

GNU Offloading and Multi Processing Runtime Library

The GNU OpenMP and OpenACC Implementation

Published by the Free Software Foundation
51 Franklin Street, Fifth Floor
Boston, MA 02110-1301, USA

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Short Contents

1	Enabling OpenMP.....	1
2	OpenMP Implementation Status	3
3	OpenMP Runtime Library Routines	15
4	OpenMP Environment Variables	59
5	Enabling OpenACC.....	71
6	OpenACC Runtime Library Routines	73
7	OpenACC Environment Variables	93
8	CUDA Streams Usage.....	95
9	OpenACC Library Interoperability	97
10	OpenACC Profiling Interface	101
11	OpenMP-Implementation Specifics.....	107
12	Offload-Target Specifics.....	113
13	The libgomp ABI.....	119
14	Reporting Bugs	125
	GNU General Public License	127
	GNU Free Documentation License.....	139
	Funding Free Software	147
	Library Index	149

1 Enabling OpenMP

To activate the OpenMP extensions for C/C++ and Fortran, the compile-time flag `-fopenmp` must be specified. For C and C++, this enables the handling of the OpenMP directives using `#pragma omp` and the `[[omp::directive(...)]]`, `[[omp::sequence(...)]]` and `[[omp::decl(...)]]` attributes. For Fortran, it enables for free source form the `!$omp` sentinel for directives and the `!$` conditional compilation sentinel and for fixed source form the `c$omp`, `*$omp` and `!$omp` sentinels for directives and the `c$`, `*$` and `!$` conditional compilation sentinels. The flag also arranges for automatic linking of the OpenMP runtime library (Chapter 3 [Runtime Library Routines], page 15).

The `-fopenmp-simd` flag can be used to enable a subset of OpenMP directives that do not require the linking of either the OpenMP runtime library or the POSIX threads library.

A complete description of all OpenMP directives may be found in the OpenMP Application Program Interface (<https://www.openmp.org>) manuals. See also Chapter 2 [OpenMP Implementation Status], page 3.

8 CUDA Streams Usage

This applies to the `nvptx` plugin only.

The library provides elements that perform asynchronous movement of data and asynchronous operation of computing constructs. This asynchronous functionality is implemented by making use of CUDA streams¹.

The primary means by that the asynchronous functionality is accessed is through the use of those OpenACC directives which make use of the `async` and `wait` clauses. When the `async` clause is first used with a directive, it creates a CUDA stream. If an `async-argument` is used with the `async` clause, then the stream is associated with the specified `async-argument`.

Following the creation of an association between a CUDA stream and the `async-argument` of an `async` clause, both the `wait` clause and the `wait` directive can be used. When either the clause or directive is used after stream creation, it creates a rendezvous point whereby execution waits until all operations associated with the `async-argument`, that is, stream, have completed.

Normally, the management of the streams that are created as a result of using the `async` clause, is done without any intervention by the caller. This implies the association between the `async-argument` and the CUDA stream is maintained for the lifetime of the program. However, this association can be changed through the use of the library function `acc_set_cuda_stream`. When the function `acc_set_cuda_stream` is called, the CUDA stream that was originally associated with the `async` clause is destroyed. Caution should be taken when changing the association as subsequent references to the `async-argument` refer to a different CUDA stream.

¹ See "Stream Management" in "CUDA Driver API", TRM-06703-001, Version 5.5, for additional information

9.3 First invocation: OpenACC library API

In this second use case (see below), a function in the OpenACC library is called prior to any of the functions in the CUBLAS library. More specifically, the function `acc_set_device_num()`.

In the use case presented here, the function `acc_set_device_num()` is used to both initialize the OpenACC library and allocate the hardware resources on the host and the device. In the call to the function, the call parameters specify which device to use and what device type to use, i.e., `acc_device_nvidia`. It should be noted that this is but one method to initialize the OpenACC library and allocate the appropriate hardware resources. Other methods are available through the use of environment variables and these is discussed in the next section.

Once the call to `acc_set_device_num()` has completed, other OpenACC functions can be called as seen with multiple calls being made to `acc_copyin()`. In addition, calls can be made to functions in the CUBLAS library. In the use case a call to `cublasCreate()` is made subsequent to the calls to `acc_copyin()`. As seen in the previous use case, a call to `cublasCreate()` initializes the CUBLAS library and allocates the hardware resources on the host and the device. However, since the device has already been allocated, `cublasCreate()` only initializes the CUBLAS library and allocates the appropriate hardware resources on the host. The context that was created as part of the OpenACC initialization is shared with the CUBLAS library, similarly to the first use case.

```
dev = 0;

acc_set_device_num(dev, acc_device_nvidia);

/* Copy the first set to the device */
d_X = acc_copyin(&h_X[0], N * sizeof (float));
if (d_X == NULL)
{
    fprintf(stderr, "copyin error h_X\n");
    exit(EXIT_FAILURE);
}

/* Copy the second set to the device */
d_Y = acc_copyin(&h_Y1[0], N * sizeof (float));
if (d_Y == NULL)
{
    fprintf(stderr, "copyin error h_Y1\n");
    exit(EXIT_FAILURE);
}

/* Create the handle */
s = cublasCreate(&h);
if (s != CUBLAS_STATUS_SUCCESS)
{
    fprintf(stderr, "cublasCreate failed %d\n", s);
    exit(EXIT_FAILURE);
}

/* Perform saxpy using CUBLAS library function */
s = cublasSaxpy(h, N, &alpha, d_X, 1, d_Y, 1);
if (s != CUBLAS_STATUS_SUCCESS)
{
```

```
        fprintf(stderr, "cublasSaxpy failed %d\n", s);
        exit(EXIT_FAILURE);
    }

    /* Copy the results from the device */
    acc_memcpy_from_device(&h_Y1[0], d_Y, N * sizeof (float));
```

Use Case 2

9.4 OpenACC library and environment variables

There are two environment variables associated with the OpenACC library that may be used to control the device type and device number: `ACC_DEVICE_TYPE` and `ACC_DEVICE_NUM`, respectively. These two environment variables can be used as an alternative to calling `acc_set_device_num()`. As seen in the second use case, the device type and device number were specified using `acc_set_device_num()`. If however, the aforementioned environment variables were set, then the call to `acc_set_device_num()` would not be required.

The use of the environment variables is only relevant when an OpenACC function is called prior to a call to `cudaCreate()`. If `cudaCreate()` is called prior to a call to an OpenACC function, then you must call `acc_set_device_num()`²

² More complete information about `ACC_DEVICE_TYPE` and `ACC_DEVICE_NUM` can be found in sections 4.1 and 4.2 of the OpenACC (<https://www.openacc.org>) Application Programming Interface, Version 2.6.

10 OpenACC Profiling Interface

10.1 Implementation Status and Implementation-Defined Behavior

We’re implementing the OpenACC Profiling Interface as defined by the OpenACC 2.6 specification. We’re clarifying some aspects here as *implementation-defined behavior*, while they’re still under discussion within the OpenACC Technical Committee.

This implementation is tuned to keep the performance impact as low as possible for the (very common) case that the Profiling Interface is not enabled. This is relevant, as the Profiling Interface affects all the *hot* code paths (in the target code, not in the offloaded code). Users of the OpenACC Profiling Interface can be expected to understand that performance is impacted to some degree once the Profiling Interface is enabled: for example, because of the *runtime* (libgomp) calling into a third-party *library* for every event that has been registered.

We’re not yet accounting for the fact that *OpenACC events may occur during event processing*. We just handle one case specially, as required by CUDA 9.0 `nvprof`, that `acc_get_device_type` (Section 6.3 [`acc_get_device_type`], page 73)) may be called from `acc_ev_device_init_start`, `acc_ev_device_init_end` callbacks.

We’re not yet implementing initialization via a `acc_register_library` function that is either statically linked in, or dynamically via `LD_PRELOAD`. Initialization via `acc_register_library` functions dynamically loaded via the `ACC_PROFLIB` environment variable does work, as does directly calling `acc_prof_register`, `acc_prof_unregister`, `acc_prof_lookup`.

As currently there are no inquiry functions defined, calls to `acc_prof_lookup` always returns `NULL`.

There aren’t separate *start*, *stop* events defined for the event types `acc_ev_create`, `acc_ev_delete`, `acc_ev_alloc`, `acc_ev_free`. It’s not clear if these should be triggered before or after the actual device-specific call is made. We trigger them after.

Remarks about data provided to callbacks:

`acc_prof_info.event_type`

It’s not clear if for *nested* event callbacks (for example, `acc_ev_enqueue_launch_start` as part of a parent compute construct), this should be set for the nested event (`acc_ev_enqueue_launch_start`), or if the value of the parent construct should remain (`acc_ev_compute_construct_start`). In this implementation, the value generally corresponds to the innermost nested event type.

`acc_prof_info.device_type`

- For `acc_ev_compute_construct_start`, and in presence of an `if` clause with *false* argument, this still refers to the offloading device type. It’s not clear if that’s the expected behavior.
- Complementary to the item before, for `acc_ev_compute_construct_end`, this is set to `acc_device_host` in presence of an `if` clause with *false* argument. It’s not clear if that’s the expected behavior.

- Callbacks for these event types will also be invoked when processing variable mappings specified in OpenACC *declare* directives. It's not clear if they should be.

Callbacks for the following event types will be invoked, but dispatch and information provided therein has not yet been thoroughly reviewed:

- `acc_ev_alloc`
- `acc_ev_free`
- `acc_ev_update_start`, `acc_ev_update_end`
- `acc_ev_enqueue_upload_start`, `acc_ev_enqueue_upload_end`
- `acc_ev_enqueue_download_start`, `acc_ev_enqueue_download_end`

During device initialization, and finalization, respectively, callbacks for the following event types will not yet be invoked:

- `acc_ev_alloc`
- `acc_ev_free`

Callbacks for the following event types have not yet been implemented, so currently won't be invoked:

- `acc_ev_device_shutdown_start`, `acc_ev_device_shutdown_end`
- `acc_ev_runtime_shutdown`
- `acc_ev_create`, `acc_ev_delete`
- `acc_ev_wait_start`, `acc_ev_wait_end`

For the following runtime library functions, not all expected callbacks will be invoked (mostly concerning implicit device initialization):

- `acc_get_num_devices`
- `acc_set_device_type`
- `acc_get_device_type`
- `acc_set_device_num`
- `acc_get_device_num`
- `acc_init`
- `acc_shutdown`

Aside from implicit device initialization, for the following runtime library functions, no callbacks will be invoked for shared-memory offloading devices (it's not clear if they should be):

- `acc_malloc`
- `acc_free`
- `acc_copyin`, `acc_present_or_copyin`, `acc_copyin_async`
- `acc_create`, `acc_present_or_create`, `acc_create_async`
- `acc_copyout`, `acc_copyout_async`, `acc_copyout_finalize`, `acc_copyout_finalize_async`
- `acc_delete`, `acc_delete_async`, `acc_delete_finalize`, `acc_delete_finalize_async`

- `acc_update_device`, `acc_update_device_async`
- `acc_update_self`, `acc_update_self_async`
- `acc_map_data`, `acc_unmap_data`
- `acc_memcpy_to_device`, `acc_memcpy_to_device_async`
- `acc_memcpy_from_device`, `acc_memcpy_from_device_async`

- The `allocate` clause, except when the `allocator` modifier is a constant expression with value `omp_default_mem_alloc` and no `align` modifier has been specified. (In that case, the normal `malloc` allocation is used.)
- The `allocate` directive for variables in static memory; while the alignment is honored, the normal static memory is used.
- Using the `allocate` directive for automatic/stack variables, except when the `allocator` clause is a constant expression with value `omp_default_mem_alloc` and no `align` clause has been specified. (In that case, the normal allocation is used: stack allocation and, sometimes for Fortran, also `malloc` [depending on flags such as `-fstack-arrays`].)
- In Fortran, the `allocators` directive and the executable `allocate` directive for Fortran pointers and allocatables is supported, but requires that files containing those directives has to be compiled with `-fopenmp-allocators`. Additionally, all files that might explicitly or implicitly deallocate memory allocated that way must also be compiled with that option.
- The used alignment is the maximum of the value the `align` clause and the alignment of the type after honoring, if present, the `aligned` (GNU::`aligned`) attribute and C's `_Alignas` and C++'s `alignas`. However, the `align` clause of the `allocate` directive has no effect on the value of C's `_Alignof` and C++'s `alignof`.

GCC supports the following predefined allocators and predefined memory spaces:

Predefined allocators	Associated predefined memory spaces
<code>omp_default_mem_alloc</code>	<code>omp_default_mem_space</code>
<code>omp_large_cap_mem_alloc</code>	<code>omp_large_cap_mem_space</code>
<code>omp_const_mem_alloc</code>	<code>omp_const_mem_space</code>
<code>omp_high_bw_mem_alloc</code>	<code>omp_high_bw_mem_space</code>
<code>omp_low_lat_mem_alloc</code>	<code>omp_low_lat_mem_space</code>
<code>omp_cgroup_mem_alloc</code>	<code>omp_low_lat_mem_space</code> (implementation defined)
<code>omp_pteam_mem_alloc</code>	<code>omp_low_lat_mem_space</code> (implementation defined)
<code>omp_thread_mem_alloc</code>	<code>omp_low_lat_mem_space</code> (implementation defined)
<code>ompx_gnu_pinned_mem_alloc</code>	<code>omp_default_mem_space</code> (GNU extension)
<code>ompx_gnu_managed_mem_alloc</code>	<code>ompx_gnu_managed_mem_space</code> (GNU extension)

Each predefined allocator, including `omp_null_allocator`, has a corresponding allocator class template that meet the C++ allocator completeness requirements. These are located in the `omp::allocator` namespace, and the `ompx::allocator` namespace for gnu extensions. This allows the allocator-aware C++ standard library containers to use OpenMP allocation routines; for instance:

```
std::vector<int, omp::allocator::cgroup_mem<int>> vec;
```

The following allocator templates are supported:

Predefined allocators	Associated allocator template
<code>omp_null_allocator</code>	<code>omp::allocator::null_allocator</code>

- `ompx_gnu_managed_mem_space` is a GNU extension that provides managed memory accessible by both host and devices. The memory space is available if the offload target associated with the *default-device-var* ICV supports managed memory (see Chapter 12 [Offload-Target Specifics], page 113). This memory is accessible by both the host and the device at the same address, so it need not be mapped with `map` clauses. Instead, use the `is_device_ptr` clause or `has_device_addr` clause to indicate that the pointer is already accessible on the device. If managed memory is not supported by the default device, as configured at the moment the allocator is called, then the allocator will use the fall-back setting. If the default device is configured differently when the memory is freed, via `omp_free` or `omp_realloc`, the result may be undefined.

On Linux systems, where the memkind library (<https://github.com/memkind/memkind>) (`libmemkind.so.0`) is available at runtime and the respective memkind kind is supported, it is used when creating memory allocators requesting

- the `partition` trait `interleaved` except when the memory space is `omp_large_cap_mem_space` (uses `MEMKIND_HBW_INTERLEAVE`)
- the memory space is `omp_high_bw_mem_space` (uses `MEMKIND_HBW_PREFERRED`)
- the memory space is `omp_large_cap_mem_space` (uses `MEMKIND_DAX_KMEM_ALL` or, if not available, `MEMKIND_DAX_KMEM`)

On Linux systems, where the numa library (<https://github.com/numactl/numactl>) (`libnuma.so.1`) is available at runtime, it is used when creating memory allocators requesting

- the `partition` trait `nearest`, except when both the libmemkind library is available and the memory space is either `omp_large_cap_mem_space` or `omp_high_bw_mem_space`

Note that the numa library will round up the allocation size to a multiple of the system page size; therefore, consider using it only with large data or by sharing allocations via the `pool_size` trait. Furthermore, the Linux kernel does not guarantee that an allocation will always be on the nearest NUMA node nor that after reallocation the same node will be used. Note additionally that, on Linux, the default setting of the memory placement policy is to use the current node; therefore, unless the memory placement policy has been overridden, the `partition` trait `environment` (the default) will be effectively a `nearest` allocation.

Additional notes regarding the traits:

- The `pinned` trait is supported on Linux hosts, but is usually subject to the OS `ulimit/rlimit` locked memory settings (see Chapter 12 [Offload-Target Specifics], page 113, for exceptions). The implementation uses a custom allocator to try to use as few memory pages as possible. At present, freed pinned memory is not returned to the OS (although it may be reused by subsequent pinned allocations).
- The default for the `pool_size` trait is no pool and for every (re)allocation the associated library routine is called, which might internally use a memory pool. Currently, the same applies when a `pool_size` has been specified, except that once allocations exceed the pool size, the action of the `fallback` trait applies.
- For the `partition` trait, the partition part size will be the same as the requested size (i.e. `interleaved` or `blocked` has no effect), except for `interleaved` when the memkind library is available. Furthermore, for `nearest` and unless the numa library is available, the memory might not be on the same NUMA node as thread that allocated

the memory; on Linux, this is in particular the case when the memory placement policy is set to preferred.

- The `access` trait has no effect such that memory is always accessible by all threads. (Except on supported no-host devices.)
- The `sync_hint` trait has no effect.

See also: Chapter 12 [Offload-Target Specifics], page 113,

12 Offload-Target Specifics

The following sections present notes on the offload-target specifics

12.1 AMD Radeon (GCN)

On the hardware side, there is the hierarchy (fine to coarse):

- work item (thread)
- wavefront
- work group
- compute unit (CU)

All OpenMP and OpenACC levels are used, i.e.

- OpenMP's `simd` and OpenACC's vector map to work items (thread)
- OpenMP's threads ("parallel") and OpenACC's workers map to wavefronts
- OpenMP's teams and OpenACC's gang use a threadpool with the size of the number of teams or gangs, respectively.

The used sizes are

- Number of teams is the specified `num_teams` (OpenMP) or `num_gangs` (OpenACC) or otherwise the number of CU. It is limited by two times the number of CU.
- Number of wavefronts is 4 for gfx900 and 16 otherwise; `num_threads` (OpenMP) and `num_workers` (OpenACC) overrides this if smaller.
- The wavefront has 102 scalars and 64 vectors
- Number of workitems is always 64
- The hardware permits maximally 40 workgroups/CU and 16 wavefronts/workgroup up to a limit of 40 wavefronts in total per CU.
- 80 scalars registers and 24 vector registers in non-kernel functions (the chosen procedure-calling API).
- For the kernel itself: as many as register pressure demands (number of teams and number of threads, scaled down if registers are exhausted)

The implementation remark:

- I/O within OpenMP target regions and OpenACC compute regions is supported using the C library `printf` functions and the Fortran `print/write` statements.
- Reverse offload regions (i.e. `target` regions with `device(ancestor:1)`) are processed serially per `target` region such that the next reverse offload region is only executed after the previous one returned.
- OpenMP code that has a `requires` directive with `self_maps` or `unified_shared_memory` is only supported if *all* the AMD GPUs present have the `HSA_AMD_SYSTEM_INFO_SVM_ACCESSIBLE_BY_DEFAULT` property; some systems require the "xnack" feature enabled for this to be true, in which case the runtime will attempt to set the `HSA_XNACK` environment variable to '1' automatically (user-set values are not overridden, and the setting only affects the executable itself and any child processes). If any AMD GPU device is not supported, all AMD GPUs are removed from the list of available devices ("host fallback").

- The available stack size can be changed using the `GCN_STACK_SIZE` environment variable; the default is 32 kiB per thread.
- Low-latency memory (`omp_low_lat_mem_space`) is supported when the `access` trait is set to `cgroup`. The default pool size is automatically scaled to share the 64 kiB LDS memory between the number of teams configured to run on each compute-unit, but may be adjusted at runtime by setting environment variable `GOMP_GCN_LOWLAT_POOL=bytes`.
- `omp_low_lat_mem_alloc` cannot be used with true low-latency memory because the definition implies the `omp_atv_all` trait; main graphics memory is used instead.
- `omp_cgroup_mem_alloc`, `omp_pteam_mem_alloc`, and `omp_thread_mem_alloc`, all use low-latency memory as first preference, and fall back to main graphics memory when the low-latency pool is exhausted.
- Pinned memory allocated using `omp_alloc` with the `ompx_gnu_pinned_mem_alloc` allocator or the `pinned` trait is obtained via the CUDA API when an NVPTX device is present. This provides a performance boost for NVPTX offload code and also allows unlimited use of pinned memory regardless of the OS `ulimit/rlimit` settings.
- Managed memory allocated on the host with the `ompx_gnu_managed_mem_alloc` allocator or in the `ompx_gnu_managed_mem_space` (both GNU extensions) allocate memory equivalent to HIP Managed Memory, although *not* actually allocated using `hipMallocManaged`. This memory is accessible by both the host and the device at the same address, so it need not be mapped with `map` clauses. Instead, use the `is_device_ptr` clause or `has_device_addr` clause to indicate that the pointer is already accessible on the device. The ROCm runtime will automatically handle data migration between host and device as needed. Not all AMD GPU devices support this feature, and many that do require that `-mxnack=on` is configured at compile time. If managed memory is not supported by the default device, as configured at the moment the allocator is called, then the allocator will use the fall-back setting. If the default device is configured differently when the memory is freed, via `omp_free` or `omp_realloc`, the result may be undefined. If the current device does not support Unified Shared Memory (or it is not enabled with `HSA_XNACK=1`) then Managed Memory might still work, but allocations may only be visible to a single device (whichever was the default device when the *first* allocation was made).
- The OpenMP routines `omp_target_memcpy_rect` and `omp_target_memcpy_rect_async` and the `target update` directive for non-contiguous list items use the 3D memory-copy function of the HSA library. Higher dimensions call this functions in a loop and are therefore supported.
- The unique identifier (UID), used with OpenMP's API UID routines, is the value returned by the HSA runtime library for `HSA_AMD_AGENT_INFO_UUID`. For GPUs, it is currently 'GPU-' followed by 16 lower-case hex digits, yielding a string like `GPU-f914a2142fc3413a`. The output matches the one used by `rocminfo`.

12.1.1 OpenMP interop – Foreign-Runtime Support for AMD GPUs

On AMD GPUs, the foreign runtimes are HIP (C++ Heterogeneous-Compute Interface for Portability) and HSA (Heterogeneous System Architecture), where HIP is the default. The

- warp
- thread block
- streaming multiprocessor

All OpenMP and OpenACC levels are used, i.e.

- OpenMP's `simd` and OpenACC's vector map to threads
- OpenMP's threads ("parallel") and OpenACC's workers map to warps
- OpenMP's teams and OpenACC's gang use a threadpool with the size of the number of teams or gangs, respectively.

The used sizes are

- The `warp_size` is always 32
- CUDA kernel launched: `dim={#teams,1,1}`, `blocks={#threads,warp_size,1}`.
- The number of teams is limited by the number of blocks the device can host simultaneously.

Additional information can be obtained by setting the environment variable to `GOMP_DEBUG=1` (very verbose; grep for `kernel.*launch` for launch parameters).

GCC generates generic PTX ISA code, which is just-in-time compiled by CUDA, which caches the JIT in the user's directory (see CUDA documentation; can be tuned by the environment variables `CUDA_CACHE_{DISABLE,MAXSIZE,PATH}`).

Note: While PTX ISA is generic, the `-mptx=` and `-march=` commandline options still affect the used PTX ISA code and, thus, the requirements on CUDA version and hardware.

The implementation remark:

- I/O within OpenMP target regions and OpenACC compute regions is supported using the C library `printf` functions. Additionally, the Fortran `print/write` statements are supported within OpenMP target regions, but not yet within OpenACC compute regions.
- Compilation OpenMP code that contains `requires reverse_offload` requires at least `-march=sm_35`, compiling for `-march=sm_30` is not supported.
- For code containing reverse offload (i.e. target regions with `device(ancestor:1)`), there is a slight performance penalty for *all* target regions, consisting mostly of shut-down delay Per device, reverse offload regions are processed serially such that the next reverse offload region is only executed after the previous one returned.
- OpenMP code that has a `requires` directive with `self_maps` or `unified_shared_memory` runs on nvptx devices if and only if all of those support the `pageableMemoryAccess` property;¹ otherwise, all nvptx device are removed from the list of available devices ("host fallback").
- The default per-warp stack size is 128 kiB; see also `-msoft-stack` in the GCC manual.
- Low-latency memory (`omp_low_lat_mem_space`) is supported when the `access` trait is set to `cgroup`, and libgomp has been built for PTX ISA version 4.1 or higher (such as in GCC's default configuration). The default pool size is 8 kiB per team,

¹ <https://docs.nvidia.com/cuda/cuda-c-programming-guide/index.html#um-requirements>

but may be adjusted at runtime by setting environment variable `GOMP_NVPTX_LOWLAT_POOL=bytes`. The maximum value is limited by the available hardware, and care should be taken that the selected pool size does not unduly limit the number of teams that can run simultaneously.

- `omp_low_lat_mem_alloc` cannot be used with true low-latency memory because the definition implies the `omp_atv_all` trait; main graphics memory is used instead.
- `omp_cgroup_mem_alloc`, `omp_pteam_mem_alloc`, and `omp_thread_mem_alloc`, all use low-latency memory as first preference, and fall back to main graphics memory when the low-latency pool is exhausted.
- Managed memory allocated on the host with the `ompx_gnu_managed_mem_alloc` allocator or in the `ompx_gnu_managed_mem_space` (both GNU extensions) allocate memory in the CUDA Managed Memory space using `cuMemAllocManaged`. This memory is accessible by both the host and the device at the same address, so it need not be mapped with `map` clauses. Instead, use the `is_device_ptr` clause or `has_device_addr` clause to indicate that the pointer is already accessible on the device. The CUDA runtime will automatically handle data migration between host and device as needed. If managed memory is not supported by the default device, as configured at the moment the allocator is called, then the allocator will use the fall-back setting. If the default device is configured differently when the memory is freed, via `omp_free` or `omp_realloc`, the result may be undefined.
- The OpenMP routines `omp_target_memcpy_rect` and `omp_target_memcpy_rect_async` and the `target update` directive for non-contiguous list items use the 2D and 3D memory-copy functions of the CUDA library. Higher dimensions call those functions in a loop and are therefore supported.
- The unique identifier (UID), used with OpenMP's API UID routines, consists of the 'GPU-' prefix followed by the 16-bytes UUID as returned by the CUDA runtime library. This UUID is output in grouped lower-case hex digits; the grouping of those 32 digits is: 8 digits, hyphen, 4 digits, hyphen, 4 digits, hyphen, 16 digits. This leads to a string like `GPU-a8081c9e-f03e-18eb-1827-bf5ba95afa5d`. The output matches the format used by `nvidia-smi`.

12.2.1 OpenMP interop – Foreign-Runtime Support for Nvidia GPUs

On Nvidia GPUs, the foreign runtimes APIs are the CUDA runtime API, the CUDA driver API, and HIP, the C++ Heterogeneous-Compute Interface for Portability that is—on CUDA-based systems—a very thin layer on top of the CUDA API. By default, CUDA is used. The interop object is created using OpenMP's `interop` directive or, implicitly, when invoking a `declare variant` procedure that has the `append_args` clause. In either case, the `prefer_type` modifier determines whether CUDA, CUDA driver, or HSA is used.

When specifying the `targetsync` modifier, a CUDA stream is created using the `CU_STREAM_DEFAULT` flag.

Invoke the Section 3.11 [Interoperability Routines], page 46, on an interop object to obtain the following properties. For properties with integral (int), pointer (ptr), or string (str) data type, call `omp_get_interop_int`, `omp_get_interop_ptr`, or `omp_get_interop_`

13 The libgomp ABI

The following sections present notes on the external ABI as presented by libgomp. Only maintainers should need them.

13.1 Implementing MASKED and MASTER construct

```
if (omp_get_thread_num () == thread_num)
    block
```

Hereby, *thread_num* has the value of the argument to the `filter` clause or zero if not specified.

Alternately, we generate two copies of the parallel subfunction and only include this in the version run by the *thread_num* thread. Surely this is not worthwhile though...

13.2 Implementing CRITICAL construct

Without a specified name,

```
void GOMP_critical_start (void);
void GOMP_critical_end (void);
```

so that we don't get COPY relocations from libgomp to the main application.

With a specified name, use `omp_set_lock` and `omp_unset_lock` with name being transformed into a variable declared like

```
omp_lock_t gomp_critical_user_<name> __attribute__((common))
```

Ideally the ABI would specify that all zero is a valid unlocked state, and so we wouldn't need to initialize this at startup.

13.3 Implementing ATOMIC construct

The target should implement the `__sync` builtins.

Failing that we could add

```
void GOMP_atomic_enter (void)
void GOMP_atomic_exit (void)
```

which reuses the regular lock code, but with yet another lock object private to the library.

13.4 Implementing FLUSH construct

Expands to the `__sync_synchronize` builtin.

13.5 Implementing BARRIER construct

```
void GOMP_barrier (void)
```

13.6 Implementing THREADPRIVATE construct

In `_most_` cases we can map this directly to `__thread`. Except that OMP allows constructors for C++ objects. We can either refuse to support this (how often is it used?) or we can implement something akin to `.ctors`.

Even more ideally, this ctor feature is handled by extensions to the main pthreads library. Failing that, we can have a set of entry points to register ctor functions to be called.

13.7 Implementing PRIVATE clause

In association with a PARALLEL, or within the lexical extent of a PARALLEL block, the variable becomes a local variable in the parallel subfunction.

In association with FOR or SECTIONS blocks, create a new automatic variable within the current function. This preserves the semantic of new variable creation.

13.8 Implementing FIRSTPRIVATE LASTPRIVATE COPYIN and COPYPRIVATE clauses

This seems simple enough for PARALLEL blocks. Create a private struct for communicating between the parent and subfunction. In the parent, copy in values for scalar and "small" structs; copy in addresses for others TREE_ADDRESSABLE types. In the subfunction, copy the value into the local variable.

It is not clear what to do with bare FOR or SECTION blocks. The only thing I can figure is that we do something like:

```
#pragma omp for firstprivate(x) lastprivate(y)
for (int i = 0; i < n; ++i)
  body;
```

which becomes

```
{
  int x = x, y;

  // for stuff

  if (i == n)
    y = y;
}
```

where the "x=x" and "y=y" assignments actually have different uids for the two variables, i.e. not something you could write directly in C. Presumably this only makes sense if the "outer" x and y are global variables.

COPYPRIVATE would work the same way, except the structure broadcast would have to happen via SINGLE machinery instead.

13.9 Implementing REDUCTION clause

The private struct mentioned in the previous section should have a pointer to an array of the type of the variable, indexed by the thread's *team_id*. The thread stores its final value into the array, and after the barrier, the primary thread iterates over the array to collect the values.

13.10 Implementing PARALLEL construct

```
#pragma omp parallel
{
  body;
}
```

becomes

```
void subfunction (void *data)
{
```

```

    use data;
    body;
}

setup data;
GOMP_parallel_start (subfunction, &data, num_threads);
subfunction (&data);
GOMP_parallel_end ();

void GOMP_parallel_start (void (*fn)(void *), void *data, unsigned num_threads)

```

The *FN* argument is the subfunction to be run in parallel.

The *DATA* argument is a pointer to a structure used to communicate data in and out of the subfunction, as discussed above with respect to *FIRSTPRIVATE* et al.

The *NUM_THREADS* argument is 1 if an *IF* clause is present and false, or the value of the *NUM_THREADS* clause, if present, or 0.

The function needs to create the appropriate number of threads and/or launch them from the dock. It needs to create the team structure and assign team ids.

```
void GOMP_parallel_end (void)
```

Tears down the team and returns us to the previous `omp_in_parallel()` state.

13.11 Implementing FOR construct

```

#pragma omp parallel for
for (i = lb; i <= ub; i++)
    body;

```

becomes

```

void subfunction (void *data)
{
    long _s0, _e0;
    while (GOMP_loop_static_next (&_s0, &_e0))
    {
        long _e1 = _e0, i;
        for (i = _s0; i < _e1; i++)
            body;
    }
    GOMP_loop_end_nowait ();
}

GOMP_parallel_loop_static (subfunction, NULL, 0, lb, ub+1, 1, 0);
subfunction (NULL);
GOMP_parallel_end ();

#pragma omp for schedule(runtime)
for (i = 0; i < n; i++)
    body;

```

becomes

```

{
    long i, _s0, _e0;
    if (GOMP_loop_runtime_start (0, n, 1, &_s0, &_e0))
        do {
            long _e1 = _e0;
            for (i = _s0, i < _e0; i++)
                body;
        } while (GOMP_loop_runtime_next (&_s0, &_e0));
}

```

```
GOMP_loop_end ();
}
```

Note that while it looks like there is trickiness to propagating a non-constant STEP, there isn't really. We're explicitly allowed to evaluate it as many times as we want, and any variables involved should automatically be handled as PRIVATE or SHARED like any other variables. So the expression should remain evaluable in the subfunction. We can also pull it into a local variable if we like, but since its supposed to remain unchanged, we can also not if we like.

If we have SCHEDULE(STATIC), and no ORDERED, then we ought to be able to get away with no work-sharing context at all, since we can simply perform the arithmetic directly in each thread to divide up the iterations. Which would mean that we wouldn't need to call any of these routines.

There are separate routines for handling loops with an ORDERED clause. Bookkeeping for that is non-trivial...

13.12 Implementing ORDERED construct

```
void GOMP_ordered_start (void)
void GOMP_ordered_end (void)
```

13.13 Implementing SECTIONS construct

A block as

```
#pragma omp sections
{
    #pragma omp section
    stmt1;
    #pragma omp section
    stmt2;
    #pragma omp section
    stmt3;
}
```

becomes

```
for (i = GOMP_sections_start (3); i != 0; i = GOMP_sections_next ())
    switch (i)
    {
        case 1:
            stmt1;
            break;
        case 2:
            stmt2;
            break;
        case 3:
            stmt3;
            break;
    }
GOMP_barrier ();
```

13.14 Implementing SINGLE construct

A block like

```
#pragma omp single
```

```

{
    body;
}

```

becomes

```

if (GOMP_single_start ())
    body;
GOMP_barrier ();

```

while

```

#pragma omp single copyprivate(x)
    body;

```

becomes

```

datap = GOMP_single_copy_start ();
if (datap == NULL)
{
    body;
    data.x = x;
    GOMP_single_copy_end (&data);
}
else
    x = datap->x;
GOMP_barrier ();

```

13.15 Implementing OpenACC's PARALLEL construct

```

void GOACC_parallel ()

```


14 Reporting Bugs

Bugs in the GNU Offloading and Multi Processing Runtime Library should be reported via Bugzilla (<https://gcc.gnu.org/bugzilla/>). Please add "openacc", or "openmp", or both to the keywords field in the bug report, as appropriate.

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Version 3, 29 June 2007

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Library Index

A

acc_get_property 74
 acc_get_property_string 74

E

Environment Variable ... 59, 60, 61, 62, 63, 64, 65,
 66, 67, 68

F

FDL, GNU Free Documentation License 139

I

Implementation specific setting.. 63, 65, 66, 68, 107