn't specify an allocator. If it was found to be beneficial an additional class could easily be added. With the current implementation, the _Sp_counted_deleter and __shared_count constructors taking a custom deleter but no allocator are technically redundant and could be removed, changing callers to always specify an allocator. If a separate pointer+deleter class was added the __shared_count constructor would be needed, so it has been kept for now.

The hack used to get the address of the managed object from `_Sp_counted_ptr_inplace::_M_get_deleter()` is accessible to users. This could be prevented if `get_deleter<_Sp_make_shared_tag>()` always returned NULL, since the hack only needs to work at a lower level, not in the public API. This wouldn't be difficult, but hasn't been done since there is no danger of accidental misuse: users already know they are relying on unsupported features if they refer to implementation details such as _Sp_make_shared_tag.

tr1::_Sp_deleter could be a private member of tr1::__shared_count but it would alter the ABI.

6.3.3.5 Acknowledgments

The original authors of the Boost shared_ptr, which is really nice code to work with, Peter Dimov in particular for his help and invaluable advice on thread safety. Phillip Jordan and Paolo Carlini for the lock policy implementation.

6.3.3.6 Bibliography

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[17] *C++ Standard Library Active Issues List* , N2456 .

[18] *Working Draft, Standard for Programming Language C++* , N2461 .

[19] *Boost C++ Libraries documentation, shared_ptr* , N2461 .

6.4 Traits

Chapter 7

Strings

7.1 String Classes

7.1.1 Simple Transformations

Here are Standard, simple, and portable ways to perform common transformations on a `string` instance, such as "convert to all upper case." The word transformations is especially apt, because the standard template function `transform<>` is used.

This code will go through some iterations. Here's a simple version:

```
#include <string>
#include <algorithm>
#include <cctype>      // old <ctype.h>

struct ToLower
{
  char operator() (char c) const  { return std::tolower(c); }
};

struct ToUpper
{
  char operator() (char c) const  { return std::toupper(c); }
};

int main()
{
  std::string  s ("Some Kind Of Initial Input Goes Here");

  // Change everything into upper case
  std::transform (s.begin(), s.end(), s.begin(), ToUpper());

  // Change everything into lower case
  std::transform (s.begin(), s.end(), s.begin(), ToLower());

  // Change everything back into upper case, but store the
  // result in a different string
  std::string  capital_s;
  capital_s.resize(s.size());
  std::transform (s.begin(), s.end(), capital_s.begin(), ToUpper());
}
```

Note that these calls all involve the global C locale through the use of the C functions `toupper`/`tolower`. This is absolutely guaranteed to work -- but *only* if the string contains *only* characters from the basic source character set, and there are *only* 96 of those. Which means that not even all English text can be represented (certain British spellings, proper names, and so forth). So, if all your input forevermore consists of only those 96 characters (hahahahahaha), then you're done.

Note that the `ToUpper` and `ToLower` function objects are needed because `toupper` and `tolower` are overloaded names (declared in `<cctype>` and `<locale>`) so the template-arguments for `transform<>` cannot be deduced, as explained in this message. At minimum, you can write short wrappers like

```
char toLower (char c)
{
   // std::tolower(c) is undefined if c < 0 so cast to unsigned char.
   return std::tolower((unsigned char)c);
}
```

(Thanks to James Kanze for assistance and suggestions on all of this.)

Since C++11 the wrapper can be replaced with a lambda expression, which can perform the conversion to `unsigned char` and also ensure the single-argument form of `std::lower` is used:

```
    std::transform (s.begin(), s.end(), capital_s.begin(),
                    [](unsigned char c) { return std::tolower(c); });
```

Another common operation is trimming off excess whitespace. Much like transformations, this task is trivial with the use of string's `find` family. These examples are broken into multiple statements for readability:

```
std::string  str (" \t blah blah blah    \n ");

// trim leading whitespace
string::size_type  notwhite = str.find_first_not_of(" \t\n");
str.erase(0,notwhite);

// trim trailing whitespace
notwhite = str.find_last_not_of(" \t\n");
str.erase(notwhite+1);
```

Obviously, the calls to `find` could be inserted directly into the calls to `erase`, in case your compiler does not optimize named temporaries out of existence.

7.1.2 Case Sensitivity

The well-known-and-if-it-isn't-well-known-it-ought-to-be Guru of the Week discussions held on Usenet covered this topic in January of 1998. Briefly, the challenge was, "write a 'ci_string' class which is identical to the standard 'string' class, but is case-insensitive in the same way as the (common but nonstandard) C function stricmp()".

```
ci_string s( "AbCdE" );

// case insensitive
assert( s == "abcde" );
assert( s == "ABCDE" );

// still case-preserving, of course
assert( strcmp( s.c_str(), "AbCdE" ) == 0 );
assert( strcmp( s.c_str(), "abcde" ) != 0 );
```

The solution is surprisingly easy. The original answer was posted on Usenet, and a revised version appears in Herb Sutter's book *Exceptional C++* and on his website as GotW 29.

See? Told you it was easy!

Added June 2000: The May 2000 issue of C++ Report contains a fascinating article by Matt Austern (yes, *the* Matt Austern) on why case-insensitive comparisons are not as easy as they seem, and why creating a class is the *wrong* way to go about it in production code. (The GotW answer mentions one of the principle difficulties; his article mentions more.)

Basically, this is "easy" only if you ignore some things, things which may be too important to your program to ignore. (I chose to ignore them when originally writing this entry, and am surprised that nobody ever called me on it...) The GotW question and answer remain useful instructional tools, however.

Added September 2000: James Kanze provided a link to a Unicode Technical Report discussing case handling, which provides some very good information.

7.1.3 Arbitrary Character Types

The `std::basic_string` is tantalizingly general, in that it is parameterized on the type of the characters which it holds. In theory, you could whip up a Unicode character class and instantiate `std::basic_string<my_unicode_char>`, or assuming that integers are wider than characters on your platform, maybe just declare variables of type `std::basic_string<int>`.

That's the theory. Remember however that basic_string has additional type parameters, which take default arguments based on the character type (called `CharT` here):

```
      template <typename CharT,
    typename Traits = char_traits<CharT>,
    typename Alloc = allocator<CharT> >
      class basic_string { .... };
```

Now, `allocator<CharT>` will probably Do The Right Thing by default, unless you need to implement your own allocator for your characters.

But `char_traits` takes more work. The char_traits template is *declared* but not *defined*. That means there is only

```
      template <typename CharT>
  struct char_traits
  {
      static void foo (type1 x, type2 y);
      ...
  };
```

and functions such as char_traits<CharT>::foo() are not actually defined anywhere for the general case. The C++ standard permits this, because writing such a definition to fit all possible CharT's cannot be done.

The C++ standard also requires that char_traits be specialized for instantiations of `char` and `wchar_t`, and it is these template specializations that permit entities like `basic_string<char,char_traits<char>>` to work.

If you want to use character types other than char and wchar_t, such as `unsigned char` and `int`, you will need suitable specializations for them. For a time, in earlier versions of GCC, there was a mostly-correct implementation that let programmers be lazy but it broke under many situations, so it was removed. GCC 3.4 introduced a new implementation that mostly works and can be specialized even for `int` and other built-in types.

If you want to use your own special character class, then you have a lot of work to do, especially if you with to use i18n features (facets require traits information but don't have a traits argument).

Another example of how to specialize char_traits was given on the mailing list and at a later date was put into the file `include/ext/p`
We agree that the way it's used with basic_string (scroll down to main()) doesn't look nice, but that's because the nice-looking first attempt turned out to not be conforming C++, due to the rule that CharT must be a POD. (See how tricky this is?)

7.1.4 Tokenizing

The Standard C (and C++) function `strtok()` leaves a lot to be desired in terms of user-friendliness. It's unintuitive, it destroys the character string on which it operates, and it requires you to handle all the memory problems. But it does let the client code decide what to use to break the string into pieces; it allows you to choose the "whitespace," so to speak.

A C++ implementation lets us keep the good things and fix those annoyances. The implementation here is more intuitive (you only call it once, not in a loop with varying argument), it does not affect the original string at all, and all the memory allocation is handled for you.

It's called stringtok, and it's a template function. Sources are as below, in a less-portable form than it could be, to keep this example simple (for example, see the comments on what kind of string it will accept).

```
#include <string>
template <typename Container>
void
stringtok(Container &container, string const &in,
    const char * const delimiters = " \t\n")
{
    const string::size_type len = in.length();
    string::size_type i = 0;

    while (i < len)
    {
  // Eat leading whitespace
  i = in.find_first_not_of(delimiters, i);
  if (i == string::npos)
    return;   // Nothing left but white space

  // Find the end of the token
  string::size_type j = in.find_first_of(delimiters, i);

  // Push token
  if (j == string::npos)
  {
    container.push_back(in.substr(i));
    return;
  }
  else
    container.push_back(in.substr(i, j-i));

  // Set up for next loop
  i = j + 1;
    }
}
```

The author uses a more general (but less readable) form of it for parsing command strings and the like. If you compiled and ran this code using it:

```
   std::list<string>  ls;
   stringtok (ls, " this  \t is\t\n  a test  ");
   for (std::list<string>const_iterator i = ls.begin();
  i != ls.end(); ++i)
   {
       std::cerr << ':' << (*i) << ":\n";
   }
```

You would see this as output:

```
   :this:
   :is:
   :a:
   :test:
```

with all the whitespace removed. The original `s` is still available for use, `ls` will clean up after itself, and `ls.size()` will return how many tokens there were.

As always, there is a price paid here, in that stringtok is not as fast as strtok. The other benefits usually outweigh that, however.

Added February 2001: Mark Wilden pointed out that the standard `std::getline()` function can be used with standard `istringstreams` to perform tokenizing as well. Build an istringstream from the input text, and then use std::getline with varying delimiters (the three-argument signature) to extract tokens into a string.

7.1.5 Shrink to Fit

From GCC 3.4 calling `s.reserve(res)` on a `string s` with `res < s.capacity()` will reduce the string's capacity to `std::max(s.size(), res)`.

This behaviour is suggested, but not required by the standard. Prior to GCC 3.4 the following alternative can be used instead

```
std::string(str.data(), str.size()).swap(str);
```

This is similar to the idiom for reducing a `vector`'s memory usage (see this FAQ entry) but the regular copy constructor cannot be used because libstdc++'s `string` is Copy-On-Write in GCC 3.

From GCC 4.5 in C++11 mode you can call `s.shrink_to_fit()` to achieve the same effect as `s.reserve(s.size())`.

7.1.6 CString (MFC)

A common lament seen in various newsgroups deals with the Standard string class as opposed to the Microsoft Foundation Class called CString. Often programmers realize that a standard portable answer is better than a proprietary nonportable one, but in porting their application from a Win32 platform, they discover that they are relying on special functions offered by the CString class.

Things are not as bad as they seem. In this message, Joe Buck points out a few very important things:

- The Standard `string` supports all the operations that CString does, with three exceptions.
- Two of those exceptions (whitespace trimming and case conversion) are trivial to implement. In fact, we do so on this page.
- The third is `CString::Format`, which allows formatting in the style of `sprintf`. This deserves some mention:

The old libg++ library had a function called form(), which did much the same thing. But for a Standard solution, you should use the stringstream classes. These are the bridge between the iostream hierarchy and the string class, and they operate with regular streams seamlessly because they inherit from the iostream hierarchy. An quick example:

```
#include <iostream>
#include <string>
#include <sstream>

string f (string& incoming)     // incoming is "foo  N"
{
    istringstream   incoming_stream(incoming);
    string          the_word;
    int             the_number;

    incoming_stream >> the_word        // extract "foo"
        >> the_number;     // extract N

    ostringstream   output_stream;
    output_stream << "The word was " << the_word
      << " and 3*N was " << (3*the_number);

    return output_stream.str();
}
```

A serious problem with CString is a design bug in its memory allocation. Specifically, quoting from that same message:

```
CString suffers from a common programming error that results in
poor performance.  Consider the following code:

CString n_copies_of (const CString& foo, unsigned n)
{
  CString tmp;
```

```
    for (unsigned i = 0; i < n; i++)
      tmp += foo;
    return tmp;
  }

  This function is O(n^2), not O(n).  The reason is that each +=
  causes a reallocation and copy of the existing string.  Microsoft
  applications are full of this kind of thing (quadratic performance
  on tasks that can be done in linear time) -- on the other hand,
  we should be thankful, as it’s created such a big market for high-end
  ix86 hardware. :-)

  If you replace CString with string in the above function, the
  performance is O(n).
```

Joe Buck also pointed out some other things to keep in mind when comparing CString and the Standard string class:

- CString permits access to its internal representation; coders who exploited that may have problems moving to `string`.
- Microsoft ships the source to CString (in the files MFC\SRC\Str{core,ex}.cpp), so you could fix the allocation bug and rebuild your MFC libraries. Note: *It looks like the CString shipped with VC++6.0 has fixed this, although it may in fact have been one of the VC++ SPs that did it.*
- `string` operations like this have O(n) complexity *if the implementors do it correctly*. The libstdc++ implementors did it correctly. Other vendors might not.
- While parts of the SGI STL are used in libstdc++, their string class is not. The SGI `string` is essentially `vector<char>` and does not do any reference counting like libstdc++’s does. (It is O(n), though.) So if you’re thinking about SGI’s string or rope classes, you’re now looking at four possibilities: CString, the libstdc++ string, the SGI string, and the SGI rope, and this is all before any allocator or traits customizations! (More choices than you can shake a stick at -- want fries with that?)

Chapter 8

Localization

8.1 Locales

8.1.1 locale

Describes the basic locale object, including nested classes id, facet, and the reference-counted implementation object, class _Impl.

8.1.1.1 Requirements

Class locale is non-templatized and has two distinct types nested inside of it:

> *class facet 22.1.1.1.2 Class locale::facet*

Facets actually implement locale functionality. For instance, a facet called numpunct is the data object that can be used to query for the thousands separator in the locale.

Literally, a facet is strictly defined:

- Containing the following public data member:
  `static locale::id id;`
- Derived from another facet:
  `class gnu_codecvt:  public std::ctype<user-defined-type>`

Of interest in this class are the memory management options explicitly specified as an argument to facet's constructor. Each constructor of a facet class takes a std::size_t __refs argument: if __refs == 0, the facet is deleted when the locale containing it is destroyed. If __refs == 1, the facet is not destroyed, even when it is no longer referenced.

> *class id 22.1.1.1.3 - Class locale::id*

Provides an index for looking up specific facets.

8.1.1.2 Design

The major design challenge is fitting an object-orientated and non-global locale design on top of POSIX and other relevant standards, which include the Single Unix (nee X/Open.)

Because C and earlier versions of POSIX fall down so completely, portability is an issue.

8.1.1.3 Implementation

8.1.1.3.1 Interacting with "C" locales

- `locale -a` displays available locales.

```
af_ZA
ar_AE
ar_AE.utf8
ar_BH
ar_BH.utf8
ar_DZ
ar_DZ.utf8
ar_EG
ar_EG.utf8
ar_IN
ar_IQ
ar_IQ.utf8
ar_JO
ar_JO.utf8
ar_KW
ar_KW.utf8
ar_LB
ar_LB.utf8
ar_LY
ar_LY.utf8
ar_MA
ar_MA.utf8
ar_OM
ar_OM.utf8
ar_QA
ar_QA.utf8
ar_SA
ar_SA.utf8
ar_SD
ar_SD.utf8
ar_SY
ar_SY.utf8
ar_TN
ar_TN.utf8
ar_YE
ar_YE.utf8
be_BY
be_BY.utf8
bg_BG
bg_BG.utf8
br_FR
bs_BA
C
ca_ES
ca_ES@euro
ca_ES.utf8
ca_ES.utf8@euro
cs_CZ
cs_CZ.utf8
cy_GB
da_DK
da_DK.iso885915
da_DK.utf8
de_AT
de_AT@euro
```

```
de_AT.utf8
de_AT.utf8@euro
de_BE
de_BE@euro
de_BE.utf8
de_BE.utf8@euro
de_CH
de_CH.utf8
de_DE
de_DE@euro
de_DE.utf8
de_DE.utf8@euro
de_LU
de_LU@euro
de_LU.utf8
de_LU.utf8@euro
el_GR
el_GR.utf8
en_AU
en_AU.utf8
en_BW
en_BW.utf8
en_CA
en_CA.utf8
en_DK
en_DK.utf8
en_GB
en_GB.iso885915
en_GB.utf8
en_HK
en_HK.utf8
en_IE
en_IE@euro
en_IE.utf8
en_IE.utf8@euro
en_IN
en_NZ
en_NZ.utf8
en_PH
en_PH.utf8
en_SG
en_SG.utf8
en_US
en_US.iso885915
en_US.utf8
en_ZA
en_ZA.utf8
en_ZW
en_ZW.utf8
es_AR
es_AR.utf8
es_BO
es_BO.utf8
es_CL
es_CL.utf8
es_CO
es_CO.utf8
es_CR
es_CR.utf8
es_DO
es_DO.utf8
es_EC
```

```
es_EC.utf8
es_ES
es_ES@euro
es_ES.utf8
es_ES.utf8@euro
es_GT
es_GT.utf8
es_HN
es_HN.utf8
es_MX
es_MX.utf8
es_NI
es_NI.utf8
es_PA
es_PA.utf8
es_PE
es_PE.utf8
es_PR
es_PR.utf8
es_PY
es_PY.utf8
es_SV
es_SV.utf8
es_US
es_US.utf8
es_UY
es_UY.utf8
es_VE
es_VE.utf8
et_EE
et_EE.utf8
eu_ES
eu_ES@euro
eu_ES.utf8
eu_ES.utf8@euro
fa_IR
fi_FI
fi_FI@euro
fi_FI.utf8
fi_FI.utf8@euro
fo_FO
fo_FO.utf8
fr_BE
fr_BE@euro
fr_BE.utf8
fr_BE.utf8@euro
fr_CA
fr_CA.utf8
fr_CH
fr_CH.utf8
fr_FR
fr_FR@euro
fr_FR.utf8
fr_FR.utf8@euro
fr_LU
fr_LU@euro
fr_LU.utf8
fr_LU.utf8@euro
ga_IE
ga_IE@euro
ga_IE.utf8
ga_IE.utf8@euro
```

```
gl_ES
gl_ES@euro
gl_ES.utf8
gl_ES.utf8@euro
gv_GB
gv_GB.utf8
he_IL
he_IL.utf8
hi_IN
hr_HR
hr_HR.utf8
hu_HU
hu_HU.utf8
id_ID
id_ID.utf8
is_IS
is_IS.utf8
it_CH
it_CH.utf8
it_IT
it_IT@euro
it_IT.utf8
it_IT.utf8@euro
iw_IL
iw_IL.utf8
ja_JP.eucjp
ja_JP.utf8
ka_GE
kl_GL
kl_GL.utf8
ko_KR.euckr
ko_KR.utf8
kw_GB
kw_GB.utf8
lt_LT
lt_LT.utf8
lv_LV
lv_LV.utf8
mi_NZ
mk_MK
mk_MK.utf8
mr_IN
ms_MY
ms_MY.utf8
mt_MT
mt_MT.utf8
nl_BE
nl_BE@euro
nl_BE.utf8
nl_BE.utf8@euro
nl_NL
nl_NL@euro
nl_NL.utf8
nl_NL.utf8@euro
nn_NO
nn_NO.utf8
no_NO
no_NO.utf8
oc_FR
pl_PL
pl_PL.utf8
POSIX
```

```
pt_BR
pt_BR.utf8
pt_PT
pt_PT@euro
pt_PT.utf8
pt_PT.utf8@euro
ro_RO
ro_RO.utf8
ru_RU
ru_RU.koi8r
ru_RU.utf8
ru_UA
ru_UA.utf8
se_NO
sk_SK
sk_SK.utf8
sl_SI
sl_SI.utf8
sq_AL
sq_AL.utf8
sr_YU
sr_YU@cyrillic
sr_YU.utf8
sr_YU.utf8@cyrillic
sv_FI
sv_FI@euro
sv_FI.utf8
sv_FI.utf8@euro
sv_SE
sv_SE.iso885915
sv_SE.utf8
ta_IN
te_IN
tg_TJ
th_TH
th_TH.utf8
tl_PH
tr_TR
tr_TR.utf8
uk_UA
uk_UA.utf8
ur_PK
uz_UZ
vi_VN
vi_VN.tcvn
wa_BE
wa_BE@euro
yi_US
zh_CN
zh_CN.gb18030
zh_CN.gbk
zh_CN.utf8
zh_HK
zh_HK.utf8
zh_TW
zh_TW.euctw
zh_TW.utf8
```

- `` `locale` `` displays environmental variables that impact how locale("") will be deduced.

```
LANG=en_US
```

```
LC_CTYPE="en_US"
LC_NUMERIC="en_US"
LC_TIME="en_US"
LC_COLLATE="en_US"
LC_MONETARY="en_US"
LC_MESSAGES="en_US"
LC_PAPER="en_US"
LC_NAME="en_US"
LC_ADDRESS="en_US"
LC_TELEPHONE="en_US"
LC_MEASUREMENT="en_US"
LC_IDENTIFICATION="en_US"
LC_ALL=
```

From Josuttis, p. 697-698, which says, that "there is only *one* relation (of the C++ locale mechanism) to the C locale mechanism: the global C locale is modified if a named C++ locale object is set as the global locale" (emphasis Paolo), that is:

```
std::locale::global(std::locale(""));
```

affects the C functions as if the following call was made:

```
std::setlocale(LC_ALL, "");
```

On the other hand, there is *no* vice versa, that is, calling setlocale has *no* whatsoever on the C++ locale mechanism, in particular on the working of locale(""), which constructs the locale object from the environment of the running program, that is, in practice, the set of LC_ALL, LANG, etc. variable of the shell.

8.1.1.4 Future

- Locale initialization: at what point does _S_classic, _S_global get initialized? Can named locales assume this initialization has already taken place?
- Document how named locales error check when filling data members. I.e., a fr_FR locale that doesn't have numpunct::truename(): does it use "true"? Or is it a blank string? What's the convention?
- Explain how locale aliasing happens. When does "de_DE" use "de" information? What is the rule for locales composed of just an ISO language code (say, "de") and locales with both an ISO language code and ISO country code (say, "de_DE").
- What should non-required facet instantiations do? If the generic implementation is provided, then how to end-users provide specializations?

8.1.1.5 Bibliography

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8.2 Facets

8.2.1 ctype

8.2.1.1 Implementation

8.2.1.1.1 Specializations

For the required specialization `codecvt<wchar_t, char, mbstate_t>`, conversions are made between the internal character set (always UCS4 on GNU/Linux) and whatever the currently selected locale for the `LC_CTYPE` category implements.

The two required specializations are implemented as follows:

`ctype<char>`

This is simple specialization. Implementing this was a piece of cake.

`ctype<wchar_t>`

This specialization, by specifying all the template parameters, pretty much ties the hands of implementors. As such, the implementation is straightforward, involving `mcsrtombs` for the conversions between char to wchar_t and `wcsrtombs` for conversions between wchar_t and char.

Neither of these two required specializations deals with Unicode characters.

8.2.1.2 Future

- How to deal with the global locale issue?
- How to deal with types other than char, wchar_t?
- Overlap between codecvt/ctype: narrow/widen
- mask typedef in `codecvt_base`, argument types in codecvt. what is know about this type?
- Why mask* argument in codecvt?
- Can this be made (more) generic? is there a simple way to straighten out the configure-time mess that is a by-product of this class?
- Get the ctype<wchar_t>::mask stuff under control. Need to make some kind of static table, and not do lookup every time somebody hits the `do_is...` functions. Too bad we can't just redefine mask for `ctype<wchar_t>`
- Rename abstract base class. See if just smash-overriding is a better approach. Clarify, add sanity to naming.

8.2.1.3 Bibliography

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8.2.2 codecvt

The standard class codecvt attempts to address conversions between different character encoding schemes. In particular, the standard attempts to detail conversions between the implementation-defined wide characters (hereafter referred to as wchar_t) and the standard type char that is so beloved in classic “C” (which can now be referred to as narrow characters.) This document attempts to describe how the GNU libstdc++ implementation deals with the conversion between wide and narrow characters, and also presents a framework for dealing with the huge number of other encodings that iconv can convert, including Unicode and UTF8. Design issues and requirements are addressed, and examples of correct usage for both the required specializations for wide and narrow characters and the implementation-provided extended functionality are given.

8.2.2.1 Requirements

Around page 425 of the C++ Standard, this charming heading comes into view:

> 22.2.1.5 - Template class codecvt

The text around the codecvt definition gives some clues:

> *-1- The class* codecvt<internT,externT,stateT> *is for use when converting from one codeset to another, such as from wide characters to multibyte characters, between wide character encodings such as Unicode and EUC.*

Hmm. So, in some unspecified way, Unicode encodings and translations between other character sets should be handled by this class.

> *-2- The stateT argument selects the pair of codesets being mapped between.*

Ah ha! Another clue...

> *-3- The instantiations required in the Table 51 (lib.locale.category), namely* codecvt<wchar_t,char,mbstate_t> *and* codecvt<char,char,mbstate_t>*, convert the implementation-defined native character set.* codecvt<char,char *implements a degenerate conversion; it does not convert at all.* codecvt<wchar_t,char,mbstate_t> *converts between the native character sets for tiny and wide characters. Instantiations on mbstate_t perform conversion between encodings known to the library implementor. Other encodings can be converted by specializing on a user-defined stateT type. The stateT object can contain any state that is useful to communicate to or from the specialized* do_convert *member.*

At this point, a couple points become clear:

One: The standard clearly implies that attempts to add non-required (yet useful and widely used) conversions need to do so through the third template parameter, stateT.

Two: The required conversions, by specifying mbstate_t as the third template parameter, imply an implementation strategy that is mostly (or wholly) based on the underlying C library, and the functions mcsrtombs and wcsrtombs in particular.

8.2.2.2 Design

8.2.2.2.1 wchar_t Size

The simple implementation detail of wchar_t’s size seems to repeatedly confound people. Many systems use a two byte, unsigned integral type to represent wide characters, and use an internal encoding of Unicode or UCS2. (See AIX, Microsoft NT, Java, others.) Other systems, use a four byte, unsigned integral type to represent wide characters, and use an internal encoding of UCS4. (GNU/Linux systems using glibc, in particular.) The C programming language (and thus C++) does not specify a specific size for the type wchar_t.

Thus, portable C++ code cannot assume a byte size (or endianness) either.

8.2.2.2.2 Support for Unicode

Probably the most frequently asked question about code conversion is: "So dudes, what's the deal with Unicode strings?" The dude part is optional, but apparently the usefulness of Unicode strings is pretty widely appreciated. The Unicode character set (and useful encodings like UTF-8, UCS-4, ISO 8859-10, etc etc etc) were not mentioned in the first C++ standard. (The 2011 standard added support for string literals with different encodings and some library facilities for converting between encodings, but the notes below have not been updated to reflect that.)

A couple of comments:

The thought that all one needs to convert between two arbitrary codesets is two types and some kind of state argument is unfortunate. In particular, encodings may be stateless. The naming of the third parameter as stateT is unfortunate, as what is really needed is some kind of generalized type that accounts for the issues that abstract encodings will need. The minimum information that is required includes:

- Identifiers for each of the codesets involved in the conversion. For example, using the iconv family of functions from the Single Unix Specification (what used to be called X/Open) hosted on the GNU/Linux operating system allows bi-directional mapping between far more than the following tantalizing possibilities:

  (An edited list taken from `` `iconv --list` `` on a Red Hat 6.2/Intel system:

  ```
  8859_1, 8859_9, 10646-1:1993, 10646-1:1993/UCS4, ARABIC, ARABIC7,
  ASCII, EUC-CN, EUC-JP, EUC-KR, EUC-TW, GREEK-CCIcode, GREEK, GREEK7-OLD,
  GREEK7, GREEK8, HEBREW, ISO-8859-1, ISO-8859-2, ISO-8859-3,
  ISO-8859-4, ISO-8859-5, ISO-8859-6, ISO-8859-7, ISO-8859-8,
  ISO-8859-9, ISO-8859-10, ISO-8859-11, ISO-8859-13, ISO-8859-14,
  ISO-8859-15, ISO-10646, ISO-10646/UCS2, ISO-10646/UCS4,
  ISO-10646/UTF-8, ISO-10646/UTF8, SHIFT-JIS, SHIFT_JIS, UCS-2, UCS-4,
  UCS2, UCS4, UNICODE, UNICODEBIG, UNICODELIcodeLE, US-ASCII, US, UTF-8,
  UTF-16, UTF8, UTF16).
  ```

  For iconv-based implementations, string literals for each of the encodings (i.e. "UCS-2" and "UTF-8") are necessary, although for other, non-iconv implementations a table of enumerated values or some other mechanism may be required.

- Maximum length of the identifying string literal.
- Some encodings require explicit endian-ness. As such, some kind of endian marker or other byte-order marker will be necessary. See "Footnotes for C/C++ developers" in Haible for more information on UCS-2/Unicode endian issues. (Summary: big endian seems most likely, however implementations, most notably Microsoft, vary.)
- Types representing the conversion state, for conversions involving the machinery in the "C" library, or the conversion descriptor, for conversions using iconv (such as the type iconv_t.) Note that the conversion descriptor encodes more information than a simple encoding state type.
- Conversion descriptors for both directions of encoding. (i.e., both UCS-2 to UTF-8 and UTF-8 to UCS-2.)
- Something to indicate if the conversion requested if valid.
- Something to represent if the conversion descriptors are valid.
- Some way to enforce strict type checking on the internal and external types. As part of this, the size of the internal and external types will need to be known.

8.2.2.2.3 Other Issues

In addition, multi-threaded and multi-locale environments also impact the design and requirements for code conversions. In particular, they affect the required specialization `codecvt<wchar_t, char, mbstate_t>` when implemented using standard "C" functions.

Three problems arise, one big, one of medium importance, and one small.

First, the small: `mcsrtombs` and `wcsrtombs` may not be multithread-safe on all systems required by the GNU tools. For GNU/Linux and glibc, this is not an issue.

Of medium concern, in the grand scope of things, is that the functions used to implement this specialization work on null-terminated strings. Buffers, especially file buffers, may not be null-terminated, thus giving conversions that end prematurely or are otherwise incorrect. Yikes!

The last, and fundamental problem, is the assumption of a global locale for all the "C" functions referenced above. For something like C++ iostreams (where codecvt is explicitly used) the notion of multiple locales is fundamental. In practice, most users may not run into this limitation. However, as a quality of implementation issue, the GNU C++ library would like to offer a solution that allows multiple locales and or simultaneous usage with computationally correct results. In short, libstdc++ is trying to offer, as an option, a high-quality implementation, damn the additional complexity!

For the required specialization `codecvt<wchar_t, char, mbstate_t>`, conversions are made between the internal character set (always UCS4 on GNU/Linux) and whatever the currently selected locale for the LC_CTYPE category implements.

8.2.2.3 Implementation

The two required specializations are implemented as follows:

`codecvt<char, char, mbstate_t>`

This is a degenerate (i.e., does nothing) specialization. Implementing this was a piece of cake.

`codecvt<char, wchar_t, mbstate_t>`

This specialization, by specifying all the template parameters, pretty much ties the hands of implementors. As such, the implementation is straightforward, involving `mcsrtombs` for the conversions between char to wchar_t and `wcsrtombs` for conversions between wchar_t and char.

Neither of these two required specializations deals with Unicode characters. As such, libstdc++ implements a partial specialization of the codecvt class with an iconv wrapper class, `encoding_state` as the third template parameter.

This implementation should be standards conformant. First of all, the standard explicitly points out that instantiations on the third template parameter, stateT, are the proper way to implement non-required conversions. Second of all, the standard says (in Chapter 17) that partial specializations of required classes are A-OK. Third of all, the requirements for the stateT type elsewhere in the standard (see 21.1.2 traits typedefs) only indicate that this type be copy constructible.

As such, the type encoding_state is defined as a non-templatized, POD type to be used as the third type of a codecvt instantiation. This type is just a wrapper class for iconv, and provides an easy interface to iconv functionality.

There are two constructors for encoding_state:

`encoding_state() :  __in_desc(0), __out_desc(0)`

This default constructor sets the internal encoding to some default (currently UCS4) and the external encoding to whatever is returned by `nl_langinfo(CODESET)`.

`encoding_state(const char* __int, const char* __ext)`

This constructor takes as parameters string literals that indicate the desired internal and external encoding. There are no defaults for either argument.

One of the issues with iconv is that the string literals identifying conversions are not standardized. Because of this, the thought of mandating and/or enforcing some set of pre-determined valid identifiers seems iffy: thus, a more practical (and non-migraine inducing) strategy was implemented: end-users can specify any string (subject to a pre-determined length qualifier, currently 32 bytes) for encodings. It is up to the user to make sure that these strings are valid on the target system.

`void _M_init()`

Strangely enough, this member function attempts to open conversion descriptors for a given encoding_state object. If the conversion descriptors are not valid, the conversion descriptors returned will not be valid and the resulting calls to the codecvt conversion functions will return error.

`bool _M_good()`

Provides a way to see if the given encoding_state object has been properly initialized. If the string literals describing the desired internal and external encoding are not valid, initialization will fail, and this will return false. If the internal and external encodings are valid, but `iconv_open` could not allocate conversion descriptors, this will also return false. Otherwise, the object is ready to convert and will return true.

`encoding_state(const encoding_state&)`

As iconv allocates memory and sets up conversion descriptors, the copy constructor can only copy the member data pertaining to the internal and external code conversions, and not the conversion descriptors themselves.

Definitions for all the required codecvt member functions are provided for this specialization, and usage of `codecvt<`*`internal character type`*`, `*`external character type`*`, `*`encoding_state`*`>` is consistent with other codecvt usage.

8.2.2.4 Use

A conversion involving a string literal.

```
typedef codecvt_base::result                    result;
typedef unsigned short                          unicode_t;
typedef unicode_t                               int_type;
typedef char                                    ext_type;
typedef encoding_state                            state_type;
typedef codecvt<int_type, ext_type, state_type> unicode_codecvt;

const ext_type*       e_lit = "black pearl jasmine tea";
int                   size = strlen(e_lit);
int_type              i_lit_base[24] =
{ 25088, 27648, 24832, 25344, 27392, 8192, 28672, 25856, 24832, 29184,
  27648, 8192, 27136, 24832, 29440, 27904, 26880, 28160, 25856, 8192, 29696,
  25856, 24832, 2560
};
const int_type*       i_lit = i_lit_base;
const ext_type*       efrom_next;
const int_type*       ifrom_next;
ext_type*             e_arr = new ext_type[size + 1];
ext_type*             eto_next;
int_type*             i_arr = new int_type[size + 1];
int_type*             ito_next;

// construct a locale object with the specialized facet.
locale                loc(locale::classic(), new unicode_codecvt);
// sanity check the constructed locale has the specialized facet.
VERIFY( has_facet<unicode_codecvt>(loc) );
const unicode_codecvt& cvt = use_facet<unicode_codecvt>(loc);
// convert between const char* and unicode strings
unicode_codecvt::state_type state01("UNICODE", "ISO_8859-1");
initialize_state(state01);
result r1 = cvt.in(state01, e_lit, e_lit + size, efrom_next,
       i_arr, i_arr + size, ito_next);
VERIFY( r1 == codecvt_base::ok );
VERIFY( !int_traits::compare(i_arr, i_lit, size) );
VERIFY( efrom_next == e_lit + size );
VERIFY( ito_next == i_arr + size );
```

8.2.2.5 Future

- a. things that are sketchy, or remain unimplemented: do_encoding, max_length and length member functions are only weakly implemented. I have no idea how to do this correctly, and in a generic manner. Nathan?
- b. conversions involving std::string

  - how should operators != and == work for string of different/same encoding?
  - what is equal? A byte by byte comparison or an encoding then byte comparison?
  - conversions between narrow, wide, and unicode strings

- c. conversions involving std::filebuf and std::ostream

  - how to initialize the state object in a standards-conformant manner?
  - how to synchronize the "C" and "C++" conversion information?
  - wchar_t/char internal buffers and conversions between internal/external buffers?

8.2.2.6 Bibliography

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8.2.3 messages

The `std::messages` facet implements message retrieval functionality equivalent to Java's `java.text.MessageFormat` using either GNU `gettext` or IEEE 1003.1-200 functions.

8.2.3.1 Requirements

The `std::messages` facet is probably the most vaguely defined facet in the standard library. It's assumed that this facility was built into the standard library in order to convert string literals from one locale to the other. For instance, converting the "C" locale's `const char* c = "please"` to a German-localized `"bitte"` during program execution.

> 22.2.7.1 - Template class messages [lib.locale.messages]

This class has three public member functions, which directly correspond to three protected virtual member functions.

The public member functions are:

`catalog open(const string&, const locale&) const`

`string_type get(catalog, int, int, const string_type&) const`

`void close(catalog) const`

While the virtual functions are:

`catalog do_open(const string& name, const locale& loc) const`

-1- Returns: A value that may be passed to `get()` to retrieve a message, from the message catalog identified by the string `name` according to an implementation-defined mapping. The result can be used until it is passed to `close()`. Returns a value less than 0 if no such catalog can be opened.

```
string_type do_get(catalog cat, int set , int msgid, const string_type& dfault) const
```

-3- Requires: A catalog `cat` obtained from `open()` and not yet closed. -4- Returns: A message identified by arguments `set`, `msgid`, and `dfault`, according to an implementation-defined mapping. If no such message can be found, returns `dfault`.

```
void do_close(catalog cat) const
```

-5- Requires: A catalog cat obtained from `open()` and not yet closed. -6- Effects: Releases unspecified resources associated with `cat`. -7- Notes: The limit on such resources, if any, is implementation-defined.

8.2.3.2 Design

A couple of notes on the standard.

First, why is `messages_base::catalog` specified as a typedef to int? This makes sense for implementations that use `catopen` and define `nl_catd` as int, but not for others. Fortunately, it's not heavily used and so only a minor irritant. This has been reported as a possible defect in the standard (LWG 2028).

Second, by making the member functions `const`, it is impossible to save state in them. Thus, storing away information used in the 'open' member function for use in 'get' is impossible. This is unfortunate.

The 'open' member function in particular seems to be oddly designed. The signature seems quite peculiar. Why specify a `const string&` argument, for instance, instead of just `const char*`? Or, why specify a `const locale&` argument that is to be used in the 'get' member function? How, exactly, is this locale argument useful? What was the intent? It might make sense if a locale argument was associated with a given default message string in the 'open' member function, for instance. Quite murky and unclear, on reflection.

Lastly, it seems odd that messages, which explicitly require code conversion, don't use the codecvt facet. Because the messages facet has only one template parameter, it is assumed that ctype, and not codecvt, is to be used to convert between character sets.

It is implicitly assumed that the locale for the default message string in 'get' is in the "C" locale. Thus, all source code is assumed to be written in English, so translations are always from "en_US" to other, explicitly named locales.

8.2.3.3 Implementation

8.2.3.3.1 Models

This is a relatively simple class, on the face of it. The standard specifies very little in concrete terms, so generic implementations that are conforming yet do very little are the norm. Adding functionality that would be useful to programmers and comparable to Java's java.text.MessageFormat takes a bit of work, and is highly dependent on the capabilities of the underlying operating system.

Three different mechanisms have been provided, selectable via configure flags:

- generic

  This model does very little, and is what is used by default.

- gnu

  The gnu model is complete and fully tested. It's based on the GNU gettext package, which is part of glibc. It uses the functions `textdomain, bindtextdomain, gettext` to implement full functionality. Creating message catalogs is a relatively straight-forward process and is lightly documented below, and fully documented in gettext's distributed documentation.

- ieee_1003.1-200x

  This is a complete, though untested, implementation based on the IEEE standard. The functions `catopen, catgets, catclose` are used to retrieve locale-specific messages given the appropriate message catalogs that have been constructed for their use. Note, the script `po2msg.sed` that is part of the gettext distribution can convert gettext catalogs into catalogs that `catopen` can use.

A new, standards-conformant non-virtual member function signature was added for 'open' so that a directory could be specified with a given message catalog. This simplifies calling conventions for the gnu model.

8.2.3.3.2 The GNU Model

The messages facet, because it is retrieving and converting between characters sets, depends on the ctype and perhaps the codecvt facet in a given locale. In addition, underlying "C" library locale support is necessary for more than just the `LC_MESSAGES` mask: `LC_CTYPE` is also necessary. To avoid any unpleasantness, all bits of the "C" mask (i.e. `LC_ALL`) are set before retrieving messages.

Making the message catalogs can be initially tricky, but become quite simple with practice. For complete info, see the gettext documentation. Here's an idea of what is required:

- Make a source file with the required string literals that need to be translated. See `intl/string_literals.cc` for an example.
- Make initial catalog (see "4 Making the PO Template File" from the gettext docs).

  `xgettext --c++ --debug string_literals.cc -o libstdc++.pot`
- Make language and country-specific locale catalogs.

  `cp libstdc++.pot fr_FR.po`

  `cp libstdc++.pot de_DE.po`
- Edit localized catalogs in emacs so that strings are translated.

  `emacs fr_FR.po`
- Make the binary mo files.

  `msgfmt fr_FR.po -o fr_FR.mo`

  `msgfmt de_DE.po -o de_DE.mo`
- Copy the binary files into the correct directory structure.

  `cp fr_FR.mo (dir)/fr_FR/LC_MESSAGES/libstdc++.mo`

  `cp de_DE.mo (dir)/de_DE/LC_MESSAGES/libstdc++.mo`
- Use the new message catalogs.

  `locale loc_de("de_DE");`

  `use_facet<messages<char> >(loc_de).open("libstdc++", locale(), dir);`

8.2.3.4 Use

A simple example using the GNU model of message conversion.

```
#include <iostream>
#include <locale>
using namespace std;

void test01()
{
  typedef messages<char>::catalog catalog;
```

```
  const char* dir =
  "/mnt/egcs/build/i686-pc-linux-gnu/libstdc++/po/share/locale";
  const locale loc_de("de_DE");
  const messages<char>& mssg_de = use_facet<messages<char> >(loc_de);

  catalog cat_de = mssg_de.open("libstdc++", loc_de, dir);
  string s01 = mssg_de.get(cat_de, 0, 0, "please");
  string s02 = mssg_de.get(cat_de, 0, 0, "thank you");
  cout << "please in german:" << s01 << '\n';
  cout << "thank you in german:" << s02 << '\n';
  mssg_de.close(cat_de);
}
```

8.2.3.5 Future

- Things that are sketchy, or remain unimplemented:
  - _M_convert_from_char, _M_convert_to_char are in flux, depending on how the library ends up doing character set conversions. It might not be possible to do a real character set based conversion, due to the fact that the template parameter for messages is not enough to instantiate the codecvt facet (1 supplied, need at least 2 but would prefer 3).
  - There are issues with gettext needing the global locale set to extract a message. This dependence on the global locale makes the current "gnu" model non MT-safe. Future versions of glibc, i.e. glibc 2.3.x will fix this, and the C++ library bits are already in place.
- Development versions of the GNU "C" library, glibc 2.3 will allow a more efficient, MT implementation of std::messages, and will allow the removal of the _M_name_messages data member. If this is done, it will change the library ABI. The C++ parts to support glibc 2.3 have already been coded, but are not in use: once this version of the "C" library is released, the marked parts of the messages implementation can be switched over to the new "C" library functionality.
- At some point in the near future, std::numpunct will probably use std::messages facilities to implement truename/falsename correctly. This is currently not done, but entries in libstdc++.pot have already been made for "true" and "false" string literals, so all that remains is the std::numpunct coding and the configure/make hassles to make the installed library search its own catalog. Currently the libstdc++.mo catalog is only searched for the testsuite cases involving messages members.
- The following member functions:

  `catalog open(const basic_string<char>& __s, const locale& __loc) const`

  `catalog open(const basic_string<char>&, const locale&, const char*) const;`

  Don't actually return a "value less than 0 if no such catalog can be opened" as required by the standard in the "gnu" model. As of this writing, it is unknown how to query to see if a specified message catalog exists using the gettext package.

8.2.3.6 Bibliography

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Chapter 9

Containers

9.1 Sequences

9.1.1 list

9.1.1.1 list::size() is O(n)

Yes it is, at least using the old ABI, and that's okay. This is a decision that we preserved when we imported SGI's STL implementation. The following is quoted from their FAQ:

> The size() member function, for list and slist, takes time proportional to the number of elements in the list. This was a deliberate tradeoff. The only way to get a constant-time size() for linked lists would be to maintain an extra member variable containing the list's size. This would require taking extra time to update that variable (it would make splice() a linear time operation, for example), and it would also make the list larger. Many list algorithms don't require that extra word (algorithms that do require it might do better with vectors than with lists), and, when it is necessary to maintain an explicit size count, it's something that users can do themselves.
>
> This choice is permitted by the C++ standard. The standard says that size() "should" be constant time, and "should" does not mean the same thing as "shall". This is the officially recommended ISO wording for saying that an implementation is supposed to do something unless there is a good reason not to.
>
> One implication of linear time size(): you should never write
>
> ```
> if (L.size() == 0)
>     ...
> ```
>
> Instead, you should write
>
> ```
> if (L.empty())
>     ...
> ```

9.2 Associative

9.2.1 Insertion Hints

Section [23.1.2], Table 69, of the C++ standard lists this function for all of the associative containers (map, set, etc):

```
a.insert(p,t);
```

where 'p' is an iterator into the container 'a', and 't' is the item to insert. The standard says that "`t` is inserted as close as possible to the position just prior to `p`." (Library DR #233 addresses this topic, referring to N1780. Since version 4.2 GCC implements the resolution to DR 233, so that insertions happen as close as possible to the hint. For earlier releases the hint was only used as described below.

Here we'll describe how the hinting works in the libstdc++ implementation, and what you need to do in order to take advantage of it. (Insertions can change from logarithmic complexity to amortized constant time, if the hint is properly used.) Also, since the current implementation is based on the SGI STL one, these points may hold true for other library implementations also, since the HP/SGI code is used in a lot of places.

In the following text, the phrases *greater than* and *less than* refer to the results of the strict weak ordering imposed on the container by its comparison object, which defaults to (basically) "<". Using those phrases is semantically sloppy, but I didn't want to get bogged down in syntax. I assume that if you are intelligent enough to use your own comparison objects, you are also intelligent enough to assign "greater" and "lesser" their new meanings in the next paragraph. *grin*

If the `hint` parameter ('p' above) is equivalent to:

- `begin()`, then the item being inserted should have a key less than all the other keys in the container. The item will be inserted at the beginning of the container, becoming the new entry at `begin()`.
- `end()`, then the item being inserted should have a key greater than all the other keys in the container. The item will be inserted at the end of the container, becoming the new entry before `end()`.
- neither `begin()` nor `end()`, then: Let `h` be the entry in the container pointed to by `hint`, that is, `h = *hint`. Then the item being inserted should have a key less than that of `h`, and greater than that of the item preceding `h`. The new item will be inserted between `h` and `h`'s predecessor.

For `multimap` and `multiset`, the restrictions are slightly looser: "greater than" should be replaced by "not less than"and "less than" should be replaced by "not greater than." (Why not replace greater with greater-than-or-equal-to? You probably could in your head, but the mathematicians will tell you that it isn't the same thing.)

If the conditions are not met, then the hint is not used, and the insertion proceeds as if you had called `a.insert(t)` instead. (*Note* that GCC releases prior to 3.0.2 had a bug in the case with `hint == begin()` for the `map` and `set` classes. You should not use a hint argument in those releases.)

This behavior goes well with other containers' `insert()` functions which take an iterator: if used, the new item will be inserted before the iterator passed as an argument, same as the other containers.

Note also that the hint in this implementation is a one-shot. The older insertion-with-hint routines check the immediately surrounding entries to ensure that the new item would in fact belong there. If the hint does not point to the correct place, then no further local searching is done; the search begins from scratch in logarithmic time.

9.2.2 bitset

9.2.2.1 Size Variable

No, you cannot write code of the form

```
   #include <bitset>

   void foo (size_t n)
   {
 std::bitset<n>   bits;
 ....
   }
```

because `n` must be known at compile time. Your compiler is correct; it is not a bug. That's the way templates work. (Yes, it *is* a feature.)

There are a couple of ways to handle this kind of thing. Please consider all of them before passing judgement. They include, in no particular order:

- A very large N in `bitset<N>`.
- A container<bool>.
- Extremely weird solutions.

A very large N in `bitset<N>`. It has been pointed out a few times in newsgroups that N bits only takes up (N/8) bytes on most systems, and division by a factor of eight is pretty impressive when speaking of memory. Half a megabyte given over to a bitset (recall that there is zero space overhead for housekeeping info; it is known at compile time exactly how large the set is) will hold over four million bits. If you're using those bits as status flags (e.g., "changed"/"unchanged" flags), that's a *lot* of state.

You can then keep track of the "maximum bit used" during some testing runs on representative data, make note of how many of those bits really need to be there, and then reduce N to a smaller number. Leave some extra space, of course. (If you plan to write code like the incorrect example above, where the bitset is a local variable, then you may have to talk your compiler into allowing that much stack space; there may be zero space overhead, but it's all allocated inside the object.)

A container<bool>. The Committee made provision for the space savings possible with that (N/8) usage previously mentioned, so that you don't have to do wasteful things like `Container<char>` or `Container<short int>`. Specifically, `vector<bool>` is required to be specialized for that space savings.

The problem is that `vector<bool>` doesn't behave like a normal vector anymore. There have been journal articles which discuss the problems (the ones by Herb Sutter in the May and July/August 1999 issues of C++ Report cover it well). Future revisions of the ISO C++ Standard will change the requirement for `vector<bool>` specialization. In the meantime, `deque<bool>` is recommended (although its behavior is sane, you probably will not get the space savings, but the allocation scheme is different than that of vector).

Extremely weird solutions. If you have access to the compiler and linker at runtime, you can do something insane, like figuring out just how many bits you need, then writing a temporary source code file. That file contains an instantiation of `bitset` for the required number of bits, inside some wrapper functions with unchanging signatures. Have your program then call the compiler on that file using Position Independent Code, then open the newly-created object file and load those wrapper functions. You'll have an instantiation of `bitset<N>` for the exact `N` that you need at the time. Don't forget to delete the temporary files. (Yes, this *can* be, and *has been*, done.)

This would be the approach of either a visionary genius or a raving lunatic, depending on your programming and management style. Probably the latter.

Which of the above techniques you use, if any, are up to you and your intended application. Some time/space profiling is indicated if it really matters (don't just guess). And, if you manage to do anything along the lines of the third category, the author would love to hear from you...

Also note that the implementation of bitset used in libstdc++ has some extensions.

9.2.2.2 Type String

Bitmasks do not take char* nor const char* arguments in their constructors. This is something of an accident, but you can read about the problem: follow the library's "Links" from the homepage, and from the C++ information "defect reflector" link, select the library issues list. Issue number 116 describes the problem.

For now you can simply make a temporary string object using the constructor expression:

```
std::bitset<5> b ( std::string("10110") );
```

instead of

```
std::bitset<5> b ( "10110" );    // invalid
```

9.3 Unordered Associative

9.3.1 Insertion Hints

Here is how the hinting works in the libstdc++ implementation of unordered containers, and the rationale behind this behavior.

In the following text, the phrase *equivalent to* refer to the result of the invocation of the equal predicate imposed on the container by its `key_equal` object, which defaults to (basically) “==”.

Unordered containers can be seen as a `std::vector` of `std::forward_list`. The `std::vector` represents the buckets and each `std::forward_list` is the list of nodes belonging to the same bucket. When inserting an element in such a data structure we first need to compute the element hash code to find the bucket to insert the element to, the second step depends on the uniqueness of elements in the container.

In the case of `std::unordered_set` and `std::unordered_map` you need to look through all bucket’s elements for an equivalent one. If there is none the insertion can be achieved, otherwise the insertion fails. As we always need to loop though all bucket’s elements, the hint doesn’t tell us if the element is already present, and we don’t have any constraint on where the new element is to be inserted, the hint won’t be of any help and will then be ignored.

In the case of `std::unordered_multiset` and `std::unordered_multimap` equivalent elements must be linked together so that the `equal_range(const key_type&)` can return the range of iterators pointing to all equivalent elements. This is where hinting can be used to point to another equivalent element already part of the container and so skip all non equivalent elements of the bucket. So to be useful the hint shall point to an element equivalent to the one being inserted. The new element will be then inserted right after the hint. Note that because of an implementation detail inserting after a node can require updating the bucket of the following node. To check if the next bucket is to be modified we need to compute the following node’s hash code. So if you want your hint to be really efficient it should be followed by another equivalent element, the implementation will detect this equivalence and won’t compute next element hash code.

It is highly advised to start using unordered containers hints only if you have a benchmark that will demonstrate the benefit of it. If you don’t then do not use hints, it might do more harm than good.

9.3.2 Hash Code

9.3.2.1 Hash Code Caching Policy

The unordered containers in libstdc++ may cache the hash code for each element alongside the element itself. In some cases not recalculating the hash code every time it’s needed can improve performance, but the additional memory overhead can also reduce performance, so whether an unordered associative container caches the hash code or not depends on the properties described below.

The C++ standard requires that `erase` and `swap` operations must not throw exceptions. Those operations might need an element’s hash code, but cannot use the hash function if it could throw. This means the hash codes will be cached unless the hash function has a non-throwing exception specification such as `noexcept` or `throw()`.

If the hash function is non-throwing then libstdc++ doesn’t need to cache the hash code for correctness, but might still do so for performance if computing a hash code is an expensive operation, as it may be for arbitrarily long strings. As an extension libstdc++ provides a trait type to describe whether a hash function is fast. By default hash functions are assumed to be fast unless the trait is specialized for the hash function and the trait’s value is false, in which case the hash code will always be cached. The trait can be specialized for user-defined hash functions like so:

```
#include <unordered_set>

struct hasher
{
  std::size_t operator()(int val) const noexcept
  {
    // Some very slow computation of a hash code from an int !
    ...
  }
}
```

```
namespace std
{
  template<>
    struct __is_fast_hash<hasher> : std::false_type
    { };
}
```

9.4 Interacting with C

9.4.1 Containers vs. Arrays

You're writing some code and can't decide whether to use builtin arrays or some kind of container. There are compelling reasons to use one of the container classes, but you're afraid that you'll eventually run into difficulties, change everything back to arrays, and then have to change all the code that uses those data types to keep up with the change.

If your code makes use of the standard algorithms, this isn't as scary as it sounds. The algorithms don't know, nor care, about the kind of "container" on which they work, since the algorithms are only given endpoints to work with. For the container classes, these are iterators (usually `begin()` and `end()`, but not always). For builtin arrays, these are the address of the first element and the past-the-end element.

Some very simple wrapper functions can hide all of that from the rest of the code. For example, a pair of functions called `beginof` can be written, one that takes an array, another that takes a vector. The first returns a pointer to the first element, and the second returns the vector's `begin()` iterator.

The functions should be made template functions, and should also be declared inline. As pointed out in the comments in the code below, this can lead to `beginof` being optimized out of existence, so you pay absolutely nothing in terms of increased code size or execution time.

The result is that if all your algorithm calls look like

```
std::transform(beginof(foo), endof(foo), beginof(foo), SomeFunction);
```

then the type of foo can change from an array of ints to a vector of ints to a deque of ints and back again, without ever changing any client code.

```
// beginof
template<typename T>
  inline typename vector<T>::iterator
  beginof(vector<T> &v)
  { return v.begin(); }

template<typename T, unsigned int sz>
  inline T*
  beginof(T (&array)[sz]) { return array; }

// endof
template<typename T>
  inline typename vector<T>::iterator
  endof(vector<T> &v)
  { return v.end(); }

template<typename T, unsigned int sz>
  inline T*
  endof(T (&array)[sz]) { return array + sz; }

// lengthof
template<typename T>
  inline typename vector<T>::size_type
  lengthof(vector<T> &v)
```

```
  { return v.size(); }

template<typename T, unsigned int sz>
  inline unsigned int
  lengthof(T (&)[sz]) { return sz; }
```

Astute readers will notice two things at once: first, that the container class is still a `vector<T>` instead of a more general `Container<T>`. This would mean that three functions for `deque` would have to be added, another three for `list`, and so on. This is due to problems with getting template resolution correct; I find it easier just to give the extra three lines and avoid confusion.

Second, the line

```
    inline unsigned int lengthof (T (&)[sz]) { return sz; }
```

looks just weird! Hint: unused parameters can be left nameless.

Chapter 10

Iterators

10.1 Predefined

10.1.1 Iterators vs. Pointers

The following FAQ entry points out that iterators are not implemented as pointers. They are a generalization of pointers, but they are implemented in libstdc++ as separate classes.

Keeping that simple fact in mind as you design your code will prevent a whole lot of difficult-to-understand bugs.

You can think of it the other way 'round, even. Since iterators are a generalization, that means that *pointers* are *iterators*, and that pointers can be used whenever an iterator would be. All those functions in the Algorithms section of the Standard will work just as well on plain arrays and their pointers.

That doesn't mean that when you pass in a pointer, it gets wrapped into some special delegating iterator-to-pointer class with a layer of overhead. (If you think that's the case anywhere, you don't understand templates to begin with...) Oh, no; if you pass in a pointer, then the compiler will instantiate that template using T* as a type, and good old high-speed pointer arithmetic as its operations, so the resulting code will be doing exactly the same things as it would be doing if you had hand-coded it yourself (for the 273rd time).

How much overhead *is* there when using an iterator class? Very little. Most of the layering classes contain nothing but typedefs, and typedefs are "meta-information" that simply tell the compiler some nicknames; they don't create code. That information gets passed down through inheritance, so while the compiler has to do work looking up all the names, your runtime code does not. (This has been a prime concern from the beginning.)

10.1.2 One Past the End

This starts off sounding complicated, but is actually very easy, especially towards the end. Trust me.

Beginners usually have a little trouble understand the whole 'past-the-end' thing, until they remember their early algebra classes (see, they *told* you that stuff would come in handy!) and the concept of half-open ranges.

First, some history, and a reminder of some of the funkier rules in C and C++ for builtin arrays. The following rules have always been true for both languages:

1. You can point anywhere in the array, *or to the first element past the end of the array*. A pointer that points to one past the end of the array is guaranteed to be as unique as a pointer to somewhere inside the array, so that you can compare such pointers safely.
2. You can only dereference a pointer that points into an array. If your array pointer points outside the array -- even to just one past the end -- and you dereference it, Bad Things happen.

3. Strictly speaking, simply pointing anywhere else invokes undefined behavior. Most programs won't puke until such a pointer is actually dereferenced, but the standards leave that up to the platform.

The reason this past-the-end addressing was allowed is to make it easy to write a loop to go over an entire array, e.g., while (*d++ = *s++);.

So, when you think of two pointers delimiting an array, don't think of them as indexing 0 through n-1. Think of them as *boundary markers*:

```
  beginning            end
    |                   |
    |                   |               This is bad.  Always having to
    |                   |               remember to add or subtract one.
    |                   |               Off-by-one bugs very common here.
    V                   V
 array of N elements
    |---|---|--...--|---|---|
    | 0 | 1 |  ...  |N-2|N-1|
    |---|---|--...--|---|---|

    ^                       ^
    |                       |
    |                       |           This is good.  This is safe.  This
    |                       |           is guaranteed to work.  Just don't
    |                       |           dereference 'end'.
  beginning                end
```

See? Everything between the boundary markers is chapter of the array. Simple.

Now think back to your junior-high school algebra course, when you were learning how to draw graphs. Remember that a graph terminating with a solid dot meant, "Everything up through this point," and a graph terminating with an open dot meant, "Everything up to, but not including, this point," respectively called closed and open ranges? Remember how closed ranges were written with brackets, *[a,b]*, and open ranges were written with parentheses, *(a,b)*?

The boundary markers for arrays describe a *half-open range*, starting with (and including) the first element, and ending with (but not including) the last element: *[beginning,end)*. See, I told you it would be simple in the end.

Iterators, and everything working with iterators, follows this same time-honored tradition. A container's `begin()` method returns an iterator referring to the first element, and its `end()` method returns a past-the-end iterator, which is guaranteed to be unique and comparable against any other iterator pointing into the middle of the container.

Container constructors, container methods, and algorithms, all take pairs of iterators describing a range of values on which to operate. All of these ranges are half-open ranges, so you pass the beginning iterator as the starting parameter, and the one-past-the-end iterator as the finishing parameter.

This generalizes very well. You can operate on sub-ranges quite easily this way; functions accepting a *[first,last)* range don't know or care whether they are the boundaries of an entire {array, sequence, container, whatever}, or whether they only enclose a few elements from the center. This approach also makes zero-length sequences very simple to recognize: if the two endpoints compare equal, then the {array, sequence, container, whatever} is empty.

Just don't dereference `end()`.

Chapter 11

Algorithms

The neatest accomplishment of the algorithms section is that all the work is done via iterators, not containers directly. This means two important things:

1. Anything that behaves like an iterator can be used in one of these algorithms. Raw pointers make great candidates, thus built-in arrays are fine containers, as well as your own iterators.
2. The algorithms do not (and cannot) affect the container as a whole; only the things between the two iterator endpoints. If you pass a range of iterators only enclosing the middle third of a container, then anything outside that range is inviolate.

Even strings can be fed through the algorithms here, although the string class has specialized versions of many of these functions (for example, `string::find()`). Most of the examples on this page will use simple arrays of integers as a playground for algorithms, just to keep things simple. The use of *N* as a size in the examples is to keep things easy to read but probably won't be valid code. You can use wrappers such as those described in the containers section to keep real code readable.

The single thing that trips people up the most is the definition of *range* used with iterators; the famous "past-the-end" rule that everybody loves to hate. The iterators section of this document has a complete explanation of this simple rule that seems to cause so much confusion. Once you get *range* into your head (it's not that hard, honest!), then the algorithms are a cakewalk.

11.1 Mutating

11.1.1 swap

11.1.1.1 Specializations

If you call `std::swap(x,y);` where x and y are standard containers, then the call will automatically be replaced by a call to `x.swap(y);` instead.

This allows member functions of each container class to take over, and containers' swap functions should have O(1) complexity according to the standard. (And while "should" allows implementations to behave otherwise and remain compliant, this implementation does in fact use constant-time swaps.) This should not be surprising, since for two containers of the same type to swap contents, only some internal pointers to storage need to be exchanged.

Chapter 12

Numerics

12.1 Complex

12.1.1 complex Processing

Using `complex<>` becomes even more comple- er, sorry, *complicated*, with the not-quite-gratuitously-incompatible addition of complex types to the C language. David Tribble has compiled a list of C++98 and C99 conflict points; his description of C's new type versus those of C++ and how to get them playing together nicely is here.

`complex<>` is intended to be instantiated with a floating-point type. As long as you meet that and some other basic requirements, then the resulting instantiation has all of the usual math operators defined, as well as definitions of `op<<` and `op>>` that work with iostreams: `op<<` prints `(u,v)` and `op>>` can read `u`, `(u)`, and `(u,v)`.

As an extension to C++11 and for increased compatibility with C, `<complex.h>` includes both `<complex>` and the C99 `<complex.h>` (if the C library provides it).

12.2 Generalized Operations

There are four generalized functions in the <numeric> header that follow the same conventions as those in <algorithm>. Each of them is overloaded: one signature for common default operations, and a second for fully general operations. Their names are self-explanatory to anyone who works with numerics on a regular basis:

- `accumulate`
- `inner_product`
- `partial_sum`
- `adjacent_difference`

Here is a simple example of the two forms of `accumulate`.

```
int   ar[50];
int   someval = somefunction();

// ...initialize members of ar to something...

int  sum       = std::accumulate(ar,ar+50,0);
int  sum_stuff = std::accumulate(ar,ar+50,someval);
int  product   = std::accumulate(ar,ar+50,1,std::multiplies<int>());
```

The first call adds all the members of the array, using zero as an initial value for `sum`. The second does the same, but uses `someval` as the starting value (thus, `sum_stuff == sum + someval`). The final call uses the second of the two signatures, and multiplies all the members of the array; here we must obviously use 1 as a starting value instead of 0.

The other three functions have similar dual-signature forms.

12.3 Interacting with C

12.3.1 Numerics vs. Arrays

One of the major reasons why FORTRAN can chew through numbers so well is that it is defined to be free of pointer aliasing, an assumption that C89 is not allowed to make, and neither is C++98. C99 adds a new keyword, `restrict`, to apply to individual pointers. The C++ solution is contained in the library rather than the language (although many vendors can be expected to add this to their compilers as an extension).

That library solution is a set of two classes, five template classes, and "a whole bunch" of functions. The classes are required to be free of pointer aliasing, so compilers can optimize the daylights out of them the same way that they have been for FORTRAN. They are collectively called `valarray`, although strictly speaking this is only one of the five template classes, and they are designed to be familiar to people who have worked with the BLAS libraries before.

12.3.2 C99

In addition to the other topics on this page, we'll note here some of the C99 features that appear in libstdc++.

The C99 features depend on the `--enable-c99` configure flag. This flag is already on by default, but it can be disabled by the user. Also, the configuration machinery will disable it if the necessary support for C99 (e.g., header files) cannot be found.

As of GCC 3.0, C99 support includes classification functions such as `isnormal`, `isgreater`, `isnan`, etc. The functions used for 'long long' support such as `strtoll` are supported, as is the `lldiv_t` typedef. Also supported are the wide character functions using 'long long', like `wcstoll`.

Chapter 13

Input and Output

13.1 Iostream Objects

To minimize the time you have to wait on the compiler, it's good to only include the headers you really need. Many people simply include <iostream> when they don't need to -- and that can *penalize your runtime as well.* Here are some tips on which header to use for which situations, starting with the simplest.

<iosfwd> should be included whenever you simply need the *name* of an I/O-related class, such as "ofstream" or "basic_streamb
Like the name implies, these are forward declarations. (A word to all you fellow old school programmers: trying to forward declare classes like "class istream;" won't work. Look in the <iosfwd> header if you'd like to know why.) For example,

```
   #include <iosfwd>

   class MyClass
   {
 ....
 std::ifstream&   input_file;
   };

   extern std::ostream& operator<< (std::ostream&, MyClass&);
```

<ios> declares the base classes for the entire I/O stream hierarchy, std::ios_base and std::basic_ios<charT>, the counting types std::streamoff and std::streamsize, the file positioning type std::fpos, and the various manipulators like std::hex, std::fixed, std::noshowbase, and so forth.

The ios_base class is what holds the format flags, the state flags, and the functions which change them (setf(), width(), precision(), etc). You can also store extra data and register callback functions through ios_base, but that has been historically underused. Anything which doesn't depend on the type of characters stored is consolidated here.

The class template basic_ios is the highest class template in the hierarchy; it is the first one depending on the character type, and holds all general state associated with that type: the pointer to the polymorphic stream buffer, the facet information, etc.

<streambuf> declares the class template basic_streambuf, and two standard instantiations, streambuf and wstreambuf. If you need to work with the vastly useful and capable stream buffer classes, e.g., to create a new form of storage transport, this header is the one to include.

<istream> and *<ostream>* are the headers to include when you are using the overloaded >> and << operators, or any of the other abstract stream formatting functions. For example,

```
   #include <istream>

   std::ostream& operator<< (std::ostream& os, MyClass& c)
   {
      return os << c.data1() << c.data2();
   }
```

The std::istream and std::ostream classes are the abstract parents of the various concrete implementations. If you are only using the interfaces, then you only need to use the appropriate interface header.

<iomanip> provides "extractors and inserters that alter information maintained by class `ios_base` and its derived classes," such as `std::setprecision` and `std::setw`. If you need to write expressions like `os << setw(3);` or `is >> setbase(8);`, you must include `<iomanip>`.

<sstream> and *<fstream>* declare the six stringstream and fstream classes. As they are the standard concrete descendants of istream and ostream, you will already know about them.

Finally, *<iostream>* provides the eight standard global objects (`cin`, `cout`, etc). To do this correctly, this header also provides the contents of the `<istream>` and `<ostream>` headers, but nothing else. The contents of this header look like:

```
   #include <ostream>
   #include <istream>

   namespace std
   {
 extern istream cin;
 extern ostream cout;
 ....

 // this is explained below
 static ios_base::Init __foo;    // not its real name
   }
```

Now, the runtime penalty mentioned previously: the global objects must be initialized before any of your own code uses them; this is guaranteed by the standard. Like any other global object, they must be initialized once and only once. This is typically done with a construct like the one above, and the nested class `ios_base::Init` is specified in the standard for just this reason.

How does it work? Because the header is included before any of your code, the *__foo* object is constructed before any of your objects. (Global objects are built in the order in which they are declared, and destroyed in reverse order.) The first time the constructor runs, the eight stream objects are set up.

The `static` keyword means that each object file compiled from a source file containing `<iostream>` will have its own private copy of *__foo*. There is no specified order of construction across object files (it's one of those pesky NP complete problems that make life so interesting), so one copy in each object file means that the stream objects are guaranteed to be set up before any of your code which uses them could run, thereby meeting the requirements of the standard.

The penalty, of course, is that after the first copy of *__foo* is constructed, all the others are just wasted processor time. The time spent is merely for an increment-and-test inside a function call, but over several dozen or hundreds of object files, that time can add up. (It's not in a tight loop, either.)

The lesson? Only include `<iostream>` when you need to use one of the standard objects in that source file; you'll pay less startup time. Only include the header files you need to in general; your compile times will go down when there's less parsing work to do.

13.2 Stream Buffers

13.2.1 Derived streambuf Classes

Creating your own stream buffers for I/O can be remarkably easy. If you are interested in doing so, we highly recommend two very excellent books: Standard C++ IOStreams and Locales by Langer and Kreft, ISBN 0-201-18395-1, and The C++ Standard Library by Nicolai Josuttis, ISBN 0-201-37926-0. Both are published by Addison-Wesley, who isn't paying us a cent for saying that, honest.

Here is a simple example, io/outbuf1, from the Josuttis text. It transforms everything sent through it to uppercase. This version assumes many things about the nature of the character type being used (for more information, read the books or the newsgroups):

```
   #include <iostream>
   #include <streambuf>
```

```
  #include <locale>
  #include <cstdio>

  class outbuf : public std::streambuf
  {
    protected:
/* central output function
 * - print characters in uppercase mode
 */
virtual int_type overflow (int_type c) {
    if (c != EOF) {
  // convert lowercase to uppercase
  c = std::toupper(static_cast<char>(c),getloc());

  // and write the character to the standard output
  if (putchar(c) == EOF) {
      return EOF;
  }
    }
    return c;
}
  };

  int main()
  {
// create special output buffer
outbuf ob;
// initialize output stream with that output buffer
std::ostream out(&ob);

out << "31 hexadecimal: "
    << std::hex << 31 << std::endl;
return 0;
  }
```

Try it yourself! More examples can be found in 3.1.x code, in `include/ext/*_filebuf.h`, and in the article Filtering Streambufs by James Kanze.

13.2.2 Buffering

First, are you sure that you understand buffering? Particularly the fact that C++ may not, in fact, have anything to do with it?

The rules for buffering can be a little odd, but they aren't any different from those of C. (Maybe that's why they can be a bit odd.) Many people think that writing a newline to an output stream automatically flushes the output buffer. This is true only when the output stream is, in fact, a terminal and not a file or some other device -- and *that* may not even be true since C++ says nothing about files nor terminals. All of that is system-dependent. (The "newline-buffer-flushing only occurring on terminals" thing is mostly true on Unix systems, though.)

Some people also believe that sending `endl` down an output stream only writes a newline. This is incorrect; after a newline is written, the buffer is also flushed. Perhaps this is the effect you want when writing to a screen -- get the text out as soon as possible, etc -- but the buffering is largely wasted when doing this to a file:

```
output << "a line of text" << endl;
output << some_data_variable << endl;
output << "another line of text" << endl;
```

The proper thing to do in this case to just write the data out and let the libraries and the system worry about the buffering. If you need a newline, just write a newline:

```
output << "a line of text\n"
 << some_data_variable << '\n'
```

```
    << "another line of text\n";
```

I have also joined the output statements into a single statement. You could make the code prettier by moving the single newline to the start of the quoted text on the last line, for example.

If you do need to flush the buffer above, you can send an `endl` if you also need a newline, or just flush the buffer yourself:

```
output << ...... << flush;    // can use std::flush manipulator
output.flush();               // or call a member fn
```

On the other hand, there are times when writing to a file should be like writing to standard error; no buffering should be done because the data needs to appear quickly (a prime example is a log file for security-related information). The way to do this is just to turn off the buffering *before any I/O operations at all* have been done (note that opening counts as an I/O operation):

```
std::ofstream    os;
std::ifstream    is;
int   i;

os.rdbuf()->pubsetbuf(0,0);
is.rdbuf()->pubsetbuf(0,0);

os.open("/foo/bar/baz");
is.open("/qux/quux/quuux");
...
os << "this data is written immediately\n";
is >> i;   // and this will probably cause a disk read
```

Since all aspects of buffering are handled by a streambuf-derived member, it is necessary to get at that member with `rdbuf()`. Then the public version of `setbuf` can be called. The arguments are the same as those for the Standard C I/O Library function (a buffer area followed by its size).

A great deal of this is implementation-dependent. For example, `streambuf` does not specify any actions for its own `setbuf()`-ish functions; the classes derived from `streambuf` each define behavior that "makes sense" for that class: an argument of (0,0) turns off buffering for `filebuf` but does nothing at all for its siblings `stringbuf` and `strstreambuf`, and specifying anything other than (0,0) has varying effects. User-defined classes derived from `streambuf` can do whatever they want. (For `filebuf` and arguments for `(p,s)` other than zeros, libstdc++ does what you'd expect: the first `s` bytes of `p` are used as a buffer, which you must allocate and deallocate.)

A last reminder: there are usually more buffers involved than just those at the language/library level. Kernel buffers, disk buffers, and the like will also have an effect. Inspecting and changing those are system-dependent.

13.3 Memory Based Streams

13.3.1 Compatibility With strstream

Stringstreams (defined in the header `<sstream>`) are in this author's opinion one of the coolest things since sliced time. An example of their use is in the Received Wisdom section for Sect1 21 (Strings), describing how to format strings.

The quick definition is: they are siblings of ifstream and ofstream, and they do for `std::string` what their siblings do for files. All that work you put into writing << and >> functions for your classes now pays off *again!* Need to format a string before passing the string to a function? Send your stuff via << to an ostringstream. You've read a string as input and need to parse it? Initialize an istringstream with that string, and then pull pieces out of it with >>. Have a stringstream and need to get a copy of the string inside? Just call the `str()` member function.

This only works if you've written your <</>> functions correctly, though, and correctly means that they take istreams and ostreams as parameters, not *if*streams and *of*streams. If they take the latter, then your I/O operators will work fine with file streams, but with nothing else -- including stringstreams.

If you are a user of the strstream classes, you need to update your code. You don't have to explicitly append `ends` to terminate the C-style character array, you don't have to mess with "freezing" functions, and you don't have to manage the memory yourself. The strstreams have been officially deprecated, which means that 1) future revisions of the C++ Standard won't support them, and 2) if you use them, people will laugh at you.

13.4 File Based Streams

13.4.1 Copying a File

So you want to copy a file quickly and easily, and most important, completely portably. And since this is C++, you have an open ifstream (call it IN) and an open ofstream (call it OUT):

```
#include <fstream>

std::ifstream  IN ("input_file");
std::ofstream  OUT ("output_file");
```

Here's the easiest way to get it completely wrong:

```
OUT << IN;
```

For those of you who don't already know why this doesn't work (probably from having done it before), I invite you to quickly create a simple text file called "input_file" containing the sentence

```
   The quick brown fox jumped over the lazy dog.
```

surrounded by blank lines. Code it up and try it. The contents of "output_file" may surprise you.

Seriously, go do it. Get surprised, then come back. It's worth it.

The thing to remember is that the `basic_[io]stream` classes handle formatting, nothing else. In particular, they break up on whitespace. The actual reading, writing, and storing of data is handled by the `basic_streambuf` family. Fortunately, the `operator<<` is overloaded to take an ostream and a pointer-to-streambuf, in order to help with just this kind of "dump the data verbatim" situation.

Why a *pointer* to streambuf and not just a streambuf? Well, the [io]streams hold pointers (or references, depending on the implementation) to their buffers, not the actual buffers. This allows polymorphic behavior on the chapter of the buffers as well as the streams themselves. The pointer is easily retrieved using the `rdbuf()` member function. Therefore, the easiest way to copy the file is:

```
OUT << IN.rdbuf();
```

So what *was* happening with OUT<<IN? Undefined behavior, since that particular << isn't defined by the Standard. I have seen instances where it is implemented, but the character extraction process removes all the whitespace, leaving you with no blank lines and only "Thequickbrownfox...". With libraries that do not define that operator, IN (or one of IN's member pointers) sometimes gets converted to a void*, and the output file then contains a perfect text representation of a hexadecimal address (quite a big surprise). Others don't compile at all.

Also note that none of this is specific to o*f*streams. The operators shown above are all defined in the parent basic_ostream class and are therefore available with all possible descendants.

13.4.2 Binary Input and Output

The first and most important thing to remember about binary I/O is that opening a file with `ios::binary` is not, repeat *not*, the only thing you have to do. It is not a silver bullet, and will not allow you to use the `<</>>` operators of the normal fstreams to do binary I/O.

Sorry. Them's the breaks.

This isn't going to try and be a complete tutorial on reading and writing binary files (because "binary" covers a lot of ground), but we will try and clear up a couple of misconceptions and common errors.

First, `ios::binary` has exactly one defined effect, no more and no less. Normal text mode has to be concerned with the newline characters, and the runtime system will translate between (for example) '\n' and the appropriate end-of-line sequence (LF on Unix, CRLF on DOS, CR on Macintosh, etc). (There are other things that normal mode does, but that's the most obvious.)

Opening a file in binary mode disables this conversion, so reading a CRLF sequence under Windows won't accidentally get mapped to a '\n' character, etc. Binary mode is not supposed to suddenly give you a bitstream, and if it is doing so in your program then you've discovered a bug in your vendor's compiler (or some other chapter of the C++ implementation, possibly the runtime system).

Second, using << to write and >> to read isn't going to work with the standard file stream classes, even if you use `skipws` during reading. Why not? Because ifstream and ofstream exist for the purpose of *formatting*, not reading and writing. Their job is to interpret the data into text characters, and that's exactly what you don't want to happen during binary I/O.

Third, using the `get()` and `put()/write()` member functions still aren't guaranteed to help you. These are "unformatted" I/O functions, but still character-based. (This may or may not be what you want, see below.)

Notice how all the problems here are due to the inappropriate use of *formatting* functions and classes to perform something which *requires* that formatting not be done? There are a seemingly infinite number of solutions, and a few are listed here:

- "Derive your own fstream-type classes and write your own <</>> operators to do binary I/O on whatever data types you're using."

  This is a Bad Thing, because while the compiler would probably be just fine with it, other humans are going to be confused. The overloaded bitshift operators have a well-defined meaning (formatting), and this breaks it.

- "Build the file structure in memory, then `mmap()` the file and copy the structure. "

  Well, this is easy to make work, and easy to break, and is pretty equivalent to using `::read()` and `::write()` directly, and makes no use of the iostream library at all...

- "Use streambufs, that's what they're there for."

  While not trivial for the beginner, this is the best of all solutions. The streambuf/filebuf layer is the layer that is responsible for actual I/O. If you want to use the C++ library for binary I/O, this is where you start.

How to go about using streambufs is a bit beyond the scope of this document (at least for now), but while streambufs go a long way, they still leave a couple of things up to you, the programmer. As an example, byte ordering is completely between you and the operating system, and you have to handle it yourself.

Deriving a streambuf or filebuf class from the standard ones, one that is specific to your data types (or an abstraction thereof) is probably a good idea, and lots of examples exist in journals and on Usenet. Using the standard filebufs directly (either by declaring your own or by using the pointer returned from an fstream's `rdbuf()`) is certainly feasible as well.

One area that causes problems is trying to do bit-by-bit operations with filebufs. C++ is no different from C in this respect: I/O must be done at the byte level. If you're trying to read or write a few bits at a time, you're going about it the wrong way. You must read/write an integral number of bytes and then process the bytes. (For example, the streambuf functions take and return variables of type `int_type`.)

Another area of problems is opening text files in binary mode. Generally, binary mode is intended for binary files, and opening text files in binary mode means that you now have to deal with all of those end-of-line and end-of-file problems that we mentioned before.

An instructive thread from comp.lang.c++.moderated delved off into this topic starting more or less at this post and continuing to the end of the thread. (The subject heading is "binary iostreams" on both comp.std.c++ and comp.lang.c++.moderated.) Take special note of the replies by James Kanze and Dietmar Kühl.

Briefly, the problems of byte ordering and type sizes mean that the unformatted functions like `ostream::put()` and `istream::get` cannot safely be used to communicate between arbitrary programs, or across a network, or from one invocation of a program to another invocation of the same program on a different platform, etc.

13.5 Interacting with C

13.5.1 Using FILE* and file descriptors

See the extensions for using FILE and file descriptors with `ofstream` and `ifstream`.

13.5.2 Performance

Pathetic Performance? Ditch C.

It sounds like a flame on C, but it isn't. Really. Calm down. I'm just saying it to get your attention.

Because the C++ library includes the C library, both C-style and C++-style I/O have to work at the same time. For example:

```
#include <iostream>
#include <cstdio>

std::cout << "Hel";
std::printf ("lo, worl");
std::cout << "d!\n";
```

This must do what you think it does.

Alert members of the audience will immediately notice that buffering is going to make a hash of the output unless special steps are taken.

The special steps taken by libstdc++, at least for version 3.0, involve doing very little buffering for the standard streams, leaving most of the buffering to the underlying C library. (This kind of thing is tricky to get right.) The upside is that correctness is ensured. The downside is that writing through `cout` can quite easily lead to awful performance when the C++ I/O library is layered on top of the C I/O library (as it is for 3.0 by default). Some patches have been applied which improve the situation for 3.1.

However, the C and C++ standard streams only need to be kept in sync when both libraries' facilities are in use. If your program only uses C++ I/O, then there's no need to sync with the C streams. The right thing to do in this case is to call

```
#include any of the I/O headers such as ios, iostream, etc

std::ios::sync_with_stdio(false);
```

You must do this before performing any I/O via the C++ stream objects. Once you call this, the C++ streams will operate independently of the (unused) C streams. For GCC 3.x, this means that `cout` and company will become fully buffered on their own.

Note, by the way, that the synchronization requirement only applies to the standard streams (`cin`, `cout`, `cerr`, `clog`, and their wide-character counterparts). File stream objects that you declare yourself have no such requirement and are fully buffered.

Chapter 14

Atomics

Facilities for atomic operations.

14.1 API Reference

All items are declared in the standard header file `atomic`.

Set of typedefs that map int to `atomic_int`, and so on for all builtin integral types. Global enumeration memory_order to control memory ordering. Also includes `atomic`, a class template with member functions such as `load` and `store` that is instantiable such that `atomic_int` is the base class of `atomic<int>`.

Full API details.

Chapter 15

Concurrency

Facilities for concurrent operation, and control thereof.

15.1 API Reference

All items are declared in one of four standard header files.

In header `mutex`, class template `mutex` and variants, class `once_flag`, and class template `unique_lock`.

In header `condition_variable`, classes `condition_variable` and `condition_variable_any`.

In header `thread`, class `thread` and namespace `this_thread`.

In header `future`, class template `future` and class template `shared_future`, class template `promise`, and `packaged_task`.

Full API details.

Part III

Extensions

Here we will make an attempt at describing the non-Standard extensions to the library. Some of these are from older versions of standard library components, namely SGI's STL, and some of these are GNU's.

Before you leap in and use any of these extensions, be aware of two things:

1. Non-Standard means exactly that.

   The behavior, and the very existence, of these extensions may change with little or no warning. (Ideally, the really good ones will appear in the next revision of C++.) Also, other platforms, other compilers, other versions of g++ or libstdc++ may not recognize these names, or treat them differently, or...

2. You should know how to access these headers properly.

Chapter 16

Compile Time Checks

Also known as concept checking.

In 1999, SGI added *concept checkers* to their implementation of the STL: code which checked the template parameters of instantiated pieces of the STL, in order to insure that the parameters being used met the requirements of the standard. For example, the Standard requires that types passed as template parameters to `vector` be “Assignable” (which means what you think it means). The checking was done during compilation, and none of the code was executed at runtime.

Unfortunately, the size of the compiler files grew significantly as a result. The checking code itself was cumbersome. And bugs were found in it on more than one occasion.

The primary author of the checking code, Jeremy Siek, had already started work on a replacement implementation. The new code has been formally reviewed and accepted into the Boost libraries, and we are pleased to incorporate it into the GNU C++ library.

The new version imposes a much smaller space overhead on the generated object file. The checks are also cleaner and easier to read and understand.

They are off by default for all GCC 3.0 and all later versions. They can be enabled at configure time with --enable-concept-checks. You can enable them on a per-translation-unit basis with #define _GLIBCXX_CONCEPT_CHECKS for GCC 3.4 and higher (or with `#define _GLIBCPP_CONCEPT_CHECKS` for versions 3.1, 3.2 and 3.3).

Please note that the concept checks only validate the requirements of the old C++03 standard and reject some valid code that meets the relaxed requirements of C++11 and later standards. C++11 was expected to have first-class support for template parameter constraints based on concepts in the core language. This would have obviated the need for the library-simulated concept checking described above, but was not part of C++11. C++20 adds a different model of concepts, which is now used to constrain some new parts of the C++20 library, e.g. the `<ranges>` header and the new overloads in the `<algorithm>` header for working with ranges. The old library-simulated concept checks might be removed at a future date.

Chapter 17

Debug Mode

17.1 Intro

By default, libstdc++ is built with efficiency in mind, and therefore performs little or no error checking that is not required by the C++ standard. This means that programs that incorrectly use the C++ standard library will exhibit behavior that is not portable and may not even be predictable, because they tread into implementation-specific or undefined behavior. To detect some of these errors before they can become problematic, libstdc++ offers a debug mode that provides additional checking of library facilities, and will report errors in the use of libstdc++ as soon as they can be detected by emitting a description of the problem to standard error and aborting the program. This debug mode is available with GCC 3.4.0 and later versions.

The libstdc++ debug mode performs checking for many areas of the C++ standard, but the focus is on checking interactions among standard iterators, containers, and algorithms, including:

- *Safe iterators*: Iterators keep track of the container whose elements they reference, so errors such as incrementing a past-the-end iterator or dereferencing an iterator that points to a container that has been destructed are diagnosed immediately.
- *Algorithm preconditions*: Algorithms attempt to validate their input parameters to detect errors as early as possible. For instance, the `set_intersection` algorithm requires that its iterator parameters `first1` and `last1` form a valid iterator range, and that the sequence [`first1`, `last1`) is sorted according to the same predicate that was passed to `set_intersection`; the libstdc++ debug mode will detect an error if the sequence is not sorted or was sorted by a different predicate.

17.2 Semantics

A program that uses the C++ standard library correctly will maintain the same semantics under debug mode as it had with the normal (release) library. All functional and exception-handling guarantees made by the normal library also hold for the debug mode library, with one exception: performance guarantees made by the normal library may not hold in the debug mode library. For instance, erasing an element in a `std::list` is a constant-time operation in normal library, but in debug mode it is linear in the number of iterators that reference that particular list. So while your (correct) program won't change its results, it is likely to execute more slowly.

libstdc++ includes many extensions to the C++ standard library. In some cases the extensions are obvious, such as the hashed associative containers, whereas other extensions give predictable results to behavior that would otherwise be undefined, such as throwing an exception when a `std::basic_string` is constructed from a NULL character pointer. This latter category also includes implementation-defined and unspecified semantics, such as the growth rate of a vector. Use of these extensions is not considered incorrect, so code that relies on them will not be rejected by debug mode. However, use of these extensions may affect the portability of code to other implementations of the C++ standard library, and is therefore somewhat hazardous. For this reason, the libstdc++ debug mode offers a "pedantic" mode (similar to GCC's `-pedantic` compiler flag) that attempts to emulate the semantics guaranteed by the C++ standard. For instance, constructing a `std::basic_string` with a NULL character pointer would result in an exception under normal mode or non-pedantic debug mode (this is a libstdc++ extension), whereas under pedantic debug mode libstdc++ would signal an error. To enable the pedantic debug mode, compile your program with both `-D_GLIBCXX_DEBUG` and `-D_GLIBCXX_DEBUG_PEDANTIC` . (N.B. In GCC 3.4.x and 4.0.0, due to a bug, `-D_GLIBXX_DEBUG_PEDANTIC` was also needed. The problem has been fixed in GCC 4.0.1 and later versions.)

The following library components provide extra debugging capabilities in debug mode:

- `std::array` (no safe iterators)
- `std::basic_string` (no safe iterators and see note below)
- `std::bitset`
- `std::deque`
- `std::list`
- `std::map`
- `std::multimap`
- `std::multiset`
- `std::set`
- `std::vector`
- `std::unordered_map`
- `std::unordered_multimap`
- `std::unordered_set`
- `std::unordered_multiset`

N.B. although there are precondition checks for some string operations, e.g. `operator[]`, they will not always be run when using the `char` and `wchar_t` specializations (`std::string` and `std::wstring`). This is because libstdc++ uses GCC's `extern template` extension to provide explicit instantiations of `std::string` and `std::wstring`, and those explicit instantiations don't include the debug-mode checks. If the containing functions are inlined then the checks will run, so compiling with `-O1` might be enough to enable them. Alternatively `-D_GLIBCXX_EXTERN_TEMPLATE=0` will suppress the declarations of the explicit instantiations and cause the functions to be instantiated with the debug-mode checks included, but this is unsupported and not guaranteed to work. For full debug-mode support you can use the `__gnu_debug::basic_string` debugging container directly, which always works correctly.

17.3 Using

17.3.1 Using the Debug Mode

To use the libstdc++ debug mode, compile your application with the compiler flag `-D_GLIBCXX_DEBUG`. Note that this flag changes the sizes and behavior of standard class templates such as `std::vector`, and therefore you can only link code compiled with debug mode and code compiled without debug mode if no instantiation of a container is passed between the two translation units.

By default, error messages are formatted to fit on lines of about 78 characters. The environment variable `GLIBCXX_DEBUG_MESSAGE_` can be used to request a different length.

Note that libstdc++ is able to produce backtraces on error. To enable these, compile with `-D_GLIBCXX_DEBUG_BACKTRACE` and then link with `-lstdc++exp`. These backtraces are not supported on all platforms.

Container	Header	Debug container	Debug header
`std::bitset`	`bitset`	`__gnu_debug::bitset`	`<debug/bitset>`
`std::deque`	`deque`	`__gnu_debug::deque`	`<debug/deque>`
`std::list`	`list`	`__gnu_debug::list`	`<debug/list>`
`std::map`	`map`	`__gnu_debug::map`	`<debug/map>`
`std::multimap`	`map`	`__gnu_debug::multimap`	`<debug/map>`
`std::multiset`	`set`	`__gnu_debug::multiset`	`<debug/set>`
`std::set`	`set`	`__gnu_debug::set`	`<debug/set>`
`std::string`	`string`	`__gnu_debug::string`	`<debug/string>`
`std::wstring`	`string`	`__gnu_debug::wstring`	`<debug/string>`
`std::basic_string`	`string`	`__gnu_debug::basic_string`	`<debug/string>`
`std::vector`	`vector`	`__gnu_debug::vector`	`<debug/vector>`

Table 17.1: Debugging Containers

17.3.2 Using a Specific Debug Container

When it is not feasible to recompile your entire application, or only specific containers need checking, debugging containers are available as GNU extensions. These debugging containers are functionally equivalent to the standard drop-in containers used in debug mode, but they are available in a separate namespace as GNU extensions and may be used in programs compiled with either release mode or with debug mode. The following table provides the names and headers of the debugging containers:

When compiling in C++11 mode (or newer), these containers have additional debug capability.

Container	Header	Debug container	Debug header
`std::forward_list`	`forward_list`	`__gnu_debug::forward_list`	`<debug/forward_list>`
`std::unordered_map`	`unordered_map`	`__gnu_debug::unordered_map`	`<debug/unordered_map>`
`std::unordered_multimap`	`unordered_map`	`__gnu_debug::unordered_multimap`	`<debug/unordered_map>`
`std::unordered_set`	`unordered_set`	`__gnu_debug::unordered_set`	`<debug/unordered_set>`
`std::unordered_multiset`	`unordered_set`	`__gnu_debug::unordered_multiset`	`<debug/unordered_set>`

Table 17.2: Debugging Containers C++11

Prior to GCC 11 a debug version of `std::array` was available as `__gnu_debug::array` in the header `<debug/array>`. Because `array::iterator` is just a pointer, the debug `array` can't check iterator operations, it can only check direct accesses to the container. Starting with GCC 11 all the debug capabilities are available in `std::array`, without needing a separate type, so `__gnu_debug::array` is just an alias for `std::array`. That alias is deprecated and may be removed in a future release.

17.4 Design

17.4.1 Goals

The libstdc++ debug mode replaces unsafe (but efficient) standard containers and iterators with semantically equivalent safe standard containers and iterators to aid in debugging user programs. The following goals directed the design of the libstdc++ debug mode:

- *Correctness*: the libstdc++ debug mode must not change the semantics of the standard library for all cases specified in the ANSI/ISO C++ standard. The essence of this constraint is that any valid C++ program should behave in the same manner regardless of whether it is compiled with debug mode or release mode. In particular, entities that are defined in namespace std in release mode should remain defined in namespace std in debug mode, so that legal specializations of namespace std entities will remain valid. A program that is not valid C++ (e.g., invokes undefined behavior) is not required to behave similarly, although the debug mode will abort with a diagnostic when it detects undefined behavior.

- *Performance*: the additional of the libstdc++ debug mode must not affect the performance of the library when it is compiled in release mode. Performance of the libstdc++ debug mode is secondary (and, in fact, will be worse than the release mode).
- *Usability*: the libstdc++ debug mode should be easy to use. It should be easily incorporated into the user's development environment (e.g., by requiring only a single new compiler switch) and should produce reasonable diagnostics when it detects a problem with the user program. Usability also involves detection of errors when using the debug mode incorrectly, e.g., by linking a release-compiled object against a debug-compiled object if in fact the resulting program will not run correctly.
- *Minimize recompilation*: While it is expected that users recompile at least part of their program to use debug mode, the amount of recompilation affects the detect-compile-debug turnaround time. This indirectly affects the usefulness of the debug mode, because debugging some applications may require rebuilding a large amount of code, which may not be feasible when the suspect code may be very localized. There are several levels of conformance to this requirement, each with its own usability and implementation characteristics. In general, the higher-numbered conformance levels are more usable (i.e., require less recompilation) but are more complicated to implement than the lower-numbered conformance levels.
  1. *Full recompilation*: The user must recompile their entire application and all C++ libraries it depends on, including the C++ standard library that ships with the compiler. This must be done even if only a small part of the program can use debugging features.
  2. *Full user recompilation*: The user must recompile their entire application and all C++ libraries it depends on, but not the C++ standard library itself. This must be done even if only a small part of the program can use debugging features. This can be achieved given a full recompilation system by compiling two versions of the standard library when the compiler is installed and linking against the appropriate one, e.g., a multilibs approach.
  3. *Partial recompilation*: The user must recompile the parts of their application and the C++ libraries it depends on that will use the debugging facilities directly. This means that any code that uses the debuggable standard containers would need to be recompiled, but code that does not use them (but may, for instance, use IOStreams) would not have to be recompiled.
  4. *Per-use recompilation*: The user must recompile the parts of their application and the C++ libraries it depends on where debugging should occur, and any other code that interacts with those containers. This means that a set of translation units that accesses a particular standard container instance may either be compiled in release mode (no checking) or debug mode (full checking), but must all be compiled in the same way; a translation unit that does not see that standard container instance need not be recompiled. This also means that a translation unit *A* that contains a particular instantiation (say, `std::vector<int>`) compiled in release mode can be linked against a translation unit *B* that contains the same instantiation compiled in debug mode (a feature not present with partial recompilation). While this behavior is technically a violation of the One Definition Rule, this ability tends to be very important in practice. The libstdc++ debug mode supports this level of recompilation.
  5. *Per-unit recompilation*: The user must only recompile the translation units where checking should occur, regardless of where debuggable standard containers are used. This has also been dubbed "`-g` mode", because the `-g` compiler switch works in this way, emitting debugging information at a per--translation-unit granularity. We believe that this level of recompilation is in fact not possible if we intend to supply safe iterators, leave the program semantics unchanged, and not regress in performance under release mode because we cannot associate extra information with an iterator (to form a safe iterator) without either reserving that space in release mode (performance regression) or allocating extra memory associated with each iterator with `new` (changes the program semantics).

17.4.2 Methods

This section provides an overall view of the design of the libstdc++ debug mode and details the relationship between design decisions and the stated design goals.

17.4.2.1 The Wrapper Model

The libstdc++ debug mode uses a wrapper model where the debugging versions of library components (e.g., iterators and containers) form a layer on top of the release versions of the library components. The debugging components first verify that the operation is correct (aborting with a diagnostic if an error is found) and will then forward to the underlying release-mode container that will perform the actual work. This design decision ensures that we cannot regress release-mode performance (because the release-mode containers are left untouched) and partially enables mixing debug and release code at link time, although that will not be discussed at this time.

Two types of wrappers are used in the implementation of the debug mode: container wrappers and iterator wrappers. The two types of wrappers interact to maintain relationships between iterators and their associated containers, which are necessary to detect certain types of standard library usage errors such as dereferencing past-the-end iterators or inserting into a container using an iterator from a different container.

17.4.2.1.1 Safe Iterators

Iterator wrappers provide a debugging layer over any iterator that is attached to a particular container, and will manage the information detailing the iterator's state (singular, dereferenceable, etc.) and tracking the container to which the iterator is attached. Because iterators have a well-defined, common interface the iterator wrapper is implemented with the iterator adaptor class template `__gnu_debug::_Safe_iterator`, which takes two template parameters:

- `Iterator`: The underlying iterator type, which must be either the `iterator` or `const_iterator` typedef from the sequence type this iterator can reference.
- `Sequence`: The type of sequence that this iterator references. This sequence must be a safe sequence (discussed below) whose `iterator` or `const_iterator` typedef is the type of the safe iterator.

17.4.2.1.2 Safe Sequences (Containers)

Container wrappers provide a debugging layer over a particular container type. Because containers vary greatly in the member functions they support and the semantics of those member functions (especially in the area of iterator invalidation), container wrappers are tailored to the container they reference, e.g., the debugging version of `std::list` duplicates the entire interface of `std::list`, adding additional semantic checks and then forwarding operations to the real `std::list` (a public base class of the debugging version) as appropriate. However, all safe containers inherit from the class template `__gnu_debug::_Safe_sequence`, instantiated with the type of the safe container itself (an instance of the curiously recurring template pattern).

The iterators of a container wrapper will be safe iterators that reference sequences of this type and wrap the iterators provided by the release-mode base class. The debugging container will use only the safe iterators within its own interface (therefore requiring the user to use safe iterators, although this does not change correct user code) and will communicate with the release-mode base class with only the underlying, unsafe, release-mode iterators that the base class exports.

The debugging version of `std::list` will have the following basic structure:

```
template<typename _Tp, typename _Allocator = allocator<_Tp>
  class debug-list :
    public release-list<_Tp, _Allocator>,
    public __gnu_debug::_Safe_sequence<debug-list<_Tp, _Allocator> >
  {
    typedef release-list<_Tp, _Allocator> _Base;
    typedef debug-list<_Tp, _Allocator>   _Self;

  public:
    typedef __gnu_debug::_Safe_iterator<typename _Base::iterator, _Self>       iterator;
    typedef __gnu_debug::_Safe_iterator<typename _Base::const_iterator, _Self>  ←
        const_iterator;

    // duplicate std::list interface with debugging semantics
  };
```

17.4.2.2 Precondition Checking

The debug mode operates primarily by checking the preconditions of all standard library operations that it supports. Preconditions that are always checked (regardless of whether or not we are in debug mode) are checked via the `__check_xxx` macros defined and documented in the source file `include/debug/debug.h`. Preconditions that may or may not be checked, depending on the debug-mode macro `_GLIBCXX_DEBUG`, are checked via the `__requires_xxx` macros defined and documented in the same source file. Preconditions are validated using any additional information available at run-time, e.g., the containers that are associated with a particular iterator, the position of the iterator within those containers, the distance between two iterators that may form a valid range, etc. In the absence of suitable information, e.g., an input iterator that is not a safe iterator, these precondition checks will silently succeed.

The majority of precondition checks use the aforementioned macros, which have the secondary benefit of having prewritten debug messages that use information about the current status of the objects involved (e.g., whether an iterator is singular or what sequence it is attached to) along with some static information (e.g., the names of the function parameters corresponding to the objects involved). When not using these macros, the debug mode uses either the debug-mode assertion macro `_GLIBCXX_DEBUG_ASSERT` , its pedantic cousin `_GLIBCXX_DEBUG_PEDASSERT`, or the assertion check macro that supports more advance formulation of error messages, `_GLIBCXX_DEBUG_VERIFY`. These macros are documented more thoroughly in the debug mode source code.

17.4.2.3 Release- and debug-mode coexistence

The libstdc++ debug mode is the first debug mode we know of that is able to provide the "Per-use recompilation" (4) guarantee, that allows release-compiled and debug-compiled code to be linked and executed together without causing unpredictable behavior. This guarantee minimizes the recompilation that users are required to perform, shortening the detect-compile-debug bug hunting cycle and making the debug mode easier to incorporate into development environments by minimizing dependencies.

Achieving link- and run-time coexistence is not a trivial implementation task. To achieve this goal we use inline namespaces and a complex organization of debug- and release-modes. The end result is that we have achieved per-use recompilation but have had to give up some checking of the `std::basic_string` class template (namely, safe iterators).

17.4.2.3.1 Compile-time coexistence of release- and debug-mode components

Both the release-mode components and the debug-mode components need to exist within a single translation unit so that the debug versions can wrap the release versions. However, only one of these components should be user-visible at any particular time with the standard name, e.g., `std::list`.

In release mode, we define only the release-mode version of the component with its standard name and do not include the debugging component at all. The release mode version is defined within the namespace `std`. Minus the namespace associations, this method leaves the behavior of release mode completely unchanged from its behavior prior to the introduction of the libstdc++ debug mode. Here's an example of what this ends up looking like, in C++.

```
namespace std
{
  template<typename _Tp, typename _Alloc = allocator<_Tp> >
    class list
    {
      // ...
     };
} // namespace std
```

In debug mode we include the release-mode container (which is now defined in the namespace `__cxx1998`) and also the debug-mode container. The debug-mode container is defined within the namespace `__debug`, which is associated with namespace `std` via the C++11 namespace association language feature. This method allows the debug and release versions of the same component to coexist at compile-time and link-time without causing an unreasonable maintenance burden, while minimizing confusion. Again, this boils down to C++ code as follows:

```
namespace std
{
  namespace __cxx1998
```

```
  {
    template<typename _Tp, typename _Alloc = allocator<_Tp> >
      class list
      {
  // ...
      };
  } // namespace __gnu_norm

  namespace __debug
  {
    template<typename _Tp, typename _Alloc = allocator<_Tp> >
      class list
      : public __cxx1998::list<_Tp, _Alloc>,
  public __gnu_debug::_Safe_sequence<list<_Tp, _Alloc> >
      {
  // ...
      };
  } // namespace __cxx1998

  inline namespace __debug { }
}
```

17.4.2.3.2 Link- and run-time coexistence of release- and debug-mode components

Because each component has a distinct and separate release and debug implementation, there is no issue with link-time coexistence: the separate namespaces result in different mangled names, and thus unique linkage.

However, components that are defined and used within the C++ standard library itself face additional constraints. For instance, some of the member functions of `std::moneypunct` return `std::basic_string`. Normally, this is not a problem, but with a mixed mode standard library that could be using either debug-mode or release-mode `basic_string` objects, things get more complicated. As the return value of a function is not encoded into the mangled name, there is no way to specify a release-mode or a debug-mode string. In practice, this results in runtime errors. A simplified example of this problem is as follows.

Take this translation unit, compiled in debug-mode:

```
// -D_GLIBCXX_DEBUG
#include <string>

std::string test02();

std::string test01()
{
  return test02();
}

int main()
{
  test01();
  return 0;
}
```

... and linked to this translation unit, compiled in release mode:

```
#include <string>

std::string
test02()
{
  return std::string("toast");
}
```

For this reason we cannot easily provide safe iterators for the `std::basic_string` class template, as it is present throughout the C++ standard library. For instance, locale facets define typedefs that include `basic_string`: in a mixed debug/release program, should that typedef be based on the debug-mode `basic_string` or the release-mode `basic_string`? While the answer could be "both", and the difference hidden via renaming a la the debug/release containers, we must note two things about locale facets:

1. They exist as shared state: one can create a facet in one translation unit and access the facet via the same type name in a different translation unit. This means that we cannot have two different versions of locale facets, because the types would not be the same across debug/release-mode translation unit barriers.
2. They have virtual functions returning strings: these functions mangle in the same way regardless of the mangling of their return types (see above), and their precise signatures can be relied upon by users because they may be overridden in derived classes.

With the design of libstdc++ debug mode, we cannot effectively hide the differences between debug and release-mode strings from the user. Failure to hide the differences may result in unpredictable behavior, and for this reason we have opted to only perform `basic_string` changes that do not require ABI changes. The effect on users is expected to be minimal, as there are simple alternatives (e.g., `__gnu_debug::basic_string`), and the usability benefit we gain from the ability to mix debug- and release-compiled translation units is enormous.

17.4.2.3.3 Alternatives for Coexistence

The coexistence scheme above was chosen over many alternatives, including language-only solutions and solutions that also required extensions to the C++ front end. The following is a partial list of solutions, with justifications for our rejection of each.

- *Completely separate debug/release libraries*: This is by far the simplest implementation option, where we do not allow any coexistence of debug- and release-compiled translation units in a program. This solution has an extreme negative affect on usability, because it is quite likely that some libraries an application depends on cannot be recompiled easily. This would not meet our *usability* or *minimize recompilation* criteria well.
- *Add a `Debug` boolean template parameter*: Partial specialization could be used to select the debug implementation when `Debug == true`, and the state of `_GLIBCXX_DEBUG` could decide whether the default `Debug` argument is `true` or `false`. This option would break conformance with the C++ standard in both debug *and* release modes. This would not meet our *correctness* criteria.
- *Packaging a debug flag in the allocators*: We could reuse the `Allocator` template parameter of containers by adding a sentinel wrapper `debug<>` that signals the user's intention to use debugging, and pick up the `debug<>` allocator wrapper in a partial specialization. However, this has two drawbacks: first, there is a conformance issue because the default allocator would not be the standard-specified `std::allocator<T>`. Secondly (and more importantly), users that specify allocators instead of implicitly using the default allocator would not get debugging containers. Thus this solution fails the *correctness* criteria.
- *Define debug containers in another namespace, and employ a `using` declaration (or directive)*: This is an enticing option, because it would eliminate the need for the `link_name` extension by aliasing the templates. However, there is no true template aliasing mechanism in C++, because both `using` directives and using declarations disallow specialization. This method fails the *correctness* criteria.
- *Use implementation-specific properties of anonymous namespaces.* See this post. This method fails the *correctness* criteria.
- *Extension: allow reopening on namespaces*: This would allow the debug mode to effectively alias the namespace `std` to an internal namespace, such as `__gnu_std_debug`, so that it is completely separate from the release-mode `std` namespace. While this will solve some renaming problems and ensure that debug- and release-compiled code cannot be mixed unsafely, it ensures that debug- and release-compiled code cannot be mixed at all. For instance, the program would have two `std::cout` objects! This solution would fails the *minimize recompilation* requirement, because we would only be able to support option (1) or (2).
- *Extension: use link name*: This option involves complicated re-naming between debug-mode and release-mode components at compile time, and then a g++ extension called *link name* to recover the original names at link time. There are two drawbacks to this approach. One, it's very verbose, relying on macro renaming at compile time and several levels of include ordering. Two, ODR issues remained with container member functions taking no arguments in mixed-mode settings resulting in equivalent link names, `vector::push_back()` being one example. See proof-of-concept using link name.

Other options may exist for implementing the debug mode, many of which have probably been considered and others that may still be lurking. This list may be expanded over time to include other options that we could have implemented, but in all cases the full ramifications of the approach (as measured against the design goals for a libstdc++ debug mode) should be considered first. The DejaGNU testsuite includes some testcases that check for known problems with some solutions (e.g., the `using` declaration solution that breaks user specialization), and additional testcases will be added as we are able to identify other typical problem cases. These test cases will serve as a benchmark by which we can compare debug mode implementations.

17.4.3 Other Implementations

There are several existing implementations of debug modes for C++ standard library implementations, although none of them directly supports debugging for programs using libstdc++. The existing implementations include:

- SafeSTL: SafeSTL was the original debugging version of the Standard Template Library (STL), implemented by Cay S. Horstmann on top of the Hewlett-Packard STL. Though it inspired much work in this area, it has not been kept up-to-date for use with modern compilers or C++ standard library implementations.
- STLport: STLport is a free implementation of the C++ standard library derived from the SGI implementation, and ported to many other platforms. It includes a debug mode that uses a wrapper model (that in some ways inspired the libstdc++ debug mode design), although at the time of this writing the debug mode is somewhat incomplete and meets only the "Full user recompilation" (2) recompilation guarantee by requiring the user to link against a different library in debug mode vs. release mode.
- Metrowerks CodeWarrior: The C++ standard library that ships with Metrowerks CodeWarrior includes a debug mode. It is a full debug-mode implementation (including debugging for CodeWarrior extensions) and is easy to use, although it meets only the "Full recompilation" (1) recompilation guarantee.

Chapter 18

Parallel Mode

The libstdc++ parallel mode is an experimental parallel implementation of many algorithms of the C++ Standard Library.

Several of the standard algorithms, for instance `std::sort`, are made parallel using OpenMP annotations. These parallel mode constructs can be invoked by explicit source declaration or by compiling existing sources with a specific compiler flag.

Note
The parallel mode has not been kept up to date with recent C++ standards and so it only conforms to the C++03 requirements. That means that move-only predicates may not work with parallel mode algorithms, and for C++20 most of the algorithms cannot be used in `constexpr` functions.
For C++17 and above there are new overloads of the standard algorithms which take an execution policy argument. You should consider using those instead of the non-standard parallel mode extensions.

18.1 Intro

The following library components in the include `numeric` are included in the parallel mode:

- `std::accumulate`
- `std::adjacent_difference`
- `std::inner_product`
- `std::partial_sum`

The following library components in the include `algorithm` are included in the parallel mode:

- `std::adjacent_find`
- `std::count`
- `std::count_if`
- `std::equal`
- `std::find`
- `std::find_if`
- `std::find_first_of`
- `std::for_each`

- std::generate
- std::generate_n
- std::lexicographical_compare
- std::mismatch
- std::search
- std::search_n
- std::transform
- std::replace
- std::replace_if
- std::max_element
- std::merge
- std::min_element
- std::nth_element
- std::partial_sort
- std::partition
- std::random_shuffle
- std::set_union
- std::set_intersection
- std::set_symmetric_difference
- std::set_difference
- std::sort
- std::stable_sort
- std::unique_copy

18.2 Semantics

The parallel mode STL algorithms are currently not exception-safe, i.e. user-defined functors must not throw exceptions. Also, the order of execution is not guaranteed for some functions, of course. Therefore, user-defined functors should not have any concurrent side effects.

Since the current GCC OpenMP implementation does not support OpenMP parallel regions in concurrent threads, it is not possible to call parallel STL algorithm in concurrent threads, either. It might work with other compilers, though.

18.3 Using

18.3.1 Prerequisite Compiler Flags

Any use of parallel functionality requires additional compiler and runtime support, in particular support for OpenMP. Adding this support is not difficult: just compile your application with the compiler flag `-fopenmp`. This will link in `libgomp`, the GNU Offloading and Multi Processing Runtime Library, whose presence is mandatory.

In addition, hardware that supports atomic operations and a compiler capable of producing atomic operations is mandatory: GCC defaults to no support for atomic operations on some common hardware architectures. Activating atomic operations may require explicit compiler flags on some targets (like sparc and x86), such as `-march=i686`, `-march=native` or `-mcpu=v9`. See the GCC manual for more information.

18.3.2 Using Parallel Mode

To use the libstdc++ parallel mode, compile your application with the prerequisite flags as detailed above, and in addition add `-D_GLIBCXX_PARALLEL`. This will convert all use of the standard (sequential) algorithms to the appropriate parallel equivalents. Please note that this doesn't necessarily mean that everything will end up being executed in a parallel manner, but rather that the heuristics and settings coded into the parallel versions will be used to determine if all, some, or no algorithms will be executed using parallel variants.

Note that the `_GLIBCXX_PARALLEL` define may change the sizes and behavior of standard class templates such as `std::search`, and therefore one can only link code compiled with parallel mode and code compiled without parallel mode if no instantiation of a container is passed between the two translation units. Parallel mode functionality has distinct linkage, and cannot be confused with normal mode symbols.

18.3.3 Using Specific Parallel Components

When it is not feasible to recompile your entire application, or only specific algorithms need to be parallel-aware, individual parallel algorithms can be made available explicitly. These parallel algorithms are functionally equivalent to the standard drop-in algorithms used in parallel mode, but they are available in a separate namespace as GNU extensions and may be used in programs compiled with either release mode or with parallel mode.

An example of using a parallel version of `std::sort`, but no other parallel algorithms, is:

```
#include <vector>
#include <parallel/algorithm>

int main()
{
  std::vector<int> v(100);

  // ...

  // Explicitly force a call to parallel sort.
  __gnu_parallel::sort(v.begin(), v.end());
  return 0;
}
```

Then compile this code with the prerequisite compiler flags (`-fopenmp` and any necessary architecture-specific flags for atomic operations.)

The following table provides the names and headers of all the parallel algorithms that can be used in a similar manner:

Algorithm	Header	Parallel algorithm	Parallel header
std::accumulate	numeric	__gnu_parallel::accumulate	parallel/numeric
std::adjacent_difference	numeric	__gnu_parallel::adjacent_difference	parallel/numeric
std::inner_product	numeric	__gnu_parallel::inner_product	parallel/numeric
std::partial_sum	numeric	__gnu_parallel::partial_sum	parallel/numeric
std::adjacent_find	algorithm	__gnu_parallel::adjacent_find	parallel/algorithm
std::count	algorithm	__gnu_parallel::count	parallel/algorithm
std::count_if	algorithm	__gnu_parallel::count_if	parallel/algorithm
std::equal	algorithm	__gnu_parallel::equal	parallel/algorithm
std::find	algorithm	__gnu_parallel::find	parallel/algorithm
std::find_if	algorithm	__gnu_parallel::find_if	parallel/algorithm
std::find_first_of	algorithm	__gnu_parallel::find_first_of	parallel/algorithm
std::for_each	algorithm	__gnu_parallel::for_each	parallel/algorithm
std::generate	algorithm	__gnu_parallel::generate	parallel/algorithm
std::generate_n	algorithm	__gnu_parallel::generate_n	parallel/algorithm
std::lexicographical_compare	algorithm	__gnu_parallel::lexicographical_compare	parallel/algorithm
std::mismatch	algorithm	__gnu_parallel::mismatch	parallel/algorithm
std::search	algorithm	__gnu_parallel::search	parallel/algorithm
std::search_n	algorithm	__gnu_parallel::search_n	parallel/algorithm
std::transform	algorithm	__gnu_parallel::transform	parallel/algorithm
std::replace	algorithm	__gnu_parallel::replace	parallel/algorithm
std::replace_if	algorithm	__gnu_parallel::replace_if	parallel/algorithm
std::max_element	algorithm	__gnu_parallel::max_element	parallel/algorithm
std::merge	algorithm	__gnu_parallel::merge	parallel/algorithm
std::min_element	algorithm	__gnu_parallel::min_element	parallel/algorithm
std::nth_element	algorithm	__gnu_parallel::nth_element	parallel/algorithm
std::partial_sort	algorithm	__gnu_parallel::partial_sort	parallel/algorithm
std::partition	algorithm	__gnu_parallel::partition	parallel/algorithm
std::random_shuffle	algorithm	__gnu_parallel::random_shuffle	parallel/algorithm
std::set_union	algorithm	__gnu_parallel::set_union	parallel/algorithm
std::set_intersection	algorithm	__gnu_parallel::set_intersection	parallel/algorithm
std::set_symmetric_difference	algorithm	__gnu_parallel::set_symmetric_difference	parallel/algorithm
std::set_difference	algorithm	__gnu_parallel::set_difference	parallel/algorithm
std::sort	algorithm	__gnu_parallel::sort	parallel/algorithm
std::stable_sort	algorithm	__gnu_parallel::stable_sort	parallel/algorithm
std::unique_copy	algorithm	__gnu_parallel::unique_copy	parallel/algorithm

Table 18.1: Parallel Algorithms

18.4 Design

18.4.1 Interface Basics

All parallel algorithms are intended to have signatures that are equivalent to the ISO C++ algorithms replaced. For instance, the `std::adjacent_find` function is declared as:

```
namespace std
{
  template<typename _FIter>
    _FIter
    adjacent_find(_FIter, _FIter);
}
```

Which means that there should be something equivalent for the parallel version. Indeed, this is the case:

```
namespace std
{
  namespace __parallel
  {
    template<typename _FIter>
      _FIter
      adjacent_find(_FIter, _FIter);

    ...
  }
}
```

But.... why the ellipses?

The ellipses in the example above represent additional overloads required for the parallel version of the function. These additional overloads are used to dispatch calls from the ISO C++ function signature to the appropriate parallel function (or sequential function, if no parallel functions are deemed worthy), based on either compile-time or run-time conditions.

The available signature options are specific for the different algorithms/algorithm classes.

The general view of overloads for the parallel algorithms look like this:

- ISO C++ signature
- ISO C++ signature + sequential_tag argument
- ISO C++ signature + algorithm-specific tag type (several signatures)

Please note that the implementation may use additional functions (designated with the `_switch` suffix) to dispatch from the ISO C++ signature to the correct parallel version. Also, some of the algorithms do not have support for run-time conditions, so the last overload is therefore missing.

18.4.2 Configuration and Tuning

18.4.2.1 Setting up the OpenMP Environment

Several aspects of the overall runtime environment can be manipulated by standard OpenMP function calls.

To specify the number of threads to be used for the algorithms globally, use the function `omp_set_num_threads`. An example:

```
#include <stdlib.h>
#include <omp.h>

int main()
{
  // Explicitly set number of threads.
  const int threads_wanted = 20;
  omp_set_dynamic(false);
  omp_set_num_threads(threads_wanted);

  // Call parallel mode algorithms.

  return 0;
}
```

Some algorithms allow the number of threads being set for a particular call, by augmenting the algorithm variant. See the next section for further information.

Other parts of the runtime environment able to be manipulated include nested parallelism (`omp_set_nested`), schedule kind (`omp_set_schedule`), and others. See the OpenMP documentation for more information.

18.4.2.2 Compile Time Switches

To force an algorithm to execute sequentially, even though parallelism is switched on in general via the macro `_GLIBCXX_PARALLEL`, add `__gnu_parallel::sequential_tag()` to the end of the algorithm's argument list.

Like so:

```
std::sort(v.begin(), v.end(), __gnu_parallel::sequential_tag());
```

Some parallel algorithm variants can be excluded from compilation by preprocessor defines. See the doxygen documentation on `compiletime_settings.h` and `features.h` for details.

For some algorithms, the desired variant can be chosen at compile-time by appending a tag object. The available options are specific to the particular algorithm (class).

For the "embarrassingly parallel" algorithms, there is only one "tag object type", the enum _Parallelism. It takes one of the following values, `__gnu_parallel::parallel_tag`, `__gnu_parallel::balanced_tag`, `__gnu_parallel::unbalance` `__gnu_parallel::omp_loop_tag`, `__gnu_parallel::omp_loop_static_tag`. This means that the actual parallelization strategy is chosen at run-time. (Choosing the variants at compile-time will come soon.)

For the following algorithms in general, we have `__gnu_parallel::parallel_tag` and `__gnu_parallel::default_par` in addition to `__gnu_parallel::sequential_tag`. `__gnu_parallel::default_parallel_tag` chooses the default algorithm at compiletime, as does omitting the tag. `__gnu_parallel::parallel_tag` postpones the decision to runtime (see next section). For all tags, the number of threads desired for this call can optionally be passed to the respective tag's constructor.

The `multiway_merge` algorithm comes with the additional choices, `__gnu_parallel::exact_tag` and `__gnu_parallel:` Exact and sampling are the two available splitting strategies.

For the `sort` and `stable_sort` algorithms, there are several additional choices, namely `__gnu_parallel::multiway_merge` `__gnu_parallel::multiway_mergesort_exact_tag`, `__gnu_parallel::multiway_mergesort_sampling_ta` `__gnu_parallel::quicksort_tag`, and `__gnu_parallel::balanced_quicksort_tag`. Multiway mergesort comes with the two splitting strategies for multi-way merging. The quicksort options cannot be used for `stable_sort`.

18.4.2.3 Run Time Settings and Defaults

The default parallelization strategy, the choice of specific algorithm strategy, the minimum threshold limits for individual parallel algorithms, and aspects of the underlying hardware can be specified as desired via manipulation of `__gnu_parallel::_Settings` member data.

First off, the choice of parallelization strategy: serial, parallel, or heuristically deduced. This corresponds to `__gnu_parallel::_Se` and is a value of enum __gnu_parallel::_AlgorithmStrategy type. Choices include: heuristic, force_sequential, and force_parallel. The default is heuristic.

Next, the sub-choices for algorithm variant, if not fixed at compile-time. Specific algorithms like `find` or `sort` can be implemented in multiple ways: when this is the case, a `__gnu_parallel::_Settings` member exists to pick the default strategy. For example, `__gnu_parallel::_Settings::sort_algorithm` can have any values of enum __gnu_parallel::_SortAlgorithm MWMS, QS, or QS_BALANCED.

Likewise for setting the minimal threshold for algorithm parallelization. Parallelism always incurs some overhead. Thus, it is not helpful to parallelize operations on very small sets of data. Because of this, measures are taken to avoid parallelizing below a certain, pre-determined threshold. For each algorithm, a minimum problem size is encoded as a variable in the active `__gnu_parallel::_Settings` object. This threshold variable follows the following naming scheme: `__gnu_parallel::_Se` So, for `fill`, the threshold variable is `__gnu_parallel::_Settings::fill_minimal_n`,

Finally, hardware details like L1/L2 cache size can be hardwired via `__gnu_parallel::_Settings::L1_cache_size` and friends.

All these configuration variables can be changed by the user, if desired. There exists one global instance of the class `_Settings`, i. e. it is a singleton. It can be read and written by calling `__gnu_parallel::_Settings::get` and `__gnu_parallel::_Set` respectively. Please note that the first call return a const object, so direct manipulation is forbidden. See <parallel/settings.h> for complete details.

A small example of tuning the default:

```
#include <parallel/algorithm>
#include <parallel/settings.h>

int main()
{
  __gnu_parallel::_Settings s;
  s.algorithm_strategy = __gnu_parallel::force_parallel;
  __gnu_parallel::_Settings::set(s);

  // Do work... all algorithms will be parallelized, always.

  return 0;
}
```

18.4.3 Implementation Namespaces

One namespace contain versions of code that are always explicitly sequential: `__gnu_serial`.

Two namespaces contain the parallel mode: `std::__parallel` and `__gnu_parallel`.

Parallel implementations of standard components, including template helpers to select parallelism, are defined in `namespace std::__parallel`. For instance, `std::transform` from `algorithm` has a parallel counterpart in `std::__parallel::tra` from `parallel/algorithm`. In addition, these parallel implementations are injected into `namespace __gnu_parallel` with using declarations.

Support and general infrastructure is in `namespace __gnu_parallel`.

More information, and an organized index of types and functions related to the parallel mode on a per-namespace basis, can be found in the generated source documentation.

18.5 Testing

Both the normal conformance and regression tests and the supplemental performance tests work.

To run the conformance and regression tests with the parallel mode active,

```
make check-parallel
```

The log and summary files for conformance testing are in the `testsuite/parallel` directory.

To run the performance tests with the parallel mode active,

```
make check-performance-parallel
```

The result file for performance testing are in the `testsuite` directory, in the file `libstdc++_performance.sum`. In addition, the policy-based containers have their own visualizations, which have additional software dependencies than the usual bare-boned text file, and can be generated by using the `make doc-performance` rule in the testsuite's Makefile.

18.6 Bibliography

[53] Johannes SinglerLeonor Frias, Copyright © 2007 , Workshop on Highly Parallel Processing on a Chip (HPPC) 2007. (LNCS) .

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Chapter 19

The mt_allocator

19.1 Intro

The mt allocator [hereinafter referred to simply as "the allocator"] is a fixed size (power of two) allocator that was initially developed specifically to suit the needs of multi-threaded applications [hereinafter referred to as an MT application]. Over time the allocator has evolved and been improved in many ways, in particular it now also does a good job in single-threaded applications [hereinafter referred to as an ST application]. (Note: In this document, when referring to single-threaded applications this also includes applications that are compiled with gcc without thread support enabled. This is accomplished using ifdef's on __GTHREADS). This allocator is tunable, very flexible, and capable of high-performance.

The aim of this document is to describe - from an application point of view - the "inner workings" of the allocator.

19.2 Design Issues

19.2.1 Overview

There are three general components to the allocator: a datum describing the characteristics of the memory pool, a policy class containing this pool that links instantiation types to common or individual pools, and a class inheriting from the policy class that is the actual allocator.

The datum describing pools characteristics is

```
template<bool _Thread>
  class __pool
```

This class is parametrized on thread support, and is explicitly specialized for both multiple threads (with `bool==true`) and single threads (via `bool==false`.) It is possible to use a custom pool datum instead of the default class that is provided.

There are two distinct policy classes, each of which can be used with either type of underlying pool datum.

```
template<bool _Thread>
  struct __common_pool_policy

template<typename _Tp, bool _Thread>
  struct __per_type_pool_policy
```

The first policy, `__common_pool_policy`, implements a common pool. This means that allocators that are instantiated with different types, say `char` and `long` will both use the same pool. This is the default policy.

The second policy, `__per_type_pool_policy`, implements a separate pool for each instantiating type. Thus, `char` and `long` will use separate pools. This allows per-type tuning, for instance.

Putting this all together, the actual allocator class is

```
  template<typename _Tp, typename _Poolp = __default_policy>
    class __mt_alloc : public __mt_alloc_base<_Tp>,  _Poolp
```

This class has the interface required for standard library allocator classes, namely member functions `allocate` and `deallocate`, plus others.

19.3 Implementation

19.3.1 Tunable Parameters

Certain allocation parameters can be modified, or tuned. There exists a nested `struct __pool_base::_Tune` that contains all these parameters, which include settings for

- Alignment
- Maximum bytes before calling `::operator new` directly
- Minimum bytes
- Size of underlying global allocations
- Maximum number of supported threads
- Migration of deallocations to the global free list
- Shunt for global `new` and `delete`

Adjusting parameters for a given instance of an allocator can only happen before any allocations take place, when the allocator itself is initialized. For instance:

```
#include <ext/mt_allocator.h>

struct pod
{
  int i;
  int j;
};

int main()
{
  typedef pod value_type;
  typedef __gnu_cxx::__mt_alloc<value_type> allocator_type;
  typedef __gnu_cxx::__pool_base::_Tune tune_type;

  tune_type t_default;
  tune_type t_opt(16, 5120, 32, 5120, 20, 10, false);
  tune_type t_single(16, 5120, 32, 5120, 1, 10, false);

  tune_type t;
  t = allocator_type::_M_get_options();
  allocator_type::_M_set_options(t_opt);
  t = allocator_type::_M_get_options();

  allocator_type a;
  allocator_type::pointer p1 = a.allocate(128);
  allocator_type::pointer p2 = a.allocate(5128);

  a.deallocate(p1, 128);
  a.deallocate(p2, 5128);
```

```
  return 0;
}
```

19.3.2 Initialization

The static variables (pointers to freelists, tuning parameters etc) are initialized as above, or are set to the global defaults.

The very first allocate() call will always call the _S_initialize_once() function. In order to make sure that this function is called exactly once we make use of a __gthread_once call in MT applications and check a static bool (_S_init) in ST applications.

The _S_initialize() function: - If the GLIBCXX_FORCE_NEW environment variable is set, it sets the bool _S_force_new to true and then returns. This will cause subsequent calls to allocate() to return memory directly from a new() call, and deallocate will only do a delete() call.

- If the GLIBCXX_FORCE_NEW environment variable is not set, both ST and MT applications will: - Calculate the number of bins needed. A bin is a specific power of two size of bytes. I.e., by default the allocator will deal with requests of up to 128 bytes (or whatever the value of _S_max_bytes is when _S_init() is called). This means that there will be bins of the following sizes (in bytes): 1, 2, 4, 8, 16, 32, 64, 128. - Create the _S_binmap array. All requests are rounded up to the next "large enough" bin. I.e., a request for 29 bytes will cause a block from the "32 byte bin" to be returned to the application. The purpose of _S_binmap is to speed up the process of finding out which bin to use. I.e., the value of _S_binmap[29] is initialized to 5 (bin 5 = 32 bytes).

- Create the _S_bin array. This array consists of bin_records. There will be as many bin_records in this array as the number of bins that we calculated earlier. I.e., if _S_max_bytes = 128 there will be 8 entries. Each bin_record is then initialized: - bin_record->first = An array of pointers to block_records. There will be as many block_records pointers as there are maximum number of threads (in a ST application there is only 1 thread, in a MT application there are _S_max_threads). This holds the pointer to the first free block for each thread in this bin. I.e., if we would like to know where the first free block of size 32 for thread number 3 is we would look this up by: _S_bin[5].first[3] The above created block_record pointers members are now initialized to their initial values. I.e. _S_bin[n].first[n] = NULL;

- Additionally a MT application will: - Create a list of free thread id's. The pointer to the first entry is stored in _S_thread_freelist_first. The reason for this approach is that the __gthread_self() call will not return a value that corresponds to the maximum number of threads allowed but rather a process id number or something else. So what we do is that we create a list of thread_records. This list is _S_max_threads long and each entry holds a size_t thread_id which is initialized to 1, 2, 3, 4, 5 and so on up to _S_max_threads. Each time a thread calls allocate() or deallocate() we call _S_get_thread_id() which looks at the value of _S_thread_key which is a thread local storage pointer. If this is NULL we know that this is a newly created thread and we pop the first entry from this list and saves the pointer to this record in the _S_thread_key variable. The next time we will get the pointer to the thread_record back and we use the thread_record->thread_id as identification. I.e., the first thread that calls allocate will get the first record in this list and thus be thread number 1 and will then find the pointer to its first free 32 byte block in _S_bin[5].first[1] When we create the _S_thread_key we also define a destructor (_S_thread_key_destr) which means that when the thread dies, this thread_record is returned to the front of this list and the thread id can then be reused if a new thread is created. This list is protected by a mutex (_S_thread_freelist_mutex) which is only locked when records are removed or added to the list.

- Initialize the free and used counters of each bin_record: - bin_record->free = An array of size_t. This keeps track of the number of blocks on a specific thread's freelist in each bin. I.e., if a thread has 12 32-byte blocks on it's freelists and allocates one of these, this counter would be decreased to 11. - bin_record->used = An array of size_t. This keeps track of the number of blocks currently in use of this size by this thread. I.e., if a thread has made 678 requests (and no deallocations...) of 32-byte blocks this counter will read 678. The above created arrays are now initialized with their initial values. I.e. _S_bin[n].free[n] = 0;

- Initialize the mutex of each bin_record: The bin_record->mutex is used to protect the global freelist. This concept of a global freelist is explained in more detail in the section "A multi threaded example", but basically this mutex is locked whenever a block of memory is retrieved or returned to the global freelist for this specific bin. This only occurs when a number of blocks are grabbed from the global list to a thread specific list or when a thread decides to return some blocks to the global freelist.

19.3.3 Deallocation Notes

Notes about deallocation. This allocator does not explicitly release memory back to the OS, but keeps its own freelists instead. Because of this, memory debugging programs like valgrind or purify may notice leaks: sorry about this inconvenience. Operating systems will reclaim allocated memory at program termination anyway. If sidestepping this kind of noise is desired, there are three options: use an allocator, like `new_allocator` that releases memory while debugging, use GLIBCXX_FORCE_NEW to bypass the allocator's internal pools, or use a custom pool datum that releases resources on destruction.

On systems with the function `__cxa_atexit`, the allocator can be forced to free all memory allocated before program termination with the member function `__pool_type::_M_destroy`. However, because this member function relies on the precise and exactly-conforming ordering of static destructors, including those of a static local `__pool` object, it should not be used, ever, on systems that don't have the necessary underlying support. In addition, in practice, forcing deallocation can be tricky, as it requires the `__pool` object to be fully-constructed before the object that uses it is fully constructed. For most (but not all) STL containers, this works, as an instance of the allocator is constructed as part of a container's constructor. However, this assumption is implementation-specific, and subject to change. For an example of a pool that frees memory, see the `ext/mt_allocator/deallocate_local-6.cc` example.

19.4 Single Thread Example

Let's start by describing how the data on a freelist is laid out in memory. This is the first two blocks in freelist for thread id 3 in bin 3 (8 bytes):

```
+----------------+
| next* ---------|--+  (_S_bin[ 3 ].first[ 3 ] points here)
|                |  |
|                |  |
|                |  |
+----------------+  |
| thread_id = 3  |  |
|                |  |
|                |  |
|                |  |
+----------------+  |
| DATA           |  |  (A pointer to here is what is returned to the
|                |  |   the application when needed)
|                |  |
|                |  |
|                |  |
|                |  |
|                |  |
|                |  |
+----------------+  |
+----------------+  |
| next*          |<-+  (If next == NULL it's the last one on the list)
|                |
|                |
|                |
+----------------+
| thread_id = 3  |
|                |
|                |
|                |
+----------------+
| DATA           |
|                |
|                |
|                |
|                |
|                |
|                |
|                |
+----------------+
```

With this in mind we simplify things a bit for a while and say that there is only one thread (a ST application). In this case all operations are made to what is referred to as the global pool - thread id 0 (No thread may be assigned this id since they span from 1 to _S_max_threads in a MT application).

When the application requests memory (calling allocate()) we first look at the requested size and if this is > _S_max_bytes we call new() directly and return.

If the requested size is within limits we start by finding out from which bin we should serve this request by looking in _S_binmap.

A quick look at _S_bin[bin].first[0] tells us if there are any blocks of this size on the freelist (0). If this is not NULL - fine, just remove the block that _S_bin[bin].first[0] points to from the list, update _S_bin[bin].first[0] and return a pointer to that blocks data.

If the freelist is empty (the pointer is NULL) we must get memory from the system and build us a freelist within this memory. All requests for new memory is made in chunks of _S_chunk_size. Knowing the size of a block_record and the bytes that this bin stores we then calculate how many blocks we can create within this chunk, build the list, remove the first block, update the pointer (_S_bin[bin].first[0]) and return a pointer to that blocks data.

Deallocation is equally simple; the pointer is casted back to a block_record pointer, lookup which bin to use based on the size, add the block to the front of the global freelist and update the pointer as needed (_S_bin[bin].first[0]).

The decision to add deallocated blocks to the front of the freelist was made after a set of performance measurements that showed that this is roughly 10% faster than maintaining a set of "last pointers" as well.

19.5 Multiple Thread Example

In the ST example we never used the thread_id variable present in each block. Let's start by explaining the purpose of this in a MT application.

The concept of "ownership" was introduced since many MT applications allocate and deallocate memory to shared containers from different threads (such as a cache shared amongst all threads). This introduces a problem if the allocator only returns memory to the current threads freelist (I.e., there might be one thread doing all the allocation and thus obtaining ever more memory from the system and another thread that is getting a longer and longer freelist - this will in the end consume all available memory).

Each time a block is moved from the global list (where ownership is irrelevant), to a threads freelist (or when a new freelist is built from a chunk directly onto a threads freelist or when a deallocation occurs on a block which was not allocated by the same thread id as the one doing the deallocation) the thread id is set to the current one.

What's the use? Well, when a deallocation occurs we can now look at the thread id and find out if it was allocated by another thread id and decrease the used counter of that thread instead, thus keeping the free and used counters correct. And keeping the free and used counters corrects is very important since the relationship between these two variables decides if memory should be returned to the global pool or not when a deallocation occurs.

When the application requests memory (calling allocate()) we first look at the requested size and if this is >_S_max_bytes we call new() directly and return.

If the requested size is within limits we start by finding out from which bin we should serve this request by looking in _S_binmap.

A call to _S_get_thread_id() returns the thread id for the calling thread (and if no value has been set in _S_thread_key, a new id is assigned and returned).

A quick look at _S_bin[bin].first[thread_id] tells us if there are any blocks of this size on the current threads freelist. If this is not NULL - fine, just remove the block that _S_bin[bin].first[thread_id] points to from the list, update _S_bin[bin].first[thread_id], update the free and used counters and return a pointer to that blocks data.

If the freelist is empty (the pointer is NULL) we start by looking at the global freelist (0). If there are blocks available on the global freelist we lock this bins mutex and move up to block_count (the number of blocks of this bins size that will fit into a _S_chunk_size) or until end of list - whatever comes first - to the current threads freelist and at the same time change the thread_id ownership and update the counters and pointers. When the bins mutex has been unlocked, we remove the block that _S_bin[bin].first[thread_id] points to from the list, update _S_bin[bin].first[thread_id], update the free and used counters, and return a pointer to that blocks data.

The reason that the number of blocks moved to the current threads freelist is limited to block_count is to minimize the chance that a subsequent deallocate() call will return the excess blocks to the global freelist (based on the _S_freelist_headroom calculation, see below).

However if there isn't any memory on the global pool we need to get memory from the system - this is done in exactly the same way as in a single threaded application with one major difference; the list built in the newly allocated memory (of _S_chunk_size size) is added to the current threads freelist instead of to the global.

The basic process of a deallocation call is simple: always add the block to the front of the current threads freelist and update the counters and pointers (as described earlier with the specific check of ownership that causes the used counter of the thread that originally allocated the block to be decreased instead of the current threads counter).

And here comes the free and used counters to service. Each time a deallocation() call is made, the length of the current threads freelist is compared to the amount memory in use by this thread.

Let's go back to the example of an application that has one thread that does all the allocations and one that deallocates. Both these threads use say 516 32-byte blocks that was allocated during thread creation for example. Their used counters will both say 516 at this point. The allocation thread now grabs 1000 32-byte blocks and puts them in a shared container. The used counter for this thread is now 1516.

The deallocation thread now deallocates 500 of these blocks. For each deallocation made the used counter of the allocating thread is decreased and the freelist of the deallocation thread gets longer and longer. But the calculation made in deallocate() will limit the length of the freelist in the deallocation thread to _S_freelist_headroom % of it's used counter. In this case, when the freelist (given that the _S_freelist_headroom is at it's default value of 10%) exceeds 52 (516/10) blocks will be returned to the global pool where the allocating thread may pick them up and reuse them.

In order to reduce lock contention (since this requires this bins mutex to be locked) this operation is also made in chunks of blocks (just like when chunks of blocks are moved from the global freelist to a threads freelist mentioned above). The "formula" used can probably be improved to further reduce the risk of blocks being "bounced back and forth" between freelists.

Chapter 20

The bitmap_allocator

20.1 Design

As this name suggests, this allocator uses a bit-map to keep track of the used and unused memory locations for its book-keeping purposes.

This allocator will make use of 1 single bit to keep track of whether it has been allocated or not. A bit 1 indicates free, while 0 indicates allocated. This has been done so that you can easily check a collection of bits for a free block. This kind of Bitmapped strategy works best for single object allocations, and with the STL type parameterized allocators, we do not need to choose any size for the block which will be represented by a single bit. This will be the size of the parameter around which the allocator has been parameterized. Thus, close to optimal performance will result. Hence, this should be used for node based containers which call the allocate function with an argument of 1.

The bitmapped allocator's internal pool is exponentially growing. Meaning that internally, the blocks acquired from the Free List Store will double every time the bitmapped allocator runs out of memory.

The macro `__GTHREADS` decides whether to use Mutex Protection around every allocation/deallocation. The state of the macro is picked up automatically from the gthr abstraction layer.

20.2 Implementation

20.2.1 Free List Store

The Free List Store (referred to as FLS for the remaining part of this document) is the Global memory pool that is shared by all instances of the bitmapped allocator instantiated for any type. This maintains a sorted order of all free memory blocks given back to it by the bitmapped allocator, and is also responsible for giving memory to the bitmapped allocator when it asks for more.

Internally, there is a Free List threshold which indicates the Maximum number of free lists that the FLS can hold internally (cache). Currently, this value is set at 64. So, if there are more than 64 free lists coming in, then some of them will be given back to the OS using operator delete so that at any given time the Free List's size does not exceed 64 entries. This is done because a Binary Search is used to locate an entry in a free list when a request for memory comes along. Thus, the run-time complexity of the search would go up given an increasing size, for 64 entries however, lg(64) == 6 comparisons are enough to locate the correct free list if it exists.

Suppose the free list size has reached its threshold, then the largest block from among those in the list and the new block will be selected and given back to the OS. This is done because it reduces external fragmentation, and allows the OS to use the larger blocks later in an orderly fashion, possibly merging them later. Also, on some systems, large blocks are obtained via calls to mmap, so giving them back to free system resources becomes most important.

The function _S_should_i_give decides the policy that determines whether the current block of memory should be given to the allocator for the request that it has made. That's because we may not always have exact fits for the memory size that the allocator requests. We do this mainly to prevent external fragmentation at the cost of a little internal fragmentation. Now, the value of this internal fragmentation has to be decided by this function. I can see 3 possibilities right now. Please add more as and when you find better strategies.

1. Equal size check. Return true only when the 2 blocks are of equal size.
2. Difference Threshold: Return true only when the _block_size is greater than or equal to the _required_size, and if the _BS is > _RS by a difference of less than some THRESHOLD value, then return true, else return false.
3. Percentage Threshold. Return true only when the _block_size is greater than or equal to the _required_size, and if the _BS is > _RS by a percentage of less than some THRESHOLD value, then return true, else return false.

Currently, (3) is being used with a value of 36% Maximum wastage per Super Block.

20.2.2 Super Block

A super block is the block of memory acquired from the FLS from which the bitmap allocator carves out memory for single objects and satisfies the user's requests. These super blocks come in sizes that are powers of 2 and multiples of 32 (_Bits_Per_Block). Yes both at the same time! That's because the next super block acquired will be 2 times the previous one, and also all super blocks have to be multiples of the _Bits_Per_Block value.

How does it interact with the free list store?

The super block is contained in the FLS, and the FLS is responsible for getting / returning Super Bocks to and from the OS using operator new as defined by the C++ standard.

20.2.3 Super Block Data Layout

Each Super Block will be of some size that is a multiple of the number of Bits Per Block. Typically, this value is chosen as Bits_Per_Byte x sizeof(size_t). On an x86 system, this gives the figure 8 x 4 = 32. Thus, each Super Block will be of size 32 x Some_Value. This Some_Value is sizeof(value_type). For now, let it be called 'K'. Thus, finally, Super Block size is 32 x K bytes.

This value of 32 has been chosen because each size_t has 32-bits and Maximum use of these can be made with such a figure.

Consider a block of size 64 ints. In memory, it would look like this: (assume a 32-bit system where, size_t is a 32-bit entity).

268	0	4294967295	4294967295	Data -> Space for 64 ints

Table 20.1: Bitmap Allocator Memory Map

The first Column(268) represents the size of the Block in bytes as seen by the Bitmap Allocator. Internally, a global free list is used to keep track of the free blocks used and given back by the bitmap allocator. It is this Free List Store that is responsible for writing and managing this information. Actually the number of bytes allocated in this case would be: 4 + 4 + (4x2) + (64x4) = 272 bytes, but the first 4 bytes are an addition by the Free List Store, so the Bitmap Allocator sees only 268 bytes. These first 4 bytes about which the bitmapped allocator is not aware hold the value 268.

What do the remaining values represent?

The 2nd 4 in the expression is the sizeof(size_t) because the Bitmapped Allocator maintains a used count for each Super Block, which is initially set to 0 (as indicated in the diagram). This is incremented every time a block is removed from this super block (allocated), and decremented whenever it is given back. So, when the used count falls to 0, the whole super block will be given back to the Free List Store.

The value 4294967295 represents the integer corresponding to the bit representation of all bits set: 1111111111111111111111111111111

The 3rd 4x2 is size of the bitmap itself, which is the size of 32-bits x 2, which is 8-bytes, or 2 x sizeof(size_t).

20.2.4 Maximum Wasted Percentage

This has nothing to do with the algorithm per-se, only with some vales that must be chosen correctly to ensure that the allocator performs well in a real word scenario, and maintains a good balance between the memory consumption and the allocation/deallocation speed.

The formula for calculating the maximum wastage as a percentage:

(32 x k + 1) / (2 x (32 x k + 1 + 32 x c)) x 100.

where k is the constant overhead per node (e.g., for list, it is 8 bytes, and for map it is 12 bytes) and c is the size of the base type on which the map/list is instantiated. Thus, suppose the type1 is int and type2 is double, they are related by the relation sizeof(double) == 2*sizeof(int). Thus, all types must have this double size relation for this formula to work properly.

Plugging-in: For List: k = 8 and c = 4 (int and double), we get: 33.376%

For map/multimap: k = 12, and c = 4 (int and double), we get: 37.524%

Thus, knowing these values, and based on the sizeof(value_type), we may create a function that returns the Max_Wastage_Percentage for us to use.

20.2.5 `allocate`

The allocate function is specialized for single object allocation ONLY. Thus, ONLY if n == 1, will the bitmap_allocator's specialized algorithm be used. Otherwise, the request is satisfied directly by calling operator new.

Suppose n == 1, then the allocator does the following:

1. Checks to see whether a free block exists somewhere in a region of memory close to the last satisfied request. If so, then that block is marked as allocated in the bit map and given to the user. If not, then (2) is executed.
2. Is there a free block anywhere after the current block right up to the end of the memory that we have? If so, that block is found, and the same procedure is applied as above, and returned to the user. If not, then (3) is executed.
3. Is there any block in whatever region of memory that we own free? This is done by checking
   - The use count for each super block, and if that fails then
   - The individual bit-maps for each super block.

   Note: Here we are never touching any of the memory that the user will be given, and we are confining all memory accesses to a small region of memory! This helps reduce cache misses. If this succeeds then we apply the same procedure on that bit-map as (1), and return that block of memory to the user. However, if this process fails, then we resort to (4).
4. This process involves Refilling the internal exponentially growing memory pool. The said effect is achieved by calling _S_refill_pool which does the following:
   - Gets more memory from the Global Free List of the Required size.
   - Adjusts the size for the next call to itself.
   - Writes the appropriate headers in the bit-maps.
   - Sets the use count for that super-block just allocated to 0 (zero).
   - All of the above accounts to maintaining the basic invariant for the allocator. If the invariant is maintained, we are sure that all is well. Now, the same process is applied on the newly acquired free blocks, which are dispatched accordingly.

Thus, you can clearly see that the allocate function is nothing but a combination of the next-fit and first-fit algorithm optimized ONLY for single object allocations.

20.2.6 `deallocate`

The deallocate function again is specialized for single objects ONLY. For all n belonging to > 1, the operator delete is called without further ado, and the deallocate function returns.

However for n == 1, a series of steps are performed:

1. We first need to locate that super-block which holds the memory location given to us by the user. For that purpose, we maintain a static variable _S_last_dealloc_index, which holds the index into the vector of block pairs which indicates the index of the last super-block from which memory was freed. We use this strategy in the hope that the user will deallocate memory in a region close to what he/she deallocated the last time around. If the check for belongs_to succeeds, then we determine the bit-map for the given pointer, and locate the index into that bit-map, and mark that bit as free by setting it.
2. If the _S_last_dealloc_index does not point to the memory block that we're looking for, then we do a linear search on the block stored in the vector of Block Pairs. This vector in code is called _S_mem_blocks. When the corresponding super-block is found, we apply the same procedure as we did for (1) to mark the block as free in the bit-map.

Now, whenever a block is freed, the use count of that particular super block goes down by 1. When this use count hits 0, we remove that super block from the list of all valid super blocks stored in the vector. While doing this, we also make sure that the basic invariant is maintained by making sure that _S_last_request and _S_last_dealloc_index point to valid locations within the vector.

20.2.7 Questions

20.2.7.1 1

Q1) The "Data Layout" section is cryptic. I have no idea of what you are trying to say. Layout of what? The free-list? Each bitmap? The Super Block?

The layout of a Super Block of a given size. In the example, a super block of size 32 x 1 is taken. The general formula for calculating the size of a super block is 32 x sizeof(value_type) x 2^n, where n ranges from 0 to 32 for 32-bit systems.

20.2.7.2 2

And since I just mentioned the term `each bitmap', what in the world is meant by it? What does each bitmap manage? How does it relate to the super block? Is the Super Block a bitmap as well?

Each bitmap is part of a Super Block which is made up of 3 parts as I have mentioned earlier. Re-iterating, 1. The use count, 2. The bit-map for that Super Block. 3. The actual memory that will be eventually given to the user. Each bitmap is a multiple of 32 in size. If there are 32 x (2^3) blocks of single objects to be given, there will be '32 x (2^3)' bits present. Each 32 bits managing the allocated / free status for 32 blocks. Since each size_t contains 32-bits, one size_t can manage up to 32 blocks' status. Each bit-map is made up of a number of size_t, whose exact number for a super-block of a given size I have just mentioned.

20.2.7.3 3

How do the allocate and deallocate functions work in regard to bitmaps?

The allocate and deallocate functions manipulate the bitmaps and have nothing to do with the memory that is given to the user. As I have earlier mentioned, a 1 in the bitmap's bit field indicates free, while a 0 indicates allocated. This lets us check 32 bits at a time to check whether there is at lease one free block in those 32 blocks by testing for equality with (0). Now, the allocate function will given a memory block find the corresponding bit in the bitmap, and will reset it (i.e., make it re-set (0)). And when the deallocate function is called, it will again set that bit after locating it to indicate that that particular block corresponding to this bit in the bit-map is not being used by anyone, and may be used to satisfy future requests.

e.g.: Consider a bit-map of 64-bits as represented below: 1111111111111111111111111111111111111111111111111111111111111111

Now, when the first request for allocation of a single object comes along, the first block in address order is returned. And since the bit-maps in the reverse order to that of the address order, the last bit (LSB if the bit-map is considered as a binary word of 64-bits) is re-set to 0.

The bit-map now looks like this: 1111111111111111111111111111111111111111111111111111111111111110

20.2.8 Locality

Another issue would be whether to keep the all bitmaps in a separate area in memory, or to keep them near the actual blocks that will be given out or allocated for the client. After some testing, I've decided to keep these bitmaps close to the actual blocks. This will help in 2 ways.

1. Constant time access for the bitmap themselves, since no kind of look up will be needed to find the correct bitmap list or its equivalent.
2. And also this would preserve the cache as far as possible.

So in effect, this kind of an allocator might prove beneficial from a purely cache point of view. But this allocator has been made to try and roll out the defects of the node_allocator, wherein the nodes get skewed about in memory, if they are not returned in the exact reverse order or in the same order in which they were allocated. Also, the new_allocator's book keeping overhead is too much for small objects and single object allocations, though it preserves the locality of blocks very well when they are returned back to the allocator.

20.2.9 Overhead and Grow Policy

Expected overhead per block would be 1 bit in memory. Also, once the address of the free list has been found, the cost for allocation/deallocation would be negligible, and is supposed to be constant time. For these very reasons, it is very important to minimize the linear time costs, which include finding a free list with a free block while allocating, and finding the corresponding free list for a block while deallocating. Therefore, I have decided that the growth of the internal pool for this allocator will be exponential as compared to linear for node_allocator. There, linear time works well, because we are mainly concerned with speed of allocation/deallocation and memory consumption, whereas here, the allocation/deallocation part does have some linear/logarithmic complexity components in it. Thus, to try and minimize them would be a good thing to do at the cost of a little bit of memory.

Another thing to be noted is the pool size will double every time the internal pool gets exhausted, and all the free blocks have been given away. The initial size of the pool would be sizeof(size_t) x 8 which is the number of bits in an integer, which can fit exactly in a CPU register. Hence, the term given is exponential growth of the internal pool.

Chapter 21

Policy-Based Data Structures

21.1 Intro

This is a library of policy-based elementary data structures: associative containers and priority queues. It is designed for high-performance, flexibility, semantic safety, and conformance to the corresponding containers in `std` and `std::tr1` (except for some points where it differs by design).

21.1.1 Performance Issues

An attempt is made to categorize the wide variety of possible container designs in terms of performance-impacting factors. These performance factors are translated into design policies and incorporated into container design.

There is tension between unravelling factors into a coherent set of policies. Every attempt is made to make a minimal set of factors. However, in many cases multiple factors make for long template names. Every attempt is made to alias and use typedefs in the source files, but the generated names for external symbols can be large for binary files or debuggers.

In many cases, the longer names allow capabilities and behaviours controlled by macros to also be unamibiguously emitted as distinct generated names.

Specific issues found while unraveling performance factors in the design of associative containers and priority queues follow.

21.1.1.1 Associative

Associative containers depend on their composite policies to a very large extent. Implicitly hard-wiring policies can hamper their performance and limit their functionality. An efficient hash-based container, for example, requires policies for testing key equivalence, hashing keys, translating hash values into positions within the hash table, and determining when and how to resize the table internally. A tree-based container can efficiently support order statistics, i.e. the ability to query what is the order of each key within the sequence of keys in the container, but only if the container is supplied with a policy to internally update meta-data. There are many other such examples.

Ideally, all associative containers would share the same interface. Unfortunately, underlying data structures and mapping semantics differentiate between different containers. For example, suppose one writes a generic function manipulating an associative container.

```
template<typename Cntnr>
void
some_op_sequence(Cntnr& r_cnt)
{
...
}
```

Given this, then what can one assume about the instantiating container? The answer varies according to its underlying data structure. If the underlying data structure of `Cntnr` is based on a tree or trie, then the order of elements is well defined; otherwise, it is not, in general. If the underlying data structure of `Cntnr` is based on a collision-chaining hash table, then modifying r_`Cntnr` will not invalidate its iterators' order; if the underlying data structure is a probing hash table, then this is not the case. If the underlying data structure is based on a tree or trie, then a reference to the container can efficiently be split; otherwise, it cannot, in general. If the underlying data structure is a red-black tree, then splitting a reference to the container is exception-free; if it is an ordered-vector tree, exceptions can be thrown.

21.1.1.2 Priority Que

Priority queues are useful when one needs to efficiently access a minimum (or maximum) value as the set of values changes.

Most useful data structures for priority queues have a relatively simple structure, as they are geared toward relatively simple requirements. Unfortunately, these structures do not support access to an arbitrary value, which turns out to be necessary in many algorithms. Say, decreasing an arbitrary value in a graph algorithm. Therefore, some extra mechanism is necessary and must be invented for accessing arbitrary values. There are at least two alternatives: embedding an associative container in a priority queue, or allowing cross-referencing through iterators. The first solution adds significant overhead; the second solution requires a precise definition of iterator invalidation. Which is the next point...

Priority queues, like hash-based containers, store values in an order that is meaningless and undefined externally. For example, a `push` operation can internally reorganize the values. Because of this characteristic, describing a priority queues' iterator is difficult: on one hand, the values to which iterators point can remain valid, but on the other, the logical order of iterators can change unpredictably.

Roughly speaking, any element that is both inserted to a priority queue (e.g. through `push`) and removed from it (e.g., through `pop`), incurs a logarithmic overhead (in the amortized sense). Different underlying data structures place the actual cost differently: some are optimized for amortized complexity, whereas others guarantee that specific operations only have a constant cost. One underlying data structure might be chosen if modifying a value is frequent (Dijkstra's shortest-path algorithm), whereas a different one might be chosen otherwise. Unfortunately, an array-based binary heap - an underlying data structure that optimizes (in the amortized sense) `push` and `pop` operations, differs from the others in terms of its invalidation guarantees. Other design decisions also impact the cost and placement of the overhead, at the expense of more difference in the kinds of operations that the underlying data structure can support. These differences pose a challenge when creating a uniform interface for priority queues.

21.1.2 Goals

Many fine associative-container libraries were already written, most notably, the C++ standard's associative containers. Why then write another library? This section shows some possible advantages of this library, when considering the challenges in the introduction. Many of these points stem from the fact that the ISO C++ process introduced associative-containers in a two-step process (first standardizing tree-based containers, only then adding hash-based containers, which are fundamentally different), did not standardize priority queues as containers, and (in our opinion) overloads the iterator concept.

21.1.2.1 Associative

21.1.2.1.1 Policy Choices

Associative containers require a relatively large number of policies to function efficiently in various settings. In some cases this is needed for making their common operations more efficient, and in other cases this allows them to support a larger set of operations

1. Hash-based containers, for example, support look-up and insertion methods (`find` and `insert`). In order to locate elements quickly, they are supplied a hash functor, which instruct how to transform a key object into some size type; a hash functor might transform `"hello"` into `1123002298`. A hash table, though, requires transforming each key object into some size-type type in some specific domain; a hash table with a 128-long table might transform `"hello"` into position `63`. The policy by which the hash value is transformed into a position within the table can dramatically affect performance. Hash-based containers also do not resize naturally (as opposed to tree-based containers, for example). The appropriate resize policy is unfortunately intertwined with the policy that transforms hash value into a position within the table.

2. Tree-based containers, for example, also support look-up and insertion methods, and are primarily useful when maintaining order between elements is important. In some cases, though, one can utilize their balancing algorithms for completely different purposes.

   Figure A shows a tree whose each node contains two entries: a floating-point key, and some size-type *metadata* (in bold beneath it) that is the number of nodes in the sub-tree. (The root has key 0.99, and has 5 nodes (including itself) in its sub-tree.) A container based on this data structure can obviously answer efficiently whether 0.3 is in the container object, but it can also answer what is the order of 0.3 among all those in the container object: see [66].

   As another example, Figure B shows a tree whose each node contains two entries: a half-open geometric line interval, and a number *metadata* (in bold beneath it) that is the largest endpoint of all intervals in its sub-tree. (The root describes the interval `[20, 36)`, and the largest endpoint in its sub-tree is 99.) A container based on this data structure can obviously answer efficiently whether `[3, 41)` is in the container object, but it can also answer efficiently whether the container object has intervals that intersect `[3, 41)`. These types of queries are very useful in geometric algorithms and lease-management algorithms.

   It is important to note, however, that as the trees are modified, their internal structure changes. To maintain these invariants, one must supply some policy that is aware of these changes. Without this, it would be better to use a linked list (in itself very efficient for these purposes).

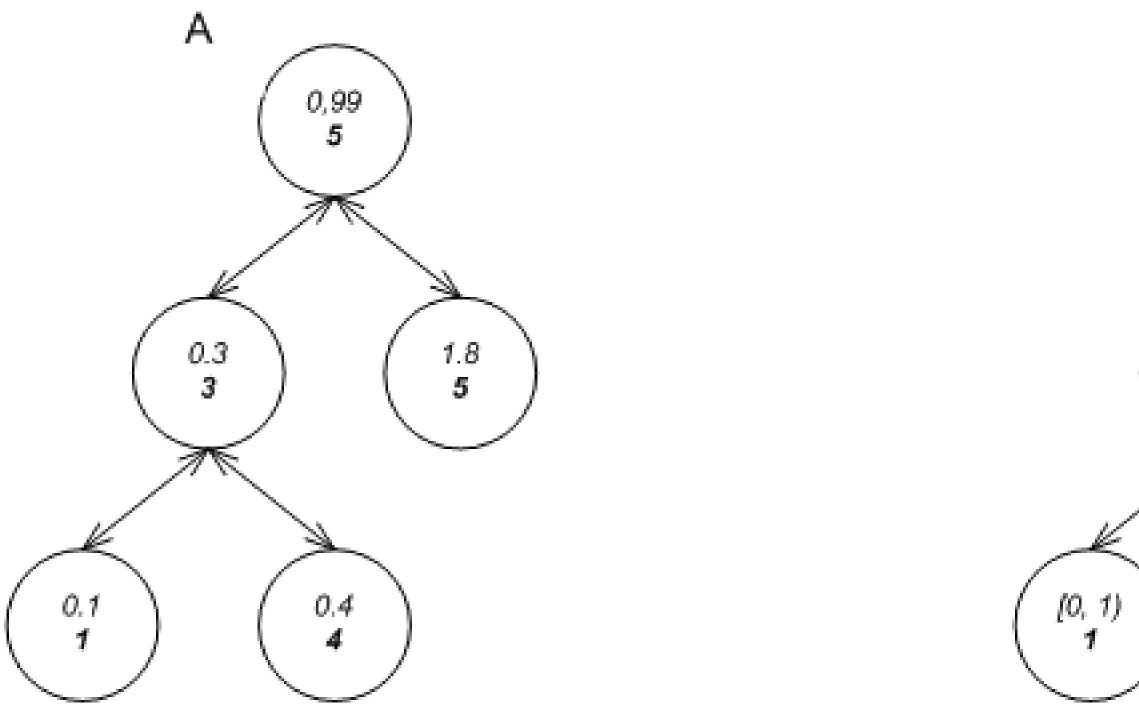


Figure 21.1: Node Invariants

21.1.2.1.2 Underlying Data Structures

The standard C++ library contains associative containers based on red-black trees and collision-chaining hash tables. These are very useful, but they are not ideal for all types of settings.

The figure below shows the different underlying data structures currently supported in this library.

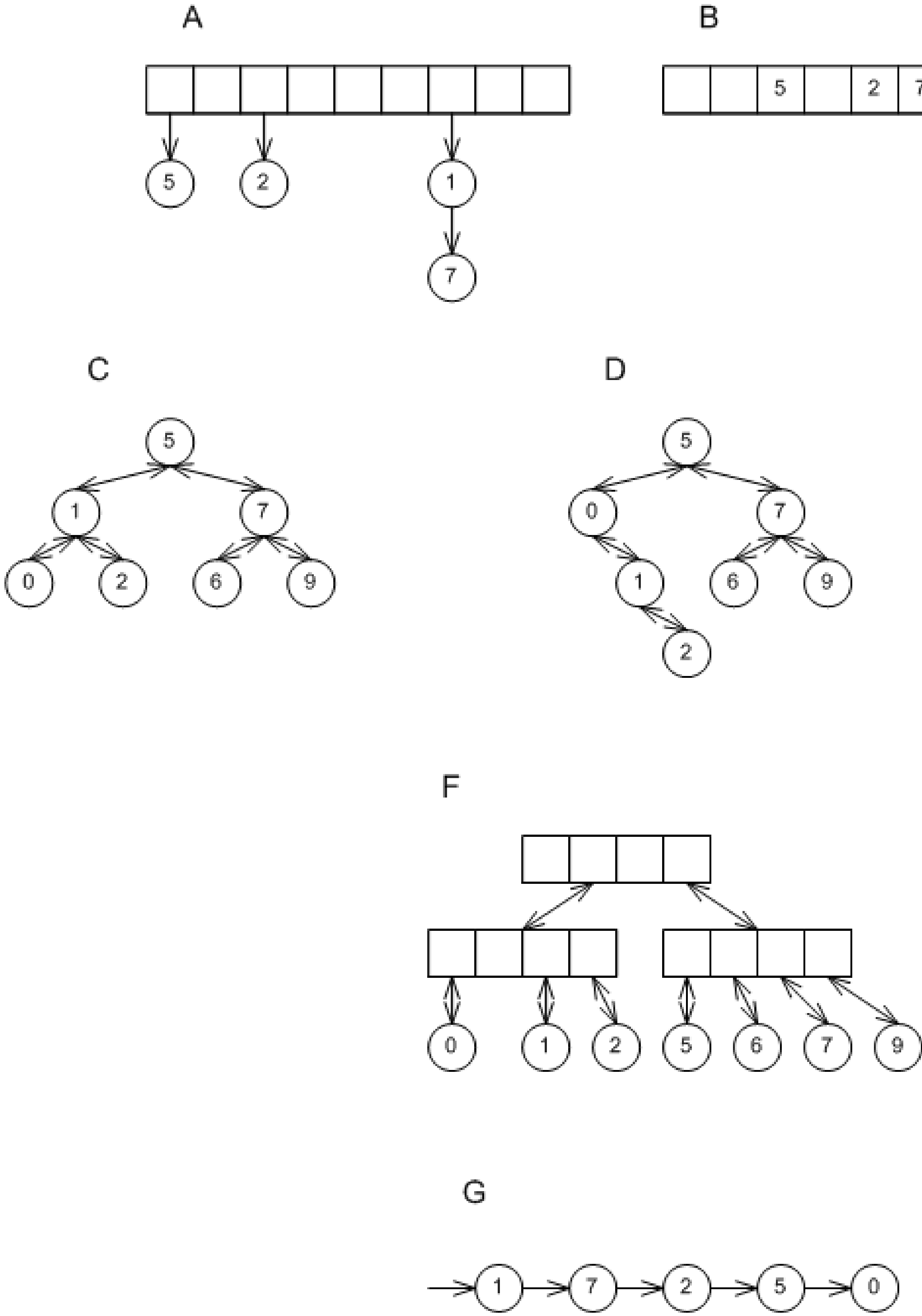


Figure 21.2: Underlying Associative Data Structures

A shows a collision-chaining hash-table, B shows a probing hash-table, C shows a red-black tree, D shows a splay tree, E shows a tree based on an ordered vector(implicit in the order of the elements), F shows a PATRICIA trie, and G shows a list-based container with update policies.

Each of these data structures has some performance benefits, in terms of speed, size or both. For now, note that vector-based trees and probing hash tables manipulate memory more efficiently than red-black trees and collision-chaining hash tables, and that list-based associative containers are very useful for constructing "multimaps".

Now consider a function manipulating a generic associative container,

```
template<class Cntnr>
int
some_op_sequence(Cntnr &r_cnt)
{
...
}
```

Ideally, the underlying data structure of `Cntnr` would not affect what can be done with `r_cnt`. Unfortunately, this is not the case.

For example, if `Cntnr` is `std::map`, then the function can use

```
std::for_each(r_cnt.find(foo), r_cnt.find(bar), foobar)
```

in order to apply `foobar` to all elements between `foo` and `bar`. If `Cntnr` is a hash-based container, then this call's results are undefined.

Also, if `Cntnr` is tree-based, the type and object of the comparison functor can be accessed. If `Cntnr` is hash based, these queries are nonsensical.

There are various other differences based on the container's underlying data structure. For one, they can be constructed by, and queried for, different policies. Furthermore:

1. Containers based on C, D, E and F store elements in a meaningful order; the others store elements in a meaningless (and probably time-varying) order. By implication, only containers based on C, D, E and F can support `erase` operations taking an iterator and returning an iterator to the following element without performance loss.

2. Containers based on C, D, E, and F can be split and joined efficiently, while the others cannot. Containers based on C and D, furthermore, can guarantee that this is exception-free; containers based on E cannot guarantee this.

3. Containers based on all but E can guarantee that erasing an element is exception free; containers based on E cannot guarantee this. Containers based on all but B and E can guarantee that modifying an object of their type does not invalidate iterators or references to their elements, while containers based on B and E cannot. Containers based on C, D, and E can furthermore make a stronger guarantee, namely that modifying an object of their type does not affect the order of iterators.

A unified tag and traits system (as used for the C++ standard library iterators, for example) can ease generic manipulation of associative containers based on different underlying data structures.

21.1.2.1.3 Iterators

Iterators are centric to the design of the standard library containers, because of the container/algorithm/iterator decomposition that allows an algorithm to operate on a range through iterators of some sequence. Iterators, then, are useful because they allow going over a specific *sequence*. The standard library also uses iterators for accessing a specific *element*: when an associative container returns one through `find`. The standard library consistently uses the same types of iterators for both purposes: going over a range, and accessing a specific found element. Before the introduction of hash-based containers to the standard library, this made sense (with the exception of priority queues, which are discussed later).

Using the standard associative containers together with non-order-preserving associative containers (and also because of priority-queues container), there is a possible need for different types of iterators for self-organizing containers: the iterator concept seems overloaded to mean two different things (in some cases).

21.1.2.1.3.1 Using Point Iterators for Range Operations

Suppose `cntnr` is some associative container, and say `c` is an object of type `cntnr`. Then what will be the outcome of

```
        std::for_each(c.find(1), c.find(5), foo);
```

If `cntnr` is a tree-based container object, then an in-order walk will apply `foo` to the relevant elements, as in the graphic below, label A. If `c` is a hash-based container, then the order of elements between any two elements is undefined (and probably time-varying); there is no guarantee that the elements traversed will coincide with the *logical* elements between 1 and 5, as in label B.

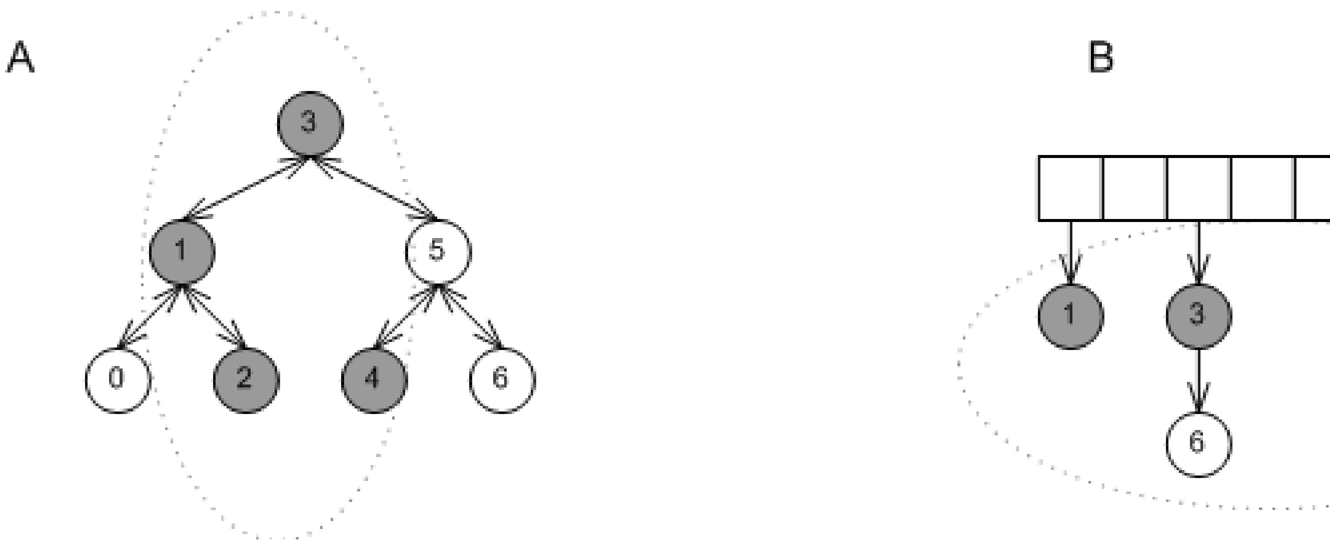


Figure 21.3: Range Iteration in Different Data Structures

In our opinion, this problem is not caused just because red-black trees are order preserving while collision-chaining hash tables are (generally) not - it is more fundamental. Most of the standard's containers order sequences in a well-defined manner that is determined by their *interface*: calling `insert` on a tree-based container modifies its sequence in a predictable way, as does calling `push_back` on a list or a vector. Conversely, collision-chaining hash tables, probing hash tables, priority queues, and list-based containers (which are very useful for "multimaps") are self-organizing data structures; the effect of each operation modifies their sequences in a manner that is (practically) determined by their *implementation*.

Consequently, applying an algorithm to a sequence obtained from most containers may or may not make sense, but applying it to a sub-sequence of a self-organizing container does not.

21.1.2.1.3.2 Cost to Point Iterators to Enable Range Operations

Suppose `c` is some collision-chaining hash-based container object, and one calls

```
c.find(3)
```

Then what composes the returned iterator?

In the graphic below, label A shows the simplest (and most efficient) implementation of a collision-chaining hash table. The little box marked `point_iterator` shows an object that contains a pointer to the element's node. Note that this "iterator" has no way to move to the next element (it cannot support `operator++`). Conversely, the little box marked `iterator` stores both a pointer to the element, as well as some other information (the bucket number of the element). the second iterator, then, is "heavier" than the first one- it requires more time and space. If we were to use a different container to cross-reference into this hash-table using these iterators - it would take much more space. As noted above, nothing much can be done by incrementing these iterators, so why is this extra information needed?

Alternatively, one might create a collision-chaining hash-table where the lists might be linked, forming a monolithic total-element list, as in the graphic below, label B. Here the iterators are as light as can be, but the hash-table's operations are more complicated.

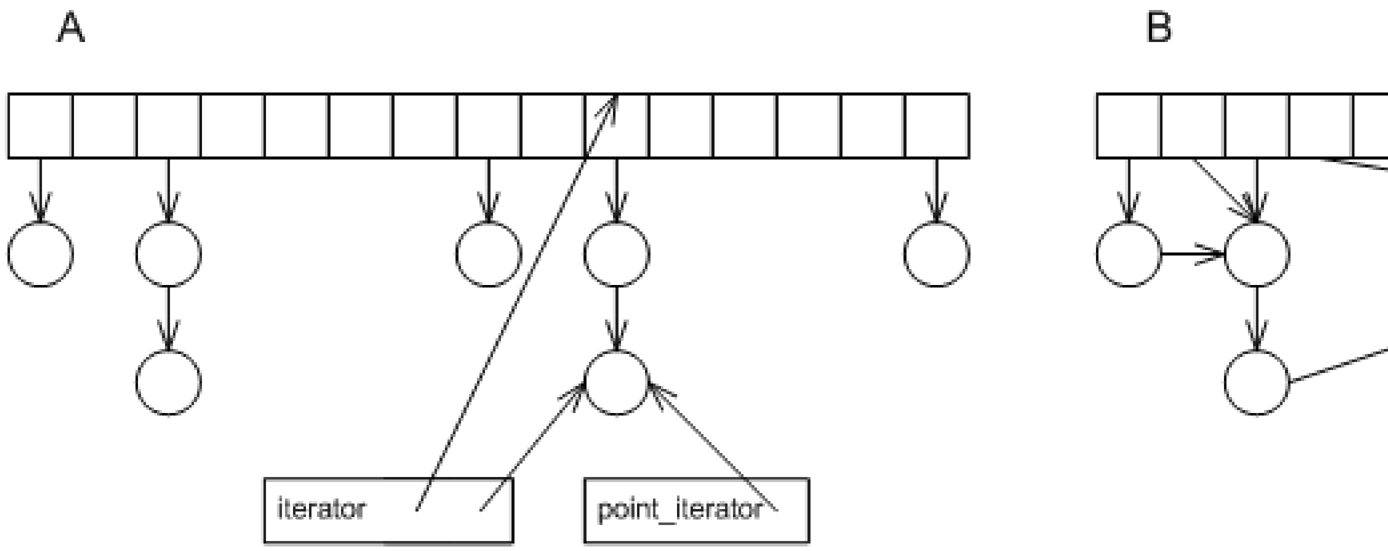


Figure 21.4: Point Iteration in Hash Data Structures

It should be noted that containers based on collision-chaining hash-tables are not the only ones with this type of behavior; many other self-organizing data structures display it as well.

21.1.2.1.3.3 Invalidation Guarantees

Consider the following snippet:

```
it = c.find(3);
c.erase(5);
```

Following the call to `erase`, what is the validity of `it`: can it be de-referenced? can it be incremented?

The answer depends on the underlying data structure of the container. The graphic below shows three cases: A1 and A2 show a red-black tree; B1 and B2 show a probing hash-table; C1 and C2 show a collision-chaining hash table.

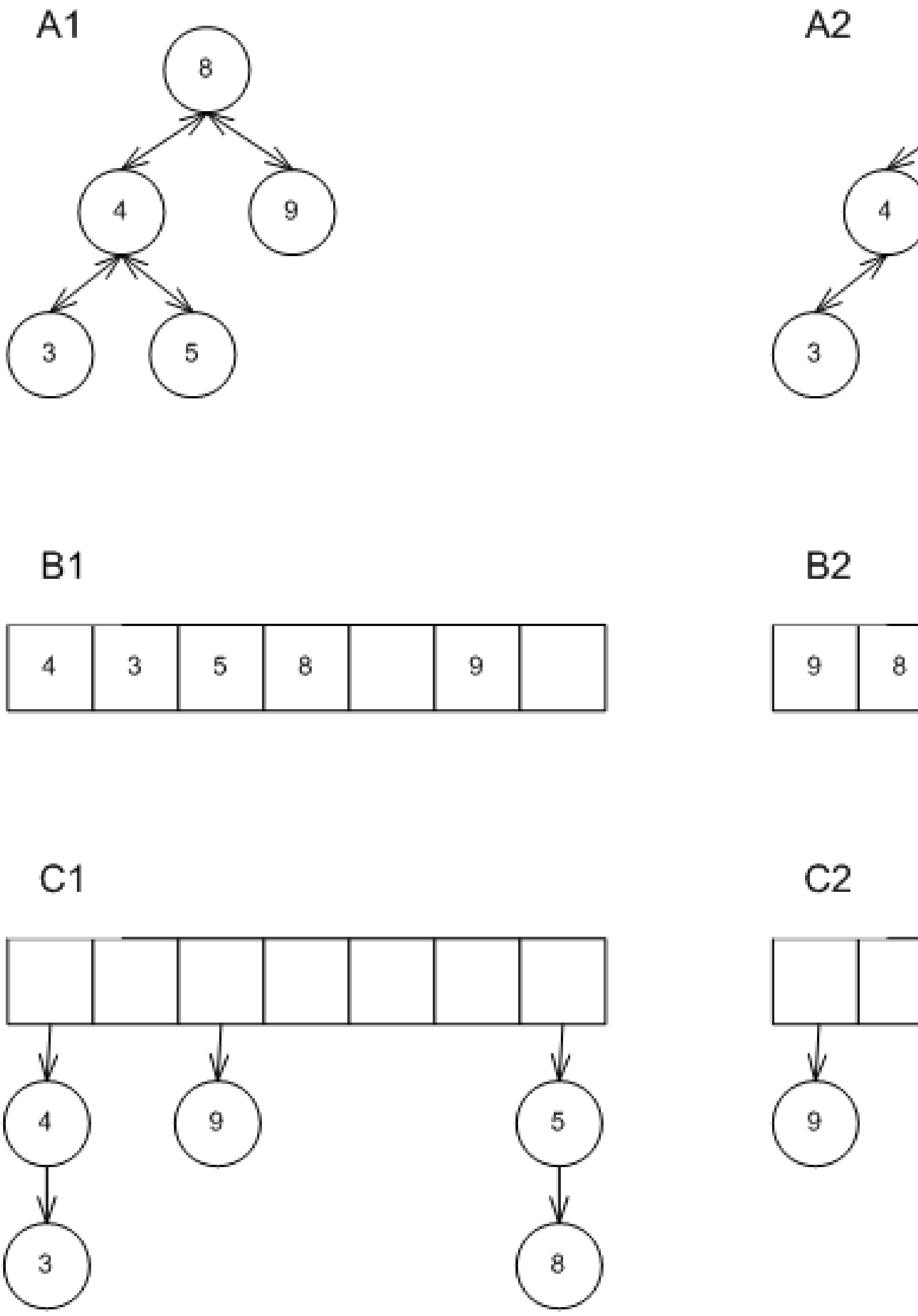


Figure 21.5: Effect of erase in different underlying data structures

1. Erasing 5 from A1 yields A2. Clearly, an iterator to 3 can be de-referenced and incremented. The sequence of iterators changed, but in a way that is well-defined by the interface.

2. Erasing 5 from B1 yields B2. Clearly, an iterator to 3 is not valid at all - it cannot be de-referenced or incremented; the order of iterators changed in a way that is (practically) determined by the implementation and not by the interface.

3. Erasing 5 from C1 yields C2. Here the situation is more complicated. On the one hand, there is no problem in de-referencing `it`. On the other hand, the order of iterators changed in a way that is (practically) determined by the implementation and not by the interface.

So in the standard library containers, it is not always possible to express whether `it` is valid or not. This is true also for `insert`. Again, the iterator concept seems overloaded.

21.1.2.1.4 Functional

The design of the functional overlay to the underlying data structures differs slightly from some of the conventions used in the C++ standard. A strict public interface of methods that comprise only operations which depend on the class's internal structure; other operations are best designed as external functions. (See [84]).With this rubric, the standard associative containers lack some useful methods, and provide other methods which would be better removed.

21.1.2.1.4.1 `erase`

1. Order-preserving standard associative containers provide the method

```
iterator
erase(iterator it)
```

which takes an iterator, erases the corresponding element, and returns an iterator to the following element. Also standardd hash-based associative containers provide this method. This seemingly increasesgenericity between associative containers, since it is possible to use

```
typename C::iterator it = c.begin();
typename C::iterator e_it = c.end();

while(it != e_it)
it = pred(*it)? c.erase(it) : ++it;
```

in order to erase from a container object `c` all element which match a predicate `pred`. However, in a different sense this actually decreases genericity: an integral implication of this method is that tree-based associative containers' memory use is linear in the total number of elements they store, while hash-based containers' memory use is unbounded in the total number of elements they store. Assume a hash-based container is allowed to decrease its size when an element is erased. Then the elements might be rehashed, which means that there is no "next" element - it is simply undefined. Consequently, it is possible to infer from the fact that the standard library's hash-based containers provide this method that they cannot downsize when elements are erased. As a consequence, different code is needed to manipulate different containers, assuming that memory should be conserved. Therefor, this library's non-order preserving associative containers omit this method.

2. All associative containers include a conditional-erase method

```
template<
class Pred>
size_type
erase_if
(Pred pred)
```

which erases all elements matching a predicate. This is probably the only way to ensure linear-time multiple-item erase which can actually downsize a container.

3. The standard associative containers provide methods for multiple-item erase of the form

```
size_type
erase(It b, It e)
```

erasing a range of elements given by a pair of iterators. For tree-based or trie-based containers, this can implemented more efficiently as a (small) sequence of split and join operations. For other, unordered, containers, this method isn't much better than an external loop. Moreover, if c is a hash-based container, then

```
c.erase(c.find(2), c.find(5))
```

is almost certain to do something different than erasing all elements whose keys are between 2 and 5, and is likely to produce other undefined behavior.

21.1.2.1.4.2 split and join

It is well-known that tree-based and trie-based container objects can be efficiently split or joined (See [66]). Externally splitting or joining trees is super-linear, and, furthermore, can throw exceptions. Split and join methods, consequently, seem good choices for tree-based container methods, especially, since as noted just before, they are efficient replacements for erasing sub-sequences.

21.1.2.1.4.3 insert

The standard associative containers provide methods of the form

```
template<class It>
size_type
insert(It b, It e);
```

for inserting a range of elements given by a pair of iterators. At best, this can be implemented as an external loop, or, even more efficiently, as a join operation (for the case of tree-based or trie-based containers). Moreover, these methods seem similar to constructors taking a range given by a pair of iterators; the constructors, however, are transactional, whereas the insert methods are not; this is possibly confusing.

21.1.2.1.4.4 operator== and operator<=

Associative containers are parametrized by policies allowing to test key equivalence: a hash-based container can do this through its equivalence functor, and a tree-based container can do this through its comparison functor. In addition, some standard associative containers have global function operators, like operator== and operator<=, that allow comparing entire associative containers.

In our opinion, these functions are better left out. To begin with, they do not significantly improve over an external loop. More importantly, however, they are possibly misleading - operator==, for example, usually checks for equivalence, or interchangeability, but the associative container cannot check for values' equivalence, only keys' equivalence; also, are two containers considered equivalent if they store the same values in different order? this is an arbitrary decision.

21.1.2.2 Priority Queues

21.1.2.2.1 Policy Choices

Priority queues are containers that allow efficiently inserting values and accessing the maximal value (in the sense of the container's comparison functor). Their interface supports push and pop. The standard container std::priorityqueue indeed support these methods, but little else. For algorithmic and software-engineering purposes, other methods are needed:

1. Many graph algorithms (see [66]) require increasing a value in a priority queue (again, in the sense of the container's comparison functor), or joining two priority-queue objects.

2. The return type of priority_queue's push method is a point-type iterator, which can be used for modifying or erasing arbitrary values. For example:

```
priority_queue<int> p;
priority_queue<int>::point_iterator it = p.push(3);
p.modify(it, 4);
```

These types of cross-referencing operations are necessary for making priority queues useful for different applications, especially graph applications.

3. It is sometimes necessary to erase an arbitrary value in a priority queue. For example, consider the `select` function for monitoring file descriptors:

```
int
select(int nfds, fd_set *readfds, fd_set *writefds, fd_set *errorfds,
struct timeval *timeout);
```

then, as the select documentation states:

“ The nfds argument specifies the range of file descriptors to be tested. The select() function tests file descriptors in the range of 0 to nfds-1.”

It stands to reason, therefore, that we might wish to maintain a minimal value for `nfds`, and priority queues immediately come to mind. Note, though, that when a socket is closed, the minimal file description might change; in the absence of an efficient means to erase an arbitrary value from a priority queue, we might as well avoid its use altogether.

The standard containers typically support iterators. It is somewhat unusual for `std::priority_queue` to omit them (See [83]). One might ask why do priority queues need to support iterators, since they are self-organizing containers with a different purpose than abstracting sequences. There are several reasons:

(a) Iterators (even in self-organizing containers) are useful for many purposes: cross-referencing containers, serialization, and debugging code that uses these containers.

(b) The standard library’s hash-based containers support iterators, even though they too are self-organizing containers with a different purpose than abstracting sequences.

(c) In standard-library-like containers, it is natural to specify the interface of operations for modifying a value or erasing a value (discussed previously) in terms of a iterators. It should be noted that the standard containers also use iterators for accessing and manipulating a specific value. In hash-based containers, one checks the existence of a key by comparing the iterator returned by `find` to the iterator returned by `end`, and not by comparing a pointer returned by `find` to NULL.

21.1.2.2.2 Underlying Data Structures

There are three main implementations of priority queues: the first employs a binary heap, typically one which uses a sequence; the second uses a tree (or forest of trees), which is typically less structured than an associative container’s tree; the third simply uses an associative container. These are shown in the figure below with labels A1 and A2, B, and C.

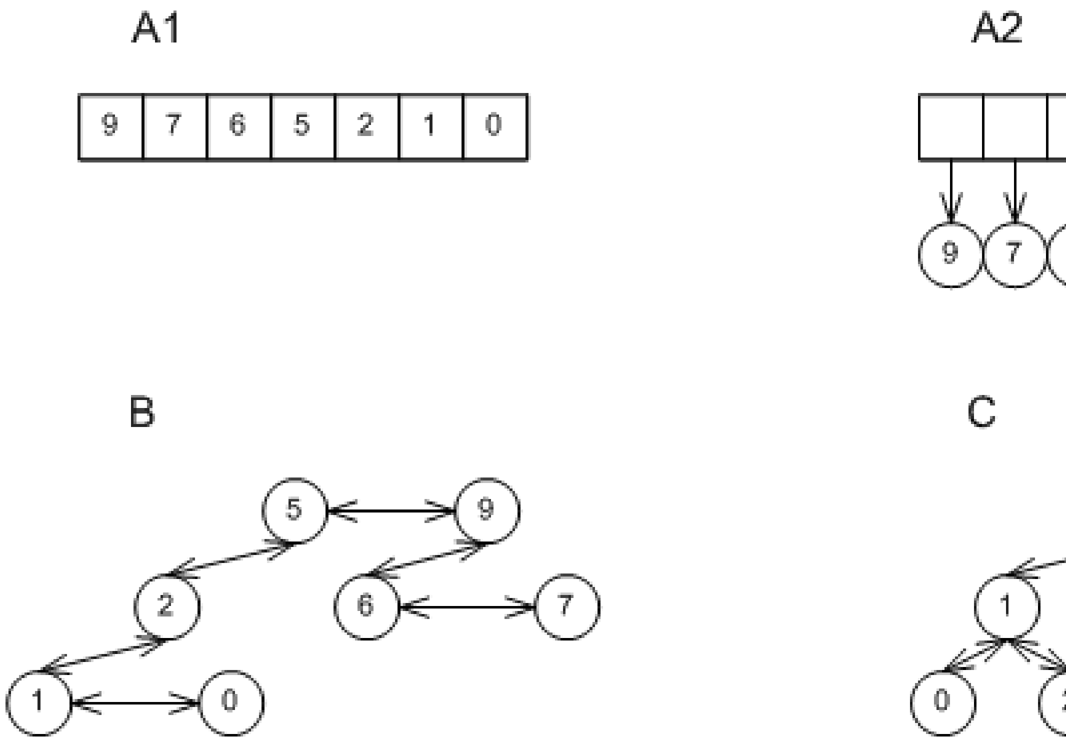


Figure 21.6: Underlying Priority Queue Data Structures

No single implementation can completely replace any of the others. Some have better `push` and `pop` amortized performance, some have better bounded (worst case) response time than others, some optimize a single method at the expense of others, etc. In general the "best" implementation is dictated by the specific problem.

As with associative containers, the more implementations co-exist, the more necessary a traits mechanism is for handling generic containers safely and efficiently. This is especially important for priority queues, since the invalidation guarantees of one of the most useful data structures - binary heaps - is markedly different than those of most of the others.

21.1.2.2.3 Binary Heaps

Binary heaps are one of the most useful underlying data structures for priority queues. They are very efficient in terms of memory (since they don't require per-value structure metadata), and have the best amortized `push` and `pop` performance for primitive types like int.

The standard library's `priority_queue` implements this data structure as an adapter over a sequence, typically `std::vector` or `std::deque`, which correspond to labels A1 and A2 respectively in the graphic above.

This is indeed an elegant example of the adapter concept and the algorithm/container/iterator decomposition. (See [89]). There are several reasons why a binary-heap priority queue may be better implemented as a container instead of a sequence adapter:

1. `std::priority_queue` cannot erase values from its adapted sequence (irrespective of the sequence type). This means that the memory use of an `std::priority_queue` object is always proportional to the maximal number of values it ever contained, and not to the number of values that it currently contains. (See `performance/priority_queue_text_pop_mem_usage.cc`.) This implementation of binary heaps acts very differently than other underlying data structures (See also pairing heaps).

2. Some combinations of adapted sequences and value types are very inefficient or just don't make sense. If one uses `std::priority_queue<std::vector<std::string> > >`, for example, then not only will each operation perform a logarithmic number of `std::string` assignments, but, furthermore, any operation (including `pop`) can render the container useless due to exceptions. Conversely, if one uses `std::priority_queue<std::deque<int> > >`, then each operation uses incurs a logarithmic number of indirect accesses (through pointers) unnecessarily. It might be better to let the container make a conservative deduction whether to use the structure in the graphic above, labels A1 or A2.

3. There does not seem to be a systematic way to determine what exactly can be done with the priority queue.

   (a) If `p` is a priority queue adapting an `std::vector`, then it is possible to iterate over all values by using `&p.top()` and `&p.top() + p.size()`, but this will not work if `p` is adapting an `std::deque`; in any case, one cannot use `p.begin()` and `p.end()`. If a different sequence is adapted, it is even more difficult to determine what can be done.

   (b) If `p` is a priority queue adapting an `std::deque`, then the reference return by

   ```
   p.top()
   ```

   will remain valid until it is popped, but if `p` adapts an `std::vector`, the next `push` will invalidate it. If a different sequence is adapted, it is even more difficult to determine what can be done.

4. Sequence-based binary heaps can still implement linear-time `erase` and `modify` operations. This means that if one needs to erase a small (say logarithmic) number of values, then one might still choose this underlying data structure. Using `std::priority_queue`, however, this will generally change the order of growth of the entire sequence of operations.

21.2 Using

21.2.1 Prerequisites

The library contains only header files, and does not require any other libraries except the standard C++ library . All classes are defined in namespace `__gnu_pbds`. The library internally uses macros beginning with `PB_DS`, but `#undef`s anything it `#define`s (except for header guards). Compiling the library in an environment where macros beginning in `PB_DS` are defined, may yield unpredictable results in compilation, execution, or both.

Further dependencies are necessary to create the visual output for the performance tests. To create these graphs, an additional package is needed: **pychart**.

21.2.2 Organization

The various data structures are organized as follows.

- Branch-Based
  - `basic_branch` is an abstract base class for branched-based associative-containers
  - `tree` is a concrete base class for tree-based associative-containers
  - `trie` is a concrete base class trie-based associative-containers
- Hash-Based
  - `basic_hash_table` is an abstract base class for hash-based associative-containers
  - `cc_hash_table` is a concrete collision-chaining hash-based associative-containers
  - `gp_hash_table` is a concrete (general) probing hash-based associative-containers
- List-Based

- list_update list-based update-policy associative container

- Heap-Based
  - priority_queue A priority queue.

The hierarchy is composed naturally so that commonality is captured by base classes. Thus operator[] is defined at the base of any hierarchy, since all derived containers support it. Conversely split is defined in basic_branch, since only tree-like containers support it.

In addition, there are the following diagnostics classes, used to report errors specific to this library's data structures.

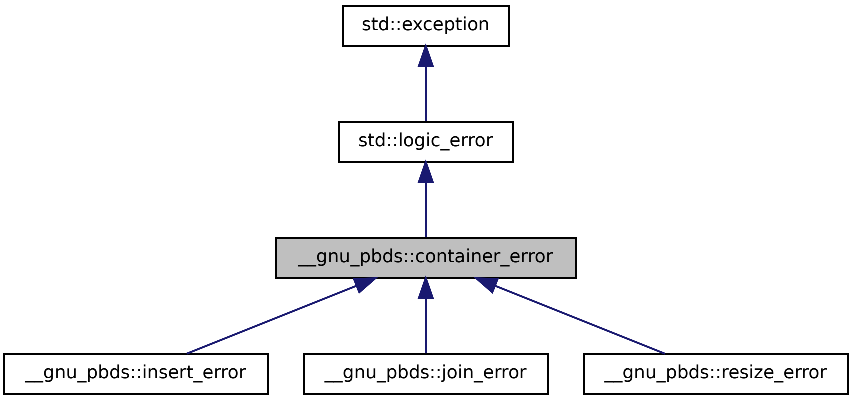


Figure 21.7: Exception Hierarchy

21.2.3 Tutorial

21.2.3.1 Basic Use

For the most part, the policy-based containers containers in namespace __gnu_pbds have the same interface as the equivalent containers in the standard C++ library, except for the names used for the container classes themselves. For example, this shows basic operations on a collision-chaining hash-based container:

```
#include <ext/pb_ds/assoc_container.h>

int main()
{
__gnu_pbds::cc_hash_table<int, char> c;
c[2] = 'b';
assert(c.find(1) == c.end());
};
```

The container is called __gnu_pbds::cc_hash_table instead of std::unordered_map, since “unordered map” does not necessarily mean a hash-based map as implied by the C++ library (C++11 or TR1). For example, list-based associative containers, which are very useful for the construction of "multimaps," are also unordered.

This snippet shows a red-black tree based container:

```
#include <ext/pb_ds/assoc_container.h>

int main()
{
__gnu_pbds::tree<int, char> c;
c[2] = 'b';
assert(c.find(2) != c.end());
};
```

The container is called `tree` instead of `map` since the underlying data structures are being named with specificity.

The member function naming convention is to strive to be the same as the equivalent member functions in other C++ standard library containers. The familiar methods are unchanged: `begin`, `end`, `size`, `empty`, and `clear`.

This isn't to say that things are exactly as one would expect, given the container requirments and interfaces in the C++ standard.

The names of containers' policies and policy accessors are different then the usual. For example, if hash_type is some type of hash-based container, then

```
hash_type::hash_fn
```

gives the type of its hash functor, and if `obj` is some hash-based container object, then

```
obj.get_hash_fn()
```

will return a reference to its hash-functor object.

Similarly, if tree_type is some type of tree-based container, then

```
tree_type::cmp_fn
```

gives the type of its comparison functor, and if `obj` is some tree-based container object, then

```
obj.get_cmp_fn()
```

will return a reference to its comparison-functor object.

It would be nice to give names consistent with those in the existing C++ standard (inclusive of TR1). Unfortunately, these standard containers don't consistently name types and methods. For example, `std::tr1::unordered_map` uses hasher for the hash functor, but `std::map` uses key_compare for the comparison functor. Also, we could not find an accessor for `std::tr1::unordered_map`'s hash functor, but `std::map` uses `compare` for accessing the comparison functor.

Instead, `__gnu_pbds` attempts to be internally consistent, and uses standard-derived terminology if possible.

Another source of difference is in scope: `__gnu_pbds` contains more types of associative containers than the standard C++ library, and more opportunities to configure these new containers, since different types of associative containers are useful in different settings.

Namespace `__gnu_pbds` contains different classes for hash-based containers, tree-based containers, trie-based containers, and list-based containers.

Since associative containers share parts of their interface, they are organized as a class hierarchy.

Each type or method is defined in the most-common ancestor in which it makes sense.

For example, all associative containers support iteration expressed in the following form:

```
const_iterator
begin() const;

iterator
begin();

const_iterator
end() const;

iterator
end();
```

But not all containers contain or use hash functors. Yet, both collision-chaining and (general) probing hash-based associative containers have a hash functor, so `basic_hash_table` contains the interface:

```
const hash_fn&
get_hash_fn() const;

hash_fn&
get_hash_fn();
```

so all hash-based associative containers inherit the same hash-functor accessor methods.

21.2.3.2 Configuring via Template Parameters

In general, each of this library's containers is parametrized by more policies than those of the standard library. For example, the standard hash-based container is parametrized as follows:

```
template<typename Key, typename Mapped, typename Hash,
typename Pred, typename Allocator, bool Cache_Hashe_Code>
class unordered_map;
```

and so can be configured by key type, mapped type, a functor that translates keys to unsigned integral types, an equivalence predicate, an allocator, and an indicator whether to store hash values with each entry. this library's collision-chaining hash-based container is parametrized as

```
template<typename Key, typename Mapped, typename Hash_Fn,
typename Eq_Fn, typename Comb_Hash_Fn,
typename Resize_Policy, bool Store_Hash
typename Allocator>
class cc_hash_table;
```

and so can be configured by the first four types of `std::tr1::unordered_map`, then a policy for translating the key-hash result into a position within the table, then a policy by which the table resizes, an indicator whether to store hash values with each entry, and an allocator (which is typically the last template parameter in standard containers).

Nearly all policy parameters have default values, so this need not be considered for casual use. It is important to note, however, that hash-based containers' policies can dramatically alter their performance in different settings, and that tree-based containers' policies can make them useful for other purposes than just look-up.

As opposed to associative containers, priority queues have relatively few configuration options. The priority queue is parametrized as follows:

```
template<typename Value_Type, typename Cmp_Fn,typename Tag,
typename Allocator>
class priority_queue;
```

The `Value_Type`, `Cmp_Fn`, and `Allocator` parameters are the container's value type, comparison-functor type, and allocator type, respectively; these are very similar to the standard's priority queue. The `Tag` parameter is different: there are a number of pre-defined tag types corresponding to binary heaps, binomial heaps, etc., and `Tag` should be instantiated by one of them.

Note that as opposed to the `std::priority_queue`, `__gnu_pbds::priority_queue` is not a sequence-adapter; it is a regular container.

21.2.3.3 Querying Container Attributes

A containers underlying data structure affect their performance; Unfortunately, they can also affect their interface. When manipulating generically associative containers, it is often useful to be able to statically determine what they can support and what the cannot.

Happily, the standard provides a good solution to a similar problem - that of the different behavior of iterators. If `It` is an iterator, then

```
typename std::iterator_traits<It>::iterator_category
```

is one of a small number of pre-defined tag classes, and

```
typename std::iterator_traits<It>::value_type
```

is the value type to which the iterator "points".

Similarly, in this library, if C is a container, then `container_traits` is a trait class that stores information about the kind of container that is implemented.

```
typename container_traits<C>::container_category
```

is one of a small number of predefined tag structures that uniquely identifies the type of underlying data structure.

In most cases, however, the exact underlying data structure is not really important, but what is important is one of its other attributes: whether it guarantees storing elements by key order, for example. For this one can use

```
typename container_traits<C>::order_preserving
```

Also,

```
typename container_traits<C>::invalidation_guarantee
```

is the container's invalidation guarantee. Invalidation guarantees are especially important regarding priority queues, since in this library's design, iterators are practically the only way to manipulate them.

21.2.3.4 Point and Range Iteration

This library differentiates between two types of methods and iterators: point-type, and range-type. For example, `find` and `insert` are point-type methods, since they each deal with a specific element; their returned iterators are point-type iterators. `begin` and `end` are range-type methods, since they are not used to find a specific element, but rather to go over all elements in a container object; their returned iterators are range-type iterators.

Most containers store elements in an order that is determined by their interface. Correspondingly, it is fine that their point-type iterators are synonymous with their range-type iterators. For example, in the following snippet

```
std::for_each(c.find(1), c.find(5), foo);
```

two point-type iterators (returned by `find`) are used for a range-type purpose - going over all elements whose key is between 1 and 5.

Conversely, the above snippet makes no sense for self-organizing containers - ones that order (and reorder) their elements by implementation. It would be nice to have a uniform iterator system that would allow the above snippet to compile only if it made sense.

This could trivially be done by specializing `std::for_each` for the case of iterators returned by `std::tr1::unordered_map`, but this would only solve the problem for one algorithm and one container. Fundamentally, the problem is that one can loop using a self-organizing container's point-type iterators.

This library's containers define two families of iterators: point_const_iterator and point_iterator are the iterator types returned by point-type methods; const_iterator and iterator are the iterator types returned by range-type methods.

```
class <- some container ->
{
public:
...

typedef <- something -> const_iterator;

typedef <- something -> iterator;

typedef <- something -> point_const_iterator;

typedef <- something -> point_iterator;

...

public:
...

const_iterator begin () const;

iterator begin();
```

```
point_const_iterator find(...) const;

point_iterator find(...);
};
```

For containers whose interface defines sequence order , it is very simple: point-type and range-type iterators are exactly the same, which means that the above snippet will compile if it is used for an order-preserving associative container.

For self-organizing containers, however, (hash-based containers as a special example), the preceding snippet will not compile, because their point-type iterators do not support `operator++`.

In any case, both for order-preserving and self-organizing containers, the following snippet will compile:

```
typename Cntnr::point_iterator it = c.find(2);
```

because a range-type iterator can always be converted to a point-type iterator.

Distingushing between iterator types also raises the point that a container's iterators might have different invalidation rules concerning their de-referencing abilities and movement abilities. This now corresponds exactly to the question of whether point-type and range-type iterators are valid. As explained above, `container_traits` allows querying a container for its data structure attributes. The iterator-invalidation guarantees are certainly a property of the underlying data structure, and so

```
container_traits<C>::invalidation_guarantee
```

gives one of three pre-determined types that answer this query.

21.2.4 Examples

Additional code examples are provided in the source distribution, as part of the regression and performance testsuite.

21.2.4.1 Intermediate Use

- Basic use of maps: `basic_map.cc`
- Basic use of sets: `basic_set.cc`
- Conditionally erasing values from an associative container object: `erase_if.cc`
- Basic use of multimaps: `basic_multimap.cc`
- Basic use of multisets: `basic_multiset.cc`
- Basic use of priority queues: `basic_priority_queue.cc`
- Splitting and joining priority queues: `priority_queue_split_join.cc`
- Conditionally erasing values from a priority queue: `priority_queue_erase_if.cc`

21.2.4.2 Querying with `container_traits`

- Using `container_traits` to query about underlying data structure behavior: `assoc_container_traits.cc`
- A non-compiling example showing wrong use of finding keys in hash-based containers: `hash_find_neg.cc`
- Using `container_traits` to query about underlying data structure behavior: `priority_queue_container_traits.cc`

21.2.4.3 By Container Method

21.2.4.3.1 Hash-Based

21.2.4.3.1.1 size Related

- Setting the initial size of a hash-based container object: `hash_initial_size.cc`
- A non-compiling example showing how not to resize a hash-based container object: `hash_resize_neg.cc`
- Resizing the size of a hash-based container object: `hash_resize.cc`
- Showing an illegal resize of a hash-based container object: `hash_illegal_resize.cc`
- Changing the load factors of a hash-based container object: `hash_load_set_change.cc`

21.2.4.3.1.2 Hashing Function Related

- Using a modulo range-hashing function for the case of an unknown skewed key distribution: `hash_mod.cc`
- Writing a range-hashing functor for the case of a known skewed key distribution: `shift_mask.cc`
- Storing the hash value along with each key: `store_hash.cc`
- Writing a ranged-hash functor: `ranged_hash.cc`

21.2.4.3.2 Branch-Based

21.2.4.3.2.1 split or join Related

- Joining two tree-based container objects: `tree_join.cc`
- Splitting a PATRICIA trie container object: `trie_split.cc`
- Order statistics while joining two tree-based container objects: `tree_order_statistics_join.cc`

21.2.4.3.2.2 Node Invariants

- Using trees for order statistics: `tree_order_statistics.cc`
- Augmenting trees to support operations on line intervals: `tree_intervals.cc`

21.2.4.3.2.3 trie

- Using a PATRICIA trie for DNA strings: `trie_dna.cc`
- Using a PATRICIA trie for finding all entries whose key matches a given prefix: `trie_prefix_search.cc`

21.2.4.3.3 Priority Queues

- Cross referencing an associative container and a priority queue: `priority_queue_xref.cc`
- Cross referencing a vector and a priority queue using a very simple version of Dijkstra's shortest path algorithm: `priority_queue_dijkstra.cc`

21.3 Design

21.3.1 Concepts

21.3.1.1 Null Policy Classes

Associative containers are typically parametrized by various policies. For example, a hash-based associative container is parametrized by a hash-functor, transforming each key into an non-negative numerical type. Each such value is then further mapped into a position within the table. The mapping of a key into a position within the table is therefore a two-step process.

In some cases, instantiations are redundant. For example, when the keys are integers, it is possible to use a redundant hash policy, which transforms each key into its value.

In some other cases, these policies are irrelevant. For example, a hash-based associative container might transform keys into positions within a table by a different method than the two-step method described above. In such a case, the hash functor is simply irrelevant.

When a policy is either redundant or irrelevant, it can be replaced by `null_type`.

For example, a *set* is an associative container with one of its template parameters (the one for the mapped type) replaced with `null_type`. Other places simplifications are made possible with this technique include node updates in tree and trie data structures, and hash and probe functions for hash data structures.

21.3.1.2 Map and Set Semantics

21.3.1.2.1 Distinguishing Between Maps and Sets

Anyone familiar with the standard knows that there are four kinds of associative containers: maps, sets, multimaps, and multisets. The map datatype associates each key to some data.

Sets are associative containers that simply store keys - they do not map them to anything. In the standard, each map class has a corresponding set class. E.g., `std::map<int, char>` maps each `int` to a `char`, but `std::set<int, char>` simply stores `ints`. In this library, however, there are no distinct classes for maps and sets. Instead, an associative container's `Mapped` template parameter is a policy: if it is instantiated by `null_type`, then it is a "set"; otherwise, it is a "map". E.g.,

```
cc_hash_table<int, char>
```

is a "map" mapping each int value to a char, but

```
cc_hash_table<int, null_type>
```

is a type that uniquely stores int values.

Once the `Mapped` template parameter is instantiated by `null_type`, then the "set" acts very similarly to the standard's sets - it does not map each key to a distinct `null_type` object. Also, , the container's value_type is essentially its key_type - just as with the standard's sets .

The standard's multimaps and multisets allow, respectively, non-uniquely mapping keys and non-uniquely storing keys. As discussed, the reasons why this might be necessary are 1) that a key might be decomposed into a primary key and a secondary key, 2) that a key might appear more than once, or 3) any arbitrary combination of 1)s and 2)s. Correspondingly, one should use 1) "maps" mapping primary keys to secondary keys, 2) "maps" mapping keys to size types, or 3) any arbitrary combination of 1)s and 2)s. Thus, for example, an `std::multiset<int>` might be used to store multiple instances of integers, but using this library's containers, one might use

```
tree<int, size_t>
```

i.e., a `map` of ints to size_ts.

These "multimaps" and "multisets" might be confusing to anyone familiar with the standard's `std::multimap` and `std::multiset` because there is no clear correspondence between the two. For example, in some cases where one uses `std::multiset` in the standard, one might use in this library a "multimap" of "multisets" - i.e., a container that maps primary keys each to an associative container that maps each secondary key to the number of times it occurs.

When one uses a "multimap," one should choose with care the type of container used for secondary keys.

21.3.1.2.2 Alternatives to `std::multiset` and `std::multimap`

Brace onself: this library does not contain containers like `std::multimap` or `std::multiset`. Instead, these data structures can be synthesized via manipulation of the `Mapped` template parameter.

One maps the unique part of a key - the primary key, into an associative-container of the (originally) non-unique parts of the key - the secondary key. A primary associative-container is an associative container of primary keys; a secondary associative-container is an associative container of secondary keys.

Stepping back a bit, and starting in from the beginning.

Maps (or sets) allow mapping (or storing) unique-key values. The standard library also supplies associative containers which map (or store) multiple values with equivalent keys: `std::multimap`, `std::multiset`, `std::tr1::unordered_multimap`, and `unordered_multiset`. We first discuss how these might be used, then why we think it is best to avoid them.

Suppose one builds a simple bank-account application that records for each client (identified by an `std::string`) and account-id (marked by an unsigned long) - the balance in the account (described by a float). Suppose further that ordering this information is not useful, so a hash-based container is preferable to a tree based container. Then one can use

```
std::tr1::unordered_map<std::pair<std::string, unsigned long>, float, ...>
```

which hashes every combination of client and account-id. This might work well, except for the fact that it is now impossible to efficiently list all of the accounts of a specific client (this would practically require iterating over all entries). Instead, one can use

```
std::tr1::unordered_multimap<std::pair<std::string, unsigned long>, float, ...>
```

which hashes every client, and decides equivalence based on client only. This will ensure that all accounts belonging to a specific user are stored consecutively.

Also, suppose one wants an integers' priority queue (a container that supports `push`, `pop`, and `top` operations, the last of which returns the largest int) that also supports operations such as `find` and `lower_bound`. A reasonable solution is to build an adapter over `std::set<int>`. In this adapter, `push` will just call the tree-based associative container's `insert` method; `pop` will call its `end` method, and use it to return the preceding element (which must be the largest). Then this might work well, except that the container object cannot hold multiple instances of the same integer (`push(4)`, will be a no-op if `4` is already in the container object). If multiple keys are necessary, then one might build the adapter over an `std::multiset<int>`.

The standard library's non-unique-mapping containers are useful when (1) a key can be decomposed in to a primary key and a secondary key, (2) a key is needed multiple times, or (3) any combination of (1) and (2).

The graphic below shows how the standard library's container design works internally; in this figure nodes shaded equally represent equivalent-key values. Equivalent keys are stored consecutively using the properties of the underlying data structure: binary search trees (label A) store equivalent-key values consecutively (in the sense of an in-order walk) naturally; collision-chaining hash tables (label B) store equivalent-key values in the same bucket, the bucket can be arranged so that equivalent-key values are consecutive.

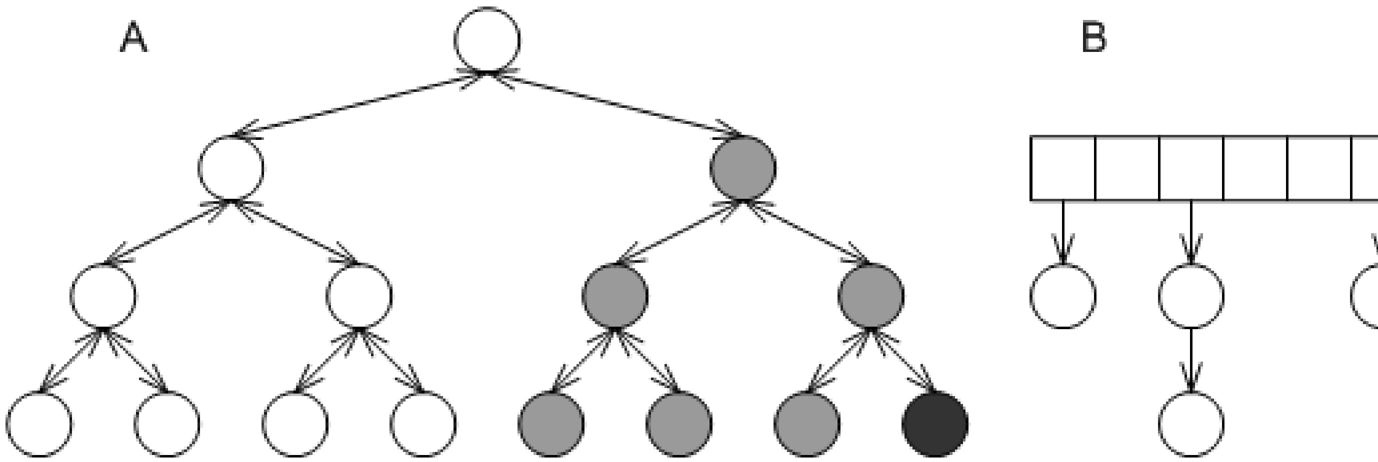


Figure 21.8: Non-unique Mapping Standard Containers

Put differently, the standards' non-unique mapping associative-containers are associative containers that map primary keys to linked lists that are embedded into the container. The graphic below shows again the two containers from the first graphic above, this time with the embedded linked lists of the grayed nodes marked explicitly.

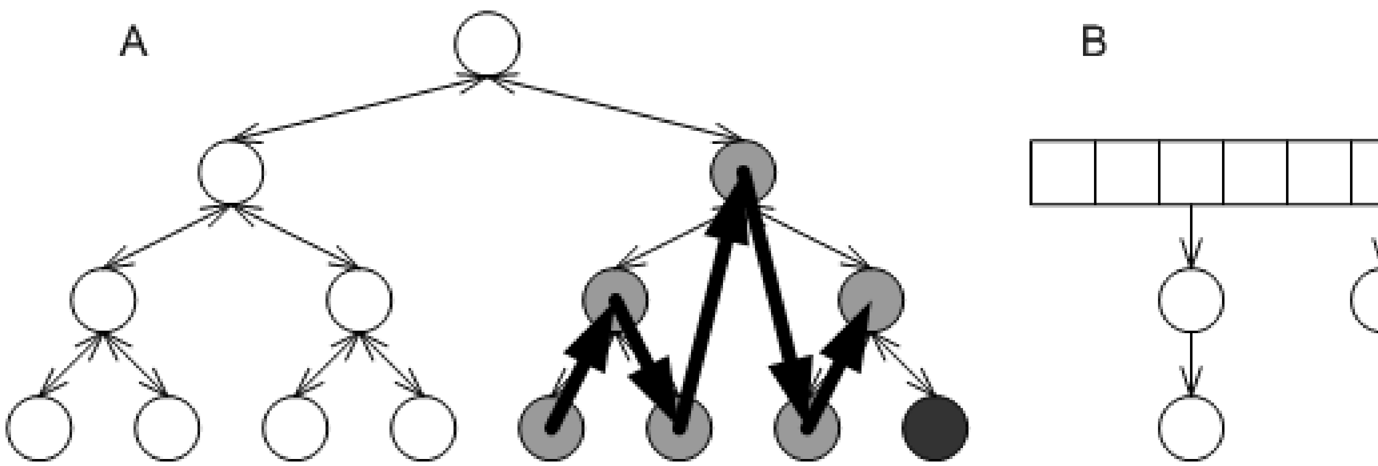


Figure 21.9: Effect of embedded lists in `std::multimap`

These embedded linked lists have several disadvantages.

1. The underlying data structure embeds the linked lists according to its own consideration, which means that the search path for a value might include several different equivalent-key values. For example, the search path for the the black node in either of the first graphic, labels A or B, includes more than a single gray node.
2. The links of the linked lists are the underlying data structures' nodes, which typically are quite structured. In the case of tree-based containers (the grapic above, label B), each "link" is actually a node with three pointers (one to a parent and two to children), and a relatively-complicated iteration algorithm. The linked lists, therefore, can take up quite a lot of memory, and iterating over all values equal to a given key (through the return value of the standard library's `equal_range`) can be expensive.
3. The primary key is stored multiply; this uses more memory.
4. Finally, the interface of this design excludes several useful underlying data structures. Of all the unordered self-organizing data structures, practically only collision-chaining hash tables can (efficiently) guarantee that equivalent-key values are stored consecutively.

The above reasons hold even when the ratio of secondary keys to primary keys (or average number of identical keys) is small, but when it is large, there are more severe problems:

1. The underlying data structures order the links inside each embedded linked-lists according to their internal considerations, which effectively means that each of the links is unordered. Irrespective of the underlying data structure, searching for a specific value can degrade to linear complexity.
2. Similarly to the above point, it is impossible to apply to the secondary keys considerations that apply to primary keys. For example, it is not possible to maintain secondary keys by sorted order.
3. While the interface "understands" that all equivalent-key values constitute a distinct list (through `equal_range`), the underlying data structure typically does not. This means that operations such as erasing from a tree-based container all values whose keys are equivalent to a a given key can be super-linear in the size of the tree; this is also true also for several other operations that target a specific list.

In this library, all associative containers map (or store) unique-key values. One can (1) map primary keys to secondary associative-containers (containers of secondary keys) or non-associative containers (2) map identical keys to a size-type representing the number of times they occur, or (3) any combination of (1) and (2). Instead of allowing multiple equivalent-key values, this library supplies associative containers based on underlying data structures that are suitable as secondary associative-containers.

In the figure below, labels A and B show the equivalent underlying data structures in this library, as mapped to the first graphic above. Labels A and B, respectively. Each shaded box represents some size-type or secondary associative-container.

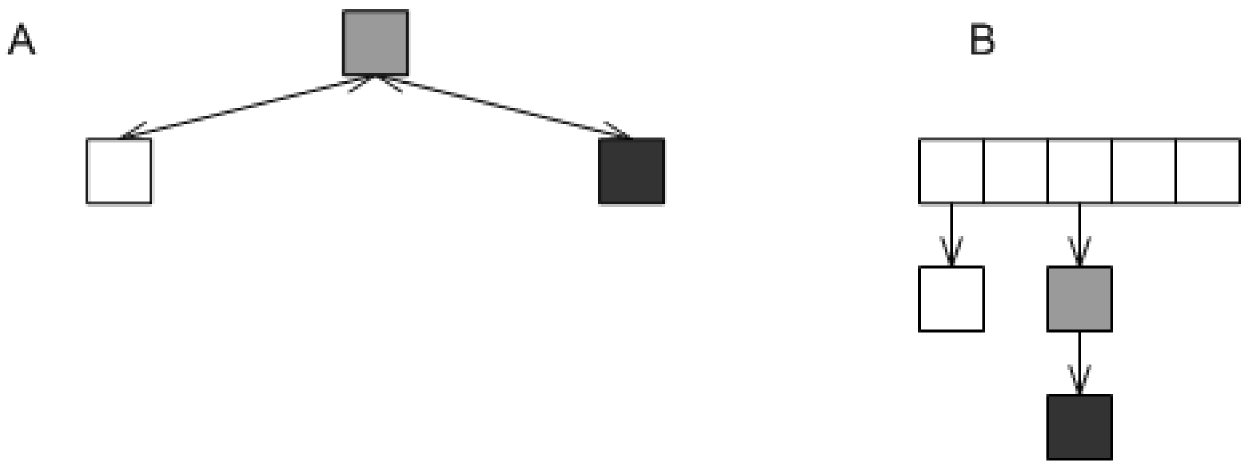


Figure 21.10: Non-unique Mapping Containers

In the first example above, then, one would use an associative container mapping each user to an associative container which maps each application id to a start time (see `example/basic_multimap.cc`); in the second example, one would use an associative container mapping each `int` to some size-type indicating the number of times it logically occurs (see `example/basic_multiset.cc`.

See the discussion in list-based container types for containers especially suited as secondary associative-containers.

21.3.1.3 Iterator Semantics

21.3.1.3.1 Point and Range Iterators

Iterator concepts are bifurcated in this design, and are comprised of point-type and range-type iteration.

A point-type iterator is an iterator that refers to a specific element as returned through an associative-container's `find` method.

A range-type iterator is an iterator that is used to go over a sequence of elements, as returned by a container's `find` method.

A point-type method is a method that returns a point-type iterator; a range-type method is a method that returns a range-type iterator.

For most containers, these types are synonymous; for self-organizing containers, such as hash-based containers or priority queues, these are inherently different (in any implementation, including that of C++ standard library components), but in this design, it is made explicit. They are distinct types.

21.3.1.3.2 Distinguishing Point and Range Iterators

When using this library, is necessary to differentiate between two types of methods and iterators: point-type methods and iterators, and range-type methods and iterators. Each associative container's interface includes the methods:

```
point_const_iterator
find(const_key_reference r_key) const;

point_iterator
find(const_key_reference r_key);

std::pair<point_iterator,bool>
insert(const_reference r_val);
```

The relationship between these iterator types varies between container types. The figure below shows the most general invariant between point-type and range-type iterators: In *A* `iterator`, can always be converted to `point_iterator`. In *B* shows invariants for order-preserving containers: point-type iterators are synonymous with range-type iterators. Orthogonally, *C*shows invariants for "set" containers: iterators are synonymous with const iterators.

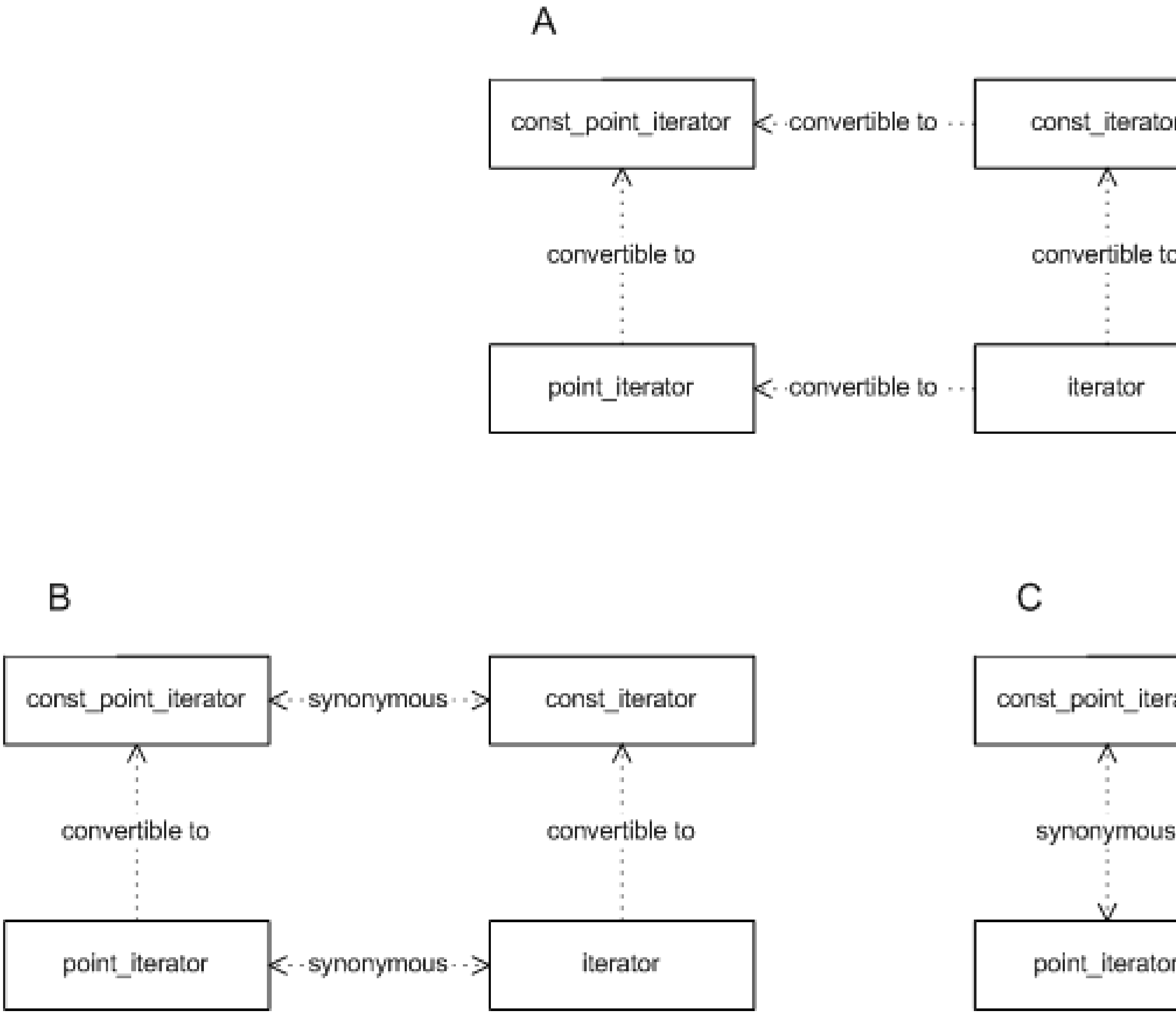


Figure 21.11: Point Iterator Hierarchy

Note that point-type iterators in self-organizing containers (hash-based associative containers) lack movement operators, such as `operator++` - in fact, this is the reason why this library differentiates from the standard C++ librarys design on this point.

Typically, one can determine an iterator's movement capabilities using `std::iterator_traits<It>iterator_category`, which is a `struct` indicating the iterator's movement capabilities. Unfortunately, none of the standard predefined categories reflect a pointer's *not* having any movement capabilities whatsoever. Consequently, `pb_ds` adds a type `trivial_iterator_tag` (whose name is taken from a concept in C++ standardese, which is the category of iterators with no movement capabilities.) All other standard C++ library tags, such as `forward_iterator_tag` retain their common use.

21.3.1.3.3 Invalidation Guarantees

If one manipulates a container object, then iterators previously obtained from it can be invalidated. In some cases a previously-obtained iterator cannot be de-referenced; in other cases, the iterator's next or previous element might have changed unpredictably. This corresponds exactly to the question whether a point-type or range-type iterator (see previous concept) is valid or not. In this design, one can query a container (in compile time) about its invalidation guarantees.

Given three different types of associative containers, a modifying operation (in that example, `erase`) invalidated iterators in three different ways: the iterator of one container remained completely valid - it could be de-referenced and incremented; the iterator of a different container could not even be de-referenced; the iterator of the third container could be de-referenced, but its "next" iterator changed unpredictably.

Distinguishing between find and range types allows fine-grained invalidation guarantees, because these questions correspond exactly to the question of whether point-type iterators and range-type iterators are valid. The graphic below shows tags corresponding to different types of invalidation guarantees.

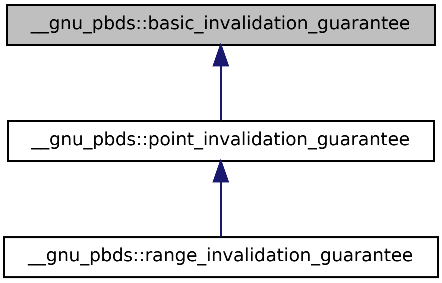


Figure 21.12: Invalidation Guarantee Tags Hierarchy

- `basic_invalidation_guarantee` corresponds to a basic guarantee that a point-type iterator, a found pointer, or a found reference, remains valid as long as the container object is not modified.
- `point_invalidation_guarantee` corresponds to a guarantee that a point-type iterator, a found pointer, or a found reference, remains valid even if the container object is modified.
- `range_invalidation_guarantee` corresponds to a guarantee that a range-type iterator remains valid even if the container object is modified.

To find the invalidation guarantee of a container, one can use

```
typename container_traits<Cntnr>::invalidation_guarantee
```

Note that this hierarchy corresponds to the logic it represents: if a container has range-invalidation guarantees, then it must also have find invalidation guarantees; correspondingly, its invalidation guarantee (in this case `range_invalidation_guarantee`) can be cast to its base class (in this case `point_invalidation_guarantee`). This means that this this hierarchy can be used easily using standard metaprogramming techniques, by specializing on the type of `invalidation_guarantee`.

These types of problems were addressed, in a more general setting, in [81] - Item 2. In our opinion, an invalidation-guarantee hierarchy would solve these problems in all container types - not just associative containers.

21.3.1.4 Genericity

The design attempts to address the following problem of data-structure genericity. When writing a function manipulating a generic container object, what is the behavior of the object? Suppose one writes

```
template<typename Cntnr>
void
some_op_sequence(Cntnr &r_container)
{
...
}
```

then one needs to address the following questions in the body of `some_op_sequence`:

- Which types and methods does `Cntnr` support? Containers based on hash tables can be queries for the hash-functor type and object; this is meaningless for tree-based containers. Containers based on trees can be split, joined, or can erase iterators and return the following iterator; this cannot be done by hash-based containers.
- What are the exception and invalidation guarantees of `Cntnr`? A container based on a probing hash-table invalidates all iterators when it is modified; this is not the case for containers based on node-based trees. Containers based on a node-based tree can be split or joined without exceptions; this is not the case for containers based on vector-based trees.
- How does the container maintain its elements? Tree-based and Trie-based containers store elements by key order; others, typically, do not. A container based on a splay trees or lists with update policies "cache" "frequently accessed" elements; containers based on most other underlying data structures do not.
- How does one query a container about characteristics and capabilities? What is the relationship between two different data structures, if anything?

The remainder of this section explains these issues in detail.

21.3.1.4.1 Tag

Tags are very useful for manipulating generic types. For example, if `It` is an iterator class, then `typename It::iterator_catego` or `typename std::iterator_traits<It>::iterator_category` will yield its category, and `typename std::itera` will yield its value type.

This library contains a container tag hierarchy corresponding to the diagram below.

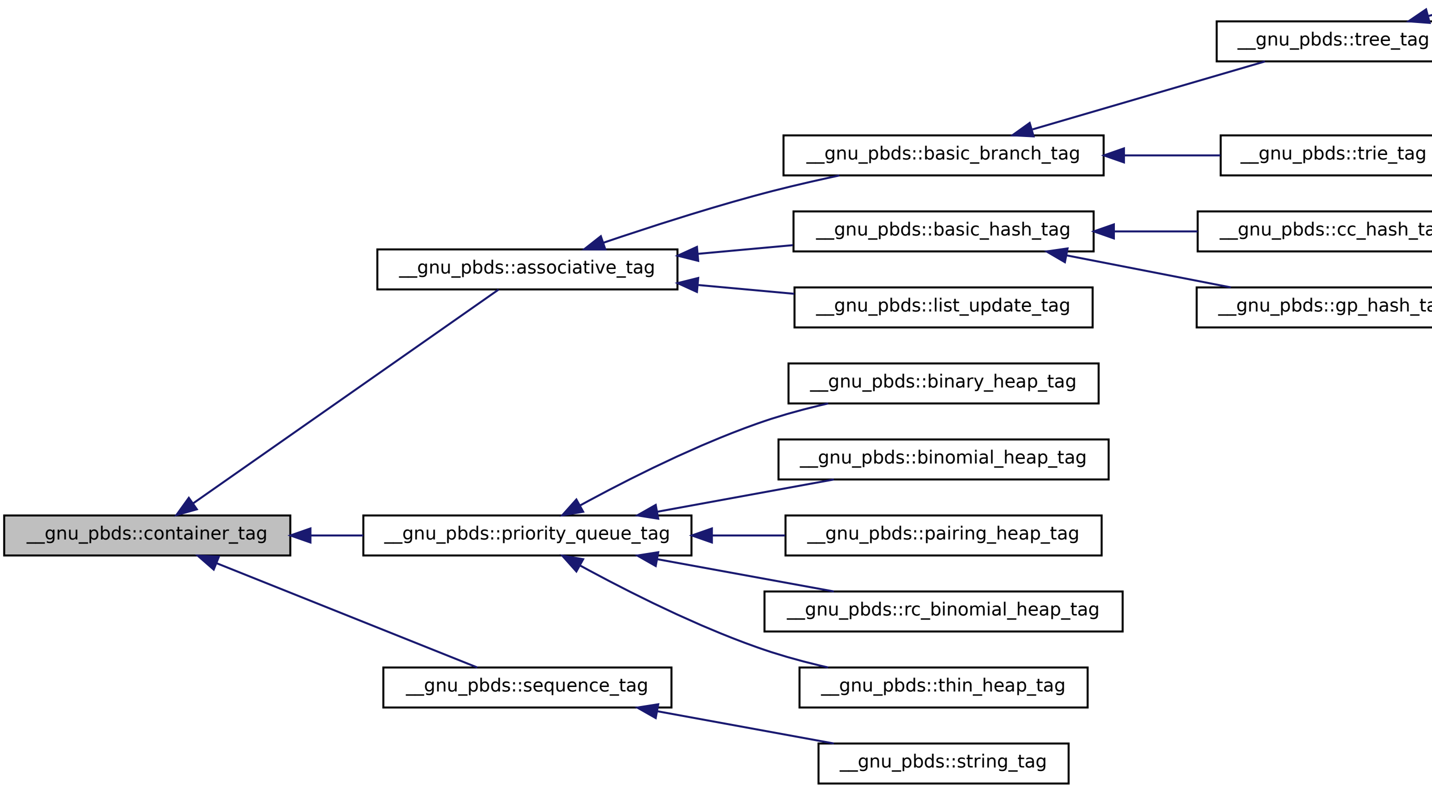


Figure 21.13: Container Tag Hierarchy

Given any container Cntnr, the tag of the underlying data structure can be found via `typename Cntnr::container_category`.

21.3.1.4.2 Traits

Additionally, a traits mechanism can be used to query a container type for its attributes. Given any container `Cntnr`, then `<Cntnr>` is a traits class identifying the properties of the container.

To find if a container can throw when a key is erased (which is true for vector-based trees, for example), one can use

```
container_traits<Cntnr>::erase_can_throw
```

Some of the definitions in `container_traits` are dependent on other definitions. If `container_traits<Cntnr>::order_p` is `true` (which is the case for containers based on trees and tries), then the container can be split or joined; in this case, `container_traits<Cntnr>::split_join_can_throw` indicates whether splits or joins can throw exceptions (which is true for vector-based trees); otherwise `container_traits<Cntnr>::split_join_can_throw` will yield a compilation error. (This is somewhat similar to a compile-time version of the COM model).

21.3.2 By Container

21.3.2.1 hash

21.3.2.1.1 Interface

The collision-chaining hash-based container has the following declaration.

```
template<
typename Key,
typename Mapped,
typename Hash_Fn = std::hash<Key>,
typename Eq_Fn = std::equal_to<Key>,
typename Comb_Hash_Fn =  direct_mask_range_hashing<>
typename Resize_Policy = default explained below.
bool Store_Hash = false,
typename Allocator = std::allocator<char> >
class cc_hash_table;
```

The parameters have the following meaning:

1. `Key` is the key type.
2. `Mapped` is the mapped-policy.
3. `Hash_Fn` is a key hashing functor.
4. `Eq_Fn` is a key equivalence functor.
5. `Comb_Hash_Fn` is a range-hashing_functor; it describes how to translate hash values into positions within the table.
6. `Resize_Policy` describes how a container object should change its internal size.
7. `Store_Hash` indicates whether the hash value should be stored with each entry.
8. `Allocator` is an allocator type.

The probing hash-based container has the following declaration.

```
template<
typename Key,
typename Mapped,
typename Hash_Fn = std::hash<Key>,
typename Eq_Fn = std::equal_to<Key>,
typename Comb_Probe_Fn = direct_mask_range_hashing<>
typename Probe_Fn = default explained below.
```

```
    typename Resize_Policy = default explained below.
    bool Store_Hash = false,
    typename Allocator =  std::allocator<char> >
    class gp_hash_table;
```

The parameters are identical to those of the collision-chaining container, except for the following.

1. `Comb_Probe_Fn` describes how to transform a probe sequence into a sequence of positions within the table.
2. `Probe_Fn` describes a probe sequence policy.

Some of the default template values depend on the values of other parameters, and are explained below.

21.3.2.1.2 Details

21.3.2.1.2.1 Hash Policies

21.3.2.1.2.2 General

Following is an explanation of some functions which hashing involves. The graphic below illustrates the discussion.

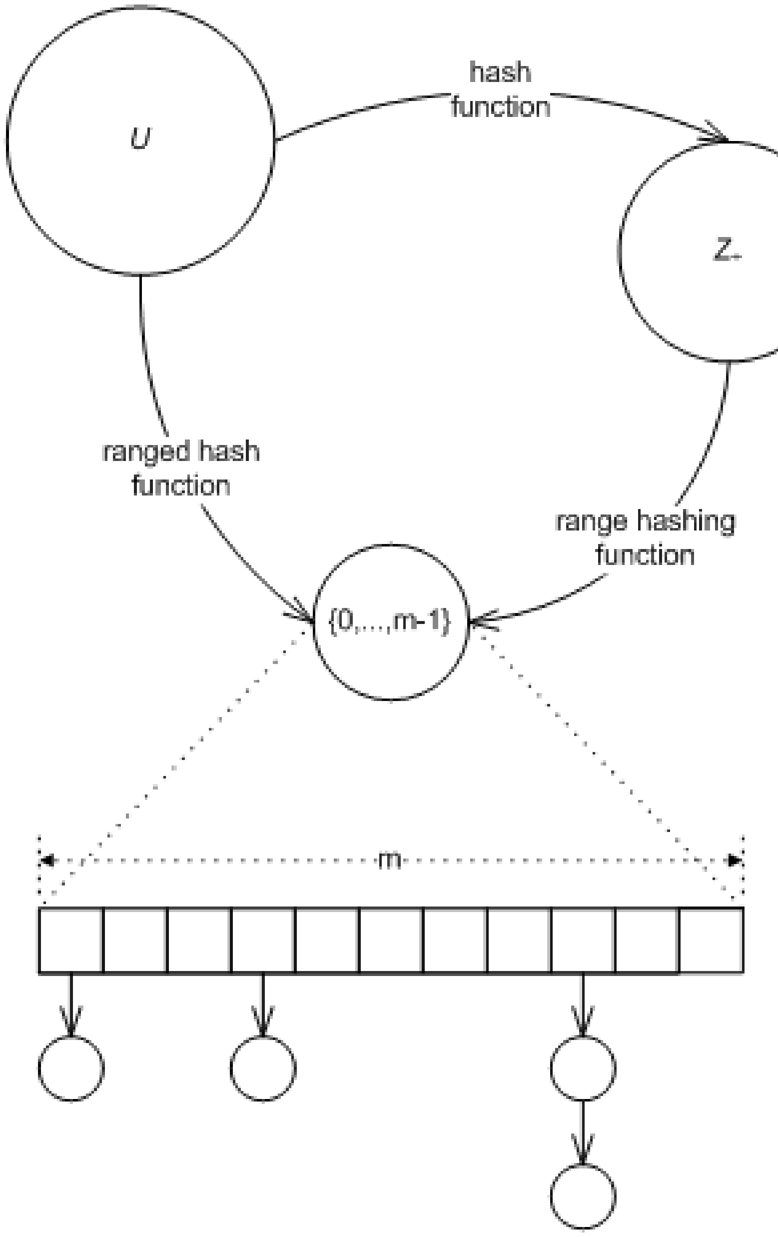


Figure 21.14: Hash functions, ranged-hash functions, and range-hashing functions

Let U be a domain (e.g., the integers, or the strings of 3 characters). A hash-table algorithm needs to map elements of U "uniformly" into the range [0,..., m - 1] (where m is a non-negative integral value, and is, in general, time varying). I.e., the algorithm needs a ranged-hash function

$f : U \times Z_+ \rightarrow Z_+$

such that for any u in U ,

$0 \leq f(u, m) \leq m - 1$

and which has "good uniformity" properties (say [77].) One common solution is to use the composition of the hash function

$h : U \rightarrow Z_+$,

which maps elements of U into the non-negative integrals, and

$g : Z_+ \times Z_+ \rightarrow Z_+$,

which maps a non-negative hash value, and a non-negative range upper-bound into a non-negative integral in the range between 0 (inclusive) and the range upper bound (exclusive), i.e., for any r in Z_+,

$0 \leq g(r, m) \leq m - 1$

The resulting ranged-hash function, is

$f(u , m) = g(h(u), m)$

EQUATION 21.1: Ranged Hash Function

From the above, it is obvious that given g and h, f can always be composed (however the converse is not true). The standard's hash-based containers allow specifying a hash function, and use a hard-wired range-hashing function; the ranged-hash function is implicitly composed.

The above describes the case where a key is to be mapped into a single position within a hash table, e.g., in a collision-chaining table. In other cases, a key is to be mapped into a sequence of positions within a table, e.g., in a probing table. Similar terms apply in this case: the table requires a ranged probe function, mapping a key into a sequence of positions withing the table. This is typically achieved by composing a hash function mapping the key into a non-negative integral type, a probe function transforming the hash value into a sequence of hash values, and a range-hashing function transforming the sequence of hash values into a sequence of positions.

21.3.2.1.2.3 Range Hashing

Some common choices for range-hashing functions are the division, multiplication, and middle-square methods ([77]), defined as

$g(r, m) = r \bmod m$

EQUATION 21.2: Range-Hashing, Division Method

$g(r, m) = \lceil u/v (a r \bmod v) \rceil$

and

$g(r, m) = \lceil u/v (r^2 \bmod v) \rceil$

respectively, for some positive integrals u and v (typically powers of 2), and some a. Each of these range-hashing functions works best for some different setting.

The division method (see above) is a very common choice. However, even this single method can be implemented in two very different ways. It is possible to implement using the low level % (modulo) operation (for any m), or the low level & (bit-mask) operation (for the case where m is a power of 2), i.e.,

$g(r, m) = r \% m$

EQUATION 21.3: Division via Prime Modulo

and

$g(r, m) = r \& m - 1$, (with $m = 2^k$ for some k)

EQUATION 21.4: Division via Bit Mask

respectively.

The % (modulo) implementation has the advantage that for m a prime far from a power of 2, g(r, m) is affected by all the bits of r (minimizing the chance of collision). It has the disadvantage of using the costly modulo operation. This method is hard-wired into SGI's implementation .

The & (bit-mask) implementation has the advantage of relying on the fast bit-wise and operation. It has the disadvantage that for g(r, m) is affected only by the low order bits of r. This method is hard-wired into Dinkumware's implementation.

21.3.2.1.2.4 Ranged Hash

In cases it is beneficial to allow the client to directly specify a ranged-hash hash function. It is true, that the writer of the ranged-hash function cannot rely on the values of m having specific numerical properties suitable for hashing (in the sense used in [77]), since the values of m are determined by a resize policy with possibly orthogonal considerations.

There are two cases where a ranged-hash function can be superior. The firs is when using perfect hashing: the second is when the values of m can be used to estimate the "general" number of distinct values required. This is described in the following.

Let

$s = [s_0,..., s_{t - 1}]$

be a string of t characters, each of which is from domain S. Consider the following ranged-hash function:

$f_1(s, m) = \sum_{i = 0}^{t - 1} s_i a^i \bmod m$

EQUATION 21.5: A Standard String Hash Function

where a is some non-negative integral value. This is the standard string-hashing function used in SGI's implementation (with a = 5). Its advantage is that it takes into account all of the characters of the string.

Now assume that s is the string representation of a of a long DNA sequence (and so S = {'A', 'C', 'G', 'T'}). In this case, scanning the entire string might be prohibitively expensive. A possible alternative might be to use only the first k characters of the string, where

$|S|^k \geq m$,

i.e., using the hash function

$f_2(s, m) = \sum_{i = 0}^{k - 1} s_i a^i \bmod m$

EQUATION 21.6: Only k String DNA Hash

requiring scanning over only

$k = \log_4(m)$

characters.

Other more elaborate hash-functions might scan k characters starting at a random position (determined at each resize), or scanning k random positions (determined at each resize), i.e., using

$f_3(s, m) = \sum_{i = r}0^{r_0 + k - 1} s_i a^i \bmod m$,

or

$f_4(s, m) = \sum_{i = 0}^{k - 1} s_r i\ a^{r_i} \bmod m$,

respectively, for $r_0,..., r_{k-1}$ each in the (inclusive) range [0,...,t-1].

It should be noted that the above functions cannot be decomposed as per a ranged hash composed of hash and range hashing.

21.3.2.1.2.5 Implementation

This sub-subsection describes the implementation of the above in this library. It first explains range-hashing functions in collision-chaining tables, then ranged-hash functions in collision-chaining tables, then probing-based tables, and finally lists the relevant classes in this library.

21.3.2.1.2.6 Range-Hashing and Ranged-Hashes in Collision-Chaining Tables

`cc_hash_table` is parametrized by `Hash_Fn` and `Comb_Hash_Fn`, a hash functor and a combining hash functor, respectively.

In general, `Comb_Hash_Fn` is considered a range-hashing functor. `cc_hash_table` synthesizes a ranged-hash function from `Hash_Fn` and `Comb_Hash_Fn`. The figure below shows an `insert` sequence diagram for this case. The user inserts an element (point A), the container transforms the key into a non-negative integral using the hash functor (points B and C), and transforms the result into a position using the combining functor (points D and E).

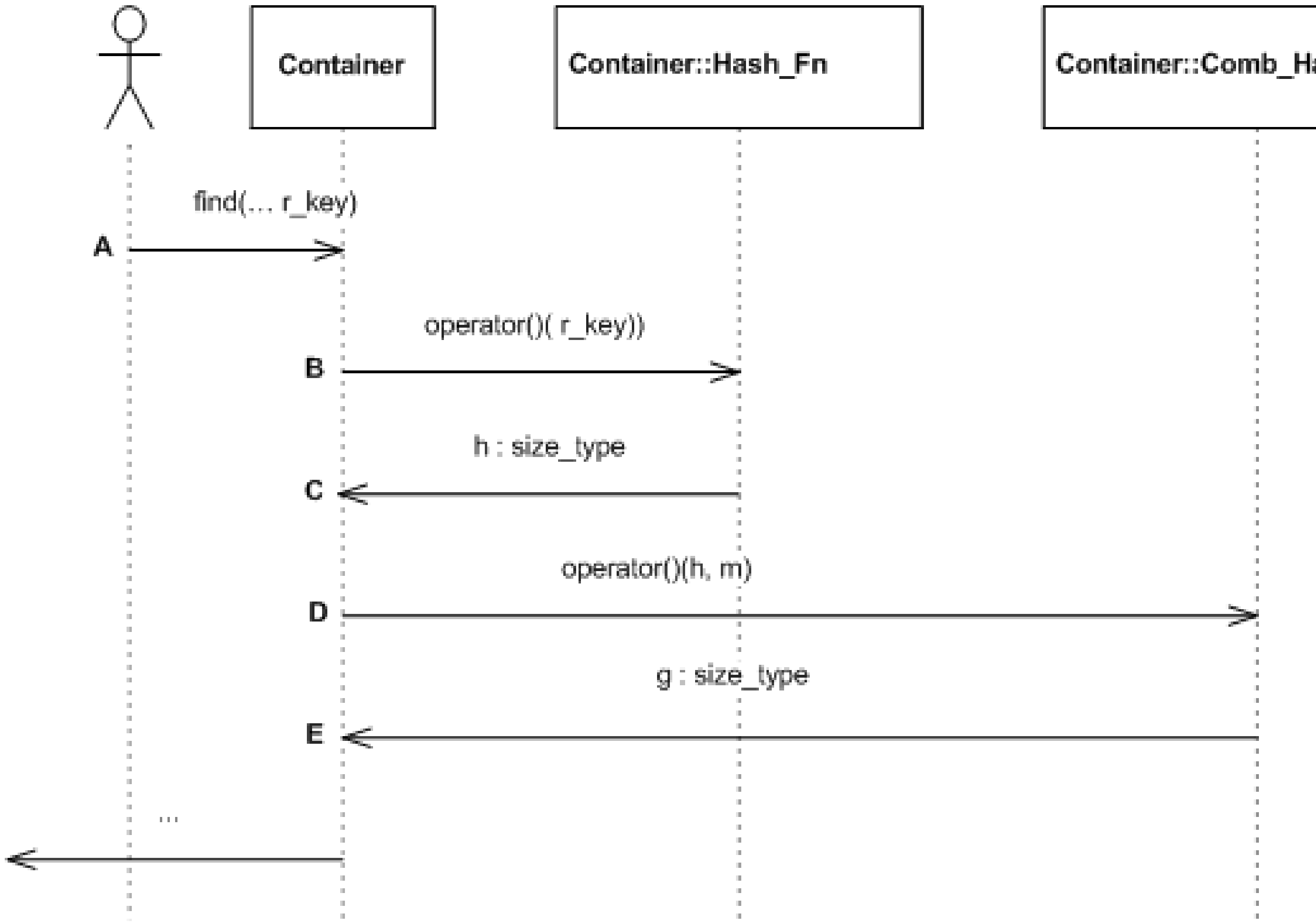


Figure 21.15: Insert hash sequence diagram

If `cc_hash_table`'s hash-functor, `Hash_Fn` is instantiated by `null_type` , then `Comb_Hash_Fn` is taken to be a ranged-hash function. The graphic below shows an `insert` sequence diagram. The user inserts an element (point A), the container transforms the key into a position using the combining functor (points B and C).

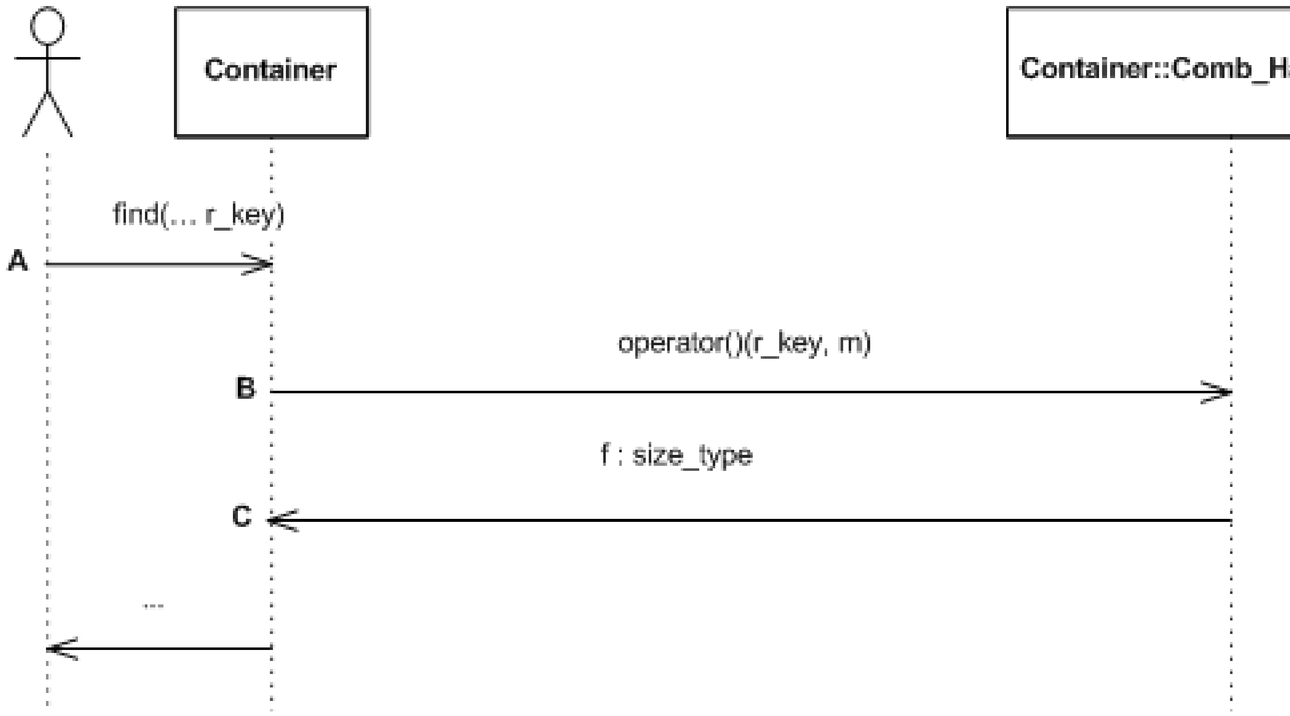


Figure 21.16: Insert hash sequence diagram with a null policy

21.3.2.1.2.7 Probing tables

`gp_hash_table` is parametrized by `Hash_Fn`, `Probe_Fn`, and `Comb_Probe_Fn`. As before, if `Hash_Fn` and `Probe_Fn` are both `null_type`, then `Comb_Probe_Fn` is a ranged-probe functor. Otherwise, `Hash_Fn` is a hash functor, `Probe_Fn` is a functor for offsets from a hash value, and `Comb_Probe_Fn` transforms a probe sequence into a sequence of positions within the table.

21.3.2.1.2.8 Pre-Defined Policies

This library contains some pre-defined classes implementing range-hashing and probing functions:

1. `direct_mask_range_hashing` and `direct_mod_range_hashing` are range-hashing functions based on a bit-mask and a modulo operation, respectively.
2. `linear_probe_fn`, and `quadratic_probe_fn` are a linear probe and a quadratic probe function, respectively.

The graphic below shows the relationships.

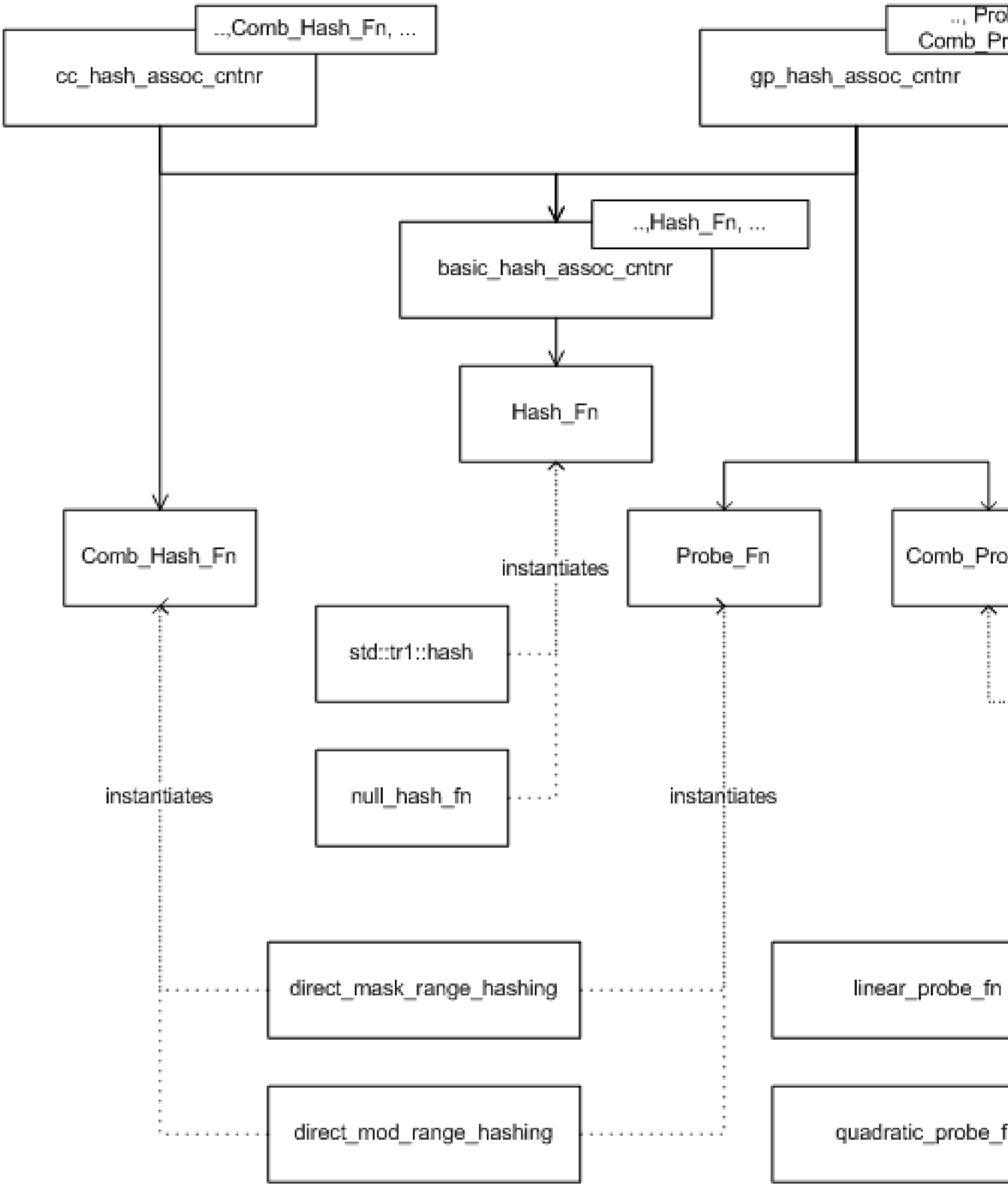


Figure 21.17: Hash policy class diagram

21.3.2.1.2.9 Resize Policies

21.3.2.1.2.10 General

Hash-tables, as opposed to trees, do not naturally grow or shrink. It is necessary to specify policies to determine how and when a hash table should change its size. Usually, resize policies can be decomposed into orthogonal policies:

1. A size policy indicating how a hash table should grow (e.g., it should multiply by powers of 2).
2. A trigger policy indicating when a hash table should grow (e.g., a load factor is exceeded).

21.3.2.1.2.11 Size Policies

Size policies determine how a hash table changes size. These policies are simple, and there are relatively few sensible options. An exponential-size policy (with the initial size and growth factors both powers of 2) works well with a mask-based range-hashing function, and is the hard-wired policy used by Dinkumware. A prime-list based policy works well with a modulo-prime range hashing function and is the hard-wired policy used by SGI's implementation.

21.3.2.1.2.12 Trigger Policies

Trigger policies determine when a hash table changes size. Following is a description of two policies: load-check policies, and collision-check policies.

Load-check policies are straightforward. The user specifies two factors, A_{min} and A_{max}, and the hash table maintains the invariant that

$A_{min} \leq$ (number of stored elements) / (hash-table size) $\leq A_{max}$

Collision-check policies work in the opposite direction of load-check policies. They focus on keeping the number of collisions moderate and hoping that the size of the table will not grow very large, instead of keeping a moderate load-factor and hoping that the number of collisions will be small. A maximal collision-check policy resizes when the longest probe-sequence grows too large.

Consider the graphic below. Let the size of the hash table be denoted by m, the length of a probe sequence be denoted by k, and some load factor be denoted by A. We would like to calculate the minimal length of k, such that if there were A m elements in the hash table, a probe sequence of length k would be found with probability at most 1/m.

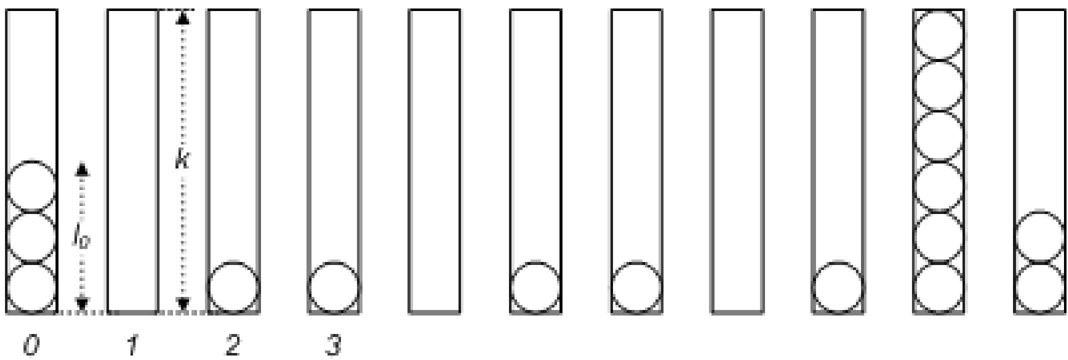


Figure 21.18: Balls and bins

Denote the probability that a probe sequence of length k appears in bin i by p_i, the length of the probe sequence of bin i by l_i, and assume uniform distribution. Then

p_1 =

EQUATION 21.7: Probability of Probe Sequence of Length k

$P(l_1 \geq k) =$

$P(l_1 \geq \alpha (1 + k / \alpha - 1) \leq$ (a)

e ^ $(- (\alpha (k / \alpha - 1)^2) /2)$

where (a) follows from the Chernoff bound ([85]). To calculate the probability that some bin contains a probe sequence greater than k, we note that the l_i are negatively-dependent ([67]) . Let I(.) denote the indicator function. Then

$P(\text{exists}_i\ l_i \geq k) =$

EQUATION 21.8: Probability Probe Sequence in Some Bin

$P (\sum_{i = 1}^m I(l_i \geq k) \geq 1) =$

$P (\sum_{i = 1}^m I (l_i \geq k) \geq m p_1 (1 + 1 / (m p_1) - 1)) \leq$ (a)

e ^ $((- m p_1 (1 / (m p_1) - 1) ^2) / 2)$,

where (a) follows from the fact that the Chernoff bound can be applied to negatively-dependent variables ([67]). Inserting the first probability equation into the second one, and equating with 1/m, we obtain

$k \sim \sqrt{(2 \alpha \ln 2 m \ln(m))}$.

21.3.2.1.2.13 Implementation

This sub-subsection describes the implementation of the above in this library. It first describes resize policies and their decomposition into trigger and size policies, then describes pre-defined classes, and finally discusses controlled access the policies' internals.

21.3.2.1.2.14 Decomposition

Each hash-based container is parametrized by a `Resize_Policy` parameter; the container derives `public`ly from `Resize_Policy`. For example:

```
cc_hash_table<typename Key,
typename Mapped,
...
typename Resize_Policy
...> : public Resize_Policy
```

As a container object is modified, it continuously notifies its `Resize_Policy` base of internal changes (e.g., collisions encountered and elements being inserted). It queries its `Resize_Policy` base whether it needs to be resized, and if so, to what size.

The graphic below shows a (possible) sequence diagram of an insert operation. The user inserts an element; the hash table notifies its resize policy that a search has started (point A); in this case, a single collision is encountered - the table notifies its resize policy of this (point B); the container finally notifies its resize policy that the search has ended (point C); it then queries its resize policy whether a resize is needed, and if so, what is the new size (points D to G); following the resize, it notifies the policy that a resize has completed (point H); finally, the element is inserted, and the policy notified (point I).

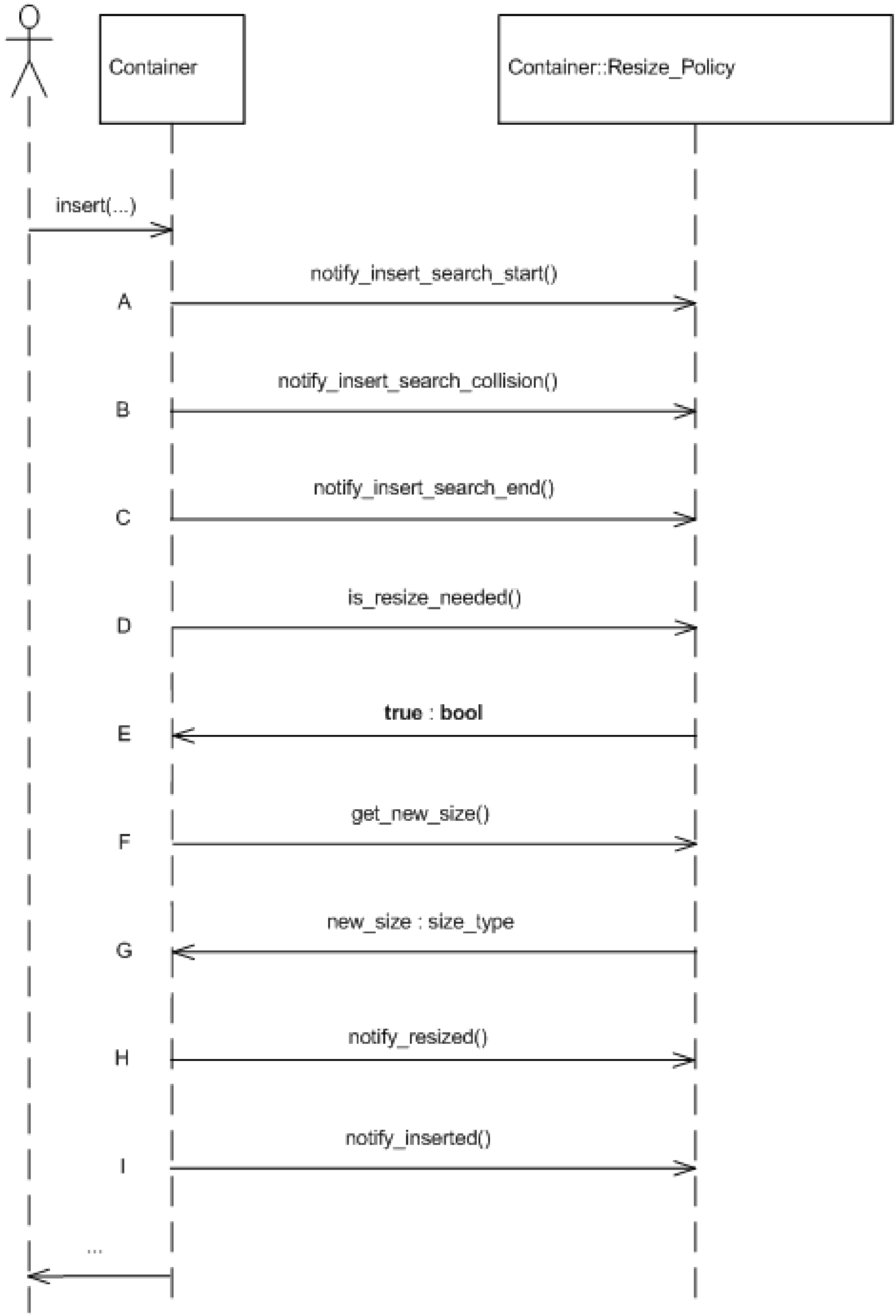


Figure 21.19: Insert resize sequence diagram

In practice, a resize policy can be usually orthogonally decomposed to a size policy and a trigger policy. Consequently, the library contains a single class for instantiating a resize policy: `hash_standard_resize_policy` is parametrized by `Size_Policy` and `Trigger_Policy`, derives `public`ly from both, and acts as a standard delegate ([71]) to these policies.

The two graphics immediately below show sequence diagrams illustrating the interaction between the standard resize policy and its trigger and size policies, respectively.

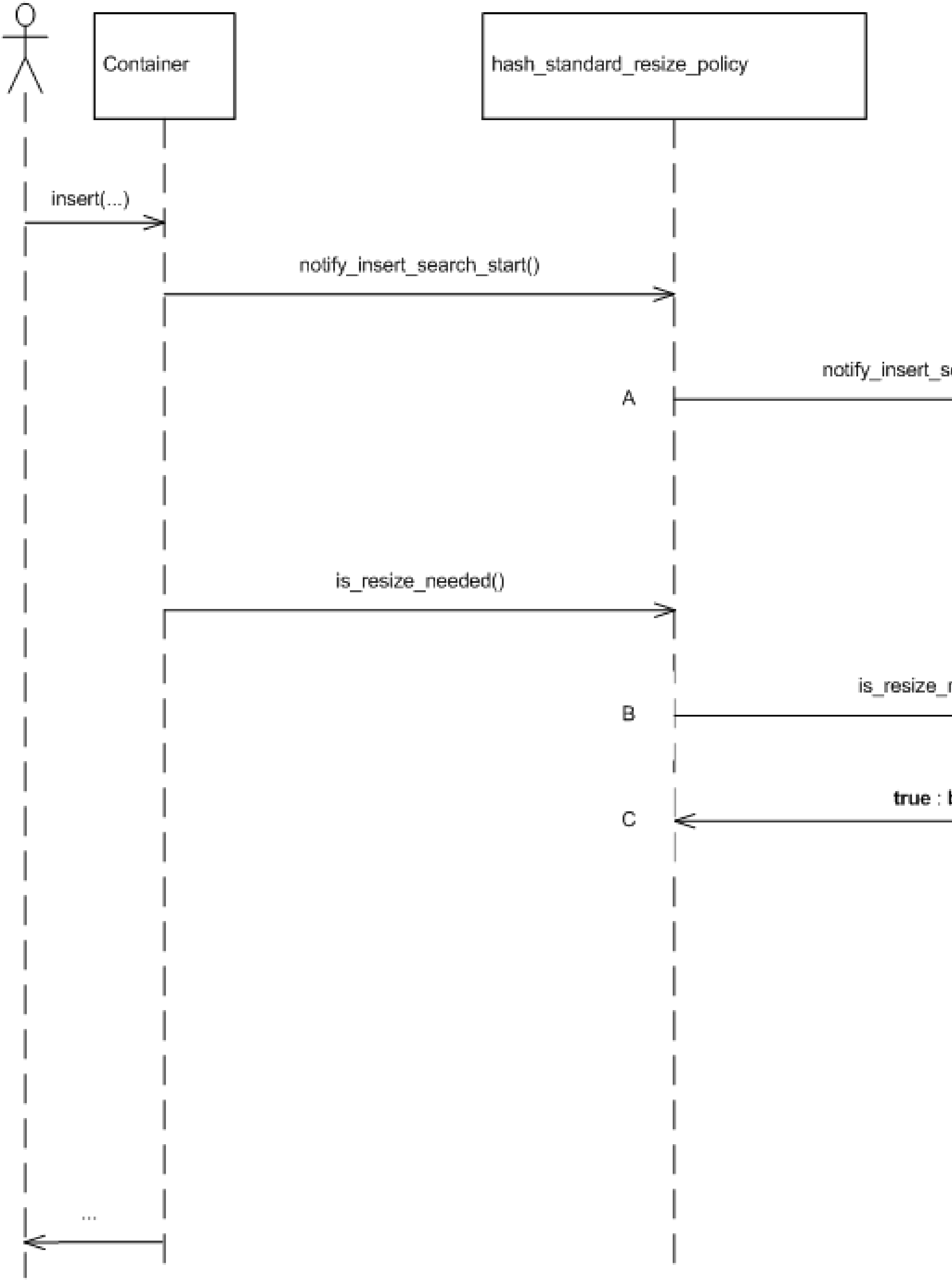


Figure 21.20: Standard resize policy trigger sequence diagram

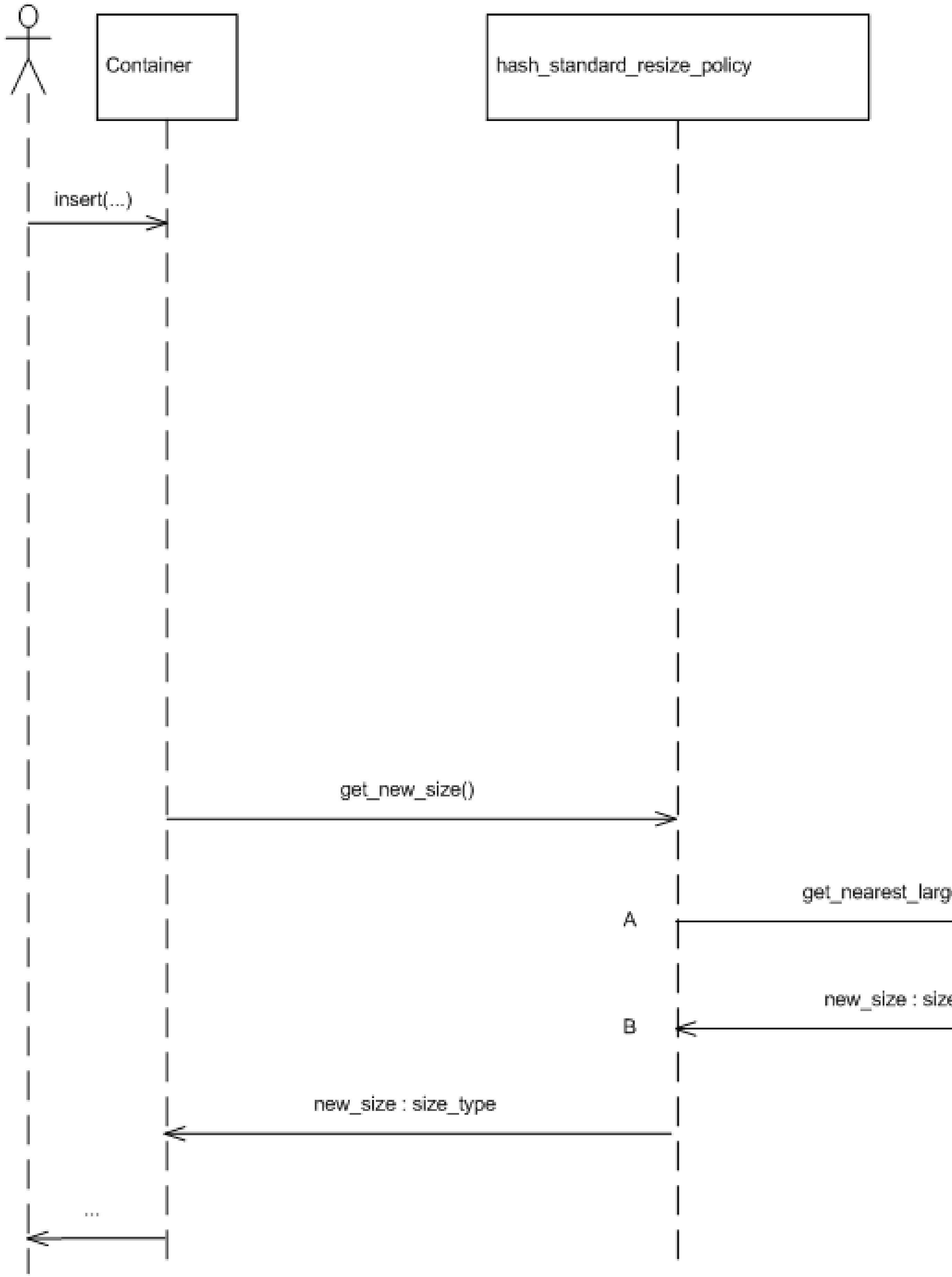


Figure 21.21: Standard resize policy size sequence diagram

21.3.2.1.2.15 Predefined Policies

The library includes the following instantiations of size and trigger policies:

1. `hash_load_check_resize_trigger` implements a load check trigger policy.
2. `cc_hash_max_collision_check_resize_trigger` implements a collision check trigger policy.
3. `hash_exponential_size_policy` implements an exponential-size policy (which should be used with mask range hashing).
4. `hash_prime_size_policy` implementing a size policy based on a sequence of primes (which should be used with mod range hashing

The graphic below gives an overall picture of the resize-related classes. `basic_hash_table` is parametrized by `Resize_Policy`, which it subclasses publicly. This class is currently instantiated only by `hash_standard_resize_policy`. `hash_standard_re` itself is parametrized by `Trigger_Policy` and `Size_Policy`. Currently, `Trigger_Policy` is instantiated by `hash_load_che` or `cc_hash_max_collision_check_resize_trigger`; `Size_Policy` is instantiated by `hash_exponential_size_p` or `hash_prime_size_policy`.

21.3.2.1.2.16 Controling Access to Internals

There are cases where (controlled) access to resize policies' internals is beneficial. E.g., it is sometimes useful to query a hash-table for the table's actual size (as opposed to its `size()` - the number of values it currently holds); it is sometimes useful to set a table's initial size, externally resize it, or change load factors.

Clearly, supporting such methods both decreases the encapsulation of hash-based containers, and increases the diversity between different associative-containers' interfaces. Conversely, omitting such methods can decrease containers' flexibility.

In order to avoid, to the extent possible, the above conflict, the hash-based containers themselves do not address any of these questions; this is deferred to the resize policies, which are easier to change or replace. Thus, for example, neither `cc_hash_table` nor `gp_hash_table` contain methods for querying the actual size of the table; this is deferred to `hash_standard_resize_polic`

Furthermore, the policies themselves are parametrized by template arguments that determine the methods they support ([56] shows techniques for doing so). `hash_standard_resize_policy` is parametrized by `External_Size_Access` that determines whether it supports methods for querying the actual size of the table or resizing it. `hash_load_check_resize_trigge` is parametrized by `External_Load_Access` that determines whether it supports methods for querying or modifying the loads. `cc_hash_max_collision_check_resize_trigger` is parametrized by `External_Load_Access` that determines whether it supports methods for querying the load.

Some operations, for example, resizing a container at run time, or changing the load factors of a load-check trigger policy, require the container itself to resize. As mentioned above, the hash-based containers themselves do not contain these types of methods, only their resize policies. Consequently, there must be some mechanism for a resize policy to manipulate the hash-based container. As the hash-based container is a subclass of the resize policy, this is done through virtual methods. Each hash-based container has a `private virtual` method:

```
virtual void
do_resize
(size_type new_size);
```

which resizes the container. Implementations of `Resize_Policy` can export public methods for resizing the container externally; these methods internally call `do_resize` to resize the table.

21.3.2.1.2.17 Policy Interactions

Hash-tables are unfortunately especially susceptible to choice of policies. One of the more complicated aspects of this is that poor combinations of good policies can form a poor container. Following are some considerations.

21.3.2.1.2.18 probe/size/trigger

Some combinations do not work well for probing containers. For example, combining a quadratic probe policy with an exponential size policy can yield a poor container: when an element is inserted, a trigger policy might decide that there is no need to resize, as the table still contains unused entries; the probe sequence, however, might never reach any of the unused entries.

Unfortunately, this library cannot detect such problems at compilation (they are halting reducible). It therefore defines an exception class `insert_error` to throw an exception in this case.

21.3.2.1.2.19 hash/trigger

Some trigger policies are especially susceptible to poor hash functions. Suppose, as an extreme case, that the hash function transforms each key to the same hash value. After some inserts, a collision detecting policy will always indicate that the container needs to grow.

The library, therefore, by design, limits each operation to one resize. For each `insert`, for example, it queries only once whether a resize is needed.

21.3.2.1.2.20 equivalence functors/storing hash values/hash

`cc_hash_table` and `gp_hash_table` are parametrized by an equivalence functor and by a `Store_Hash` parameter. If the latter parameter is `true`, then the container stores with each entry a hash value, and uses this value in case of collisions to determine whether to apply a hash value. This can lower the cost of collision for some types, but increase the cost of collisions for other types.

If a ranged-hash function or ranged probe function is directly supplied, however, then it makes no sense to store the hash value with each entry. This library's container will fail at compilation, by design, if this is attempted.

21.3.2.1.2.21 size/load-check trigger

Assume a size policy issues an increasing sequence of sizes a, a q, a q^1, a q^2, ... For example, an exponential size policy might issue the sequence of sizes 8, 16, 32, 64, ...

If a load-check trigger policy is used, with loads α_{min} and α_{max}, respectively, then it is a good idea to have:

1. α_{max} ~ 1 / q
2. α_{min} < 1 / (2 q)

This will ensure that the amortized hash cost of each modifying operation is at most approximately 3.

α_{min} ~ α_{max} is, in any case, a bad choice, and $\alpha_{min} > \alpha_{max}$ is horrendous.

21.3.2.2 tree

21.3.2.2.1 Interface

The tree-based container has the following declaration:

```
template<
typename Key,
typename Mapped,
typename Cmp_Fn = std::less<Key>,
typename Tag = rb_tree_tag,
template<
typename Const_Node_Iterator,
typename Node_Iterator,
typename Cmp_Fn_,
typename Allocator_>
class Node_Update = null_node_update,
typename Allocator = std::allocator<char> >
class tree;
```

The parameters have the following meaning:

1. `Key` is the key type.
2. `Mapped` is the mapped-policy.
3. `Cmp_Fn` is a key comparison functor
4. `Tag` specifies which underlying data structure to use.
5. `Node_Update` is a policy for updating node invariants.
6. `Allocator` is an allocator type.

The `Tag` parameter specifies which underlying data structure to use. Instantiating it by `rb_tree_tag`, `splay_tree_tag`, or `ov_tree_tag`, specifies an underlying red-black tree, splay tree, or ordered-vector tree, respectively; any other tag is illegal. Note that containers based on the former two contain more types and methods than the latter (e.g., `reverse_iterator` and `rbegin`), and different exception and invalidation guarantees.

21.3.2.2.2 Details

21.3.2.2.2.1 Node Invariants

Consider the two trees in the graphic below, labels A and B. The first is a tree of floats; the second is a tree of pairs, each signifying a geometric line interval. Each element in a tree is referred to as a node of the tree. Of course, each of these trees can support the usual queries: the first can easily search for `0.4`; the second can easily search for `std::make_pair(10, 41).`

Each of these trees can efficiently support other queries. The first can efficiently determine that the 2rd key in the tree is `0.3`; the second can efficiently determine whether any of its intervals overlaps

```
std::make_pair(29,42)
```

(useful in geometric applications or distributed file systems with leases, for example). It should be noted that an `std::set` can only solve these types of problems with linear complexity.

In order to do so, each tree stores some metadata in each node, and maintains node invariants (see [66].) The first stores in each node the size of the sub-tree rooted at the node; the second stores at each node the maximal endpoint of the intervals at the sub-tree rooted at the node.

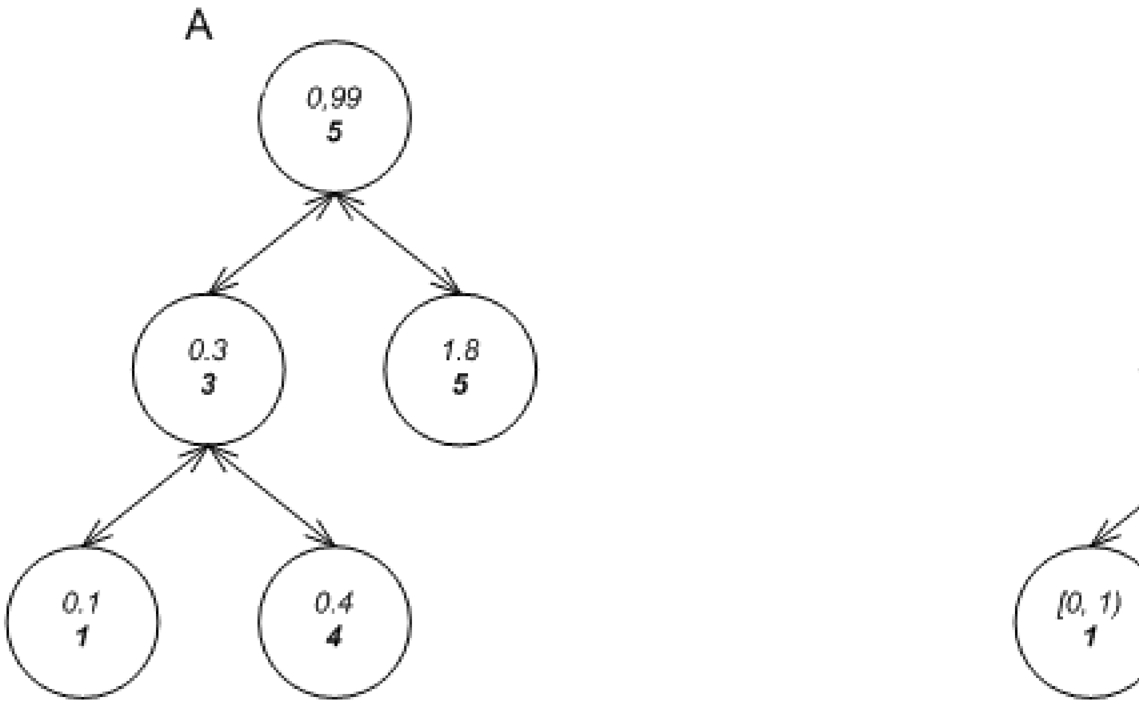


Figure 21.22: Tree node invariants

Supporting such trees is difficult for a number of reasons:

1. There must be a way to specify what a node's metadata should be (if any).
2. Various operations can invalidate node invariants. The graphic below shows how a right rotation, performed on A, results in B, with nodes x and y having corrupted invariants (the grayed nodes in C). The graphic shows how an insert, performed on D, results in E, with nodes x and y having corrupted invariants (the grayed nodes in F). It is not feasible to know outside the tree the effect of an operation on the nodes of the tree.
3. The search paths of standard associative containers are defined by comparisons between keys, and not through metadata.
4. It is not feasible to know in advance which methods trees can support. Besides the usual `find` method, the first tree can support a `find_by_order` method, while the second can support an `overlaps` method.

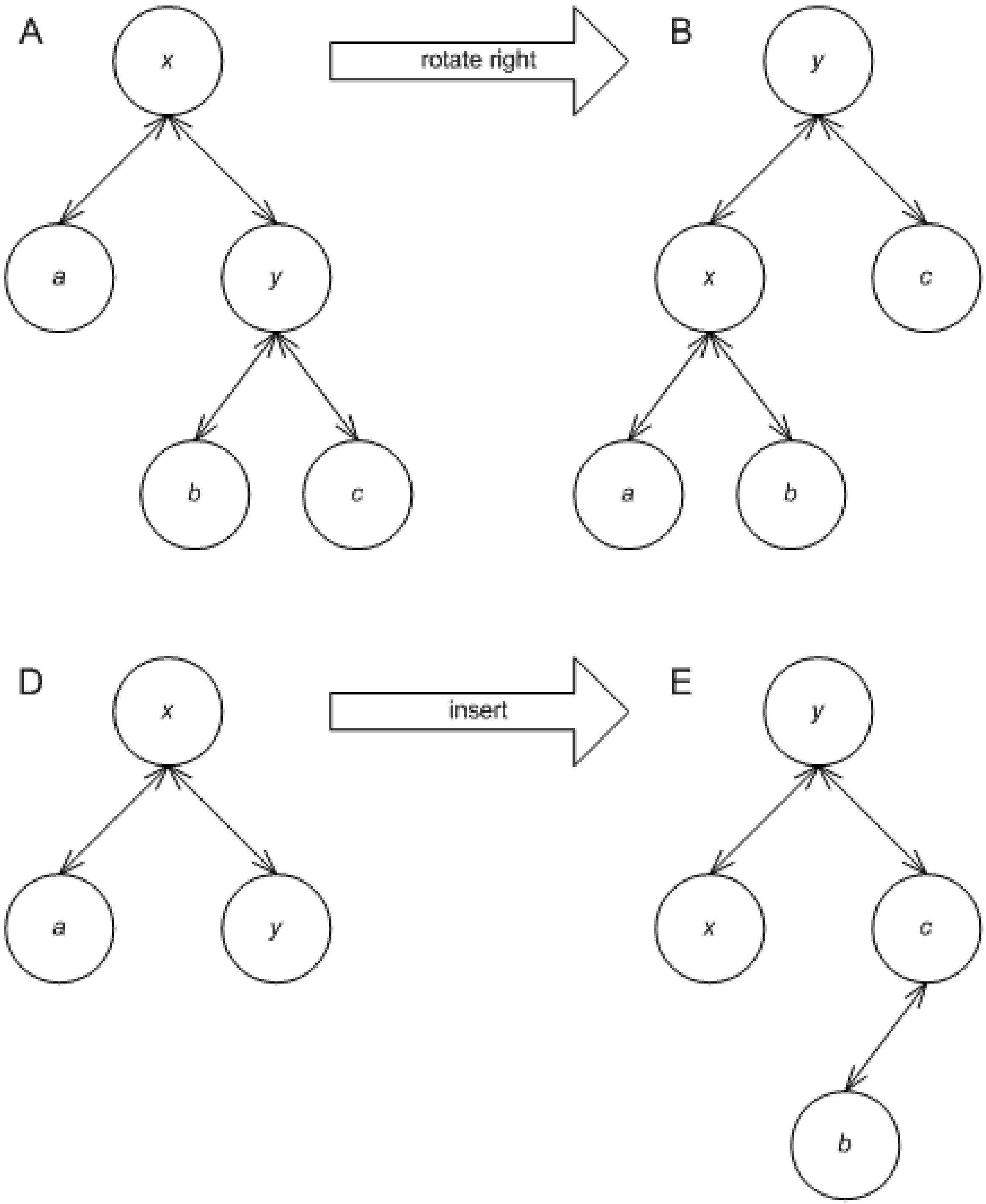


Figure 21.23: Tree node invalidation

These problems are solved by a combination of two means: node iterators, and template-template node updater parameters.

21.3.2.2.2.2 Node Iterators

Each tree-based container defines two additional iterator types, `const_node_iterator` and `node_iterator`. These iterators allow descending from a node to one of its children. Node iterator allow search paths different than those determined by the comparison functor. The `tree` supports the methods:

```
const_node_iterator
node_begin() const;

node_iterator
node_begin();

const_node_iterator
node_end() const;

node_iterator
node_end();
```

The first pairs return node iterators corresponding to the root node of the tree; the latter pair returns node iterators corresponding to a just-after-leaf node.

21.3.2.2.2.3 Node Updator

The tree-based containers are parametrized by a `Node_Update` template-template parameter. A tree-based container instantiates `Node_Update` to some `node_update` class, and publicly subclasses `node_update`. The graphic below shows this scheme, as well as some predefined policies (which are explained below).

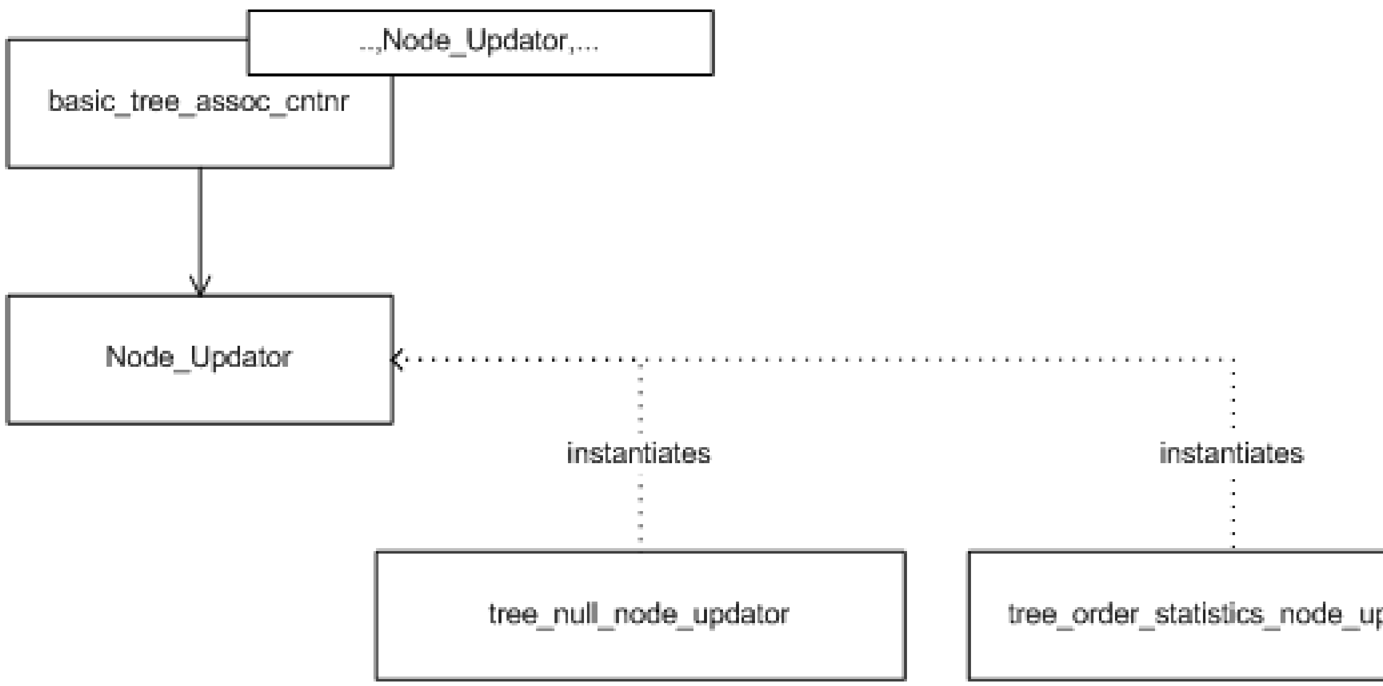


Figure 21.24: A tree and its update policy

`node_update` (an instantiation of `Node_Update`) must define `metadata_type` as the type of metadata it requires. For order statistics, e.g., `metadata_type` might be `size_t`. The tree defines within each node a `metadata_type` object.

`node_update` must also define the following method for restoring node invariants:

```
void
operator()(node_iterator nd_it, const_node_iterator end_nd_it)
```

In this method, nd_it is a node_iterator corresponding to a node whose A) all descendants have valid invariants, and B) its own invariants might be violated; end_nd_it is a const_node_iterator corresponding to a just-after-leaf node. This method should correct the node invariants of the node pointed to by nd_it. For example, say node x in the graphic below label A has an invalid invariant, but its' children, y and z have valid invariants. After the invocation, all three nodes should have valid invariants, as in label B.

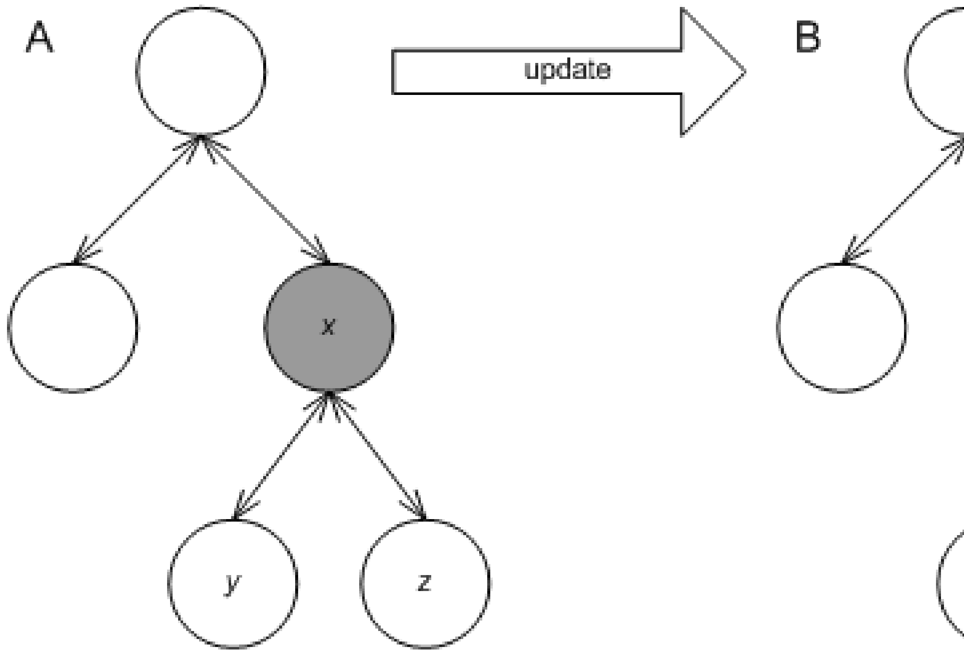


Figure 21.25: Restoring node invariants

When a tree operation might invalidate some node invariant, it invokes this method in its node_update base to restore the invariant. For example, the graphic below shows an insert operation (point A); the tree performs some operations, and calls the update functor three times (points B, C, and D). (It is well known that any insert, erase, split or join, can restore all node invariants by a small number of node invariant updates ([66]) .

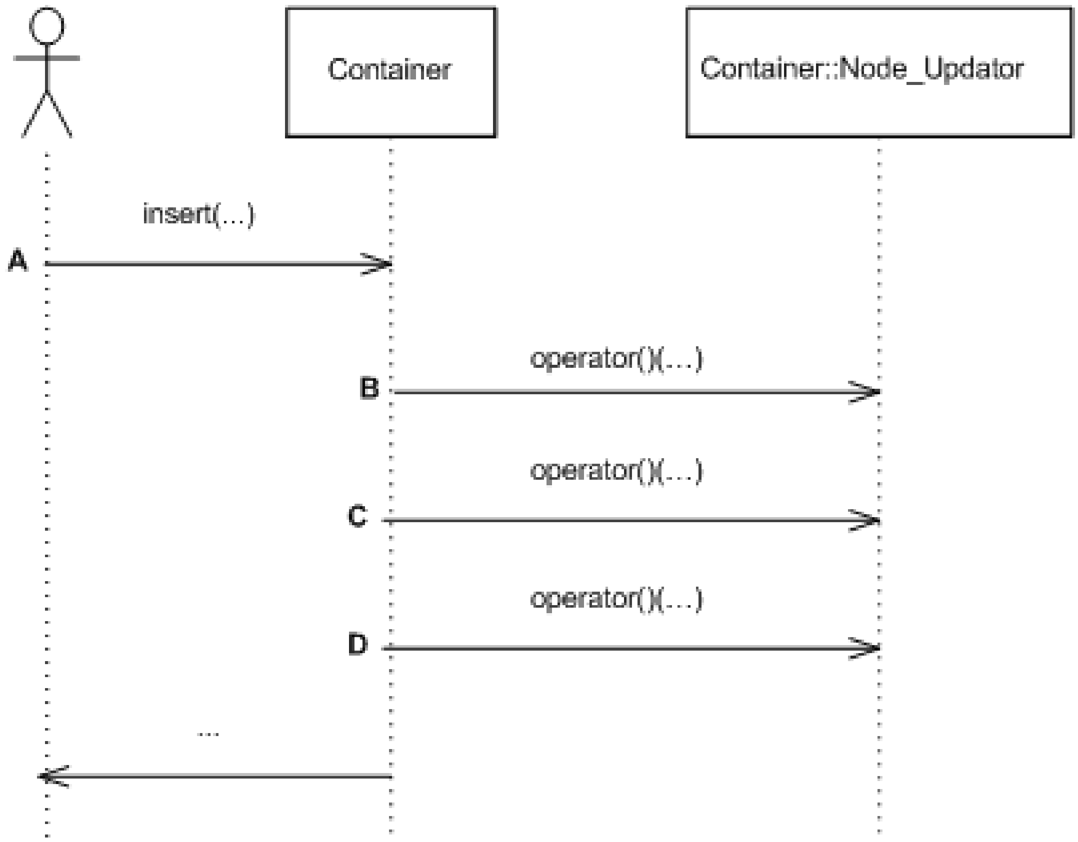


Figure 21.26: Insert update sequence

To complete the description of the scheme, three questions need to be answered:

1. How can a tree which supports order statistics define a method such as `find_by_order`?
2. How can the node updater base access methods of the tree?
3. How can the following cyclic dependency be resolved? `node_update` is a base class of the tree, yet it uses node iterators defined in the tree (its child).

The first two questions are answered by the fact that `node_update` (an instantiation of `Node_Update`) is a *public* base class of the tree. Consequently:

1. Any public methods of `node_update` are automatically methods of the tree ([56]). Thus an order-statistics node updater, `tree_order_statistics_node_update` defines the `find_by_order` method; any tree instantiated by this policy consequently supports this method as well.
2. In C++, if a base class declares a method as `virtual`, it is `virtual` in its subclasses. If `node_update` needs to access one of the tree's methods, say the member function `end`, it simply declares that method as `virtual` abstract.

The cyclic dependency is solved through template-template parameters. `Node_Update` is parametrized by the tree's node iterators, its comparison functor, and its allocator type. Thus, instantiations of `Node_Update` have all information required.

This library assumes that constructing a metadata object and modifying it are exception free. Suppose that during some method, say `insert`, a metadata-related operation (e.g., changing the value of a metadata) throws an exception. Ack! Rolling back the method is unusually complex.

Previously, a distinction was made between redundant policies and null policies. Node invariants show a case where null policies are required.

Assume a regular tree is required, one which need not support order statistics or interval overlap queries. Seemingly, in this case a redundant policy - a policy which doesn't affect nodes' contents would suffice. This, would lead to the following drawbacks:

1. Each node would carry a useless metadata object, wasting space.
2. The tree cannot know if its `Node_Update` policy actually modifies a node's metadata (this is halting reducible). In the graphic below, assume the shaded node is inserted. The tree would have to traverse the useless path shown to the root, applying redundant updates all the way.

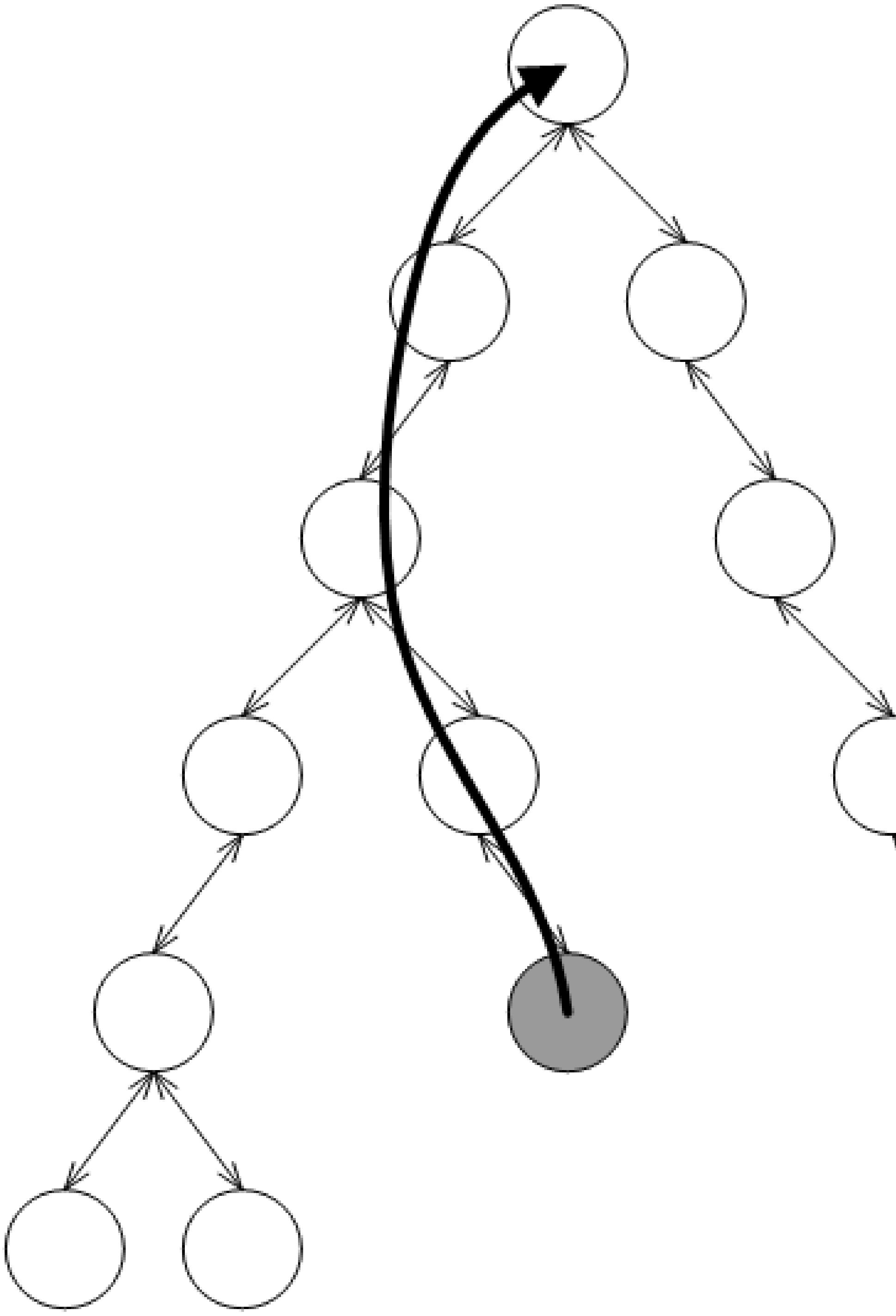


Figure 21.27: Useless update path

A null policy class, `null_node_update` solves both these problems. The tree detects that node invariants are irrelevant, and defines all accordingly.

21.3.2.2.2.4 Split and Join

Tree-based containers support split and join methods. It is possible to split a tree so that it passes all nodes with keys larger than a given key to a different tree. These methods have the following advantages over the alternative of externally inserting to the destination tree and erasing from the source tree:

1. These methods are efficient - red-black trees are split and joined in poly-logarithmic complexity; ordered-vector trees are split and joined at linear complexity. The alternatives have super-linear complexity.
2. Aside from orders of growth, these operations perform few allocations and de-allocations. For red-black trees, allocations are not performed, and the methods are exception-free.

21.3.2.3 Trie

21.3.2.3.1 Interface

The trie-based container has the following declaration:

```
template<typename Key,
typename Mapped,
typename Cmp_Fn = std::less<Key>,
typename Tag = pat_trie_tag,
template<typename Const_Node_Iterator,
typename Node_Iterator,
typename E_Access_Traits_,
typename Allocator_>
class Node_Update = null_node_update,
typename Allocator = std::allocator<char> >
class trie;
```

The parameters have the following meaning:

1. `Key` is the key type.
2. `Mapped` is the mapped-policy.
3. `E_Access_Traits` is described in below.
4. `Tag` specifies which underlying data structure to use, and is described shortly.
5. `Node_Update` is a policy for updating node invariants. This is described below.
6. `Allocator` is an allocator type.

The `Tag` parameter specifies which underlying data structure to use. Instantiating it by `pat_trie_tag`, specifies an underlying PATRICIA trie (explained shortly); any other tag is currently illegal.

Following is a description of a (PATRICIA) trie (this implementation follows [90] and [69]).

A (PATRICIA) trie is similar to a tree, but with the following differences:

1. It explicitly views keys as a sequence of elements. E.g., a trie can view a string as a sequence of characters; a trie can view a number as a sequence of bits.
2. It is not (necessarily) binary. Each node has fan-out n + 1, where n is the number of distinct elements.
3. It stores values only at leaf nodes.
4. Internal nodes have the properties that A) each has at least two children, and B) each shares the same prefix with any of its descendant.

A (PATRICIA) trie has some useful properties:

1. It can be configured to use large node fan-out, giving it very efficient find performance (albeit at insertion complexity and size).
2. It works well for common-prefix keys.
3. It can support efficiently queries such as which keys match a certain prefix. This is sometimes useful in file systems and routers, and for "type-ahead" aka predictive text matching on mobile devices.

21.3.2.3.2 Details

21.3.2.3.2.1 Element Access Traits

A trie inherently views its keys as sequences of elements. For example, a trie can view a string as a sequence of characters. A trie needs to map each of n elements to a number in {0, n - 1}. For example, a trie can map a character `c` to

```
static_cast<size_t>(c)
```

.

Seemingly, then, a trie can assume that its keys support (const) iterators, and that the `value_type` of this iterator can be cast to a `size_t`. There are several reasons, though, to decouple the mechanism by which the trie accesses its keys' elements from the trie:

1. In some cases, the numerical value of an element is inappropriate. Consider a trie storing DNA strings. It is logical to use a trie with a fan-out of 5 = 1 + |{'A', 'C', 'G', 'T'}|. This requires mapping 'T' to 3, though.
2. In some cases the keys' iterators are different than what is needed. For example, a trie can be used to search for common suffixes, by using strings' `reverse_iterator`. As another example, a trie mapping UNICODE strings would have a huge fan-out if each node would branch on a UNICODE character; instead, one can define an iterator iterating over 8-bit (or less) groups.

trie is, consequently, parametrized by `E_Access_Traits` - traits which instruct how to access sequences' elements. `string_trie_` is a traits class for strings. Each such traits define some types, like:

```
typename E_Access_Traits::const_iterator
```

is a const iterator iterating over a key's elements. The traits class must also define methods for obtaining an iterator to the first and last element of a key.

The graphic below shows a (PATRICIA) trie resulting from inserting the words: "I wish that I could ever see a poem lovely as a trie" (which, unfortunately, does not rhyme).

The leaf nodes contain values; each internal node contains two `typename E_Access_Traits::const_iterator` objects, indicating the maximal common prefix of all keys in the sub-tree. For example, the shaded internal node roots a sub-tree with leafs "a" and "as". The maximal common prefix is "a". The internal node contains, consequently, to const iterators, one pointing to `'a'`, and the other to `'s'`.

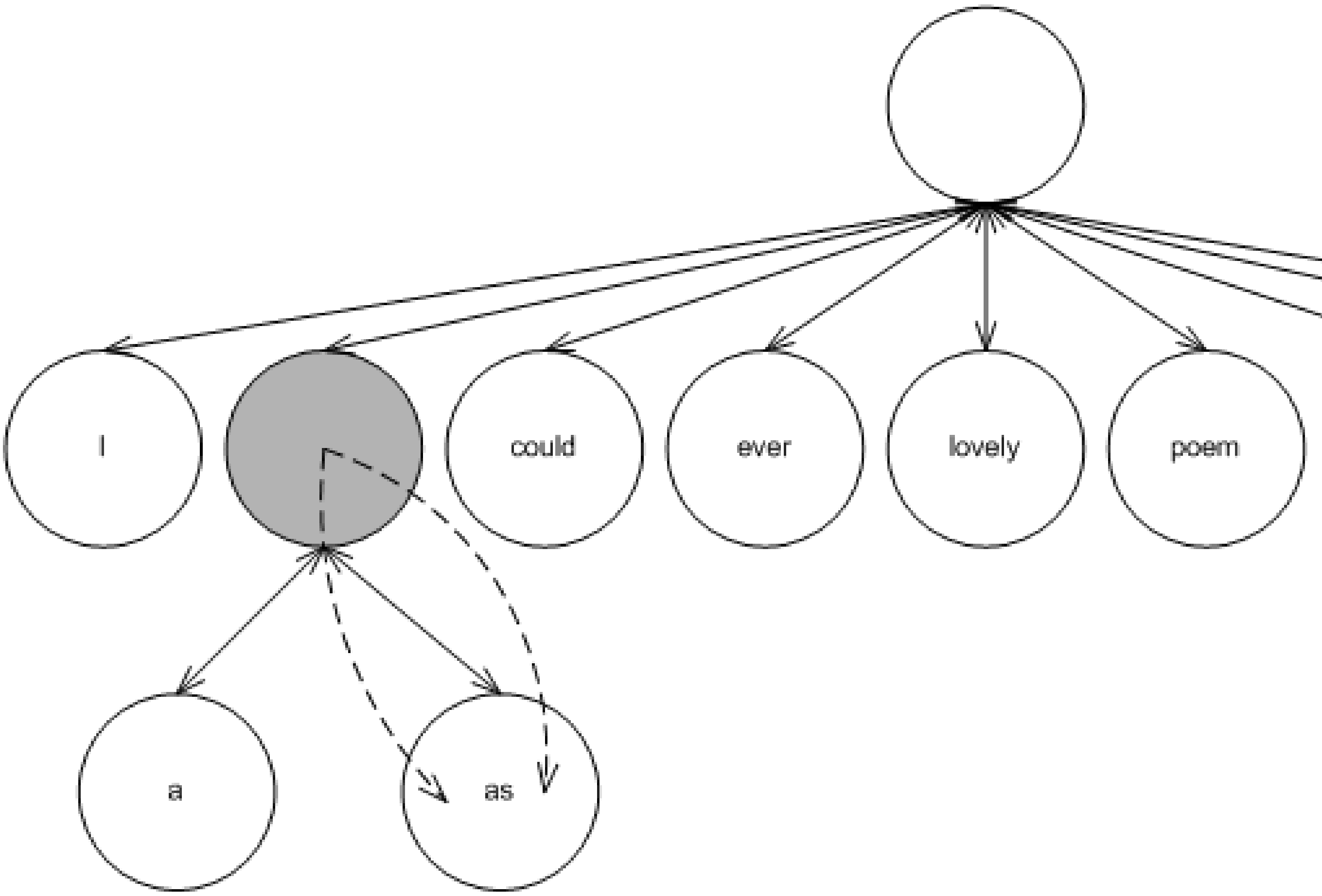


Figure 21.28: A PATRICIA trie

21.3.2.3.2.2 Node Invariants

Trie-based containers support node invariants, as do tree-based containers. There are two minor differences, though, which, unfortunately, thwart sharing them sharing the same node-updating policies:

1. A trie's `Node_Update` template-template parameter is parametrized by `E_Access_Traits`, while a tree's `Node_Update` template-template parameter is parametrized by `Cmp_Fn`.
2. Tree-based containers store values in all nodes, while trie-based containers (at least in this implementation) store values in leafs.

The graphic below shows the scheme, as well as some predefined policies (which are explained below).

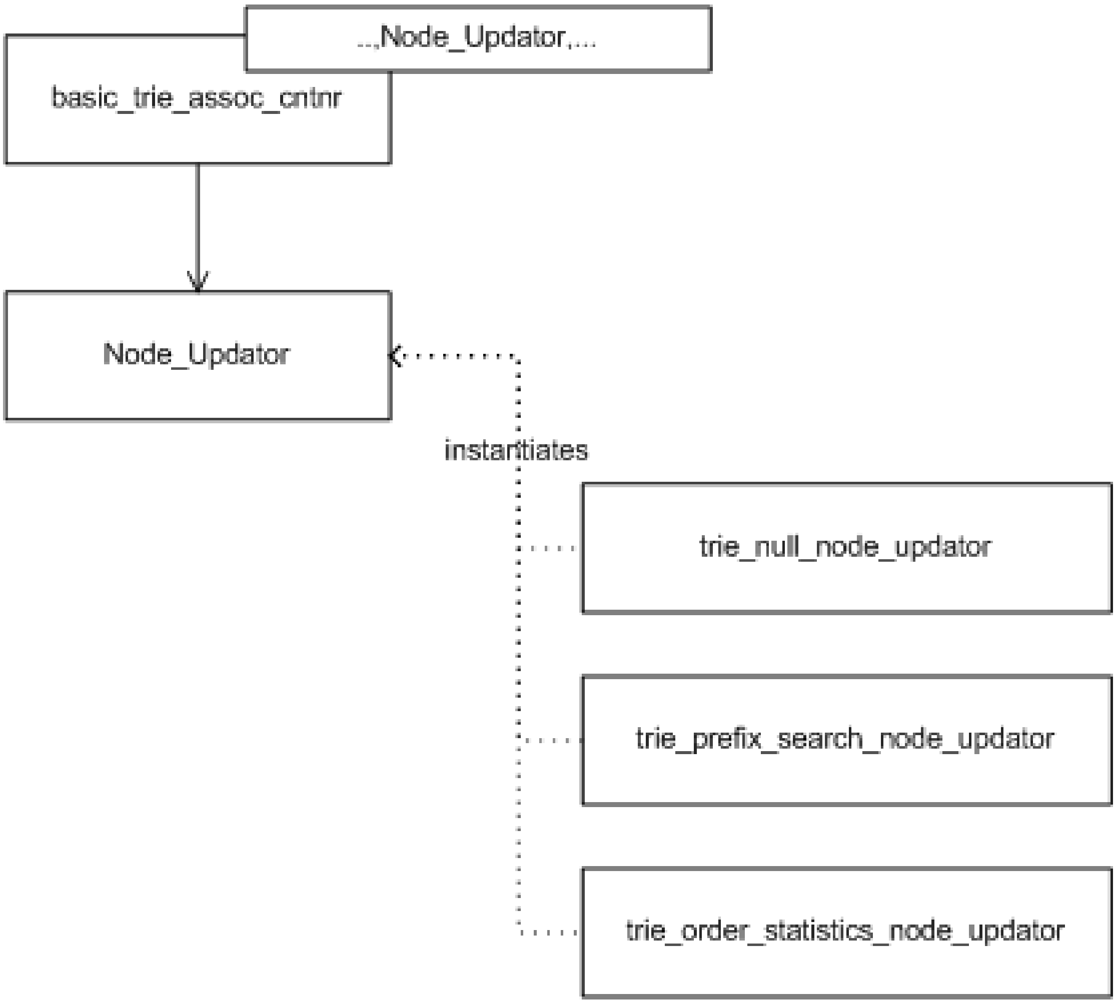


Figure 21.29: A trie and its update policy

This library offers the following pre-defined trie node updating policies:

1. `trie_order_statistics_node_update` supports order statistics.
2. `trie_prefix_search_node_update` supports searching for ranges that match a given prefix.
3. `null_node_update` is the null node updater.

21.3.2.3.2.3 Split and Join

Trie-based containers support split and join methods; the rationale is equal to that of tree-based containers supporting these methods.

21.3.2.4 List

21.3.2.4.1 Interface

The list-based container has the following declaration:

```
template<typename Key,
typename Mapped,
typename Eq_Fn = std::equal_to<Key>,
typename Update_Policy = move_to_front_lu_policy<>,
typename Allocator = std::allocator<char> >
class list_update;
```

The parameters have the following meaning:

1. `Key` is the key type.
2. `Mapped` is the mapped-policy.
3. `Eq_Fn` is a key equivalence functor.
4. `Update_Policy` is a policy updating positions in the list based on access patterns. It is described in the following subsection.
5. `Allocator` is an allocator type.

A list-based associative container is a container that stores elements in a linked-list. It does not order the elements by any particular order related to the keys. List-based containers are primarily useful for creating "multimaps". In fact, list-based containers are designed in this library expressly for this purpose.

List-based containers might also be useful for some rare cases, where a key is encapsulated to the extent that only key-equivalence can be tested. Hash-based containers need to know how to transform a key into a size type, and tree-based containers need to know if some key is larger than another. List-based associative containers, conversely, only need to know if two keys are equivalent.

Since a list-based associative container does not order elements by keys, is it possible to order the list in some useful manner? Remarkably, many on-line competitive algorithms exist for reordering lists to reflect access prediction. (See [85] and [57]).

21.3.2.4.2 Details

21.3.2.4.2.1 Underlying Data Structure

The graphic below shows a simple list of integer keys. If we search for the integer 6, we are paying an overhead: the link with key 6 is only the fifth link; if it were the first link, it could be accessed faster.

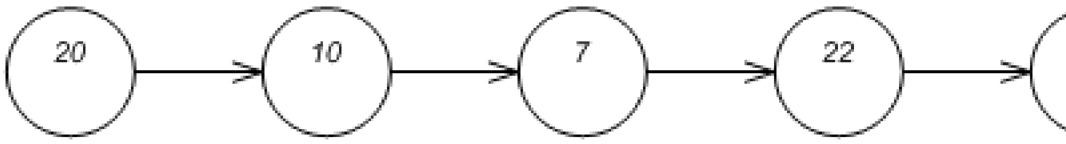


Figure 21.30: A simple list

List-update algorithms reorder lists as elements are accessed. They try to determine, by the access history, which keys to move to the front of the list. Some of these algorithms require adding some metadata alongside each entry.

For example, in the graphic below label A shows the counter algorithm. Each node contains both a key and a count metadata (shown in bold). When an element is accessed (e.g. 6) its count is incremented, as shown in label B. If the count reaches some predetermined value, say 10, as shown in label C, the count is set to 0 and the node is moved to the front of the list, as in label D.

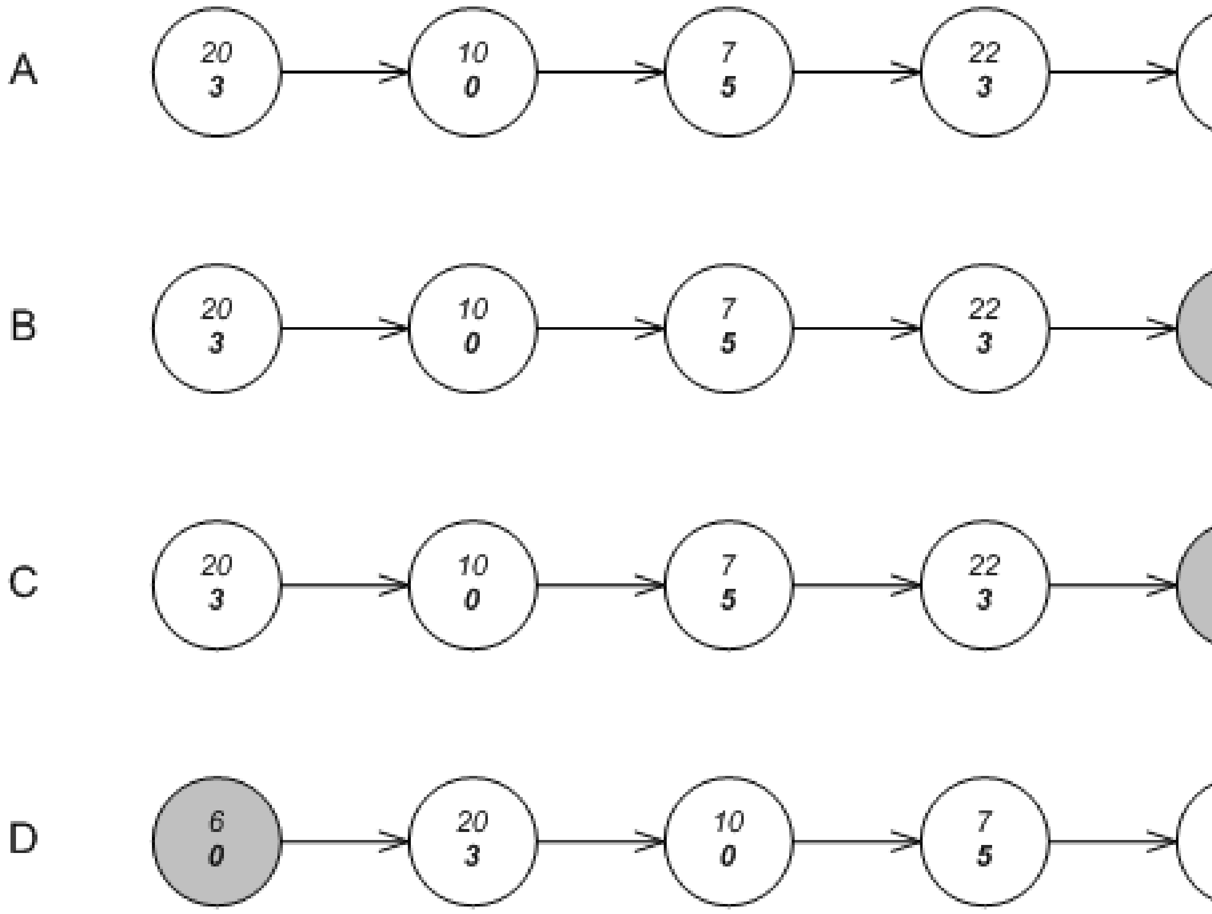


Figure 21.31: The counter algorithm

21.3.2.4.2.2 Policies

this library allows instantiating lists with policies implementing any algorithm moving nodes to the front of the list (policies implementing algorithms interchanging nodes are unsupported).

Associative containers based on lists are parametrized by a `Update_Policy` parameter. This parameter defines the type of metadata each node contains, how to create the metadata, and how to decide, using this metadata, whether to move a node to the front of the list. A list-based associative container object derives (publicly) from its update policy.

An instantiation of `Update_Policy` must define internally `update_metadata` as the metadata it requires. Internally, each node of the list contains, besides the usual key and data, an instance of `typename Update_Policy::update_metadata`.

An instantiation of `Update_Policy` must define internally two operators:

```
update_metadata
operator()();

bool
operator()(update_metadata &);
```

The first is called by the container object, when creating a new node, to create the node's metadata. The second is called by the container object, when a node is accessed (when a find operation's key is equivalent to the key of the node), to determine whether to move the node to the front of the list.

The library contains two predefined implementations of list-update policies. The first is lu_counter_policy, which implements the counter algorithm described above. The second is lu_move_to_front_policy, which unconditionally move an accessed element to the front of the list. The latter type is very useful in this library, since there is no need to associate metadata with each element. (See [57]

21.3.2.4.2.3 Use in Multimaps

In this library, there are no equivalents for the standard's multimaps and multisets; instead one uses an associative container mapping primary keys to secondary keys.

List-based containers are especially useful as associative containers for secondary keys. In fact, they are implemented here expressly for this purpose.

To begin with, these containers use very little per-entry structure memory overhead, since they can be implemented as singly-linked lists. (Arrays use even lower per-entry memory overhead, but they are less flexible in moving around entries, and have weaker invalidation guarantees).

More importantly, though, list-based containers use very little per-container memory overhead. The memory overhead of an empty list-based container is practically that of a pointer. This is important for when they are used as secondary associative-containers in situations where the average ratio of secondary keys to primary keys is low (or even 1).

In order to reduce the per-container memory overhead as much as possible, they are implemented as closely as possible to singly-linked lists.

1. List-based containers do not store internally the number of values that they hold. This means that their size method has linear complexity (just like std::list). Note that finding the number of equivalent-key values in a standard multimap also has linear complexity (because it must be done, via std::distance of the multimap's equal_range method), but usually with higher constants.

2. Most associative-container objects each hold a policy object (a hash-based container object holds a hash functor). List-based containers, conversely, only have class-wide policy objects.

21.3.2.5 Priority Queue

21.3.2.5.1 Interface

The priority queue container has the following declaration:

```
template<typename  Value_Type,
typename  Cmp_Fn = std::less<Value_Type>,
typename  Tag = pairing_heap_tag,
typename  Allocator = std::allocator<char > >
class priority_queue;
```

The parameters have the following meaning:

1. Value_Type is the value type.

2. Cmp_Fn is a value comparison functor

3. Tag specifies which underlying data structure to use.

4. Allocator is an allocator type.

The Tag parameter specifies which underlying data structure to use. Instantiating it bypairing_heap_tag,binary_heap_tag, binomial_heap_tag, rc_binomial_heap_tag, or thin_heap_tag, specifies, respectively, an underlying pairing heap ([70]), binary heap ([66]), binomial heap ([66]), a binomial heap with a redundant binary counter ([80]), or a thin heap ([75]).

As mentioned in the tutorial, __gnu_pbds::priority_queue shares most of the same interface with std::priority_queue. E.g. if q is a priority queue of type Q, then q.top() will return the "largest" value in the container (according to typename

Q::cmp_fn). __gnu_pbds::priority_queue has a larger (and very slightly different) interface than std::priority_queu however, since typically push and pop are deemed insufficient for manipulating priority-queues.

Different settings require different priority-queue implementations which are described in later; see traits discusses ways to differentiate between the different traits of different implementations.

21.3.2.5.2 Details

21.3.2.5.2.1 Iterators

There are many different underlying-data structures for implementing priority queues. Unfortunately, most such structures are oriented towards making push and top efficient, and consequently don't allow efficient access of other elements: for instance, they cannot support an efficient find method. In the use case where it is important to both access and "do something with" an arbitrary value, one would be out of luck. For example, many graph algorithms require modifying a value (typically increasing it in the sense of the priority queue's comparison functor).

In order to access and manipulate an arbitrary value in a priority queue, one needs to reference the internals of the priority queue from some form of an associative container - this is unavoidable. Of course, in order to maintain the encapsulation of the priority queue, this needs to be done in a way that minimizes exposure to implementation internals.

In this library the priority queue's insert method returns an iterator, which if valid can be used for subsequent modify and erase operations. This both preserves the priority queue's encapsulation, and allows accessing arbitrary values (since the returned iterators from the push operation can be stored in some form of associative container).

Priority queues' iterators present a problem regarding their invalidation guarantees. One assumes that calling operator++ on an iterator will associate it with the "next" value. Priority-queues are self-organizing: each operation changes what the "next" value means. Consequently, it does not make sense that push will return an iterator that can be incremented - this can have no possible use. Also, as in the case of hash-based containers, it is awkward to define if a subsequent push operation invalidates a prior returned iterator: it invalidates it in the sense that its "next" value is not related to what it previously considered to be its "next" value. However, it might not invalidate it, in the sense that it can be de-referenced and used for modify and erase operations.

Similarly to the case of the other unordered associative containers, this library uses a distinction between point-type and range type iterators. A priority queue's iterator can always be converted to a point_iterator, and a const_iterator can always be converted to a point_const_iterator.

The following snippet demonstrates manipulating an arbitrary value:

```
// A priority queue of integers.
priority_queue<int > p;

// Insert some values into the priority queue.
priority_queue<int >::point_iterator it = p.push(0);

p.push(1);
p.push(2);

// Now modify a value.
p.modify(it, 3);

assert(p.top() == 3);
```

It should be noted that an alternative design could embed an associative container in a priority queue. Could, but most probably should not. To begin with, it should be noted that one could always encapsulate a priority queue and an associative container mapping values to priority queue iterators with no performance loss. One cannot, however, "un-encapsulate" a priority queue embedding an associative container, which might lead to performance loss. Assume, that one needs to associate each value with some data unrelated to priority queues. Then using this library's design, one could use an associative container mapping each value to a pair consisting of this data and a priority queue's iterator. Using the embedded method would need to use two associative containers. Similar problems might arise in cases where a value can reside simultaneously in many priority queues.

21.3.2.5.2.2 Underlying Data Structure

There are three main implementations of priority queues: the first employs a binary heap, typically one which uses a sequence; the second uses a tree (or forest of trees), which is typically less structured than an associative container's tree; the third simply uses an associative container. These are shown in the graphic below, in labels A1 and A2, label B, and label C.

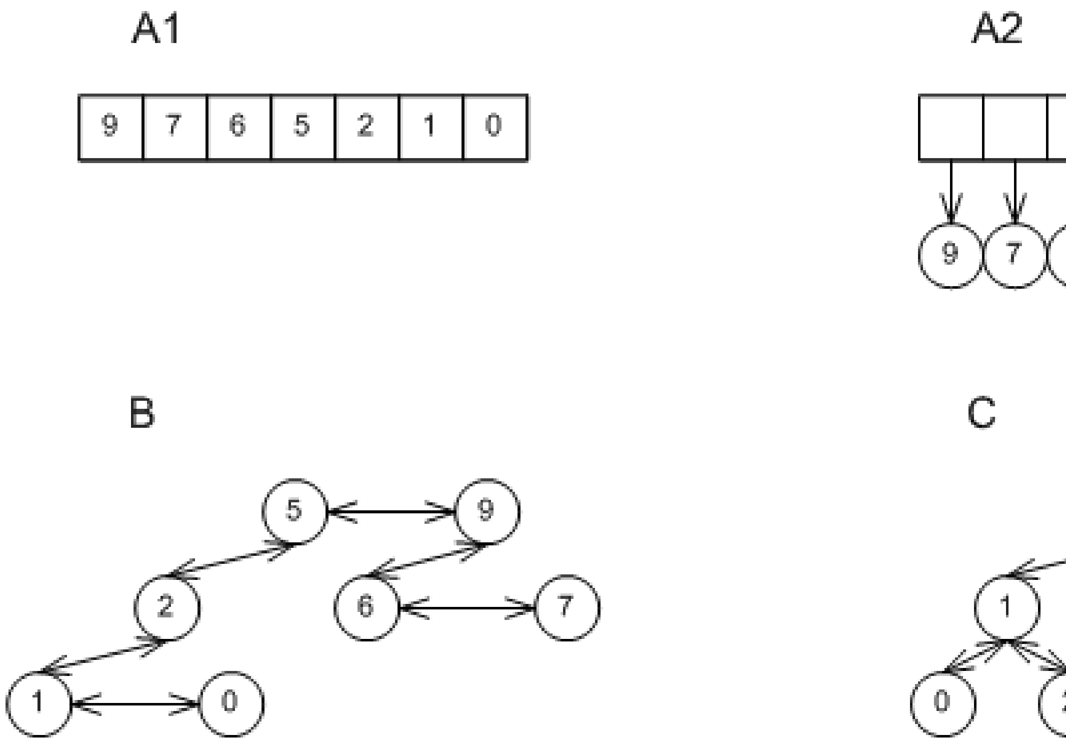


Figure 21.32: Underlying Priority-Queue Data-Structures.

Roughly speaking, any value that is both pushed and popped from a priority queue must incur a logarithmic expense (in the amortized sense). Any priority queue implementation that would avoid this, would violate known bounds on comparison-based sorting (see [66] and [64]).

Most implementations do not differ in the asymptotic amortized complexity of `push` and `pop` operations, but they differ in the constants involved, in the complexity of other operations (e.g., `modify`), and in the worst-case complexity of single operations. In general, the more "structured" an implementation (i.e., the more internal invariants it possesses) - the higher its amortized complexity of `push` and `pop` operations.

This library implements different algorithms using a single class: `priority_queue`. Instantiating the `Tag` template parameter, "selects" the implementation:

1. Instantiating `Tag = binary_heap_tag` creates a binary heap of the form in represented in the graphic with labels A1 or A2. The former is internally selected by priority_queue if `Value_Type` is instantiated by a primitive type (e.g., an int); the latter is internally selected for all other types (e.g., `std::string`). This implementations is relatively unstructured, and so has good `push` and `pop` performance; it is the "best-in-kind" for primitive types, e.g., ints. Conversely, it has high worst-case performance, and can support only linear-time `modify` and `erase` operations.
2. Instantiating `Tag = pairing_heap_tag` creates a pairing heap of the form in represented by label B in the graphic above. This implementations too is relatively unstructured, and so has good `push` and `pop` performance; it is the "best-in-kind" for non-primitive types, e.g., `std:strings`. It also has very good worst-case `push` and `join` performance (O(1)), but has high worst-case `pop` complexity.

3. Instantiating `Tag = binomial_heap_tag` creates a binomial heap of the form repsented by label B in the graphic above. This implementations is more structured than a pairing heap, and so has worse `push` and `pop` performance. Conversely, it has sub-linear worst-case bounds for `pop`, e.g., and so it might be preferred in cases where responsiveness is important.

4. Instantiating `Tag = rc_binomial_heap_tag` creates a binomial heap of the form represented in label B above, accompanied by a redundant counter which governs the trees. This implementations is therefore more structured than a binomial heap, and so has worse `push` and `pop` performance. Conversely, it guarantees O(1) `push` complexity, and so it might be preferred in cases where the responsiveness of a binomial heap is insufficient.

5. Instantiating `Tag = thin_heap_tag` creates a thin heap of the form represented by the label B in the graphic above. This implementations too is more structured than a pairing heap, and so has worse `push` and `pop` performance. Conversely, it has better worst-case and identical amortized complexities than a Fibonacci heap, and so might be more appropriate for some graph algorithms.

Of course, one can use any order-preserving associative container as a priority queue, as in the graphic above label C, possibly by creating an adapter class over the associative container (much as `std::priority_queue` can adapt `std::vector`). This has the advantage that no cross-referencing is necessary at all; the priority queue itself is an associative container. Most associative containers are too structured to compete with priority queues in terms of `push` and `pop` performance.

21.3.2.5.2.3 Traits

It would be nice if all priority queues could share exactly the same behavior regardless of implementation. Sadly, this is not possible. Just one for instance is in join operations: joining two binary heaps might throw an exception (not corrupt any of the heaps on which it operates), but joining two pairing heaps is exception free.

Tags and traits are very useful for manipulating generic types. `__gnu_pbds::priority_queue` publicly defines `container_ca` as one of the tags. Given any container `Cntnr`, the tag of the underlying data structure can be found via `typename Cntnr::contai` this is one of the possible tags shown in the graphic below.

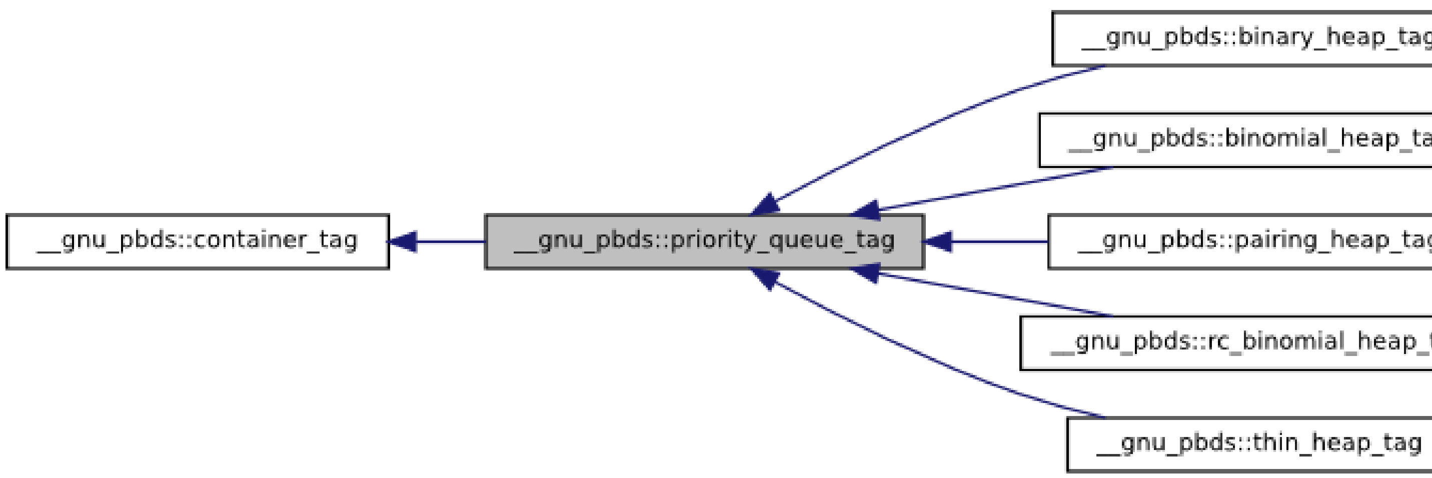


Figure 21.33: Priority-Queue Data-Structure Tags.

Additionally, a traits mechanism can be used to query a container type for its attributes. Given any container `Cntnr`, then

```
__gnu_pbds::container_traits<Cntnr>
```

is a traits class identifying the properties of the container.

To find if a container might throw if two of its objects are joined, one can use

```
      container_traits<Cntnr>::split_join_can_throw
```

Different priority-queue implementations have different invalidation guarantees. This is especially important, since there is no way to access an arbitrary value of priority queues except for iterators. Similarly to associative containers, one can use

```
container_traits<Cntnr>::invalidation_guarantee
```

to get the invalidation guarantee type of a priority queue.

It is easy to understand from the graphic above, what `container_traits<Cntnr>::invalidation_guarantee` will be for different implementations. All implementations of type represented by label B have `point_invalidation_guarantee`: the container can freely internally reorganize the nodes - range-type iterators are invalidated, but point-type iterators are always valid. Implementations of type represented by labels A1 and A2 have `basic_invalidation_guarantee`: the container can freely internally reallocate the array - both point-type and range-type iterators might be invalidated.

This has major implications, and constitutes a good reason to avoid using binary heaps. A binary heap can perform `modify` or `erase` efficiently given a valid point-type iterator. However, in order to supply it with a valid point-type iterator, one needs to iterate (linearly) over all values, then supply the relevant iterator (recall that a range-type iterator can always be converted to a point-type iterator). This means that if the number of `modify` or `erase` operations is non-negligible (say super-logarithmic in the total sequence of operations) - binary heaps will perform badly.

21.4 Testing

21.4.1 Regression

The library contains a single comprehensive regression test. For a given container type in this library, the test creates an object of the container type and an object of the corresponding standard type (e.g., `std::set`). It then performs a random sequence of methods with random arguments (e.g., inserts, erases, and so forth) on both objects. At each operation, the test checks the return value of the method, and optionally both compares this library's object with the standard's object as well as performing other consistency checks on this library's object (e.g., order preservation, when applicable, or node invariants, when applicable).

Additionally, the test integrally checks exception safety and resource leaks. This is done as follows. A special allocator type, written for the purpose of the test, both randomly throws an exceptions when allocations are performed, and tracks allocations and de-allocations. The exceptions thrown at allocations simulate memory-allocation failures; the tracking mechanism checks for memory-related bugs (e.g., resource leaks and multiple de-allocations). Both this library's containers and the containers' value-types are configured to use this allocator.

For granularity, the test is split into the several sources, each checking only some containers.

For more details, consult the files in `testsuite/ext/pb_ds/regression`.

21.4.2 Performance

21.4.2.1 Hash-Based

21.4.2.1.1 Text `find`

21.4.2.1.1.1 Description

This test inserts a number of values with keys from an arbitrary text ([98]) into a container, then performs a series of finds using `find` . It measures the average time for `find` as a function of the number of values inserted.

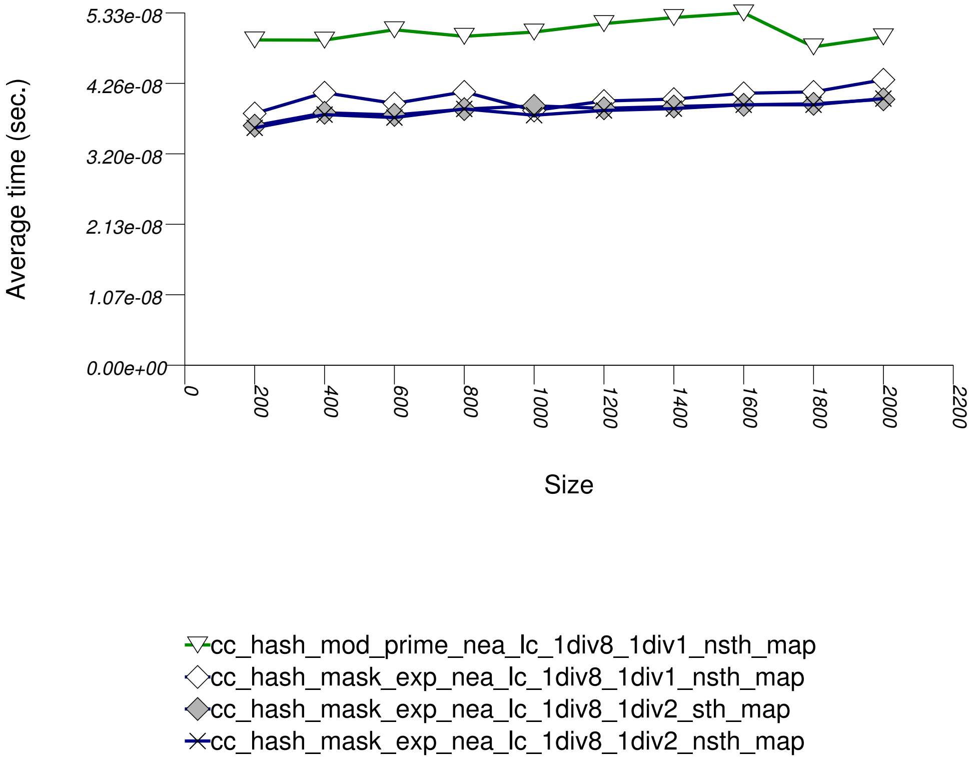
It uses the test file: `performance/ext/pb_ds/text_find_timing_test.cc`

And uses the data file: `filethirty_years_among_the_dead_preproc.txt`

The test checks the effect of different range-hashing functions, trigger policies, and cache-hashing policies.

21.4.2.1.1.2 Results

The graphic below show the results for the native and collision-chaining hash types the function applied being a text find timing test using `find`.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
`std::tr1::unordered_map`	`cache_hash_code`	`false`		
cc_hash_mod_prime_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mask_exp_1div2_sth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2
cc_hash_mask_exp_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mask_exp_1div2_nsth_map				

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.1.1.3 Observations

In this setting, the range-hashing scheme affects performance more than other policies. As the results show, containers using mod-based range-hashing (including the native hash-based container, which is currently hard-wired to this scheme) have lower performance than those using mask-based range-hashing. A modulo-based range-hashing scheme's main benefit is that it takes into account all hash-value bits. Standard string hash-functions are designed to create hash values that are nearly-uniform as is ([77]).

Trigger policies, i.e. the load-checks constants, affect performance to a lesser extent.

Perhaps surprisingly, storing the hash value alongside each entry affects performance only marginally, at least in this library's implementation. (Unfortunately, it was not possible to run the tests with `std::tr1::unordered_map` 's `cache_hash_code = true` , as it appeared to malfuntion.)

21.4.2.1.2 Integer `find`

21.4.2.1.2.1 Description

This test inserts a number of values with uniform integer keys into a container, then performs a series of finds using `find`. It measures the average time for `find` as a function of the number of values inserted.

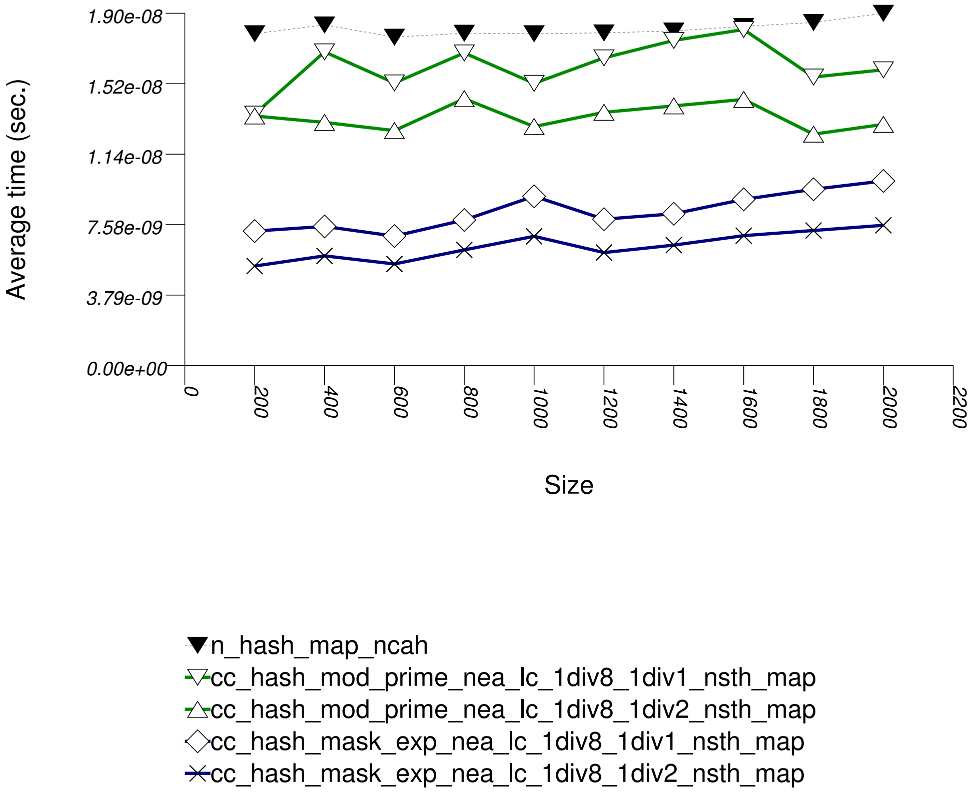
It uses the test file: `performance/ext/pb_ds/random_int_find_timing.cc`

The test checks the effect of different underlying hash-tables, range-hashing functions, and trigger policies.

21.4.2.1.2.2 Results

There are two sets of results for this type, one for collision-chaining hashes, and one for general-probe hashes.

The first graphic below shows the results for the native and collision-chaining hash types. The function applied being a random integer timing test using `find`.

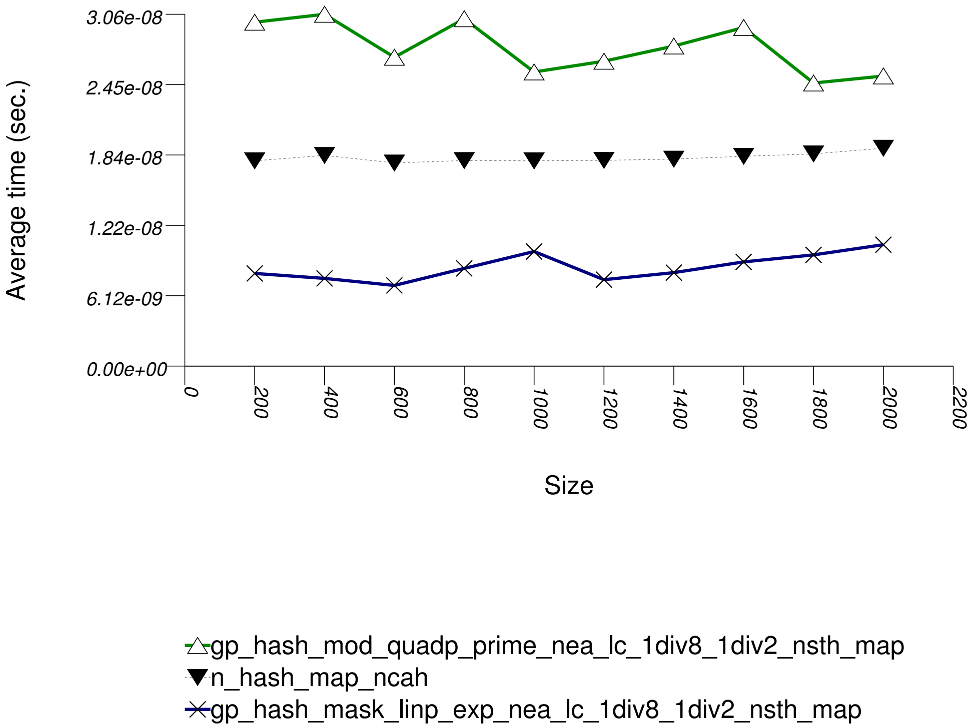


The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
`std::tr1::unordered_map`	`cache_hash_code`	`false`		
cc_hash_mod_prime_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_polic`
			`Trigger_Policy`	`hash_load_check_resiz` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mod_prime_1div2_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_polic`
			`Trigger_Policy`	`hash_load_check_resiz` with α_{min} = 1/8 and α_{max} = 1/2
cc_hash_mask_exp_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resiz` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mask_exp_1div2_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
			Trigger_Policy	hash_load_check_resize with α_{min} = 1/8 and α_{max} = 1/2

And the second graphic shows the results for the native and general-probe hash types. The function applied being a random integer timing test using find.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
std::tr1::unordered_map	cache_hash_code	false		
gp_hash_mod_quadp_prime_1div2_nsth_map				
gp_hash_table	Comb_Hash_Fn	direct_mod_range_hashing		
	Probe_Fn	quadratic_probe_fn		
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_prime_size_policy
			Trigger_Policy	hash_load_check_resize with α_{min} = 1/8 and α_{max} = 1/2
gp_hash_mask_linp_exp_1div2_nsth_map				
gp_hash_table	Comb_Hash_Fn	direct_mask_range_hashing		
	Probe_Fn	linear_probe_fn		
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_size_
			Trigger_Policy	hash_load_check_resize with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.1.2.3 Observations

In this setting, the choice of underlying hash-table affects performance most, then the range-hashing scheme and, only finally, other policies.

When comparing probing and chaining containers, it is apparent that the probing containers are less efficient than the collision-chaining containers (`std::tr1::unordered_map` uses collision-chaining) in this case.

Hash-Based Integer Subscript Insert Timing Test shows a different case, where the situation is reversed;

Within each type of hash-table, the range-hashing scheme affects performance more than other policies; Hash-Based Text `find` Find Timing Test also shows this. In the above graphics should be noted that `std::tr1::unordered_map` are hard-wired currently to mod-based schemes.

21.4.2.1.3 Integer Subscript `find`

21.4.2.1.3.1 Description

This test inserts a number of values with uniform integer keys into a container, then performs a series of finds using `operator[]`. It measures the average time for `operator[]` as a function of the number of values inserted.

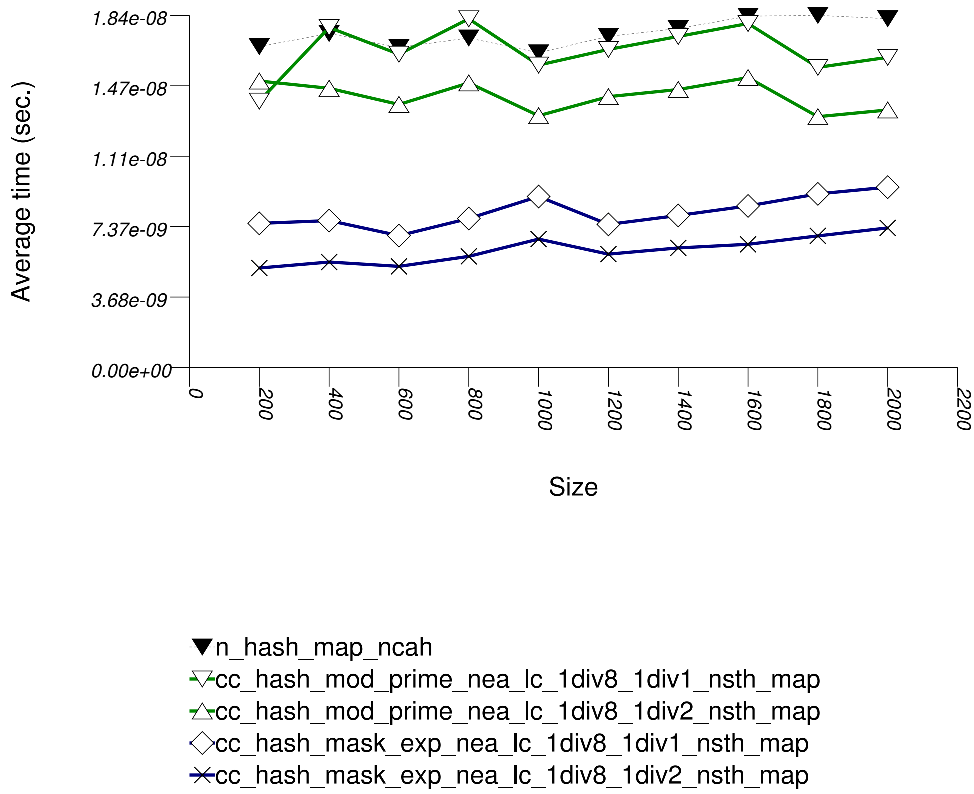
It uses the test file: `performance/ext/pb_ds/random_int_subscript_find_timing.cc`

The test checks the effect of different underlying hash-tables, range-hashing functions, and trigger policies.

21.4.2.1.3.2 Results

There are two sets of results for this type, one for collision-chaining hashes, and one for general-probe hashes.

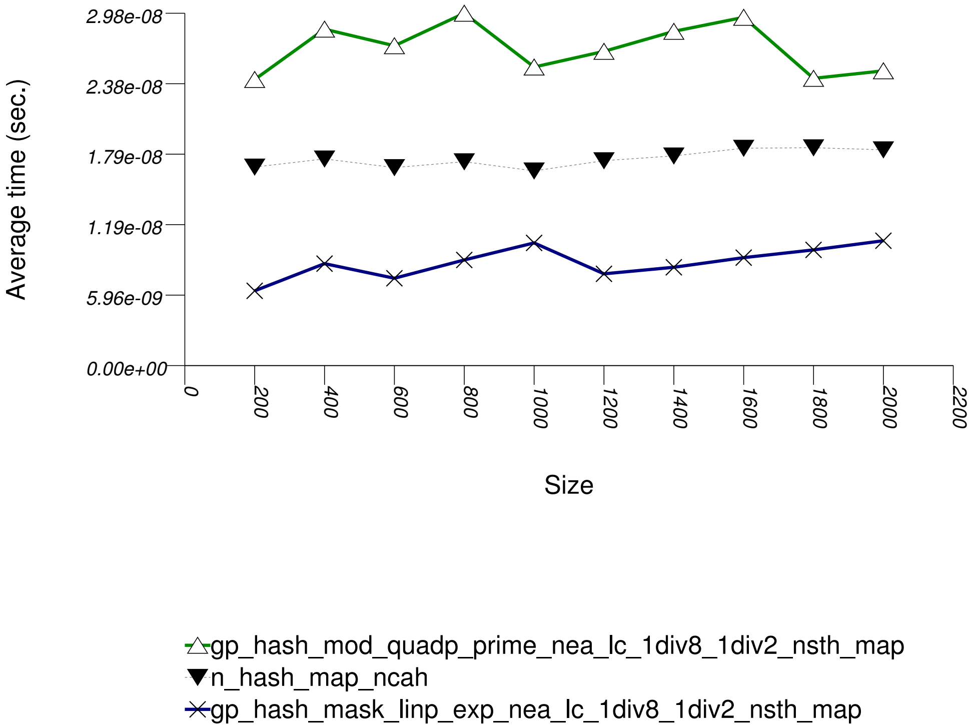
The first graphic below shows the results for the native and collision-chaining hash types, using as the function applied an integer subscript timing test with `find`.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
`std::tr1::unordered_map`	`cache_hash_code`	`false`		
cc_hash_mod_prime_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mod_prime_1div2_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2
cc_hash_mask_exp_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mask_exp_1div2_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2

And the second graphic shows the results for the native and general-probe hash types. The function applied being a random integer timing test using `find`.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
`std::tr1::unordered_map`	`cache_hash_code`	`false`		
gp_hash_mod_quadp_prime_1div2_nsth_map				
`gp_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Probe_Fn`	`quadratic_probe_fn`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2
gp_hash_mask_linp_exp_1div2_nsth_map				
`gp_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Probe_Fn`	`linear_probe_fn`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.1.3.3 Observations

This test shows similar results to Hash-Based Integer `find` Find Timing test.

21.4.2.1.4 Integer Subscript `insert`

21.4.2.1.4.1 Description

This test inserts a number of values with uniform i.i.d. integer keys into a container, using `operator[]`. It measures the average time for `operator[]` as a function of the number of values inserted.

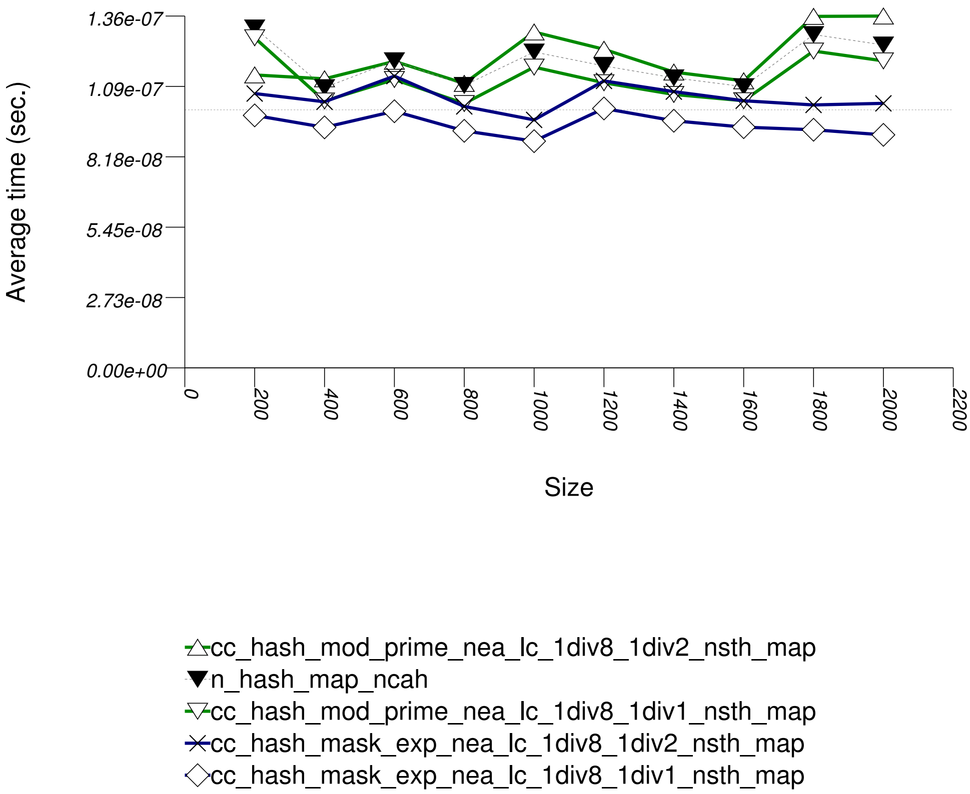
It uses the test file: `performance/ext/pb_ds/random_int_subscript_insert_timing.cc`

The test checks the effect of different underlying hash-tables.

21.4.2.1.4.2 Results

There are two sets of results for this type, one for collision-chaining hashes, and one for general-probe hashes.

The first graphic below shows the results for the native and collision-chaining hash types, using as the function applied an integer subscript timing test with `insert`.

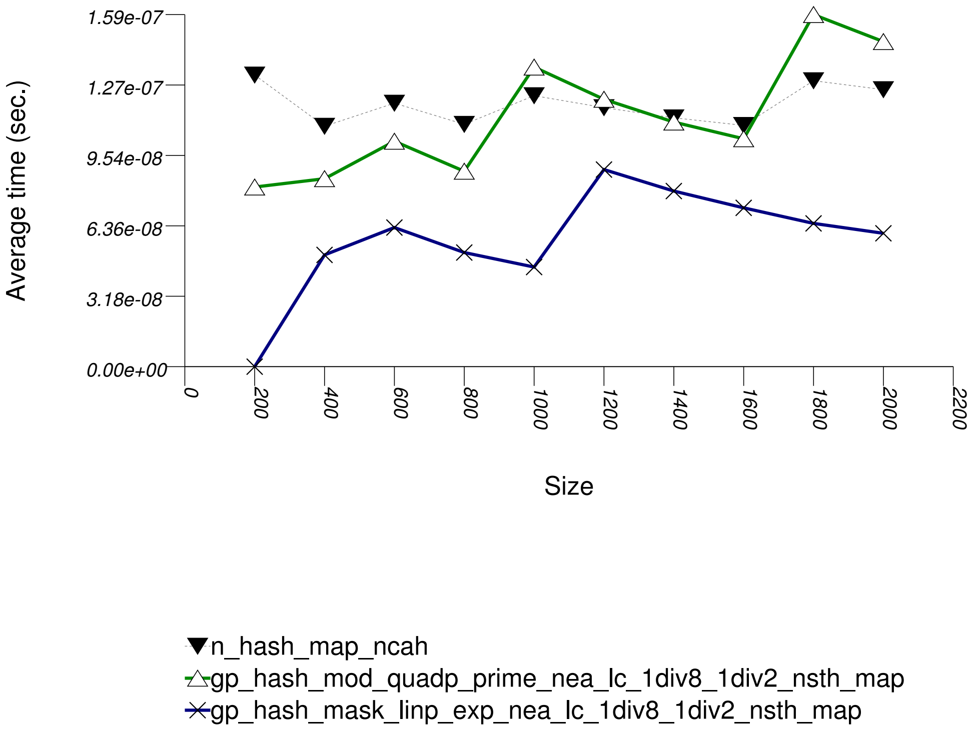


The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
`std::tr1::unordered_map`	`cache_hash_code`	`false`		
cc_hash_mod_prime_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mod_prime_1div2_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2
cc_hash_mask_exp_1div1_nsth_map				

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mask_exp_1div2_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2

And the second graphic shows the results for the native and general-probe hash types. The function applied being a random integer timing test using `find`.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
`std::tr1::unordered_map`	`cache_hash_code`	`false`		
gp_hash_mod_quadp_prime_1div2_nsth_map				
`gp_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Probe_Fn`	`quadratic_probe_fn`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2

Name/Instantiating Type	*Parameter*	*Details*	*Parameter*	*Details*
gp_hash_mask_linp_exp_1div2_nsth_map				
gp_hash_table	Comb_Hash_Fn	direct_mask_range_hashing		
	Probe_Fn	linear_probe_fn		
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_size_
			Trigger_Policy	hash_load_check_resize with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.1.4.3 Observations

In this setting, as in Hash-Based Text `find` Find Timing test and Hash-Based Integer `find` Find Timing test , the choice of underlying hash-table underlying hash-table affects performance most, then the range-hashing scheme, and finally any other policies.

There are some differences, however:

1. In this setting, probing tables function sometimes more efficiently than collision-chaining tables. This is explained shortly.
2. The performance graphs have a "saw-tooth" shape. The average insert time rises and falls. As values are inserted into the container, the load factor grows larger. Eventually, a resize occurs. The reallocations and rehashing are relatively expensive. After this, the load factor is smaller than before.

Collision-chaining containers use indirection for greater flexibility; probing containers store values contiguously, in an array (see Figure Motivation::Different underlying data structures A and B, respectively). It follows that for simple data types, probing containers access their allocator less frequently than collision-chaining containers, (although they still have less efficient probing sequences). This explains why some probing containers fare better than collision-chaining containers in this case.

Within each type of hash-table, the range-hashing scheme affects performance more than other policies. This is similar to the situation in Hash-Based Text `find` Find Timing Test and Hash-Based Integer `find` Find Timing Test. Unsurprisingly, however, containers with lower α_{max} perform worse in this case, since more re-hashes are performed.

21.4.2.1.5 Integer `find` with Skewed-Distribution

21.4.2.1.5.1 Description

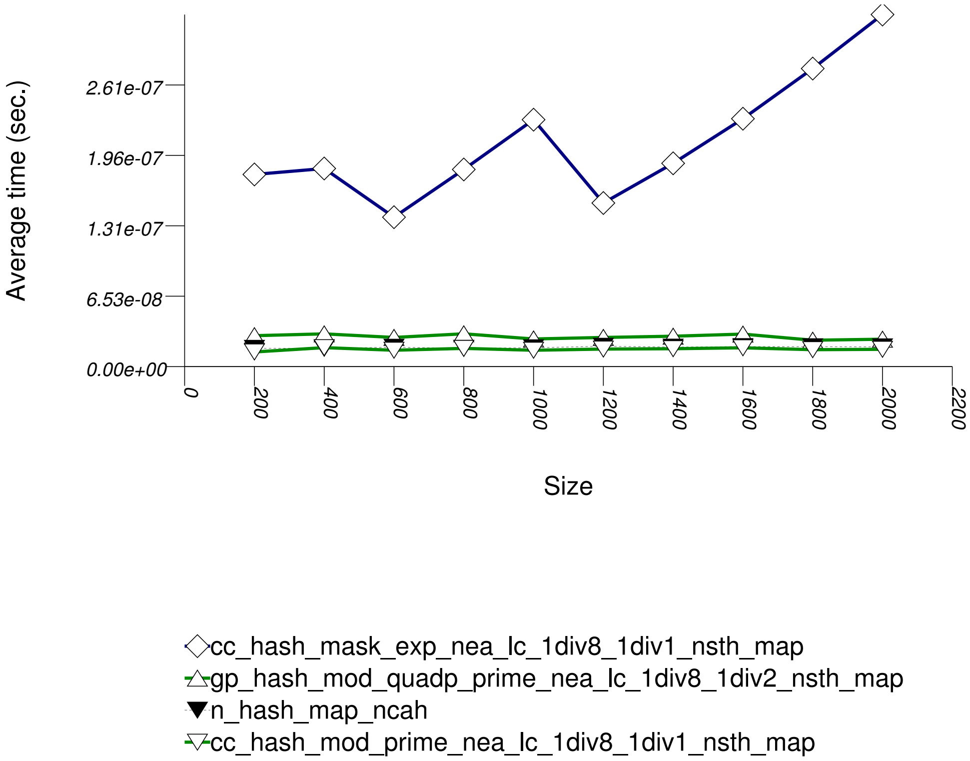
This test inserts a number of values with a markedly non-uniform integer keys into a container, then performs a series of finds using `find`. It measures the average time for `find` as a function of the number of values in the containers. The keys are generated as follows. First, a uniform integer is created. Then it is then shifted left 8 bits.

It uses the test file: `performance/ext/pb_ds/hash_zlob_random_int_find_timing.cc`

The test checks the effect of different range-hashing functions and trigger policies.

21.4.2.1.5.2 Results

The graphic below show the results for the native, collision-chaining, and general-probing hash types.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
`std::tr1::unordered_map`	`cache_hash_code`	`false`		
cc_hash_mod_prime_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mask_exp_1div1_nsth_map				
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/1
gp_hash_mod_quadp_prime_1div2_nsth_map				
`gp_hash_table`	`Comb_Hash_Fn`	`direct_mod_range_hashing`		
	`Probe_Fn`	`quadratic_probe_fn`		
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_prime_size_policy`
			`Trigger_Policy`	`hash_load_check_resize` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.1.5.3 Observations

In this setting, the distribution of keys is so skewed that the underlying hash-table type affects performance marginally. (This is in contrast with Hash-Based Text `find` Find Timing Test, Hash-Based Integer `find` Find Timing Test, Hash-Based Integer Subscript Find Timing Test and Hash-Based Integer Subscript Insert Timing Test.)

The range-hashing scheme affects performance dramatically. A mask-based range-hashing scheme effectively maps all values into the same bucket. Access degenerates into a search within an unordered linked-list. In the graphic above, it should be noted that `std::tr1::unordered_map` is hard-wired currently to mod-based and mask-based schemes, respectively.

When observing the settings of this test, it is apparent that the keys' distribution is far from natural. One might ask if the test is not contrived to show that, in some cases, mod-based range hashing does better than mask-based range hashing. This is, in fact just the case. A more natural case in which mod-based range hashing is better was not encountered. Thus the inescapable conclusion: real-life key distributions are handled better with an appropriate hash function and a mask-based range-hashing function. (`pb_ds/example/hash_shift_mask.cc` shows an example of handling this a-priori known skewed distribution with a mask-based range-hashing function). If hash performance is bad, a χ^2 test can be used to check how to transform it into a more uniform distribution.

For this reason, this library's default range-hashing function is mask-based.

21.4.2.1.6 Erase Memory Use

21.4.2.1.6.1 Description

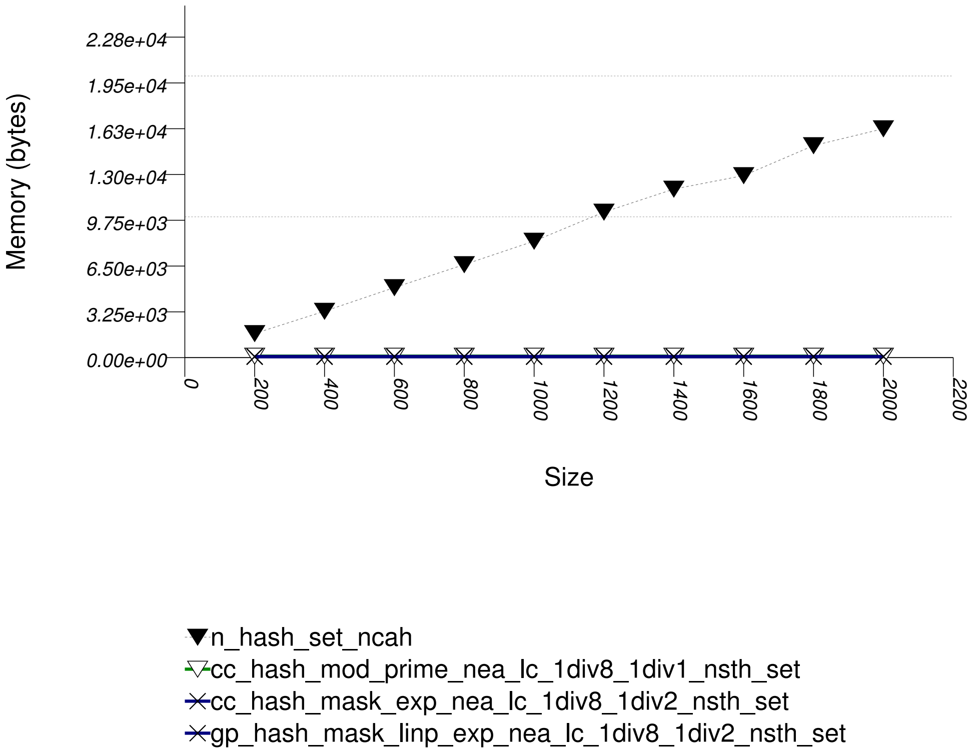
This test inserts a number of uniform integer keys into a container, then erases all keys except one. It measures the final size of the container.

It uses the test file: `performance/ext/pb_ds/hash_random_int_erase_mem_usage.cc`

The test checks how containers adjust internally as their logical size decreases.

21.4.2.1.6.2 Results

The graphic below show the results for the native, collision-chaining, and general-probing hash types.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_map_ncah				
std::tr1::unordered_map	cache_hash_code	false		
cc_hash_mod_prime_1div1_nsth_map				
cc_hash_table	Comb_Hash_Fn	direct_mod_range_hashing		
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_prime_size_polic
			Trigger_Policy	hash_load_check_resiz with α_{min} = 1/8 and α_{max} = 1/1
cc_hash_mask_exp_1div2_nsth_map				
cc_hash_table	Comb_Hash_Fn	direct_mask_range_hashing		
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_size_
			Trigger_Policy	hash_load_check_resiz with α_{min} = 1/8 and α_{max} = 1/2
gp_hash_mask_linp_exp_1div2_nsth_set				
gp_hash_table	Comb_Hash_Fn	direct_mask_range_hashing		
	Probe_Fn	linear_probe_fn		
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_size_
			Trigger_Policy	hash_load_check_resiz with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.1.6.3 Observations

The standard's hash-based containers act very differently than trees in this respect. When erasing numerous keys from an standard associative-container, the resulting memory user varies greatly depending on whether the container is tree-based or hash-based. This is a fundamental consequence of the standard's interface for associative containers, and it is not due to a specific implementation.

21.4.2.2 Branch-Based

21.4.2.2.1 Text `insert`

21.4.2.2.1.1 Description

This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into a container using `insert` . It measures the average time for `insert` as a function of the number of values inserted.

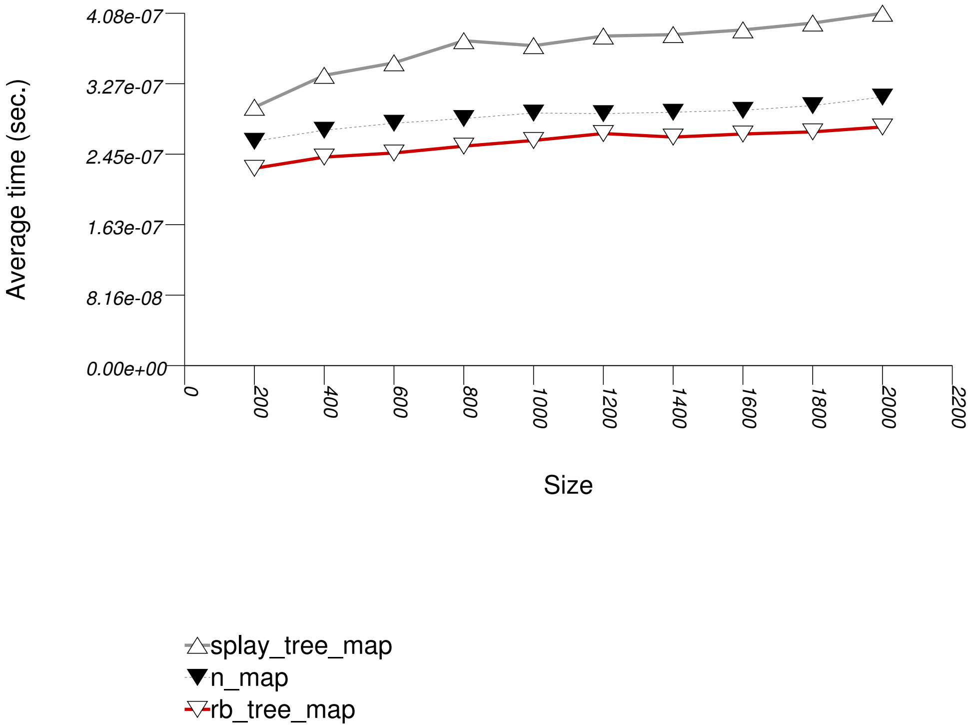
The test checks the effect of different underlying data structures.

It uses the test file: `performance/ext/pb_ds/tree_text_insert_timing.cc`

21.4.2.2.1.2 Results

The three graphics below show the results for the native tree and this library's node-based trees, the native tree and this library's vector-based trees, and the native tree and this library's PATRICIA-trie, respectively.

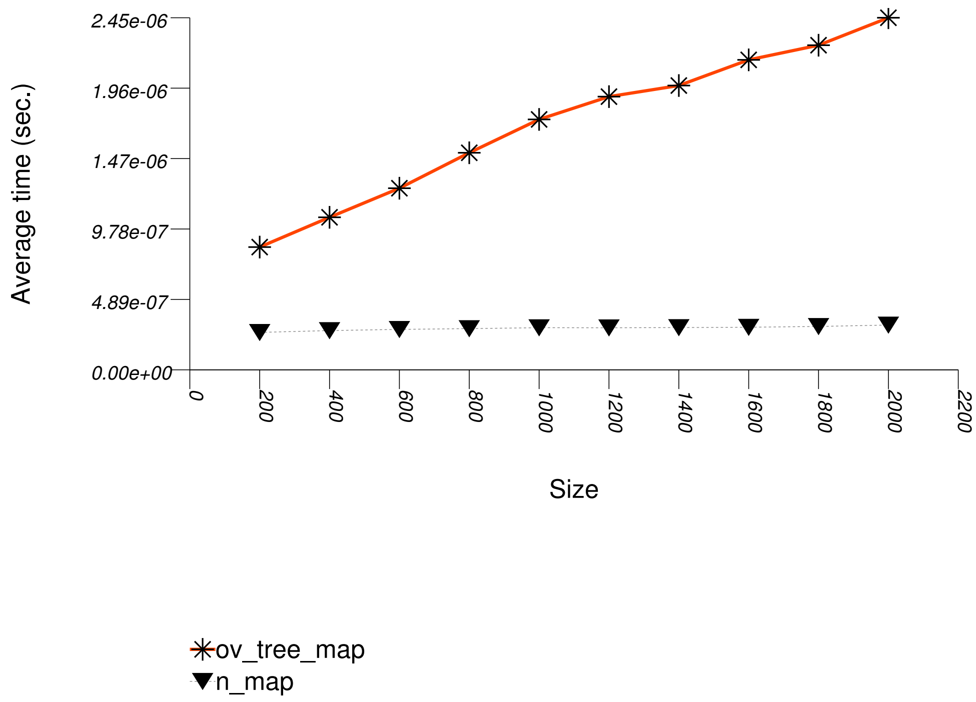
The graphic immediately below shows the results for the native tree type and several node-based tree types.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_map		
`std::map`		
splay_tree_map		
`tree`	`Tag`	`splay_tree_tag`
	`Node_update`	`null_node_update`
rb_tree_map		
`tree`	`Tag`	`rb_tree_tag`
	`Node_update`	`null_node_update`

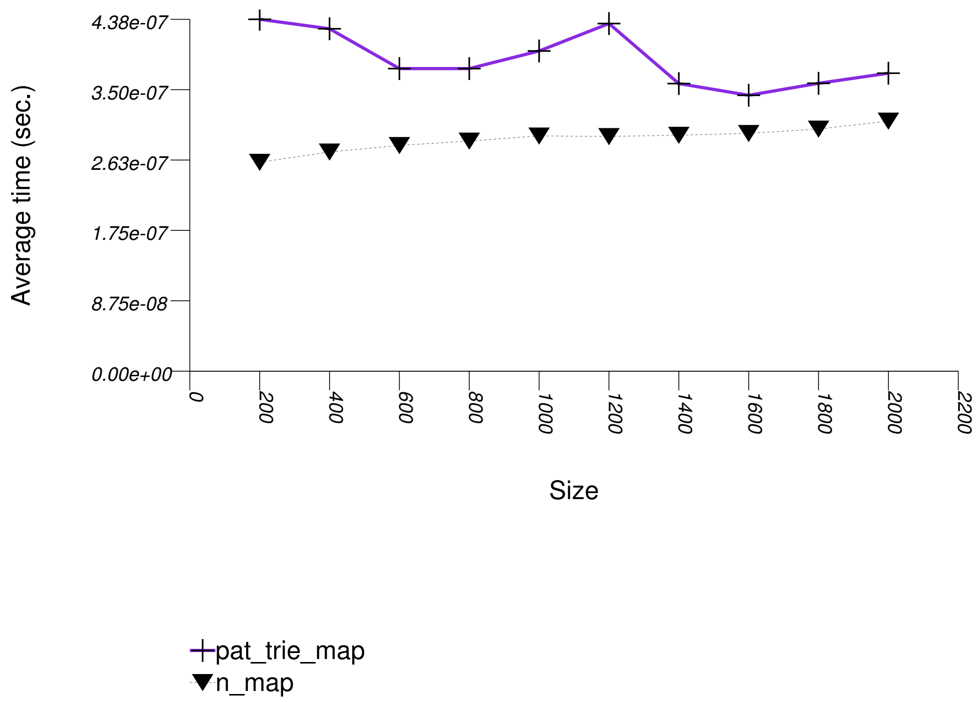
The graphic below shows the results for the native tree type and a vector-based tree type.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_map		
`std::map`		
ov_tree_map		
`tree`	`Tag`	`ov_tree_tag`
	`Node_update`	`null_node_update`

The graphic below shows the results for the native tree type and a PATRICIA trie type.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_map		
`std::map`		
pat_trie_map		
`tree`	`Tag`	`pat_trie_tag`
	`Node_update`	`null_node_update`

21.4.2.2.1.3 Observations

Observing the first graphic implies that for this setting, a splay tree (`tree` with `Tag` = `splay_tree_tag`) does not do well. See also the Branch-Based Text `find` Find Timing Test. The two red-black trees perform better.

Observing the second graphic, an ordered-vector tree (`tree` with `Tag` = `ov_tree_tag`) performs abysmally. Inserting into this type of tree has linear complexity [austern00noset].

Observing the third and last graphic, A PATRICIA trie (`trie` with `Tag` = `pat_trie_tag`) has abysmal performance, as well. This is not that surprising, since a large-fan-out PATRICIA trie works like a hash table with collisions resolved by a sub-trie. Each time a collision is encountered, a new "hash-table" is built A large fan-out PATRICIA trie, however, doe does well in look-ups (see Branch-Based Text `find` Find Timing Test). It may be beneficial in semi-static settings.

21.4.2.2.2 Text **`find`**

21.4.2.2.2.1 Description

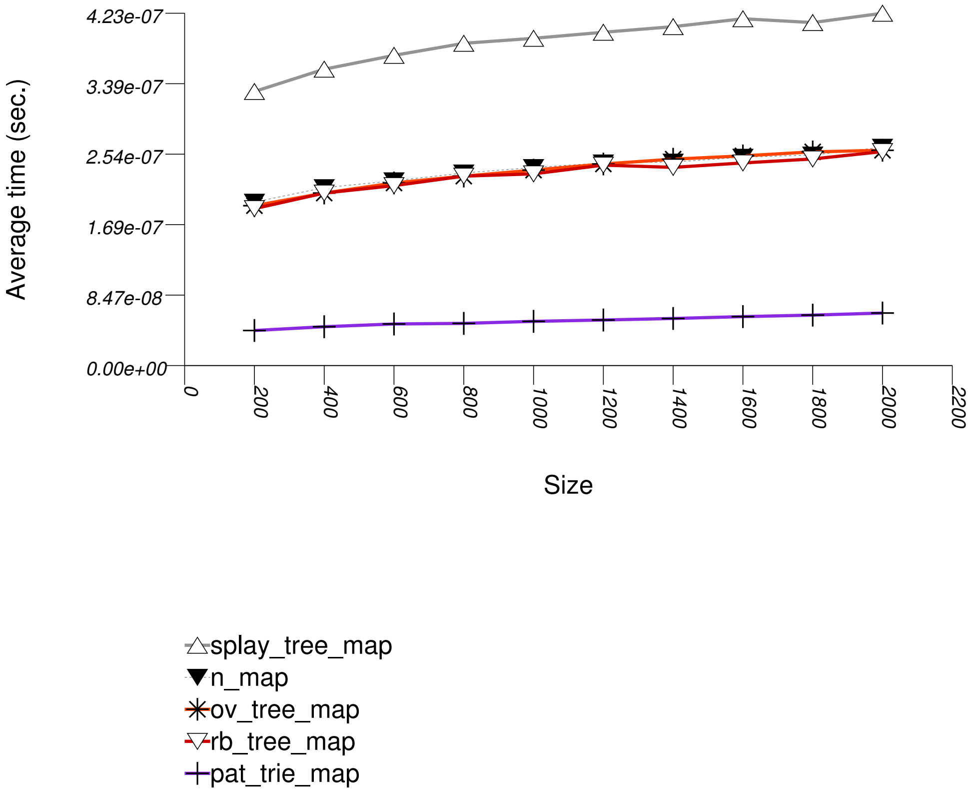
This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into a container, then performs a series of finds using `find`. It measures the average time for `find` as a function of the number of values inserted.

It uses the test file: `performance/ext/pb_ds/text_find_timing.cc`

The test checks the effect of different underlying data structures.

21.4.2.2.2.2 Results

The graphic immediately below shows the results for the native tree type and several other tree types.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_map		
`std::map`		
splay_tree_map		
`tree`	`Tag`	`splay_tree_tag`
	`Node_Update`	`null_node_update`
rb_tree_map		
`tree`	`Tag`	`rb_tree_tag`
	`Node_Update`	`null_node_update`
ov_tree_map		
`tree`	`Tag`	`ov_tree_tag`
	`Node_Update`	`null_node_update`
pat_trie_map		
`tree`	`Tag`	`pat_trie_tag`
	`Node_Update`	`null_node_update`

21.4.2.2.2.3 Observations

For this setting, a splay tree (`tree` with `Tag` = `splay_tree_tag`) does not do well. This is possibly due to two reasons:

1. A splay tree is not guaranteed to be balanced [motwani95random]. If a splay tree contains n nodes, its average root-leaf path can be m >> log(n).
2. Assume a specific root-leaf search path has length m, and the search-target node has distance m’ from the root. A red-black tree will require m + 1 comparisons to find the required node; a splay tree will require 2 m’ comparisons. A splay tree, consequently, can perform many more comparisons than a red-black tree.

An ordered-vector tree (`tree` with `Tag` = `ov_tree_tag`), a red-black tree (`tree` with `Tag` = `rb_tree_tag`), and the native red-black tree all share approximately the same performance.

An ordered-vector tree is slightly slower than red-black trees, since it requires, in order to find a key, more math operations than they do. Conversely, an ordered-vector tree requires far lower space than the others. ([austern00noset], however, seems to have an implementation that is also faster than a red-black tree).

A PATRICIA trie (`trie` with `Tag` = `pat_trie_tag`) has good look-up performance, due to its large fan-out in this case. In this setting, a PATRICIA trie has look-up performance comparable to a hash table (see Hash-Based Text `find` Timing Test), but it is order preserving. This is not that surprising, since a large-fan-out PATRICIA trie works like a hash table with collisions resolved by a sub-trie. A large-fan-out PATRICIA trie does not do well on modifications (see Tree-Based and Trie-Based Text Insert Timing Test). Therefore, it is possibly beneficial in semi-static settings.

21.4.2.2.3 Text `find` with Locality-of-Reference

21.4.2.2.3.1 Description

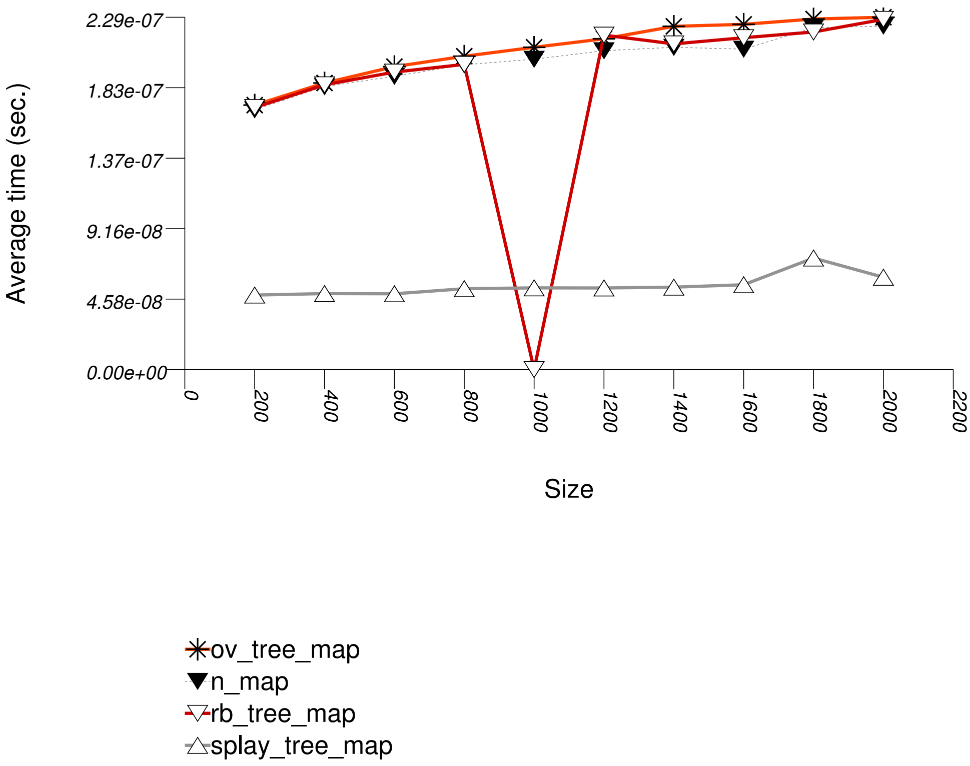
This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into a container, then performs a series of finds using `find`. It is different than Tree-Based and Trie-Based Text `find` Find Timing Test in the sequence of finds it performs: this test performs multiple `find`s on the same key before moving on to the next key. It measures the average time for `find` as a function of the number of values inserted.

It uses the test file: `performance/ext/pb_ds/tree_text_lor_find_timing.cc`

The test checks the effect of different underlying data structures in a locality-of-reference setting.

21.4.2.2.3.2 Results

The graphic immediately below shows the results for the native tree type and several other tree types.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	*Parameter*	*Details*
n_map		
std::map		
splay_tree_map		
tree	Tag	splay_tree_tag
	Node_Update	null_node_update
rb_tree_map		
tree	Tag	rb_tree_tag
	Node_Update	null_node_update
ov_tree_map		
tree	Tag	ov_tree_tag
	Node_Update	null_node_update
pat_trie_map		
tree	Tag	pat_trie_tag
	Node_Update	null_node_update

21.4.2.2.3.3 Observations

For this setting, an ordered-vector tree (tree with Tag = ov_tree_tag), a red-black tree (tree with Tag = rb_tree_tag), and the native red-black tree all share approximately the same performance.

A splay tree (tree with Tag = splay_tree_tag) does much better, since each (successful) find "bubbles" the corresponding node to the root of the tree.

21.4.2.2.4 split and join

21.4.2.2.4.1 Description

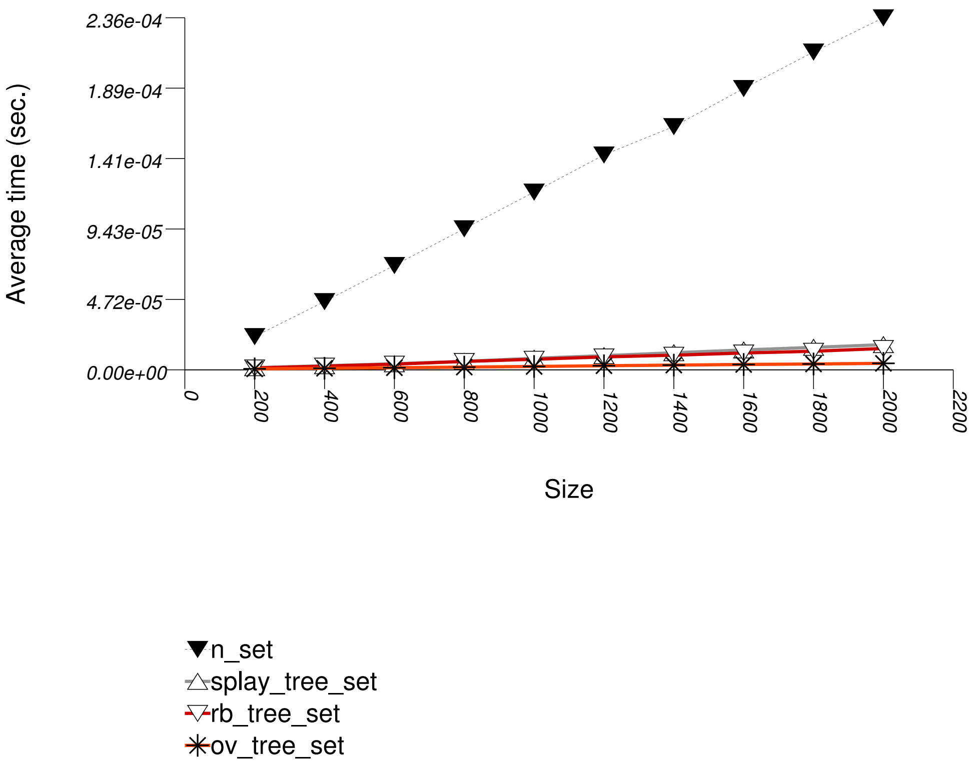
This test a container, inserts into a number of values, splits the container at the median, and joins the two containers. (If the containers are one of this library's trees, it splits and joins with the split and join method; otherwise, it uses the erase and insert methods.) It measures the time for splitting and joining the containers as a function of the number of values inserted.

It uses the test file: performance/ext/pb_ds/tree_split_join_timing.cc

The test checks the performance difference of join as opposed to a sequence of insert operations; by implication, this test checks the most efficient way to erase a sub-sequence from a tree-like-based container, since this can always be performed by a small sequence of splits and joins.

21.4.2.2.4.2 Results

The graphic immediately below shows the results for the native tree type and several other tree types.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_set		
`std::set`		
splay_tree_set		
`tree`	`Tag`	`splay_tree_tag`
	`Node_Update`	`null_node_update`
rb_tree_set		
`tree`	`Tag`	`rb_tree_tag`
	`Node_Update`	`null_node_update`
ov_tree_set		
`tree`	`Tag`	`ov_tree_tag`
	`Node_Update`	`null_node_update`
pat_trie_map		
`tree`	`Tag`	`pat_trie_tag`
	`Node_Update`	`null_node_update`

21.4.2.2.4.3 Observations

In this test, the native red-black trees must be split and joined externally, through a sequence of `erase` and `insert` operations. This is clearly super-linear, and it is not that surprising that the cost is high.

This library's tree-based containers use in this test the `split` and `join` methods, which have lower complexity: the `join` method of a splay tree (`tree` with `Tag = splay_tree_tag`) is quadratic in the length of the longest root-leaf path, and linear in the total number of elements; the `join` method of a red-black tree (`tree` with `Tag = rb_tree_tag`) or an ordered-vector tree (`tree` with `Tag = ov_tree_tag`) is linear in the number of elements.

Asides from orders of growth, this library's trees access their allocator very little in these operations, and some of them do not access it at all. This leads to lower constants in their complexity, and, for some containers, to exception-free splits and joins (which can be determined via `container_traits`).

It is important to note that `split` and `join` are not esoteric methods - they are the most efficient means of erasing a contiguous range of values from a tree based container.

21.4.2.2.5 Order-Statistics

21.4.2.2.5.1 Description

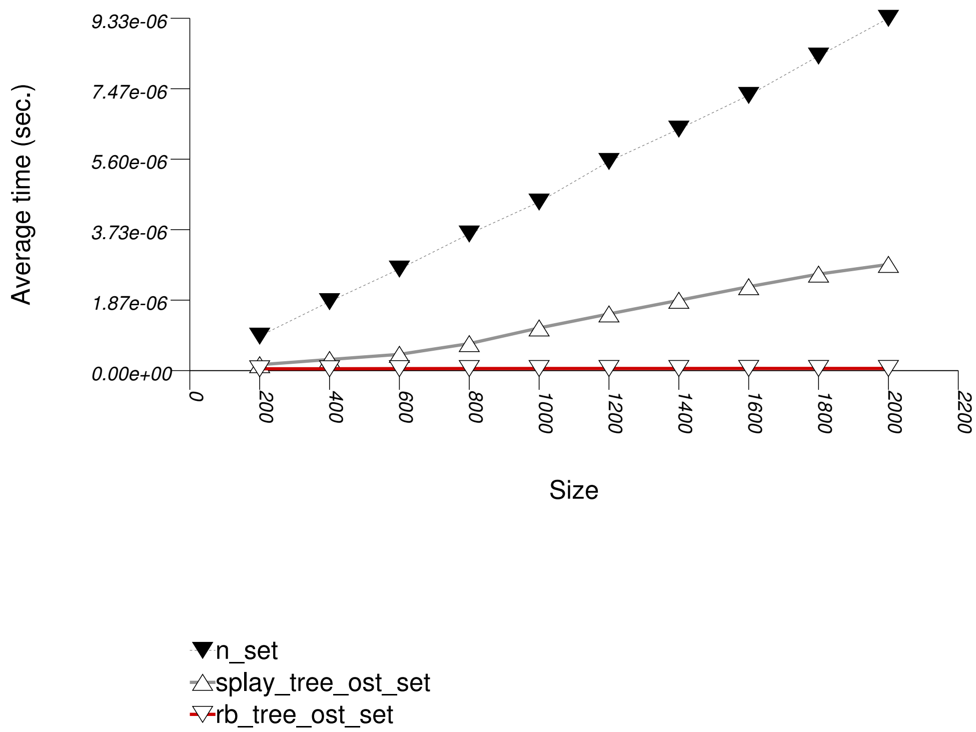
This test creates a container, inserts random integers into the the container, and then checks the order-statistics of the container's values. (If the container is one of this library's trees, it does this with the `order_of_key` method of `tree_order_statistics_no`
; otherwise, it uses the `find` method and `std::distance`.) It measures the average time for such queries as a function of the number of values inserted.

It uses the test file: `performance/ext/pb_ds/tree_order_statistics_timing.cc`

The test checks the performance difference of policies based on node-invariant as opposed to a external functions.

21.4.2.2.5.2 Results

The graphic immediately below shows the results for the native tree type and several other tree types.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_set		
`std::set`		
splay_tree_ost_set		
`tree`	`Tag`	`splay_tree_tag`
	`Node_Update`	`tree_order_statistics_node_update`
rb_tree_ost_set		
`tree`	`Tag`	`rb_tree_tag`
	`Node_Update`	`tree_order_statistics_node_update`

21.4.2.2.5.3 Observations

In this test, the native red-black tree can support order-statistics queries only externally, by performing a `find` (alternatively, `lower_bound` or `upper_bound`) and then using `std::distance` . This is clearly linear, and it is not that surprising that the cost is high.

This library's tree-based containers use in this test the `order_of_key` method of `tree_order_statistics_node_update`. This method has only linear complexity in the length of the root-node path. Unfortunately, the average path of a splay tree (`tree` with `Tag = splay_tree_tag`) can be higher than logarithmic; the longest path of a red-black tree (`tree` with `Tag = rb_tree_tag`) is logarithmic in the number of elements. Consequently, the splay tree has worse performance than the red-black tree.

21.4.2.3 Multimap

21.4.2.3.1 Text **`find`** with Small Secondary-to-Primary Key Ratios

21.4.2.3.1.1 Description

This test inserts a number of pairs into a container. The first item of each pair is a string from an arbitrary text ([wickland96thirty]), and the second is a uniform i.i.d.integer. The container is a "multimap" - it considers the first member of each pair as a primary key, and the second member of each pair as a secondary key (see Motivation::Associative Containers::Alternative to Multiple Equivalent Keys). There are 400 distinct primary keys, and the ratio of secondary keys to primary keys ranges from 1 to 5.

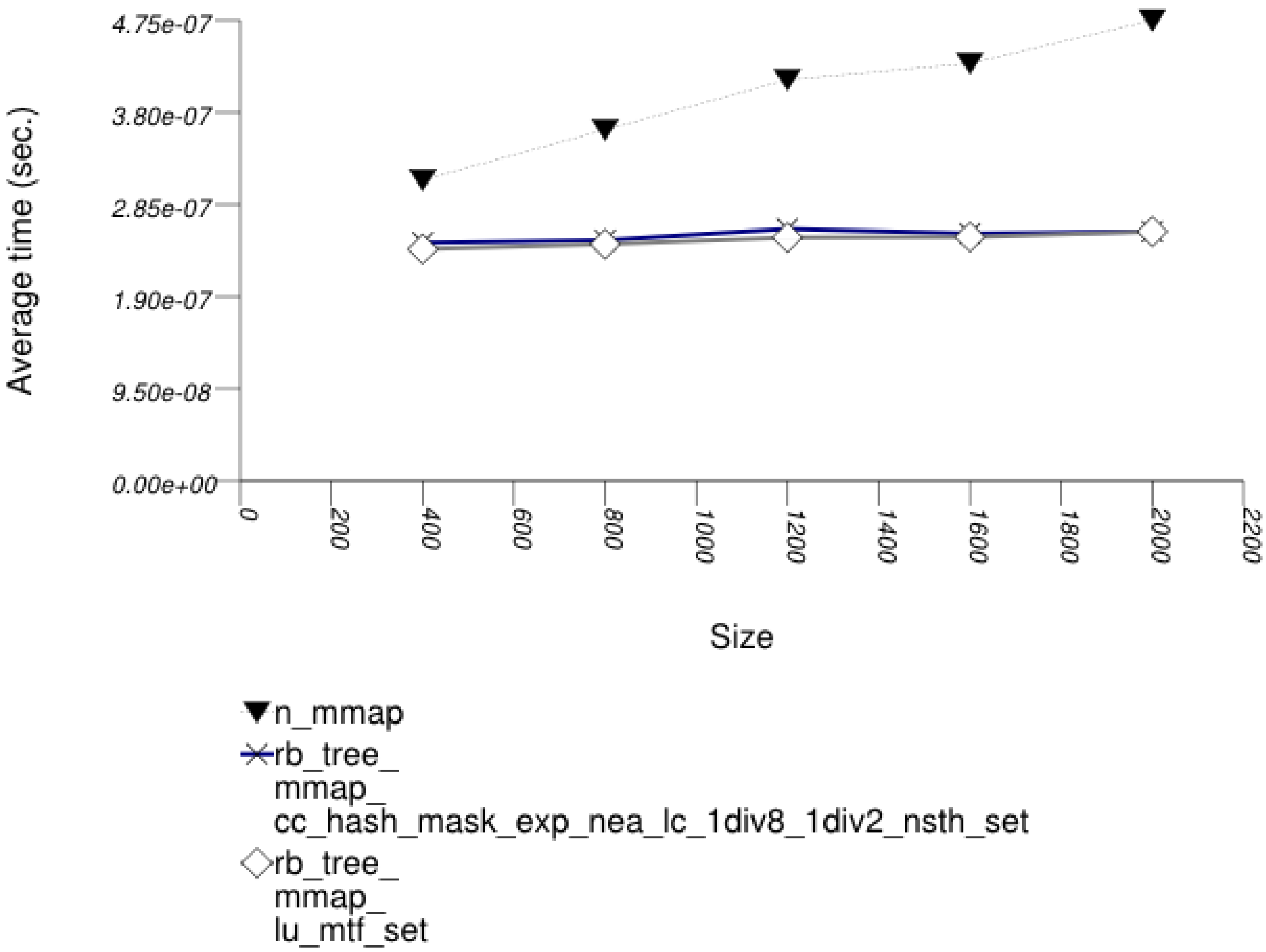
The test measures the average find-time as a function of the number of values inserted. For this library's containers, it finds the secondary key from a container obtained from finding a primary key. For the native multimaps, it searches a range obtained using `std::equal_range` on a primary key.

It uses the test file: `performance/ext/pb_ds/multimap_text_find_timing_small.cc`

The test checks the find-time scalability of different "multimap" designs.

21.4.2.3.1.2 Results

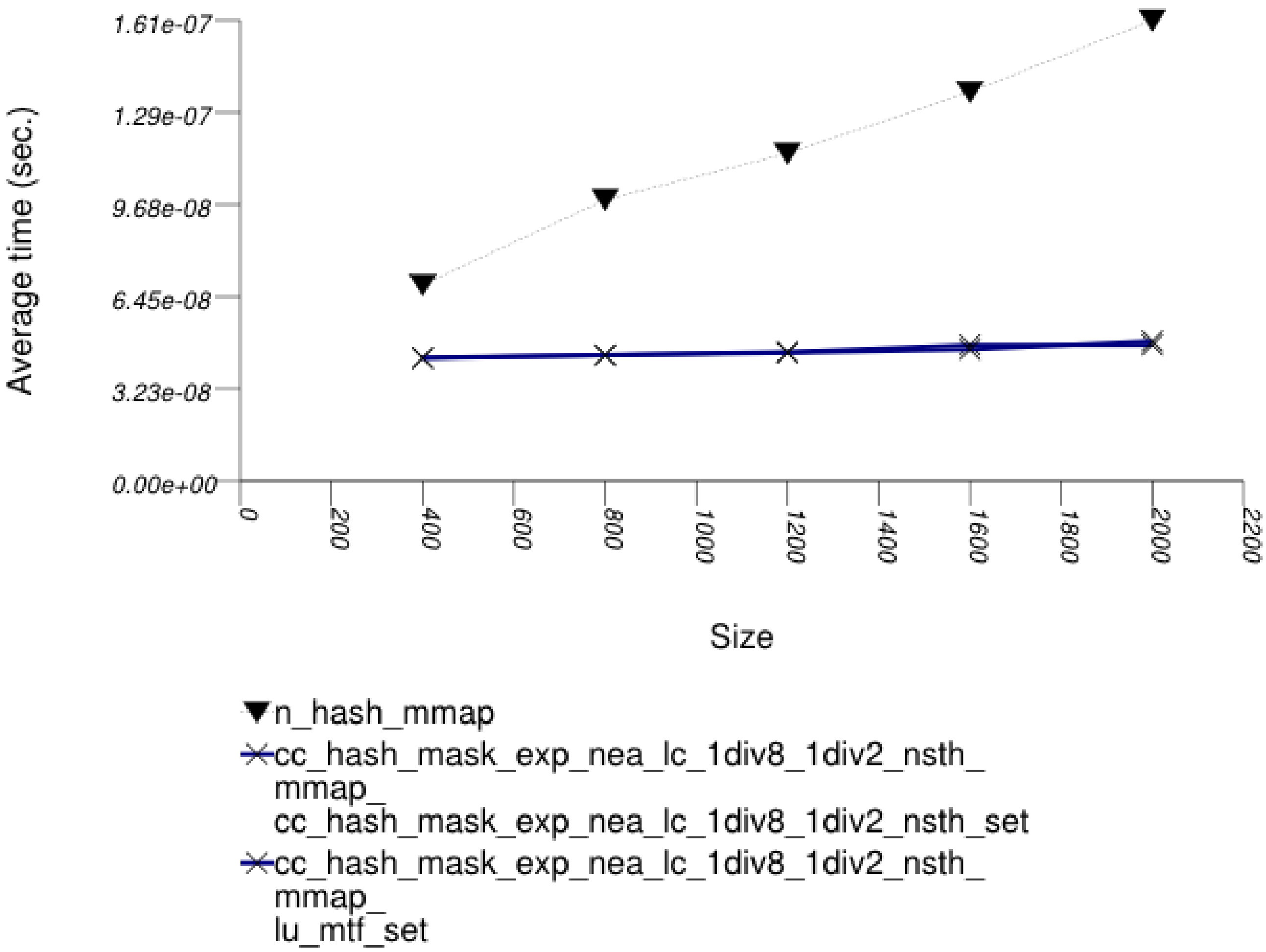
The graphic below show the results for "multimaps" which use a tree-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_mmap						
`std::multimap`						
rb_tree_mmap_lu_mtf_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

The graphic below show the results for "multimaps" which use a hash-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_mmap						
`std::tr1::unordered_multimap`						
rb_tree_mmap_lu_mtf_set						
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`				
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_policy`		
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2		
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`				
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_policy`		
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2		
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`

Name/Instantiating Type	*Parameter*	*Details*	*Parameter*	*Details*	*Parameter*	*Details*
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.3.1.3 Observations

See Observations::Mapping-Semantics Considerations.

21.4.2.3.2 Text `find` with Large Secondary-to-Primary Key Ratios

21.4.2.3.2.1 Description

This test inserts a number of pairs into a container. The first item of each pair is a string from an arbitrary text ([wickland96thirty]), and the second is a uniform integer. The container is a "multimap" - it considers the first member of each pair as a primary key, and the second member of each pair as a secondary key. There are 400 distinct primary keys, and the ratio of secondary keys to primary keys ranges from 1 to 5.

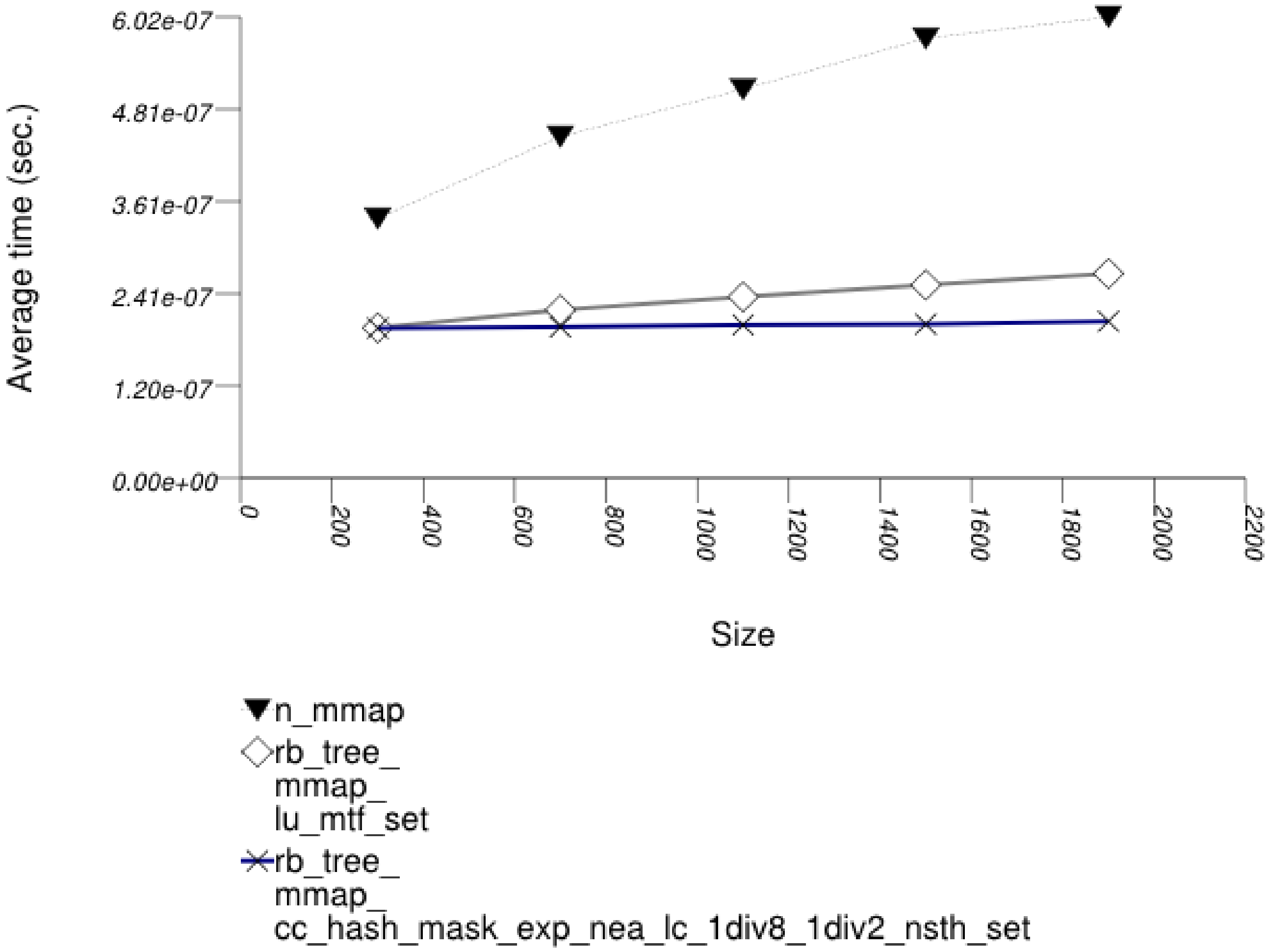
The test measures the average find-time as a function of the number of values inserted. For this library's containers, it finds the secondary key from a container obtained from finding a primary key. For the native multimaps, it searches a range obtained using `std::equal_range` on a primary key.

It uses the test file: `performance/ext/pb_ds/multimap_text_find_timing_large.cc`

The test checks the find-time scalability of different "multimap" designs.

21.4.2.3.2.2 Results

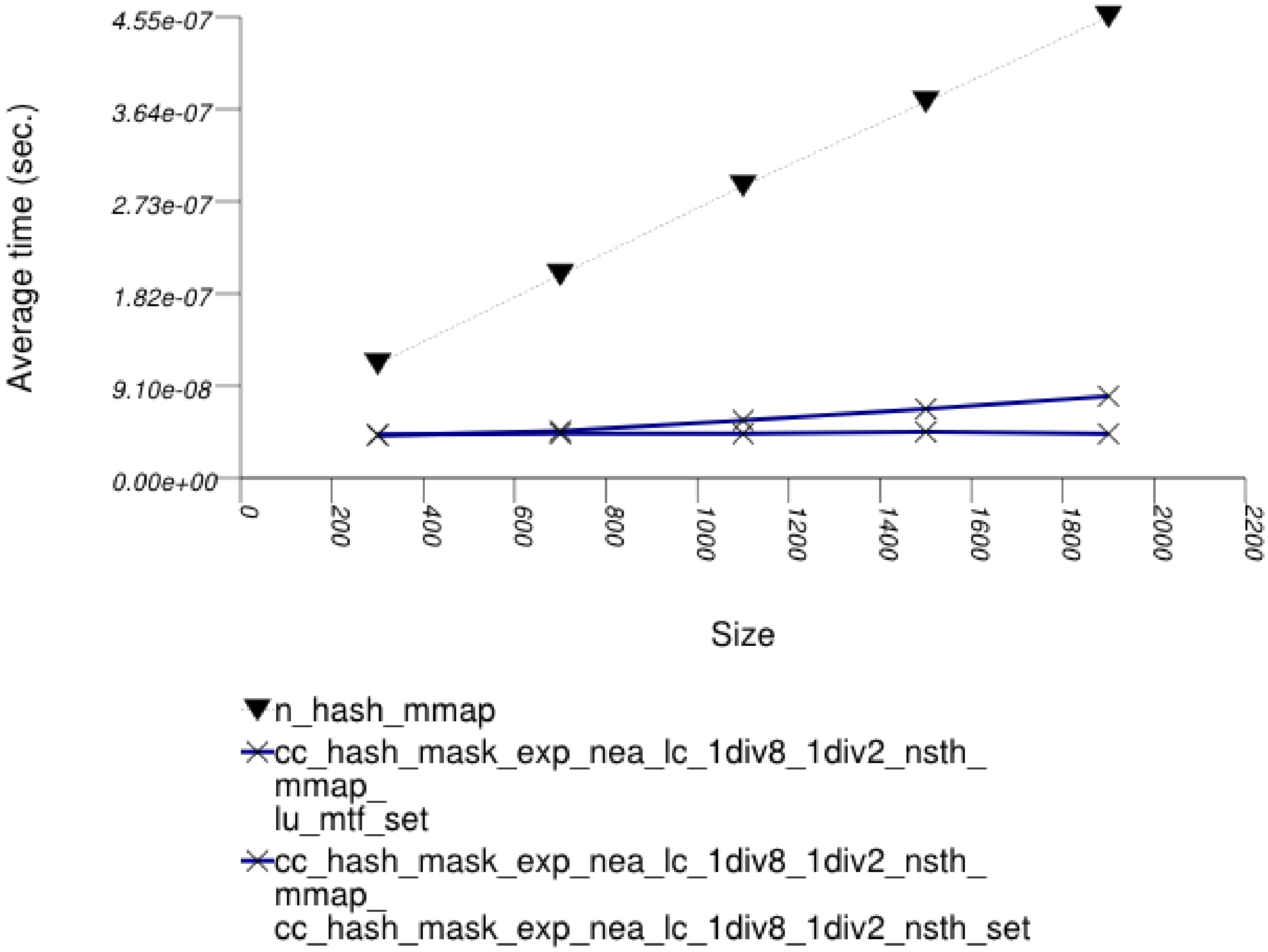
The graphic below show the results for "multimaps" which use a tree-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_mmap						
`std::multimap`						
rb_tree_mmap_lu_mtf_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

The graphic below show the results for "multimaps" which use a hash-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_mmap						
std::tr1::unordered_multimap						
rb_tree_mmap_lu_mtf_set						
cc_hash_table	Comb_Hash_Fn	direct_mask_range_hashing				
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_size_policy		
			Trigger_Policy	hash_load_check_resize_trigger with α_{min} = 1/8 and α_{max} = 1/2		
	Mapped	list_update	Update_Policy	lu_move_to_front_policy		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
cc_hash_table	Comb_Hash_Fn	direct_mask_range_hashing				
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_size_policy		
			Trigger_Policy	hash_load_check_resize_trigger with α_{min} = 1/8 and α_{max} = 1/2		
	Mapped	cc_hash_table	Comb_Hash_Fn	direct_mask_range_hashing		
			Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_

Name/Instantiating Type	Parameter	Details	Parameter	Details	Parameter	Details
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.3.2.3 Observations

See Observations::Mapping-Semantics Considerations.

21.4.2.3.3 Text `insert` with Small Secondary-to-Primary Key Ratios

21.4.2.3.3.1 Description

This test inserts a number of pairs into a container. The first item of each pair is a string from an arbitrary text ([wickland96thirty]), and the second is a uniform integer. The container is a "multimap" - it considers the first member of each pair as a primary key, and the second member of each pair as a secondary key. There are 400 distinct primary keys, and the ratio of secondary keys to primary keys ranges from 1 to 5.

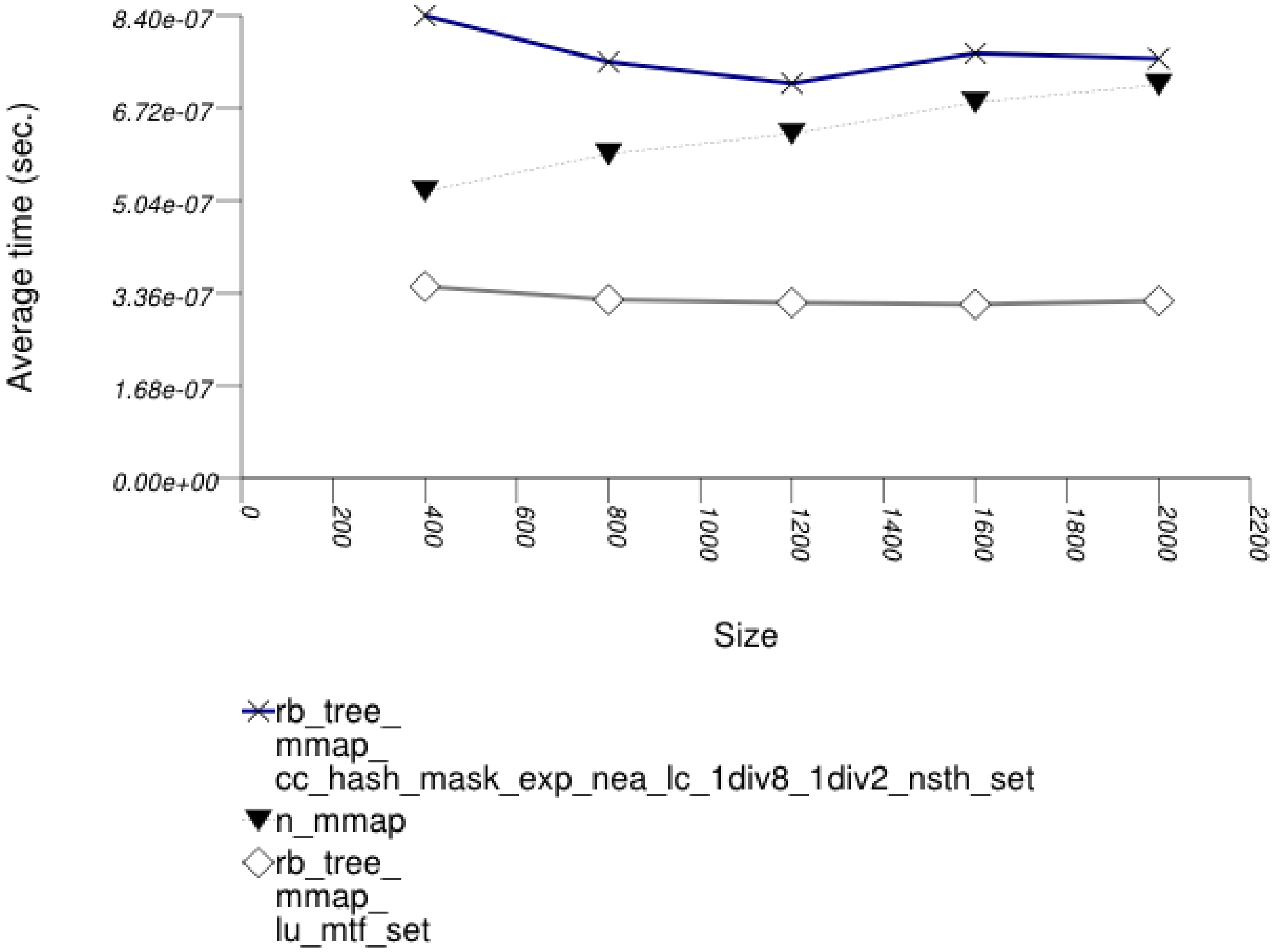
The test measures the average insert-time as a function of the number of values inserted. For this library's containers, it inserts a primary key into the primary associative container, then a secondary key into the secondary associative container. For the native multimaps, it obtains a range using `std::equal_range`, and inserts a value only if it was not contained already.

It uses the test file: `performance/ext/pb_ds/multimap_text_insert_timing_small.cc`

The test checks the insert-time scalability of different "multimap" designs.

21.4.2.3.3.2 Results

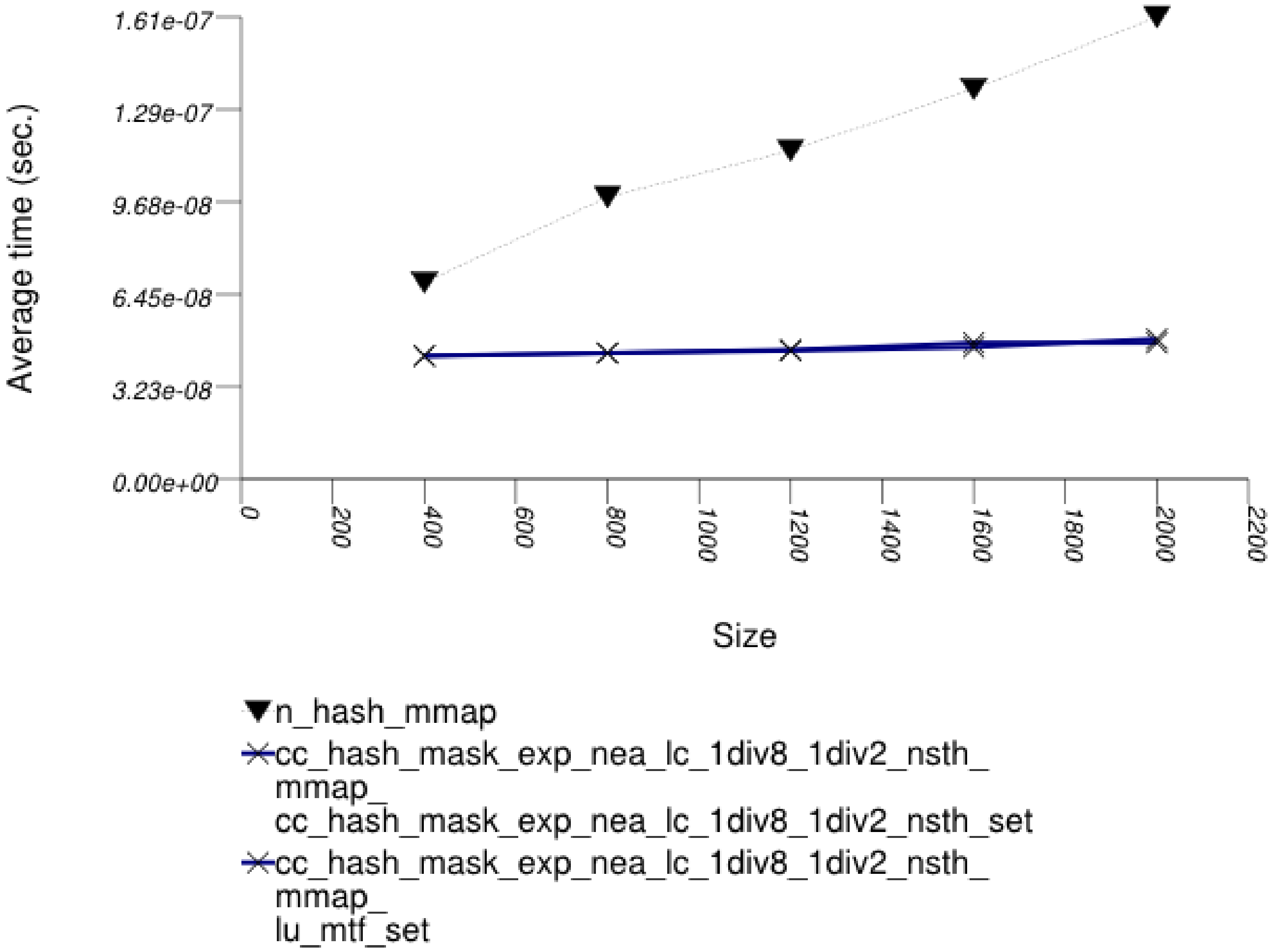
The graphic below show the results for "multimaps" which use a tree-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_mmap						
`std::multimap`						
rb_tree_mmap_lu_mtf_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

The graphic below show the results for "multimaps" which use a hash-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_mmap						
`std::tr1::unordered_multimap`						
rb_tree_mmap_lu_mtf_set						
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`				
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_policy`		
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2		
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`				
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_policy`		
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2		
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`

Name/Instantiating Type	Parameter	Details	Parameter	Details	Parameter	Details
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.3.3.3 Observations

See Observations::Mapping-Semantics Considerations.

21.4.2.3.4 Text `insert` with Small Secondary-to-Primary Key Ratios

21.4.2.3.4.1 Description

This test inserts a number of pairs into a container. The first item of each pair is a string from an arbitrary text ([wickland96thirty]), and the second is a uniform integer. The container is a "multimap" - it considers the first member of each pair as a primary key, and the second member of each pair as a secondary key. There are 400 distinct primary keys, and the ratio of secondary keys to primary keys ranges from 1 to 5.

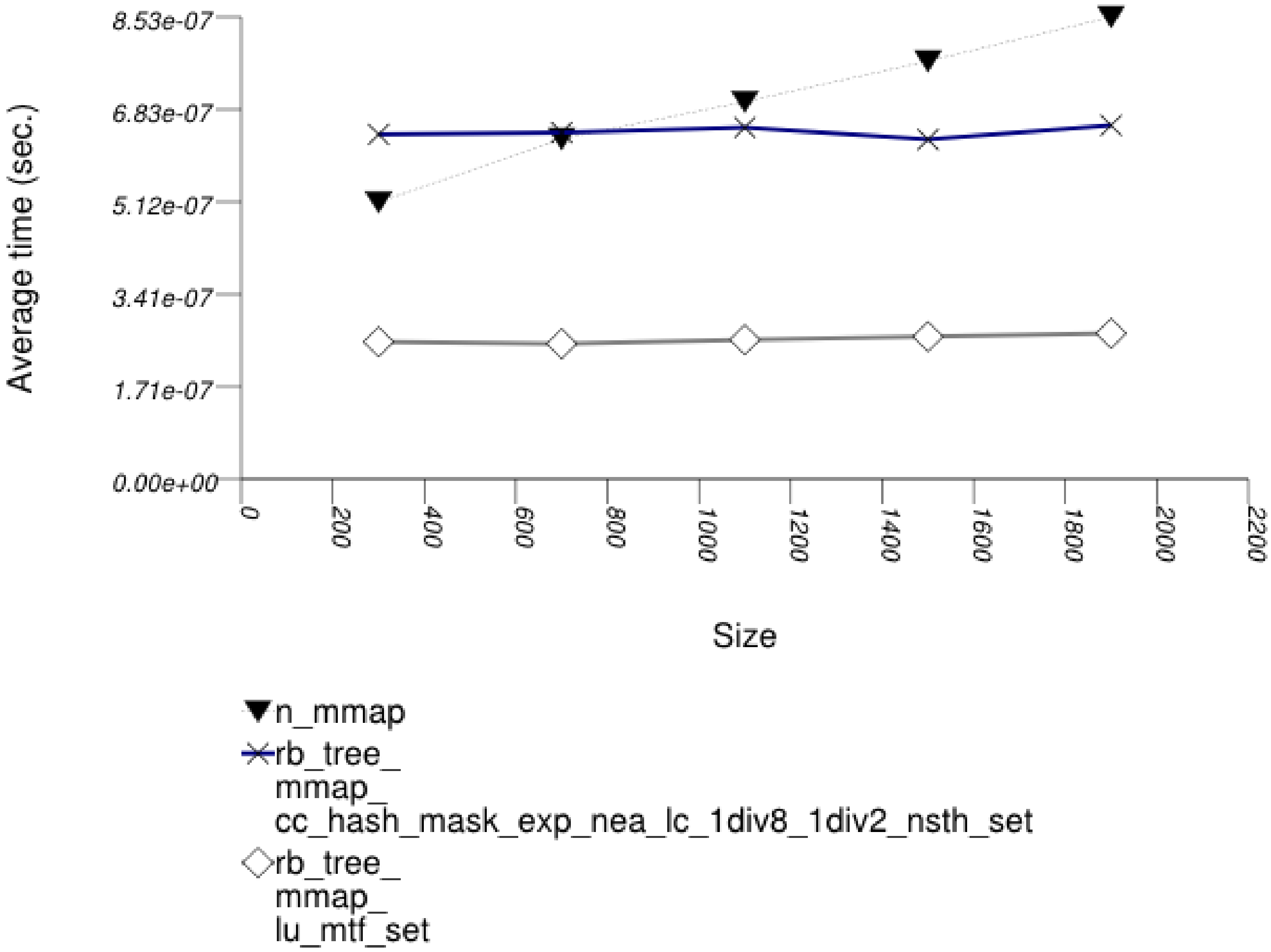
The test measures the average insert-time as a function of the number of values inserted. For this library's containers, it inserts a primary key into the primary associative container, then a secondary key into the secondary associative container. For the native multimaps, it obtains a range using `std::equal_range`, and inserts a value only if it was not contained already.

It uses the test file: `performance/ext/pb_ds/multimap_text_insert_timing_large.cc`

The test checks the insert-time scalability of different "multimap" designs.

21.4.2.3.4.2 Results

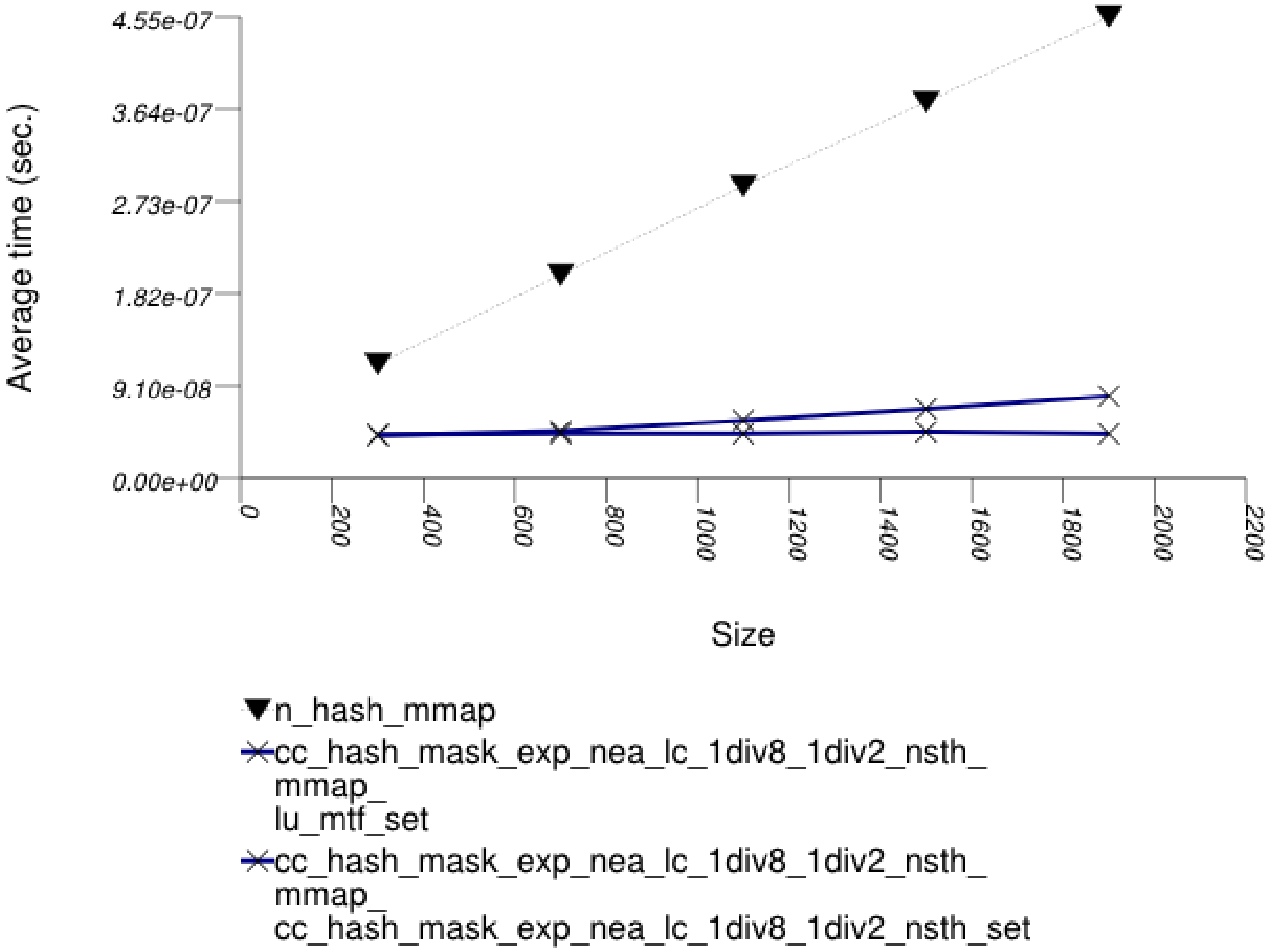
The graphic below show the results for "multimaps" which use a tree-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_mmap						
`std::multimap`						
rb_tree_mmap_lu_mtf_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

The graphic below show the results for "multimaps" which use a hash-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_mmap						
std::tr1::unordered_multimap						
rb_tree_mmap_lu_mtf_set						
cc_hash_table	Comb_Hash_Fn	direct_mask_range_hashing				
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_size_policy		
			Trigger_Policy	hash_load_check_resize_trigger with α_{min} = 1/8 and α_{max} = 1/2		
	Mapped	list_update	Update_Policy	lu_move_to_front_policy		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
cc_hash_table	Comb_Hash_Fn	direct_mask_range_hashing				
	Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_size_policy		
			Trigger_Policy	hash_load_check_resize_trigger with α_{min} = 1/8 and α_{max} = 1/2		
	Mapped	cc_hash_table	Comb_Hash_Fn	direct_mask_range_hashing		
			Resize_Policy	hash_standard_resize_policy	Size_Policy	hash_exponential_

Name/Instantiating Type	Parameter	Details	Parameter	Details	Parameter	Details
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.3.4.3 Observations

See Observations::Mapping-Semantics Considerations.

21.4.2.3.5 Text `insert` with Small Secondary-to-Primary Key Ratios Memory Use

21.4.2.3.5.1 Description

This test inserts a number of pairs into a container. The first item of each pair is a string from an arbitrary text ([wickland96thirty]), and the second is a uniform integer. The container is a "multimap" - it considers the first member of each pair as a primary key, and the second member of each pair as a secondary key. There are 100 distinct primary keys, and the ratio of secondary keys to primary keys ranges to about 20.

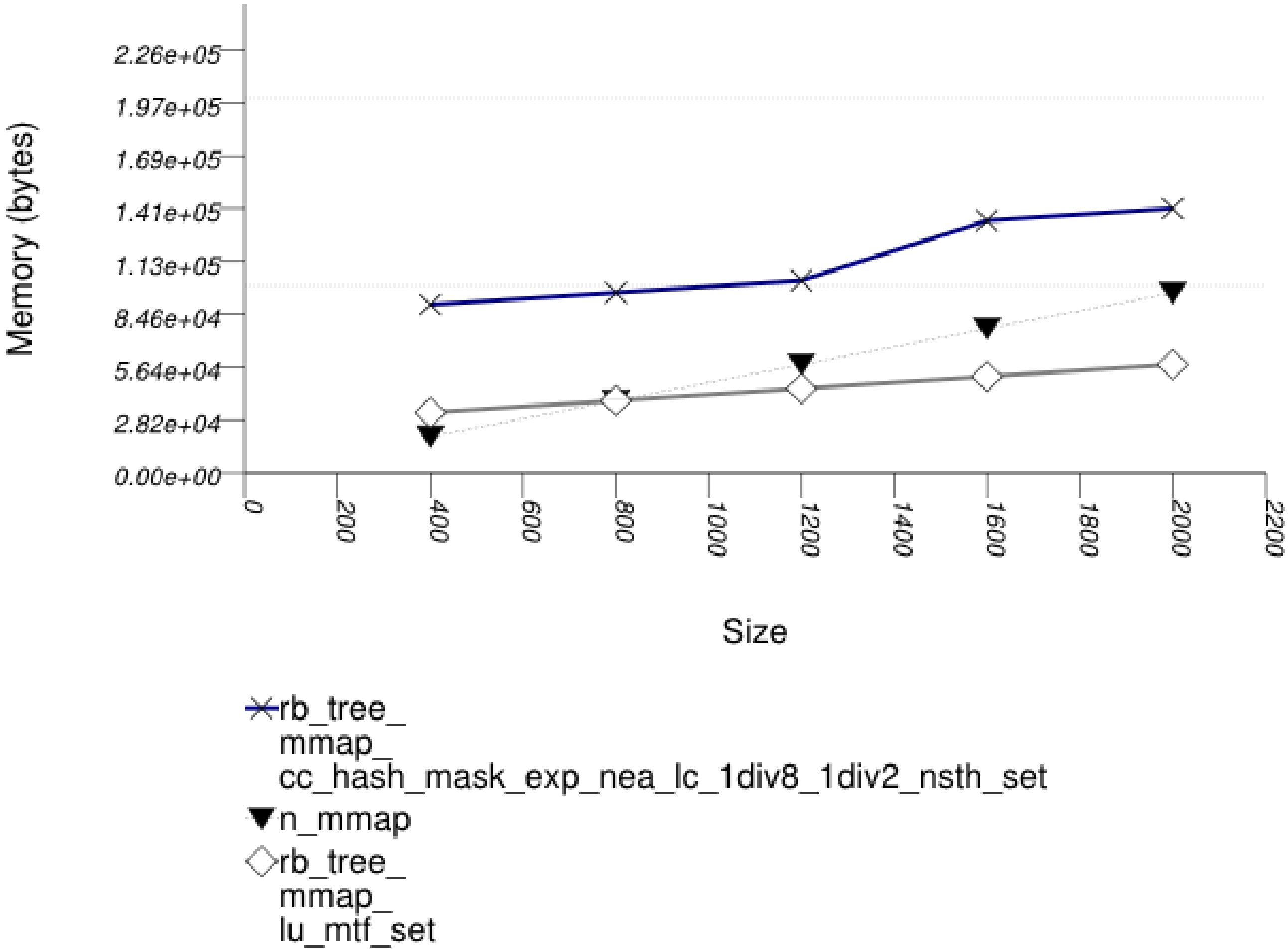
The test measures the memory use as a function of the number of values inserted.

It uses the test file: `performance/ext/pb_ds/multimap_text_insert_mem_usage_small.cc`

The test checks the memory scalability of different "multimap" designs.

21.4.2.3.5.2 Results

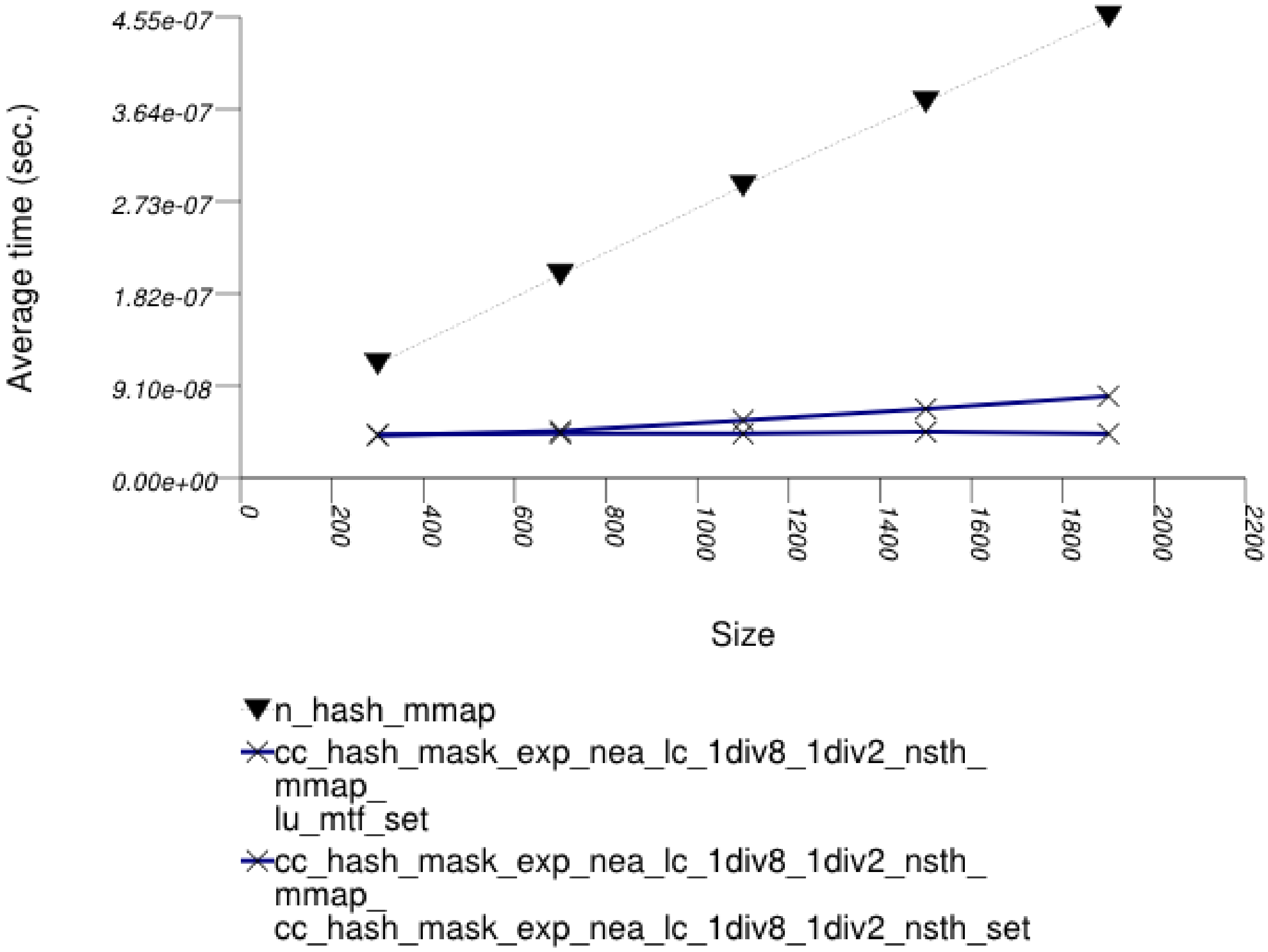
The graphic below show the results for "multimaps" which use a tree-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_mmap						
`std::multimap`						
rb_tree_mmap_lu_mtf_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

The graphic below show the results for "multimaps" which use a hash-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_hash_mmap						
`std::tr1::unordered_multimap`						
rb_tree_mmap_lu_mtf_set						
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`				
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_policy`		
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2		
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`				
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_policy`		
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2		
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`

Name/Instantiating Type	*Parameter*	*Details*	*Parameter*	*Details*	*Parameter*	*Details*
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.3.5.3 Observations

See Observations::Mapping-Semantics Considerations.

21.4.2.3.6 Text `insert` with Small Secondary-to-Primary Key Ratios Memory Use

21.4.2.3.6.1 Description

This test inserts a number of pairs into a container. The first item of each pair is a string from an arbitrary text ([wickland96thirty]), and the second is a uniform integer. The container is a "multimap" - it considers the first member of each pair as a primary key, and the second member of each pair as a secondary key. There are 100 distinct primary keys, and the ratio of secondary keys to primary keys ranges to about 20.

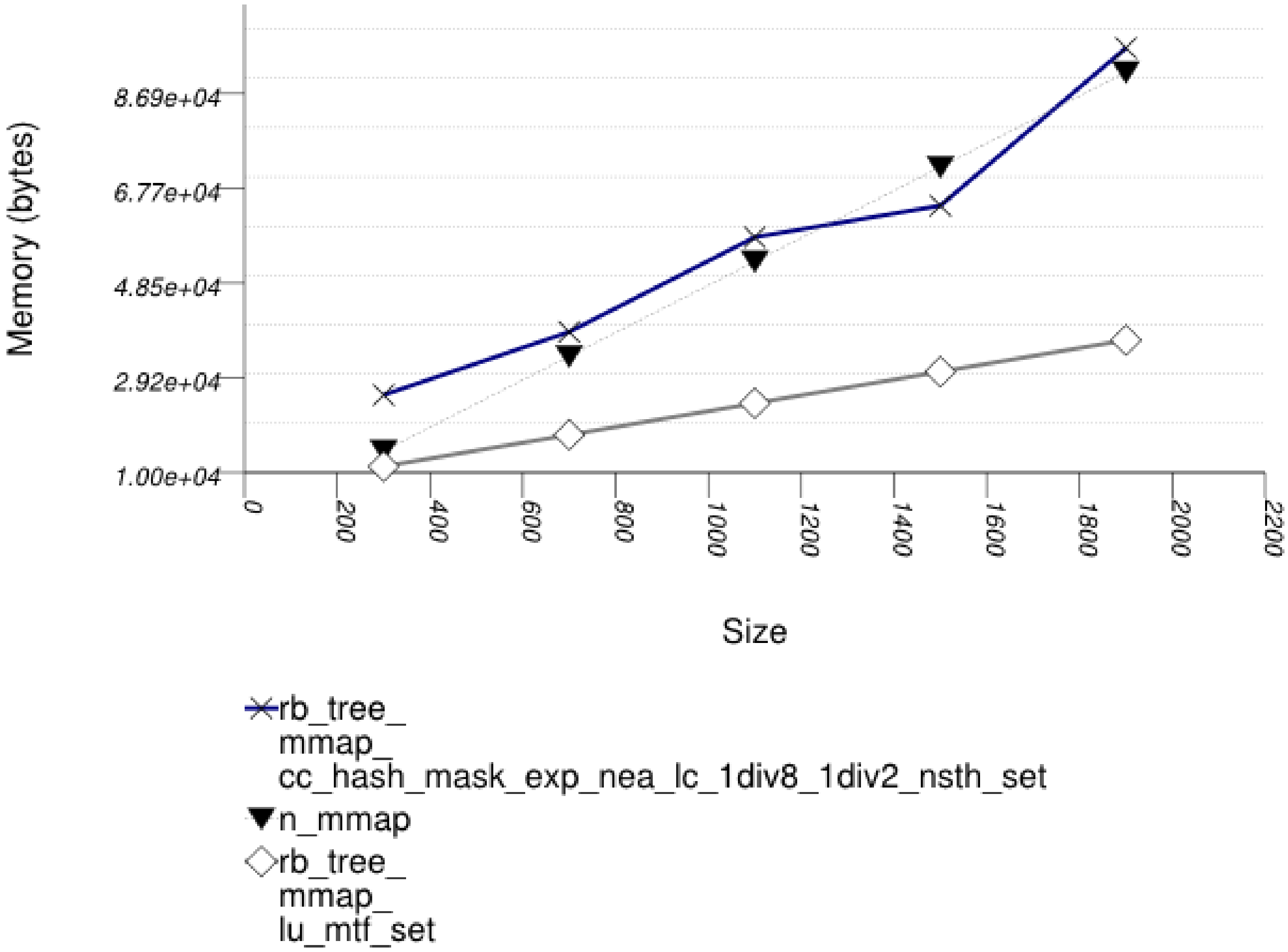
The test measures the memory use as a function of the number of values inserted.

It uses the test file: `performance/ext/pb_ds/multimap_text_insert_mem_usage_large.cc`

The test checks the memory scalability of different "multimap" designs.

21.4.2.3.6.2 Results

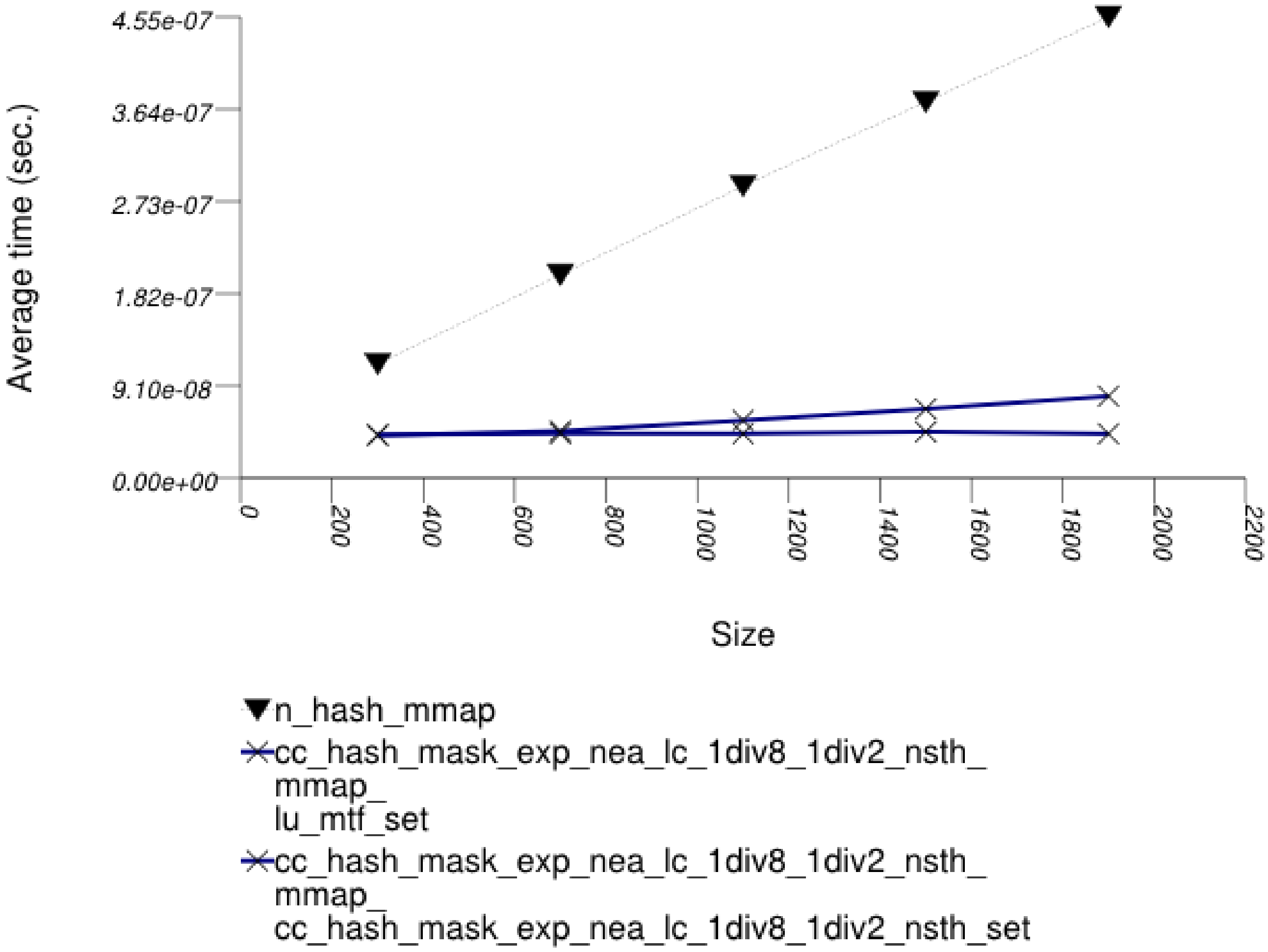
The graphic below show the results for "multimaps" which use a tree-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***	***Parameter***	***Details***	***Parameter***	***Details***
n_mmap						
`std::multimap`						
rb_tree_mmap_lu_mtf_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`tree`	`Tag`	`rb_tree_tag`				
	`Node_Update`	`null_node_update`				
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

The graphic below show the results for "multimaps" which use a hash-based container for primary keys.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	*Parameter*	*Details*	*Parameter*	*Details*	*Parameter*	*Details*
n_hash_mmap						
`std::tr1::unordered_multimap`						
rb_tree_mmap_lu_mtf_set						
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`				
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_policy`		
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2		
	`Mapped`	`list_update`	`Update_Policy`	`lu_move_to_front_policy`		
rb_tree_mmap_cc_hash_mask_exp_1div2_nsth_set						
`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`				
	`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_size_policy`		
			`Trigger_Policy`	`hash_load_check_resize_trigger` with α_{min} = 1/8 and α_{max} = 1/2		
	`Mapped`	`cc_hash_table`	`Comb_Hash_Fn`	`direct_mask_range_hashing`		
			`Resize_Policy`	`hash_standard_resize_policy`	`Size_Policy`	`hash_exponential_`

Name/Instantiating Type	*Parameter*	*Details*	*Parameter*	*Details*	*Parameter*	*Details*
					`Trigger_Policy`	`hash_load_check_r` with α_{min} = 1/8 and α_{max} = 1/2

21.4.2.3.6.3 Observations

See Observations::Mapping-Semantics Considerations.

21.4.2.4 Priority Queue

21.4.2.4.1 Text `push`

21.4.2.4.1.1 Description

This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into a container using `push`. It measures the average time for `push` as a function of the number of values pushed.

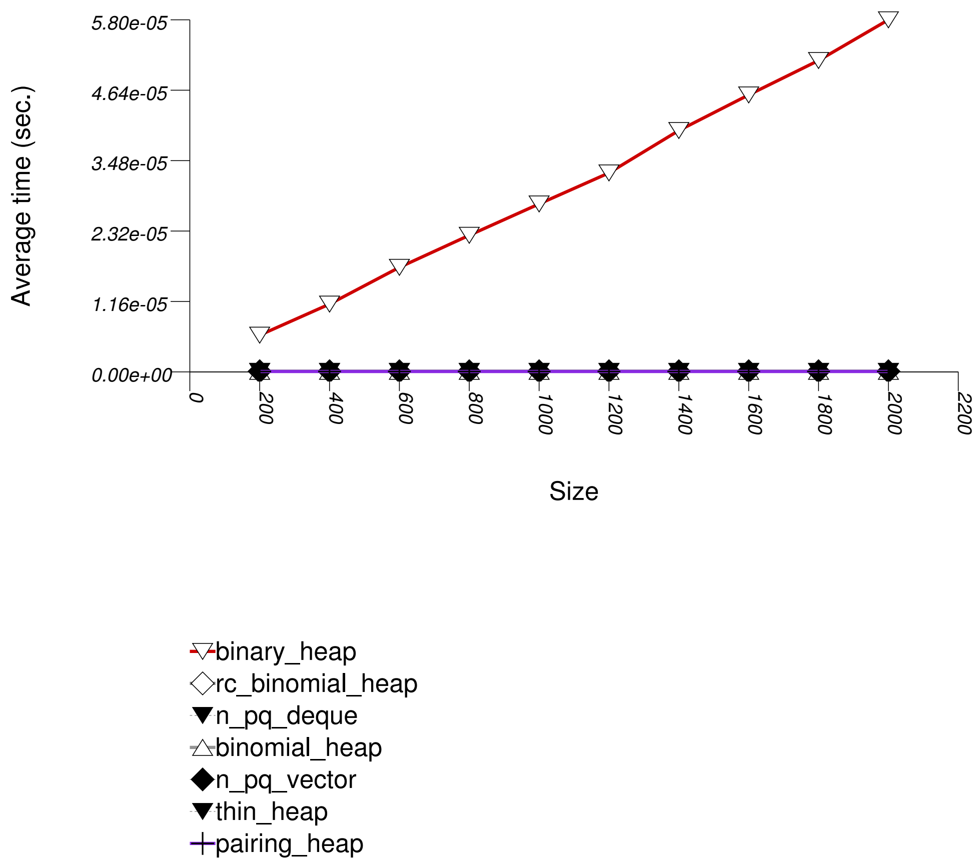
It uses the test file: `performance/ext/pb_ds/priority_queue_text_push_timing.cc`

The test checks the effect of different underlying data structures.

21.4.2.4.1.2 Results

The two graphics below show the results for the native priority_queues and this library's priority_queues.

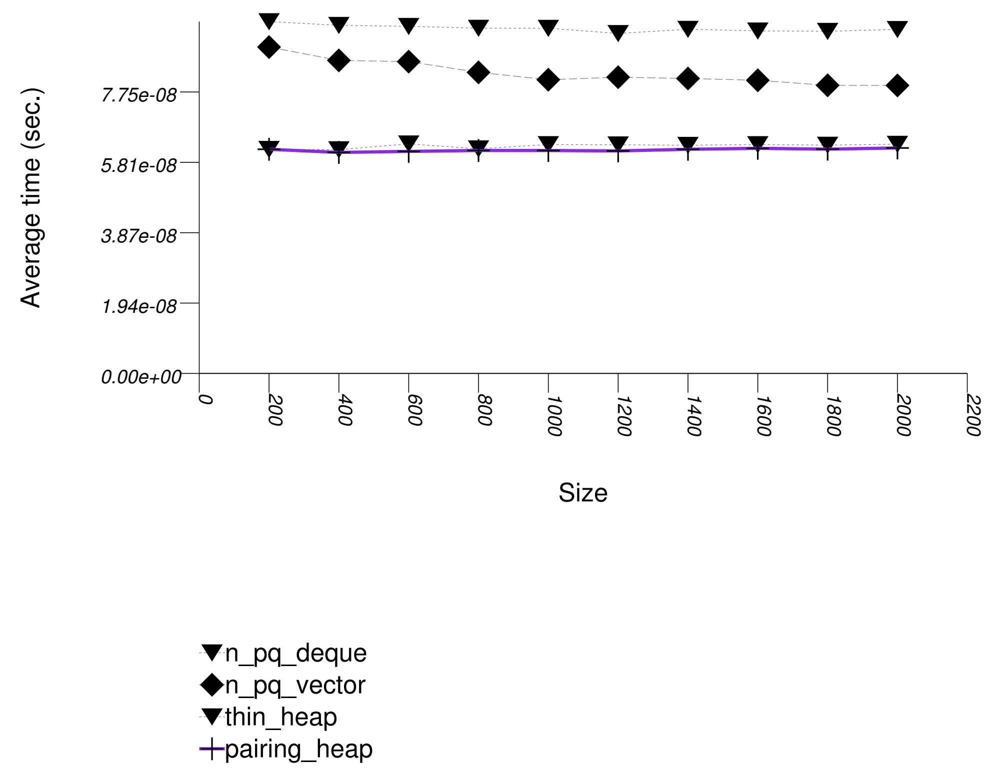
The graphic immediately below shows the results for the native priority_queue type instantiated with different underlying container types versus several different versions of library's priority_queues.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
binary_heap		
`priority_queue`	`Tag`	`binary_heap_tag`
binomial_heap		
`priority_queue`	`Tag`	`binomial_heap_tag`
rc_binomial_heap		
`priority_queue`	`Tag`	`rc_binomial_heap_tag`
thin_heap		
`priority_queue`	`Tag`	`thin_heap_tag`
pairing_heap		
`priority_queue`	`Tag`	`pairing_heap_tag`

The graphic below shows the results for the binary-heap based native priority queues and this library's pairing-heap priority_queue data structures.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
thin_heap		
`priority_queue`	`Tag`	`thin_heap_tag`

Name/Instantiating Type	Parameter	Details
pairing_heap		
priority_queue	Tag	pairing_heap_tag

21.4.2.4.1.3 Observations

Pairing heaps (priority_queue with Tag = pairing_heap_tag) are the most suited for sequences of push and pop operations of non-primitive types (e.g. std::strings). (See Priority Queue Text push and pop Timing Test.) They are less constrained than binomial heaps, e.g., and since they are node-based, they outperform binary heaps. (See Priority Queue Random Integer push Timing Test for the case of primitive types.)

The standard's priority queues do not seem to perform well in this case: the std::vector implementation needs to perform a logarithmic sequence of string operations for each operation, and the deque implementation is possibly hampered by its need to manipulate a relatively-complex type (deques support a O(1) push_front, even though it is not used by std::priority_queue.)

21.4.2.4.2 Text push and pop

21.4.2.4.2.1 Description

This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into a container using push , then removes them using pop . It measures the average time for push as a function of the number of values.

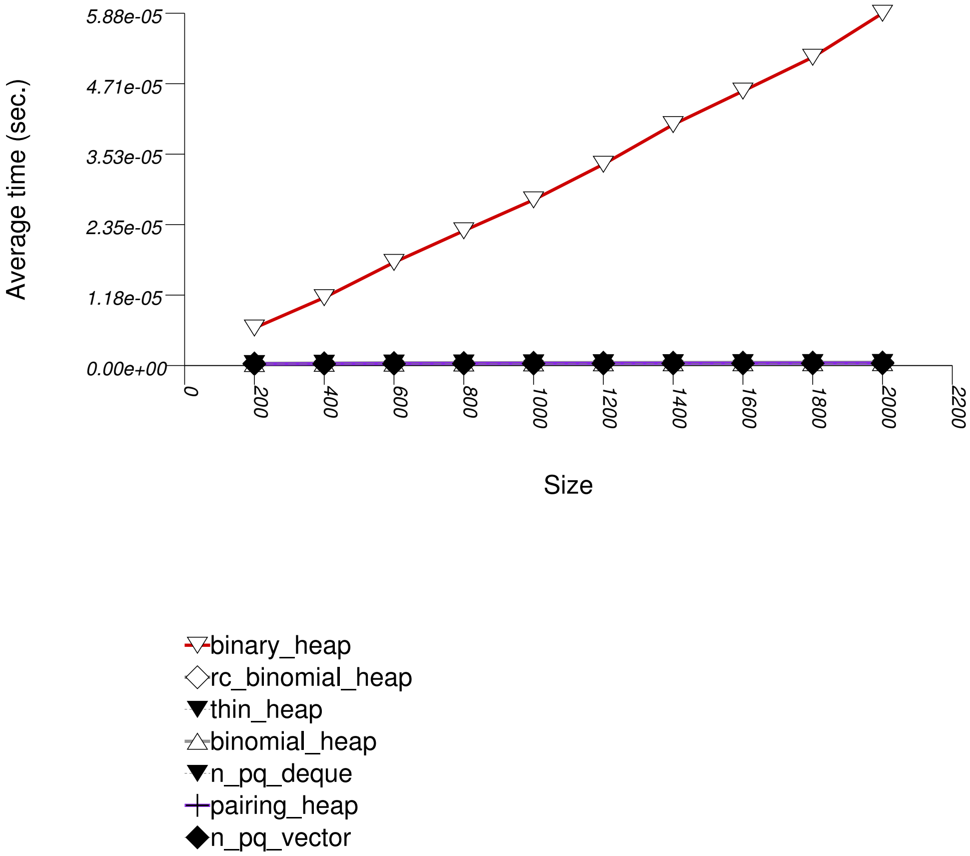
It uses the test file: performance/ext/pb_ds/priority_queue_text_push_pop_timing.cc

The test checks the effect of different underlying data structures.

21.4.2.4.2.2 Results

The two graphics below show the results for the native priority_queues and this library's priority_queues.

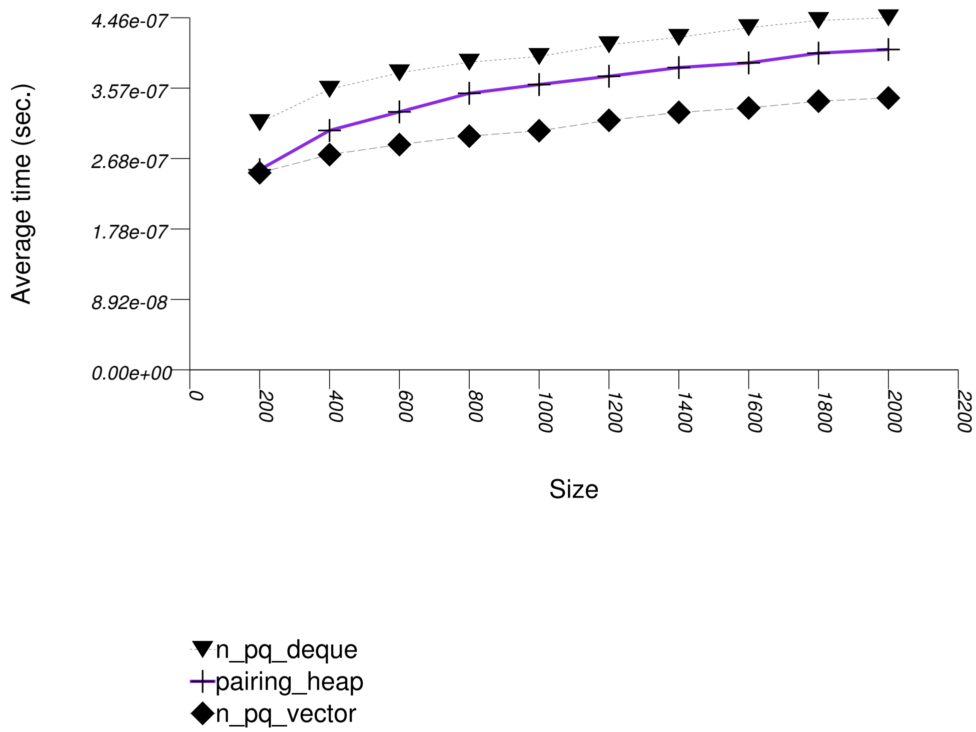
The graphic immediately below shows the results for the native priority_queue type instantiated with different underlying container types versus several different versions of library's priority_queues.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
binary_heap		
`priority_queue`	`Tag`	`binary_heap_tag`
binomial_heap		
`priority_queue`	`Tag`	`binomial_heap_tag`
rc_binomial_heap		
`priority_queue`	`Tag`	`rc_binomial_heap_tag`
thin_heap		
`priority_queue`	`Tag`	`thin_heap_tag`
pairing_heap		
`priority_queue`	`Tag`	`pairing_heap_tag`

The graphic below shows the results for the native priority queues and this library's pairing-heap priority_queue data structures.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_pq_vector		
`std::priority_queue` adapting `std::vector`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
pairing_heap		
`priority_queue`	`Tag`	`pairing_heap_tag`

21.4.2.4.2.3 Observations

These results are very similar to Priority Queue Text `push` Timing Test. As stated there, pairing heaps (`priority_queue` with `Tag` = `pairing_heap_tag`) are most suited for `push` and `pop` sequences of non-primitive types such as strings. Observing these two tests, one can note that a pairing heap outperforms the others in terms of `push` operations, but equals binary heaps (`priority_queue` with `Tag` = `binary_heap_tag`) if the number of `push` and `pop` operations is equal. As the number of `pop` operations is at most equal to the number of `push` operations, pairing heaps are better in this case. See Priority Queue Random Integer `push` and `pop` Timing Test for a case which is different.

21.4.2.4.3 Integer `push`

21.4.2.4.3.1 Description

This test inserts a number of values with integer keys into a container using `push`. It measures the average time for `push` as a function of the number of values.

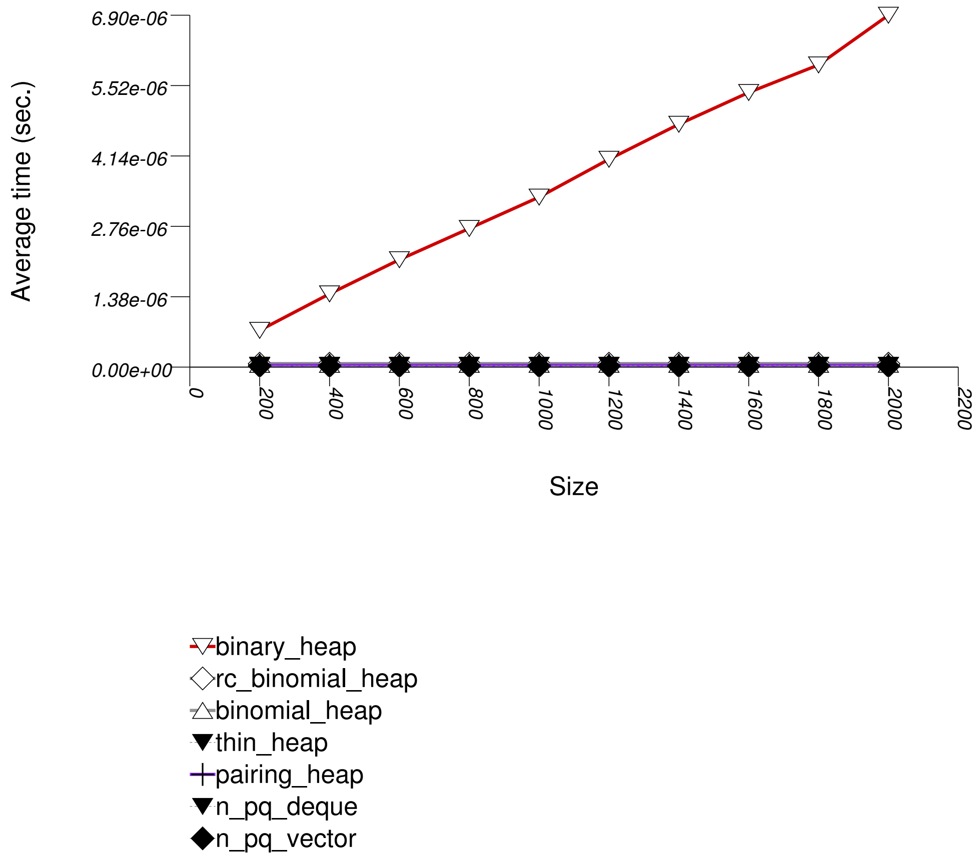
It uses the test file: `performance/ext/pb_ds/priority_queue_random_int_push_timing.cc`

The test checks the effect of different underlying data structures.

21.4.2.4.3.2 Results

The two graphics below show the results for the native priority_queues and this library's priority_queues.

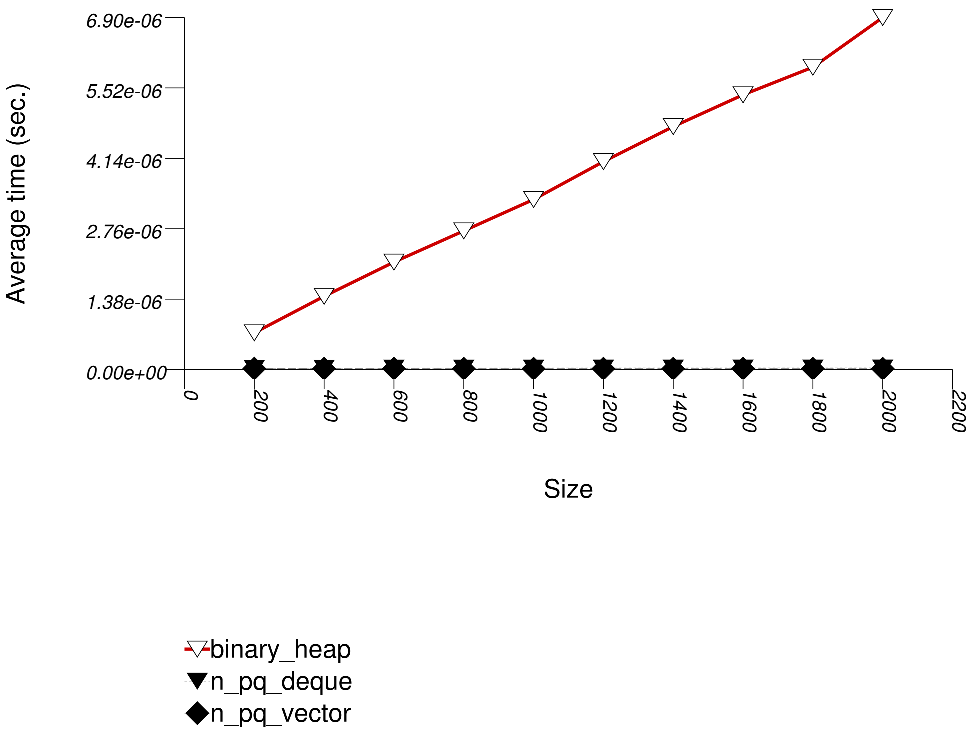
The graphic immediately below shows the results for the native priority_queue type instantiated with different underlying container types versus several different versions of library's priority_queues.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
binary_heap		
`priority_queue`	`Tag`	`binary_heap_tag`
binomial_heap		
`priority_queue`	`Tag`	`binomial_heap_tag`
rc_binomial_heap		
`priority_queue`	`Tag`	`rc_binomial_heap_tag`
thin_heap		
`priority_queue`	`Tag`	`thin_heap_tag`
pairing_heap		
`priority_queue`	`Tag`	`pairing_heap_tag`

The graphic below shows the results for the binary-heap based native priority queues and this library's priority_queue data structures.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_pq_vector		
`std::priority_queue` adapting `std::vector`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
binary_heap		
`priority_queue`	`Tag`	`binary_heap_tag`

21.4.2.4.3.3 Observations

Binary heaps are the most suited for sequences of `push` and `pop` operations of primitive types (e.g. ints). They are less constrained than any other type, and since it is very efficient to store such types in arrays, they outperform even pairing heaps. (See Priority Queue Text `push` Timing Test for the case of non-primitive types.)

21.4.2.4.4 Integer `push`

21.4.2.4.4.1 Description

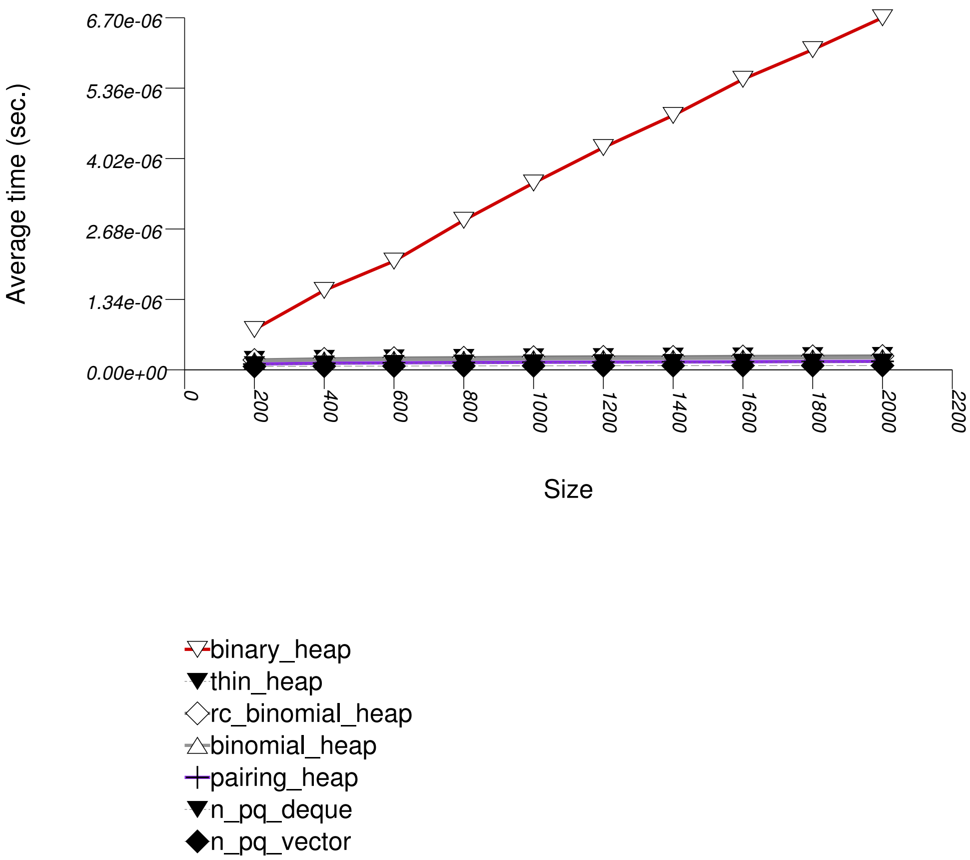
This test inserts a number of values with integer keys into a container using `push` , then removes them using `pop` . It measures the average time for `push` and `pop` as a function of the number of values.

It uses the test file: `performance/ext/pb_ds/priority_queue_random_int_push_pop_timing.cc`

The test checks the effect of different underlying data structures.

21.4.2.4.4.2 Results

The graphic immediately below shows the results for the native priority_queue type instantiated with different underlying container types versus several different versions of library's priority_queues.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	*Parameter*	*Details*
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
binary_heap		
`priority_queue`	`Tag`	`binary_heap_tag`
binomial_heap		
`priority_queue`	`Tag`	`binomial_heap_tag`
rc_binomial_heap		
`priority_queue`	`Tag`	`rc_binomial_heap_tag`
thin_heap		
`priority_queue`	`Tag`	`thin_heap_tag`
pairing_heap		
`priority_queue`	`Tag`	`pairing_heap_tag`

21.4.2.4.4.3 Observations

Binary heaps are the most suited for sequences of `push` and `pop` operations of primitive types (e.g. ints). This is explained in Priority Queue Random Int `push` Timing Test. (See Priority Queue Text `push` Timing Test for the case of primitive types.)

At first glance it seems that the standard's vector-based priority queue is approximately on par with this library's corresponding priority queue. There are two differences however:

1. The standard's priority queue does not downsize the underlying vector (or deque) as the priority queue becomes smaller (see Priority Queue Text `pop` Memory Use Test). It is therefore gaining some speed at the expense of space.

2. From Priority Queue Random Integer `push` and `pop` Timing Test, it seems that the standard's priority queue is slower in terms of `push` operations. Since the number of `pop` operations is at most that of `push` operations, the test here is the "best" for the standard's priority queue.

21.4.2.4.5 Text pop Memory Use

21.4.2.4.5.1 Description

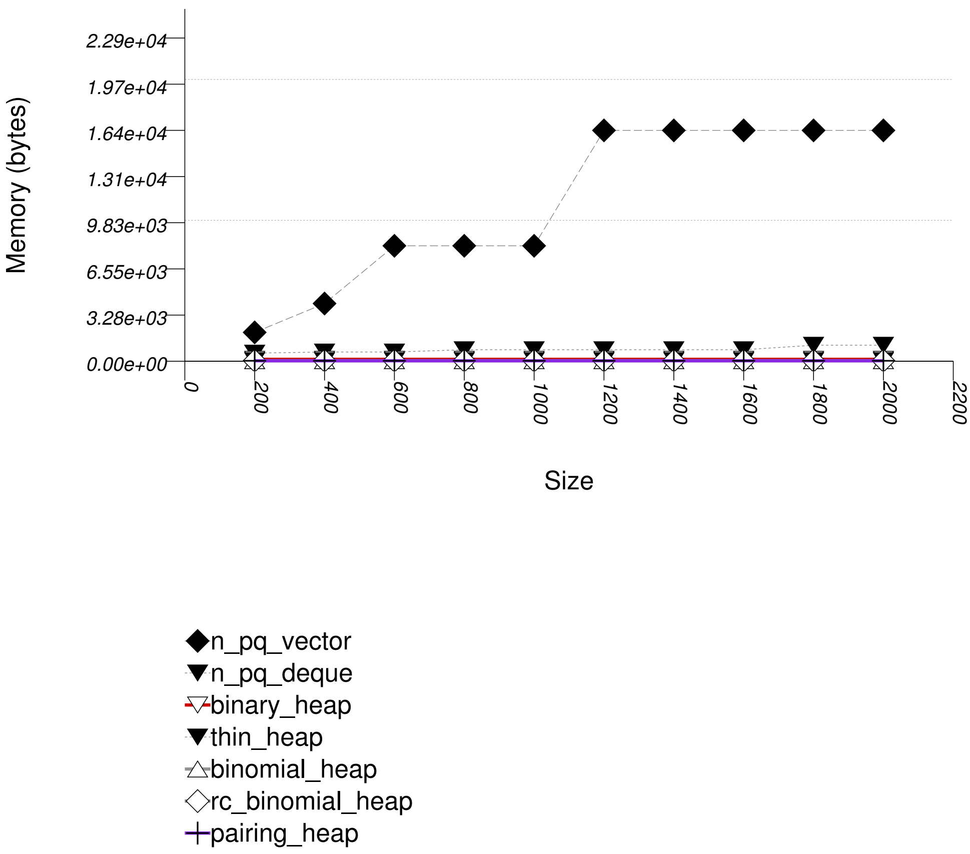
This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into a container, then pops them until only one is left in the container. It measures the memory use as a function of the number of values pushed to the container.

It uses the test file: `performance/ext/pb_ds/priority_queue_text_pop_mem_usage.cc`

The test checks the effect of different underlying data structures.

21.4.2.4.5.2 Results

The graphic immediately below shows the results for the native priority_queue type instantiated with different underlying container types versus several different versions of library's priority_queues.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
binary_heap		

Name/Instantiating Type	*Parameter*	*Details*
priority_queue	Tag	binary_heap_tag
binomial_heap		
priority_queue	Tag	binomial_heap_tag
rc_binomial_heap		
priority_queue	Tag	rc_binomial_heap_tag
thin_heap		
priority_queue	Tag	thin_heap_tag
pairing_heap		
priority_queue	Tag	pairing_heap_tag

21.4.2.4.5.3 Observations

The priority queue implementations (excluding the standard's) use memory proportionally to the number of values they hold: node-based implementations (e.g., a pairing heap) do so naturally; this library's binary heap de-allocates memory when a certain lower threshold is exceeded.

Note from Priority Queue Text `push` and `pop` Timing Test and Priority Queue Random Integer `push` and `pop` Timing Test that this does not impede performance compared to the standard's priority queues.

See Hash-Based Erase Memory Use Test for a similar phenomenon regarding priority queues.

21.4.2.4.6 Text `join`

21.4.2.4.6.1 Description

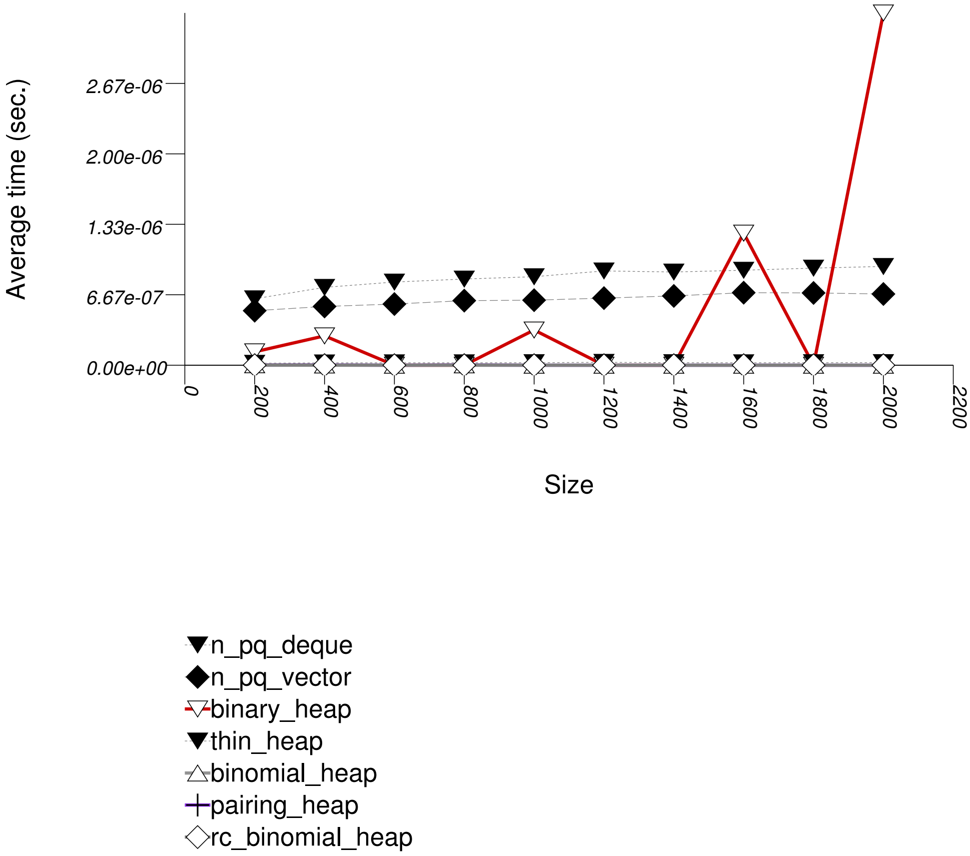
This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into two containers, then merges the containers. It uses `join` for this library's priority queues; for the standard's priority queues, it successively pops values from one container and pushes them into the other. The test measures the average time as a function of the number of values.

It uses the test file: `performance/ext/pb_ds/priority_queue_text_join_timing.cc`

The test checks the effect of different underlying data structures.

21.4.2.4.6.2 Results

The graphic immediately below shows the results for the native priority_queue type instantiated with different underlying container types versus several different versions of library's priority_queues.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	***Parameter***	***Details***
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
binary_heap		
`priority_queue`	`Tag`	`binary_heap_tag`
binomial_heap		
`priority_queue`	`Tag`	`binomial_heap_tag`
rc_binomial_heap		
`priority_queue`	`Tag`	`rc_binomial_heap_tag`
thin_heap		
`priority_queue`	`Tag`	`thin_heap_tag`
pairing_heap		
`priority_queue`	`Tag`	`pairing_heap_tag`

21.4.2.4.6.3 Observations

In this test the node-based heaps perform `join` in either logarithmic or constant time. The binary heap requires linear time, since the well-known heapify algorithm [clrs2001] is linear.

It would be possible to apply the heapify algorithm to the standard containers, if they would support iteration (which they don't). Barring iterators, it is still somehow possible to perform linear-time merge on a `std::vector`-based standard priority queue, using `top()` and `size()` (since they are enough to expose the underlying array), but this is impossible for a `std::deque`-based standard priority queue. Without heapify, the cost is super-linear.

21.4.2.4.7 Text `modify` Up

21.4.2.4.7.1 Description

This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into into a container then modifies each one "up" (i.e., it makes it larger). It uses `modify` for this library's priority queues; for the standard's priority queues, it pops values from a container until it reaches the value that should be modified, then pushes values back in. It measures the average time for `modify` as a function of the number of values.

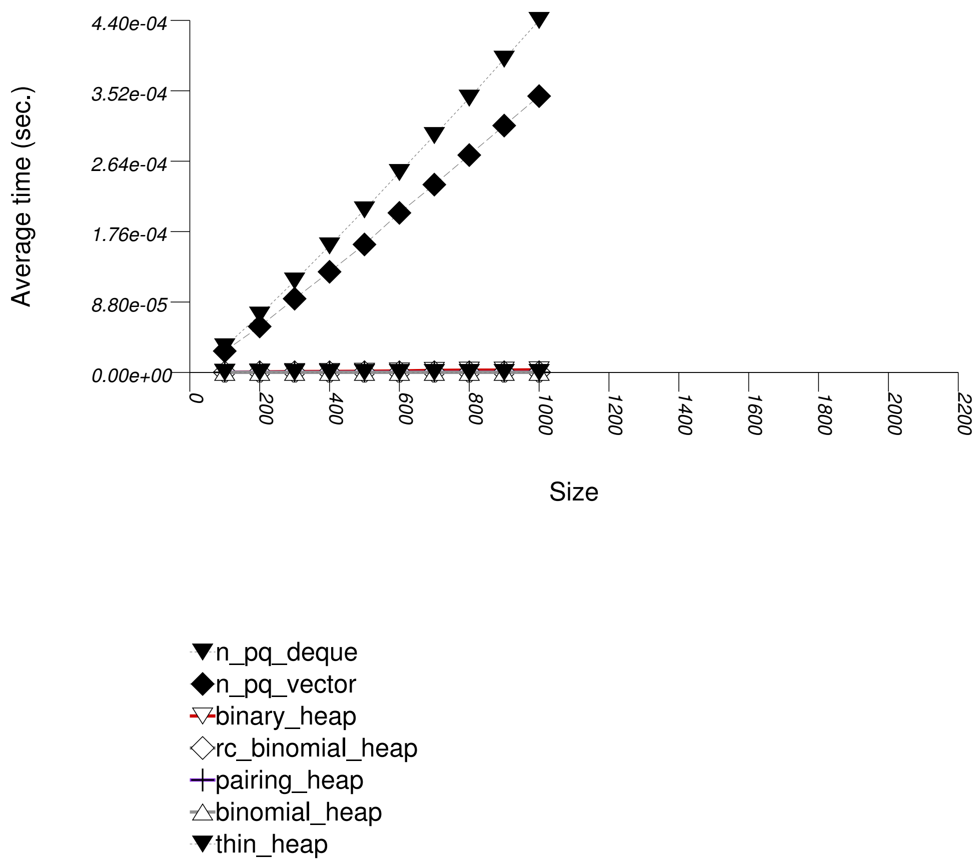
It uses the test file: `performance/ext/pb_ds/priority_queue_text_modify_up_timing.cc`

The test checks the effect of different underlying data structures for graph algorithms settings. Note that making an arbitrary value larger (in the sense of the priority queue's comparison functor) corresponds to decrease-key in standard graph algorithms [clrs2001].

21.4.2.4.7.2 Results

The two graphics below show the results for the native priority_queues and this library's priority_queues.

The graphic immediately below shows the results for the native priority_queue type instantiated with different underlying container types versus several different versions of library's priority_queues.

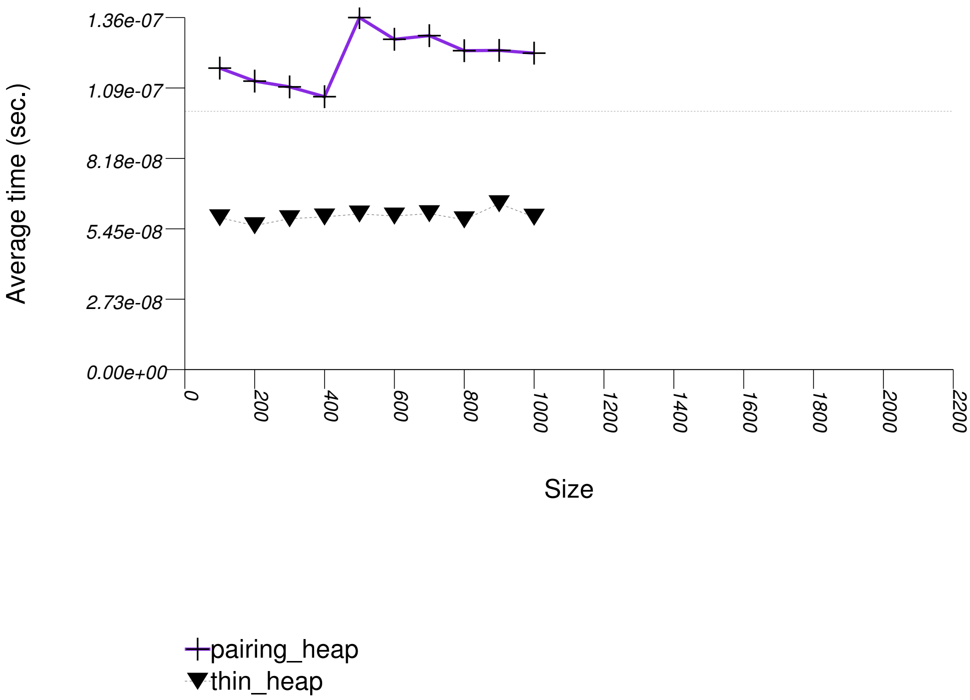


The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	*Parameter*	*Details*
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		

Name/Instantiating Type	*Parameter*	*Details*
std::priority_queue	Sequence	std::deque
binary_heap		
priority_queue	Tag	binary_heap_tag
binomial_heap		
priority_queue	Tag	binomial_heap_tag
rc_binomial_heap		
priority_queue	Tag	rc_binomial_heap_tag
thin_heap		
priority_queue	Tag	thin_heap_tag
pairing_heap		
priority_queue	Tag	pairing_heap_tag

The graphic below shows the results for the native priority queues and this library's pairing and thin heap priority_queue data structures.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	*Parameter*	*Details*
thin_heap		
priority_queue	Tag	thin_heap_tag
pairing_heap		
priority_queue	Tag	pairing_heap_tag

21.4.2.4.7.3 Observations

As noted above, increasing an arbitrary value (in the sense of the priority queue's comparison functor) is very common in graph-related algorithms. In this case, a thin heap (`priority_queue` with `Tag` = `thin_heap_tag`) outperforms a pairing heap (`priority_queue` with `Tag` = `pairing_heap_tag`). Conversely, Priority Queue Text `push` Timing Test, Priority Queue Text `push` and `pop` Timing Test, Priority Queue Random Integer `push` Timing Test, and Priority Queue Random Integer `push` and `pop` Timing Test show that the situation is reversed for other operations. It is not clear when to prefer one of these two different types.

In this test this library's binary heaps effectively perform modify in linear time. As explained in Priority Queue Design::Traits, given a valid point-type iterator, a binary heap can perform `modify` logarithmically. The problem is that binary heaps invalidate their find iterators with each modifying operation, and so the only way to obtain a valid point-type iterator is to iterate using a range-type iterator until finding the appropriate value, then use the range-type iterator for the `modify` operation.

The explanation for the standard's priority queues' performance is similar to that in Priority Queue Text `join` Timing Test.

21.4.2.4.8 Text `modify` Down

21.4.2.4.8.1 Description

This test inserts a number of values with keys from an arbitrary text ([wickland96thirty]) into into a container then modifies each one "down" (i.e., it makes it smaller). It uses `modify` for this library's priority queues; for the standard's priority queues, it pops values from a container until it reaches the value that should be modified, then pushes values back in. It measures the average time for `modify` as a function of the number of values.

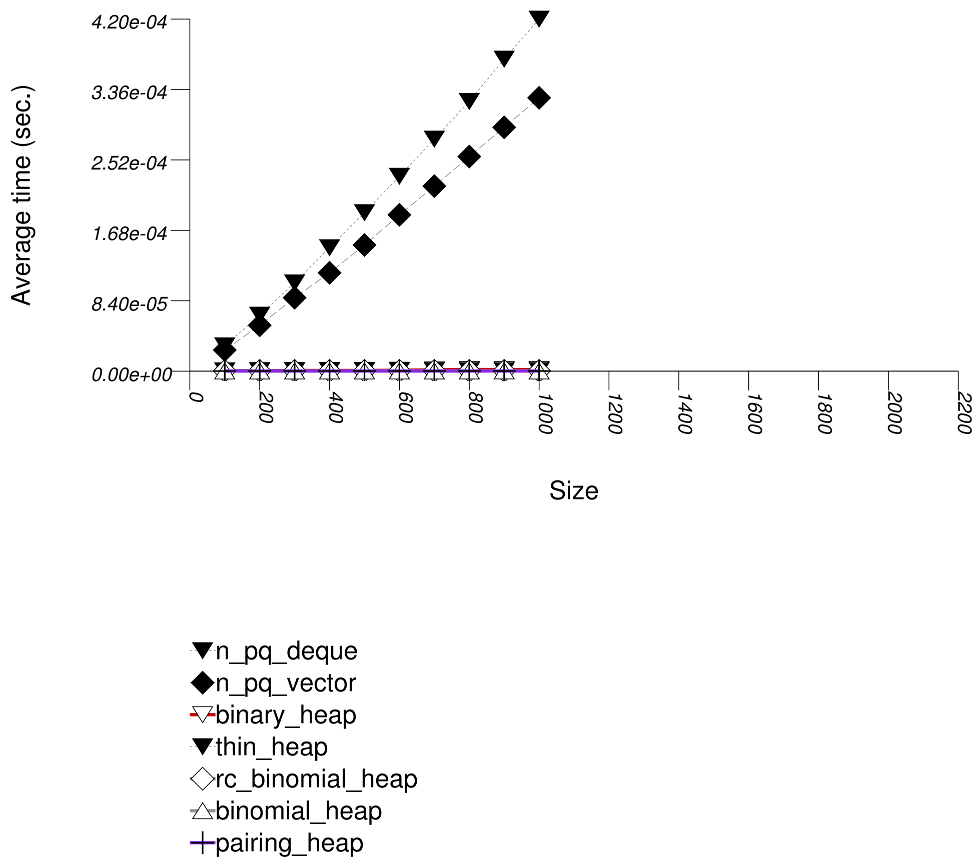
It uses the test file: `performance/ext/pb_ds/priority_queue_text_modify_down_timing.cc`

The main purpose of this test is to contrast Priority Queue Text `modify` Up Timing Test.

21.4.2.4.8.2 Results

The two graphics below show the results for the native priority_queues and this library's priority_queues.

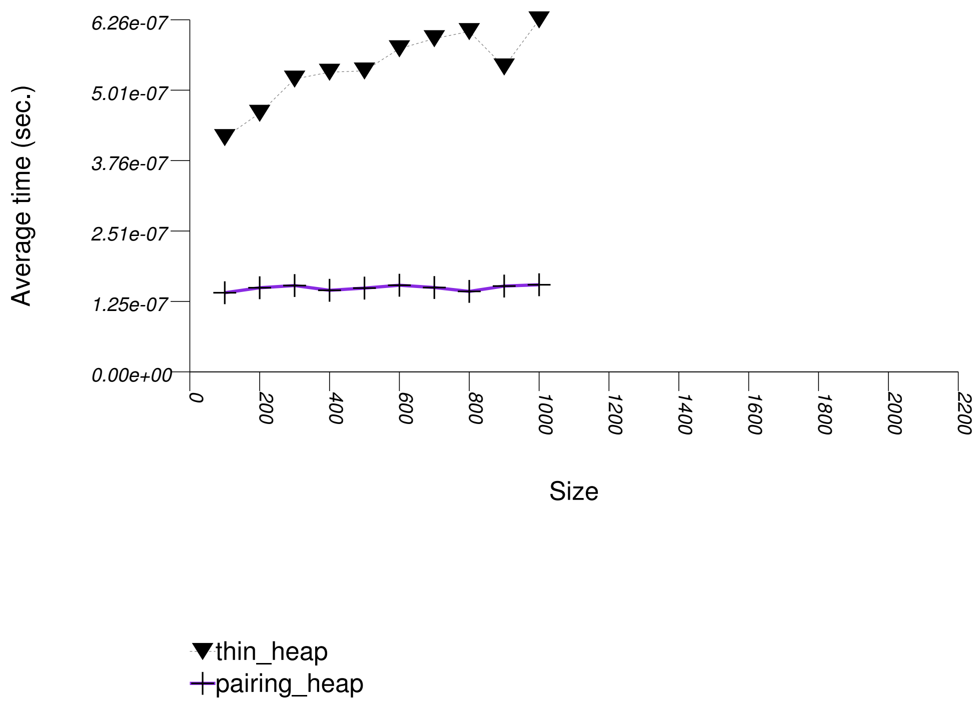
The graphic immediately below shows the results for the native priority_queue type instantiated with different underlying container types versus several different versions of library's priority_queues.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	*Parameter*	*Details*
n_pq_vector		
`std::priority_queue`	`Sequence`	`std::vector`
n_pq_deque		
`std::priority_queue`	`Sequence`	`std::deque`
binary_heap		
`priority_queue`	`Tag`	`binary_heap_tag`
binomial_heap		
`priority_queue`	`Tag`	`binomial_heap_tag`
rc_binomial_heap		
`priority_queue`	`Tag`	`rc_binomial_heap_tag`
thin_heap		
`priority_queue`	`Tag`	`thin_heap_tag`
pairing_heap		
`priority_queue`	`Tag`	`pairing_heap_tag`

The graphic below shows the results for the native priority queues and this library's pairing and thin heap priority_queue data structures.



The abbreviated names in the legend of the graphic above are instantiated with the types in the following table.

Name/Instantiating Type	*Parameter*	*Details*
thin_heap		
`priority_queue`	`Tag`	`thin_heap_tag`
pairing_heap		
`priority_queue`	`Tag`	`pairing_heap_tag`

21.4.2.4.8.3 Observations

Most points in these results are similar to Priority Queue Text `modify` Up Timing Test.

It is interesting to note, however, that as opposed to that test, a thin heap (`priority_queue` with `Tag` = `thin_heap_tag`) is outperformed by a pairing heap (`priority_queue` with `Tag` = `pairing_heap_tag`). In this case, both heaps essentially perform an `erase` operation followed by a `push` operation. As the other tests show, a pairing heap is usually far more efficient than a thin heap, so this is not surprising.

Most algorithms that involve priority queues increase values (in the sense of the priority queue's comparison functor), and so Priority Queue Text `modify` Up Timing Test - is more interesting than this test.

21.4.2.5 Observations

21.4.2.5.1 Associative

21.4.2.5.1.1 Underlying Data-Structure Families

In general, hash-based containers have better timing performance than containers based on different underlying-data structures. The main reason to choose a tree-based or trie-based container is if a byproduct of the tree-like structure is required: either order-preservation, or the ability to utilize node invariants. If memory-use is the major factor, an ordered-vector tree gives optimal results (albeit with high modificiation costs), and a list-based container gives reasonable results.

21.4.2.5.1.2 Hash-Based Containers

Hash-based containers are typically either collision chaining or probing. Collision-chaining containers are more flexible internally, and so offer better timing performance. Probing containers, if used for simple value-types, manage memory more efficiently (they perform far fewer allocation-related calls). In general, therefore, a collision-chaining table should be used. A probing container, conversely, might be used efficiently for operations such as eliminating duplicates in a sequence, or counting the number of occurrences within a sequence. Probing containers might be more useful also in multithreaded applications where each thread manipulates a hash-based container: in the standard, allocators have class-wise semantics (see [meyers96more] - Item 10); a probing container might incur less contention in this case.

21.4.2.5.1.3 Hash Policies

In hash-based containers, the range-hashing scheme seems to affect performance more than other considerations. In most settings, a mask-based scheme works well (or can be made to work well). If the key-distribution can be estimated a-priori, a simple hash function can produce nearly uniform hash-value distribution. In many other cases (e.g., text hashing, floating-point hashing), the hash function is powerful enough to generate hash values with good uniformity properties [knuth98sorting]; a modulo-based scheme, taking into account all bits of the hash value, appears to overlap the hash function in its effort.

The range-hashing scheme determines many of the other policies. A mask-based scheme works well with an exponential-size policy; for probing-based containers, it goes well with a linear-probe function.

An orthogonal consideration is the trigger policy. This presents difficult tradeoffs. E.g., different load factors in a load-check trigger policy yield a space/amortized-cost tradeoff.

21.4.2.5.1.4 Branch-Based Containers

In general, there are several families of tree-based underlying data structures: balanced node-based trees (e.g., red-black or AVL trees), high-probability balanced node-based trees (e.g., random treaps or skip-lists), competitive node-based trees (e.g., splay trees), vector-based "trees", and tries. (Additionally, there are disk-residing or network-residing trees, such as B-Trees and their numerous variants. An interface for this would have to deal with the execution model and ACID guarantees; this is out of the scope of this library.) Following are some observations on their application to different settings.

Of the balanced node-based trees, this library includes a red-black tree, as does standard (in practice). This type of tree is the "workhorse" of tree-based containers: it offers both reasonable modification and reasonable lookup time. Unfortunately, this data structure stores a huge amount of metadata. Each node must contain, besides a value, three pointers and a boolean. This type might be avoided if space is at a premium [austern00noset].

High-probability balanced node-based trees suffer the drawbacks of deterministic balanced trees. Although they are fascinating data structures, preliminary tests with them showed their performance was worse than red-black trees. The library does not contain any such trees, therefore.

Competitive node-based trees have two drawbacks. They are usually somewhat unbalanced, and they perform a large number of comparisons. Balanced trees perform one comparison per each node they encounter on a search path; a splay tree performs two comparisons. If the keys are complex objects, e.g., `std::string`, this can increase the running time. Conversely, such trees do well when there is much locality of reference. It is difficult to determine in which case to prefer such trees over balanced trees. This library includes a splay tree.

Ordered-vector trees use very little space [austern00noset]. They do not have any other advantages (at least in this implementation).

Large-fan-out PATRICIA tries have excellent lookup performance, but they do so through maintaining, for each node, a miniature "hash-table". Their space efficiency is low, and their modification performance is bad. These tries might be used for semi-static settings, where order preservation is important. Alternatively, red-black trees cross-referenced with hash tables can be used. [okasaki98mereable] discusses small-fan-out PATRICIA tries for integers, but the cited results seem to indicate that the amortized cost of maintaining such trees is higher than that of balanced trees. Moderate-fan-out trees might be useful for sequences where each element has a limited number of choices, e.g., DNA strings.

21.4.2.5.1.5 Mapping-Semantics

Different mapping semantics were discussed in the introduction and design sections.Here the focus will be on the case where a keys can be composed into primary keys and secondary keys. (In the case where some keys are completely identical, it is trivial that one should use an associative container mapping values to size types.) In this case there are (at least) five possibilities:

1. Use an associative container that allows equivalent-key values (such as `std::multimap`)
2. Use a unique-key value associative container that maps each primary key to some complex associative container of secondary keys, say a tree-based or hash-based container.
3. Use a unique-key value associative container that maps each primary key to some simple associative container of secondary keys, say a list-based container.
4. Use a unique-key value associative container that maps each primary key to some non-associative container (e.g., `std::vector`)
5. Use a unique-key value associative container that takes into account both primary and secondary keys.

Stated simply: there is a simple answer for this. (Excluding option 1, which should be avoided in all cases).

If the expected ratio of secondary keys to primary keys is small, then 3 and 4 seem reasonable. Both types of secondary containers are relatively lightweight (in terms of memory use and construction time), and so creating an entire container object for each primary key is not too expensive. Option 4 might be preferable to option 3 if changing the secondary key of some primary key is frequent - one cannot modify an associative container's key, and the only possibility, therefore, is erasing the secondary key and inserting another one instead; a non-associative container, conversely, can support in-place modification. The actual cost of erasing a secondary key and inserting another one depends also on the allocator used for secondary associative-containers (The tests above used the standard allocator, but in practice one might choose to use, e.g., [boost_pool]). Option 2 is definitely an overkill in this case. Option 1 loses out either immediately (when there is one secondary key per primary key) or almost immediately after that. Option 5 has the same drawbacks as option 2, but it has the additional drawback that finding all values whose primary key is equivalent to some key, might be linear in the total number of values stored (for example, if using a hash-based container).

If the expected ratio of secondary keys to primary keys is large, then the answer is more complicated. It depends on the distribution of secondary keys to primary keys, the distribution of accesses according to primary keys, and the types of operations most frequent.

To be more precise, assume there are m primary keys, primary key i is mapped to n_i secondary keys, and each primary key is mapped, on average, to n secondary keys (i.e., $E(n_i) = n$).

Suppose one wants to find a specific pair of primary and secondary keys. Using 1 with a tree based container (`std::multimap`), the expected cost is $E(\Theta(\log(m) + n_i)) = \Theta(\log(m) + n)$; using 1 with a hash-based container (`std::tr1::unordered_multimap`), the expected cost is $\Theta(n)$. Using 2 with a primary hash-based container and secondary hash-based containers, the expected cost is $O(1)$; using 2 with a primary tree-based container and secondary tree-based containers, the expected cost is (using the Jensen inequality [motwani95random]) E(O(log(m) + log(n_i)) = O(log(m)) + E(O(log(n_i)) = O(log(m)) + O(log(n)), assuming that primary keys are accessed equiprobably. 3 and 4 are similar to 1, but with lower constants. Using 5 with a hash-based container, the expected cost is O(1); using 5 with a tree based container, the cost is E(Θ(log(mn))) = Θ(log(m) + log(n)).

Suppose one needs the values whose primary key matches some given key. Using 1 with a hash-based container, the expected cost is Θ(n), but the values will not be ordered by secondary keys (which may or may not be required); using 1 with a tree-based container, the expected cost is Θ(log(m) + n), but with high constants; again the values will not be ordered by secondary keys. 2, 3, and 4 are similar to 1, but typically with lower constants (and, additionally, if one uses a tree-based container for secondary keys, they will be ordered). Using 5 with a hash-based container, the cost is Θ(mn).

Suppose one wants to assign to a primary key all secondary keys assigned to a different primary key. Using 1 with a hash-based container, the expected cost is Θ(n), but with very high constants; using 1 with a tree-based container, the cost is Θ(nlog(mn)). Using 2, 3, and 4, the expected cost is Θ(n), but typically with far lower costs than 1. 5 is similar to 1.

21.4.2.5.2 Priority_Queue

21.4.2.5.2.1 Complexity

The following table shows the complexities of the different underlying data structures in terms of orders of growth. It is interesting to note that this table implies something about the constants of the operations as well (see Amortized `push` and `pop` operations).

	push	***pop***	***modify***	***erase***	***join***
`std::priority_queue`	Θ(n) worst Θ(log(n)) amortized	Θ(log(n)) Worst	Θ(n log(n)) Worst [std note 1]	Θ(n log(n)) [std note 2]	Θ(n log(n)) [std note 1]
`priority_queue <Tag = pairing_heap_tag>`	O(1)	Θ(n) worst Θ(log(n)) amortized	Θ(n) worst Θ(log(n)) amortized	Θ(n) worst Θ(log(n)) amortized	O(1)
`priority_queue <Tag = binary_heap_tag>`	Θ(n) worst Θ(log(n)) amortized	Θ(n) worst Θ(log(n)) amortized	Θ(n)	Θ(n)	Θ(n)
`priority_queue <Tag = binomial_heap_tag>`	Θ(log(n)) worst O(1) amortized	Θ(log(n))	Θ(log(n))	Θ(log(n))	Θ(log(n))
`priority_queue <Tag = rc_binomial_heap_tag>`	O(1)	Θ(log(n))	Θ(log(n))	Θ(log(n))	Θ(log(n))
`priority_queue<Tag = thin_heap_tag>`	O(1)	Θ(n) worst Θ(log(n)) amortized	Θ(log(n)) worst O(1) amortized, or Θ(log(n)) amortized [thin_heap_note]	Θ(n) worst Θ(log(n)) amortized	Θ(n)

[std note 1] This is not a property of the algorithm, but rather due to the fact that the standard's priority queue implementation does not support iterators (and consequently the ability to access a specific value inside it). If the priority queue is adapting an `std::vector`, then it is still possible to reduce this to Θ(n) by adapting over the standard's adapter and using the fact that `top` returns a reference to the first value; if, however, it is adapting an `std::deque`, then this is impossible.

[std note 2] As with [std note 1], this is not a property of the algorithm, but rather the standard's implementation. Again, if the priority queue is adapting an `std::vector` then it is possible to reduce this to Θ(n), but with a very high constant (one must call `std::make_heap` which is an expensive linear operation); if the priority queue is adapting an `std::deque`, then this is impossible.

[thin_heap_note] A thin heap has Θ(log(n)) worst case `modify` time always, but the amortized time depends on the nature of the operation: I) if the operation increases the key (in the sense of the priority queue's comparison functor), then the amortized time is O(1), but if II) it decreases it, then the amortized time is the same as the worst case time. Note that for most algorithms, I) is important and II) is not.

21.4.2.5.2.2 Amortized push and pop operations

In many cases, a priority queue is needed primarily for sequences of `push` and `pop` operations. All of the underlying data structures have the same amortized logarithmic complexity, but they differ in terms of constants.

The table above shows that the different data structures are "constrained" in some respects. In general, if a data structure has lower worst-case complexity than another, then it will perform slower in the amortized sense. Thus, for example a redundant-counter binomial heap (`priority_queue` with `Tag` = `rc_binomial_heap_tag`) has lower worst-case `push` performance than a binomial heap (`priority_queue` with `Tag` = `binomial_heap_tag`), and so its amortized `push` performance is slower in terms of constants.

As the table shows, the "least constrained" underlying data structures are binary heaps and pairing heaps. Consequently, it is not surprising that they perform best in terms of amortized constants.

1. Pairing heaps seem to perform best for non-primitive types (e.g., `std::strings`), as shown by Priority Queue Text `push` Timing Test and Priority Queue Text `push` and `pop` Timing Test

2. binary heaps seem to perform best for primitive types (e.g., ints), as shown by Priority Queue Random Integer `push` Timing Test and Priority Queue Random Integer `push` and `pop` Timing Test.

21.4.2.5.2.3 Graph Algorithms

In some graph algorithms, a decrease-key operation is required [clrs2001]; this operation is identical to `modify` if a value is increased (in the sense of the priority queue's comparison functor). The table above and Priority Queue Text `modify` Up Timing Test show that a thin heap (`priority_queue` with `Tag = thin_heap_tag`) outperforms a pairing heap (`priority_queue` with `Tag` = `Tag` = `pairing_heap_tag`), but the rest of the tests show otherwise.

This makes it difficult to decide which implementation to use in this case. Dijkstra's shortest-path algorithm, for example, requires $\Theta(n)$ `push` and `pop` operations (in the number of vertices), but $O(n^2)$ `modify` operations, which can be in practice $\Theta(n)$ as well. It is difficult to find an a-priori characterization of graphs in which the actual number of `modify` operations will dwarf the number of `push` and `pop` operations.

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This library was partially written at IBM's Haifa Research Labs. It is based heavily on policy-based design and uses many useful techniques from Modern C++ Design: Generic Programming and Design Patterns Applied by Andrei Alexandrescu.

Two ideas are borrowed from the SGI-STL implementation:

1. The prime-based resize policies use a list of primes taken from the SGI-STL implementation.

2. The red-black trees contain both a root node and a header node (containing metadata), connected in a way that forward and reverse iteration can be performed efficiently.

Some test utilities borrow ideas from boost::timer.

We would like to thank Scott Meyers for useful comments (without attributing to him any flaws in the design or implementation of the library).

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Chapter 22

HP/SGI Extensions

22.1 Backwards Compatibility

A few extensions and nods to backwards-compatibility have been made with containers. Those dealing with older SGI-style allocators are dealt with elsewhere. The remaining ones all deal with bits:

The old pre-standard `bit_vector` class is present for backwards compatibility. It is simply a typedef for the `vector<bool>` specialization.

The `bitset` class has a number of extensions, described in the rest of this item. First, we'll mention that this implementation of `bitset<N>` is specialized for cases where N number of bits will fit into a single word of storage. If your choice of N is within that range (<=32 on i686-pc-linux-gnu, for example), then all of the operations will be faster.

There are versions of single-bit test, set, reset, and flip member functions which do no range-checking. If we call them member functions of an instantiation of `bitset<N>`, then their names and signatures are:

```
bitset<N>&   _Unchecked_set   (size_t pos);
bitset<N>&   _Unchecked_set   (size_t pos, int val);
bitset<N>&   _Unchecked_reset (size_t pos);
bitset<N>&   _Unchecked_flip  (size_t pos);
bool         _Unchecked_test  (size_t pos);
```

Note that these may in fact be removed in the future, although we have no present plans to do so (and there doesn't seem to be any immediate reason to).

The member function `operator[]` on a const bitset returns a bool, and for a non-const bitset returns a `reference` (a nested type). No range-checking is done on the index argument, in keeping with other containers' `operator[]` requirements.

Finally, two additional searching functions have been added. They return the index of the first "on" bit, and the index of the first "on" bit that is after `prev`, respectively:

```
size_t _Find_first() const;
size_t _Find_next (size_t prev) const;
```

The same caveat given for the _Unchecked_* functions applies here also.

22.2 Deprecated

The SGI hashing classes `hash_set` and `hash_set` have been deprecated by the unordered_set, unordered_multiset, unordered_map, unordered_multimap containers in TR1 and C++11, and may be removed in future releases.

The SGI headers

```
<hash_map>
<hash_set>
<rope>
<slist>
<rb_tree>
```

are all here; `<backwards/hash_map>` and `<backwards/hash_set>` are deprecated but available as backwards-compatible extensions, as discussed further below. `<ext/rope>` is the SGI specialization for large strings ("rope," "large strings," get it? Love that geeky humor.) `<ext/slist>` (superseded in C++11 by `<forward_list>`) is a singly-linked list, for when the doubly-linked `list<>` is too much space overhead, and `<ext/rb_tree>` exposes the red-black tree classes used in the implementation of the standard maps and sets.

Each of the associative containers map, multimap, set, and multiset have a counterpart which uses a hashing function to do the arranging, instead of a strict weak ordering function. The classes take as one of their template parameters a function object that will return the hash value; by default, an instantiation of hash. You should specialize this functor for your class, or define your own, before trying to use one of the hashing classes.

The hashing classes support all the usual associative container functions, as well as some extra constructors specifying the number of buckets, etc.

Why would you want to use a hashing class instead of the “normal”implementations? Matt Austern writes:

> *[W]ith a well chosen hash function, hash tables generally provide much better average-case performance than binary search trees, and much worse worst-case performance. So if your implementation has hash_map, if you don’t mind using nonstandard components, and if you aren’t scared about the possibility of pathological cases, you’ll probably get better performance from hash_map.*

The deprecated hash tables are superseded by the standard unordered associative containers defined in the ISO C++ 2011 standard in the headers `<unordered_map>` and `<unordered_set>`.

Chapter 23

Utilities

The `<functional>` header contains many additional functors and helper functions, extending section 20.3. They are implemented in the file stl_function.h:

- `identity_element` for addition and multiplication.
- The functor `identity`, whose `operator()` returns the argument unchanged.
- Composition functors `unary_function` and `binary_function`, and their helpers `compose1` and `compose2`.
- `select1st` and `select2nd`, to strip pairs.
- `project1st` and `project2nd`.
- A set of functors/functions which always return the same result. They are `constant_void_fun`, `constant_binary_fun`, `constant_unary_fun`, `constant0`, `constant1`, and `constant2`.
- The class `subtractive_rng`.
- mem_fun adaptor helpers `mem_fun1` and `mem_fun1_ref` are provided for backwards compatibility.

20.4.1 can use several different allocators; they are described on the main extensions page.

20.4.3 is extended with a special version of `get_temporary_buffer` taking a second argument. The argument is a pointer, which is ignored, but can be used to specify the template type (instead of using explicit function template arguments like the standard version does). That is, in addition to

```
get_temporary_buffer<int>(5);
```

you can also use

```
get_temporary_buffer(5, (int*)0);
```

A class `temporary_buffer` is given in stl_tempbuf.h.

The specialized algorithms of section 20.4.4 are extended with `uninitialized_copy_n`.

Chapter 24

Algorithms

25.1.6 (count, count_if) is extended with two more versions of count and count_if. The standard versions return their results. The additional signatures return void, but take a final parameter by reference to which they assign their results, e.g.,

```
void count (first, last, value, n);
```

25.2 (mutating algorithms) is extended with two families of signatures, random_sample and random_sample_n.

25.2.1 (copy) is extended with

```
copy_n (_InputIter first, _Size count, _OutputIter result);
```

which copies the first 'count' elements at 'first' into 'result'.

25.3 (sorting 'n' heaps 'n' stuff) is extended with some helper predicates. Look in the doxygen-generated pages for notes on these.

- `is_heap` tests whether or not a range is a heap.
- `is_sorted` tests whether or not a range is sorted in nondescending order.

25.3.8 (lexicographical_compare) is extended with

```
lexicographical_compare_3way(_InputIter1 first1, _InputIter1 last1,
      _InputIter2 first2, _InputIter2 last2)
```

which does... what?

Chapter 25

Numerics

26.4, the generalized numeric operations such as `accumulate`, are extended with the following functions:

```
power (x, n);
power (x, n, monoid_operation);
```

Returns, in FORTRAN syntax, "`x ** n`" where `n >= 0`. In the case of `n == 0`, returns the identity element for the monoid operation. The two-argument signature uses multiplication (for a true "power" implementation), but addition is supported as well. The operation functor must be associative.

The `iota` function wins the award for Extension With the Coolest Name (the name comes from Ken Iverson's APL language.) As described in the SGI documentation, it "assigns sequentially increasing values to a range. That is, it assigns `value` to `*first`, `value + 1` to `*(first + 1)` and so on."

```
void iota(_ForwardIter first, _ForwardIter last, _Tp value);
```

The `iota` function is included in the ISO C++ 2011 standard.

Chapter 26

Iterators

24.3.2 describes `struct iterator`, which didn't exist in the original HP STL implementation (the language wasn't rich enough at the time). For backwards compatibility, base classes are provided which declare the same nested typedefs:

- input_iterator
- output_iterator
- forward_iterator
- bidirectional_iterator
- random_access_iterator

24.3.4 describes iterator operation `distance`, which takes two iterators and returns a result. It is extended by another signature which takes two iterators and a reference to a result. The result is modified, and the function returns nothing.

Chapter 27

Input and Output

Extensions allowing `filebufs` to be constructed from "C" types like FILE*s and file descriptors.

27.1 Derived filebufs

The v2 library included non-standard extensions to construct `std::filebufs` from C stdio types such as `FILE*`s and POSIX file descriptors. Today the recommended way to use stdio types with libstdc++ IOStreams is via the `stdio_filebuf` class (see below), but earlier releases provided slightly different mechanisms.

- 3.0.x `filebufs` have another ctor with this signature: `basic_filebuf(__c_file_type*, ios_base::openmode, int_type);` This comes in very handy in a number of places, such as attaching Unix sockets, pipes, and anything else which uses file descriptors, into the IOStream buffering classes. The three arguments are as follows:
  - `__c_file_type* F` // the __c_file_type typedef usually boils down to stdio's FILE
  - `ios_base::openmode M` // same as all the other uses of openmode
  - `int_type B` // buffer size, defaults to BUFSIZ if not specified

  For those wanting to use file descriptors instead of FILE*'s, I invite you to contemplate the mysteries of C's `fdopen()`.
- In library snapshot 3.0.95 and later, `filebufs` bring back an old extension: the `fd()` member function. The integer returned from this function can be used for whatever file descriptors can be used for on your platform. Naturally, the library cannot track what you do on your own with a file descriptor, so if you perform any I/O directly, don't expect the library to be aware of it.
- Beginning with 3.1, the extra `basic_filebuf` constructor and the `fd()` function were removed from the standard filebuf. Instead, `<ext/stdio_filebuf.h>` contains a derived class template called `__gnu_cxx::stdio_filebuf`. This class can be constructed from a C `FILE*` or a file descriptor, and provides the `fd()` function.

Chapter 28

Demangling

Transforming C++ ABI identifiers (like RTTI symbols) into the original C++ source identifiers is called "demangling."

If you have read the source documentation for `namespace abi` then you are aware of the cross-vendor C++ ABI in use by GCC. One of the exposed functions is used for demangling, `abi::__cxa_demangle`.

In programs like **c++filt**, the linker, and other tools have the ability to decode C++ ABI names, and now so can you.

(The function itself might use different demanglers, but that's the whole point of abstract interfaces. If we change the implementation, you won't notice.)

Probably the only time you'll be interested in demangling at runtime is when you're seeing `typeid` strings in RTTI. For example:

```
#include <iostream>
#include <cstdlib>
#include <cxxabi.h>

struct empty { };

template <typename T, int N>
  struct bar { };

int main()
{
  int     status;
  char   *realname;

  // typeid
  bar<empty,17>          u;
  const std::type_info  &ti = typeid(u);

  realname = abi::__cxa_demangle(ti.name(), NULL, NULL, &status);
  std::cout << ti.name() << "\t=> " << realname << "\t: " << status << '\n';
  std::free(realname);
}
```

This prints

```
      3barI5emptyLi17EE       => bar<empty, 17>       : 0
```

The demangler interface is described in the source documentation linked to above. It is actually written in C, so you don't need to be writing C++ in order to demangle C++. (That also means we have to use crummy memory management facilities, so don't forget to `free()` the returned char array.)

Chapter 29

Concurrency

29.1 Design

29.1.1 Interface to Locks and Mutexes

The file `<ext/concurrence.h>` contains all the higher-level constructs for playing with threads. In contrast to the atomics layer, the concurrence layer consists largely of types. All types are defined within `namespace __gnu_cxx`.

These types can be used in a portable manner, regardless of the specific environment. They are carefully designed to provide optimum efficiency and speed, abstracting out underlying thread calls and accesses when compiling for single-threaded situations (even on hosts that support multiple threads.)

The enumerated type `_Lock_policy` details the set of available locking policies: `_S_single`, `_S_mutex`, and `_S_atomic`.

- `_S_single`

  Indicates single-threaded code that does not need locking.

- `_S_mutex`

  Indicates multi-threaded code using thread-layer abstractions.

- `_S_atomic`

  Indicates multi-threaded code using atomic operations.

The compile-time constant `__default_lock_policy` is set to one of the three values above, depending on characteristics of the host environment and the current compilation flags.

Two more datatypes make up the rest of the interface: `__mutex`, and `__scoped_lock`.

The scoped lock idiom is well-discussed within the C++ community. This version takes a `__mutex` reference, and locks it during construction of `__scoped_lock` and unlocks it during destruction. This is an efficient way of locking critical sections, while retaining exception-safety. These types have been superseded in the ISO C++ 2011 standard by the mutex and lock types defined in the header `<mutex>`.

29.1.2 Interface to Atomic Functions

Two functions and one type form the base of atomic support.

The type `_Atomic_word` is a signed integral type supporting atomic operations.

The two functions functions are:

```
_Atomic_word
__exchange_and_add_dispatch(volatile _Atomic_word*, int);

void
__atomic_add_dispatch(volatile _Atomic_word*, int);
```

Both of these functions are declared in the header file <ext/atomicity.h>, and are in `namespace __gnu_cxx`.

- `__exchange_and_add_dispatch`

  Adds the second argument's value to the first argument. Returns the old value.

- `__atomic_add_dispatch`

  Adds the second argument's value to the first argument. Has no return value.

These functions forward to one of several specialized helper functions, depending on the circumstances. For instance,

`__exchange_and_add_dispatch`

Calls through to either of:

- `__exchange_and_add`

  Multi-thread version. Inlined if compiler-generated builtin atomics can be used, otherwise resolved at link time to a non-builtin code sequence.

- `__exchange_and_add_single`

  Single threaded version. Inlined.

However, only `__exchange_and_add_dispatch` and `__atomic_add_dispatch` should be used. These functions can be used in a portable manner, regardless of the specific environment. They are carefully designed to provide optimum efficiency and speed, abstracting out atomic accesses when they are not required (even on hosts that support compiler intrinsics for atomic operations.)

In addition, there are two macros

`_GLIBCXX_READ_MEM_BARRIER`

`_GLIBCXX_WRITE_MEM_BARRIER`

Which expand to the appropriate write and read barrier required by the host hardware and operating system.

29.2 Implementation

29.2.1 Using Built-in Atomic Functions

The functions for atomic operations described above are either implemented via compiler intrinsics (if the underlying host is capable) or by library fallbacks.

Compiler intrinsics (builtins) are always preferred. However, as the compiler builtins for atomics are not universally implemented, using them directly is problematic, and can result in undefined function calls.

Prior to GCC 4.7 the older `__sync` intrinsics were used. An example of an undefined symbol from the use of `__sync_fetch_and_a` on an unsupported host is a missing reference to `__sync_fetch_and_add_4`.

Current releases use the newer `__atomic` intrinsics, which are implemented by library calls if the hardware doesn't support them. Undefined references to functions like `__atomic_is_lock_free` should be resolved by linking to `libatomic`, which is usually installed alongside libstdc++.

In addition, on some hosts the compiler intrinsics are enabled conditionally, via the `-march` command line flag. This makes usage vary depending on the target hardware and the flags used during compile.

If builtins are possible for bool-sized integral types, `ATOMIC_BOOL_LOCK_FREE` will be defined. If builtins are possible for int-sized integral types, `ATOMIC_INT_LOCK_FREE` will be defined.

For the following hosts, intrinsics are enabled by default.

- alpha
- ia64
- powerpc
- s390

For others, some form of `-march` may work. On non-ancient x86 hardware, `-march=native` usually does the trick.

For hosts without compiler intrinsics, but with capable hardware, hand-crafted assembly is selected. This is the case for the following hosts:

- cris
- hppa
- i386
- i486
- m48k
- mips
- sparc

And for the rest, a simulated atomic lock via pthreads.

Detailed information about compiler intrinsics for atomic operations can be found in the GCC documentation.

More details on the library fallbacks from the porting section.

29.2.2 Thread Abstraction

A thin layer above IEEE 1003.1 (i.e. pthreads) is used to abstract the thread interface for GCC. This layer is called "gthread," and is comprised of one header file that wraps the host's default thread layer with a POSIX-like interface.

The file <gthr-default.h> points to the deduced wrapper for the current host. In libstdc++ implementation files, <bits/gthr.h> is used to select the proper gthreads file.

Within libstdc++ sources, all calls to underlying thread functionality use this layer. More detail as to the specific interface can be found in the source documentation.

By design, the gthread layer is interoperable with the types, functions, and usage found in the usual <pthread.h> file, including `pthread_t`, `pthread_once_t`, `pthread_create`, etc.

29.3 Use

Typical usage of the last two constructs is demonstrated as follows:

```
#include <ext/concurrence.h>

namespace
{
  __gnu_cxx::__mutex safe_base_mutex;
} // anonymous namespace

namespace other
{
  void
  foo()
  {
    __gnu_cxx::__scoped_lock sentry(safe_base_mutex);
    for (int i = 0; i < max;  ++i)
      {
  _Safe_iterator_base* __old = __iter;
  __iter = __iter-<_M_next;
  __old-<_M_detach_single();
      }
}
```

In this sample code, an anonymous namespace is used to keep the `__mutex` private to the compilation unit, and `__scoped_lock` is used to guard access to the critical section within the for loop, locking the mutex on creation and freeing the mutex as control moves out of this block.

Several exception classes are used to keep track of concurrence-related errors. These classes are: `__concurrence_lock_error`, `__concurrence_unlock_error`, `__concurrence_wait_error`, and `__concurrence_broadcast_error`.

Part IV

Appendices

Appendix A

Contributing

The GNU C++ Library is part of GCC and follows the same development model, so the general rules for contributing to GCC apply. Active contributors are assigned maintainership responsibility, and given write access to the source repository. First-time contributors should follow this procedure:

A.1 Contributor Checklist

A.1.1 Reading

- Get and read the relevant sections of the C++ language specification. Copies of the full ISO 14882 standard are available on line via the ISO mirror site for committee members. Non-members, or those who have not paid for the privilege of sitting on the committee and sustained their two meeting commitment for voting rights, may get a copy of the standard from their respective national standards organization. In the USA, this national standards organization is ANSI. (And if you've already registered with them you can buy the standard on-line.)
- The library working group bugs, and known defects, can be obtained here: https://www.open-std.org/jtc1/sc22/wg21
- Peruse the GNU Coding Standards, and chuckle when you hit the part about "Using Languages Other Than C".
- Be familiar with the extensions that preceded these general GNU rules. These style issues for libstdc++ can be found in Coding Style.
- And last but certainly not least, read the library-specific information found in Porting and Maintenance.

A.1.2 Assignment

See the legal prerequisites for all GCC contributions.

Historically, the libstdc++ assignment form added the following question:

" Which Belgian comic book character is better, Tintin or Asterix, and why? "

While not strictly necessary, humoring the maintainers and answering this question would be appreciated.

Please contact Jonathan Wakely at jwakely+assign@redhat.com if you are confused about the assignment or have general licensing questions. When requesting an assignment form from assign@gnu.org, please CC the libstdc++ maintainer above so that progress can be monitored.

A.1.3 Getting Sources

Getting write access (look for "Write after approval")

A.1.4 Submitting Patches

Every patch must have several pieces of information before it can be properly evaluated. Ideally (and to ensure the fastest possible response from the maintainers) it would have all of these pieces:

- A description of the bug and how your patch fixes this bug. For new features a description of the feature and your implementation.
- A ChangeLog entry as part of the Git commit message. Check some recent commits for format and content. The `contrib/mklog.py` script can be used to generate a ChangeLog template for commit messages. See Read-write Git access for scripts and aliases that are useful here.
- A testsuite submission or sample program that will easily and simply show the existing error or test new functionality.
- The patch itself. If you are using the Git repository use **git show** or **git format-patch** to produce a patch; otherwise, use **diff -cp OLD NEW**. If your version of diff does not support these options, then get the latest version of GNU diff.
- When you have all these pieces, bundle them up in a mail message and send it to libstdc++@gcc.gnu.org. All patches and related discussion should be sent to the libstdc++ mailing list. In common with the rest of GCC, patches should also be sent to the gcc-patches mailing list. So you could send your email To:libstdc++@gcc.gnu.org and Cc:gcc-patches@gcc.gnu.org for example.

A.2 Directory Layout and Source Conventions

The `libstdc++-v3` directory in the GCC sources contains the files needed to create the GNU C++ Library.

It has subdirectories:

`doc` Files in HTML and text format that document usage, quirks of the implementation, and contributor checklists.

`include` All header files for the C++ library are within this directory, modulo specific runtime-related files that are in the libsupc++ directory.

- **`include/std`** Files meant to be found by `#include <name>` directives in standard-conforming user programs.
- **`include/c`** Headers intended to directly include standard C headers. [NB: this can be enabled via `--enable-cheaders=c`]
- **`include/c_global`** Headers intended to include standard C headers in the global namespace, and put select names into the `std::` namespace. [NB: this is the default, and is the same as `--enable-cheaders=c_global`]
- **`include/c_std`** Headers intended to include standard C headers already in namespace std, and put select names into the `std::` namespace. [NB: this is the same as `--enable-cheaders=c_std`]
- **`include/bits`** Files included by standard headers and by other files in the bits directory.
- **`include/backward`** Headers provided for backward compatibility, such as `<backward/hash_map>`. They are not used in this library.
- **`include/ext`** Headers that define extensions to the standard library. No standard header refers to any of them, in theory (there are some exceptions).
- **`include/debug`, `include/parallel`, and** Headers that implement the Debug Mode and Parallel Mode extensions.

`scripts` Scripts that are used during the configure, build, make, or test process.

`src` Files that are used in constructing the library, but are not installed.

- **`src/c++98`** Source files compiled using `-std=gnu++98`.
- **`src/c++11`** Source files compiled using `-std=gnu++11`.
- **`src/filesystem`** Source files for the Filesystem TS.

src/shared Source code included by other files under both `src/c++98` and `src/c++11`

testsuites/[backward, demangle, ext, performance, thread, 17_* to 30_*] Test programs are here, and may be used to begin to exercise the library. Support for "make check" and "make check-install" is complete, and runs through all the subdirectories here when this command is issued from the build directory. Please note that "make check" requires DejaGnu 1.4 or later to be installed, or for extra permutations DejaGnu 1.5.3 or later.

Other subdirectories contain variant versions of certain files that are meant to be copied or linked by the configure script. Currently these are:

```
config/abi
config/allocator
config/cpu
config/io
config/locale
config/os
```

In addition, a subdirectory holds the convenience library libsupc++.

libsupc++ Contains the runtime library for C++, including exception handling and memory allocation and deallocation, RTTI, terminate handlers, etc.

Note that glibc also has a `bits/` subdirectory. We need to be careful not to collide with names in its `bits/` directory. For example `<bits/std_mutex.h>` has to be renamed from `<bits/mutex.h>`. Another solution would be to rename `bits` to (e.g.) `cppbits`.

In files throughout the system, lines marked with an "XXX" indicate a bug or incompletely-implemented feature. Lines marked "XXX MT" indicate a place that may require attention for multi-thread safety.

A.3 Coding Style

A.3.1 Bad Identifiers

Identifiers that conflict and should be avoided.

```
This is the list of names reserved to the
implementation that have been claimed by certain
compilers and system headers of interest, and should not be used
in the library. It will grow, of course.  We generally are
interested in names that are not all-caps, except for those like
"_T"

For Solaris:
_B
_C
_L
_N
_P
_S
_U
_X
_E1
..
_E24

Irix adds:
```

```
_A
_G

MS adds:
_T
__deref

BSD adds:
__used
__unused
__inline
_Complex
__istype
__maskrune
__tolower
__toupper
__wchar_t
__wint_t
_res
_res_ext
__tg_*

VxWorks adds:
_C2

For GCC:

[Note that this list is out of date. It applies to the old
name-mangling; in G++ 3.0 and higher a different name-mangling is
used. In addition, many of the bugs relating to G++ interpreting
these names as operators have been fixed.]

The full set of __* identifiers (combined from gcc/cp/lex.c and
gcc/cplus-dem.c) that are either old or new, but are definitely
recognized by the demangler, is:

__aa
__aad
__ad
__addr
__adv
__aer
__als
__alshift
__amd
__ami
__aml
__amu
__aor
__apl
__array
__ars
__arshift
__as
__bit_and
__bit_ior
__bit_not
```

```
__bit_xor
__call
__cl
__cm
__cn
__co
__component
__compound
__cond
__convert
__delete
__dl
__dv
__eq
__er
__ge
__gt
__indirect
__le
__ls
__lt
__max
__md
__method_call
__mi
__min
__minus
__ml
__mm
__mn
__mult
__mx
__ne
__negate
__new
__nop
__nt
__nw
__oo
__op
__or
__pl
__plus
__postdecrement
__postincrement
__pp
__pt
__rf
__rm
__rs
__sz
__trunc_div
__trunc_mod
__truth_andif
__truth_not
__truth_orif
__vc
```

```
__vd
__vn

SGI badnames:
__builtin_alloca
__builtin_fsqrt
__builtin_sqrt
__builtin_fabs
__builtin_dabs
__builtin_cast_f2i
__builtin_cast_i2f
__builtin_cast_d2ll
__builtin_cast_ll2d
__builtin_copy_dhi2i
__builtin_copy_i2dhi
__builtin_copy_dlo2i
__builtin_copy_i2dlo
__add_and_fetch
__sub_and_fetch
__or_and_fetch
__xor_and_fetch
__and_and_fetch
__nand_and_fetch
__mpy_and_fetch
__min_and_fetch
__max_and_fetch
__fetch_and_add
__fetch_and_sub
__fetch_and_or
__fetch_and_xor
__fetch_and_and
__fetch_and_nand
__fetch_and_mpy
__fetch_and_min
__fetch_and_max
__lock_test_and_set
__lock_release
__lock_acquire
__compare_and_swap
__synchronize
__high_multiply
__unix
__sgi
__linux__
__i386__
__i486__
__cplusplus
__embedded_cplusplus
// long double conversion members mangled as __opr
// http://gcc.gnu.org/ml/libstdc++/1999-q4/msg00060.html
__opr
```

A.3.2 By Example

```
This library is written to appropriate C++ coding standards. As such,
```

```
      it is intended to precede the recommendations of the GNU Coding
      Standard, which can be referenced in full here:

      https://www.gnu.org/prep/standards/standards.html#Formatting

      The rest of this is also interesting reading, but skip the "Design
      Advice" part.

      The GCC coding conventions are here, and are also useful:
      https://gcc.gnu.org/codingconventions.html

      In addition, because it doesn't seem to be stated explicitly anywhere
      else, there is an 80 column source limit.

      ChangeLog entries for member functions should use the
      classname::member function name syntax as follows:


1999-04-15  Dennis Ritchie  <dr@att.com>

      * src/basic_file.cc (__basic_file::open): Fix thinko in
      _G_HAVE_IO_FILE_OPEN bits.


      Notable areas of divergence from what may be previous local practice
      (particularly for GNU C) include:

      01. Pointers and references

        char* p = "flop";
        char& c = *p;
          -NOT-
        char *p = "flop";  // wrong
        char &c = *p;      // wrong


      Reason: In C++, definitions are mixed with executable code. Here,
      p is being initialized, not *p.  This is near-universal
      practice among C++ programmers; it is normal for C hackers
      to switch spontaneously as they gain experience.

      02. Operator names and parentheses

        operator==(type)
          -NOT-
        operator == (type)  // wrong


      Reason: The == is part of the function name. Separating
      it makes the declaration look like an expression.

      03. Function names and parentheses

        void mangle()
          -NOT-
        void mangle ()  // wrong
```

```
Reason: no space before parentheses (except after a control-flow
keyword) is near-universal practice for C++. It identifies the
parentheses as the function-call operator or declarator, as
opposed to an expression or other overloaded use of parentheses.

04. Template function indentation

  template<typename T>
    void
    template_function(args)
    { }
    -NOT-
  template<class T>
  void template_function(args) {};


Reason: In class definitions, without indentation whitespace is
needed both above and below the declaration to distinguish
it visually from other members. (Also, re: "typename"
rather than "class".)  T often could be int, which is
not a class. ("class", here, is an anachronism.)

05. Template class indentation

  template<typename _CharT, typename _Traits>
    class basic_ios : public ios_base
    {
    public:
      // Types:
    };
    -NOT-
  template<class _CharT, class _Traits>
  class basic_ios : public ios_base
    {
    public:
      // Types:
    };
    -NOT-
  template<class _CharT, class _Traits>
    class basic_ios : public ios_base
  {
    public:
      // Types:
  };


06. Enumerators

  enum
  {
    space = _ISspace,
    print = _ISprint,
    cntrl = _IScntrl
  };
    -NOT-
  enum { space = _ISspace, print = _ISprint, cntrl = _IScntrl };
```

```
07. Member initialization lists
All one line, separate from class name.


  gribble::gribble()
  : _M_private_data(0), _M_more_stuff(0), _M_helper(0)
  { }
    -NOT-
  gribble::gribble() : _M_private_data(0), _M_more_stuff(0), _M_helper(0)
  { }


08. Try/Catch blocks

  try
    {
      //
    }
  catch (...)
    {
      //
    }
    -NOT-
  try {
    //
  } catch(...) {
    //
  }


09. Member functions declarations and definitions
Keywords such as extern, static, export, explicit, inline, etc
go on the line above the function name. Thus


virtual int
foo()
-NOT-
virtual int foo()


Reason: GNU coding conventions dictate return types for functions
are on a separate line than the function name and parameter list
for definitions. For C++, where we have member functions that can
be either inline definitions or declarations, keeping to this
standard allows all member function names for a given class to be
aligned to the same margin, increasing readability.


10. Invocation of member functions with "this->"
For non-uglified names, use this->name to call the function.


this->sync()
-NOT-
```

```
sync()


Reason: Koenig lookup.

11. Namespaces

namespace std
{
  blah blah blah;
} // namespace std

-NOT-

namespace std {
  blah blah blah;
} // namespace std


12. Spacing under protected and private in class declarations:
space above, none below
i.e.


public:
  int foo;

-NOT-
public:

  int foo;


13. Spacing WRT return statements.
no extra spacing before returns, no parenthesis
i.e.


}
return __ret;

-NOT-
}

return __ret;

-NOT-

}
return (__ret);



14. Location of global variables.
All global variables of class type, whether in the "user visible"
space (e.g., cin) or the implementation namespace, must be defined
as a character array with the appropriate alignment and then later
```

```
re-initialized to the correct value.

This is due to startup issues on certain platforms, such as AIX.
For more explanation and examples, see src/globals.cc. All such
variables should be contained in that file, for simplicity.

15. Exception abstractions
Use the exception abstractions found in functexcept.h, which allow
C++ programmers to use this library with -fno-exceptions.  (Even if
that is rarely advisable, it's a necessary evil for backwards
compatibility.)

16. Exception error messages
All start with the name of the function where the exception is
thrown, and then (optional) descriptive text is added. Example:


__throw_logic_error(__N("basic_string::_S_construct NULL not valid"));


Reason: The verbose terminate handler prints out exception::what(),
as well as the typeinfo for the thrown exception. As this is the
default terminate handler, by putting location info into the
exception string, a very useful error message is printed out for
uncaught exceptions. So useful, in fact, that non-programmers can
give useful error messages, and programmers can intelligently
speculate what went wrong without even using a debugger.

17. The doxygen style guide to comments is a separate document,
see index.

The library currently has a mixture of GNU-C and modern C++ coding
styles. The GNU C usages will be combed out gradually.

Name patterns:

For nonstandard names appearing in Standard headers, we are constrained
to use names that begin with underscores. This is called "uglification".
The convention is:

Local and argument names:  __[a-z].*

Examples:  __count  __ix  __s1

Type names and template formal-argument names: _[A-Z][^_].*

Examples:  _Helper  _CharT  _Nm

Member data and function names: _M_.*

Examples:  _M_num_elements  _M_initialize ()

Static data and function members, constants, and enumerations: _S_.*

Examples: _S_max_elements  _S_default_value

Don't use names in the same scope that differ only in the prefix,
```

```
e.g. _S_top and _M_top. See BADNAMES for a list of forbidden names.
(The most tempting of these seem to be and "_T" and "_N".)

Names must never have "__" internally; it would confuse name
unmanglers on some targets. Also, never use "__[0-9]", same reason.

--------------------------

[BY EXAMPLE]


#ifndef  _HEADER_
#define  _HEADER_ 1

namespace std
{
  class gribble
  {
  public:
    gribble() throw();

    gribble(const gribble&);

    explicit
    gribble(int __howmany);

    gribble&
    operator=(const gribble&);

    virtual
    ~gribble() throw ();

    // Start with a capital letter, end with a period.
    inline void
    public_member(const char* __arg) const;

    // In-class function definitions should be restricted to one-liners.
    int
    one_line() { return 0 }

    int
    two_lines(const char* arg)
    { return strchr(arg, 'a'); }

    inline int
    three_lines();  // inline, but defined below.

    // Note indentation.
    template<typename _Formal_argument>
      void
      public_template() const throw();

    template<typename _Iterator>
      void
      other_template();

  private:
```

```
    class _Helper;

    int _M_private_data;
    int _M_more_stuff;
    _Helper* _M_helper;
    int _M_private_function();

    enum _Enum
      {
        _S_one,
        _S_two
      };

    static void
    _S_initialize_library();
  };

  // More-or-less-standard language features described by lack, not presence ↩
     .
# ifndef _G_NO_LONGLONG
  extern long long _G_global_with_a_good_long_name;  // avoid globals!
# endif

  // Avoid in-class inline definitions, define separately;
  // likewise for member class definitions:
  inline int
  gribble::public_member() const
  { int __local = 0; return __local; }

  class gribble::_Helper
  {
    int _M_stuff;

    friend class gribble;
  };
}

// Names beginning with "__": only for arguments and
//   local variables; never use "__" in a type name, or
//   within any name; never use "__[0-9]".

#endif /* _HEADER_ */


namespace std
{
  template<typename T>  // notice: "typename", not "class", no space
    long_return_value_type<with_many, args>
    function_name(char* pointer,               // "char *pointer" is wrong.
                  char* argument,
                  const Reference& ref)
    {
      // int a_local;  /* wrong; see below. */
      if (test)
      {
        nested code
      }
```

```
      int a_local = 0;  // declare variable at first use.

      //  char a, b, *p;   /* wrong */
      char a = 'a';
      char b = a + 1;
      char* c = "abc";  // each variable goes on its own line, always.

      // except maybe here...
      for (unsigned i = 0, mask = 1; mask; ++i, mask <<= 1) {
        // ...
      }
    }

  gribble::gribble()
  : _M_private_data(0), _M_more_stuff(0), _M_helper(0)
  { }

  int
  gribble::three_lines()
  {
    // doesn't fit in one line.
  }
} // namespace std
```

A.4 Design Notes

```
The Library
-----------

This paper is covers two major areas:

- Features and policies not mentioned in the standard that
the quality of the library implementation depends on, including
extensions and "implementation-defined" features;

- Plans for required but unimplemented library features and
optimizations to them.

Overhead
--------

The standard defines a large library, much larger than the standard
C library. A naive implementation would suffer substantial overhead
in compile time, executable size, and speed, rendering it unusable
in many (particularly embedded) applications. The alternative demands
care in construction, and some compiler support, but there is no
need for library subsets.

What are the sources of this overhead?  There are four main causes:

- The library is specified almost entirely as templates, which
with current compilers must be included in-line, resulting in
```

```
very slow builds as tens or hundreds of thousands of lines
of function definitions are read for each user source file.
Indeed, the entire SGI STL, as well as the dos Reis valarray,
are provided purely as header files, largely for simplicity in
porting. Iostream/locale is (or will be) as large again.

- The library is very flexible, specifying a multitude of hooks
where users can insert their own code in place of defaults.
When these hooks are not used, any time and code expended to
support that flexibility is wasted.

- Templates are often described as causing to "code bloat". In
practice, this refers (when it refers to anything real) to several
independent processes. First, when a class template is manually
instantiated in its entirely, current compilers place the definitions
for all members in a single object file, so that a program linking
to one member gets definitions of all. Second, template functions
which do not actually depend on the template argument are, under
current compilers, generated anew for each instantiation, rather
than being shared with other instantiations. Third, some of the
flexibility mentioned above comes from virtual functions (both in
regular classes and template classes) which current linkers add
to the executable file even when they manifestly cannot be called.

- The library is specified to use a language feature, exceptions,
which in the current gcc compiler ABI imposes a run time and
code space cost to handle the possibility of exceptions even when
they are not used. Under the new ABI (accessed with -fnew-abi),
there is a space overhead and a small reduction in code efficiency
resulting from lost optimization opportunities associated with
non-local branches associated with exceptions.

What can be done to eliminate this overhead?  A variety of coding
techniques, and compiler, linker and library improvements and
extensions may be used, as covered below. Most are not difficult,
and some are already implemented in varying degrees.

Overhead: Compilation Time
--------------------------

Providing "ready-instantiated" template code in object code archives
allows us to avoid generating and optimizing template instantiations
in each compilation unit which uses them. However, the number of such
instantiations that are useful to provide is limited, and anyway this
is not enough, by itself, to minimize compilation time. In particular,
it does not reduce time spent parsing conforming headers.

Quicker header parsing will depend on library extensions and compiler
improvements.  One approach is some variation on the techniques
previously marketed as "pre-compiled headers", now standardized as
support for the "export" keyword. "Exported" template definitions
can be placed (once) in a "repository" -- really just a library, but
of template definitions rather than object code -- to be drawn upon
at link time when an instantiation is needed, rather than placed in
header files to be parsed along with every compilation unit.

Until "export" is implemented we can put some of the lengthy template
```

```
definitions in #if guards or alternative headers so that users can skip
over the full definitions when they need only the ready-instantiated
specializations.

To be precise, this means that certain headers which define
templates which users normally use only for certain arguments
can be instrumented to avoid exposing the template definitions
to the compiler unless a macro is defined. For example, in
<string>, we might have:

template <class _CharT, ... > class basic_string {
... // member declarations
};
... // operator declarations

#ifdef _STRICT_ISO_
# if _G_NO_TEMPLATE_EXPORT
#   include <bits/std_locale.h>  // headers needed by definitions
#   ...
#   include <bits/string.tcc>  // member and global template definitions.
# endif
#endif

Users who compile without specifying a strict-ISO-conforming flag
would not see many of the template definitions they now see, and rely
instead on ready-instantiated specializations in the library. This
technique would be useful for the following substantial components:
string, locale/iostreams, valarray. It would *not* be useful or
usable with the following: containers, algorithms, iterators,
allocator. Since these constitute a large (though decreasing)
fraction of the library, the benefit the technique offers is
limited.

The language specifies the semantics of the "export" keyword, but
the gcc compiler does not yet support it. When it does, problems
with large template inclusions can largely disappear, given some
minor library reorganization, along with the need for the apparatus
described above.

Overhead: Flexibility Cost
--------------------------

The library offers many places where users can specify operations
to be performed by the library in place of defaults. Sometimes
this seems to require that the library use a more-roundabout, and
possibly slower, way to accomplish the default requirements than
would be used otherwise.

The primary protection against this overhead is thorough compiler
optimization, to crush out layers of inline function interfaces.
Kuck & Associates has demonstrated the practicality of this kind
of optimization.

The second line of defense against this overhead is explicit
specialization. By defining helper function templates, and writing
specialized code for the default case, overhead can be eliminated
for that case without sacrificing flexibility. This takes full
```

```
advantage of any ability of the optimizer to crush out degenerate
code.

The library specifies many virtual functions which current linkers
load even when they cannot be called. Some minor improvements to the
compiler and to ld would eliminate any such overhead by simply
omitting virtual functions that the complete program does not call.
A prototype of this work has already been done. For targets where
GNU ld is not used, a "pre-linker" could do the same job.

The main areas in the standard interface where user flexibility
can result in overhead are:

- Allocators:  Containers are specified to use user-definable
allocator types and objects, making tuning for the container
characteristics tricky.

- Locales: the standard specifies locale objects used to implement
iostream operations, involving many virtual functions which use
streambuf iterators.

- Algorithms and containers: these may be instantiated on any type,
frequently duplicating code for identical operations.

- Iostreams and strings: users are permitted to use these on their
own types, and specify the operations the stream must use on these
types.

Note that these sources of overhead are _avoidable_. The techniques
to avoid them are covered below.

Code Bloat
----------

In the SGI STL, and in some other headers, many of the templates
are defined "inline" -- either explicitly or by their placement
in class definitions -- which should not be inline. This is a
source of code bloat. Matt had remarked that he was relying on
the compiler to recognize what was too big to benefit from inlining,
and generate it out-of-line automatically. However, this also can
result in code bloat except where the linker can eliminate the extra
copies.

Fixing these cases will require an audit of all inline functions
defined in the library to determine which merit inlining, and moving
the rest out of line. This is an issue mainly in clauses 23, 25, and
27. Of course it can be done incrementally, and we should generally
accept patches that move large functions out of line and into ".tcc"
files, which can later be pulled into a repository. Compiler/linker
improvements to recognize very large inline functions and move them
out-of-line, but shared among compilation units, could make this
work unnecessary.

Pre-instantiating template specializations currently produces large
amounts of dead code which bloats statically linked programs. The
current state of the static library, libstdc++.a, is intolerable on
this account, and will fuel further confused speculation about a need
```

```
for a library "subset". A compiler improvement that treats each
instantiated function as a separate object file, for linking purposes,
would be one solution to this problem. An alternative would be to
split up the manual instantiation files into dozens upon dozens of
little files, each compiled separately, but an abortive attempt at
this was done for <string> and, though it is far from complete, it
is already a nuisance. A better interim solution (just until we have
"export") is badly needed.

When building a shared library, the current compiler/linker cannot
automatically generate the instantiations needed. This creates a
miserable situation; it means any time something is changed in the
library, before a shared library can be built someone must manually
copy the declarations of all templates that are needed by other parts
of the library to an "instantiation" file, and add it to the build
system to be compiled and linked to the library. This process is
readily automated, and should be automated as soon as possible.
Users building their own shared libraries experience identical
frustrations.

Sharing common aspects of template definitions among instantiations
can radically reduce code bloat. The compiler could help a great
deal here by recognizing when a function depends on nothing about
a template parameter, or only on its size, and giving the resulting
function a link-name "equate" that allows it to be shared with other
instantiations. Implementation code could take advantage of the
capability by factoring out code that does not depend on the template
argument into separate functions to be merged by the compiler.

Until such a compiler optimization is implemented, much can be done
manually (if tediously) in this direction. One such optimization is
to derive class templates from non-template classes, and move as much
implementation as possible into the base class. Another is to partial-
specialize certain common instantiations, such as vector<T*>, to share
code for instantiations on all types T. While these techniques work,
they are far from the complete solution that a compiler improvement
would afford.

Overhead: Expensive Language Features
-------------------------------------

The main "expensive" language feature used in the standard library
is exception support, which requires compiling in cleanup code with
static table data to locate it, and linking in library code to use
the table. For small embedded programs the amount of such library
code and table data is assumed by some to be excessive. Under the
"new" ABI this perception is generally exaggerated, although in some
cases it may actually be excessive.

To implement a library which does not use exceptions directly is
not difficult given minor compiler support (to "turn off" exceptions
and ignore exception constructs), and results in no great library
maintenance difficulties. To be precise, given "-fno-exceptions",
the compiler should treat "try" blocks as ordinary blocks, and
"catch" blocks as dead code to ignore or eliminate. Compiler
support is not strictly necessary, except in the case of "function
try blocks"; otherwise the following macros almost suffice:
```

```
#define throw(X)
#define try      if (true)
#define catch(X) else if (false)

However, there may be a need to use function try blocks in the
library implementation, and use of macros in this way can make
correct diagnostics impossible. Furthermore, use of this scheme
would require the library to call a function to re-throw exceptions
from a try block. Implementing the above semantics in the compiler
is preferable.

Given the support above (however implemented) it only remains to
replace code that "throws" with a call to a well-documented "handler"
function in a separate compilation unit which may be replaced by
the user. The main source of exceptions that would be difficult
for users to avoid is memory allocation failures, but users can
define their own memory allocation primitives that never throw.
Otherwise, the complete list of such handlers, and which library
functions may call them, would be needed for users to be able to
implement the necessary substitutes. (Fortunately, they have the
source code.)

Opportunities
-------------

The template capabilities of C++ offer enormous opportunities for
optimizing common library operations, well beyond what would be
considered "eliminating overhead". In particular, many operations
done in Glibc with macros that depend on proprietary language
extensions can be implemented in pristine Standard C++. For example,
the chapter 25 algorithms, and even C library functions such as strchr,
can be specialized for the case of static arrays of known (small) size.

Detailed optimization opportunities are identified below where
the component where they would appear is discussed. Of course new
opportunities will be identified during implementation.

Unimplemented Required Library Features
---------------------------------------

The standard specifies hundreds of components, grouped broadly by
chapter. These are listed in excruciating detail in the CHECKLIST
file.

17 general
18 support
19 diagnostics
20 utilities
21 string
22 locale
23 containers
24 iterators
25 algorithms
26 numerics
27 iostreams
Annex D  backward compatibility
```

Anyone participating in implementation of the library should obtain a copy of the standard, ISO 14882. People in the U.S. can obtain an electronic copy for US$18 from ANSI's web site. Those from other countries should visit http://www.iso.org/ to find out the location of their country's representation in ISO, in order to know who can sell them a copy.

The emphasis in the following sections is on unimplemented features and optimization opportunities.

Chapter 17 General

Chapter 17 concerns overall library requirements.

The standard doesn't mention threads. A multi-thread (MT) extension primarily affects operators new and delete (18), allocator (20), string (21), locale (22), and iostreams (27). The common underlying support needed for this is discussed under chapter 20.

The standard requirements on names from the C headers create a lot of work, mostly done. Names in the C headers must be visible in the std:: and sometimes the global namespace; the names in the two scopes must refer to the same object. More stringent is that Koenig lookup implies that any types specified as defined in std:: really are defined in std::. Names optionally implemented as macros in C cannot be macros in C++. (An overview may be read at <http://www.cantrip.org/cheaders.html>). The scripts "inclosure" and "mkcshadow", and the directories shadow/ and cshadow/, are the beginning of an effort to conform in this area.

A correct conforming definition of C header names based on underlying C library headers, and practical linking of conforming namespaced customer code with third-party C libraries depends ultimately on an ABI change, allowing namespaced C type names to be mangled into type names as if they were global, somewhat as C function names in a namespace, or C++ global variable names, are left unmangled. Perhaps another "extern" mode, such as 'extern "C-global"' would be an appropriate place for such type definitions. Such a type would affect mangling as follows:

```
namespace A {
struct X {};
extern "C-global" {  // or maybe just 'extern "C"'
struct Y {};
};
}
void f(A::X*);  // mangles to f__FPQ21A1X
void f(A::Y*);  // mangles to f__FP1Y
```

(It may be that this is really the appropriate semantics for regular 'extern "C"', and 'extern "C-global"', as an extension, would not be necessary.) This would allow functions declared in non-standard C headers (and thus fixable by neither us nor users) to link properly with functions declared using C types defined in properly-namespaced headers. The problem this solves is that C headers (which C++ programmers do persist

```
in using) frequently forward-declare C struct tags without including
the header where the type is defined, as in

struct tm;
void munge(tm*);

Without some compiler accommodation, munge cannot be called by correct
C++ code using a pointer to a correctly-scoped tm* value.

The current C headers use the preprocessor extension "#include_next",
which the compiler complains about when run "-pedantic".
(Incidentally, it appears that "-fpedantic" is currently ignored,
probably a bug.)  The solution in the C compiler is to use
"-isystem" rather than "-I", but unfortunately in g++ this seems
also to wrap the whole header in an 'extern "C"' block, so it's
unusable for C++ headers. The correct solution appears to be to
allow the various special include-directory options, if not given
an argument, to affect subsequent include-directory options additively,
so that if one said

-pedantic -iprefix $(prefix) \
-idirafter -ino-pedantic -ino-extern-c -iwithprefix -I g++-v3 \
-iwithprefix -I g++-v3/ext

the compiler would search $(prefix)/g++-v3 and not report
pedantic warnings for files found there, but treat files in
$(prefix)/g++-v3/ext pedantically. (The undocumented semantics
of "-isystem" in g++ stink. Can they be rescinded?  If not it
must be replaced with something more rationally behaved.)

All the C headers need the treatment above; in the standard these
headers are mentioned in various clauses. Below, I have only
mentioned those that present interesting implementation issues.

The components identified as "mostly complete", below, have not been
audited for conformance. In many cases where the library passes
conformance tests we have non-conforming extensions that must be
wrapped in #if guards for "pedantic" use, and in some cases renamed
in a conforming way for continued use in the implementation regardless
of conformance flags.

The STL portion of the library still depends on a header
stl/bits/stl_config.h full of #ifdef clauses. This apparatus
should be replaced with autoconf/automake machinery.

The SGI STL defines a type_traits<> template, specialized for
many types in their code including the built-in numeric and
pointer types and some library types, to direct optimizations of
standard functions. The SGI compiler has been extended to generate
specializations of this template automatically for user types,
so that use of STL templates on user types can take advantage of
these optimizations. Specializations for other, non-STL, types
would make more optimizations possible, but extending the gcc
compiler in the same way would be much better. Probably the next
round of standardization will ratify this, but probably with
changes, so it probably should be renamed to place it in the
implementation namespace.
```

```
The SGI STL also defines a large number of extensions visible in
standard headers. (Other extensions that appear in separate headers
have been sequestered in subdirectories ext/ and backward/.)  All
these extensions should be moved to other headers where possible,
and in any case wrapped in a namespace (not std!), and (where kept
in a standard header) girded about with macro guards. Some cannot be
moved out of standard headers because they are used to implement
standard features.  The canonical method for accommodating these
is to use a protected name, aliased in macro guards to a user-space
name. Unfortunately C++ offers no satisfactory template typedef
mechanism, so very ad-hoc and unsatisfactory aliasing must be used
instead.

Implementation of a template typedef mechanism should have the highest
priority among possible extensions, on the same level as implementation
of the template "export" feature.

Chapter 18  Language support
----------------------------

Headers: <limits> <new> <typeinfo> <exception>
C headers: <cstddef> <climits> <cfloat>  <cstdarg> <csetjmp>
<ctime>   <csignal> <cstdlib> (also 21, 25, 26)

This defines the built-in exceptions, rtti, numeric_limits<>,
operator new and delete. Much of this is provided by the
compiler in its static runtime library.

Work to do includes defining numeric_limits<> specializations in
separate files for all target architectures. Values for integer types
except for bool and wchar_t are readily obtained from the C header
<limits.h>, but values for the remaining numeric types (bool, wchar_t,
float, double, long double) must be entered manually. This is
largely dog work except for those members whose values are not
easily deduced from available documentation. Also, this involves
some work in target configuration to identify the correct choice of
file to build against and to install.

The definitions of the various operators new and delete must be
made thread-safe, which depends on a portable exclusion mechanism,
discussed under chapter 20.  Of course there is always plenty of
room for improvements to the speed of operators new and delete.

<cstdarg>, in Glibc, defines some macros that gcc does not allow to
be wrapped into an inline function. Probably this header will demand
attention whenever a new target is chosen. The functions atexit(),
exit(), and abort() in cstdlib have different semantics in C++, so
must be re-implemented for C++.

Chapter 19  Diagnostics
-----------------------

Headers: <stdexcept>
C headers: <cassert> <cerrno>

This defines the standard exception objects, which are "mostly complete".
```

```
Cygnus has a version, and now SGI provides a slightly different one.
It makes little difference which we use.

The C global name "errno", which C allows to be a variable or a macro,
is required in C++ to be a macro. For MT it must typically result in
a function call.

Chapter 20  Utilities
---------------------
Headers: <utility> <functional> <memory>
C header: <ctime> (also in 18)

SGI STL provides "mostly complete" versions of all the components
defined in this chapter. However, the auto_ptr<> implementation
is known to be wrong. Furthermore, the standard definition of it
is known to be unimplementable as written. A minor change to the
standard would fix it, and auto_ptr<> should be adjusted to match.

Multi-threading affects the allocator implementation, and there must
be configuration/installation choices for different users' MT
requirements. Anyway, users will want to tune allocator options
to support different target conditions, MT or no.

The primitives used for MT implementation should be exposed, as an
extension, for users' own work. We need cross-CPU "mutex" support,
multi-processor shared-memory atomic integer operations, and single-
processor uninterruptible integer operations, and all three configurable
to be stubbed out for non-MT use, or to use an appropriately-loaded
dynamic library for the actual runtime environment, or statically
compiled in for cases where the target architecture is known.

Chapter 21  String
------------------
Headers: <string>
C headers: <cctype> <cwctype> <cstring> <cwchar> (also in 27)
<cstdlib> (also in 18, 25, 26)

We have "mostly-complete" char_traits<> implementations. Many of the
char_traits<char> operations might be optimized further using existing
proprietary language extensions.

We have a "mostly-complete" basic_string<> implementation. The work
to manually instantiate char and wchar_t specializations in object
files to improve link-time behavior is extremely unsatisfactory,
literally tripling library-build time with no commensurate improvement
in static program link sizes. It must be redone. (Similar work is
needed for some components in clauses 22 and 27.)

Other work needed for strings is MT-safety, as discussed under the
chapter 20 heading.

The standard C type mbstate_t from <cwchar> and used in char_traits<>
must be different in C++ than in C, because in C++ the default constructor
value mbstate_t() must be the "base" or "ground" sequence state.
(According to the likely resolution of a recently raised Core issue,
this may become unnecessary. However, there are other reasons to
use a state type not as limited as whatever the C library provides.)
```

```
If we might want to provide conversions from (e.g.) internally-
represented EUC-wide to externally-represented Unicode, or vice-
versa, the mbstate_t we choose will need to be more accommodating
than what might be provided by an underlying C library.

There remain some basic_string template-member functions which do
not overload properly with their non-template brethren. The infamous
hack akin to what was done in vector<> is needed, to conform to
23.1.1 para 10. The CHECKLIST items for basic_string marked 'X',
or incomplete, are so marked for this reason.

Replacing the string iterators, which currently are simple character
pointers, with class objects would greatly increase the safety of the
client interface, and also permit a "debug" mode in which range,
ownership, and validity are rigorously checked. The current use of
raw pointers as string iterators is evil. vector<> iterators need the
same treatment. Note that the current implementation freely mixes
pointers and iterators, and that must be fixed before safer iterators
can be introduced.

Some of the functions in <cstring> are different from the C version.
generally overloaded on const and non-const argument pointers. For
example, in <cstring> strchr is overloaded. The functions isupper
etc. in <cctype> typically implemented as macros in C are functions
in C++, because they are overloaded with others of the same name
defined in <locale>.

Many of the functions required in <cwctype> and <cwchar> cannot be
implemented using underlying C facilities on intended targets because
such facilities only partly exist.

Chapter 22  Locale
------------------
Headers: <locale>
C headers: <clocale>

We have a "mostly complete" class locale, with the exception of
code for constructing, and handling the names of, named locales.
The ways that locales are named (particularly when categories
(e.g. LC_TIME, LC_COLLATE) are different) varies among all target
environments. This code must be written in various versions and
chosen by configuration parameters.

Members of many of the facets defined in <locale> are stubs. Generally,
there are two sets of facets: the base class facets (which are supposed
to implement the "C" locale) and the "byname" facets, which are supposed
to read files to determine their behavior. The base ctype<>, collate<>,
and numpunct<> facets are "mostly complete", except that the table of
bitmask values used for "is" operations, and corresponding mask values,
are still defined in libio and just included/linked. (We will need to
implement these tables independently, soon, but should take advantage
of libio where possible.)  The num_put<>::put members for integer types
are "mostly complete".

A complete list of what has and has not been implemented may be
found in CHECKLIST. However, note that the current definition of
codecvt<wchar_t,char,mbstate_t> is wrong. It should simply write
```

```
out the raw bytes representing the wide characters, rather than
trying to convert each to a corresponding single "char" value.

Some of the facets are more important than others. Specifically,
the members of ctype<>, numpunct<>, num_put<>, and num_get<> facets
are used by other library facilities defined in <string>, <istream>,
and <ostream>, and the codecvt<> facet is used by basic_filebuf<>
in <fstream>, so a conforming iostream implementation depends on
these.

The "long long" type eventually must be supported, but code mentioning
it should be wrapped in #if guards to allow pedantic-mode compiling.

Performance of num_put<> and num_get<> depend critically on
caching computed values in ios_base objects, and on extensions
to the interface with streambufs.

Specifically: retrieving a copy of the locale object, extracting
the needed facets, and gathering data from them, for each call to
(e.g.) operator<< would be prohibitively slow.  To cache format
data for use by num_put<> and num_get<> we have a _Format_cache<>
object stored in the ios_base::pword() array. This is constructed
and initialized lazily, and is organized purely for utility. It
is discarded when a new locale with different facets is imbued.

Using only the public interfaces of the iterator arguments to the
facet functions would limit performance by forbidding "vector-style"
character operations. The streambuf iterator optimizations are
described under chapter 24, but facets can also bypass the streambuf
iterators via explicit specializations and operate directly on the
streambufs, and use extended interfaces to get direct access to the
streambuf internal buffer arrays. These extensions are mentioned
under chapter 27. These optimizations are particularly important
for input parsing.

Unused virtual members of locale facets can be omitted, as mentioned
above, by a smart linker.

Chapter 23  Containers
----------------------
Headers: <deque> <list> <queue> <stack> <vector> <map> <set> <bitset>

All the components in chapter 23 are implemented in the SGI STL.
They are "mostly complete"; they include a large number of
nonconforming extensions which must be wrapped. Some of these
are used internally and must be renamed or duplicated.

The SGI components are optimized for large-memory environments. For
embedded targets, different criteria might be more appropriate. Users
will want to be able to tune this behavior. We should provide
ways for users to compile the library with different memory usage
characteristics.

A lot more work is needed on factoring out common code from different
specializations to reduce code size here and in chapter 25. The
easiest fix for this would be a compiler/ABI improvement that allows
the compiler to recognize when a specialization depends only on the
```

```
size (or other gross quality) of a template argument, and allow the
linker to share the code with similar specializations. In its
absence, many of the algorithms and containers can be partial-
specialized, at least for the case of pointers, but this only solves
a small part of the problem. Use of a type_traits-style template
allows a few more optimization opportunities, more if the compiler
can generate the specializations automatically.

As an optimization, containers can specialize on the default allocator
and bypass it, or take advantage of details of its implementation
after it has been improved upon.

Replacing the vector iterators, which currently are simple element
pointers, with class objects would greatly increase the safety of the
client interface, and also permit a "debug" mode in which range,
ownership, and validity are rigorously checked. The current use of
pointers for iterators is evil.

As mentioned for chapter 24, the deque iterator is a good example of
an opportunity to implement a "staged" iterator that would benefit
from specializations of some algorithms.

Chapter 24  Iterators
---------------------
Headers: <iterator>

Standard iterators are "mostly complete", with the exception of
the stream iterators, which are not yet templatized on the
stream type. Also, the base class template iterator<> appears
to be wrong, so everything derived from it must also be wrong,
currently.

The streambuf iterators (currently located in stl/bits/std_iterator.h,
but should be under bits/) can be rewritten to take advantage of
friendship with the streambuf implementation.

Matt Austern has identified opportunities where certain iterator
types, particularly including streambuf iterators and deque
iterators, have a "two-stage" quality, such that an intermediate
limit can be checked much more quickly than the true limit on
range operations. If identified with a member of iterator_traits,
algorithms may be specialized for this case. Of course the
iterators that have this quality can be identified by specializing
a traits class.

Many of the algorithms must be specialized for the streambuf
iterators, to take advantage of block-mode operations, in order
to allow iostream/locale operations' performance not to suffer.
It may be that they could be treated as staged iterators and
take advantage of those optimizations.

Chapter 25  Algorithms
----------------------
Headers: <algorithm>
C headers: <cstdlib> (also in 18, 21, 26))

The algorithms are "mostly complete". As mentioned above, they
```

```
are optimized for speed at the expense of code and data size.

Specializations of many of the algorithms for non-STL types would
give performance improvements, but we must use great care not to
interfere with fragile template overloading semantics for the
standard interfaces. Conventionally the standard function template
interface is an inline which delegates to a non-standard function
which is then overloaded (this is already done in many places in
the library). Particularly appealing opportunities for the sake of
iostream performance are for copy and find applied to streambuf
iterators or (as noted elsewhere) for staged iterators, of which
the streambuf iterators are a good example.

The bsearch and qsort functions cannot be overloaded properly as
required by the standard because gcc does not yet allow overloading
on the extern-"C"-ness of a function pointer.

Chapter 26  Numerics
--------------------
Headers: <complex> <valarray> <numeric>
C headers: <cmath>, <cstdlib> (also 18, 21, 25)

Numeric components: Gabriel dos Reis's valarray, Drepper's complex,
and the few algorithms from the STL are "mostly done".  Of course
optimization opportunities abound for the numerically literate. It
is not clear whether the valarray implementation really conforms
fully, in the assumptions it makes about aliasing (and lack thereof)
in its arguments.

The C div() and ldiv() functions are interesting, because they are the
only case where a C library function returns a class object by value.
Since the C++ type div_t must be different from the underlying C type
(which is in the wrong namespace) the underlying functions div() and
ldiv() cannot be re-used efficiently. Fortunately they are trivial to
re-implement.

Chapter 27  Iostreams
---------------------
Headers: <iosfwd> <streambuf> <ios> <ostream> <istream> <iostream>
<iomanip> <sstream> <fstream>
C headers: <cstdio> <cwchar> (also in 21)

Iostream is currently in a very incomplete state. <iosfwd>, <iomanip>,
ios_base, and basic_ios<> are "mostly complete". basic_streambuf<> and
basic_ostream<> are well along, but basic_istream<> has had little work
done. The standard stream objects, <sstream> and <fstream> have been
started; basic_filebuf<> "write" functions have been implemented just
enough to do "hello, world".

Most of the istream and ostream operators << and >> (with the exception
of the op<<(integer) ones) have not been changed to use locale primitives,
sentry objects, or char_traits members.

All these templates should be manually instantiated for char and
wchar_t in a way that links only used members into user programs.

Streambuf is fertile ground for optimization extensions. An extended
```

```
interface giving iterator access to its internal buffer would be very
useful for other library components.

Iostream operations (primarily operators << and >>) can take advantage
of the case where user code has not specified a locale, and bypass locale
operations entirely. The current implementation of op<</num_put<>::put,
for the integer types, demonstrates how they can cache encoding details
from the locale on each operation. There is lots more room for
optimization in this area.

The definition of the relationship between the standard streams
cout et al. and stdout et al. requires something like a "stdiobuf".
The SGI solution of using double-indirection to actually use a
stdio FILE object for buffering is unsatisfactory, because it
interferes with peephole loop optimizations.

The <sstream> header work has begun. stringbuf can benefit from
friendship with basic_string<> and basic_string<>::_Rep to use
those objects directly as buffers, and avoid allocating and making
copies.

The basic_filebuf<> template is a complex beast. It is specified to
use the locale facet codecvt<> to translate characters between native
files and the locale character encoding. In general this involves
two buffers, one of "char" representing the file and another of
"char_type", for the stream, with codecvt<> translating. The process
is complicated by the variable-length nature of the translation, and
the need to seek to corresponding places in the two representations.
For the case of basic_filebuf<char>, when no translation is needed,
a single buffer suffices. A specialized filebuf can be used to reduce
code space overhead when no locale has been imbued. Matt Austern’s
work at SGI will be useful, perhaps directly as a source of code, or
at least as an example to draw on.

Filebuf, almost uniquely (cf. operator new), depends heavily on
underlying environmental facilities. In current releases iostream
depends fairly heavily on libio constant definitions, but it should
be made independent.  It also depends on operating system primitives
for file operations. There is immense room for optimizations using
(e.g.) mmap for reading. The shadow/ directory wraps, besides the
standard C headers, the libio.h and unistd.h headers, for use mainly
by filebuf. These wrappings have not been completed, though there
is scaffolding in place.

The encapsulation of certain C header <cstdio> names presents an
interesting problem. It is possible to define an inline std::fprintf()
implemented in terms of the ’extern "C"’ vfprintf(), but there is no
standard vfscanf() to use to implement std::fscanf(). It appears that
vfscanf but be re-implemented in C++ for targets where no vfscanf
extension has been defined. This is interesting in that it seems
to be the only significant case in the C library where this kind of
rewriting is necessary. (Of course Glibc provides the vfscanf()
extension.)  (The functions related to exit() must be rewritten
for other reasons.)


Annex D
```

```
-------
Headers: <strstream>

Annex D defines many non-library features, and many minor
modifications to various headers, and a complete header.
It is "mostly done", except that the libstdc++-2 <strstream>
header has not been adopted into the library, or checked to
verify that it matches the draft in those details that were
clarified by the committee. Certainly it must at least be
moved into the std namespace.

We still need to wrap all the deprecated features in #if guards
so that pedantic compile modes can detect their use.

Nonstandard Extensions
----------------------
Headers: <iostream.h> <strstream.h> <hash> <rbtree>
<pthread_alloc> <stdiobuf> (etc.)

User code has come to depend on a variety of nonstandard components
that we must not omit. Much of this code can be adopted from
libstdc++-v2 or from the SGI STL. This particularly includes
<iostream.h>, <strstream.h>, and various SGI extensions such
as <hash_map.h>. Many of these are already placed in the
subdirectories ext/ and backward/. (Note that it is better to
include them via "<backward/hash_map.h>" or "<ext/hash_map>" than
to search the subdirectory itself via a "-I" directive.
```

Appendix B

Porting and Maintenance

B.1 Configure and Build Hacking

B.1.1 Prerequisites

As noted previously, certain other tools are necessary for hacking on files that control configure (`configure.ac`, `acinclude.m4`) and make (`Makefile.am`). These additional tools (`automake`, and `autoconf`) are further described in detail in their respective manuals. All the libraries in GCC try to stay in sync with each other in terms of versions of the auto-tools used, so please try to play nicely with the neighbors.

B.1.2 Overview

B.1.2.1 General Process

The configure process begins the act of building libstdc++, and is started via:

```
configure
```

The `configure` file is a script generated (via **autoconf**) from the file `configure.ac`.

After the configure process is complete,

```
make all
```

in the build directory starts the build process. The `all` target comes from the `Makefile` file, which is generated via **configure** from the `Makefile.in` file, which is in turn generated (via **automake**) from the file `Makefile.am`.

B.1.2.2 What Comes from Where

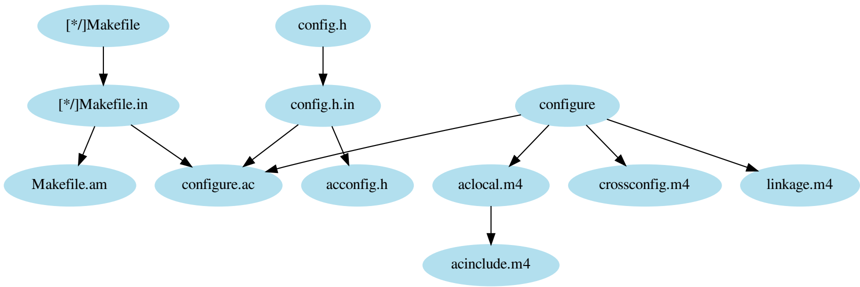

Figure B.1: Configure and Build File Dependencies

Regenerate all generated files by using the command **autoreconf** at the top level of the libstdc++ source directory.

B.1.3 Configure

B.1.3.1 Storing Information in non-AC files (like configure.host)

Until that glorious day when we can use `AC_TRY_LINK` with a cross-compiler, we have to hardcode the results of what the tests would have shown if they could be run. So we have an inflexible mess like `crossconfig.m4`.

Wouldn't it be nice if we could store that information in files like configure.host, which can be modified without needing to regenerate anything, and can even be tweaked without really knowing how the configury all works? Perhaps break the pieces of `crossconfig.m4` out and place them in their appropriate `config/{cpu,os}` directory.

Alas, writing macros like "`AC_DEFINE(HAVE_A_NICE_DAY)`" can only be done inside files which are passed through autoconf. Files which are pure shell script can be source'd at configure time. Files which contain autoconf macros must be processed with autoconf. We could still try breaking the pieces out into "config/*/cross.m4" bits, for instance, but then we would need arguments to aclocal/autoconf to properly find them all when generating configure. I would discourage that.

B.1.3.2 Coding and Commenting Conventions

Most comments should use {octothorpes, shibboleths, hash marks, pound signs, whatever} rather than "`dnl`". Nearly all comments in `configure.ac` should. Comments inside macros written in ancillary `.m4` files should. About the only comments which should *not* use `#`, but use `dnl` instead, are comments *outside* our own macros in the ancillary files. The difference is that `#` comments show up in `configure` (which is most helpful for debugging), while `dnl`'d lines just vanish. Since the macros in ancillary files generate code which appears in odd places, their "outside" comments tend to not be useful while reading `configure`.

Do not use any `$target*` variables, such as `$target_alias`. The single exception is in `configure.ac`, for automake+dejagnu's sake.

B.1.3.3 The acinclude.m4 layout

The nice thing about `acinclude.m4`/`aclocal.m4` is that macros aren't actually performed/called/expanded/whatever here, just loaded. So we can arrange the contents however we like. As of this writing, `acinclude.m4` is arranged as follows:

```
GLIBCXX_CHECK_HOST
GLIBCXX_TOPREL_CONFIGURE
GLIBCXX_CONFIGURE
```

All the major variable "discovery" is done here. `CXX`, multilibs, etc.

```
fragments included from elsewhere
```

Right now, "fragments" == "the math/linkage bits".

```
GLIBCXX_CHECK_COMPILER_FEATURES
GLIBCXX_CHECK_LINKER_FEATURES
GLIBCXX_CHECK_WCHAR_T_SUPPORT
```

Next come extra compiler/linker feature tests. Wide character support was placed here because I couldn't think of another place for it. It will probably get broken apart like the math tests, because we're still disabling wchars on systems which could actually support them.

```
GLIBCXX_CHECK_SETRLIMIT_ancilliary
GLIBCXX_CHECK_SETRLIMIT
GLIBCXX_CHECK_S_ISREG_OR_S_IFREG
GLIBCXX_CHECK_POLL
GLIBCXX_CHECK_WRITEV

GLIBCXX_CONFIGURE_TESTSUITE
```

Feature tests which only get used in one place. Here, things used only in the testsuite, plus a couple bits used in the guts of I/O.

```
GLIBCXX_EXPORT_INCLUDES
GLIBCXX_EXPORT_FLAGS
GLIBCXX_EXPORT_INSTALL_INFO
```

Installation variables, multilibs, working with the rest of the compiler. Many of the critical variables used in the makefiles are set here.

```
GLIBGCC_ENABLE
GLIBCXX_ENABLE_C99
GLIBCXX_ENABLE_CHEADERS
GLIBCXX_ENABLE_CLOCALE
GLIBCXX_ENABLE_CONCEPT_CHECKS
GLIBCXX_ENABLE_CSTDIO
GLIBCXX_ENABLE_CXX_FLAGS
GLIBCXX_ENABLE_C_MBCHAR
GLIBCXX_ENABLE_DEBUG
GLIBCXX_ENABLE_DEBUG_FLAGS
GLIBCXX_ENABLE_LONG_LONG
GLIBCXX_ENABLE_PCH
GLIBCXX_ENABLE_SYMVERS
GLIBCXX_ENABLE_THREADS
```

All the features which can be controlled with enable/disable configure options. Note how they're alphabetized now? Keep them like that. :-)

```
AC_LC_MESSAGES
libtool bits
```

Things which we don't seem to use directly, but just has to be present otherwise stuff magically goes wonky.

B.1.3.4 GLIBCXX_ENABLE, the --enable maker

All the GLIBCXX_ENABLE_FOO macros use a common helper, GLIBCXX_ENABLE. (You don't have to use it, but it's easy.) The helper does two things for us:

1. Builds the call to the AC_ARG_ENABLE macro, with --help text properly quoted and aligned. (Death to changequote!)
2. Checks the result against a list of allowed possibilities, and signals a fatal error if there's no match. This means that the rest of the GLIBCXX_ENABLE_FOO macro doesn't need to test for strange arguments, nor do we need to protect against empty/whitespace strings with the "x$foo" = "xbar" idiom.

Doing these things correctly takes some extra autoconf/autom4te code, which made our macros nearly illegible. So all the ugliness is factored out into this one helper macro.

Many of the macros take an argument, passed from when they are expanded in configure.ac. The argument controls the default value of the enable/disable switch. Previously, the arguments themselves had defaults. Now they don't, because that's extra complexity with zero gain for us.

There are three "overloaded signatures". When reading the descriptions below, keep in mind that the brackets are autoconf's quotation characters, and that they will be stripped. Examples of just about everything occur in acinclude.m4, if you want to look.

```
GLIBCXX_ENABLE (FEATURE, DEFAULT, HELP-ARG, HELP-STRING)
GLIBCXX_ENABLE (FEATURE, DEFAULT, HELP-ARG, HELP-STRING, permit a|b|c)
GLIBCXX_ENABLE (FEATURE, DEFAULT, HELP-ARG, HELP-STRING, SHELL-CODE-HANDLER)
```

- FEATURE is the string that follows --enable. The results of the test (such as it is) will be in the variable $enable_FEATURE, where FEATURE has been squashed. Example: [extra-foo], controlled by the --enable-extra-foo option and stored in $enable_extra_foo.
- DEFAULT is the value to store in $enable_FEATURE if the user does not pass --enable/--disable. It should be one of the permitted values passed later. Examples: [yes], or [bar], or [$1] (which passes the argument given to the GLIBCXX_ENABLE_FOO macro as the default).

  For cases where we need to probe for particular models of things, it is useful to have an undocumented "auto" value here (see GLIBCXX_ENABLE_CLOCALE for an example).
- HELP-ARG is any text to append to the option string itself in the --help output. Examples: [] (i.e., an empty string, which appends nothing), [=BAR], which produces --enable-extra-foo=BAR, and [@<:@=BAR@:>@], which produces --enable-extra-foo[=BAR]. See the difference? See what it implies to the user?

  If you're wondering what that line noise in the last example was, that's how you embed autoconf special characters in output text. They're called *quadrigraphs* and you should use them whenever necessary.
- HELP-STRING is what you think it is. Do not include the "default" text like we used to do; it will be done for you by GLIBCXX_ENABLE. By convention, these are not full English sentences. Example: [turn on extra foo]

With no other arguments, only the standard autoconf patterns are allowed: "--{enable,disable}-foo[={yes,no}]" The $enable_FEATURE variable is guaranteed to equal either "yes" or "no" after the macro. If the user tries to pass something else, an explanatory error message will be given, and configure will halt.

The second signature takes a fifth argument, "[permit a | b | c | ...]" This allows *a* or *b* or ... after the equals sign in the option, and $enable_FEATURE is guaranteed to equal one of them after the macro. Note that if you want to allow plain --enable/--disable with no "=whatever", you must include "yes" and "no" in the list of permitted values. Also note that whatever you passed as DEFAULT must be in the list. If the user tries to pass something not on the list, a semi-explanatory error message will be given, and configure will halt. Example: [permit generic|gnu|ieee_1003.1-2001|yes|no|auto]

The third signature takes a fifth argument. It is arbitrary shell code to execute if the user actually passes the enable/disable option. (If the user does not, the default is used. Duh.) No argument checking at all is done in this signature. See GLIBCXX_ENABLE_CXX_FLAGS for an example of handling, and an error message.

B.1.3.5 Shared Library Versioning

The `libstdc++.so` shared library must be carefully managed to maintain binary compatible with older versions of the library. This ensures a new version of the library is still usable by programs that were linked against an older version.

Dependent on the target supporting it, the library uses ELF symbol versioning for all exported symbols. The symbol versions are defined by a linker script that assigns a version to every symbol. The set of symbols in each version is fixed when a GCC release is made, and must not change after that.

When new symbols are added to the library they must be added to a new symbol version, which must be created the first time new symbols are added after a release. Adding a new symbol version involves the following steps:

- Edit `acinclude.m4` to update the "revision" value of `libtool_VERSION`, e.g. from `6:22:0` to `6:23:0`, which will cause the shared library to be built as `libstdc++.so.6.0.23`.
- Regenerate the `configure` script by running the **autoreconf** tool from the correct version of the Autoconf package (as dictated by the GCC prerequisites).
- Edit the file `config/abi/pre/gnu.ver` to add a new version node after the last new node. The node name should be `GLIBCXX_3.4.X` where `X` is the new revision set in `acinclude.m4`, and the node should depend on the previous version e.g.

  ```
  GLIBCXX_3.4.23 {

  } GLIBCXX_3.4.22;
  ```

  For symbols in the ABI runtime, libsupc++, the symbol version naming uses `CXXABI_1.3.Y` where `Y` increases monotonically with each new version. Again, the new node must depend on the previous version node e.g.

  ```
  CXXABI_1.3.11 {

  } CXXABI_1.3.10;
  ```

- In order for the check-abi test target to pass the testsuite must be updated to know about the new symbol version(s). Edit the file `testsuite/util/testsuite_abi.cc` file to add the new versions to the `known_versions` list, and update the checks for the latest versions that set the `latestp` variable).
- Add the library (`libstdc++.so.6.0.X`) and symbols versions (`GLIBCXX_3.4.X` and `CXXABI_1.3.Y`) to the History section in `doc/xml/manual/abi.xml` at the relevant places.

Once the new symbol version has been added you can add the names of your new symbols in the new version node:

```
GLIBCXX_3.4.23 {

  # basic_string<C, T, A>::_Alloc_hider::_Alloc_hider(C*, A&&)
  _ZNSt7__cxx1112basic_stringI[cw]St11char_traitsI[cw]ESaI[cw]EE12_Alloc_hiderC[12]EP[ ↩
      cw]OS3_;

} GLIBCXX_3.4.22;
```

You can either use mangled names, or demangled names inside an `extern "C++"` block. You might find that the new symbol matches an existing pattern in an old symbol version (causing the `check-abi` test target to fail). If that happens then the existing pattern must be adjusted to be more specific so that it doesn't match the new symbol.

For an example of these steps, including adjusting old patterns to be less greedy, see https://gcc.gnu.org/ml/gcc-patches/2016-07/msg01926.html and the attached patch.

If it wasn't done for the last release, you might also need to regenerate the `baseline_symbols.txt` file that defines the set of expected symbols for old symbol versions. A new baseline file can be generated by running **`make new-abi-baseline`** in the *`libbuilddir`*`/testsuite` directory. Be sure to generate the baseline from a clean build using unmodified sources, or you will incorporate your local changes into the baseline file.

B.1.4 Make

The build process has to make all of object files needed for static or shared libraries, but first it has to generate some include files. The general order is as follows:

1. make include files, make pre-compiled headers
2. make libsupc++

   Generates a libtool convenience library, `libsupc++convenience` with language-support routines. Also generates a freestanding static library, `libsupc++.a`.
3. make src

   Generates several convenience libraries, various compatibility files for shared and static libraries, and then collects all the generated bits and creates the final libstdc++ libraries.

   (a) make src/c++98

   Generates a libtool convenience library, `libc++98convenience` with the library components defined by C++98. Uses the `-std=gnu++98` dialect.

   (b) make src/c++11

   Generates a libtool convenience library, `libc++11convenience` with the library components that were added or changed in C++11. Uses the `-std=gnu++11` dialect.

   (c) make src/c++17

   Generates a libtool convenience library, `libc++17convenience` with the library components that were added or changed in C++17. Uses the `-std=gnu++17` dialect.

   (d) make src/c++20

   Generates a libtool convenience library, `libc++20convenience` with the library components that were added or changed in C++20. Uses the `-std=gnu++20` dialect.

   (e) make src/c++23

   Generates a libtool convenience library, `libc++23convenience` with the library components that were added or changed in C++23. At the time of writing (GCC 14) this convenience library is included in `libstdc++exp.a` and not in the final `libstdc++` libraries. Uses the `-std=gnu++23` dialect.

   (f) make src/filesystem

   Generates a libtool convenience library, `libstdc++fsconvenience`, and a standalone static library, `libstdc++fs.a`. These contain definitions of the Filesystem TS extensions. Uses the `-std=gnu++17` dialect.

   (g) make src/libbacktrace

   Generates a libtool convenience library, `libstdc++_libbacktrace`, containing the libbacktrace definitions used by the C++23 `std::stacktrace` feature.

   (h) make src/experimental

   Generates a standalone static library, `libstdc++exp.a`, containing the symbol definitions for experimental features and extensions. This collects the convenience libraries `libstdc++fsconvenience`, `libstdc++_libbacktra` and (at the time of writing) `libc++23convenience` and combines them into one. Uses the `-std=gnu++17` dialect.

   (i) make src

   Generates needed compatibility objects for shared and static libraries. Shared-only code is seggregated at compile-time via the macro `_GLIBCXX_SHARED`.

   Then, collects all the generated convenience libraries that weren't added to `libstdc++exp.a`, adds in any required compatibility objects, and creates the final shared and static libraries: `libstdc++.so` and `libstdc++.a`.

B.1.5 Generated files

Some files in the libstdc++ source tree are auto-generated from other files. In general, these are not regenerated automatically, so it must be done manually when the files they depend on are updated.

- The header file `include/bits/version.h` is generated from `version.def` and `version.tpl` in the same directory. After editing those files, either run **autogen version.def** in the `include` directory of the source tree, or run **make update-version** in the `include` directory of the build tree.
- The header file `include/bits/unicode-data.h` is generated by the Python script `../contrib/unicode/gen_libstdcxx_unicode_data.py` using data files in the same directory. The script contains information on which data files it uses and how to update them.
- The header file `include/bits/text_encoding-data.h` is generated by the Python script `scripts/gen_text_encoding_data.py` using the CSV file `https://www.iana.org/assignments/character-sets/character-se csv` from the IANA Character Sets registry.
- The data file `src/c++20/tzdata.zi` is copied verbatim from the IANA Time Zone Database (the latest version can be downloaded from `https://data.iana.org/time-zones/tzdb/tzdata.zi`). Libstdc++ uses this data file to populate a `std::chrono::tzdb` object in case the system does not provide a copy of the file. See Configuring for the `--with-libstdcxx-zoneinfo` option that determines whether this file is used.
- The header file `src/c++20/windows_zones-map.h` is generated by the Python script `scripts/gen_windows_zones_map.py` using the XML file `https://github.com/unicode-org/cldr/blob/main/common/supplementa windowsZones.xml` from the Unicode CLDR Project.

B.2 Writing and Generating Documentation

B.2.1 Introduction

Documentation for the GNU C++ Library is created from three independent sources: a manual, a FAQ, and an API reference.

The sub-directory `doc` within the main source directory contains `Makefile.am` and `Makefile.in`, which provide rules for generating documentation, described in excruciating detail below. The `doc` sub-directory also contains three directories: `doxygen`, which contains scripts and fragments for **doxygen**, `html`, which contains an html version of the manual, and `xml`, which contains an xml version of the manual.

Diverging from established documentation conventions in the rest of the GCC project, libstdc++ does not use Texinfo as a markup language. Instead, Docbook is used to create the manual and the FAQ, and Doxygen is used to construct the API reference. Although divergent, this conforms to the GNU Project recommendations as long as the output is of sufficient quality, as per GNU Manuals.

B.2.2 Generating Documentation

Certain Makefile rules are required by the GNU Coding Standards. These standard rules generate HTML, PDF, XML, or man files. For each of the generative rules, there is an additional install rule that is used to install any generated documentation files into the prescribed installation directory. Files are installed into `share/doc` or `share/man` directories.

The standard Makefile rules are conditionally supported, based on the results of examining the host environment for prerequisites at configuration time. If requirements are not found, the rule is aliased to a dummy rule that does nothing, and produces no documentation. If the requirements are found, the rule forwards to a private rule that produces the requested documentation.

For more details on what prerequisites were found and where, please consult the file `config.log` in the libstdc++ build directory. Compare this log to what is expected for the relevant Makefile conditionals: `BUILD_INFO`, `BUILD_XML`, `BUILD_HTML`, `BUILD_MAN`, `BUILD_PDF`, and `BUILD_EPUB`.

Supported Makefile rules:

make html* , *make install-html Generates multi-page HTML documentation, and installs it in the following directories:

`doc/libstdc++/libstdc++-api.html`

`doc/libstdc++/libstdc++-manual.html`

make pdf* , *make install-pdf Generates indexed PDF documentation, and installs it as the following files:

`doc/libstdc++/libstdc++-api.pdf`

`doc/libstdc++/libstdc++-manual.pdf`

make man* , *make install-man Generates man pages, and installs it in the following directory:

`man/man3/`

The generated man pages are namespace-qualified, so to look at the man page for `vector`, one would use **man std::vector**.

make epub* , *make install-epub Generates documentation in the ebook/portable electronic reader format called Epub, and installs it as the following file.

`doc/libstdc++/libstdc++-manual.epub`

make xml* , *make install-xml Generates single-file XML documentation, and installs it as the following files:

`doc/libstdc++/libstdc++-api-single.xml`

`doc/libstdc++/libstdc++-manual-single.xml`

Makefile rules for several other formats are explicitly not supported, and are always aliased to dummy rules. These unsupported formats are: *info*, *ps*, and *dvi*.

B.2.3 Doxygen

B.2.3.1 Prerequisites

Tool	Version	Required By
coreutils	8.5	all
bash	4.1	all
doxygen	1.9.1	all
graphviz	2.26	graphical hierarchies
pdflatex	2007-59	pdf output

Table B.1: Doxygen Prerequisites

Prerequisite tools are Bash 2.0 or later, Doxygen 1.9.1 or later (for best results use at least 1.9.6), and the GNU coreutils. (GNU versions of find, xargs, and possibly sed and grep are used, just because the GNU versions make things very easy.)

To generate the pretty pictures and hierarchy graphs, the Graphviz package will need to be installed. For PDF output, pdflatex is required as well as a number of TeX packages such as `texlive-xtab` and `texlive-tocloft`.

Be warned the PDF file generated via doxygen is extremely large. At last count, the PDF file is over three thousand pages. Generating this document taxes the underlying TeX formatting system, and will require the expansion of TeX's memory capacity. Specifically, the `pool_size` variable in the configuration file `texmf.cnf` may need to be increased by a minimum factor of two. Alternatively, using **`LATEX_CMD=lualatex`** might allow the docs to be build without running out of memory.

B.2.3.2 Generating the Doxygen Files

The following Makefile rules run Doxygen to generate HTML docs, XML docs, XML docs as a single file, PDF docs, and the man pages. These rules are not conditional! If the required tools are not found, or are the wrong versions, the rule may end in an error.

```
make doc-html-doxygen
```

```
make doc-xml-doxygen
```

```
make doc-xml-single-doxygen
```

```
make doc-pdf-doxygen
```

```
make doc-man-doxygen
```

Generated files are output into separate sub directories of `doc/doxygen/` in the build directory, based on the output format. For instance, the HTML docs will be in `doc/doxygen/html`.

Careful observers will see that the Makefile rules simply call a script from the source tree, `run_doxygen`, which does the actual work of running Doxygen and then (most importantly) massaging the output files. If for some reason you prefer to not go through the Makefile, you can call this script directly. (Start by passing `--help`.)

If you wish to tweak the Doxygen settings, do so by editing `doc/doxygen/user.cfg.in`. Notes to fellow library hackers are written in triple-# comments.

B.2.3.3 Debugging Generation

Sometimes, mis-configuration of the pre-requisite tools can lead to errors when attempting to build the documentation. Here are some of the obvious errors, and ways to fix some common issues that may appear quite cryptic.

First, if using a rule like `make pdf`, try to narrow down the scope of the error to either docbook (`make doc-pdf-docbook`) or doxygen (`make doc-pdf-doxygen`).

Working on the doxygen path only, closely examine the contents of the following build directory: `build/target/libstdc++-v3/doc/doxygen/latex`. Pay attention to three files enclosed within, annotated as follows.

- *refman.tex*

  The actual latex file, or partial latex file. This is generated via **doxygen**, and is the LaTeX version of the Doxygen XML file `libstdc++-api.xml`. Go to a specific line, and look at the generated LaTeX, and try to deduce what markup in `libstdc++-api.xml` is causing it.

- *refman.log*

  A log created by **latex** as it processes the `refman.tex` file. If generating the PDF fails look at the end of this file for errors such as:

  ```
      ! LaTeX Error: File `xtab.sty' not found.
  ```

  This indicates a required TeX package is missing. For the example above the `texlive-xtab` package needs to be installed.

- *refman.out*

  A log of the compilation of the converted LaTeX form to PDF. This is a linear list, from the beginning of the `refman.tex` file: the last entry of this file should be the end of the LaTeX file. If it is truncated, then you know that the last entry is the last part of the generated LaTeX source file that is valid. Often this file contains an error with a specific line number of `refman.tex` that is incorrect, or will have clues at the end of the file with the dump of the memory usage of LaTeX.

If the error at hand is not obvious after examination, a fall-back strategy is to start commenting out the doxygen input sources, which can be found in `doc/doxygen/user.cfg.in`, look for the `INPUT` tag. Start by commenting out whole directories of header files, until the offending header is identified. Then, read the latex log files to try and find surround text, and look for that in the offending header.

B.2.3.4 Markup

In general, libstdc++ files should be formatted according to the rules found in the Coding Standard. Before any doxygen-specific formatting tweaks are made, please try to make sure that the initial formatting is sound.

Adding Doxygen markup to a file (informally called “doxygenating”) is very simple. See the Doxygen manual for details. We try to use a very-recent version of Doxygen.

For classes, use `deque`/`vector`/`list` and `std::pair` as examples. For functions, see their member functions, and the free functions in `stl_algobase.h`. Member functions of other container-like types should read similarly to these member functions.

Some commentary to accompany the first list in the Special Documentation Blocks section of the Doxygen manual:

1. For longer comments, use the Javadoc style...
2. ...not the Qt style. The intermediate *'s are preferred.
3. Use the triple-slash style only for one-line comments (the “brief” mode).
4. This is disgusting. Don't do this.

Some specific guidelines:

Use the @-style of commands, not the !-style. Please be careful about whitespace in your markup comments. Most of the time it doesn't matter; doxygen absorbs most whitespace, and both HTML and *roff are agnostic about whitespace. However, in <pre> blocks and @code/@endcode sections, spacing can have “interesting” effects.

Use either kind of grouping, as appropriate. `doxygroups.cc` exists for this purpose. See `stl_iterator.h` for a good example of the “other” kind of grouping.

Markdown can be used for formatting text. Doxygen is configured to support this, and it is a good compromise between readable comments in the C++ source and nice formatting in the generated HTML. Please format the names of function parameters in either code font or italics. Use underscores or @e for emphasis when necessary. Use backticks or @c to refer to other standard names. (Examples of all these abound in the present code.)

Complicated math functions should use the multi-line format. An example from `random.h`:

```
/**
 * @brief A model of a linear congruential random number generator.
 *
 * @f[
 *     x_{i+1}\leftarrow(ax_{i} + c) \bmod m
 * @f]
 */
```

One area of note is the markup required for `@file` markup in header files. Two details are important: for filenames that have the same name in multiple directories, include part of the installed path to disambiguate. For example:

```
/** @file debug/vector
 *  This file is a GNU debug extension to the Standard C++ Library.
 */
```

The other relevant detail for header files is the use of a libstdc++-specific doxygen alias that helps distinguish between public header files (like `random`) from implementation or private header files (like `bits/c++config.h`.) This alias is spelled `@headername` and can take one or two arguments that detail the public header file or files that should be included to use the contents of the file. All header files that are not intended for direct inclusion must use `headername` in the `file` block. An example:

```
/** @file bits/basic_string.h
 *  This is an internal header file, included by other library headers.
 *  Do not attempt to use it directly. @headername{string}
 */
```

Be careful about using certain, special characters when writing Doxygen comments. Single and double quotes, and separators in filenames are two common trouble spots. When in doubt, consult the following table.

HTML	Doxygen
\	\\
"	\"
’	\’
<i>	@a word
<b>	@b word
<code>	@c word
	@a word
	two words or more

Table B.2: HTML to Doxygen Markup Comparison

B.2.4 Docbook

B.2.4.1 Prerequisites

Tool	Version	Required By
docbook5-style-xsl	1.76.1	all
xsltproc	1.1.26	all
xmllint	2.7.7	validation
dblatex	0.3	pdf output
pdflatex	2007-59	pdf output
docbook2X	0.8.8	info output
epub3 stylesheets	b3	epub output

Table B.3: Docbook Prerequisites

An XML editor is recommended for editing the DocBook sources. Many exist: some notable options include **emacs**, Kate, or Conglomerate.

Some editors support special “XML Validation” modes that can validate the file as it is produced. Recommended is the **nXML Mode** for **emacs**.

Besides an editor, additional DocBook files and XML tools are also required.

Access to the DocBook 5.0 stylesheets and schema is required. The stylesheets are usually packaged by vendor, in something like `docbook5-style-xsl`. To exactly match generated output, please use a version of the stylesheets equivalent to `docbook5-style-xsl-1.75.2-3`. The installation directory for this package corresponds to the `XSL_STYLE_DIR` in `doc/Makefile.am` and defaults to `/usr/share/sgml/docbook/xsl-ns-stylesheets`.

For processing XML, an XSLT processor and some style sheets are necessary. Defaults are **xsltproc** provided by `libxslt`.

For validating the XML document, you’ll need something like **xmllint** and access to the relevant DocBook schema. These are provided by a vendor package like `libxml2` and `docbook5-schemas-5.0-4`

For PDF output, something that transforms valid Docbook XML to PDF is required. Possible solutions include dblatex, **xmlto**, or **prince**. Of these, **dblatex** is the default. Please consult the libstdc++@gcc.gnu.org list when preparing printed manuals for current best practice and suggestions.

For Texinfo output, something that transforms valid Docbook XML to Texinfo is required. The default choice is docbook2X.

For epub output, the stylesheets for EPUB3 are required. These stylesheets are still in development. To validate the created file, epubcheck is necessary.

B.2.4.2 Generating the DocBook Files

The following Makefile rules generate (in order): an HTML version of all the DocBook documentation, a PDF version of the same, and a single XML document. These rules are not conditional! If the required tools are not found, or are the wrong versions, the rule may end in an error.

```
make doc-html-docbook
```

```
make doc-pdf-docbook
```

```
make doc-xml-single-docbook
```

Generated files are output into separate sub-directores of `doc/docbook/` in the build directory, based on the output format. For instance, the HTML docs will be in `doc/docbook/html`.

The **`doc-html-docbook-regenerate`** target will generate the HTML files and copy them back to the libstdc++ source tree. This can be used to update the HTML files that are checked in to version control.

If the Docbook stylesheets are installed in a custom location, one can use the variable `XSL_STYLE_DIR` to override the Makefile defaults. For example:

```
make XSL_STYLE_DIR="/usr/share/xml/docbook/stylesheet/nwalsh" doc-html-docbook
```

B.2.4.3 Debugging Generation

Sometimes, mis-configuration of the pre-requisite tools can lead to errors when attempting to build the documentation. Here are some of the obvious errors, and ways to fix some common issues that may appear quite cryptic.

First, if using a rule like `make pdf`, try to narrow down the scope of the error to either docbook (`make doc-pdf-docbook`) or doxygen (`make doc-pdf-doxygen`).

Working on the docbook path only, closely examine the contents of the following build directory: `build/target/libstdc++-v3/doc/docbook/latex`. Pay attention to three files enclosed within, annotated as follows.

- *spine.tex*

  The actual latex file, or partial latex file. This is generated via **dblatex**, and is the LaTeX version of the DocBook XML file `spine.xml`. Go to a specific line, and look at the generated LaTeX, and try to deduce what markup in `spine.xml` is causing it.

- *spine.out*

  A log of the conversion from the XML form to the LaTeX form. This is a linear list, from the beginning of the `spine.xml` file: the last entry of this file should be the end of the DocBook file. If it is truncated, then you know that the last entry is the last part of the XML source file that is valid. The error is after this point.

- *spine.log*

  A log of the compilation of the converted LaTeX form to pdf. This is a linear list, from the beginning of the `spine.tex` file: the last entry of this file should be the end of the LaTeX file. If it is truncated, then you know that the last entry is the last part of the generated LaTeX source file that is valid. Often this file contains an error with a specific line number of `spine.tex` that is incorrect.

If the error at hand is not obvious after examination, or if one encounters the inscruitable “Incomplete \ifmmode” error, a fall-back strategy is to start commenting out parts of the XML document (regardless of what this does to over-all document validity). Start by commenting out each of the largest parts of the `spine.xml` file, section by section, until the offending section is identified.

B.2.4.4 Editing and Validation

After editing the xml sources, please make sure that the XML documentation and markup is still valid. This can be done easily, with the following validation rule:

```
make doc-xml-validate-docbook
```

This is equivalent to doing:

```
xmllint --noout --valid xml/index.xml
```

Please note that individual sections and chapters of the manual can be validated by substituting the file desired for `xml/index.xml` in the command above. Reducing scope in this manner can be helpful when validation on the entire manual fails.

All Docbook xml sources should always validate. No excuses!

B.2.4.5 File Organization and Basics

```
Which files are important

All Docbook files are in the directory
libstdc++-v3/doc/xml

Inside this directory, the files of importance:
spine.xml   - index to documentation set
manual/spine.xml  - index to manual
manual/*.xml    - individual chapters and sections of the manual
faq.xml     - index to FAQ
api.xml     - index to source level / API

All *.txml files are template xml files, i.e., otherwise empty files with
the correct structure, suitable for filling in with new information.

Canonical Writing Style

class template
function template
member function template
(via C++ Templates, Vandevoorde)

class in namespace std: allocator, not std::allocator

header file: iostream, not <iostream>


General structure

<set>
<book>
</book>

<book>
<chapter>
</chapter>
</book>
```

```
<book>
<part>
<chapter>
<section>
</section>

<sect1>
</sect1>

<sect1>
<sect2>
</sect2>
</sect1>
</chapter>

<chapter>
</chapter>
</part>
</book>

</set>
```

B.2.4.6 Markup By Example

Complete details on Docbook markup can be found in the DocBook Element Reference. An incomplete reference for HTML to Docbook conversion is detailed in the table below.

HTML	Docbook
<p>	<para>
<pre>	<computeroutput>, <programlisting>, <literallayout>
	<itemizedlist>
	<orderedlist>
<il>	<listitem>
<dl>	<variablelist>
<dt>	<term>
<dd>	<listitem>
<a href="">	<ulink url="">
<code>	<literal>, <programlisting>
<strong>	<emphasis>
<em>	<emphasis>
"	<quote>

Table B.4: HTML to Docbook XML Markup Comparison

And examples of detailed markup for which there are no real HTML equivalents are listed in the table below.

B.3 Porting to New Hardware or Operating Systems

This document explains how to port libstdc++ (the GNU C++ library) to a new target.

In order to make the GNU C++ library (libstdc++) work with a new target, you must edit some configuration files and provide some new header files. Unless this is done, libstdc++ will use generic settings which may not be correct for your target; even if they are correct, they will likely be inefficient.

Element	Use
<structname>	<structname>char_traits</structname>
<classname>	<classname>string</classname>
<function>	<function>clear()</function> <function>fs.clear()</function>
<type>	<type>long long</type>
<varname>	<varname>fs</varname>
<literal>	<literal>-Weffc++</literal> <literal>rel_ops</literal>
<constant>	<constant>_GNU_SOURCE</constant> <constant>3.0</constant>
<command>	<command>g++</command>
<errortext>	<errortext>In instantiation of</errortext>
<filename>	<filename class="headerfile">ctype.h</filename> <filename class="directory">/home/gcc/build</filename> <filename class="libraryfile">libstdc++.so</filename>

Table B.5: Docbook XML Element Use

Before you get started, make sure that you have a working C library on your target. The C library need not precisely comply with any particular standard, but should generally conform to the requirements imposed by the ANSI/ISO standard.

In addition, you should try to verify that the C++ compiler generally works. It is difficult to test the C++ compiler without a working library, but you should at least try some minimal test cases.

(Note that what we think of as a "target," the library refers to as a "host." The comment at the top of `configure.ac` explains why.)

B.3.1 Operating System

If you are porting to a new operating system (as opposed to a new chip using an existing operating system), you will need to create a new directory in the `config/os` hierarchy. For example, the IRIX configuration files are all in `config/os/irix`. There is no set way to organize the OS configuration directory. For example, `config/os/solaris/solaris-2.6` and `config/os/solaris/solaris-2.7` are used as configuration directories for these two versions of Solaris. On the other hand, both Solaris 2.7 and Solaris 2.8 use the `config/os/solaris/solaris-2.7` directory. The important information is that there needs to be a directory under `config/os` to store the files for your operating system.

You might have to change the `configure.host` file to ensure that your new directory is activated. Look for the switch statement that sets `os_include_dir`, and add a pattern to handle your operating system if the default will not suffice. The switch statement switches on only the OS portion of the standard target triplet; e.g., the `solaris2.8` in `sparc-sun-solaris2.8`. If the new directory is named after the OS portion of the triplet (the default), then nothing needs to be changed.

The first file to create in this directory, should be called `os_defines.h`. This file contains basic macro definitions that are required to allow the C++ library to work with your C library.

Several libstdc++ source files unconditionally define the macro `_POSIX_SOURCE`. On many systems, defining this macro causes large portions of the C library header files to be eliminated at preprocessing time. Therefore, you may have to `#undef` this macro, or define other macros (like `_LARGEFILE_SOURCE` or `__EXTENSIONS__`). You won't know what macros to define or undefine at this point; you'll have to try compiling the library and seeing what goes wrong. If you see errors about calling functions that have not been declared, look in your C library headers to see if the functions are declared there, and then figure out what macros you need to define. You will need to add them to the `CPLUSPLUS_CPP_SPEC` macro in the GCC configuration file for your target. It will not work to simply define these macros in `os_defines.h`.

At this time, there are a few libstdc++-specific macros which may be defined:

`_GLIBCXX_USE_C99_CHECK` may be defined to 1 to check C99 function declarations (which are not covered by specialization below) found in system headers against versions found in the library headers derived from the standard.

_GLIBCXX_USE_C99_DYNAMIC may be defined to an expression that yields 0 if and only if the system headers are exposing proper support for C99 functions (which are not covered by specialization below). If defined, it must be 0 while bootstrapping the compiler/rebuilding the library.

_GLIBCXX_USE_C99_LONG_LONG_CHECK may be defined to 1 to check the set of C99 long long function declarations found in system headers against versions found in the library headers derived from the standard.

_GLIBCXX_USE_C99_LONG_LONG_DYNAMIC may be defined to an expression that yields 0 if and only if the system headers are exposing proper support for the set of C99 long long functions. If defined, it must be 0 while bootstrapping the compiler/rebuilding the library.

_GLIBCXX_USE_C99_FP_MACROS_DYNAMIC may be defined to an expression that yields 0 if and only if the system headers are exposing proper support for the related set of macros. If defined, it must be 0 while bootstrapping the compiler/rebuilding the library.

_GLIBCXX_USE_C99_FLOAT_TRANSCENDENTALS_CHECK may be defined to 1 to check the related set of function declarations found in system headers against versions found in the library headers derived from the standard.

_GLIBCXX_USE_C99_FLOAT_TRANSCENDENTALS_DYNAMIC may be defined to an expression that yields 0 if and only if the system headers are exposing proper support for the related set of functions. If defined, it must be 0 while bootstrapping the compiler/rebuilding the library.

_GLIBCXX_NO_OBSOLETE_ISINF_ISNAN_DYNAMIC may be defined to an expression that yields 0 if and only if the system headers are exposing non-standard isinf(double) and isnan(double) functions in the global namespace. Those functions should be detected automatically by the configure script when libstdc++ is built but if their presence depends on compilation flags or other macros the static configuration can be overridden.

Finally, you should bracket the entire file in an include-guard, like this:

```
#ifndef _GLIBCXX_OS_DEFINES
#define _GLIBCXX_OS_DEFINES
...
#endif
```

We recommend copying an existing os_defines.h to use as a starting point.

B.3.2 CPU

If you are porting to a new chip (as opposed to a new operating system running on an existing chip), you will need to create a new directory in the config/cpu hierarchy. Much like the Operating system setup, there are no strict rules on how to organize the CPU configuration directory, but careful naming choices will allow the configury to find your setup files without explicit help.

We recommend that for a target triplet <CPU>-<vendor>-<OS>, you name your configuration directory config/cpu/<CPU>. If you do this, the configury will find the directory by itself. Otherwise you will need to edit the configure.host file and, in the switch statement that sets cpu_include_dir, add a pattern to handle your chip.

Note that some chip families share a single configuration directory, for example, alpha, alphaev5, and alphaev6 all use the config/cpu/alpha directory, and there is an entry in the configure.host switch statement to handle this.

The cpu_include_dir sets default locations for the files controlling Thread safety and Numeric limits, if the defaults are not appropriate for your chip.

B.3.3 Character Types

The library requires that you provide three header files to implement character classification, analogous to that provided by the C libraries <ctype.h> header. You can model these on the files provided in config/os/generic. However, these files will almost certainly need some modification.

The first file to write is ctype_base.h. This file provides some very basic information about character classification. The libstdc++ library assumes that your C library implements <ctype.h> by using a table (indexed by character code) containing integers, where each of these integers is a bit-mask indicating whether the character is upper-case, lower-case, alphabetic, etc. The ctype_base.h file gives the type of the integer, and the values of the various bit masks. You will have to peer at your own <ctype.h> to figure out how to define the values required by this file.

The ctype_base.h header file does not need include guards. It should contain a single struct definition called ctype_base. This struct should contain two type declarations, and one enumeration declaration, like this example, taken from the IRIX configuration:

```
  struct ctype_base
     {
       typedef unsigned int   mask;
       typedef int*     __to_type;

       enum
       {
   space = _ISspace,
   print = _ISprint,
   cntrl = _IScntrl,
   upper = _ISupper,
   lower = _ISlower,
   alpha = _ISalpha,
   digit = _ISdigit,
   punct = _ISpunct,
   xdigit = _ISxdigit,
   alnum = _ISalnum,
   graph = _ISgraph
       };
     };
```

The mask type is the type of the elements in the table. If your C library uses a table to map lower-case numbers to upper-case numbers, and vice versa, you should define __to_type to be the type of the elements in that table. If you don't mind taking a minor performance penalty, or if your library doesn't implement toupper and tolower in this way, you can pick any pointer-to-integer type, but you must still define the type.

The enumeration should give definitions for all the values in the above example, using the values from your native <ctype.h>. They can be given symbolically (as above), or numerically, if you prefer. You do not have to include <ctype.h> in this header; it will always be included before ctype_base.h is included.

The next file to write is ctype_configure_char.cc. The first function that must be written is the ctype<char>::ctype constructor. Here is the IRIX example:

```
ctype<char>::ctype(const mask* __table = 0, bool __del = false,
     size_t __refs = 0)
       : _Ctype_nois<char>(__refs), _M_del(__table != 0 && __del),
   _M_toupper(NULL),
   _M_tolower(NULL),
   _M_ctable(NULL),
   _M_table(!__table
      ? (const mask*) (__libc_attr._ctype_tbl->_class + 1)
      : __table)
       { }
```

There are two parts of this that you might choose to alter. The first, and most important, is the line involving __libc_attr. That is IRIX system-dependent code that gets the base of the table mapping character codes to attributes. You need to substitute code that obtains the address of this table on your system. If you want to use your operating system's tables to map upper-case letters to lower-case, and vice versa, you should initialize _M_toupper and _M_tolower with those tables, in similar fashion.

Now, you have to write two functions to convert from upper-case to lower-case, and vice versa. Here are the IRIX versions:

```
     char
     ctype<char>::do_toupper(char __c) const
     { return _toupper(__c); }
```

```
char
ctype<char>::do_tolower(char __c) const
{ return _tolower(__c); }
```

Your C library provides equivalents to IRIX's `_toupper` and `_tolower`. If you initialized `_M_toupper` and `_M_tolower` above, then you could use those tables instead.

Finally, you have to provide two utility functions that convert strings of characters. The versions provided here will always work - but you could use specialized routines for greater performance if you have machinery to do that on your system:

```
const char*
ctype<char>::do_toupper(char* __low, const char* __high) const
{
  while (__low < __high)
{
*__low = do_toupper(*__low);
++__low;
}
  return __high;
}

const char*
ctype<char>::do_tolower(char* __low, const char* __high) const
{
  while (__low < __high)
{
*__low = do_tolower(*__low);
++__low;
}
  return __high;
}
```

You must also provide the `ctype_inline.h` file, which contains a few more functions. On most systems, you can just copy `config/os/generic/ctype_inline.h` and use it on your system.

In detail, the functions provided test characters for particular properties; they are analogous to the functions like `isalpha` and `islower` provided by the C library.

The first function is implemented like this on IRIX:

```
bool
ctype<char>::
is(mask __m, char __c) const throw()
{ return (_M_table)[(unsigned char)(__c)] & __m; }
```

The `_M_table` is the table passed in above, in the constructor. This is the table that contains the bitmasks for each character. The implementation here should work on all systems.

The next function is:

```
const char*
ctype<char>::
is(const char* __low, const char* __high, mask* __vec) const throw()
{
  while (__low < __high)
*__vec++ = (_M_table)[(unsigned char)(*__low++)];
  return __high;
}
```

This function is similar; it copies the masks for all the characters from `__low` up until `__high` into the vector given by `__vec`.

The last two functions again are entirely generic:

```
    const char*
    ctype<char>::
    scan_is(mask __m, const char* __low, const char* __high) const throw()
    {
      while (__low < __high && !this->is(__m, *__low))
  ++__low;
      return __low;
    }

    const char*
    ctype<char>::
    scan_not(mask __m, const char* __low, const char* __high) const throw()
    {
      while (__low < __high && this->is(__m, *__low))
  ++__low;
      return __low;
    }
```

B.3.4 Thread Safety

The C++ library string functionality requires a couple of atomic operations to provide thread-safety. If you don't take any special action, the library will use stub versions of these functions that are not thread-safe. They will work fine, unless your applications are multi-threaded.

If you want to provide custom, safe, versions of these functions, there are two distinct approaches. One is to provide a version for your CPU, using assembly language constructs. The other is to use the thread-safety primitives in your operating system. In either case, you make a file called `atomicity.h`, and the variable `ATOMICITYH` must point to this file.

If you are using the assembly-language approach, put this code in `config/cpu/<chip>/atomicity.h`, where chip is the name of your processor (see CPU). No additional changes are necessary to locate the file in this case; `ATOMICITYH` will be set by default.

If you are using the operating system thread-safety primitives approach, you can also put this code in the same CPU directory, in which case no more work is needed to locate the file. For examples of this approach, see the `atomicity.h` file for IRIX or IA64.

Alternatively, if the primitives are more closely related to the OS than they are to the CPU, you can put the `atomicity.h` file in the Operating system directory instead. In this case, you must edit `configure.host`, and in the switch statement that handles operating systems, override the `ATOMICITYH` variable to point to the appropriate `os_include_dir`. For examples of this approach, see the `atomicity.h` file for AIX.

With those bits out of the way, you have to actually write `atomicity.h` itself. This file should be wrapped in an include guard named `_GLIBCXX_ATOMICITY_H`. It should define one type, and two functions.

The type is `_Atomic_word`. Here is the version used on IRIX:

```
typedef long _Atomic_word;
```

This type must be a signed integral type supporting atomic operations. If you're using the OS approach, use the same type used by your system's primitives. Otherwise, use the type for which your CPU provides atomic primitives.

Then, you must provide two functions. The bodies of these functions must be equivalent to those provided here, but using atomic operations:

```
    static inline _Atomic_word
    __attribute__ ((__unused__))
    __exchange_and_add (_Atomic_word* __mem, int __val)
    {
      _Atomic_word __result = *__mem;
      *__mem += __val;
      return __result;
```

```
}

static inline void
__attribute__ ((__unused__))
__atomic_add (_Atomic_word* __mem, int __val)
{
  *__mem += __val;
}
```

B.3.5 Numeric Limits

The C++ library requires information about the fundamental data types, such as the minimum and maximum representable values of each type. You can define each of these values individually, but it is usually easiest just to indicate how many bits are used in each of the data types and let the library do the rest. For information about the macros to define, see the top of `include/bits/std_limits.h`.

If you need to define any macros, you can do so in `os_defines.h`. However, if all operating systems for your CPU are likely to use the same values, you can provide a CPU-specific file instead so that you do not have to provide the same definitions for each operating system. To take that approach, create a new file called `cpu_limits.h` in your CPU configuration directory (see CPU).

B.3.6 Libtool

The C++ library is compiled, archived and linked with libtool. Explaining the full workings of libtool is beyond the scope of this document, but there are a few, particular bits that are necessary for porting.

Some parts of the libstdc++ library are compiled with the libtool `--tags CXX` option (the C++ definitions for libtool). Therefore, `ltcf-cxx.sh` in the top-level directory needs to have the correct logic to compile and archive objects equivalent to the C version of libtool, `ltcf-c.sh`. Some libtool targets have definitions for C but not for C++, or C++ definitions which have not been kept up to date.

The C++ run-time library contains initialization code that needs to be run as the library is loaded. Often, that requires linking in special object files when the C++ library is built as a shared library, or taking other system-specific actions.

The libstdc++ library is linked with the C version of libtool, even though it is a C++ library. Therefore, the C version of libtool needs to ensure that the run-time library initializers are run. The usual way to do this is to build the library using `gcc -shared`.

If you need to change how the library is linked, look at `ltcf-c.sh` in the top-level directory. Find the switch statement that sets `archive_cmds`. Here, adjust the setting for your operating system.

B.4 Testing

The libstdc++ testsuite includes testing for standard conformance, regressions, ABI, and performance.

B.4.1 Test Organization

B.4.1.1 Directory Layout

The directory *gccsrcdir*`/libstdc++-v3/testsuite` contains the individual test cases organized in sub-directories corresponding to clauses of the C++ standard (detailed below), the DejaGnu test harness support files, and sources to various testsuite utilities that are packaged in a separate testing library.

All test cases for functionality required by the runtime components of the C++ standard (ISO 14882) are files within the following directories:

```
17_intro
18_support
19_diagnostics
20_util
21_strings
22_locale
23_containers
24_iterators
25_algorithms
26_numerics
27_io
28_regex
29_atomics
30_threads
```

In addition, the following directories include test files:

tr1 Tests for components as described by the Technical Report on Standard Library Extensions (TR1).

backward Tests for backwards compatibility and deprecated features.

demangle Tests for `__cxa_demangle`, the IA-64 C++ ABI demangler.

ext Tests for extensions.

performance Tests for performance analysis, and performance regressions.

Some directories don't have test files, but instead contain auxiliary information:

config Files for the DejaGnu test harness.

lib Files for the DejaGnu test harness.

libstdc++* Files for the DejaGnu test harness.

data Sample text files for testing input and output.

util Files for libtestc++, utilities and testing routines.

Within a directory that includes test files, there may be additional subdirectories, or files. Originally, test cases were appended to one file that represented a particular section of the chapter under test, and was named accordingly. For instance, to test items related to `21.3.6.1 - basic_string::find [lib.string::find]` in the standard, the following was used:

```
21_strings/find.cc
```

However, that practice soon became a liability as the test cases became huge and unwieldy, and testing new or extended functionality (like wide characters or named locales) became frustrating, leading to aggressive pruning of test cases on some platforms that covered up implementation errors. Now, the test suite has a policy of one file, one test case, which solves the above issues and gives finer grained results and more manageable error debugging. As an example, the test case quoted above becomes:

```
21_strings/basic_string/find/char/1.cc
21_strings/basic_string/find/char/2.cc
21_strings/basic_string/find/char/3.cc
21_strings/basic_string/find/wchar_t/1.cc
21_strings/basic_string/find/wchar_t/2.cc
21_strings/basic_string/find/wchar_t/3.cc
```

All new tests should be written with the policy of "one test case, one file" in mind.

B.4.1.2 Naming Conventions

In addition, there are some special names and suffixes that are used within the testsuite to designate particular kinds of tests.

_xin.cc This test case expects some kind of interactive input in order to finish or pass. At the moment, the interactive tests are not run by default. Instead, they are run by hand, like:

```
g++ 27_io/objects/char/3_xin.cc
cat 27_io/objects/char/3_xin.in | a.out
```

.in This file contains the expected input for the corresponding *_xin.cc* test case.

_neg.cc This test case is expected to fail: it's a negative test. At the moment, these are almost always compile time errors.

char This can either be a directory name or part of a longer file name, and indicates that this file, or the files within this directory are testing the `char` instantiation of a template.

wchar_t This can either be a directory name or part of a longer file name, and indicates that this file, or the files within this directory are testing the `wchar_t` instantiation of a template. Some hosts do not support `wchar_t` functionality, so for these targets, all of these tests will not be run.

thread This can either be a directory name or part of a longer file name, and indicates that this file, or the files within this directory are testing situations where multiple threads are being used.

performance This can either be an enclosing directory name or part of a specific file name. This indicates a test that is used to analyze runtime performance, for performance regression testing, or for other optimization related analysis. At the moment, these test cases are not run by default.

B.4.2 Running the Testsuite

B.4.2.1 Basic

You can check the status of the build without installing it using the DejaGnu harness, much like the rest of the gcc tools, i.e. **make check** in the *libbuilddir* directory, or **make check-target-libstdc++-v3** in the *gccbuilddir* directory.

These commands are functionally equivalent and will create a 'testsuite' directory underneath *libbuilddir* containing the results of the tests. Two results files will be generated: `libstdc++.sum`, which is a PASS/FAIL summary for each test, and `libstdc++.log` which is a log of the exact command-line passed to the compiler, the compiler output, and the executable output (if any) for each test.

Archives of test results for various versions and platforms are archived on a daily basis on the gcc-testresults mailing list. Please check there for a similar combination of source version, operating system, and host CPU.

B.4.2.2 Variations

There are several options for running tests, including testing the regression tests, testing a subset of the regression tests, testing the performance tests, testing just compilation, testing installed tools, etc. In addition, there is a special rule for checking the exported symbols of the shared library.

To debug the DejaGnu test harness during runs, try invoking with a specific argument to the variable `RUNTESTFLAGS`, like so:

```
make check-target-libstdc++-v3 RUNTESTFLAGS="-v"
```

or

```
make check-target-libstdc++-v3 RUNTESTFLAGS="-v -v"
```

To run a subset of the library tests, you can either generate the `testsuite_files` file (described below) by running **make testsuite_files** in the *libbuilddir*/testsuite directory, then edit the file to remove the tests you don't want and then run the testsuite as normal, or you can specify a testsuite and a subset of tests in the RUNTESTFLAGS variable.

For example, to run only the tests for containers you could use:

```
make check-target-libstdc++-v3 RUNTESTFLAGS="conformance.exp=23_containers/*"
```

When combining this with other options in RUNTESTFLAGS the `testsuite.exp=testfiles` options must come first.

There are two ways to run on a simulator: set up DEJAGNU to point to a specially crafted `site.exp`, or pass down `--target_board` flags.

Example flags to pass down for various embedded builds are as follows:

```
--target=powerpc-eabisim (libgloss/sim)
make check-target-libstdc++-v3 RUNTESTFLAGS="--target_board=powerpc-sim"

--target=calmrisc32 (libgloss/sid)
make check-target-libstdc++-v3 RUNTESTFLAGS="--target_board=calmrisc32-sid"

--target=xscale-elf (newlib/sim)
make check-target-libstdc++-v3 RUNTESTFLAGS="--target_board=arm-sim"
```

Also, here is an example of how to run the libstdc++ testsuite for a multilibed build directory with different ABI settings:

```
make check-target-libstdc++-v3 RUNTESTFLAGS='--target_board \"unix{-mabi=32,,-mabi ↩
    =64}\"'
```

If you wish to run the testsuite in a freestanding configuration, you can pass the `-ffreestanding` flag. Doing so will run the tests that do not require hosted features, and emit a UNSUPPORTED for those that do. To run tests in the freestanding configuration, you still need to build for a target you can run programs on, e.g. `x86_64-pc-linux-gnu`, as a few tests still execute the code they build. Here's an example of how to run the testsuite with libstdc++ in freestanding mode:

```
make check-target-libstdc++-v3 RUNTESTFLAGS='--target_board=unix/-ffreestanding'
```

You can run the tests with a compiler and library that have already been installed. Make sure that the compiler (e.g., **g++**) is in your PATH. If you are using shared libraries, then you must also ensure that the directory containing the shared version of libstdc++ is in your LD_LIBRARY_PATH, or equivalent. If your GCC source tree is at `/path/to/gcc`, then you can run the tests as follows:

```
runtest --tool libstdc++ --srcdir=/path/to/gcc/libstdc++-v3/testsuite
```

The testsuite will create a number of files in the directory in which you run this command. Some of those files might use the same name as files created by other testsuites (like the ones for GCC and G++), so you should not try to run all the testsuites in parallel from the same directory.

In addition, there are some testing options that are mostly of interest to library maintainers and system integrators. As such, these tests may not work on all CPU and host combinations, and may need to be executed in the *libbuilddir*/testsuite directory. These options include, but are not necessarily limited to, the following:

make testsuite_files Five files are generated that determine what test files are run. These files are:

- **testsuite_files** This is a list of all the test cases that will be run. Each test case is on a separate line, given with an absolute path from the *libsrcdir*/testsuite directory.
- **testsuite_files_interactive** This is a list of all the interactive test cases, using the same format as the file list above. These tests are not run by default.
- **testsuite_files_performance** This is a list of all the performance test cases, using the same format as the file list above. These tests are not run by default.
- **testsuite_thread** This file indicates that the host system can run tests which involved multiple threads.

testsuite_wchar_t This file indicates that the host system can run the `wchar_t` tests, and corresponds to the macro definition `_GLIBCXX_USE_WCHAR_T` in the file `c++config.h`.

make check-abi The library ABI can be tested. This involves testing the shared library against a baseline list of symbol exports that defines the previous version of the ABI. The tests require that no exported symbols are removed, no new symbols are added to the old symbol versions, and any new symbols have the latest symbol version. See Versioning for more details of the ABI version history.

make new-abi-baseline Generate a new baseline set of symbols exported from the library (written to a file under *libsrcdir*/config/abi/post/*target*/). A different baseline symbols file is needed for each architecture and is used by the `check-abi` target described above. The files are usually re-generated by target maintainers for releases.

make check-compile This rule compiles, but does not link or execute, the `testsuite_files` test cases and displays the output on stdout.

make check-performance This rule runs through the `testsuite_files_performance` test cases and collects information for performance analysis and can be used to spot performance regressions. Various timing information is collected, as well as number of hard page faults, and memory used. This is not run by default, and the implementation is in flux.

make check-debug This rule runs through the test suite under the debug mode.

make check-parallel This rule runs through the test suite under the parallel mode.

We are interested in any strange failures of the testsuite; please email the main libstdc++ mailing list if you see something odd or have questions.

B.4.2.3 Permutations

The tests will be compiled with a set of default compiler flags defined by the *libbuilddir*/scripts/testsuite_flags file, as well as options specified in individual tests. You can run the tests with different options by adding them to the output of the `--cxxflags` option of that script, or by setting the `CXXFLAGS` variable when running **make**, or via options for the DejaGnu test framework (described below). The latter approach uses the `--target_board` option that was shown earlier, but requires DejaGnu version 1.5.3 or newer to work reliably, so that the `dg-options` in the test aren't overridden. For example, to run the tests with `-O1 -D_GLIBCXX_ASSERTIONS` you could use:

```
make check RUNTESTFLAGS=--target_board=unix/-O1/-D_GLIBCXX_ASSERTIONS
```

Since GCC 14, the libstdc++ testsuite has built-in support for running tests with more than one `-std`, similar to the G++ tests. Adding `set v3_std_list { 11 17 23 }` to `~/.dejagnurc` or to a file named by the `DEJAGNU` environment variable will cause every test to be run three times, using a different `-std` each time. Alternatively, a list of standard versions to test with can be specified as a comma-separated list in the `GLIBCXX_TESTSUITE_STDS` environment variable, e.g. `GLIBCXX_TESTSUITE_STDS=11,17,23` is equivalent to the `v3_std_list` value above. Before GCC 14, the `--target_board` option could be used to run the tests with different `-std` options, but this no longer works.

To run the libstdc++ test suite under the debug mode, use **make check-debug**. Alternatively, edit *libbuilddir*/scripts/testsuite_flags to add the compile-time flag `-D_GLIBCXX_DEBUG` to the result printed by the `--cxxflags` option. Additionally, add the `-D_GLIBCXX_DEBUG_PEDANTIC` flag to turn on pedantic checking. The libstdc++ test suite should produce the same results under debug mode that it does under release mode: any deviation indicates an error in either the library or the test suite. Note, however, that the number of tests that PASS may change, because some test cases are skipped in normal mode, and some are skipped in debug mode, as determined by the `dg-require-`*support* directives described below.

The parallel mode can be tested using **make check-parallel**, or in much the same manner as the debug mode, substituting `-D_GLIBCXX_PARALLEL` for `-D_GLIBCXX_DEBUG` in the previous paragraph.

Or, just run the testsuite `-D_GLIBCXX_DEBUG` or `-D_GLIBCXX_PARALLEL` in `CXXFLAGS` or `RUNTESTFLAGS`.

B.4.3 Writing a new test case

The first step in making a new test case is to choose the correct directory and file name, given the organization as previously described.

Historically all test files were copyright the FSF, and GPL licensed. We no longer require that, because most tests are uninteresting and contain no "original authorship", and so would not be protected by copyright anyway. Adding the FSF copyright notice to new tests is incorrect unless you (or your employer) have a copyright assignment on file with the FSF, or if the test contains code copied from another test under FSF copyright. In particular, new tests that contain original code are not copyright FSF if contributed under the DCO terms. If new tests do add the FSF copyright notice and GPL licence text, then the first copyright year should correspond to the date the file was checked in to version control. If the test code is copied from an existing file it should retain the copyright years from the original file.

The DejaGnu instructions say to always return `0` from `main` to indicate success. Strictly speaking this is redundant in C++, since returning from `main` is defined to return `0`. Most tests still have an explicit return.

A bunch of utility functions and classes have already been abstracted out into the testsuite utility library, `libtestc++`. To use this functionality, just include the appropriate header file: the library or specific object files will automatically be linked in as part of the testsuite run.

Tests that need to perform runtime checks should use the `VERIFY` macro, defined in the <testsuite_hooks.h> header. This expands to a custom assertion using `__builtin_printf` and `__builtin_abort` (to avoid using `assert` and being affected by `NDEBUG`).

The testsuite uses the DejaGnu framework to compile and run the tests. Test cases are normal C++ files which contain special directives in comments. These directives look like `{ dg-* ... }` and tell DejaGnu what to do and what kinds of behavior are to be expected for a test. The core DejaGnu directives are documented in the `dg.exp` file installed by DejaGnu. The GCC testsuites support additional directives as described in the GCC internals documentation, see Syntax and Descriptions of test directives. GCC also defines many Keywords describing target attributes (a.k.a effective targets) which can be used where a target *selector* can appear.

Some directives commonly used in the libstdc++ testsuite are:

{ dg-do *do-what-keyword* [{ target/xfail *selector* }] } Where *do-what-keyword* is usually one of `run` (which is the default), `compile`, or `link`, and typical selectors are targets such as `*-*-gnu*` or an effective target such as `c++11`.

{ dg-require-*support* args } Skip the test if the target does not provide the required support. See below for values of *support*.

{ dg-options *options* [{ target *selector* }] }

{ dg-error *regexp* [*comment* [{ target/xfail *selector* } [*line*]]] }

{ dg-excess-errors *comment* [{ target/xfail *selector* }] }

For full details of these and other directives see the main GCC DejaGnu documentation in the internals manual.

Test cases that use features of a particular C++ standard should specify the minimum required standard as an effective target:

```
// { dg-do run { target c++11 } }
```

or

```
// { dg-require-effective-target c++11 }
```

Specifying the minimum required standard for a test allows it to be run using later standards, so that we can verify that C++11 components still work correctly when compiled as C++14 or later. Specifying a minimum also means the test will be skipped if the test is compiled using an older standard, e.g. using `RUNTESTFLAGS=--target_board=unix/-std=gnu++98`.

It is possible to indicate that a test should *only* be run for a specific standard (and not later standards) using an effective target like `c++11_only`. However, this means the test will be skipped by default unless `-std=gnu++11` or `-std=c++11` is explicitly specified, either via a target board, the `v3_std_list` dejagnu variable, or the `GLIBCXX_TESTSUITE_STDS` environment variable. For tests that require a specific standard it is useful to also add a `dg-options` directive:

```
// { dg-options "-std=gnu++11" }
```

This means the test will not get skipped by default, and will always use the specific standard dialect that the test requires. This isn't needed often, and most tests should use an effective target to specify a minimum standard instead, to allow them to be tested for all possible variations.

N.B. when a `dg-options` directive is used, it must come first so dejagnu will include those options when checking against any effective targets in `dg-do` and `dg-require-effective-target` directives.

Since GCC 14, tests which depend on a newer standard than the default do not need to specify that standard in a `dg-options` directive. The testsuite will detect when a test requires a newer standard and will automatically add a suitable `-std` flag.

If a testcase requires the use of a strict language dialect, e.g. `-std=c++11` rather than `-std=gnu++11`, the following directive will cause that to be used when the testsuite decides which `-std` options to use for the test:

```
// { dg-add-options strict_std }
```

B.4.3.1 Examples of Test Directives

Example 1: Testing compilation only:

```
// { dg-do compile }
```

Example 2: Testing for expected warnings on line 36, which all targets fail:

```
// { dg-warning "string literals" "" { xfail *-*-* } 36 }
```

Example 3: Testing for expected warnings on line 36:

```
// { dg-warning "string literals" "" { target *-*-* } 36 }
```

Example 4: Testing for compilation errors on line 41:

```
// { dg-do compile }
// { dg-error "no match for" "" { target *-*-* } 41 }
```

Example 5: Testing with special command line settings, or without the use of pre-compiled headers, in particular the `stdc++.h.gch` file. Any options here will override the `DEFAULT_CXXFLAGS` and `PCH_CXXFLAGS` set up in the `normal.exp` file:

```
// { dg-options "-O0" { target *-*-* } }
```

Example 6: Compiling and linking a test only for C++14 and later, and only if Debug Mode is active:

```
// { dg-do link { target c++14 } }
// { dg-require-debug-mode "" }
```

Example 7: Running a test only on x86 targets, and only for C++11 and later, with specific options, and additional options for 32-bit x86:

```
// { dg-options "-fstrict-enums" }
// { dg-additional-options "-march=i486" { target ia32 } }
// { dg-do run { target { ia32 || x86_64-*-* } } }
// { dg-require-effective-target "c++11" }
```

More examples can be found in the `libstdc++-v3/testsuite/*/*.cc` files.

B.4.3.2 Directives Specific to Libstdc++ Tests

In addition to the usual Variants of `dg-require-`*`support`* several more directives are available for use in libstdc++ tests, including the following:

`dg-require-namedlocale` ***`name`*** The named locale must be available.

`dg-require-debug-mode` `""` Skip the test if the Debug Mode is not active (as determined by the `_GLIBCXX_DEBUG` macro).

`dg-require-parallel-mode` `""` Skip the test if the Parallel Mode is not active (as determined by the `_GLIBCXX_PARALLEL` macro).

`dg-require-normal-mode` `""` Skip the test if Debug or Parallel Mode is active.

`dg-require-atomic-builtins` `""` Skip the test if atomic operations on bool and int are not lock-free.

`dg-require-gthreads` `""` Skip the test if the C++11 thread library is not supported, as determined by the `_GLIBCXX_HAS_GTH` macro.

`dg-require-gthreads-timed` `""` Skip the test if C++11 timed mutexes are not supported, as determined by the `_GLIBCXX_HA` and `_GTHREAD_USE_MUTEX_TIMEDLOCK` macros.

`dg-require-string-conversions` `""` Skip the test if the C++11 `to_string` and `stoi`, `stod` etc. functions are not fully supported (including wide character versions).

`dg-require-filesystem-ts` `""` Skip the test if the Filesystem TS is not supported.

B.4.4 Test Harness and Utilities

B.4.4.1 DejaGnu Harness Details

Underlying details of testing for conformance and regressions are abstracted via the GNU DejaGnu package. This is similar to the rest of GCC.

This is information for those looking at making changes to the testsuite structure, and/or needing to trace DejaGnu's actions with `--verbose`. This will not be useful to people who are "merely" adding new tests to the existing structure.

The first key point when working with DejaGnu is the idea of a "tool". Files, directories, and functions are all implicitly used when they are named after the tool in use. Here, the tool will always be "libstdc++".

The `lib` subdir contains support routines. The `lib/libstdc++.exp` file ("support library") is loaded automagically, and must explicitly load the others. For example, files can be copied from the core compiler's support directory into `lib`.

Some routines in `lib/libstdc++.exp` are callbacks, some are our own. Callbacks must be prefixed with the name of the tool. To easily distinguish the others, by convention our own routines are named "v3-*".

The next key point when working with DejaGnu is "test files". Any directory whose name starts with the tool name will be searched for test files. (We have only one.) In those directories, any `.exp` file is considered a test file, and will be run in turn. Our main test file is called `normal.exp`; it runs all the tests in testsuite_files using the callbacks loaded from the support library.

The `config` directory is searched for any particular "target board" information unique to this library. This is currently unused and sets only default variables.

B.4.4.2 Utilities

The testsuite directory also contains some files that implement functionality that is intended to make writing test cases easier, or to avoid duplication, or to provide error checking in a way that is consistent across platforms and test harnesses. A stand-alone executable, called *abi_check*, and a static library called *libtestc++* are constructed. Both of these items are not installed, and only used during testing.

These files include the following functionality:

- *testsuite_abi.h*, *testsuite_abi.cc*, *testsuite_abi_check.cc*

  Creates the executable *abi_check*. Used to check correctness of symbol versioning, visibility of exported symbols, and compatibility on symbols in the shared library, for hosts that support this feature. More information can be found in the ABI documentation here

- *testsuite_allocator.h*, *testsuite_allocator.cc*

  Contains specialized allocators that keep track of construction and destruction. Also, support for overriding global new and delete operators, including verification that new and delete are called during execution, and that allocation over max_size fails.

- *testsuite_character.h*

  Contains `std::char_traits` and `std::codecvt` specializations for a user-defined POD.

- *testsuite_hooks.h*, *testsuite_hooks.cc*

  A large number of utilities, including:

  - VERIFY
  - set_memory_limits
  - verify_demangle
  - run_tests_wrapped_locale
  - run_tests_wrapped_env
  - try_named_locale
  - try_mkfifo
  - func_callback
  - counter
  - copy_tracker
  - copy_constructor
  - assignment_operator
  - destructor
  - pod_char, pod_int and associated char_traits specializations

- *testsuite_io.h*

  Error, exception, and constraint checking for `std::streambuf, std::basic_stringbuf, std::basic_filebuf`.

- *testsuite_iterators.h*

  Wrappers for various iterators.

- *testsuite_performance.h*

  A number of class abstractions for performance counters, and reporting functions including:

  - time_counter
  - resource_counter
  - report_performance

B.4.5 Special Topics

B.4.5.1 Qualifying Exception Safety Guarantees

B.4.5.1.1 Overview

Testing is composed of running a particular test sequence, and looking at what happens to the surrounding code when exceptions are thrown. Each test is composed of measuring initial state, executing a particular sequence of code under some instrumented conditions, measuring a final state, and then examining the differences between the two states.

Test sequences are composed of constructed code sequences that exercise a particular function or member function, and either confirm no exceptions were generated, or confirm the consistency/coherency of the test subject in the event of a thrown exception.

Random code paths can be constructed using the basic test sequences and instrumentation as above, only combined in a random or pseudo-random way.

To compute the code paths that throw, test instruments are used that throw on allocation events (`__gnu_cxx::throw_allocator_r` and `__gnu_cxx::throw_allocator_limit`) and copy, assignment, comparison, increment, swap, and various operators (`__gnu_cxx::throw_type_random` and `__gnu_cxx::throw_type_limit`). Looping through a given test sequence and conditionally throwing in all instrumented places. Then, when the test sequence completes without an exception being thrown, assume all potential error paths have been exercised in a sequential manner.

B.4.5.1.2 Existing tests

- Ad Hoc

  For example, `testsuite/23_containers/list/modifiers/3.cc`.

- Policy Based Data Structures

  For example, take the test functor `rand_reg_test` in in `testsuite/ext/pb_ds/regression/tree_no_data_map_rand.cc`. This uses `container_rand_regression_test` in `testsuite/util/regression/rand/assoc/container_rand_regression_test.h`.

  Which has several tests for container member functions, Includes control and test container objects. Configuration includes random seed, iterations, number of distinct values, and the probability that an exception will be thrown. Assumes instantiating container uses an extension allocator, `__gnu_cxx::throw_allocator_random`, as the allocator type.

- C++11 Container Requirements.

  Coverage is currently limited to testing container requirements for exception safety, although `__gnu_cxx::throw_type` meets the additional type requirements for testing numeric data structures and instantiating algorithms.

  Of particular interest is extending testing to algorithms and then to parallel algorithms. Also io and locales.

  The test instrumentation should also be extended to add instrumentation to `iterator` and `const_iterator` types that throw conditionally on iterator operations.

B.4.5.1.3 C++11 Requirements Test Sequence Descriptions

- Basic

  Basic consistency on exception propagation tests. For each container, an object of that container is constructed, a specific member function is exercised in a `try` block, and then any thrown exceptions lead to error checking in the appropriate `catch` block. The container's use of resources is compared to the container's use prior to the test block. Resource monitoring is limited to allocations made through the container's allocator_type, which should be sufficient for container data structures. Included in these tests are member functions are iterator and const_iterator operations, `pop_front`, `pop_back`, `push_front`, `push_back`, `insert`, `erase`, `swap`, `clear`, and `rehash`. The container in question is instantiated with two instrumented template arguments, with `__gnu_cxx::throw_allocator_limit` as the allocator type, and with `__gnu_cxx::throw_type_limit` as the value type. This allows the test to loop through conditional throw points.

  The general form is demonstrated in `testsuite/23_containers/list/requirements/exception/basic.cc` . The instantiating test object is `__gnu_test::basic_safety` and is detailed in `testsuite/util/exception/safety.h`.

- Generation Prohibited

  Exception generation tests. For each container, an object of that container is constructed and all member functions required to not throw exceptions are exercised. Included in these tests are member functions are iterator and const_iterator operations, `erase`, `pop_front`, `pop_back`, `swap`, and `clear`. The container in question is instantiated with two instrumented template arguments, with `__gnu_cxx::throw_allocator_random` as the allocator type, and with `__gnu_cxx::throw_type_` as the value type. This test does not loop, an instead is sudden death: first error fails.

  The general form is demonstrated in `testsuite/23_containers/list/requirements/exception/generation_prohibited.cc` . The instantiating test object is `__gnu_test::generation_prohibited` and is detailed in `testsuite util/exception/safety.h`.

- Propagation Consistent

  Container rollback on exception propagation tests. For each container, an object of that container is constructed, a specific member function that requires rollback to a previous known good state is exercised in a `try` block, and then any thrown exceptions lead to error checking in the appropriate `catch` block. The container is compared to the container's last known good state using such parameters as size, contents, and iterator references. Included in these tests are member functions are `push_front`, `push_back`, `insert`, and `rehash`. The container in question is instantiated with two instrumented template arguments, with `__gnu_cxx::throw_allocator_limit` as the allocator type, and with `__gnu_cxx::throw_type_limit` as the value type. This allows the test to loop through conditional throw points.

  The general form demonstrated in `testsuite/23_containers/list/requirements/exception/propagation_coherent.cc` . The instantiating test object is `__gnu_test::propagation_coherent` and is detailed in `testsuite/util/exception/safety.h`.

B.5 ABI Policy and Guidelines

B.5.1 The C++ Interface

C++ applications often depend on specific language support routines, say for throwing exceptions, or catching exceptions, and perhaps also depend on features in the C++ Standard Library.

The C++ Standard Library has many include files, types defined in those include files, specific named functions, and other behavior. The text of these behaviors, as written in source include files, is called the Application Programing Interface, or API.

Furthermore, C++ source that is compiled into object files is transformed by the compiler: it arranges objects with specific alignment and in a particular layout, mangling names according to a well-defined algorithm, has specific arrangements for the support of virtual functions, etc. These details are defined as the compiler Application Binary Interface, or ABI. From GCC version 3 onwards the GNU C++ compiler uses an industry-standard C++ ABI, the Itanium C++ ABI.

The GNU C++ compiler, g++, has a compiler command line option to switch between various different C++ ABIs. This explicit version switch is the flag `-fabi-version`. In addition, some g++ command line options may change the ABI as a side-effect of use. Such flags include `-fpack-struct` and `-fno-exceptions`, but include others: see the complete list in the GCC manual under the heading Options for Code Generation Conventions.

The configure options used when building a specific libstdc++ version may also impact the resulting library ABI. The available configure options, and their impact on the library ABI, are documented here.

Putting all of these ideas together results in the C++ Standard Library ABI, which is the compilation of a given library API by a given compiler ABI. In a nutshell:

“ library API + compiler ABI = library ABI ”

The library ABI is mostly of interest for end-users who have unresolved symbols and are linking dynamically to the C++ Standard library, and who thus must be careful to compile their application with a compiler that is compatible with the available C++ Standard library binary. In this case, compatible is defined with the equation above: given an application compiled with a given compiler ABI and library API, it will work correctly with a Standard C++ Library created with the same constraints.

To use a specific version of the C++ ABI, one must use a corresponding GNU C++ toolchain (i.e., g++ and libstdc++) that implements the C++ ABI in question.

B.5.2 Versioning

The C++ interface has evolved throughout the history of the GNU C++ toolchain. With each release, various details have been changed so as to give distinct versions to the C++ interface.

B.5.2.1 Goals

Extending existing, stable ABIs. Versioning gives subsequent releases of library binaries the ability to add new symbols and add functionality, all the while retaining compatibility with the previous releases in the series. Thus, program binaries linked with the initial release of a library binary will still run correctly if the library binary is replaced by carefully-managed subsequent library binaries. This is called forward compatibility.

The reverse (backwards compatibility) is not true. It is not possible to take program binaries linked with the latest version of a library binary in a release series (with additional symbols added), substitute in the initial release of the library binary, and remain link compatible.

Allows multiple, incompatible ABIs to coexist at the same time.

B.5.2.2 History

How can this complexity be managed? What does C++ versioning mean? Because library and compiler changes often make binaries compiled with one version of the GNU tools incompatible with binaries compiled with other (either newer or older) versions of the same GNU tools, specific techniques are used to make managing this complexity easier.

The following techniques are used:

1. Release versioning on the libgcc_s.so binary.

   This is implemented via file names and the ELF `DT_SONAME` mechanism (at least on ELF systems). It is versioned as follows:

   - GCC 3.x: libgcc_s.so.1
   - GCC 4.x: libgcc_s.so.1

   For m68k-linux the versions differ as follows:

   - GCC 3.4, GCC 4.x: libgcc_s.so.1 when configuring `--with-sjlj-exceptions`, or libgcc_s.so.2

   For hppa-linux the versions differ as follows:

   - GCC 3.4, GCC 4.[0-1]: either libgcc_s.so.1 when configuring `--with-sjlj-exceptions`, or libgcc_s.so.2
   - GCC 4.[2-7]: either libgcc_s.so.3 when configuring `--with-sjlj-exceptions`) or libgcc_s.so.4

2. Symbol versioning on the libgcc_s.so binary.

   It is versioned with the following labels and version definitions, where the version definition is the maximum for a particular release. Labels are cumulative. If a particular release is not listed, it has the same version labels as the preceding release.

   This corresponds to the mapfile: gcc/libgcc-std.ver

   - GCC 3.0.0: GCC_3.0
   - GCC 3.3.0: GCC_3.3
   - GCC 3.3.1: GCC_3.3.1
   - GCC 3.3.2: GCC_3.3.2
   - GCC 3.3.4: GCC_3.3.4
   - GCC 3.4.0: GCC_3.4
   - GCC 3.4.2: GCC_3.4.2
   - GCC 3.4.4: GCC_3.4.4
   - GCC 4.0.0: GCC_4.0.0
   - GCC 4.1.0: GCC_4.1.0
   - GCC 4.2.0: GCC_4.2.0
   - GCC 4.3.0: GCC_4.3.0
   - GCC 4.4.0: GCC_4.4.0
   - GCC 4.5.0: GCC_4.5.0
   - GCC 4.6.0: GCC_4.6.0

- GCC 4.7.0: GCC_4.7.0
- GCC 4.8.0: GCC_4.8.0
- GCC 7.1.0: GCC_7.0.0
- GCC 9.1.0: GCC_9.0.0
- GCC 11.1.0: GCC_11.0
- GCC 12.1.0: GCC_12.0.0
- GCC 13.1.0: GCC_13.0.0

3. Release versioning on the libstdc++.so binary, implemented in the same way as the libgcc_s.so binary above. Listed is the filename: `DT_SONAME` can be deduced from the filename by removing the last two period-delimited numbers. For example, filename `libstdc++.so.5.0.4` corresponds to a `DT_SONAME` of `libstdc++.so.5`. Binaries with equivalent `DT_SONAME`s are forward-compatibile: in the table below, releases incompatible with the previous one are explicitly noted. If a particular release is not listed, its libstdc++.so binary has the same filename and `DT_SONAME` as the preceding release.

   It is versioned as follows:

- GCC 3.0.0: libstdc++.so.3.0.0
- GCC 3.0.1: libstdc++.so.3.0.1
- GCC 3.0.2: libstdc++.so.3.0.2
- GCC 3.0.3: libstdc++.so.3.0.2 (See Note 1)
- GCC 3.0.4: libstdc++.so.3.0.4
- GCC 3.1.0: libstdc++.so.4.0.0 *(Incompatible with previous)*
- GCC 3.1.1: libstdc++.so.4.0.1
- GCC 3.2.0: libstdc++.so.5.0.0 *(Incompatible with previous)*
- GCC 3.2.1: libstdc++.so.5.0.1
- GCC 3.2.2: libstdc++.so.5.0.2
- GCC 3.2.3: libstdc++.so.5.0.3 (See Note 2)
- GCC 3.3.0: libstdc++.so.5.0.4
- GCC 3.3.1: libstdc++.so.5.0.5
- GCC 3.4.0: libstdc++.so.6.0.0 *(Incompatible with previous)*
- GCC 3.4.1: libstdc++.so.6.0.1
- GCC 3.4.2: libstdc++.so.6.0.2
- GCC 3.4.3: libstdc++.so.6.0.3
- GCC 4.0.0: libstdc++.so.6.0.4
- GCC 4.0.1: libstdc++.so.6.0.5
- GCC 4.0.2: libstdc++.so.6.0.6
- GCC 4.0.3: libstdc++.so.6.0.7
- GCC 4.1.0: libstdc++.so.6.0.7
- GCC 4.1.1: libstdc++.so.6.0.8
- GCC 4.2.0: libstdc++.so.6.0.9
- GCC 4.2.1: libstdc++.so.6.0.9 (See Note 3)
- GCC 4.2.2: libstdc++.so.6.0.9
- GCC 4.3.0: libstdc++.so.6.0.10
- GCC 4.4.0: libstdc++.so.6.0.11
- GCC 4.4.1: libstdc++.so.6.0.12
- GCC 4.4.2: libstdc++.so.6.0.13

- GCC 4.5.0: libstdc++.so.6.0.14
- GCC 4.6.0: libstdc++.so.6.0.15
- GCC 4.6.1: libstdc++.so.6.0.16
- GCC 4.7.0: libstdc++.so.6.0.17
- GCC 4.8.0: libstdc++.so.6.0.18
- GCC 4.8.3: libstdc++.so.6.0.19
- GCC 4.9.0: libstdc++.so.6.0.20
- GCC 5.1.0: libstdc++.so.6.0.21
- GCC 6.1.0: libstdc++.so.6.0.22
- GCC 7.1.0: libstdc++.so.6.0.23
- GCC 7.2.0: libstdc++.so.6.0.24
- GCC 8.1.0: libstdc++.so.6.0.25
- GCC 9.1.0: libstdc++.so.6.0.26
- GCC 9.2.0: libstdc++.so.6.0.27
- GCC 9.3.0: libstdc++.so.6.0.28
- GCC 10.1.0: libstdc++.so.6.0.28
- GCC 11.1.0: libstdc++.so.6.0.29
- GCC 12.1.0: libstdc++.so.6.0.30
- GCC 13.1.0: libstdc++.so.6.0.31
- GCC 13.2.0: libstdc++.so.6.0.32
- GCC 14.1.0: libstdc++.so.6.0.33

Note 1: Error should be libstdc++.so.3.0.3.

Note 2: Not strictly required.

Note 3: This release (but not previous or subsequent) has one known incompatibility, see 33678 in the GCC bug database.

4. Symbol versioning on the libstdc++.so binary.

   mapfile: libstdc++-v3/config/abi/pre/gnu.ver

   It is versioned with the following labels and version definitions, where the version definition is the maximum for a particular release. Note, only symbols which are newly introduced will use the maximum version definition. Thus, for release series with the same label, but incremented version definitions, the later release has both versions. (An example of this would be the GCC 3.2.1 release, which has GLIBCPP_3.2.1 for new symbols and GLIBCPP_3.2 for symbols that were introduced in the GCC 3.2.0 release.) If a particular release is not listed, it has the same version labels as the preceding release.

- GCC 3.0.0: (Error, not versioned)
- GCC 3.0.1: (Error, not versioned)
- GCC 3.0.2: (Error, not versioned)
- GCC 3.0.3: (Error, not versioned)
- GCC 3.0.4: (Error, not versioned)
- GCC 3.1.0: GLIBCPP_3.1, CXXABI_1
- GCC 3.1.1: GLIBCPP_3.1, CXXABI_1
- GCC 3.2.0: GLIBCPP_3.2, CXXABI_1.2
- GCC 3.2.1: GLIBCPP_3.2.1, CXXABI_1.2
- GCC 3.2.2: GLIBCPP_3.2.2, CXXABI_1.2
- GCC 3.2.3: GLIBCPP_3.2.2, CXXABI_1.2
- GCC 3.3.0: GLIBCPP_3.2.2, CXXABI_1.2.1

- GCC 3.3.1: GLIBCPP_3.2.3, CXXABI_1.2.1
- GCC 3.3.2: GLIBCPP_3.2.3, CXXABI_1.2.1
- GCC 3.3.3: GLIBCPP_3.2.3, CXXABI_1.2.1
- GCC 3.4.0: GLIBCXX_3.4, CXXABI_1.3
- GCC 3.4.1: GLIBCXX_3.4.1, CXXABI_1.3
- GCC 3.4.2: GLIBCXX_3.4.2
- GCC 3.4.3: GLIBCXX_3.4.3
- GCC 4.0.0: GLIBCXX_3.4.4, CXXABI_1.3.1
- GCC 4.0.1: GLIBCXX_3.4.5
- GCC 4.0.2: GLIBCXX_3.4.6
- GCC 4.0.3: GLIBCXX_3.4.7
- GCC 4.1.1: GLIBCXX_3.4.8
- GCC 4.2.0: GLIBCXX_3.4.9
- GCC 4.3.0: GLIBCXX_3.4.10, CXXABI_1.3.2
- GCC 4.4.0: GLIBCXX_3.4.11, CXXABI_1.3.3
- GCC 4.4.1: GLIBCXX_3.4.12, CXXABI_1.3.3
- GCC 4.4.2: GLIBCXX_3.4.13, CXXABI_1.3.3
- GCC 4.5.0: GLIBCXX_3.4.14, CXXABI_1.3.4
- GCC 4.6.0: GLIBCXX_3.4.15, CXXABI_1.3.5
- GCC 4.6.1: GLIBCXX_3.4.16, CXXABI_1.3.5
- GCC 4.7.0: GLIBCXX_3.4.17, CXXABI_1.3.6
- GCC 4.8.0: GLIBCXX_3.4.18, CXXABI_1.3.7
- GCC 4.8.3: GLIBCXX_3.4.19, CXXABI_1.3.7
- GCC 4.9.0: GLIBCXX_3.4.20, CXXABI_1.3.8
- GCC 5.1.0: GLIBCXX_3.4.21, CXXABI_1.3.9
- GCC 6.1.0: GLIBCXX_3.4.22, CXXABI_1.3.10
- GCC 7.1.0: GLIBCXX_3.4.23, CXXABI_1.3.11
- GCC 7.2.0: GLIBCXX_3.4.24, CXXABI_1.3.11
- GCC 8.1.0: GLIBCXX_3.4.25, CXXABI_1.3.11
- GCC 9.1.0: GLIBCXX_3.4.26, CXXABI_1.3.12
- GCC 9.2.0: GLIBCXX_3.4.27, CXXABI_1.3.12
- GCC 9.3.0: GLIBCXX_3.4.28, CXXABI_1.3.12
- GCC 10.1.0: GLIBCXX_3.4.28, CXXABI_1.3.12
- GCC 11.1.0: GLIBCXX_3.4.29, CXXABI_1.3.13
- GCC 12.1.0: GLIBCXX_3.4.30, CXXABI_1.3.13
- GCC 13.1.0: GLIBCXX_3.4.31, CXXABI_1.3.14
- GCC 13.2.0: GLIBCXX_3.4.32, CXXABI_1.3.14
- GCC 14.1.0: GLIBCXX_3.4.33, CXXABI_1.3.15

5. Incremental bumping of a compiler pre-defined macro, __GXX_ABI_VERSION. This macro is defined as the version of the compiler v3 ABI, with g++ 3.0 being version 100. This macro will be automatically defined whenever g++ is used (the curious can test this by invoking g++ with the '-v' flag.)

   This macro was defined in the file "lang-specs.h" in the gcc/cp directory. Later versions defined it in "c-common.c" in the gcc directory, and from G++ 3.4 it is defined in c-cppbuiltin.c and its value determined by the '-fabi-version' command line option.

   It is versioned as follows, where 'n' is given by '-fabi-version=n':

- GCC 3.0: 100
- GCC 3.1: 100 (Error, should be 101)
- GCC 3.2: 102
- GCC 3.3: 102
- GCC 3.4, GCC 4.x: 102 (when n=1)
- GCC 3.4, GCC 4.x: 1000 + n (when n>1)
- GCC 3.4, GCC 4.x: 999999 (when n=0)

6. Changes to the default compiler option for `-fabi-version`.

   It is versioned as follows:

   - GCC 3.0: (Error, not versioned)
   - GCC 3.1: (Error, not versioned)
   - GCC 3.2: `-fabi-version=1`
   - GCC 3.3: `-fabi-version=1`
   - GCC 3.4, GCC 4.x: `-fabi-version=2` *(Incompatible with previous)*
   - GCC 5 and higher: `-fabi-version=0` *(See GCC manual for meaning)*

7. Incremental bumping of a library pre-defined macro. For releases before 3.4.0, the macro is __GLIBCPP__. For later releases, it's __GLIBCXX__. (The libstdc++ project generously changed from CPP to CXX throughout its source to allow the "C" pre-processor the CPP macro namespace.) These macros are defined as the date the library was released, in compressed ISO date format, as an integer constant.

   This macro is defined in the file `c++config` in the `libstdc++-v3/include/bits` directory. Up to GCC 4.1.0, it was changed every night by an automated script. Since GCC 4.1.0 it is set during configuration to the same value as `gcc/DATESTAMP`, so for an official release its value is the same as the date of the release, which is given in the GCC Release Timeline.

   This macro can be used in code to detect whether the C++ Standard Library implementation in use is libstdc++, but is not useful for detecting the libstdc++ version, nor whether particular features are supported. The macro value might be a date after a feature was added to the development trunk, but the release could be from an older branch without the feature. For example, in the 5.4.0 release the macro has the value `20160603` which is greater than the `20160427` value of the macro in the 6.1.0 release, but there are features supported in the 6.1.0 release that are not supported in the 5.4.0 release. You also can't test for the exact values listed below to try and identify a release, because a snapshot taken from the gcc-5-branch on 2016-04-27 would have the same value for the macro as the 6.1.0 release despite being a different version. Many GNU/Linux distributions build their GCC packages from snapshots, so the macro can have dates that don't correspond to official releases.

   It is versioned as follows:

   - GCC 3.0.0: `20010615`
   - GCC 3.0.1: `20010819`
   - GCC 3.0.2: `20011023`
   - GCC 3.0.3: `20011220`
   - GCC 3.0.4: `20020220`
   - GCC 3.1.0: `20020514`
   - GCC 3.1.1: `20020725`
   - GCC 3.2.0: `20020814`
   - GCC 3.2.1: `20021119`
   - GCC 3.2.2: `20030205`
   - GCC 3.2.3: `20030422`
   - GCC 3.3.0: `20030513`

- GCC 3.3.1: `20030804`
- GCC 3.3.2: `20031016`
- GCC 3.3.3: `20040214`
- GCC 3.4.0: `20040419`
- GCC 3.4.1: `20040701`
- GCC 3.4.2: `20040906`
- GCC 3.4.3: `20041105`
- GCC 3.4.4: `20050519`
- GCC 3.4.5: `20051201`
- GCC 3.4.6: `20060306`
- GCC 4.0.0: `20050421`
- GCC 4.0.1: `20050707`
- GCC 4.0.2: `20050921`
- GCC 4.0.3: `20060309`
- GCC 4.1.0 and later: the GCC release date, as shown in the GCC Release Timeline

8. Since GCC 7, incremental bumping of a library pre-defined macro, _GLIBCXX_RELEASE. This macro is defined to the GCC major version that the libstdc++ headers belong to, as an integer constant. When compiling with GCC it has the same value as GCC's pre-defined macro __GNUC__. This macro can be used when libstdc++ is used with a non-GNU compiler where __GNUC__ is not defined, or has a different value that doesn't correspond to the libstdc++ version.

   This macro is defined in the file `c++config` in the `libstdc++-v3/include/bits` directory and is generated automatically by autoconf as part of the configure-time generation of `config.h` and subsequently `<bits/c++config.h>`.

9. Historically, incremental bumping of a library pre-defined macro, _GLIBCPP_VERSION. This macro was defined as the released version of the library, as a string literal. This was only implemented in GCC 3.1.0 releases and higher, and was deprecated in 3.4.x (where it was called _GLIBCXX_VERSION), and is not defined in 4.0.0 and higher.

   This macro is defined in the same file as _GLIBCXX_RELEASE, described above.

   It is versioned as follows:

- GCC 3.0.0: `"3.0.0"`
- GCC 3.0.1: `"3.0.0"` (Error, should be `"3.0.1"`)
- GCC 3.0.2: `"3.0.0"` (Error, should be `"3.0.2"`)
- GCC 3.0.3: `"3.0.0"` (Error, should be `"3.0.3"`)
- GCC 3.0.4: `"3.0.0"` (Error, should be `"3.0.4"`)
- GCC 3.1.0: `"3.1.0"`
- GCC 3.1.1: `"3.1.1"`
- GCC 3.2.0: `"3.2"`
- GCC 3.2.1: `"3.2.1"`
- GCC 3.2.2: `"3.2.2"`
- GCC 3.2.3: `"3.2.3"`
- GCC 3.3.0: `"3.3"`
- GCC 3.3.1: `"3.3.1"`
- GCC 3.3.2: `"3.3.2"`
- GCC 3.3.3: `"3.3.3"`
- GCC 3.4: `"version-unused"`
- GCC 4 and later: not defined

10. Matching each specific C++ compiler release to a specific set of C++ include files. This is only implemented in GCC 3.1.1 releases and higher.

    All C++ includes are installed in `include/c++`, then nested in a directory hierarchy corresponding to the C++ compiler's released version. This version corresponds to the variable "gcc_version" in "libstdc++-v3/acinclude.m4," and more details can be found in that file's macro GLIBCXX_CONFIGURE (GLIBCPP_CONFIGURE before GCC 3.4.0).

    C++ includes are versioned as follows:

    - GCC 3.0.0: include/g++-v3
    - GCC 3.0.1: include/g++-v3
    - GCC 3.0.2: include/g++-v3
    - GCC 3.0.3: include/g++-v3
    - GCC 3.0.4: include/g++-v3
    - GCC 3.1.0: include/g++-v3
    - GCC 3.1.1: include/c++/3.1.1
    - GCC 3.2.0: include/c++/3.2
    - GCC 3.2.1: include/c++/3.2.1
    - GCC 3.2.2: include/c++/3.2.2
    - GCC 3.2.3: include/c++/3.2.3
    - GCC 3.3.0: include/c++/3.3
    - GCC 3.3.1: include/c++/3.3.1
    - GCC 3.3.2: include/c++/3.3.2
    - GCC 3.3.3: include/c++/3.3.3
    - GCC 3.4.x: include/c++/3.4.x
    - GCC 4.x.y: include/c++/4.x.y
    - GCC 5.1.0: include/c++/5.1.0
    - GCC x.y.0: include/c++/x.y.0 (for releases after GCC 5.1.0)

Taken together, these techniques can accurately specify interface and implementation changes in the GNU C++ tools themselves. Used properly, they allow both the GNU C++ tools implementation, and programs using them, an evolving yet controlled development that maintains backward compatibility.

B.5.2.3 Prerequisites

Minimum environment that supports a versioned ABI: A supported dynamic linker, a GNU linker of sufficient vintage to understand demangled C++ name globbing (ld) or the Sun linker, a shared executable compiled with g++, and shared libraries (libgcc_s, libstdc++) compiled by a compiler (g++) with a compatible ABI. Phew.

On top of all that, an additional constraint: libstdc++ did not attempt to version symbols (or age gracefully, really) until version 3.1.0.

Most modern GNU/Linux and BSD versions, particularly ones using GCC 3.1 and later, will meet the requirements above, as does Solaris 2.5 and up.

B.5.2.4 Configuring

It turns out that most of the configure options that change default behavior will impact the mangled names of exported symbols, and thus impact versioning and compatibility.

For more information on configure options, including ABI impacts, see: here

There is one flag that explicitly deals with symbol versioning: --enable-symvers.

In particular, libstdc++-v3/acinclude.m4 has a macro called GLIBCXX_ENABLE_SYMVERS that defaults to yes (or the argument passed in via --enable-symvers=foo). At that point, the macro attempts to make sure that all the requirement for symbol versioning are in place. For more information, please consult acinclude.m4.

B.5.2.5 Checking Active

When the GNU C++ library is being built with symbol versioning on, you should see the following at configure time for libstdc++ (showing either 'gnu' or another of the supported styles):

```
checking versioning on shared library symbols... gnu
```

If you don't see this line in the configure output, or if this line appears but the last word is 'no', then you are out of luck.

If the compiler is pre-installed, a quick way to test is to compile the following (or any) simple C++ file and link it to the shared libstdc++ library:

```
#include <iostream>

int main()
{ std::cout << "hello" << std::endl; return 0; }

%g++ hello.cc -o hello.out

%ldd hello.out
  libstdc++.so.5 => /usr/lib/libstdc++.so.5 (0x00764000)
  libm.so.6 => /lib/tls/libm.so.6 (0x004a8000)
  libgcc_s.so.1 => /mnt/hd/bld/gcc/gcc/libgcc_s.so.1 (0x40016000)
  libc.so.6 => /lib/tls/libc.so.6 (0x0036d000)
  /lib/ld-linux.so.2 => /lib/ld-linux.so.2 (0x00355000)

%nm hello.out
```

If you see symbols in the resulting output with "GLIBCXX_3" as part of the name, then the executable is versioned. Here's an example:

`U _ZNSt8ios_base4InitC1Ev@@GLIBCXX_3.4`

On Solaris 2, you can use `pvs -r` instead:

```
%g++ hello.cc -o hello.out

%pvs -r hello.out
        libstdc++.so.6 (GLIBCXX_3.4, GLIBCXX_3.4.12);
        libgcc_s.so.1 (GCC_3.0);
        libc.so.1 (SUNWprivate_1.1, SYSVABI_1.3);
```

`ldd -v` works too, but is very verbose.

B.5.3 Allowed Changes

The following will cause the library minor version number to increase, say from "libstdc++.so.3.0.4" to "libstdc++.so.3.0.5".

1. Adding an exported global or static data member
2. Adding an exported function, static or non-virtual member function
3. Adding an exported symbol or symbols by additional instantiations

Other allowed changes are possible.

B.5.4 Prohibited Changes

The following non-exhaustive list will cause the library major version number to increase, say from "libstdc++.so.3.0.4" to "libstdc++.so.4.0.0".

1. Changes in the gcc/g++ compiler ABI
2. Changing size of an exported symbol
3. Changing alignment of an exported symbol
4. Changing the layout of an exported symbol
5. Changing mangling on an exported symbol
6. Deleting an exported symbol
7. Changing the inheritance properties of a type by adding or removing base classes
8. Changing the size, alignment, or layout of types specified in the C++ standard. These may not necessarily be instantiated or otherwise exported in the library binary, and include all the required locale facets, as well as things like std::basic_streambuf, et al.
9. Adding an explicit copy constructor or destructor to a class that would otherwise have implicit versions. This will change the way the compiler deals with this class in by-value return statements or parameters: instead of passing instances of this class in registers, the compiler will be forced to use memory. See the section on Function Calling Conventions and APIs of the C++ ABI documentation for further details.

B.5.5 Implementation

1. Separation of interface and implementation

   This is accomplished by two techniques that separate the API from the ABI: forcing undefined references to link against a library binary for definitions.

   Include files have declarations, source files have defines For non-templatized types, such as much of `class locale`, the appropriate standard C++ include, say `locale`, can contain full declarations, while various source files (say `locale.cc, locale_init.cc, localename.cc`) contain definitions.

   Extern template on required types For parts of the standard that have an explicit list of required instantiations, the GNU extension syntax `extern template` can be used to control where template definitions reside. By marking required instantiations as `extern template` in include files, and providing explicit instantiations in the appropriate instantiation files, non-inlined template functions can be versioned. This technique is mostly used on parts of the standard that require `char` and `wchar_t` instantiations, and includes `basic_string`, the locale facets, and the types in `iostreams`.

   In addition, these techniques have the additional benefit that they reduce binary size, which can increase runtime performance.

2. Namespaces linking symbol definitions to export mapfiles

   All symbols in the shared library binary are processed by a linker script at build time that either allows or disallows external linkage. Because of this, some symbols, regardless of normal C/C++ linkage, are not visible. Symbols that are internal have several appealing characteristics: by not exporting the symbols, there are no relocations when the shared library is started and thus this makes for faster runtime loading performance by the underlying dynamic loading mechanism. In addition, they have the possibility of changing without impacting ABI compatibility.

   The following namespaces are transformed by the mapfile:

   `namespace std` Defaults to exporting all symbols in label `GLIBCXX` that do not begin with an underscore, i.e., `__test_func` would not be exported by default. Select exceptional symbols are allowed to be visible.

namespace __gnu_cxx Defaults to not exporting any symbols in label `GLIBCXX`, select items are allowed to be visible.

namespace __gnu_internal Defaults to not exported, no items are allowed to be visible.

namespace __cxxabiv1, aliased to namespace abi Defaults to not exporting any symbols in label `CXXABI`, select items are allowed to be visible.

3. Freezing the API

   Disallowed changes, as above, are not made on a stable release branch. Enforcement tends to be less strict with GNU extensions that standard includes.

B.5.6 Testing

B.5.6.1 Single ABI Testing

Testing for GNU C++ ABI changes is composed of two distinct areas: testing the C++ compiler (g++) for compiler changes, and testing the C++ library (libstdc++) for library changes.

Testing the C++ compiler ABI can be done various ways.

One. Intel ABI checker.

Two. The second is yet unreleased, but has been announced on the gcc mailing list. It is yet unspecified if these tools will be freely available, and able to be included in a GNU project. Please contact Mark Mitchell (mark@codesourcery.com) for more details, and current status.

Three. Involves using the vlad.consistency test framework. This has also been discussed on the gcc mailing lists.

Testing the C++ library ABI can also be done various ways.

One. (Brendan Kehoe, Jeff Law suggestion to run 'make check-c++' two ways, one with a new compiler and an old library, and the other with an old compiler and a new library, and look for testsuite regressions)

Details on how to set this kind of test up can be found here: http://gcc.gnu.org/ml/gcc/2002-08/msg00142.html

Two. Use the 'make check-abi' rule in the libstdc++ Makefile.

This is a proactive check of the library ABI. Currently, exported symbol names that are either weak or defined are checked against a last known good baseline. Currently, this baseline is keyed off of 3.4.0 binaries, as this was the last time the .so number was incremented. In addition, all exported names are demangled, and the exported objects are checked to make sure they are the same size as the same object in the baseline. Notice that each baseline is relative to a *default* configured library and compiler: in particular, if options such as --enable-clocale, or --with-cpu, in case of multilibs, are used at configure time, the check may fail, either because of substantive differences or because of limitations of the current checking machinery.

This dataset is insufficient, yet a start. Also needed is a comprehensive check for all user-visible types part of the standard library for sizeof() and alignof() changes.

Verifying compatible layouts of objects is not even attempted. It should be possible to use sizeof, alignof, and offsetof to compute offsets for each structure and type in the standard library, saving to another datafile. Then, compute this in a similar way for new binaries, and look for differences.

Another approach might be to use the -fdump-class-hierarchy flag to get information. However, currently this approach gives insufficient data for use in library testing, as class data members, their offsets, and other detailed data is not displayed with this flag. (See PR g++/7470 on how this was used to find bugs.)

Perhaps there are other C++ ABI checkers. If so, please notify us. We'd like to know about them!

B.5.6.2 Multiple ABI Testing

A "C" application, dynamically linked to two shared libraries, liba, libb. The dependent library liba is a C++ shared library compiled with GCC 3.3, and uses io, exceptions, locale, etc. The dependent library libb is a C++ shared library compiled with GCC 3.4, and also uses io, exceptions, locale, etc.

As above, libone is constructed as follows:

```
%$bld/H-x86-gcc-3.4.0/bin/g++ -fPIC -DPIC -c a.cc

%$bld/H-x86-gcc-3.4.0/bin/g++ -shared -Wl,-soname -Wl,libone.so.1 -Wl,-O1 -Wl,-z,defs a.o - ↩
    o libone.so.1.0.0

%ln -s libone.so.1.0.0 libone.so

%$bld/H-x86-gcc-3.4.0/bin/g++ -c a.cc

%ar cru libone.a a.o
```

And, libtwo is constructed as follows:

```
%$bld/H-x86-gcc-3.3.3/bin/g++ -fPIC -DPIC -c b.cc

%$bld/H-x86-gcc-3.3.3/bin/g++ -shared -Wl,-soname -Wl,libtwo.so.1 -Wl,-O1 -Wl,-z,defs b.o - ↩
    o libtwo.so.1.0.0

%ln -s libtwo.so.1.0.0 libtwo.so

%$bld/H-x86-gcc-3.3.3/bin/g++ -c b.cc

%ar cru libtwo.a b.o
```

...with the resulting libraries looking like

```

%ldd libone.so.1.0.0
  libstdc++.so.6 => /usr/lib/libstdc++.so.6 (0x40016000)
  libm.so.6 => /lib/tls/libm.so.6 (0x400fa000)
  libgcc_s.so.1 => /mnt/hd/bld/gcc/gcc/libgcc_s.so.1 (0x4011c000)
  libc.so.6 => /lib/tls/libc.so.6 (0x40125000)
  /lib/ld-linux.so.2 => /lib/ld-linux.so.2 (0x00355000)

%ldd libtwo.so.1.0.0
  libstdc++.so.5 => /usr/lib/libstdc++.so.5 (0x40027000)
  libm.so.6 => /lib/tls/libm.so.6 (0x400e1000)
  libgcc_s.so.1 => /mnt/hd/bld/gcc/gcc/libgcc_s.so.1 (0x40103000)
  libc.so.6 => /lib/tls/libc.so.6 (0x4010c000)
  /lib/ld-linux.so.2 => /lib/ld-linux.so.2 (0x00355000)
```

Then, the "C" compiler is used to compile a source file that uses functions from each library.

```
gcc test.c -g -O2 -L. -lone -ltwo /usr/lib/libstdc++.so.5 /usr/lib/libstdc++.so.6
```

Which gives the expected:

```

%ldd a.out
  libstdc++.so.5 => /usr/lib/libstdc++.so.5 (0x00764000)
  libstdc++.so.6 => /usr/lib/libstdc++.so.6 (0x40015000)
  libc.so.6 => /lib/tls/libc.so.6 (0x0036d000)
  libm.so.6 => /lib/tls/libm.so.6 (0x004a8000)
  libgcc_s.so.1 => /mnt/hd/bld/gcc/gcc/libgcc_s.so.1 (0x400e5000)
  /lib/ld-linux.so.2 => /lib/ld-linux.so.2 (0x00355000)
```

This resulting binary, when executed, will be able to safely use code from both liba, and the dependent libstdc++.so.6, and libb, with the dependent libstdc++.so.5.

B.5.7 Outstanding Issues

Some features in the C++ language make versioning especially difficult. In particular, compiler generated constructs such as implicit instantiations for templates, typeinfo information, and virtual tables all may cause ABI leakage across shared library boundaries. Because of this, mixing C++ ABIs is not recommended at this time.

For more background on this issue, see these bugzilla entries:

24660: versioning weak symbols in libstdc++

19664: libstdc++ headers should have pop/push of the visibility around the declarations

B.5.8 Bibliography

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[101] *Linker and Libraries Guide (document 819-0690)*

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[103] Ulrich Drepper, *How to Write Shared Libraries*

[104] *C++ ABI for the ARM Architecture*

[105] Benjamin Kosnik, *Dynamic Shared Objects: Survey and Issues* , ISO C++ J16/06-0046 .

[106] Benjamin Kosnik, *Versioning With Namespaces* , ISO C++ J16/06-0083 .

[107] Pavel ShvedDenis Silakov, *Binary Compatibility of Shared Libraries Implemented in C++ on GNU/Linux Systems* , SYRCoSE 2009 .

B.6 API Evolution and Deprecation History

A list of user-visible changes, in chronological order

B.6.1 `3.0`

Extensions moved to `include/ext`.

Include files from the SGI/HP sources that pre-date the ISO standard are added. These files are placed into the `include/backward` directory and a deprecated warning is added that notifies on inclusion (`-Wno-deprecated` deactivates the warning.)

Deprecated include `<backward/strstream>` added.

Removal of include `<builtinbuf.h>`, `<indstream.h>`, `<parsestream.h>`, `<PlotFile.h>`, `<SFile.h>`, `<stdiostream.h>`, and `<stream.h>`.

B.6.2 `3.1`

Extensions from SGI/HP moved from `namespace std` to `namespace __gnu_cxx`. As part of this, the following new includes are added: `<ext/algorithm>`, `<ext/functional>`, `<ext/iterator>`, `<ext/memory>`, and `<ext/numeric>`.

Extensions to `basic_filebuf` introduced: `__gnu_cxx::enc_filebuf`, and `__gnu_cxx::stdio_filebuf`.

Extensions to tree data structures added in `<ext/rb_tree>`.

Removal of `<ext/tree>`, moved to `<backward/tree.h>`.

B.6.3 3.2

Symbol versioning introduced for shared library.

Removal of include <backward/strstream.h>.

Allocator changes. Change __malloc_alloc to malloc_allocator and __new_alloc to new_allocator.

For GCC releases from 2.95 through the 3.1 series, defining __USE_MALLOC on the gcc command line would change the default allocation strategy to instead use malloc and free. For the 3.2 and 3.3 release series the same functionality was spelled _GLIBCXX_FORCE_NEW. From GCC 3.4 onwards the default allocator uses new anyway, but for the optional pooling allocators the functionality is enabled by setting GLIBCXX_FORCE_NEW in the environment, see the mt allocator chapter for details.

Error handling in iostreams cleaned up, made consistent.

B.6.4 3.3

B.6.5 3.4

Large file support.

Extensions for generic characters and char_traits added in <ext/pod_char_traits.h>.

Support for wchar_t specializations of basic_filebuf enhanced to support UTF-8 and Unicode, depending on host. More hosts support basic wchar_t functionality.

Support for char_traits beyond builtin types.

Conformant allocator class and usage in containers. As part of this, the following extensions are added: <ext/bitmap_allocator.h>, <ext/debug_allocator.h>, <ext/mt_allocator.h>, <ext/malloc_allocator.h>,<ext/new_allocator.h>, <ext/pool_allocator.h>.

This is a change from all previous versions, and may require source-level changes due to allocator-related changes to structures names and template parameters, filenames, and file locations. Some, like __simple_alloc, __allocator, __alloc, and _Alloc_traits have been removed.

Default behavior of std::allocator has changed.

Previous versions prior to 3.4 cache allocations in a memory pool, instead of passing through to call the global allocation operators (i.e., __gnu_cxx::pool_allocator). More recent versions default to the simpler __gnu_cxx::new_allocator.

Previously, all allocators were written to the SGI style, and all STL containers expected this interface. This interface had a traits class called _Alloc_traits that attempted to provide more information for compile-time allocation selection and optimization. This traits class had another allocator wrapper, __simple_alloc<T,A>, which was a wrapper around another allocator, A, which itself is an allocator for instances of T. But wait, there's more: __allocator<T,A> is another adapter. Many of the provided allocator classes were SGI style: such classes can be changed to a conforming interface with this wrapper: __allocator<T, __alloc> is thus the same as allocator<T>.

The class allocator used the typedef __alloc to select an underlying allocator that satisfied memory allocation requests. The selection of this underlying allocator was not user-configurable.

Releases after gcc-3.4 have continued to add to the collection of available allocators. All of these new allocators are standard-style. The following table includes details, along with the first released version of GCC that included the extension allocator.

Debug mode first appears.

Precompiled header support PCH support.

Macro guard for changed, from _GLIBCPP_ to _GLIBCXX_.

Extension <ext/stdio_sync_filebuf.h> added.

Extension <ext/demangle.h> added.

Allocator (3.4)	Header (3.4)	Allocator (3.[0-3])	Header (3.[0-3])
__gnu_cxx::new_allocator<T>	<ext/new_allocator.h>	std::__new_alloc	<memory>
__gnu_cxx::malloc_allocator<T>	<ext/malloc_allocator.h>	std::__malloc_alloc_template<int>	<memory>
__gnu_cxx::debug_allocator<T>	<ext/debug_allocator.h>	std::debug_alloc<T>	<memory>
__gnu_cxx::__pool_alloc<T>	<ext/pool_allocator.h>	std::__default_alloc_template<bool,int>	<memory>
__gnu_cxx::__mt_alloc<T>	<ext/mt_allocator.h>		
__gnu_cxx::bitmap_allocator<T>	<ext/bitmap_allocator.h>		

Table B.6: Extension Allocators

Allocator	Include	Version
__gnu_cxx::array_allocator<T>	<ext/array_allocator.h>	4.0.0
__gnu_cxx::throw_allocator<T>	<ext/throw_allocator.h>	4.2.0

Table B.7: Extension Allocators Continued

B.6.6 4.0

TR1 features first appear.

Extension allocator <ext/array_allocator.h> added.

Extension codecvt specializations moved to <ext/codecvt_specializations.h>.

Removal of <ext/demangle.h>.

B.6.7 4.1

Removal of <cassert> from all standard headers: now has to be explicitly included for std::assert calls.

Extensions for policy-based data structures first added. New includes, types, namespace pb_assoc.

Extensions for typelists added in <ext/typelist.h>.

Extension for policy-based basic_string first added: __gnu_cxx::__versa_string in <ext/vstring.h>.

B.6.8 4.2

Default visibility attributes applied to namespace std. Support for -fvisibility.

TR1 <random>, <complex>, and C compatibility headers added.

Extensions for concurrent programming consolidated into <ext/concurrence.h> and <ext/atomicity.h>, including change of namespace to __gnu_cxx in some cases. Added types include _Lock_policy, __concurrence_lock_error, __concurrence_unlock_error, __mutex, __scoped_lock.

Extensions for type traits consolidated into <ext/type_traits.h>. Additional traits are added (__conditional_type, __enable_if, others.)

Extensions for policy-based data structures revised. New includes, types, namespace moved to __pb_ds.

Extensions for debug mode modified: now nested in namespace std::__debug and extensions in namespace __gnu_cxx::_

Extensions added: <ext/typelist.h> and <ext/throw_allocator.h>.

B.6.9 4.3

C++0X features first appear.

TR1 <regex> and <cmath>'s mathematical special function added.

Backward include edit.

- Removed

  <algobase.h> <algo.h> <alloc.h> <bvector.h> <complex.h> <defalloc.h> <deque.h> <fstream.h> <function.h> <hash_map.h> <hash_set.h> <hashtable.h> <heap.h> <iomanip.h> <iostream.h> <istream.h> <iterator.h> <list.h> <map.h> <multimap.h> <multiset.h> <new.h> <ostream.h> <pair.h> <queue.h> <rope.h> <set.h> <slist.h> <stack.h> <streambuf.h> <stream.h> <tempbuf.h> <tree.h> <vector.h>

- Added

  <hash_map> and <hash_set>

- Added in C++11

  <auto_ptr.h> and <binders.h>

Header dependency streamlining.

- <algorithm> no longer includes <climits>, <cstring>, or <iosfwd>
- <bitset> no longer includes <istream> or <ostream>, adds <iosfwd>
- <functional> no longer includes <cstddef>
- <iomanip> no longer includes <istream>, <istream>, or <functional>, adds <ioswd>
- <numeric> no longer includes <iterator>
- <string> no longer includes <algorithm> or <memory>
- <valarray> no longer includes <numeric> or <cstdlib>
- <tr1/hashtable> no longer includes <memory> or <functional>
- <tr1/memory> no longer includes <algorithm>
- <tr1/random> no longer includes <algorithm> or <fstream>

Debug mode for <unordered_map> and <unordered_set>.

Parallel mode first appears.

Variadic template implementations of items in <tuple> and <functional>.

Default what implementations give more elaborate exception strings for bad_cast, bad_typeid, bad_exception, and bad_alloc.

PCH binary files no longer installed. Instead, the source files are installed.

Namespace pb_ds moved to __gnu_pb_ds.

B.6.10 4.4

C++0X features.

- Added.

  <atomic>, <chrono>, <condition_variable>, <forward_list>, <initializer_list>, <mutex>, <ratio>, <thread>

- Updated and improved.

  <algorithm>, <system_error>, <type_traits>

- Use of the GNU extension namespace association converted to inline namespaces.
- Preliminary support for `initializer_list` and defaulted and deleted constructors in container classes.
- `unique_ptr`.
- Support for new character types char16_t and char32_t added to `char_traits`, `basic_string`, `numeric_limits`, and assorted compile-time type traits.
- Support for string conversions `to_string` and `to_wstring`.
- Member functions taking string arguments were added to iostreams including `basic_filebuf`, `basic_ofstream`, and `basic_ifstream`.
- Exception propagation support, including `exception_ptr`, `current_exception`, `copy_exception`, and `rethrow_exce`

Uglification of `try` to `__try` and `catch` to `__catch`.

Audit of internal mutex usage, conversion to functions returning static local mutex.

Extensions added: <ext/pointer.h> and <ext/extptr_allocator.h>. Support for non-standard pointer types has been added to `vector` and `forward_list`.

B.6.11 4.5

C++0X features.

- Added.

  <functional>, <future>, <random>

- Updated and improved.

  <atomic>, <system_error>, <type_traits>

- Add support for explicit operators and standard layout types.

Profile mode first appears.

Support for decimal floating-point arithmetic, including `decimal32`, `decimal64`, and `decimal128`.

Python pretty-printers are added for use with appropriately-advanced versions of **gdb**.

Audit for application of function attributes nothrow, const, pure, and noreturn.

The default behavior for comparing typeinfo names changed, so in <typeinfo>, `__GXX_MERGED_TYPEINFO_NAMES` now defaults to zero.

Extensions modified: <ext/throw_allocator.h>.

B.6.12 4.6

Use constexpr and nullptr where appropriate throughout the library.

The library was updated to avoid including <stddef.h> in order to reduce namespace pollution.

Reference-count annotations to assist data race detectors.

Added `make_exception_ptr` as an alias of `copy_exception`.

B.6.13 4.7

Use of noexcept throughout library.

Partial support for C++11 allocators first appears.

`monotonic_clock` renamed to `steady_clock` as required by the final C++11 standard.

A new clocale model for newlib is available.

The library was updated to avoid including <unistd.h> in order to reduce namespace pollution.

Debug Mode was improved for unordered containers.

B.6.14 4.8

New random number engines and distributions. Optimisations for random.

New --enable-libstdcxx-verbose configure option

The --enable-libstdcxx-time configure option becomes unnecessary given a sufficiently recent glibc.

B.6.15 4.9

Implementation of `regex` completed.

C++14 library and TS implementations are added.

`copy_exception` deprecated.

`__gnu_cxx::array_allocator` deprecated.

B.6.16 5

ABI transition adds new implementations of several components, using the `abi_tag` attribute and the `__cxx11` inline namespace to distinguish the new entities from the old ones.

- Use of the new or old ABI can be selected per-translation unit with the Macros.
- New non-reference-counted `string` implementation.
- New `list` implementation containing a new data member in order to provide O(1) `size()`.
- New `ios_base::failure` implementation inheriting from `system_error`.

C++11 support completed (movable iostreams, new I/O manipulators, Unicode conversion utilities, atomic operations for `shared_ptr`, functions for notifying condition variables and making futures ready at thread exit).

Changed formatting of floating point types when `ios_base::fixed|ios_base::scientific` is set in a stream's format flags.

Improved C++14 support and TS implementations.

New random number engines and distributions.

GDB Xmethods for containers and `unique_ptr` added.

`has_trivial_default_constructor`, `has_trivial_copy_constructor` and `has_trivial_copy_assign` deprecated.

B.6.16.1 5.3

Experimental implementation of the C++ Filesystem TS added.

B.6.17 6

C++14 support completed.

Support for mathematical special functions (ISO/IEC 29124:2010) added.

Assertions to check function preconditions can be enabled by defining the _GLIBCXX_ASSERTIONS macro. The initial set of assertions are a subset of the checks enabled by the Debug Mode, but without the ABI changes and changes to algorithmic complexity that are caused by enabling the full Debug Mode.

B.6.18 7

The type of exception thrown by iostreams changed to the cxx11 ABI version of std::ios_base::failure.

Experimental C++17 support added, including most new library features. The meaning of shared_ptr<T[]> changed to match the C++17 semantics.

Macros added.

has_trivial_default_constructor, has_trivial_copy_constructor and has_trivial_copy_assign removed.

Calling a std::bind result as volatile was deprecated for C++17.

Profile Mode was deprecated.

B.6.18.1 7.2

Library Fundamentals TS header <experimental/source_location> added.

B.6.18.2 7.3

Including new C++14 or C++17 headers without a suitable -std no longer causes compilation to fail via #error. Instead the header is simply empty and doesn't define anything.

B.6.19 8

The exceptions thrown by iostreams can now be caught by handlers for either version of std::ios_base::failure.

Improved experimental C++17 support. Headers <charconv> and <filesystem>. Experimental implementation of the C++17 Filesystem library added.

Experimental C++2a support (to_address and endian).

AddressSanitizer annotations added to std::vector to detect out-of-range accesses to the unused capacity of a vector.

std::char_traits<char16_t>::to_int_type(u'\uFFFF') now returns 0xFFFD, as 0xFFFF is used for std::char_

The extension allowing arithmetic on std::atomic<void*> and types like std::atomic<R(*)()> was deprecated.

The std::uncaught_exception function was deprecated for C++17 mode.

The nested typedefs std::hash::result_type and std::hash::argument_type were deprecated for C++17 mode.

The deprecated iostream members ios_base::io_state, ios_base::open_mode, ios_base::seek_dir, and basic_streambuf::stossc were removed for C++17 mode.

The non-standard C++0x `std::copy_exception` function was removed.

For `-std=c++11`, `-std=c++14`, and `-std=c++17` modes the `<complex.h>` header no longer includes the C99 `<complex.h>` header.

For the non-default `--enable-symvers=gnu-versioned-namespace` configuration, the shared library SONAME has been changed to `libstdc++.so.8`.

The extension allowing containers to be instantiated with an allocator that doesn't match the container's value type is no longer allowed in strict (`-std=c++NN`) modes, only in `-std=gnu++NN` modes.

B.6.20 9

C++17 header `<memory_resource>` added.

Experimental C++2a support improved, with new headers `<bit>` and `<version>` added. Support for new character type char8_t added to `char_traits`, `basic_string`, `numeric_limits`, and relevant locale facets and type traits.

Experimental implementation of the Networking TS library added, with new headers `<experimental/buffer>`, `<experimental/executor>`, `<experimental/internet>`, `<experimental/io_context>`, `<experimental/net>`, `<experimental/netfwd>`, `<experimental/socket>`, and `<experimental/timer>`.

B.6.21 10

Deprecated features removed:

- Profile Mode
- `__gnu_cxx::array_allocator`

The non-standard `std::__is_nullptr_t` type trait was deprecated.

The `std::packaged_task` constructors taking an allocator argument are only defined for C++11 and C++14.

Several members of `std::allocator` were removed for C++20 mode. The removed functionality has been provided by `std::allocator_traits` since C++11 and that should be used instead.

The type of the `std::iterator` base class of `std::istreambuf_iterator` was changed to be consistent for all `-std` modes. Before GCC 10.1 the base class had one type in C++98 mode and a different type in C++11 and later modes. The type in C++98 mode was changed to be the same as for C++11 and later.

Experimental C++2a support improved, with new headers `<concepts>`, `<ranges>`, `<compare>`, `<coroutine>`, `<numbers>`, `<span>`, and `<stop_token>` added.

The extension allowing containers to be instantiated with an allocator that doesn't match the container's value type is no longer allowed in C++20 mode, even in non-strict `-std=gnu++20` mode.

B.6.22 11

The `--enable-cheaders=c_std` configuration was deprecated.

When compiling as C++20, the `operator>>` overloads for extracting strings into character buffers only work with arrays, not raw pointers.

`std::string::reserve(n)` will no longer reduce the string's capacity. Calling `reserve()` with no arguments is equivalent to `shrink_to_fit()`, but is deprecated. `shrink_to_fit()` should be used instead.

B.6.23 12

The std::random_shuffle algorithms are deprecated for C++14 and later. The C++11 std::shuffle algorithm can be used instead.

The std::unexpected function and related typedef and accessors for the unexpected handler are deprecated for C++11 and later. Dynamic exception specifications should be replaced with noexcept.

C++98 adaptable function utilities (std::bind1st, std::unary_function, std::ptr_fun, std::mem_fun_ref etc.) were deprecated for C++11. std::iterator, std::raw_storage_iterator, get_temporary_buffer, and std::not_fun were deprecated for C++17.

Non-standard std::pair constructors were deprecated. A non-standard default argument for vector<bool>::insert(const_ const bool&) was deprecated.

The bitmap, mt, and pool options for --enable-libstdcxx-allocator were removed. For the new option, std::allocat no longer derives from __gnu_cxx::new_allocator; they both derive from std::__new_allocator instead.

std::condition_variable::wait changed to be noexcept(false) to allow thread cancellation exceptions to be thrown from pthread_cond_wait without aborting the process.

B.6.24 12.3

Calling a std::bind result as volatile is ill-formed for C++20 and later.

B.6.25 13

Tunables glibcxx.eh_pool.obj_count and glibcxx.eh_pool.obj_size were added.

Static library libstdc++exp.a was added to provide the symbols for the experimental C++ Contracts support.

B.6.26 13.3

Symbols for the Filesystem TS and C++23 <stacktrace> header were added to the static library libstdc++exp.a.

B.6.27 14

Deprecated the non-standard overload that allows std::setfill to be used with std::basic_istream.

The extension allowing std::basic_string to be instantiated with an allocator that doesn't match the string's character type is no longer allowed in C++20 mode.

B.6.28 15

Enabled debug assertions by default for unoptimized builds.

Added warnings when including the headers that were deprecated in C++17 and removed in C++20: <ccomplex>, <ciso646>, <cstdalign>, <cstdbool>, and <ctgmath>.

Nested result_type and argument_type removed from std::hash specializations for C++20.

B.6.29 16

Deprecated the non-standard overload of std::fabs for std::complex arguments.

Made std::is_integral_v<__int128> true for strict -std dialects.

B.7 Backwards Compatibility

B.7.1 First

The first generation GNU C++ library was called libg++. It was a separate GNU project, although reliably paired with GCC. Rumors imply that it had a working relationship with at least two kinds of dinosaur.

Some background: libg++ was designed and created when there was no ISO standard to provide guidance. Classes like linked lists are now provided for by `std::list<T>` and do not need to be created by `genclass`. (For that matter, templates exist now and are well-supported, whereas genclass (mostly) predates them.)

There are other classes in libg++ that are not specified in the ISO Standard (e.g., statistical analysis). While there are a lot of really useful things that are used by a lot of people, the Standards Committee couldn't include everything, and so a lot of those "obvious" classes didn't get included.

That project is no longer maintained or supported, and the sources archived. For the desperate, the ftp.gnu.org server still has the libg++ source.

B.7.2 Second

The second generation GNU C++ library was called libstdc++, or libstdc++-v2. It spans the time between libg++ and pre-ISO C++ standardization and is usually associated with the following GCC releases: egcs 1.x, gcc 2.95, and gcc 2.96.

The STL portions of that library are based on SGI/HP STL release 3.11.

That project is no longer maintained or supported, and the sources archived. The code was replaced and rewritten for libstdc++-v3.

B.7.3 Third

The third generation GNU C++ library is called libstdc++, or libstdc++-v3.

The subset commonly known as the Standard Template Library (clauses 23 through 25 in C++98, mostly) is adapted from the final release of the SGI STL (version 3.3), with extensive changes.

A more formal description of the V3 goals can be found in the official design document.

Portability notes and known implementation limitations are as follows.

B.7.3.1 Pre-ISO headers removed

The pre-ISO C++ headers (`<iostream.h>`, `<defalloc.h>` etc.) are not supported.

For those of you new to ISO C++ (welcome, time travelers!), the ancient pre-ISO headers have new names. The C++ FAQ has a good explanation in What's the difference between <xxx> and <xxx.h> headers?.

Porting between pre-ISO headers and ISO headers is simple: headers like `<vector.h>` can be replaced with `<vector>` and a using directive `using namespace std;` can be put at the global scope. This should be enough to get this code compiling, assuming the other usage is correct.

B.7.3.2 Extension headers hash_map, hash_set moved to ext or backwards

At this time most of the features of the SGI STL extension have been replaced by standardized libraries. In particular, the `unordered_map` and `unordered_set` containers of TR1 and C++ 2011 are suitable replacements for the non-standard `hash_map` and `hash_set` containers in the SGI STL.

Header files `<hash_map>` and `<hash_set>` moved to `<ext/hash_map>` and `<ext/hash_set>`, respectively. At the same time, all types in these files are enclosed in `namespace __gnu_cxx`. Later versions deprecate these files, and suggest using TR1's `<unordered_map>` and `<unordered_set>` instead.

The extensions are no longer in the global or `std` namespaces, instead they are declared in the `__gnu_cxx` namespace. For maximum portability, consider defining a namespace alias to use to talk about extensions, e.g.:

```
    #ifdef __GNUC__
    #if __GNUC__ < 3
#include <hash_map.h>
namespace extension { using ::hash_map; }; // inherit globals
    #else
#include <backward/hash_map>
#if __GNUC__ == 3 && __GNUC_MINOR__ == 0
  namespace extension = std;               // GCC 3.0
#else
  namespace extension = ::__gnu_cxx;       // GCC 3.1 and later
#endif
    #endif
    #else      // ...  there are other compilers, right?
namespace extension = std;
    #endif

    extension::hash_map<int,int> my_map;
```

This is a bit cleaner than defining typedefs for all the instantiations you might need.

The following autoconf tests check for working HP/SGI hash containers.

```
# AC_HEADER_EXT_HASH_MAP
AC_DEFUN([AC_HEADER_EXT_HASH_MAP], [
  AC_CACHE_CHECK(for ext/hash_map,
  ac_cv_cxx_ext_hash_map,
  [AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  ac_save_CXXFLAGS="$CXXFLAGS"
  CXXFLAGS="$CXXFLAGS -Werror"
  AC_TRY_COMPILE([#include <ext/hash_map>], [using __gnu_cxx::hash_map;],
  ac_cv_cxx_ext_hash_map=yes, ac_cv_cxx_ext_hash_map=no)
  CXXFLAGS="$ac_save_CXXFLAGS"
  AC_LANG_RESTORE
  ])
  if test "$ac_cv_cxx_ext_hash_map" = yes; then
    AC_DEFINE(HAVE_EXT_HASH_MAP,,[Define if ext/hash_map is present. ])
  fi
])
```

```
# AC_HEADER_EXT_HASH_SET
AC_DEFUN([AC_HEADER_EXT_HASH_SET], [
  AC_CACHE_CHECK(for ext/hash_set,
  ac_cv_cxx_ext_hash_set,
  [AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  ac_save_CXXFLAGS="$CXXFLAGS"
  CXXFLAGS="$CXXFLAGS -Werror"
  AC_TRY_COMPILE([#include <ext/hash_set>], [using __gnu_cxx::hash_set;],
  ac_cv_cxx_ext_hash_set=yes, ac_cv_cxx_ext_hash_set=no)
  CXXFLAGS="$ac_save_CXXFLAGS"
  AC_LANG_RESTORE
  ])
  if test "$ac_cv_cxx_ext_hash_set" = yes; then
    AC_DEFINE(HAVE_EXT_HASH_SET,,[Define if ext/hash_set is present. ])
  fi
])
```

B.7.3.3 No `ios::nocreate/ios::noreplace`.

Historically these flags were used with iostreams to control whether new files are created or not when opening a file stream, similar to the `O_CREAT` and `O_EXCL` flags for the `open(2)` system call. Because iostream modes correspond to `fopen(3)` modes these flags are not supported. For input streams a new file will not be created anyway, so `ios::nocreate` is not needed. For output streams, a new file will be created if it does not exist, which is consistent with the behaviour of `fopen`.

When one of these flags is needed a possible alternative is to attempt to open the file using std::ifstream first to determine whether the file already exists or not. This may not be reliable however, because whether the file exists or not could change between opening the std::istream and re-opening with an output stream. If you need to check for existence and open a file as a single operation then you will need to use OS-specific facilities outside the C++ standard library, such as `open(2)`.

B.7.3.4 No `stream::attach(int fd)`

Phil Edwards writes: It was considered and rejected for the ISO standard. Not all environments use file descriptors. Of those that do, not all of them use integers to represent them.

For a portable solution (among systems which use file descriptors), you need to implement a subclass of `std::streambuf` (or `std::basic_streambuf<..>`) which opens a file given a descriptor, and then pass an instance of this to the stream-constructor.

An extension is available that implements this. `<ext/stdio_filebuf.h>` contains a derived class called `__gnu_cxx::stdio_f` This class can be constructed from a C `FILE*` or a file descriptor, and provides the `fd()` function.

For another example of this, refer to fdstream example by Nicolai Josuttis.

B.7.3.5 Support for C++98 dialect.

Check for complete library coverage of the C++1998/2003 standard.

```
# AC_HEADER_STDCXX_98
AC_DEFUN([AC_HEADER_STDCXX_98], [
  AC_CACHE_CHECK(for ISO C++ 98 include files,
  ac_cv_cxx_stdcxx_98,
  [AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  AC_TRY_COMPILE([
    #include <cassert>
    #include <cctype>
    #include <cerrno>
    #include <cfloat>
    #include <ciso646>
    #include <climits>
    #include <clocale>
    #include <cmath>
    #include <csetjmp>
    #include <csignal>
    #include <cstdarg>
    #include <cstddef>
    #include <cstdio>
    #include <cstdlib>
    #include <cstring>
    #include <ctime>

    #include <algorithm>
    #include <bitset>
    #include <complex>
    #include <deque>
    #include <exception>
    #include <fstream>
    #include <functional>
```

```
    #include <iomanip>
    #include <ios>
    #include <iosfwd>
    #include <iostream>
    #include <istream>
    #include <iterator>
    #include <limits>
    #include <list>
    #include <locale>
    #include <map>
    #include <memory>
    #include <new>
    #include <numeric>
    #include <ostream>
    #include <queue>
    #include <set>
    #include <sstream>
    #include <stack>
    #include <stdexcept>
    #include <streambuf>
    #include <string>
    #include <typeinfo>
    #include <utility>
    #include <valarray>
    #include <vector>
  ],,
  ac_cv_cxx_stdcxx_98=yes, ac_cv_cxx_stdcxx_98=no)
  AC_LANG_RESTORE
  ])
  if test "$ac_cv_cxx_stdcxx_98" = yes; then
    AC_DEFINE(STDCXX_98_HEADERS,,[Define if ISO C++ 1998 header files are present. ])
  fi
])
```

B.7.3.6 Support for C++TR1 dialect.

Check for library coverage of the TR1 standard.

```
# AC_HEADER_STDCXX_TR1
AC_DEFUN([AC_HEADER_STDCXX_TR1], [
  AC_CACHE_CHECK(for ISO C++ TR1 include files,
  ac_cv_cxx_stdcxx_tr1,
  [AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  AC_TRY_COMPILE([
  #include <tr1/array>
  #include <tr1/ccomplex>
  #include <tr1/cctype>
  #include <tr1/cfenv>
  #include <tr1/cfloat>
  #include <tr1/cinttypes>
  #include <tr1/climits>
  #include <tr1/cmath>
  #include <tr1/complex>
  #include <tr1/cstdarg>
  #include <tr1/cstdbool>
  #include <tr1/cstdint>
  #include <tr1/cstdio>
  #include <tr1/cstdlib>
  #include <tr1/ctgmath>
```

```
  #include <tr1/ctime>
  #include <tr1/cwchar>
  #include <tr1/cwctype>
  #include <tr1/functional>
  #include <tr1/memory>
  #include <tr1/random>
  #include <tr1/regex>
  #include <tr1/tuple>
  #include <tr1/type_traits>
  #include <tr1/unordered_set>
  #include <tr1/unordered_map>
  #include <tr1/utility>
  ],,
  ac_cv_cxx_stdcxx_tr1=yes, ac_cv_cxx_stdcxx_tr1=no)
  AC_LANG_RESTORE
  ])
  if test "$ac_cv_cxx_stdcxx_tr1" = yes; then
    AC_DEFINE(STDCXX_TR1_HEADERS,,[Define if ISO C++ TR1 header files are present. ])
  fi
])
```

An alternative is to check just for specific TR1 includes, such as <unordered_map> and <unordered_set>.

```
# AC_HEADER_TR1_UNORDERED_MAP
AC_DEFUN([AC_HEADER_TR1_UNORDERED_MAP], [
  AC_CACHE_CHECK(for tr1/unordered_map,
  ac_cv_cxx_tr1_unordered_map,
  [AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  AC_TRY_COMPILE([#include <tr1/unordered_map>], [using std::tr1::unordered_map;],
  ac_cv_cxx_tr1_unordered_map=yes, ac_cv_cxx_tr1_unordered_map=no)
  AC_LANG_RESTORE
  ])
  if test "$ac_cv_cxx_tr1_unordered_map" = yes; then
    AC_DEFINE(HAVE_TR1_UNORDERED_MAP,,[Define if tr1/unordered_map is present. ])
  fi
])
```

```
# AC_HEADER_TR1_UNORDERED_SET
AC_DEFUN([AC_HEADER_TR1_UNORDERED_SET], [
  AC_CACHE_CHECK(for tr1/unordered_set,
  ac_cv_cxx_tr1_unordered_set,
  [AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  AC_TRY_COMPILE([#include <tr1/unordered_set>], [using std::tr1::unordered_set;],
  ac_cv_cxx_tr1_unordered_set=yes, ac_cv_cxx_tr1_unordered_set=no)
  AC_LANG_RESTORE
  ])
  if test "$ac_cv_cxx_tr1_unordered_set" = yes; then
    AC_DEFINE(HAVE_TR1_UNORDERED_SET,,[Define if tr1/unordered_set is present. ])
  fi
])
```

B.7.3.7 Support for C++11 dialect.

Check for baseline language coverage in the compiler for the C++11 standard.

```
# AC_COMPILE_STDCXX_11
AC_DEFUN([AC_COMPILE_STDCXX_11], [
  AC_CACHE_CHECK(if g++ supports C++11 features without additional flags,
```

```
ac_cv_cxx_compile_cxx11_native,
[AC_LANG_SAVE
AC_LANG_CPLUSPLUS
AC_TRY_COMPILE([
template <typename T>
  struct check final
  {
    static constexpr T value{ __cplusplus };
  };

  typedef check<check<bool>> right_angle_brackets;

  int a;
  decltype(a) b;

  typedef check<int> check_type;
  check_type c{};
  check_type&& cr = static_cast<check_type&&>(c);

  static_assert(check_type::value == 201103L, "C++11 compiler");],,
ac_cv_cxx_compile_cxx11_native=yes, ac_cv_cxx_compile_cxx11_native=no)
AC_LANG_RESTORE
])

AC_CACHE_CHECK(if g++ supports C++11 features with -std=c++11,
ac_cv_cxx_compile_cxx11_cxx,
[AC_LANG_SAVE
AC_LANG_CPLUSPLUS
ac_save_CXXFLAGS="$CXXFLAGS"
CXXFLAGS="$CXXFLAGS -std=c++11"
AC_TRY_COMPILE([
template <typename T>
  struct check final
  {
    static constexpr T value{ __cplusplus };
  };

  typedef check<check<bool>> right_angle_brackets;

  int a;
  decltype(a) b;

  typedef check<int> check_type;
  check_type c{};
  check_type&& cr = static_cast<check_type&&>(c);

  static_assert(check_type::value == 201103L, "C++11 compiler");],,
ac_cv_cxx_compile_cxx11_cxx=yes, ac_cv_cxx_compile_cxx11_cxx=no)
CXXFLAGS="$ac_save_CXXFLAGS"
AC_LANG_RESTORE
])

AC_CACHE_CHECK(if g++ supports C++11 features with -std=gnu++11,
ac_cv_cxx_compile_cxx11_gxx,
[AC_LANG_SAVE
AC_LANG_CPLUSPLUS
ac_save_CXXFLAGS="$CXXFLAGS"
CXXFLAGS="$CXXFLAGS -std=gnu++11"
AC_TRY_COMPILE([
template <typename T>
  struct check final
  {
```

```
      static constexpr T value{ __cplusplus };
    };

    typedef check<check<bool>> right_angle_brackets;

    int a;
    decltype(a) b;

    typedef check<int> check_type;
    check_type c{};
    check_type&& cr = static_cast<check_type&&>(c);

    static_assert(check_type::value == 201103L, "C++11 compiler");],,
  ac_cv_cxx_compile_cxx11_gxx=yes, ac_cv_cxx_compile_cxx11_gxx=no)
  CXXFLAGS="$ac_save_CXXFLAGS"
  AC_LANG_RESTORE
  ])

  if test "$ac_cv_cxx_compile_cxx11_native" = yes ||
     test "$ac_cv_cxx_compile_cxx11_cxx" = yes ||
     test "$ac_cv_cxx_compile_cxx11_gxx" = yes; then
    AC_DEFINE(HAVE_STDCXX_11,,[Define if g++ supports C++11 features. ])
  fi
])
```

Check for library coverage of the C++2011 standard. (Some library headers are commented out in this check, they are not currently provided by libstdc++).

```
# AC_HEADER_STDCXX_11
AC_DEFUN([AC_HEADER_STDCXX_11], [
  AC_CACHE_CHECK(for ISO C++11 include files,
  ac_cv_cxx_stdcxx_11,
  [AC_REQUIRE([AC_COMPILE_STDCXX_11])
  AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  ac_save_CXXFLAGS="$CXXFLAGS"
  CXXFLAGS="$CXXFLAGS -std=gnu++11"

  AC_TRY_COMPILE([
    #include <cassert>
    #include <ccomplex>
    #include <cctype>
    #include <cerrno>
    #include <cfenv>
    #include <cfloat>
    #include <cinttypes>
    #include <ciso646>
    #include <climits>
    #include <clocale>
    #include <cmath>
    #include <csetjmp>
    #include <csignal>
    #include <cstdalign>
    #include <cstdarg>
    #include <cstdbool>
    #include <cstddef>
    #include <cstdint>
    #include <cstdio>
    #include <cstdlib>
    #include <cstring>
    #include <ctgmath>
    #include <ctime>
```

```
    // #include <cuchar>
    #include <cwchar>
    #include <cwctype>

    #include <algorithm>
    #include <array>
    #include <atomic>
    #include <bitset>
    #include <chrono>
    // #include <codecvt>
    #include <complex>
    #include <condition_variable>
    #include <deque>
    #include <exception>
    #include <forward_list>
    #include <fstream>
    #include <functional>
    #include <future>
    #include <initializer_list>
    #include <iomanip>
    #include <ios>
    #include <iosfwd>
    #include <iostream>
    #include <istream>
    #include <iterator>
    #include <limits>
    #include <list>
    #include <locale>
    #include <map>
    #include <memory>
    #include <mutex>
    #include <new>
    #include <numeric>
    #include <ostream>
    #include <queue>
    #include <random>
    #include <ratio>
    #include <regex>
    #include <scoped_allocator>
    #include <set>
    #include <sstream>
    #include <stack>
    #include <stdexcept>
    #include <streambuf>
    #include <string>
    #include <system_error>
    #include <thread>
    #include <tuple>
    #include <typeindex>
    #include <typeinfo>
    #include <type_traits>
    #include <unordered_map>
    #include <unordered_set>
    #include <utility>
    #include <valarray>
    #include <vector>
  ],,
  ac_cv_cxx_stdcxx_11=yes, ac_cv_cxx_stdcxx_11=no)
  AC_LANG_RESTORE
  CXXFLAGS="$ac_save_CXXFLAGS"
  ])
  if test "$ac_cv_cxx_stdcxx_11" = yes; then
```

```
    AC_DEFINE(STDCXX_11_HEADERS,,[Define if ISO C++11 header files are present. ])
  fi
])
```

As is the case for TR1 support, these autoconf macros can be made for a finer-grained, per-header-file check. For `<unordered_map>`

```
# AC_HEADER_UNORDERED_MAP
AC_DEFUN([AC_HEADER_UNORDERED_MAP], [
  AC_CACHE_CHECK(for unordered_map,
  ac_cv_cxx_unordered_map,
  [AC_REQUIRE([AC_COMPILE_STDCXX_11])
  AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  ac_save_CXXFLAGS="$CXXFLAGS"
  CXXFLAGS="$CXXFLAGS -std=gnu++11"
  AC_TRY_COMPILE([#include <unordered_map>], [using std::unordered_map;],
  ac_cv_cxx_unordered_map=yes, ac_cv_cxx_unordered_map=no)
  CXXFLAGS="$ac_save_CXXFLAGS"
  AC_LANG_RESTORE
  ])
  if test "$ac_cv_cxx_unordered_map" = yes; then
    AC_DEFINE(HAVE_UNORDERED_MAP,,[Define if unordered_map is present. ])
  fi
])
```

```
# AC_HEADER_UNORDERED_SET
AC_DEFUN([AC_HEADER_UNORDERED_SET], [
  AC_CACHE_CHECK(for unordered_set,
  ac_cv_cxx_unordered_set,
  [AC_REQUIRE([AC_COMPILE_STDCXX_11])
  AC_LANG_SAVE
  AC_LANG_CPLUSPLUS
  ac_save_CXXFLAGS="$CXXFLAGS"
  CXXFLAGS="$CXXFLAGS -std=gnu++11"
  AC_TRY_COMPILE([#include <unordered_set>], [using std::unordered_set;],
  ac_cv_cxx_unordered_set=yes, ac_cv_cxx_unordered_set=no)
  CXXFLAGS="$ac_save_CXXFLAGS"
  AC_LANG_RESTORE
  ])
  if test "$ac_cv_cxx_unordered_set" = yes; then
    AC_DEFINE(HAVE_UNORDERED_SET,,[Define if unordered_set is present. ])
  fi
])
```

Some C++11 features first appeared in GCC 4.3 and could be enabled by `-std=c++0x` and `-std=gnu++0x` for GCC releases which pre-date the 2011 standard. Those C++11 features and GCC's support for them were still changing until the 2011 standard was finished, but the autoconf checks above could be extended to test for incomplete C++11 support with `-std=c++0x` and `-std=gnu++0x`.

B.7.3.8 `Container::iterator_type` is not necessarily `Container::value_type*`

This is a change in behavior from older versions. Now, most iterator_type typedefs in container classes are POD objects, not value_type pointers.

Appendix C

Free Software Needs Free Documentation

The biggest deficiency in free operating systems is not in the software--it is the lack of good free manuals that we can include in these systems. Many of our most important programs do not come with full manuals. Documentation is an essential part of any software package; when an important free software package does not come with a free manual, that is a major gap. We have many such gaps today.

Once upon a time, many years ago, I thought I would learn Perl. I got a copy of a free manual, but I found it hard to read. When I asked Perl users about alternatives, they told me that there were better introductory manuals--but those were not free.

Why was this? The authors of the good manuals had written them for O'Reilly Associates, which published them with restrictive terms--no copying, no modification, source files not available--which exclude them from the free software community.

That wasn't the first time this sort of thing has happened, and (to our community's great loss) it was far from the last. Proprietary manual publishers have enticed a great many authors to restrict their manuals since then. Many times I have heard a GNU user eagerly tell me about a manual that he is writing, with which he expects to help the GNU project--and then had my hopes dashed, as he proceeded to explain that he had signed a contract with a publisher that would restrict it so that we cannot use it.

Given that writing good English is a rare skill among programmers, we can ill afford to lose manuals this way.

Free documentation, like free software, is a matter of freedom, not price. The problem with these manuals was not that O'Reilly Associates charged a price for printed copies--that in itself is fine. (The Free Software Foundation sells printed copies of free GNU manuals, too.) But GNU manuals are available in source code form, while these manuals are available only on paper. GNU manuals come with permission to copy and modify; the Perl manuals do not. These restrictions are the problems.

The criterion for a free manual is pretty much the same as for free software: it is a matter of giving all users certain freedoms. Redistribution (including commercial redistribution) must be permitted, so that the manual can accompany every copy of the program, on-line or on paper. Permission for modification is crucial too.

As a general rule, I don't believe that it is essential for people to have permission to modify all sorts of articles and books. The issues for writings are not necessarily the same as those for software. For example, I don't think you or I are obliged to give permission to modify articles like this one, which describe our actions and our views.

But there is a particular reason why the freedom to modify is crucial for documentation for free software. When people exercise their right to modify the software, and add or change its features, if they are conscientious they will change the manual too--so they can provide accurate and usable documentation with the modified program. A manual which forbids programmers to be conscientious and finish the job, or more precisely requires them to write a new manual from scratch if they change the program, does not fill our community's needs.

While a blanket prohibition on modification is unacceptable, some kinds of limits on the method of modification pose no problem. For example, requirements to preserve the original author's copyright notice, the distribution terms, or the list of authors, are ok. It is also no problem to require modified versions to include notice that they were modified, even to have entire sections that may not be deleted or changed, as long as these sections deal with nontechnical topics. (Some GNU manuals have them.)

These kinds of restrictions are not a problem because, as a practical matter, they don't stop the conscientious programmer from adapting the manual to fit the modified program. In other words, they don't block the free software community from making full use of the manual.

However, it must be possible to modify all the *technical* content of the manual, and then distribute the result in all the usual media, through all the usual channels; otherwise, the restrictions do block the community, the manual is not free, and so we need another manual.

Unfortunately, it is often hard to find someone to write another manual when a proprietary manual exists. The obstacle is that many users think that a proprietary manual is good enough--so they don't see the need to write a free manual. They do not see that the free operating system has a gap that needs filling.

Why do users think that proprietary manuals are good enough? Some have not considered the issue. I hope this article will do something to change that.

Other users consider proprietary manuals acceptable for the same reason so many people consider proprietary software acceptable: they judge in purely practical terms, not using freedom as a criterion. These people are entitled to their opinions, but since those opinions spring from values which do not include freedom, they are no guide for those of us who do value freedom.

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Chapter 30

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