SYCL™ 2020 Specification (revision 7)

The Khronos® SYCL™ Working Group

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Chapter 2. Introduction

SYCL (pronounced “sickle”) is a royalty-free, cross-platform abstraction C++ programming model for heterogeneous computing. SYCL builds on the underlying concepts, portability and efficiency of parallel API or standards like OpenCL while adding much of the ease of use and flexibility of single-source C++.

Developers using SYCL are able to write standard modern C++ code, with many of the techniques they are accustomed to, such as inheritance and templates. At the same time, developers have access to the full range of capabilities of the underlying implementation (such as OpenCL) both through the features of the SYCL libraries and, where necessary, through interoperation with code written directly using the underneath implementation, via their APIs.

To reduce programming effort and increase the flexibility with which developers can write code, SYCL extends the concepts found in standards like OpenCL model in a few ways beyond the general use of C++ features:

- execution of parallel kernels on a heterogeneous device is made simultaneously convenient and flexible. Common parallel patterns are prioritized with simple syntax, which through a series C++ types allow the programmer to express additional requirements, such as synchronization, if needed;
- when using buffers and accessors, data access in SYCL is separated from data storage. By relying on the C++-style resource acquisition is initialization (RAII) idiom to capture data dependencies between device code blocks, the runtime library can track data movement and provide correct behavior without the complexity of manually managing event dependencies between kernel instances and without the programmer having to explicitly move data. This approach enables the data-parallel task-graphs that might be already part of the execution model to be built up easily and safely by SYCL programmers;
- Unified Shared Memory (USM) provides a mechanism for explicit data allocation and movement. This approach enables the use of pointer-based algorithms and data structures on heterogeneous devices, and allows for increased re-use of code across host and device;
- the hierarchical parallelism syntax offers a way of expressing data parallelism similar to the OpenCL device or OpenMP target device execution model in an easy-to-understand modern C++ form. It more cleanly layers parallel loops and synchronization points to avoid fragmentation of code and to more efficiently map to CPU-style architectures.

SYCL retains the execution model, runtime feature set and device capabilities inspired by the OpenCL standard. This standard imposes some limitations on the full range of C++ features that SYCL is able to support. This ensures portability of device code across as wide a range of devices as possible. As a result, while the code can be written in standard C++ syntax with interoperability with standard C++ programs, the entire set of C++ features is not available in SYCL device code. In particular, SYCL device code, as defined by this specification, does not support virtual function calls, function pointers in general, exceptions, runtime type information or the full set of C++ libraries that may depend on these features or on features of a particular host compiler. Nevertheless, these basic restrictions can be relieved by some specific Khronos or vendor extensions.

SYCL implements an SMCP design which offers the power of source integration while allowing toolchains to remain flexible. The SMCP design supports embedding of code intended to be compiled for a device, for example a GPU, inline with host code. This embedding of code offers three primary benefits:

Simplicity

For novice programmers using frameworks like OpenCL, the separation of host and device source code in OpenCL can become complicated to deal with, particularly when similar kernel code is used for multiple different operations on different data types. A single compiler flow and integrated tool chain combined with libraries that perform a lot of simple tasks simplifies initial OpenCL programs to a minimum complexity. This reduces the learning curve for programmers new to heterogeneous programming and allows them to concentrate on parallelization techniques rather than syntax.

Reuse

C++'s type system allows for complex interactions between different code units and supports efficient abstract interface design and reuse of library code. For example, a transform or map operation applied to an array of data may allow specialization on both the operation applied to each element of the array and on the type of the data. The SMCP design of SYCL enables this interaction to bridge the host code/device code boundary such that the device code to be specialized on both of these factors directly from the host code.

Efficiency

Tight integration with the type system and reuse of library code enables a compiler to perform inlining of code and to produce efficient specialized device code based on decisions made in the host code without having to generate kernel source strings dynamically.

The use of C++ features such as generic programming, templated code, functional programming and inheritance on top of existing heterogeneous execution model opens a wide scope for innovation in software design for heterogeneous systems. Clean integration of device and host code within a single C++ type system enables the development of modern, templated generic and adaptable libraries that build simple, yet efficient, interfaces to offer more developers access to heterogeneous computing capabilities and devices. SYCL is intended to serve as a foundation for innovation in programming models for heterogeneous systems, that builds on open and widely implemented standard foundation like OpenCL or Vulkan.

SYCL is designed to be as close to standard C++ as possible. In practice, this means that as long as no dependence is created on SYCL's integration with the underlying implementation, a standard C++ compiler can compile SYCL programs and they will run correctly on a host CPU. Any use of specialized low-level features can be masked using the C preprocessor in the same way that compiler-specific intrinsics may be hidden to ensure portability between different host compilers.

SYCL is designed to allow a compilation flow where the source file is passed through multiple different compilers, including a standard C++ host compiler of the developer's choice, and where the resulting application combines the results of these compilation passes. This is distinct from a single-source flow that might use language extensions that preclude the use of a standard host compiler. The SYCL standard does not preclude the use of a single compiler flow, but is designed to not require it. SYCL can also be implemented purely as a library, in which case no special compiler support is required at all.

The advantages of this design are two-fold. First, it offers better integration with existing tool chains. An application that already builds using a chosen compiler can continue to do so when SYCL code is added. Using the SYCL tools on a source file within a project will both compile for a device and let the same source file be compiled using the same host compiler that the rest of the project is compiled with. Linking and library relationships are unaffected. This design simplifies porting of pre-existing applications to SYCL. Second, the design allows the optimal compiler to be chosen for each device where different vendors may provide optimized tool-chains.

To summarize, SYCL enables computational kernels to be written inside C++ source files as normal C++ code, leading to the concept of "single-source" programming. This means that software developers can develop and use generic algorithms and data structures using standard C++ template techniques, while still supporting multi-platform, multi-device heterogeneous execution. Access to the low level APIs of an underlying implementation (such as OpenCL) is also supported. The specification has been designed to enable implementation across as wide a variety of platforms as possible as well as ease of integration with other platform-specific technologies, thereby letting both users and implementers build on top of SYCL as an open platform for system-wide heterogeneous processing innovation.

Chapter 3. SYCL architecture

This chapter describes the structure of a SYCL application, and how the SYCL generic programming model lays out on top of a number of SYCL backends.

3.1. Overview

SYCL is an open industry standard for programming a heterogeneous system. The design of SYCL allows standard C++ source code to be written such that it can run on either an heterogeneous device or on the host.

The terminology used for SYCL inherits historically from OpenCL with some SYCL-specific additions. However SYCL is a generic C++ programming model that can be laid out on top of other heterogeneous APIs apart from OpenCL. SYCL implementations can provide SYCL backends for various heterogeneous APIs, implementing the SYCL general specification on top of them. We refer to this heterogeneous API as the SYCL backend API. The SYCL general specification defines the behavior that all SYCL implementations must expose to SYCL users for a SYCL application to behave as expected.

A function object that can execute on a device exposed by a SYCL backend API is called a SYCL kernel function.

To ensure maximum interoperability with different SYCL backend APIs, software developers can access the SYCL backend API alongside the SYCL general API whenever they include the SYCL backend interoperability headers. However, interoperability is a SYCL backend-specific feature. An application that uses interoperability does not conform to the SYCL general application model, since it is not portable across backends.

The target users of SYCL are C++ programmers who want all the performance and portability features of a standard like OpenCL, but with the flexibility to use higher-level C++ abstractions across the host/device code boundary. Developers can use most of the abstraction features of C++, such as templates, classes and operator overloading.

However, some C++ language features are not permitted inside kernels, due to the limitations imposed by the capabilities of the underlying heterogeneous platforms. These features include virtual functions, virtual inheritance, throwing/catching exceptions, and run-time type-information. These features are available outside kernels as normal. Within these constraints, developers can use abstractions defined by SYCL, or they can develop their own on top. These capabilities make SYCL ideal for library developers, middleware providers and application developers who want to separate low-level highly-tuned algorithms or data structures that work on heterogeneous systems from higher-level software development. Software developers can produce templated algorithms that are easily usable by developers in other fields.

3.2. Anatomy of a SYCL application

Below is an example of a typical SYCL application which schedules a job to run in parallel on any heterogeneous device available.

```
1 #include <iostream>
2 #include <sycl/sycl.hpp>
3 using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names
4
5 int main() {
6   int data[1024]; // Allocate data to be worked on
7
8   // Create a default queue to enqueue work to the default device
```

```
 9  queue myQueue;
10
11  // By wrapping all the SYCL work in a {} block, we ensure
12  // all SYCL tasks must complete before exiting the block,
13  // because the destructor of resultBuf will wait
14  {
15    // Wrap our data variable in a buffer
16    buffer<int, 1> resultBuf { data, range<1> { 1024 } };
17
18    // Create a command group to issue commands to the queue
19    myQueue.submit([&](handler& cgh) {
20      // Request write access to the buffer without initialization
21      accessor writeResult { resultBuf, cgh, write_only, no_init };
22
23      // Enqueue a parallel_for task with 1024 work-items
24      cgh.parallel_for(1024, [=](id<1> idx) {
25        // Initialize each buffer element with its own rank number starting at 0
26        writeResult[idx] = idx;
27      }); // End of the kernel function
28    });   // End of our commands for this queue
29  }       // End of scope, so we wait for work producing resultBuf to complete
30
31  // Print result
32  for (int i = 0; i < 1024; i++)
33    std::cout << "data[" << i << "] = " << data[i] << std::endl;
34
35  return 0;
36 }
```

At line 1, we `#include` the SYCL header files, which provide all of the SYCL features that will be used.

A SYCL application runs on a SYCL Platform. The application is structured in three scopes which specify the different sections; application scope, command group scope and kernel scope. The kernel scope specifies a single kernel function that will be, or has been, compiled by a device compiler and executed on a device. In this example kernel scope is defined by lines 25 to 26. The command group scope specifies a unit of work which is comprised of a SYCL kernel function and accessors. In this example command group scope is defined by lines 20 to 28. The application scope specifies all other code outside of a command group scope. These three scopes are used to control the application flow and the construction and lifetimes of the various objects used within SYCL, as explained in Section 3.9.12.

A SYCL kernel function is the scoped block of code that will be compiled using a device compiler. This code may be defined by the body of a lambda function or by the `operator()` function of a function object. Each instance of the SYCL kernel function will be executed as a single, though not necessarily entirely independent, flow of execution and has to adhere to restrictions on what operations may be allowed to enable device compilers to safely compile it to a range of underlying devices.

The `parallel_for` member function can be templated with a class. This class is used to manually name the kernel when desired, such as to avoid a compiler-generated name when debugging a kernel defined through a lambda, to provide a known name with which to apply build options to a kernel, or to ensure compatibility with multiple compiler-pass implementations.

The `parallel_for` member function creates an instance of a kernel, which is the entity that will be enqueued within a command group. In the case of `parallel_for` the SYCL kernel function will be executed over the given range from 0 to 1023. The different member functions to execute kernels can be found in Section 4.9.4.2.

A command group scope is the syntactic scope wrapped by the construction of a command group function object as seen on line 19. The command group function object may invoke only a single SYCL kernel function, and it takes a parameter of type command group `handler`, which is constructed by the runtime.

All the requirements for a kernel to execute are defined in this command group scope, as described in Section 3.7.1. In this case the constructor used for `myQueue` on line 9 is the default constructor, which allows the queue to select the best underlying device to execute on, leaving the decision up to the runtime.

In SYCL, data that is required within a SYCL kernel function must be contained within a buffer, image, or USM allocation, as described in Section 3.8. We construct a buffer on line 16. Access to the buffer is controlled via an accessor which is constructed on line 21. The buffer is used to keep track of access to the data and the accessor is used to request access to the data on a queue, as well as to track the dependencies between SYCL kernel function. In this example the accessor is used to write to the data buffer on line 26.

3.3. Normative references

The documents in the following list are referred to within this SYCL specification, and their content is a requirement for this document.

1. **C++17:** ISO/IEC 14882:2017 Clauses 1-19, referred to in this specification as the C++ core language. The SYCL specification refers to language in the following C++ defect reports and assumes a compiler that implements them: DR2325.
2. **C++20:** ISO/IEC 14882:2020 Programming languages — C++, referred to in this specification as the next C++ specification.

3.4. Non-normative notes and examples

Unless stated otherwise, text within this SYCL specification is normative and defines the required behavior of a SYCL implementation. Non-normative / informational notes are included within this specification using a “note” callout, of the form:

Information within a note callout, such as this text, is for informational purposes and does not impose requirements on or specify behavior of a SYCL implementation.

Source code examples within the specification are provided to aid with understanding, and are non-normative.

In case of any conflict between a non-normative note or source example, and normative text within the specification, the normative text must be taken to be correct.

3.5. The SYCL platform model

The SYCL platform model is based on the OpenCL platform model. The model consists of a host connected to one or more heterogeneous devices, called devices.

A SYCL context is constructed, either directly by the user or implicitly when creating a queue, to hold all the runtime information required by the SYCL runtime and the SYCL backend to operate on a device, or group of devices. When a group of devices can be grouped together on the same context, they have some visibility of each other’s memory objects. The SYCL runtime can assume that memory is visible across all devices in the same context. Not all devices exposed from the same platform can be grouped together in the same context.

A SYCL application executes on the host as a standard C++ program. Devices are exposed through differ-

ent SYCL backends to the SYCL application. The SYCL application submits command group function objects to queues. Each queue enables execution on a given device.

The SYCL runtime then extracts operations from the command group function object, e.g. an explicit copy operation or a SYCL kernel function. When the operation is a SYCL kernel function, the SYCL runtime uses a SYCL backend-specific mechanism to extract the device binary from the SYCL application and pass it to the heterogeneous API for execution on the device.

A SYCL device is divided into one or more compute units (CUs) which are each divided into one or more processing elements (PEs). Computations on a device occur within the processing elements. How computation is mapped to PEs is SYCL backend and device specific. Two devices exposed via two different backends can map computations differently to the same device.

When a SYCL application contains SYCL kernel function objects, the SYCL implementation must provide an offline compilation mechanism that enables the integration of the device binaries into the SYCL application. The output of the offline compiler can be an intermediate representation, such as SPIR-V, that will be finalized during execution or a final device ISA.

A device may expose special purpose functionality as a *built-in* function. The SYCL API exposes functions to query and dispatch said *built-in* functions. Some SYCL backends and devices may not support programmable kernels, and only support *built-in* functions.

3.6. The SYCL backend model

SYCL is a generic programming model for the C++ language that can target multiple heterogeneous APIs, such as OpenCL.

SYCL implementations enable these target APIs by implementing SYCL backends. For a SYCL implementation to be conformant on said SYCL backend, it must execute the SYCL generic programming model on the backend. All SYCL implementations must provide at least one backend.

The present document covers the SYCL generic interface available to all SYCL backends. How the SYCL generic interface maps to a particular SYCL backend is defined either by a separate SYCL backend specification document, provided by the Khronos SYCL group, or by the SYCL implementation documentation. Whenever there is a SYCL backend specification document, this takes precedence over SYCL implementation documentation.

When a SYCL user builds their SYCL application, she decides which of the SYCL backends will be used to build the SYCL application. This is called the set of *active backends*. Implementations must ensure that the active backends selected by the user can be used simultaneously by the SYCL implementation at runtime. If two backends are available at compile time but will produce an invalid SYCL application at runtime, the SYCL implementation must emit a compilation error.

A SYCL application built with a number of active backends does not necessarily guarantee that said backends can be executed at runtime. The subset of active backends available at runtime is called *available backends*. A backend is said to be *available* if the host platform where the SYCL application is executed exposes support for the heterogeneous API required for the SYCL backend.

It is implementation dependent whether certain backends require third-party libraries to be available in the system. Failure to have all dependencies required for all active backends at runtime will cause the SYCL application to not run.

Once the application is running, users can query what SYCL platforms are available. SYCL implementations will expose the devices provided by each backend grouped into platforms. A backend must expose at least one platform.

Under the SYCL backend model, SYCL objects can contain one or multiple references to a certain SYCL backend native type. Not all SYCL objects will map directly to a SYCL backend native type. The mapping

of SYCL objects to SYCL backend native types is defined by the SYCL backend specification document when available, or by the SYCL implementation otherwise.

To guarantee that multiple SYCL backend objects can interoperate with each other, SYCL memory objects are not bound to a particular SYCL backend. SYCL memory objects can be accessed from any device exposed by an *available* backend. SYCL Implementations can potentially map SYCL memory objects to multiple native types in different SYCL backends.

Since SYCL memory objects are independent of any particular SYCL backend, SYCL command groups can request access to memory objects allocated by any SYCL backend, and execute it on the backend associated with the queue. This requires the SYCL implementation to be able to transfer memory objects across SYCL backends.

USM allocations are subject to the limitations described in Section 4.8.

When a SYCL application runs on any number of SYCL backends without relying on any SYCL backend -specific behavior or interoperability, it is said to be a SYCL general application, and it is expected to run in any SYCL-conformant implementation that supports the required features for the application.

3.6.1. Platform mixed version support

The SYCL generic programming model exposes a number of platforms, each of them exposing a number of devices. Each platform is bound to a certain SYCL backend. SYCL devices associated with said platform are associated with that SYCL backend.

Although the APIs in the SYCL generic programming model are defined according to this specification and their version is indicated by the macro `SYCL_LANGUAGE_VERSION`, this does not apply to APIs exposed by the SYCL backends. Each SYCL backend provides its own document that defines its APIs, and that document tells how to query for the device and platform versions.

3.7. SYCL execution model

As described in Section 3.2, a SYCL application is comprised of three scopes: application scope, command group scope, and kernel scope. Code in the application scope and command group scope runs on the host and is governed by the *SYCL application execution model*. Code in the kernel scope runs on a device and is governed by the *SYCL kernel execution model*.

A SYCL device does not necessarily correspond to a physical accelerator. A SYCL implementation may choose to expose some or all of the host's resources as a SYCL device; such an implementation would execute code in kernel scope on the host, but that code would still be governed by the *SYCL kernel execution model*.

3.7.1. SYCL application execution model

The SYCL application defines the execution order of the kernels by grouping each kernel with its requirements into a command group function object. Command group function objects are submitted for execution via a queue object, which defines the device where the kernel will run. This specification sometimes refers to this as "submitting the kernel to a device". The same command group object can be submitted to different queues. When a command group is submitted to a SYCL queue, the requirements of the kernel execution are captured. The implementation can start executing a kernel as soon as its requirements have been satisfied.

3.7.1.1. SYCL backend resources managed by the SYCL application

The SYCL runtime integrated with the SYCL application will manage the resources required by the SYCL backend API to manage the heterogeneous devices it is providing access to. This includes, but is not lim-

ited to, resource handlers, memory pools, dispatch queues and other temporary handler objects.

The SYCL programming interface represents the lifetime of the resources managed by the SYCL application using RAII rules. Construction of a SYCL object will typically entail the creation of multiple SYCL backend objects, which will be properly released on destruction of said SYCL object. The overall rules for construction and destruction are detailed in Chapter 4. Those SYCL backends with a SYCL backend document will detail how the resource management from SYCL objects map down to the SYCL backend objects.

In SYCL, the minimum required object for submitting work to devices is the queue, which contains references to a platform, device and a context internally.

The resources managed by SYCL are:

1. Platforms: all features of SYCL backend APIs are implemented by platforms. A platform can be viewed as a given vendor's runtime and the devices accessible through it. Some devices will only be accessible to one vendor's runtime and hence multiple platforms may be present. SYCL manages the different platforms for the user which are accessible through a `sycl::platform` object.
2. Contexts: any SYCL backend resource that is acquired by the user is attached to a context. A context contains a collection of devices that the host can use and manages memory objects that can be shared between the devices. Devices belonging to the same context must be able to access each other's global memory using some implementation-specific mechanism. A given context can only wrap devices owned by a single platform. A context is exposed to the user with a `sycl::context` object.
3. Devices: platforms provide one or more devices for executing SYCL kernels. In SYCL, a device is accessible through a `sycl::device` object.
4. Kernels: the SYCL functions that run on SYCL devices are defined as C++ function objects (a named function object type or a lambda function). A kernel can be introspected through a `sycl::kernel` object.

   Note that some SYCL backends may expose non-programmable functionality as pre-defined kernels.
5. Kernel bundles: Kernels are stored internally in the SYCL application as device images, and these device images can be grouped into a `sycl::kernel_bundle` object. These objects provide a way for the application to control the online compilation of kernels for devices.
6. Queues: SYCL kernels execute in command queues. The user must create a `sycl::queue` object, which references an associated context, platform and device. The context, platform and device may be chosen automatically, or specified by the user. SYCL queues execute kernels on a particular device of a particular context, but can have dependencies from any device on any available SYCL backend.

The SYCL implementation guarantees the correct initialization and destruction of any resource handled by the underlying SYCL backend API, except for those the user has obtained manually via the SYCL interoperability API.

3.7.1.2. SYCL command groups and execution order

By default, SYCL queues execute kernel functions in an out-of-order fashion based on dependency information. Developers only need to specify what data is required to execute a particular kernel. The SYCL runtime will guarantee that kernels are executed in an order that guarantees correctness. By specifying access modes and types of memory, a directed acyclic dependency graph (DAG) of kernels is built at runtime. This is achieved via the usage of command group objects. A SYCL command group object defines a set of requisites (R) and a kernel function (k). A command group is *submitted* to a queue when using the `sycl::queue::submit` member function.

A **requisite** (r_i) is a requirement that must be fulfilled for a kernel-function (k) to be executed on a particular device. For example, a requirement may be that certain data is available on a device, or that another command group has finished execution. An implementation may evaluate the requirements of a

command group at any point after it has been submitted. The *processing of a command group* is the process by which a SYCL runtime evaluates all the requirements in a given *R*. The SYCL runtime will execute *k* only when all r_i are satisfied (i.e., when all requirements are satisfied). To simplify the notation, in the specification we refer to the set of requirements of a command group named *foo* as $CG_{foo} = r_1, ..., r_n$.

The *evaluation of a requisite* (Satisfied(r_i)) returns the status of the requisite, which can be *True* or *False*. A *satisfied* requisite implies the requirement is met. Satisfied(r_i) never alters the requisite, only observes the current status. The implementation may not block to check the requisite, and the same check can be performed multiple times.

An **action** (a_i) is a collection of implementation-defined operations that must be performed in order to satisfy a requisite. The set of actions for a given command group *A* is permitted to be empty if no operation is required to satisfy the requirement. The notation a_i represents the action required to satisfy r_i. Actions of different requisites can be satisfied in any order with respect to each other without side effects (i.e., given two requirements r_j and r_k, $(r_j, r_k) \equiv (r_k, r_j)$). The intersection of two actions is not necessarily empty. **Actions** can include (but are not limited to): memory copy operations, mapping operations, host side synchronization, or implementation-specific behavior.

Finally, *Performing an action* (Perform(a_i)) executes the action operations required to satisfy the requisite r_j. Note that, after Perform(a_i), the evaluation Satisfied(r_j) will return *True* until the kernel is executed. After the kernel execution, it is not defined whether a different command group with the same requirements needs to perform the action again, where actions of different requisites inside the same command group object can be satisfied in any order with respect to each other without side effects: Given two requirements r_j and r_k, Perform(a_j) followed by Perform(a_k) is equivalent to Perform(a_k) followed by Perform(a_j).

The requirements of different command groups submitted to the same or different queues are evaluated in the relative order of submission. command group objects whose intersection of requirement sets is not empty are said to depend on each other. They are executed in order of submission to the queue. If command groups are submitted to different queues or by multiple threads, the order of execution is determined by the SYCL runtime. Note that independent command group objects can be submitted simultaneously without affecting dependencies.

Table 1 illustrates the execution order of three command group objects (CG_a,CG_b,CG_c) with certain requirements submitted to the same queue. Both CG_a and CG_b only have one requirement, r_1 and r_2 respectively. CG_c requires both r_1 and r_2. This enables the SYCL runtime to potentially execute CG_a and CG_b simultaneously, whereas CG_c cannot be executed until both CG_a and CG_b have been completed. The SYCL runtime evaluates the **requisites** and performs the **actions** required (if any) for the CG_a and CG_b. When evaluating the **requisites** of CG_c, they will be satisfied once the CG_a and CG_b have finished.

Table 1. Execution order of three command groups submitted to the same queue

SYCL Application Enqueue Order	SYCL Kernel Execution Order

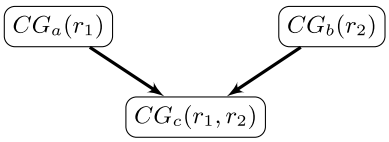
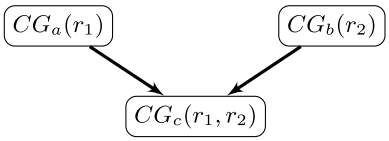
`sycl::queue syclQueue;`
`syclQueue.submit(CGa(r1));`
`syclQueue.submit(CGb(r2));`
`syclQueue.submit(CGc(r1,r2));`
	

Table 2 uses three separate SYCL queue objects to submit the same command group objects as before. Regardless of using three different queues, the execution order of the different command group objects is the same. When different threads enqueue to different queues, the execution order of the command group will be the order in which the submit member functions are executed. In this case, since the different command group objects execute on different devices, the **actions** required to satisfy the **requirements** may be different (e.g, the SYCL runtime may need to copy data to a different device in a separate context).

Table 2. Execution order of three command groups submitted to the different queues

SYCL Application Enqueue Order	SYCL Kernel Execution Order

`sycl::queue syclQueue1;`
`sycl::queue syclQueue2;`
`sycl::queue syclQueue3;`
`syclQueue1.submit(CGa(r1));`
`syclQueue2.submit(CGb(r2));`
`syclQueue3.submit(CGc(r1,r2));`
	

3.7.1.3. Controlling execution order with events

Submitting an action for execution returns an `event` object. Programmers may use these events to explicitly synchronize programs. Host code can wait for an event to complete, which will block execution on the host until the action represented by the event has completed. The `event` class is described in greater detail in Section 4.6.6.

Events may also be used to explicitly order the execution of kernels. Host code may wait for the completion of specific event, which blocks execution on the host until that event's action has completed. Events may also define requisites between command groups. Using events in this manner informs the runtime that one or more command groups must complete before another command group may begin executing. See Section 4.9.4.1 for greater detail.

3.7.2. SYCL kernel execution model

When a kernel is submitted for execution, an index space is defined. An instance of the kernel body executes for each point in this index space. This kernel instance is called a work-item and is identified by its point in the index space, which provides a global id for the work-item. Each work-item executes the same code but the specific execution pathway through the code and the data operated upon can vary by using the work-item global id to specialize the computation.

An index space of size zero is allowed. All aspects of kernel execution proceed as normal with the exception that the kernel function itself is not executed. Note this means the command queue will still schedule this kernel after satisfying the requirements and this satisfies requirements of any dependent enqueued kernels.

3.7.2.1. Basic kernels

SYCL allows a simple execution model in which a kernel is invoked over an *N*-dimensional index space defined by `range<N>`, where *N* is one, two or three. Each work-item in such a kernel executes independently.

Each work-item is identified by a value of type `item<N>`. The type `item<N>` encapsulates a work-item identifier of type `id<N>` and a `range<N>` representing the number of work-items executing the kernel.

3.7.2.2. ND-range kernels

Work-items can be organized into work groups, providing a more coarse-grained decomposition of the index space. Each work-group is assigned a unique work-group id with the same dimensionality as the index space used for the work-items. Work-items are each assigned a local id, unique within the work-group, so that a single work-item can be uniquely identified by its global id or by a combination of its local id and work-group id. The work-items in a given work-group execute on the processing elements of a single compute unit.

When work-groups are used in SYCL, the index space is called an nd-range. An ND-range is an *N*-dimensional index space, where *N* is one, two or three. In SYCL, the ND-range is represented via the

`nd_range<N>` class. An `nd_range<N>` is made up of a global range and a local range, each represented via values of type `range<N>`. Additionally, there can be a global offset, represented via a value of type `id<N>`; this is deprecated in SYCL 2020. The types `range<N>` and `id<N>` are each *N*-element arrays of integers. The iteration space defined via an `nd_range<N>` is an *N*-dimensional index space starting at the ND-range's global offset whose size is its global range, split into work-groups of the size of its local range.

Each work-item in the ND-range is identified by a value of type `nd_item<N>`. The type `nd_item<N>` encapsulates a global id, local id and work-group id, all of type `id<N>` (the iteration space offset also of type `id<N>`, but this is deprecated in SYCL 2020), as well as global and local ranges and synchronization operations necessary to make work-groups useful. Work-groups are assigned ids using a similar approach to that used for work-item global ids. Work-items are assigned to a work-group and given a local id with components in the range from zero to the size of the work-group in that dimension minus one. Hence, the combination of a work-group id and the local id within a work-group uniquely defines a work-item.

3.7.2.3. Backend-specific kernels

SYCL allows a SYCL backend to expose fixed functionality as non-programmable built-in kernels. The availability and behavior of these built-in kernels are SYCL backend-specific, and are not required to follow the SYCL execution and memory models. Furthermore the interface exposed utilize these built-in kernels is also SYCL backend-specific. See the relevant backend specification for details.

3.8. Memory model

Since SYCL is a single-source programming model, the memory model affects both the application and the device kernel parts of a program. On the SYCL application, the SYCL runtime will make sure data is available for execution of the kernels. On the SYCL device kernel, the SYCL backend rules describing how the memory behaves on a specific device are mapped to SYCL C++ constructs. Thus it is possible to program kernels efficiently in pure C++.

3.8.1. SYCL application memory model

The application running on the host uses SYCL buffer objects using instances of the `sycl::buffer` class or USM allocation functions to allocate memory in the global address space, or can allocate specialized image memory using the `sycl::unsampled_image` and `sycl::sampled_image` classes.

In the SYCL application, memory objects are bound to all devices in which they are used, regardless of the SYCL context where they reside. SYCL memory objects (namely, buffer and image objects) can encapsulate multiple underlying SYCL backend memory objects together with multiple host memory allocations to enable the same object to be shared between devices in different contexts, platforms or backends. USM allocations uniquely identify a memory allocation and are bound to a SYCL context. They are only valid on the backend used by the context.

The order of execution of command group objects ensures a sequentially consistent access to the memory from the different devices to the memory objects. Accessing a USM allocation does not alter the order of execution. Users must explicitly inform the SYCL runtime of any requirements necessary for a legal execution.

To access a memory object, the user must create an accessor object which parameterizes the type of access to the memory object that a kernel or the host requires. The accessor object defines a requirement to access a memory object, and this requirement is defined by construction of an accessor, regardless of whether there are any uses in a kernel or by the host. An accessor object specifies whether the access is via global memory, constant memory or image samplers and their associated access functions. The accessor also specifies whether the access is read-only (RO), write-only (WO) or read-write (RW). An optional `no_init` property can be added to an accessor to tell the system to discard any previous contents of the data the accessor refers to, so there are two additional requirement types: no-init-write-only (NWO) and no-init-read-write (NRW). For simplicity, when a **requisite** represents an accessor object in a

certain access mode, we represent it as MemoryObject$_{\text{AccessMode}}$. For example, an accessor that accesses memory object **buf1** in **RW** mode is represented as *buf1*$_{RW}$. A command group object that uses such an accessor is represented as *CG(buf1*$_{RW}$*)*. The **action** required to satisfy a requisite and the location of the latest copy of a memory object will vary depending on the implementation.

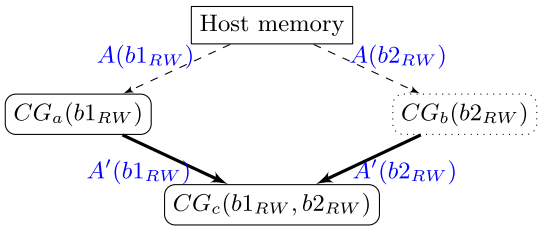
Table 3 illustrates an example where command group objects are enqueued to two separate SYCL queues executing in devices in different contexts. The **requisites** for the command group execution are the same, but the **actions** to satisfy them are different. For example, if the data is on the host before execution, *A(b1*$_{RW}$*)* and *A(b2*$_{RW}$*)* can potentially be implemented as copy operations from the host memory to `context1` or `context2` respectively. After CG_a and CG_b are executed, *A'(b1*$_{RW}$*)* will likely be an empty operation, since the result of the kernel can stay on the device. On the other hand, the results of CG_b are now on a different context than CG_c is executing, therefore *A'(b2*$_{RW}$*)* will need to copy data across two separate contexts using an implementation specific mechanism.

Table 3. Actions performed when three command groups are submitted to two distinct queues

SYCL Application Enqueue Order

```
sycl::queue q1(context1);
sycl::queue q2(context2);
q1.submit(CGa(b1RW));
q2.submit(CGb(b2RW));
q1.submit(CGc(b1RW,b2RW));
```

SYCL Kernel Execution Order



Possible implementation by a SYCL Runtime

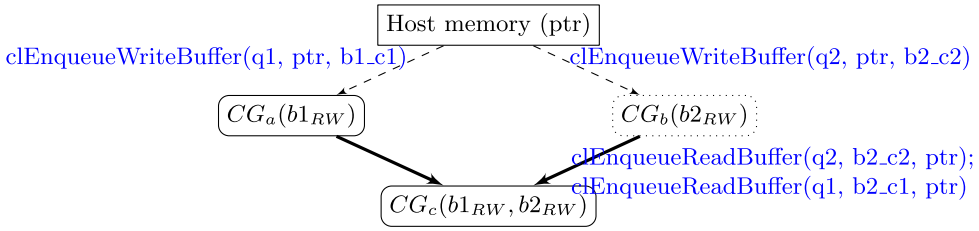


Table 3 shows actions performed when three command groups are submitted to two distinct queues, and potential implementation in an OpenCL SYCL backend by a SYCL runtime. Note that in this example, each SYCL buffer (*b2,b2*) is implemented as separate `cl_mem` objects per context.

Note that the order of the definition of the accessors within the command group is irrelevant to the requirements they define. All accessors always apply to the entire command group object where they are defined.

When multiple accessors in the same command group define different requisites to the same memory object these requisites must be resolved.

Firstly, any requisites with different access modes but the same access target are resolved into a single requisite with the union of the different access modes according to Table 4. The atomic access mode acts as if it was read-write (RW) when determining the combined requirement. The rules in Table 4 are commutative and associative.

Table 4. Combined requirement from two different accessor access modes within the same command group. The rules are commutative and associative

One access mode	Other access mode	Combined requirement
read (RO)	write (WO)	read-write (RW)
read (RO)	read-write (RW)	read-write (RW)
write (WO)	read-write (RW)	read-write (RW)
no-init-write (NWO)	no-init-read-write (NRW)	no-init-read-write (NRW)
no-init-write (NWO)	write (WO)	write (WO)
no-init-write (NWO)	read (RO)	read-write (RW)
no-init-write (NWO)	read-write (RW)	read-write (RW)
no-init-read-write (NRW)	write (WO)	read-write (RW)
no-init-read-write (NRW)	read (RO)	read-write (RW)
no-init-read-write (NRW)	read-write (RW)	read-write (RW)

The result of this should be that there should not be any requisites with the same access target.

Secondly, the remaining requisites must adhere to the following rule. Only one of the requisites may have write access (*W* or *RW*), otherwise the SYCL runtime must throw an exception. All requisites create a requirement for the data they represent to be made available in the specified access target, however only the requisite with write access determines the side effects of the command group, i.e. only the data which that requisite represents will be updated.

For example:

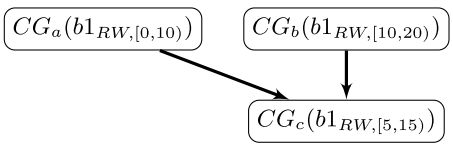
- $CG(b1^{G}_{RW}, b1^{H}_{R})$ is permitted.
- $CG(b1^{G}_{RW}, b1^{H}_{RW})$ is **not** permitted.
- $CG(b1^{G}_{W}, b1^{C}_{RW})$ is **not** permitted.

Where *G* and *C* correspond to a `target::device` and `target::constant_buffer` accessor and *H* corresponds to a host accessor.

A buffer created from a range of an existing buffer is called a sub-buffer. A buffer may be overlaid with any number of sub-buffers. Accessors can be created to operate on these sub-buffers. Refer to Section 4.7.2 for details on sub-buffer creation and restrictions. A requirement to access a sub-buffer is represented by specifying its range, e.g. $CG(b1_{RW,[0,5)})$ represents the requirement of accessing the range *[0,5)* buffer *b1* in read write mode.

If two accessors are constructed to access the same buffer, but both are to non-overlapping sub-buffers of the buffer, then the two accessors are said to not overlap, otherwise the accessors do overlap. Overlapping is the test that is used to determine the scheduling order of command groups. Command-groups with non-overlapping requirements may execute concurrently.

Table 5. Requirements on overlapping vs non-overlapping sub-buffer

SYCL Application Enqueue Order	SYCL Kernel Execution Order
`sycl::queue q1(context1);` $q1.submit(CG_a(b1_{\{RW,[0,10)\}}));$ $q1.submit(CG_b(b1_{\{RW,[10,20)\}}));$ $q1.submit(CG_c(b1_{RW,[5,15)}));$	

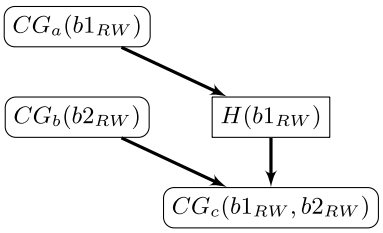
It is permissible for command groups that only read data to not copy that data back to the host or other devices after reading and for the runtime to maintain multiple read-only copies of the data on multiple

devices.

A special case of requirement is the one defined by a **host accessor**. Host accessors are represented with *H(MemoryObject$_{AccessMode}$)*, e.g, *H(b1$_{RW}$)* represents a host accessor to *b1* in read-write mode. Host accessors are a special type of accessor constructed from a memory object outside a command group, and require that the data associated with the given memory object is available on the host in the given pointer. This causes the runtime to block on construction of this object until the requirement has been satisfied. **Host accessor** objects are effectively barriers on all accesses to a certain memory object. Table 6 shows an example of multiple command groups enqueued to the same queue. Once the host accessor *H(b1$_{RW}$)* is reached, the execution cannot proceed until CG_a is finished. However, CG_b does not have any requirements on *b1*, therefore, it can execute concurrently with the barrier. Finally, CG_c will be enqueued after *H(b1$_{RW}$)* is finished, but still has to wait for CG_b to conclude for all its requirements to be satisfied. See Section 3.9.8 for details on synchronization rules.

Table 6. Execution of command groups when using host accessors

SYCL Application Enqueue Order	SYCL Kernel Execution Order

`sycl::queue q1;`
`q1.submit(CGa(b1RW));`
`q1.submit(CGb(b2RW));`
 	
`H(b1RW);`
 	
`q1.submit(CGc(b1RW, b2RW));`
	

3.8.2. SYCL device memory model

The memory model for SYCL devices is based on the OpenCL 1.2 memory model. Work-items executing in a kernel have access to three distinct address spaces (memory regions) and a virtual address space overlapping some concrete address spaces:

- Global-memory is accessible to all work-items in all work-groups. Work-items can read from or write to any element of a global memory object. Reads and writes to global memory may be cached depending on the capabilities of the device. Global memory is persistent across kernel invocations. Concurrent access to a location in an USM allocation by two or more executing kernels where at least one kernel modifies that location is a data race; there is no guarantee of correct results unless memfence and atomic operations are used.
- Local-memory is accessible to all work-items in a single work-group. Attempting to access local memory in one work-group from another work group results in undefined behavior. This memory region can be used to allocate variables that are shared by all work-items in a work-group. Work-group-level visibility allows local memory to be implemented as dedicated regions of the device memory where this is appropriate.
- Private-memory is a region of memory private to a work-item. Attempting to access private memory in one work-item from another work-item results in undefined behavior.
- Generic-memory is a virtual address space which overlaps the global, local and private address spaces. Therefore, an object that resides in the global, local, or private address space can also be accessed through the generic address space.

3.8.2.1. Access to memory

Accessors in the device kernels provide access to the memory objects, acting as pointers to the corresponding address space.

Pointers can be passed directly as kernel arguments if an implementation supports USM. See Section 4.8

for information on when it is legal to dereference pointers passed from the host inside kernels.

To allocate local memory within a kernel, the user can either pass a `sycl::local_accessor` object as a argument to an ND-range kernel (that has a user-defined work-group size), or can define a variable in work-group scope inside `sycl::parallel_for_work_group`.

Any variable defined inside a `sycl::parallel_for` scope or `sycl::parallel_for_work_item` scope will be allocated in private memory. Any variable defined inside a `sycl::parallel_for_work_group` scope will be allocated in local memory.

Users can create accessors that reference sub-buffers as well as entire buffers.

Within kernels, the underlying C++ pointer types can be obtained from an accessor. The pointer types will contain a compile-time deduced address space. So, for example, if a C++ pointer is obtained from an accessor to global memory, the C++ pointer type will have a global address space attribute attached to it. The address space attribute will be compile-time propagated to other pointer values when one pointer is initialized to another pointer value using a defined algorithm.

When developers need to explicitly state the address space of a pointer value, one of the explicit pointer classes can be used. There is a different explicit pointer class for each address space: `sycl::raw_local_ptr`, `sycl::raw_global_ptr`, `sycl::raw_private_ptr`, `sycl::raw_generic_ptr`, `sycl::decorated_local_ptr`, `sycl::decorated_global_ptr`, `sycl::decorated_private_ptr`, or `sycl::decorated_generic_ptr`.

The classes with the `decorated` prefix expose pointers that use an implementation-defined address space decoration, while the classes with the `raw` prefix do not. Buffer accessors with an access target `target::device` or `target::constant_buffer` and local accessors can be converted into explicit pointer classes (`multi_ptr`).

For templates that need to adapt to different address spaces, a `sycl::multi_ptr` class is defined which is templated via a compile-time constant enumerator value to specify the address space.

3.8.3. SYCL memory consistency model

The SYCL memory consistency model is based upon the memory consistency model of the C++ core language. Where SYCL offers extensions to classes and functions that may affect memory consistency, the default behavior when these extensions are not used always matches the behavior of standard C++.

A SYCL implementation must guarantee that the same memory consistency model is used across host and device code. Every device compiler must support the memory model defined by the minimum version of C++ described in Section 3.9.1; SYCL implementations supporting additional versions of C++ must also support the corresponding memory models.

Within a work-item, operations are ordered according to the *sequenced before* relation defined by the C++ core language.

Ensuring memory consistency across different work-items requires careful usage of group barrier operations, mem-fence operations and atomic operations. The ordering of operations across different work-items is determined by the *happens before* relation defined by the C++ core language, with a single relation governing all address spaces (memory regions).

On any SYCL device, local and global memory may be made consistent across work-items in a single group through use of a group barrier operation. On SYCL devices supporting acquire-release or sequentially consistent memory orderings, all memory visible to a set of work-items may be made consistent across the work-items in that set through the use of mem-fence and atomic operations.

Memory consistency between the host and SYCL device(s), or different SYCL devices in the same context, can be guaranteed through synchronization in the host application as defined in Section 3.9.8. On SYCL devices supporting concurrent atomic accesses to USM allocations and acquire-release or sequentially

consistent memory orderings, cross-device memory consistency can be enforced through the use of mem-fence and atomic operations.

3.8.3.1. Memory ordering

```
namespace sycl {

enum class memory_order : /* unspecified */ {
  relaxed,
  acquire,
  release,
  acq_rel,
  seq_cst
};

inline constexpr auto memory_order_relaxed = memory_order::relaxed;
inline constexpr auto memory_order_acquire = memory_order::acquire;
inline constexpr auto memory_order_release = memory_order::release;
inline constexpr auto memory_order_acq_rel = memory_order::acq_rel;
inline constexpr auto memory_order_seq_cst = memory_order::seq_cst;

} // namespace sycl
```

The memory synchronization order of a given atomic operation is controlled by a `sycl::memory_order` parameter, which can take one of the following values:

- `sycl::memory_order::relaxed`;
- `sycl::memory_order::acquire`;
- `sycl::memory_order::release`;
- `sycl::memory_order::acq_rel`;
- `sycl::memory_order::seq_cst`.

The meanings of these values are identical to those defined in the C++ core language.

The complete set of memory orders is not guaranteed to be supported by every device, nor across all combinations of devices within a context. The memory orders supported by a specific device and context can be queried using functionalities of the `sycl::device` and `sycl::context` classes, respectively.

SYCL implementations are not required to support a memory order equivalent to `std::memory_order::consume`, and using this ordering within a SYCL device kernel results in undefined behavior. Developers are encouraged to use `sycl::memory_order::acquire` instead.

3.8.3.2. Memory scope

```
namespace sycl {

enum class memory_scope : /* unspecified */ {
  work_item,
  sub_group,
  work_group,
  device,
  system
```

```
};

inline constexpr auto memory_scope_work_item = memory_scope::work_item;
inline constexpr auto memory_scope_sub_group = memory_scope::sub_group;
inline constexpr auto memory_scope_work_group = memory_scope::work_group;
inline constexpr auto memory_scope_device = memory_scope::device;
inline constexpr auto memory_scope_system = memory_scope::system;

} // namespace sycl
```

The set of work items and devices to which the memory ordering constraints of a given atomic operation apply is controlled by a `sycl::memory_scope` parameter, which can take one of the following values:

- `sycl::memory_scope::work_item` The ordering constraint applies only to the calling work-item;
- `sycl::memory_scope::sub_group` The ordering constraint applies only to work-items in the same sub-group as the calling work-item;
- `sycl::memory_scope::work_group` The ordering constraint applies only to work-items in the same work-group as the calling work-item;
- `sycl::memory_scope::device` The ordering constraint applies only to work-items executing on the same device as the calling work-item;
- `sycl::memory_scope::system` The ordering constraint applies to any work-item or host thread in the system that is currently permitted to access the memory allocation containing the referenced object, as defined by the capabilities of buffers and USM.

The broadest scope that can be applied to an atomic operation corresponds to the set of work-items which can access the associated memory location. For example, the broadest scope that can be applied to atomic operations in work-group local memory is `sycl::memory_scope::work_group`. If a broader scope is supplied, the behavior is as-if the narrowest scope containing all work-items which can access the associated memory location was supplied.

The addition of memory scopes to the C++ memory model modifies the definition of some concepts from the C++ core language. For example: data races, the synchronizes-with relationship and sequential consistency must be defined in a way that accounts for atomic operations with differing (but compatible) scopes, in a manner similar to the OpenCL 2.0 specification. Efforts to formalize the memory model of SYCL are ongoing, and a formal memory model will be included in a future version of the SYCL specification.

3.8.3.3. Atomic operations

Atomic operations can be performed on memory in buffers and USM. The `sycl::atomic_ref` class must be used to provide safe atomic access to the buffer or USM allocation from device code.

3.8.3.4. Forward progress

This section, and any subsequent section referring to progress guarantees, uses the following terms as defined in the C++ core language: thread of execution; weakly parallel forward progress guarantees; parallel forward progress guarantees; concurrent forward progress guarantees; and block with forward progress guarantee delegation.

Each work-item in SYCL is a separate thread of execution, providing at least weakly parallel forward progress guarantees. Whether work-items provide stronger forward progress guarantees is implementation-defined.

All implementations must additionally ensure that a work-item arriving at a group barrier does not pre-

vent other work-items in the same group from making progress. When a work-item arrives at a group barrier acting on group *G*, implementations must eventually select and potentially strengthen another work-item in group *G* that has not yet arrived at the barrier.

When a host thread blocks on the completion of a command previously submitted to a SYCL queue (for example, via the `sycl::queue::wait` function), it blocks with forward progress guarantee delegation.

SYCL commands submitted to a queue are not guaranteed to begin executing until a host thread blocks on their completion. In the absence of multiple host threads, there is no guarantee that host and device code will execute concurrently.

3.9. The SYCL programming model

A SYCL program is written in standard C++. Host code and device code is written in the same C++ source file, enabling instantiation of templated kernels from host code and also enabling kernel source code to be shared between host and device. The device kernels are encapsulated C++ callable types (a function object with `operator()` or a lambda function), which have been designated to be compiled as SYCL kernels.

SYCL programs target heterogeneous systems. The kernels may be compiled and optimized for multiple different processor architectures with very different binary representations.

3.9.1. Minimum version of C++

The C++ features used in SYCL are based on a specific version of C++. Implementations of SYCL must support this minimum C++ version, which defines the C++ constructs that can consequently be used by SYCL feature definitions (for example, lambdas).

The minimum C++ version of this SYCL specification is determined by the normative C++ core language defined in Section 3.3. All implementations of this specification must support at least this core language, and features within this specification are defined using features of the core language. Note that not all core language constructs are supported within SYCL kernel functions or code invoked by a SYCL kernel function, as detailed by Section 5.4.

Implementations may support newer C++ versions than the minimum required by SYCL. Code written using newer features than the SYCL requirement, though, may not be portable to other implementations that don't support the same C++ version.

3.9.2. Alignment with future versions of C++

Some features of SYCL are aligned with the next C++ specification, as defined in Section 3.3.

The following features are pre-adopted by SYCL 2020 and made available in the `sycl::` namespace: `std::span`, `std::dynamic_extent`, `std::bit_cast`. The implementations of pre-adopted features are compliant with the next C++ specification, and are expected to forward directly to standard C++ features in a future version of SYCL.

The following features of SYCL 2020 use syntax based on the next C++ specification: `sycl::atomic_ref`. These features behave as described in the next C++ specification, barring modifications to ensure compatibility with other SYCL 2020 features and heterogeneous programming. Any such modifications are documented in the corresponding sections of this specification.

3.9.3. Basic data parallel kernels

Data-parallel kernels that execute as multiple work-items and where no local synchronization is required are enqueued with the `sycl::parallel_for` function parameterized by a `sycl::range` parameter.

These kernels will execute the kernel function body once for each work-item in the specified range.

Functionality tied to groups of work-items, including group barriers and local memory, must not be used within these kernels.

Variables with reduction semantics can be added to basic data parallel kernels using the features described in Section 4.9.2.

3.9.4. Work-group data parallel kernels

Data parallel kernels can also execute in a mode where the set of work-items is divided into work-groups of user-defined dimensions. The user specifies the global range and local work-group size as parameters to the `sycl::parallel_for` function with a `sycl::nd_range` parameter. In this mode of execution, kernels execute over the nd-range in work-groups of the specified size. It is possible to share data among work-items within the same work-group in local or global memory and to synchronize between work-items in the same work-group by calling the `group_barrier` function. All work-groups in a given `parallel_for` will be the same size, and the global size defined in the nd-range must either be a multiple of the work-group size in each dimension, or the global size must be zero. When the global size is zero, the kernel function is not executed, the local size is ignored, and any dependencies are satisfied.

Work-groups may be further subdivided into sub-groups. The work-items that compose a sub-group are selected in an implementation-defined way, and therefore the size and number of sub-groups may differ for each kernel. Moreover, different devices may make different guarantees with respect to how sub-groups within a work-group are scheduled. The maximum number of work-items in any sub-group in a kernel is based on a combination of the kernel and its dispatch dimensions. The size of any sub-group in the dispatch is between 1 and this maximum sub-group size, and the size of an individual sub-group is invariant for the duration of a kernel's execution. Similarly to work-groups, the work-items within the same sub-group can be synchronized by calling the `group_barrier` function.

Portable device code must not assume that work-items within a sub-group execute in any particular order, that work-groups are subdivided into sub-groups in a specific way, nor that the work-items within a sub-group provide specific forward progress guarantees.

Variables with reduction semantics can be added to work-group data parallel kernels using the features described in Section 4.9.2.

3.9.5. Hierarchical data parallel kernels

Based on developer and implementation feedback, the hierarchical data parallel kernel feature described next is undergoing improvements to better align with the frameworks and patterns prevalent in modern programming. As this is a key part of the SYCL API and we expect to make changes to it, we temporarily recommend that new codes refrain from using this feature until the new API is finished in a near-future version of the SYCL specification, when full use of the updated feature will be recommended for use in new code. Existing codes using this feature will of course be supported by conformant implementations of this specification.

The SYCL compiler provides a way of specifying data parallel kernels that execute within work-groups via a different syntax which highlights the hierarchical nature of the parallelism. This mode is purely a compiler feature and does not change the execution model of the kernel. Instead of calling `sycl::parallel_for` the user calls `sycl::parallel_for_work_group` with a `sycl::range` value representing the number of work-groups to launch and optionally a second `sycl::range` representing the size of each work-group for performance tuning. All code within the `parallel_for_work_group` scope effectively executes once per work-group. Within the `parallel_for_work_group` scope, it is possible to call `parallel_for_work_item` which creates a new scope in which all work-items within the current work-group execute. This enables a programmer to write code that looks like there is an inner work-item loop inside an outer work-group loop,

which closely matches the effect of the execution model. All variables declared inside the `parallel_for_work_group` scope are allocated in work-group local memory, whereas all variables declared inside the `parallel_for_work_item` scope are declared in private memory. All `parallel_for_work_item` calls within a given `parallel_for_work_group` execution must have the same dimensions.

3.9.6. Kernels that are not launched over parallel instances

Simple kernels for which only a single instance of the kernel function will be executed are enqueued with the `sycl::single_task` function. The kernel enqueued takes no "work-item id" parameter and will only execute once. The behavior is logically equivalent to executing a kernel on a single compute unit with a single work-group comprising only one work-item. Such kernels may be enqueued on multiple queues and devices and as a result may be executed in task-parallel fashion.

3.9.7. Pre-defined kernels

Some SYCL backends may expose pre-defined functionality to users as kernels. These kernels are not programmable, hence they are not bound by the SYCL C++ programming model restrictions, and how they are written is implementation-defined.

3.9.8. Synchronization

Synchronization of processing elements executing inside a device is handled by the SYCL device kernel following the SYCL kernel execution model. The synchronization of the different SYCL device kernels executing with the host memory is handled by the SYCL application via the SYCL runtime.

3.9.8.1. Synchronization in the SYCL application

Synchronization points between host and device(s) are exposed through the following operations:

- *Buffer destruction*: The destructors for `sycl::buffer`, `sycl::unsampled_image` and `sycl::sampled_image` objects wait for all submitted work on those objects to complete and to copy the data back to host memory before returning. These destructors only wait if the object was constructed with attached host memory and if data needs to be copied back to the host.

  More complex forms of synchronization on buffer destruction can be specified by the user by constructing buffers with other kinds of references to memory, such as `shared_ptr` and `unique_ptr`.

- *Host Accessors*: The constructor for a host accessor waits for all kernels that modify the same buffer (or image) in any queues to complete and then copies data back to host memory before the constructor returns. Any command groups with requirements to the same memory object cannot execute until the host accessor is destroyed as shown on Table 6.
- *Command group enqueue*: The SYCL runtime internally ensures that any command groups added to queues have the correct event dependencies added to those queues to ensure correct operation. Adding command groups to queues never blocks. Instead any required synchronization is added to the queue and events of type `sycl::event` are returned by the queue's submit function that contain event information related to the specific command group.
- *Queue operations*: The user can manually use queue operations, such as `sycl::queue::wait()` to block execution of the calling thread until all the command groups submitted to the queue have finished execution. Note that this will also affect the dependencies of those command groups in other queues.
- *SYCL event objects*: SYCL provides `sycl::event` objects which can be used for synchronization. If synchronization is required across SYCL contexts from different SYCL backends, then the SYCL runtime ensures that extra host-based synchronization is added to enable the SYCL event objects to operate between contexts correctly.

Note that the destructors of other SYCL objects (`sycl::queue`, `sycl::context`,...) do not block. Only a `sycl::buffer`, `sycl::sampled_image` or `sycl::unsampled_image` destructor might block. The rationale is that

an object without any side effect on the host does not need to block on destruction as it would impact the performance. So it is up to the programmer to use a member function to wait for completion in some cases if this does not fit the goal. See Section 3.9.12 for more information on object life time.

3.9.8.2. Synchronization in SYCL kernels

In SYCL, synchronization can be either global or local within a group of work-items. Synchronization between work-items in a single group is achieved using a group barrier.

All the work-items of a group must execute the barrier before any are allowed to continue execution beyond the barrier. Note that the group barrier must be encountered by all work-items of a group executing the kernel or by none at all. In SYCL, work-group barrier and sub-group barrier functionality is exposed via the `group_barrier` function.

Synchronization between work-items in different work-groups via atomic operations is possible only on SYCL devices with certain capabilities, as described in Section 3.8.3.

3.9.9. Error handling

In SYCL, there are two types of errors: synchronous errors that can be detected immediately when an API call is made, and asynchronous errors that can only be detected later after an API call has returned. Synchronous errors, such as failure to construct an object, are reported immediately by the runtime throwing an exception. Asynchronous errors, such as an error occurring during execution of a kernel on a device, are reported via an asynchronous error-handler mechanism.

Asynchronous errors are not reported immediately as they occur. The asynchronous error handler for a context or queue is called with a `sycl::exception_list` object, which contains a list of asynchronously-generated exception objects, on the conditions described by Section 4.13.1.1 and Section 4.13.1.2.

Asynchronous errors may be generated regardless of whether the user has specified any asynchronous error handler(s), as described in Section 4.13.1.2.

Some SYCL backends can report errors that are specific to the platform they are targeting, or that are more concrete than the errors provided by the SYCL API. Any error reported by a SYCL backend must derive from the base `sycl::exception`. When a user wishes to capture specifically an error thrown by a SYCL backend, she must include the SYCL backend-specific headers for said SYCL backend.

3.9.10. Fallback mechanism

A command group function object can be submitted either to a single queue to be executed on, or to a secondary queue. If a command group function object fails to be enqueued to the primary queue, then the system will attempt to enqueue it to the secondary queue, if given as a parameter to the submit function. If the command group function object fails to be queued to both of these queues, then a synchronous SYCL exception will be thrown.

It is possible that a command group may be successfully enqueued, but then asynchronously fail to run, for some reason. In this case, it may be possible for the runtime system to execute the command group function object on the secondary queue, instead of the primary queue. The situations where a SYCL runtime may be able to achieve this asynchronous fall-back is implementation-defined.

3.9.11. Scheduling of kernels and data movement

A command group function object takes a reference to a command group `handler` as a parameter and anything within that scope is immediately executed and takes the handler object as a parameter. The intention is that a user will perform calls to SYCL functions, member functions, destructors and constructors inside that scope. These calls will be non-blocking on the host, but enqueue operations to the queue that the command group is submitted to. All user functions within the command group scope will

be called on the host as the command group function object is executed, but any commands it invokes will be added to the SYCL queue. All commands added to the queue will be executed out-of-order from each other, according to their data dependencies.

3.9.12. Managing object lifetimes

A SYCL application does not initialize any SYCL backend features until a `sycl::context` object is created. A user does not need to explicitly create a `sycl::context` object, but they do need to explicitly create a `sycl::queue` object, for which a `sycl::context` object will be implicitly created if not provided by the user.

All SYCL backend objects encapsulated in SYCL objects are reference-counted and will be destroyed once all references have been released. This means that a user needs only create a SYCL queue (which will automatically create an SYCL context) for the lifetime of their application to initialize and release any SYCL backend objects safely.

There is no global state specified to be required in SYCL implementations. This means, for example, that if the user creates two queues without explicitly constructing a common context, then a SYCL implementation does not have to create a shared context for the two queues. Implementations are free to share or cache state globally for performance, but it is not required.

Memory objects can be constructed with or without attached host memory. If no host memory is attached at the point of construction, then destruction of that memory object is non-blocking. The user may use C++ standard pointer classes for sharing the host data with the user application and for defining blocking, or non-blocking behavior of the buffers and images. If host memory is attached by using a raw pointer, then the default behavior is followed, which is that the destructor will block until any command groups operating on the memory object have completed, then, if the contents of the memory object is modified on a device those contents are copied back to host and only then does the destructor return.

In the case where host memory is shared between the user application and the SYCL runtime with a `std::shared_ptr`, then the reference counter of the `std::shared_ptr` determines whether the buffer needs to copy data back on destruction, and in that case the blocking or non-blocking behavior depends on the user application.

Instead of a `std::shared_ptr`, a `std::unique_ptr` may be provided, which uses move semantics for initializing and using the associated host memory. In this case, the behavior of the buffer in relation to the user application will be non-blocking on destruction.

As said in Section 3.9.8, the only blocking operations in SYCL (apart from explicit wait operations) are:

- host accessor constructor, which waits for any kernels enqueued before its creation that write to the corresponding object to finish and be copied back to host memory before it starts processing. The host accessor does not necessarily copy back to the same host memory as initially given by the user;
- memory object destruction, in the case where copies back to host memory have to be done or when the host memory is used as a backing-store.

3.9.13. Device discovery and selection

A user specifies which queue to submit a command group function object and each queue is targeted to run on a specific device (and context). A user can specify the actual device on queue creation, or they can specify a device selector which causes the SYCL runtime to choose a device based on the user's provided preferences. Specifying a device selector causes the SYCL runtime to perform device discovery. No device discovery is performed until a SYCL device selector is passed to a queue constructor. Device topology may be cached by the SYCL runtime, but this is not required.

Device discovery will return all devices from all platforms exposed by all the supported SYCL backends.

3.9.14. Interfacing with the SYCL backend API

There are two styles of developing a SYCL application:

1. writing a pure SYCL generic application;
2. writing a SYCL application that relies on some SYCL backend specific behavior.

When users follow 1., there is no assumption about what SYCL backend will be used during compilation or execution of the SYCL application. Therefore, the SYCL backend API is not assumed to be available to the developer. Only standard C++ types and interfaces are assumed to be available, as described in Section 3.9. Users only need to include the `<sycl/sycl.hpp>` header to write a SYCL generic application.

On the other hand, when users follow 2., they must know what SYCL backend APIs they are using. In this case, any header required for the normal programmability of the SYCL backend API is assumed to be available to the user. In addition to the `<sycl/sycl.hpp>` header, users must also include the SYCL backend-specific header as defined in Section 4.3. The SYCL backend-specific header provides the interoperability interface for the SYCL API to interact with native backend objects.

The interoperability API is defined in Section 4.5.1.

3.10. Memory objects

SYCL memory objects represent data that is handled by the SYCL runtime and can represent allocations in one or multiple devices at any time. Memory objects, both buffers and images, may have one or more underlying native backend objects to ensure that queues objects can use data in any device. A SYCL implementation may have multiple native backend objects for the same device. The SYCL runtime is responsible for ensuring the different copies are up-to-date whenever necessary, using whatever mechanism is available in the system to update the copies of the underlying native backend objects.

Implementation note

A valid mechanism for this update is to transfer the data from one SYCL backend into the system memory using the SYCL backend-specific mechanism available, and then transfer it to a different device using the mechanism exposed by the new SYCL backend.

Memory objects in SYCL fall into one of two categories: buffer objects and image objects. A buffer object stores a one-, two- or three-dimensional collection of elements that are stored linearly directly back to back in the same way C or C++ stores arrays. An image object is used to store a one-, two- or three-dimensional texture, frame-buffer or image data that may be stored in an optimized and device-specific format in memory and must be accessed through specialized operations.

Elements of a buffer object can be a scalar data type (such as an `int` or `float`), vector data type, or a user-defined structure. In SYCL, a buffer object is a templated type (`sycl::buffer`), parameterized by the element type and number of dimensions. An image object is stored in one of a limited number of formats. The elements of an image object are selected from a list of predefined image formats which are provided by an underlying SYCL backend implementation. Images are encapsulated in the `sycl::unsampled_image` or `sycl::sampled_image` types, which are templated by the number of dimensions in the image. The minimum number of elements in an image object is one. The minimum number of elements in a buffer object is zero.

The fundamental differences between a buffer and an image object are:

- elements in a buffer are stored in an array of 1, 2 or 3 dimensions and can be accessed using an accessor by a kernel executing on a device. The accessors for kernels provide a member function to get C++ pointer types, or the `sycl::global_ptr` class;
- elements of an image are stored in a format that is opaque to the user and cannot be directly accessed using a pointer. SYCL provides image accessors and samplers to allow a kernel to read from

or write to an image;

- for a buffer object the data is accessed within a kernel in the same format as it is stored in memory, but in the case of an image object the data is not necessarily accessed within a kernel in the same format as it is stored in memory;
- image elements are always a 4-component vector (each component can be a float or signed/unsigned integer) in a kernel. Accessors that read an image convert image elements from their storage format into a 4-component vector.

  Similarly, the SYCL accessor member functions provided to write to an image convert the image element from a 4-component vector to the appropriate image format specified such as four 8-bit elements, for example.

Users may want fine-grained control of the synchronization, memory management and storage semantics of SYCL image or buffer objects. For example, a user may wish to specify the host memory for a memory object to use, but may not want the memory object to block on destruction.

Depending on the control and the use cases of the SYCL applications, well established C++ classes and patterns can be used for reference counting and sharing data between user applications and the SYCL runtime. For control over memory allocation on the host and mapping between host and device memory, pre-defined or user-defined C++ `std::allocator` classes are used. For better control of synchronization between a SYCL and a non SYCL application that share data, `std::shared_ptr` and `std::mutex` classes are used.

3.11. Multi-dimensional objects and linearization

SYCL defines a number of multi-dimensional objects such as buffers and accessors. The iteration space of work-items in a kernel may also be multi-dimensional. The size of each dimension is defined by a `range` object of one, two or three dimensions, and an element in the multi-dimensional space can be identified using an `id` object with the same number of dimensions as the corresponding `range`.

If the size of any dimension is zero, there are zero elements in the multi-dimensional range.

3.11.1. Linearization

Some multi-dimensional objects can be viewed in a linear form. When this happens, the right-most term in the object's range varies fastest in the linearization.

A three-dimensional element `id{id0, id1, id2}` within a three-dimensional object of range `range{r0, r1, r2}` has a linear position defined by:

$$id2 + (id1 \cdot r2) + (id0 \cdot r1 \cdot r2)$$

A two-dimensional element `id{id0, id1}` within a two-dimensional `range{r0, r1}` follows a similar equation:

$$id1 + (id0 \cdot r1)$$

A one-dimensional element `id{id0}` within a one-dimensional range `range{r0}` is equivalent to its linear form.

3.11.2. Multi-dimensional subscript operators

Some multi-dimensional objects can be indexed using the subscript operator where consecutive subscript operators correspond to each dimension. The right-most operator varies fastest, as with standard C++ arrays. Formally, a three-dimensional subscript access `a[id0][id1][id2]` references the element at `id{id0, id1, id2}`. A two-dimensional subscript access `a[id0][id1]` references the element at `id{id0, id1}`. A one-dimensional subscript access `a[id0]` references the element at `id{id0}`.

3.12. Implementation options

The SYCL language is designed to allow several different possible implementations. The contents of this section are non-normative, so implementations need not follow the guidelines listed here. However, this section is intended to help readers understand the possible strategies that can be used to implement SYCL.

3.12.1. Single source multiple compiler passes

With this technique, known as SMCP, there are separate host and device compilers. Each SYCL source file is compiled two times: once by the host compiler and once by the device compiler. An implementation could support more than one device compiler, in which case each SYCL source file is compiled more than two times. The host compiler in this technique could be an off-the-shelf compiler with no special knowledge of SYCL, but the device compiler must be SYCL aware. The device compiler parses the source file to identify each SYCL kernel function and any device functions it calls. SYCL is designed so that this analysis can be done statically. The device compiler then generates code only for the SYCL kernel functions and the device functions.

Typically, the device compilers generate header files which interface between the host compiler and the SYCL runtime. Therefore, the device compiler runs first, and then the host compiler consumes these header files when generating the host code.

The device compilers in this technique generate one or more device images for the SYCL kernel functions, which can be read by the SYCL runtime. Each device image could either contain native ISA for a device or it could contain an intermediate language such as SPIR-V. In the later case, the SYCL runtime must translate the intermediate language into native device ISA when the SYCL kernel function is submitted to a device.

Since this technique has separate host and device compilers, there needs to be some way to associate a SYCL kernel function (which is compiled by the device compiler) with the code that invokes it (which is compiled by the host compiler). Implementations conformant to the reduced feature set (Section B.2) can do this by using the C++ type of the SYCL kernel function. This type is specified via the kernel name template parameter if the SYCL kernel function is a lambda function, or it is obtained from the class type if the SYCL kernel function is an object. Implementations conformant to the full feature set (Section B.1) do not require a kernel name at the invocation site, so they must implement some other way to make the association.

3.12.2. Single source single compiler pass

With this technique, known as SSCP, the vendor implements a custom compiler that reads each SYCL source file only once, and that compiler generates the host code as well as the device images for the SYCL kernel functions. As in the SMCP case, each device image could either contain native device ISA or an intermediate language.

3.12.3. Library-only implementation

It is also possible to implement SYCL purely as a library, using an off-the-shelf host compiler with no special support for SYCL. In such an implementation, each kernel may run on the host system.

3.13. Language restrictions in kernels

The SYCL kernels are executed on SYCL devices and all of the functions called from a SYCL kernel are going to be compiled for the device by a SYCL device compiler. Due to restrictions of the heterogeneous devices where the SYCL kernel will execute, there are certain restrictions on the base C++ language features that can be used inside kernel code. For details on language restrictions please refer to Section 5.4.

SYCL kernels use arguments that are captured by value in the command group scope or are passed from the host to the device using accessors. Sharing data structures between host and device code imposes certain restrictions, such as using only objects that are device copyable, and in general, no pointers initialized for the host can be used on the device. SYCL memory objects, such as `sycl::buffer`, `sycl::unsampled_image`, and `sycl::sampled_image`, cannot be passed to a kernel. Instead, a kernel must interact with these objects through accessors. No hierarchical structures of these memory object classes are supported and any other data containers need to be converted to the SYCL data management classes using the SYCL interface. For more details on the rules for kernel parameter passing, please refer to Section 4.12.4.

Pointers to USM allocations may be passed to a kernel either directly as arguments or indirectly inside of other objects. Pointers to USM allocations that are passed as kernel arguments are treated as being in the global address space.

3.13.1. Device copyable

The SYCL implementation may need to copy data between the host and a device or between two devices. For example, this may occur when a command group has a requirement for the contents of a buffer or when the application passes certain arguments to a SYCL kernel function (as described in Section 4.12.4). Such data must have a type that is device copyable as defined below.

Any type that is trivially copyable (as defined by the C++ core language) is implicitly device copyable.

Although implementations are not required to support device code that calls library functions from the C++ core language, some implementations may provide device support for some of these functions. If the implementation provides device support for one of the following classes, that type is also implicitly device copyable:

- `std::array<T, 0>`;
- `std::array<T, N>` if `T` is device copyable;
- `std::optional<T>` if `T` is device copyable;
- `std::pair<T1, T2>` if `T1` and `T2` are device copyable;
- `std::tuple<>`;
- `std::tuple<Types...>` if all the types in the parameter pack `Types` are device copyable;
- `std::variant<>`;
- `std::variant<Types...>` if all the types in the parameter pack `Types` are device copyable;
- `std::basic_string_view<CharT, Traits>`;
- `std::span<ElementType, Extent>` (the `std::span` type has been introduced in C++20);
- `sycl::span<ElementType, Extent>`.

If the implementation provides device support for one of the classes listed above, arrays of that class and cv-qualified versions of that class are also device copyable.

The types `std::basic_string_view<CharT, Traits>` and `std::span<ElementType, Extent>` are both view types, which reference underlying data that is not contained within their type. Although these view types are device copyable, the implementation copies just the view and not the contained data when doing an inter-device copy. In order to reference the contained data after such a copy, the application must allocate the contained data in unified shared memory (USM) that is accessible on both the host and device (or on both devices in the case of a device-to-device copy).

In addition, the implementation may allow the application to explicitly declare certain class types as device copyable. If the implementation has this support, it must predefine the preprocessor macro `SYCL_DEVICE_COPYABLE` to `1`, and it must not predefine this preprocessor macro if it does not have this sup-

port. When the implementation has this support, a class type T is device copyable if all of the following statements are true:

- The application defines the trait is_device_copyable_v<T> to true;
- Type T has at least one eligible copy constructor, move constructor, copy assignment operator, or move assignment operator;
- Each eligible copy constructor, move constructor, copy assignment operator, and move assignment operator is public;
- When doing an inter-device transfer of an object of type T, the effect of each eligible copy constructor, move constructor, copy assignment operator, and move assignment operator is the same as a bitwise copy of the object;
- Type T has a public non-deleted destructor;
- The destructor has no effect when executed on the device.

When the application explicitly declares a class type to be device copyable, arrays of that type and cv-qualified versions of that type are also device copyable, and the implementation sets the is_device_copyable_v trait to true for these array and cv-qualified types.

It is unspecified whether the implementation actually calls the copy constructor, move constructor, copy assignment operator, or move assignment operator of a class declared as is_device_copyable_v when doing an inter-device copy. Since these operations must all be the same as a bitwise copy, the implementation may simply copy the memory where the object resides. Likewise, it is unspecified whether the implementation actually calls the destructor for such a class on the device since the destructor must have no effect on the device.

3.14. Endianness support

SYCL does not mandate any particular byte order, but the byte order of the host always matches the byte order of the devices. This allows data to be copied between the host and the devices without any byte swapping.

3.15. Example SYCL application

Below is a more complex example application, combining some of the features described above.

```
#include <iostream>
#include <sycl/sycl.hpp>
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

// Size of the matrices
constexpr size_t N = 2000;
constexpr size_t M = 3000;

int main() {
  // Create a queue to work on
  queue myQueue;

  // Create some 2D buffers of float for our matrices
  buffer<float, 2> a { range<2> { N, M } };
  buffer<float, 2> b { range<2> { N, M } };
  buffer<float, 2> c { range<2> { N, M } };

```

```
// Launch an asynchronous kernel to initialize a
myQueue.submit([&](handler& cgh) {
  // The kernel writes a, so get a write accessor on it
  accessor A { a, cgh, write_only };

  // Enqueue a parallel kernel iterating on a N*M 2D iteration space
  cgh.parallel_for(range<2> { N, M },
                   [=](id<2> index) { A[index] = index[0] * 2 + index[1]; });
});

// Launch an asynchronous kernel to initialize b
myQueue.submit([&](handler& cgh) {
  // The kernel writes b, so get a write accessor on it
  accessor B { b, cgh, write_only };

  // From the access pattern above, the SYCL runtime detects that this
  // command_group is independent from the first one and can be
  // scheduled independently

  // Enqueue a parallel kernel iterating on a N*M 2D iteration space
  cgh.parallel_for(range<2> { N, M }, [=](id<2> index) {
    B[index] = index[0] * 2014 + index[1] * 42;
  });
});

// Launch an asynchronous kernel to compute matrix addition c = a + b
myQueue.submit([&](handler& cgh) {
  // In the kernel a and b are read, but c is written
  accessor A { a, cgh, read_only };
  accessor B { b, cgh, read_only };
  accessor C { c, cgh, write_only };

  // From these accessors, the SYCL runtime will ensure that when
  // this kernel is run, the kernels computing a and b have completed

  // Enqueue a parallel kernel iterating on a N*M 2D iteration space
  cgh.parallel_for(range<2> { N, M },
                   [=](id<2> index) { C[index] = A[index] + B[index]; });
});

// Ask for an accessor to read c from application scope.  The SYCL runtime
// waits for c to be ready before returning from the constructor
host_accessor C { c, read_only };
std::cout << std::endl << "Result:" << std::endl;
for (size_t i = 0; i < N; i++) {
  for (size_t j = 0; j < M; j++) {
    // Compare the result to the analytic value
    if (C[i][j] != i * (2 + 2014) + j * (1 + 42)) {
      std::cout << "Wrong value " << C[i][j] << " on element " << i << " "
                << j << std::endl;
      exit(-1);
    }
  }
}

std::cout << "Good computation!" << std::endl;
```

```
74   return 0;
75 }
```

Chapter 4. SYCL programming interface

The SYCL programming interface provides a common abstracted feature set to one or more SYCL backend APIs. This section describes the C++ library interface to the SYCL runtime which executes across those SYCL backends.

The entirety of the SYCL interface defined in this section is required to be available for any SYCL backends, with the exception of the interoperability interface, which is described in general terms in this document, not pertaining to any particular SYCL backend.

SYCL guarantees that all the member functions and special member functions of the SYCL classes described are thread safe.

The underlying types for all enumerations defined in this specification are implementation-defined. In addition, all enumerators within an enumeration have some implementation-defined unique value unless the specification specifically indicates a values for the enumerator.

4.1. Backends

The SYCL backends that can be supported by a SYCL implementation are identified using the `enum class backend`.

```
namespace sycl {
enum class backend : /* unspecified */ {
  /* see below */
};
} // namespace sycl
```

The `enum class backend` is implementation-defined and must be populated with a unique identifier for each SYCL backend that the SYCL implementation can support. Note that the SYCL backends listed in the `enum class backend` are not guaranteed to be available in a given installation.

Each named SYCL backend enumerated in the `enum class backend` must be associated with a SYCL backend specification. Many sections of this specification will refer to the associated SYCL backend specification.

4.1.1. Backend macros

As the identifiers defined in `enum class backend` are implementation-defined, and the associated backends not guaranteed to be available, a SYCL implementation must also define a preprocessor macro for each of these identifiers. If the SYCL backend is defined by the Khronos SYCL group, the name of the macro has the form `SYCL_BACKEND_<backend_name>`, where *backend_name* is the associated identifier from `backend` in all upper-case. See Chapter 6 for the name of the macro if the vendor defines the SYCL backend outside of the Khronos SYCL group.

If a backend listed in the `enum class backend` is not available, the associated macro must be left undefined.

4.2. Generic vs non-generic SYCL

The SYCL programming API is split into two categories; generic SYCL and non-generic SYCL. Almost everything in the SYCL programming API is considered generic SYCL. However any usage of the `enum class backend` is considered non-generic SYCL and should only be used for SYCL backend specialized code paths, as the identifiers defined in `backend` are implementation-defined.

In any non-generic SYCL application code where the backend enum class is used, the expression must be guarded with a preprocessor #ifdef guard using the associated preprocessor macro to ensure that the SYCL application will compile even if the SYCL implementation does not support that SYCL backend being specialized for.

4.3. Header files and namespaces

SYCL provides one standard header file: <sycl/sycl.hpp>, which needs to be included in every translation unit that uses the SYCL programming API.

All SYCL classes, constants, types and functions defined by this specification should exist within the ::sycl namespace.

For compatibility with SYCL 1.2.1, SYCL provides another standard header file: <CL/sycl.hpp>, which can be included in place of <sycl/sycl.hpp>. In that case, all SYCL classes, constants, types and functions defined by this specification should exist within the ::cl::sycl C++ namespace.

For consistency, the programming API will only refer to the <sycl/sycl.hpp> header and the ::sycl namespace, but this should be considered synonymous with the SYCL 1.2.1 header and namespace.

Include paths starting with "sycl/ext/" and "sycl/backend/" are reserved for extensions to SYCL and for backend interop headers respectively. Other include paths starting with "sycl/" and the sycl::detail namespace are reserved for implementation details.

When a SYCL backend is defined by the Khronos SYCL group, functionality for that SYCL backend is available via the header "sycl/backend/<backend_name>.hpp", and all SYCL backend-specific functionality is made available in the namespace sycl::<backend_name> where <backend_name> is the name of the SYCL backend as defined in the SYCL backend specification.

Chapter 6 defines the allowable header files and namespaces for any extensions that a vendor may provide, including any SYCL backend that the vendor may define outside of the Khronos SYCL group.

Unless otherwise specified, the behavior of a SYCL program is undefined if it adds any entity to namespace sycl or to a namespace within namespace sycl.

4.4. Class availability

In SYCL some SYCL runtime classes are available to the SYCL application, some are available within a SYCL kernel function and some are available on both and can be passed as arguments to a SYCL kernel function.

Each of the following SYCL runtime classes: buffer, buffer_allocator, context, device, device_image, event, exception, handler, host_accessor, host_sampled_image_accessor, host_unsampled_image_accessor, id, image_allocator, kernel, kernel_id, marray, kernel_bundle, nd_range, platform, queue, range, sampled_image, image_sampler, stream, unsampled_image and vec must be available to the host application.

Each of the following SYCL runtime classes: accessor, atomic_ref, device_event, group, h_item, id, item, local_accessor, marray, multi_ptr, nd_item, range, reducer, sampled_image_accessor, stream, sub_group, unsampled_image_accessor and vec must be available within a SYCL kernel function.

4.5. Common interface

When a dimension template parameter is used in SYCL classes, it is defaulted as 1 in most cases.

4.5.1. Backend interoperability

Many of the SYCL runtime classes may be implemented such that they encapsulate an object unique to the SYCL backend that underpins the functionality of that class. Where appropriate, these classes may provide an interface for interoperating between the SYCL runtime object and the native backend object in order to support interoperability within an application between SYCL and the associated SYCL backend API.

There are three forms of interoperability with SYCL runtime classes: interoperability on the SYCL application with the SYCL backend API, interoperability within a SYCL kernel function with the equivalent kernel language types of the SYCL backend, and interoperability within a host task with the `interop_handle`.

SYCL application interoperability, SYCL kernel function interoperability and host task interoperability are provided via different interfaces and may have different behavior for the same SYCL object.

SYCL application interoperability may be provided for `buffer`, `context`, `device`, `device_image`, `event`, `kernel`, `kernel_bundle`, `platform`, `queue`, `sampled_image`, and `unsampled_image`.

SYCL kernel function interoperability may be provided for `accessor`, `device_event`, `local_accessor`, `sampled_image_accessor`, `stream` and `unsampled_image_accessor` inside kernel scope only and is not available outside of that scope.

host task interoperability may be provided for `accessor`, `sampled_image_accessor`, `unsampled_image_accessor`, `queue`, `device`, `context` inside the scope of a host task only, see Section 4.10.

Support for SYCL backend interoperability is optional and therefore not required to be provided by a SYCL implementation. A SYCL application using SYCL backend interoperability is considered to be non-generic SYCL.

Details on the interoperability for a given SYCL backend are available on the SYCL backend specification document for that SYCL backend.

4.5.1.1. Type traits `backend_traits`

```
namespace sycl {

template <backend Backend> class backend_traits {
 public:
  template <class T> using input_type = /* see below */;

  template <class T> using return_type = /* see below */;

  using errc = /* see below */;
};

template <backend Backend, typename SyclType>
using backend_input_t =
    typename backend_traits<Backend>::template input_type<SyclType>;

template <backend Backend, typename SyclType>
using backend_return_t =
    typename backend_traits<Backend>::template return_type<SyclType>;

} // namespace sycl
```

A series of type traits are provided for SYCL backend interoperability, defined in the backend_traits class.

A specialization of backend_traits must be provided for each named SYCL backend enumerated in the enum class backend that is available at compile time.

- For each SYCL runtime class T which supports SYCL application interoperability with the SYCL backend, a specialization of input_type must be defined as the type of SYCL application interoperability native backend object associated with T for the SYCL backend, specified in the SYCL backend specification. input_type is used when constructing SYCL objects from backend specific native objects. See the relevant backend specification for details.
- For each SYCL runtime class T which supports SYCL application interoperability with the SYCL backend, a specialization of return_type must be defined as the type of SYCL application interoperability native backend object associated with T for the SYCL backend, specified in the SYCL backend specification. return_type is used when retrieving the backend specific native object from a SYCL object. See the relevant backend specification for details.
- For each SYCL runtime class T which supports kernel function interoperability with the SYCL backend, a specialization of return_type within backend_traits must be defined as the type of the kernel function interoperability native backend object associated with T for the SYCL backend, specified in the backend specification. See the relevant backend specification for details.
- A specialization of errc must be defined as the SYCL backend error code type.

The type alias backend_input_t is provided to enable less verbose access to the input_type type within backend_traits for a specific SYCL object of type T. The type alias backend_return_t is provided to enable less verbose access to the return_type type within backend_traits for a specific SYCL object of type T.

4.5.1.2. Template function get_native

```
namespace sycl {

template <backend Backend, class T>
backend_return_t<Backend, T> get_native(const T& syclObject);

} // namespace sycl
```

For each SYCL runtime class T which supports SYCL application interoperability, a specialization of get_native must be defined, which takes an instance of T and returns a SYCL application interoperability native backend object associated with syclObject which can be used for SYCL application interoperability. The lifetime of the object returned are backend-defined and specified in the backend specification.

For each SYCL runtime class T which supports kernel function interoperability, a specialization of get_native must be defined, which takes an instance of T and returns the kernel function interoperability native backend object associated with syclObject which can be used for kernel function interoperability. The availability and behavior of these template functions is defined by the SYCL backend specification document.

The get_native function must throw an exception with the errc::backend_mismatch error code if the backend of the SYCL object doesn't match the target backend.

4.5.1.3. Template functions make_*

```
namespace sycl {

template <backend Backend>
```

```
platform make_platform(const backend_input_t<Backend, platform>& backendObject);

template <backend Backend>
device make_device(const backend_input_t<Backend, device>& backendObject);

template <backend Backend>
context make_context(const backend_input_t<Backend, context>& backendObject,
                     const async_handler asyncHandler = {});

template <backend Backend>
queue make_queue(const backend_input_t<Backend, queue>& backendObject,
                 const context& targetContext,
                 const async_handler asyncHandler = {});

template <backend Backend>
event make_event(const backend_input_t<Backend, event>& backendObject,
                 const context& targetContext);

template <backend Backend, typename T, int Dimensions = 1,
          typename AllocatorT = buffer_allocator<std::remove_const_t<T>>>
buffer<T, Dimensions, AllocatorT>
make_buffer(const backend_input_t<Backend, buffer<T, Dimensions, AllocatorT>>&
                backendObject,
            const context& targetContext, event availableEvent);

template <backend Backend, typename T, int Dimensions = 1,
          typename AllocatorT = buffer_allocator<std::remove_const_t<T>>>
buffer<T, Dimensions, AllocatorT>
make_buffer(const backend_input_t<Backend, buffer<T, Dimensions, AllocatorT>>&
                backendObject,
            const context& targetContext);

template <backend Backend, int Dimensions = 1,
          typename AllocatorT = sycl::image_allocator>
sampled_image<Dimensions, AllocatorT> make_sampled_image(
    const backend_input_t<Backend, sampled_image<Dimensions, AllocatorT>>&
        backendObject,
    const context& targetContext, image_sampler imageSampler,
    event availableEvent);

template <backend Backend, int Dimensions = 1,
          typename AllocatorT = sycl::image_allocator>
sampled_image<Dimensions, AllocatorT> make_sampled_image(
    const backend_input_t<Backend, sampled_image<Dimensions, AllocatorT>>&
        backendObject,
    const context& targetContext, image_sampler imageSampler);

template <backend Backend, int Dimensions = 1,
          typename AllocatorT = sycl::image_allocator>
unsampled_image<Dimensions, AllocatorT> make_unsampled_image(
    const backend_input_t<Backend, unsampled_image<Dimensions, AllocatorT>>&
        backendObject,
    const context& targetContext, event availableEvent);

template <backend Backend, int Dimensions = 1,
          typename AllocatorT = sycl::image_allocator>
```

```
unsampled_image<Dimensions, AllocatorT> make_unsampled_image(
    const backend_input_t<Backend, unsampled_image<Dimensions, AllocatorT>>&
        backendObject,
    const context& targetContext);

template <backend Backend, bundle_state State>
kernel_bundle<State> make_kernel_bundle(
    const backend_input_t<Backend, kernel_bundle<State>>& backendObject,
    const context& targetContext);

template <backend Backend>
kernel make_kernel(const backend_input_t<Backend, kernel>& backendObject,
                   const context& targetContext);

} // namespace sycl
```

For each SYCL runtime class T which supports SYCL application interoperability, a specialization of the appropriate template function make_{sycl_class} where {sycl_class} is the class name of T, must be defined, which takes a SYCL application interoperability native backend object and constructs and returns an instance of T. The availability and behavior of these template functions is defined by the SYCL backend specification document.

Overloads of the make_{sycl_class} function which take a SYCL context object as an argument must throw an exception with the errc::backend_mismatch error code if the backend of the provided SYCL context doesn't match the target backend.

4.5.2. Common reference semantics

Each of the following SYCL runtime classes: accessor, buffer, context, device, device_image, event, host_accessor, host_sampled_image_accessor, host_unsampled_image_accessor, kernel, kernel_id, kernel_bundle, local_accessor, platform, queue, sampled_image, sampled_image_accessor, stream, unsampled_image and unsampled_image_accessor must obey the following statements, where T is the runtime class type:

- T must be copy constructible and copy assignable on the host application and within SYCL kernel functions in the case that T is a valid kernel argument. Any instance of T that is constructed as a copy of another instance, via either the copy constructor or copy assignment operator, must behave as-if it were the original instance and as-if any action performed on it were also performed on the original instance and must represent the same underlying native backend object as the original instance where applicable.
- T must be destructible on the host application and within SYCL kernel functions in the case that T is a valid kernel argument. When any instance of T is destroyed, including as a result of the copy assignment operator, any behavior specific to T that is specified as performed on destruction is only performed if this instance is the last remaining host copy, in accordance with the above definition of a copy.
- T must be move constructible and move assignable on the host application and within SYCL kernel functions in the case that T is a valid kernel argument. Any instance of T that is constructed as a move of another instance, via either the move constructor or move assignment operator, must replace the original instance rendering said instance invalid and must represent the same underlying native backend object as the original instance where applicable.
- T must be equality comparable on the host application. Equality between two instances of T (i.e. a == b) must be true if one instance is a copy of the other and non-equality between two instances of T (i.e. a != b) must be true if neither instance is a copy of the other, in accordance with the above definition of a copy, unless either instance has become invalidated by a move operation. By extension of the requirements above, equality on T must guarantee to be reflexive (i.e. a == a), symmetric (i.e. a == b

implies `b == a` and `a != b` implies `b != a`) and transitive (i.e. `a == b && b == c` implies `c == a`).

- A specialization of `std::hash` for `T` must exist on the host application that returns a unique value such that if two instances of T are equal, in accordance with the above definition, then their resulting hash values are also equal and subsequently if two hash values are not equal, then their corresponding instances are also not equal, in accordance with the above definition.

Some SYCL runtime classes will have additional behavior associated with copy, movement, assignment or destruction semantics. If these are specified they are in addition to those specified above unless stated otherwise.

Each of the runtime classes mentioned above must provide a common interface of special member functions in order to fulfill the copy, move, destruction requirements and hidden friend functions in order to fulfill the equality requirements.

A hidden friend function is a function first declared via a `friend` declaration with no additional out of class or namespace scope declarations. Hidden friend functions are only visible to ADL (Argument Dependent Lookup) and are hidden from qualified and unqualified lookup. Hidden friend functions have the benefits of avoiding accidental implicit conversions and faster compilation.

These common special member functions and hidden friend functions are described in Table 7 and Table 8 respectively.

```
namespace sycl {

class T {
  ...

      public : T(const T& rhs);

  T(T&& rhs);

  T& operator=(const T& rhs);

  T& operator=(T&& rhs);

  ~T();

  ...

      friend bool
      operator==(const T& lhs, const T& rhs) { /* ... */
  }

  friend bool operator!=(const T& lhs, const T& rhs) { /* ... */ }

  ...
};
} // namespace sycl
```

Table 7. Common special member functions for reference semantics

Special member function	Description
`T(const T& rhs)`	Constructs a `T` instance as a copy of the RHS SYCL `T` in accordance with the requirements set out above.

Special member function	Description
`T(T&& rhs)`	Constructs a SYCL `T` instance as a move of the RHS SYCL `T` in accordance with the requirements set out above.
`T& operator=(const T& rhs)`	Assigns this SYCL `T` instance with a copy of the RHS SYCL `T` in accordance with the requirements set out above.
`T& operator=(T&& rhs)`	Assigns this SYCL `T` instance with a move of the RHS SYCL `T` in accordance with the requirements set out above.
`~T()`	Destroys this SYCL `T` instance in accordance with the requirements set out in Section 4.5.2. On destruction of the last copy, may perform additional lifetime related operations required for the underlying native backend object specified in the SYCL backend specification document, if this SYCL `T` instance was originally constructed using one of the backend interoperability `make_*` functions specified in Section 4.5.1.3. See the relevant backend specification for details.

Table 8. Common hidden friend functions for reference semantics

Hidden friend function	Description
`bool operator==(const T& lhs, const T& rhs)`	Returns true if this LHS SYCL `T` is equal to the RHS SYCL `T` in accordance with the requirements set out above, otherwise returns false.
`bool operator!=(const T& lhs, const T& rhs)`	Returns true if this LHS SYCL `T` is not equal to the RHS SYCL `T` in accordance with the requirements set out above, otherwise returns false.

4.5.3. Common by-value semantics

Each of the following SYCL runtime classes: `id`, `range`, `item`, `nd_item`, `h_item`, `group`, `sub_group` and `nd_range` must follow the following statements, where `T` is the runtime class type:

- `T` must be default copy constructible and copy assignable on the host application (in the case where T is available on the host) and within SYCL kernel functions.
- `T` must be default destructible on the host application (in the case where T is available on the host) and within SYCL kernel functions.
- `T` must be default move constructible and default move assignable on the host application (in the case where T is available on the host) and within SYCL kernel functions.
- `T` must be equality comparable on the host application (in the case where T is available on the host) and within SYCL kernel functions. Equality between two instances of `T` (i.e. `a == b`) must be true if the value of all members are equal and non-equality between two instances of `T` (i.e. `a != b`) must be true if the value of any members are not equal, unless either instance has become invalidated by a move operation. By extension of the requirements above, equality on `T` must guarantee to be reflexive (i.e. `a == a`), symmetric (i.e. `a == b` implies `b == a` and `a != b` implies `b != a`) and transitive (i.e. `a == b && b == c` implies `c == a`).

Some SYCL runtime classes will have additional behavior associated with copy, movement, assignment or destruction semantics. If these are specified they are in addition to those specified above unless stated otherwise.

Each of the runtime classes mentioned above must provide a common interface of special member functions and member functions in order to fulfill the copy, move, destruction and equality requirements, following the rule of five and the rule of zero.

These common special member functions and hidden friend functions are described in Table 9 and Table 10 respectively.

```
namespace sycl {

class T {
  ...

      public
      :
      // If any of the following five special member functions are not
      // public, inline or defaulted, then all five of them should be
      // explicitly declared (see rule of five).
      // Otherwise, none of them should be explicitly declared
      // (see rule of zero).

      // T(const T &rhs);

      // T(T &&rhs);

      // T &operator=(const T &rhs);

      // T &operator=(T &&rhs);

      // ~T();

      ...

      friend bool
      operator==(const T& lhs, const T& rhs) { /* ... */
  }

  friend bool operator!=(const T& lhs, const T& rhs) { /* ... */ }

  ...
};
} // namespace sycl
```

Table 9. Common special member functions for by-value semantics

Special member function *(see rule of five and rule of zero)*	**Description**
`T(const T& rhs);`	Copy constructor.
`T(T&& rhs);`	Move constructor.
`T& operator=(const T& rhs);`	Copy assignment operator.
`T& operator=(T&& rhs);`	Move assignment operator.
`~T();`	Destructor.

Table 10. Common hidden friend functions for by-value semantics

Hidden friend function	Description
`bool operator==(const T& lhs, const T& rhs)`	Returns true if this LHS SYCL `T` is equal to the RHS SYCL `T` in accordance with the requirements set out above, otherwise returns false.
`bool operator!=(const T& lhs, const T& rhs)`	Returns true if this LHS SYCL `T` is not equal to the RHS SYCL `T` in accordance with the requirements set out above, otherwise returns false.

4.5.4. Properties

Each of the following SYCL runtime classes: `accessor`, `buffer`, `host_accessor`, `host_sampled_image_accessor`, `host_unsampled_image_accessor`, `context`, `local_accessor`, `queue`, `sampled_image`, `sampled_image_accessor`, `stream`, `unsampled_image`, `unsampled_image_accessor` and `usm_allocator` provide an optional parameter in each of their constructors to provide a `property_list` which contains zero or more properties. Each of those properties augments the semantics of the class with a particular feature. Each of those classes must also provide `has_property` and `get_property` member functions for querying for a particular property.

The listing below illustrates the usage of various buffer properties, described in Section 4.7.2.2.

The example illustrates how using properties does not affect the type of the object, thus, does not prevent the usage of SYCL objects in containers.

```
{
  context myContext;

  std::vector<buffer<int, 1>> bufferList {
    buffer<int, 1> { ptr, rng },
    buffer<int, 1> { ptr, rng, property::use_host_ptr {} },
    buffer<int, 1> { ptr, rng, property::context_bound { myContext } }
  };

  for (auto& buf : bufferList) {
    if (buf.has_property<property::context_bound>()) {
      auto prop = buf.get_property<property::context_bound>();
      assert(myContext == prop.get_context());
    }
  }
}
```

Each property is represented by a unique class and an instance of a property is an instance of that type. Some properties can be default constructed while others will require an argument on construction. A property may be applicable to more than one class, however some properties may not be compatible with each other. See the requirements for the properties of the SYCL `buffer` class, SYCL `unsampled_image` class and SYCL `sampled_image` class in Table 41 and Table 48 respectively.

Properties can be passed to a SYCL runtime class via an instance of `property_list`. These properties get tied to the SYCL runtime class instance and copies of the object will contain the same properties.

A SYCL implementation or a SYCL backend may provide additional properties other than those defined here, provided they are defined in accordance with the requirements described in Section 4.3.

4.5.4.1. Properties interface

Each of the runtime classes mentioned above must provide a common interface of member functions in order to fulfill the property interface requirements.

A synopsis of the common properties interface, the SYCL `property_list` class and the SYCL property classes is provided below. The member functions of the common properties interface are listed in Table 12. The constructors of the SYCL `property_list` class are listed in Table 13.

```
namespace sycl {

template <typename Property> struct is_property;

template <typename Property>
inline constexpr bool is_property_v = is_property<Property>::value;

template <typename Property, typename SyclObject> struct is_property_of;

template <typename Property, typename SyclObject>
inline constexpr bool is_property_of_v =
    is_property_of<Property, SyclObject>::value;

class T {
  ...

      template <typename Property>
      bool has_property() const noexcept;

  template <typename Property> Property get_property() const;

  ...
};

class property_list {
 public:
  template <typename... Properties> property_list(Properties... props);
};
} // namespace sycl
```

Table 11. Traits for properties

Traits	Description
`template <typename Property> struct is_property`	An explicit specialization of `is_property` that inherits from `std::true_type` must be provided for each property, where `Property` is the class defining the property. This includes both standard properties described in this specification and any additional non-standard properties defined by an implementation. All other specializations of `is_property` must inherit from `std::false_type`.
`template <typename Property> inline constexpr bool is_property_v;`	Variable containing value of `is_property<Property>`.

Traits	Description
`template <typename Property, SyclObject> struct is_property_of`	An explicit specialization of `is_property_of` that inherits from `std::true_type` must be provided for each property that can be used in constructing a given SYCL class, where `Property` is the class defining the property and `SyclObject` is the SYCL class. This includes both standard properties described in this specification and any additional non-standard properties defined by an implementation. All other specializations of `is_property_of` must inherit from `std::false_type`.
`template <typename Property, SyclObject> inline constexpr bool is_property_of_v;`	Variable containing value of `is_property_of<Property, SyclObject>`.

Table 12. Common member functions of the SYCL `property` interface

Member function	Description
`template <typename Property> bool has_property() const noexcept`	Returns true if `T` was constructed with the property specified by `Property`. Returns false if it was not.
`template <typename Property> Property get_property() const`	Returns a copy of the property of type `Property` that `T` was constructed with. Must throw an `exception` with the `errc::invalid` error code if `T` was not constructed with the `Property` property.

Table 13. Constructors of the SYCL `property_list` class

Constructor	Description
`template <typename... PropertyN> property_list(PropertyN... props)`	Available only when: `is_property<property>::value` evaluates to `true` where `property` is each property in `PropertyN`. Construct a SYCL `property_list` with zero or more properties.

4.6. SYCL runtime classes

4.6.1. Device selection

Since a system can have several SYCL-compatible devices attached, it is useful to have a way to select a specific device or a set of devices to construct a specific object such as a `device` (see Section 4.6.4) or a `queue` (see Section 4.6.5), or perform some operations on a device subset.

Device selection is done either by already having a specific instance of a `device` (see Section 4.6.4) or by providing a device selector which is a ranking function that will give an integer ranking value to all the devices on the system.

4.6.1.1. Device selector

The interface for a device selector is any object that meets the C++ named requirement `Callable`, taking a parameter of type `const device &` and returning a value that is implicitly convertible to `int`.

At any point where the SYCL runtime needs to select a SYCL `device` using a device selector, the system queries all root devices from all SYCL backends in the system, calls the device selector on each device

and selects the one which returns the highest score. If the highest value is strictly negative no device is selected.

In places where only one device has to be picked and the high score is obtained by more than one device, then one of the tied devices will be returned, but which one is not defined and may depend on enumeration order, for example, outside the control of the SYCL runtime.

Some predefined device selectors are provided by the system as described on Table 14 in a header file with some definition similar to the following:

Table 14. Standard device selectors included with all SYCL implementations

SYCL device selectors	Description
`default_selector_v`	Select a SYCL `device` from any supported SYCL backend based on an implementation-defined heuristic. Since all implementations must support at least one device, this selector must always return a device.  Implementations may choose to return an emulated device (with `aspect::emulated`) as a fallback if there is no physical device available on the system.
`gpu_selector_v`	Select a SYCL `device` from any supported SYCL backend for which the device type is `info::device_type::gpu`. The SYCL class constructor using it must throw an `exception` with the `errc::runtime` error code if no device matching this requirement can be found.
`accelerator_selector_v`	Select a SYCL `device` from any supported SYCL backend for which the device type is `info::device_type::accelerator`. The SYCL class constructor using it must throw an `exception` with the `errc::runtime` error code if no device matching this requirement can be found.
`cpu_selector_v`	Select a SYCL `device` from any supported SYCL backend for which the device type is `info::device_type::cpu`. The SYCL class constructor using it must throw an `exception` with the `errc::runtime` error code if no device matching this requirement can be found.

SYCL device selectors	Description

`__unspecified_callable__ aspect_selector(const std::vector<aspect>& aspectList, const std::vector<aspect>& denyList = {});`
 	
`template <typename... AspectList> __unspecified_callable__ aspect_selector (AspectList... aspectList);`
 	
`template <aspect... AspectList> __unspecified_callable__ aspect_selector();`
	The free function `aspect_selector` has several overloads, each of which returns a selector object that selects a SYCL `device` from any supported SYCL backend which contains all the requested aspects, i.e. for the specific device `dev` and each aspect `devAspect` from `aspectList` `dev.has(devAspect)` equals `true`. If no aspects are passed in, the generated selector behaves like `default_selector`.
	
	Required aspects can be passed in as a vector, as function arguments, or as template parameters, depending on the function overload. The function overload that takes `aspectList` as a vector takes another vector argument `denyList` where the user can specify all the aspects that have to be avoided, i.e. for the specific device `dev` and each aspect `devAspect` from `denyList` `dev.has(devAspect)` equals `false`.
	
	The SYCL class constructor using the generated selector must throw an `exception` with the `errc::runtime` error code if no device matching this requirement can be found. There are multiple overloads of this function, please refer to [header:device-selector] for full definitions and to [example:aspect-selector] for examples.

```
namespace sycl {

// Predefined device selectors
__unspecified__ default_selector_v;
__unspecified__ cpu_selector_v;
__unspecified__ gpu_selector_v;
__unspecified__ accelerator_selector_v;

// Predefined types for compatibility with old SYCL 1.2.1 device selectors
using default_selector = __unspecified__;
using cpu_selector = __unspecified__;
using gpu_selector = __unspecified__;
using accelerator_selector = __unspecified__;

// Returns a selector that selects a device based on desired aspects
__unspecified_callable__
aspect_selector(const std::vector<aspect>& aspectList,
                const std::vector<aspect>& denyList = {});
template <class... AspectList>
__unspecified_callable__ aspect_selector(AspectList... aspectList);
template <aspect... AspectList> __unspecified_callable__ aspect_selector();

} // namespace sycl
```

Typical examples of default and user-provided device selectors could be:

```
sycl::device my_gpu { sycl::gpu_selector_v };

sycl::queue my_accelerator { sycl::accelerator_selector_v };

int prefer_my_vendor(const sycl::device& d) {
  // Return 1 if the vendor name is "MyVendor" or 0 else.
  // 0 does not prevent another device to be picked as a second choice
  return d.get_info<info::device::vendor>() == "MyVendor";
}

// Get the preferred device or another one if not available
sycl::device preferred_device { prefer_my_vendor };

// This throws if there is no such device in the system
sycl::queue half_precision_controller {
  // Can use a lambda as a device ranking function.
  // Returns a negative number to fail in the case there is no such device
  [] (auto& d) { return d.has(sycl::aspect::fp16) ? 1 : -1; }
};

// To ease porting SYCL 1.2.1 code, there are types whose
// construction leads to the equivalent predefined device selector
sycl::queue my_old_style_gpu { sycl::gpu_selector {} };
```

Examples of using `aspect_selector`:

```
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

// Unrestrained selection, equivalent to default_selector
auto dev0 = device{aspect_selector()};

// Pass aspects in a vector
// Only accept CPUs that support half
auto dev1 = device{aspect_selector(std::vector{aspect::cpu, aspect::fp16})};

// Pass aspects without a vector
// Only accept GPUs that support half
auto dev2 = device{aspect_selector(aspect::gpu, aspect::fp16)};

// Pass aspects as compile-time parameters
// Only accept devices that can be debugged on host and support half
auto dev3 = device{aspect_selector<aspect::host_debuggable, aspect::fp16>()};

// Pass aspects in an allowlist and a denylist
// Only accept devices that support half and double floating point precision,
// but exclude emulated devices and devices of type "custom"
auto dev4 = device{aspect_selector(
   std::vector{aspect::fp16, aspect::fp64},
   std::vector{aspect::emulated, aspect::custom}
)};
```

In SYCL 1.2.1 the predefined device selectors were actually types that had to be instantiated to be used. Now they are just instances. To simplify porting code using the old type instantiations, a backward-compatible API is still provided, such as `sycl::default_selec-`

tor. The new predefined device selectors have their new names appended with "_v" to avoid conflicts, thus following the naming style used by traits in the C++ standard library. There is no requirement for the implementation to have for example `sycl::gpu_selector_v` being an instance of `sycl::gpu_selector`.

Implementation note: the SYCL API might rely on SFINAE or C++20 concepts to resolve some ambiguity in constructors with default parameters.

4.6.2. Platform class

The SYCL `platform` class encapsulates a single SYCL platform on which SYCL kernel functions may be executed. A SYCL platform must be associated with a single SYCL backend.

A SYCL `platform` is also associated with one or more SYCL `devices` associated with the same SYCL backend.

All member functions of the `platform` class are synchronous and errors are handled by throwing synchronous SYCL exceptions.

The execution environment for a SYCL application has a fixed number of platforms which does not vary as the application executes. The application can get a list of all these platforms via `platform::get_platforms()`, and the order of the platform objects is the same each time the application calls that function. The `platform` class also provides constructors, but constructing a new `platform` instance merely creates a new object that is a copy of one of the objects returned by `platform::get_platforms()`.

The SYCL `platform` class provides the common reference semantics (see Section 4.5.2).

4.6.2.1. Platform interface

A synopsis of the SYCL `platform` class is provided below. The constructors, member functions and static member functions of the SYCL `platform` class are listed in Table 15, Table 16 and Table 17 respectively. The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8 respectively.

```
namespace sycl {
class platform {
 public:
  platform();

  template <typename DeviceSelector>
  explicit platform(const DeviceSelector& deviceSelector);

  /* -- common interface members -- */

  backend get_backend() const noexcept;

  std::vector<device>
      get_devices(info::device_type = info::device_type::all) const;

  template <typename Param> typename Param::return_type get_info() const;

  template <typename Param>
  typename Param::return_type get_backend_info() const;

  bool has(aspect asp) const;

```

```
23   bool has_extension(const std::string& extension) const; // Deprecated
24
25   static std::vector<platform> get_platforms();
26 };
27 } // namespace sycl
```

Table 15. Constructors of the SYCL `platform` class

Constructor	Description
`platform()`	Constructs a SYCL `platform` instance that is a copy of the `platform` which contains the device returned by `default_selector_v`.
`template <typename DeviceSelector> explicit platform(const DeviceSelector&)`	Constructs a SYCL `platform` instance that is a copy of the `platform` which contains the device returned by the device selector parameter.

Table 16. Member functions of the SYCL `platform` class

Member function	Description
`backend get_backend() const noexcept`	Returns a `backend` identifying the SYCL backend associated with this `platform`.
`template <typename Param> typename Param::return_type get_info() const`	Queries this SYCL `platform` for information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the info parameters in Table 25 to facilitate returning the type associated with the `Param` parameter.
`template <typename Param> typename Param::return_type get_backend_info() const`	Queries this SYCL `platform` for SYCL backend-specific information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the SYCL backend specification. Must throw an `exception` with the `errc::backend_mismatch` error code if the SYCL backend that corresponds with `Param` is different from the SYCL backend that is associated with this `platform`.
`bool has(aspect asp) const`	Returns true if all of the SYCL `devices` associated with this SYCL `platform` have the given aspect.

Member function	Description
`bool has_extension(const std::string& extension) const`	Deprecated, use `has()` instead. Returns true if this SYCL `platform` supports the extension queried by the `extension` parameter. A SYCL `platform` can only support an extension if all associated SYCL `devices` support that extension.
`std::vector<device> get_devices(info::device_type deviceType = info::device_type::all) const`	Returns a `std::vector` containing all the root devices associated with this SYCL `platform` which have the device type encapsulated by `deviceType`.

Table 17. Static member functions of the SYCL `platform` class

Static member function	Description
`static std::vector<platform> get_platforms()`	Returns a `std::vector` containing all SYCL `platforms` from all SYCL backends available in the system.

4.6.2.2. Platform information descriptors

A platform can be queried for information using the `get_info` member function of the `platform` class, specifying one of the info parameters in `info::platform`. The possible values for each info parameter and any restrictions are defined in the specification of the SYCL backend associated with the platform. All info parameters in `info::platform` are specified in Table 18 and the synopsis for `info::platform` is described in Section A.1.

Table 18. Platform information descriptors

Platform descriptors	Return type	Description
`info::platform::version`	`std::string`	Returns a backend-defined platform version.
`info::platform::name`	`std::string`	Returns the name of the platform.
`info::platform::vendor`	`std::string`	Returns the name of the vendor providing the platform.
`info::platform::extensions`	`std::vector<std::string>`	Deprecated, use `device::get_info()` with `info::device::aspects` instead. Returns the extensions supported by the platform.

4.6.3. Context class

The context class represents a SYCL context. A context represents the runtime data structures and state required by a SYCL backend API to interact with a group of devices associated with a platform.

The SYCL `context` class provides the common reference semantics (see Section 4.5.2).

4.6.3.1. Context interface

The constructors and member functions of the SYCL `context` class are listed in Table 19 and Table 20, respectively. The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively.

All member functions of the context class are synchronous and errors are handled by throwing synchronous SYCL exceptions.

All constructors of the SYCL context class will construct an instance associated with a particular SYCL backend, determined by the constructor parameters or, in the case of the default constructor, the SYCL `device` produced by the `default_selector_v`.

A SYCL `context` can optionally be constructed with an `async_handler` parameter. In this case the `async_handler` is used to report asynchronous SYCL exceptions, as described in Section 4.13.

Information about a SYCL context may be queried through the `get_info()` member function.

```
namespace sycl {
class context {
 public:
  explicit context(const property_list& propList = {});

  explicit context(async_handler asyncHandler,
                   const property_list& propList = {});

  explicit context(const device& dev, const property_list& propList = {});

  explicit context(const device& dev, async_handler asyncHandler,
                   const property_list& propList = {});

  explicit context(const std::vector<device>& deviceList,
                   const property_list& propList = {});

  explicit context(const std::vector<device>& deviceList,
                   async_handler asyncHandler,
                   const property_list& propList = {});

  /* -- property interface members -- */

  /* -- common interface members -- */

  backend get_backend() const noexcept;

  platform get_platform() const;

  std::vector<device> get_devices() const;

  template <typename Param> typename Param::return_type get_info() const;

  template <typename Param>
  typename Param::return_type get_backend_info() const;
};
} // namespace sycl
```

Table 19. Constructors of the SYCL `context` class

Constructor	Description
`explicit context(async_handler asyncHandler = {})`	Constructs a SYCL `context` instance using an instance of `default_selector_v` to select the associated SYCL `platform` and `device(s)`. The devices that are associated with the constructed context are implementation-defined but must contain the device chosen by the device selector. The constructed SYCL `context` will use the `asyncHandler` parameter to handle exceptions.
`explicit context(const device& dev, async_handler asyncHandler = {})`	Constructs a SYCL `context` instance using the `dev` parameter as the associated SYCL `device` and the SYCL `platform` associated with the `dev` parameter as the associated SYCL `platform`. The constructed SYCL `context` will use the `asyncHandler` parameter to handle exceptions.
`explicit context(const std::vector<device>& deviceList, async_handler asyncHandler = {})`	Constructs a SYCL `context` instance using the SYCL `device(s)` in the `deviceList` parameter as the associated SYCL `device(s)` and the SYCL `platform` associated with each SYCL `device` in the `deviceList` parameter as the associated SYCL `platform`. This requires that all SYCL `devices` in the `deviceList` parameter have the same associated SYCL `platform`. The constructed SYCL `context` will use the `asyncHandler` parameter to handle exceptions.

Table 20. Member functions of the `context` class

Member function	Description
`backend get_backend() const noexcept`	Returns a `backend` identifying the SYCL backend associated with this `context`.
`template <typename Param> typename Param::return_type get_info() const`	Queries this SYCL `context` for information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the info parameters in Table 21 to facilitate returning the type associated with the `Param` parameter.

Member function	Description
`template <typename Param> typename Param::return_type get_backend_info() const`	Queries this SYCL `context` for SYCL backend-specific information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the SYCL backend specification. Must throw an `exception` with the `errc::backend_mismatch` error code if the SYCL backend that corresponds with `Param` is different from the SYCL backend that is associated with this `context`.
`platform get_platform() const`	Returns the SYCL `platform` that is associated with this SYCL `context`. The value returned must be equal to that returned by `get_info<info::context::platform>()`.
`std::vector<device> get_devices() const`	Returns a `std::vector` containing all SYCL `devices` that are associated with this SYCL `context`. The value returned must be equal to that returned by `get_info<info::context::devices>()`.

4.6.3.2. Context information descriptors

A context can be queried for information using the `get_info` member function of the `context` class, specifying one of the info parameters in `info::context`. The possible values for each info parameter and any restrictions are defined in the specification of the SYCL backend associated with the context. All info parameters in `info::context` are specified in Table 21 and the synopsis for `info::context` is described in Section A.2.

Table 21. Context information descriptors

Context Descriptors	Return type	Description
`info::context::platform`	`platform`	Returns the platform associated with the context.
`info::context::devices`	`std::vector<device>`	Returns all of the devices associated with the context.
`info::context::atomic_memory_order_capabilities`	`std::vector<memory_order>`	Returns the set of memory orderings supported by atomic operations on all devices in the context, which is guaranteed to include `relaxed`. The memory ordering of the context determines the behavior of atomic operations applied to any memory that can be concurrently accessed by multiple devices in the context.

Context Descriptors	Return type	Description
`info::context::atomic_fence_order_capabilities`	`std::vector<memory_order>`	Returns the set of memory orderings supported by `atomic_fence` on all devices in the context, which is guaranteed to include `relaxed`, `acquire`, `release` and `acq_rel`. The memory ordering of the context determines the behavior of fence operations applied to any memory that can be concurrently accessed by multiple devices in the context.
`info::context::atomic_memory_scope_capabilities`	`std::vector<memory_scope>`	Returns the set of memory scopes supported by atomic operations on all devices in the context, which is guaranteed to include `work_group`.
`info::context::atomic_fence_scope_capabilities`	`std::vector<memory_scope>`	Returns the set of memory orderings supported by `atomic_fence` on all devices in the context, which is guaranteed to include `work_group`.

4.6.3.3. Context properties

The `property_list` constructor parameters are present for extensibility.

4.6.4. Device class

The SYCL `device` class encapsulates a single SYCL device on which kernels can be executed.

All member functions of the `device` class are synchronous and errors are handled by throwing synchronous SYCL exceptions.

The execution environment for a SYCL application has a fixed number of root devices which does not vary as the application executes. The application can get a list of all these devices via `device::get_devices()`, and the order of the device objects is the same each time the application calls that function (assuming the parameter to that function is the same for each call). The `device` class also provides constructors, but constructing a new `device` instance merely creates a new object that is a copy of one of the objects returned by `device::get_devices()`.

A SYCL `device` can be partitioned into multiple SYCL devices, by calling the `create_sub_devices()` member function template. The resulting SYCL `devices` are considered sub devices, and it is valid to partition these sub devices further. The range of support for this feature is SYCL backend and device specific and can be queried for through `get_info()`.

The SYCL `device` class provides the common reference semantics (see Section 4.5.2).

4.6.4.1. Device interface

A synopsis of the SYCL `device` class is provided below. The constructors, member functions and static member functions of the SYCL `device` class are listed in Table 22, Table 23 and Table 24 respectively. The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively.

```
1 namespace sycl {
2
3 class device {
```

```
public:
 device();

 template <typename DeviceSelector>
 explicit device(const DeviceSelector& deviceSelector);

 /* -- common interface members -- */

 backend get_backend() const noexcept;

 bool is_cpu() const;

 bool is_gpu() const;

 bool is_accelerator() const;

 platform get_platform() const;

 template <typename Param> typename Param::return_type get_info() const;

 template <typename Param>
 typename Param::return_type get_backend_info() const;

 bool has(aspect asp) const;

 bool has_extension(const std::string& extension) const; // Deprecated

 // Available only when Prop == info::partition_property::partition_equally
 template <info::partition_property Prop>
 std::vector<device> create_sub_devices(size_t count) const;

 // Available only when Prop == info::partition_property::partition_by_counts
 template <info::partition_property Prop>
 std::vector<device>
 create_sub_devices(const std::vector<size_t>& counts) const;

 // Available only when Prop ==
 // info::partition_property::partition_by_affinity_domain
 template <info::partition_property Prop>
 std::vector<device>
 create_sub_devices(info::partition_affinity_domain affinityDomain) const;

 static std::vector<device>
 get_devices(info::device_type deviceType = info::device_type::all);
};
} // namespace sycl
```

Table 22. Constructors of the SYCL `device` class

Constructor	Description
`device()`	Constructs a SYCL `device` instance that is a copy of the device returned by `default_selector_v`.

Constructor	Description
`template <typename DeviceSelector> explicit device(const DeviceSelector&)`	Constructs a SYCL `device` instance that is a copy of the device returned by the device selector parameter.

Table 23. Member functions of the SYCL `device` class

Member function	Description
`backend get_backend() const noexcept`	Returns a `backend` identifying the SYCL backend associated with this `device`.
`platform get_platform() const`	Returns the associated SYCL `platform`. The value returned must be equal to that returned by `get_info<info::device::platform>()`.
`bool is_cpu() const`	Returns the same value as `has(aspect::cpu)`. See Table 26.
`bool is_gpu() const`	Returns the same value as `has(aspect::gpu)`. See Table 26.
`bool is_accelerator() const`	Returns the same value as `has(aspect::accelerator)`. See Table 26.
`template <typename Param> typename Param ::return_type get_info() const`	Queries this SYCL `device` for information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the info parameters in Table 25 to facilitate returning the type associated with the `Param` parameter.
`template <typename Param> typename Param ::return_type get_backend_info() const`	Queries this SYCL `device` for SYCL backend -specific information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the SYCL backend specification. Must throw an `exception` with the `errc::backend_mismatch` error code if the SYCL backend that corresponds with `Param` is different from the SYCL backend that is associated with this `device`.
`bool has(aspect asp) const`	Returns true if this SYCL `device` has the given aspect. SYCL applications can use this member function to determine which optional features this device supports (if any).
`bool has_extension(const std::string& extension) const`	Deprecated, use `has()` instead. Returns true if this SYCL `device` supports the extension queried by the `extension` parameter.

Member function	Description
`template <info::partition_property Prop> std::vector<device> create_sub_devices(size_t count) const`	Available only when `Prop` is `info::partition_property::partition_equally`. Returns a `std::vector` of sub devices partitioned from this SYCL `device` based on the `count` parameter. The returned vector contains as many sub devices as can be created such that each sub device contains `count` compute units. If the device's total number of compute units (as returned by `info::device::max_compute_units`) is not evenly divided by `count`, then the remaining compute units are not included in any of the sub devices. If this SYCL `device` does not support `info::partition_property::partition_equally` an `exception` with the `errc::feature_not_supported` error code must be thrown. If `count` exceeds the total number of compute units in the device, an `exception` with the `errc::invalid` error code must be thrown.
`template <info::partition_property Prop> std::vector<device> create_sub_devices(const std::vector<size_t>& counts) const`	Available only when `Prop` is `info::partition_property::partition_by_counts`. Returns a `std::vector` of sub devices partitioned from this SYCL `device` based on the `counts` parameter. For each non-zero value *M* in the `counts` vector, a sub device with *M* compute units is created. If the SYCL `device` does not support `info::partition_property::partition_by_counts` an `exception` with the `errc::feature_not_supported` error code must be thrown. If the number of non-zero values in `counts` exceeds the device's maximum number of sub devices (as returned by `info::device::partition_max_sub_devices`) or if the total of all the values in the `counts` vector exceeds the total number of compute units in the device (as returned by `info::device::max_compute_units`), an `exception` with the `errc::invalid` error code must be thrown.

Member function	Description
`template <info::partition_property Prop> std::vector<device> create_sub_devices(info::partition_affinity_domain domain) const`	Available only when `Prop` is `info::partition_property::partition_by_affinity_domain`. Returns a `std::vector` of sub devices partitioned from this SYCL `device` by affinity domain based on the `domain` parameter, which must be one of the following values: • `info::partition_affinity_domain::numa`: Split the device into sub devices comprised of compute units that share a NUMA node. • `info::partition_affinity_domain::L4_cache`: Split the device into sub devices comprised of compute units that share a level 4 data cache. • `info::partition_affinity_domain::L3_cache`: Split the device into sub devices comprised of compute units that share a level 3 data cache. • `info::partition_affinity_domain::L2_cache`: Split the device into sub devices comprised of compute units that share a level 2 data cache. • `info::partition_affinity_domain::L1_cache`: Split the device into sub devices comprised of compute units that share a level 1 data cache. • `info::partition_affinity_domain::next_partitionable`: Split the device along the next partitionable affinity domain. The implementation shall find the first level along which the device or sub device may be further subdivided in the order `numa`, `L4_cache`, `L3_cache`, `L2_cache`, `L1_cache`, and partition the device into sub devices comprised of compute units that share memory subsystems at this level. The user may determine what happened via `info::device::partition_type_affinity_domain`. If the SYCL `device` does not support `info::partition_property::partition_by_affinity_domain` or the SYCL `device` does not support the `info::partition_affinity_domain` provided, an `exception` with the `errc::feature_not_supported` error code must be thrown.

Table 24. Static member functions of the SYCL `device` class

Static member function	Description
`static std::vector<device> get_devices(info::device_type deviceType = info::device_type::all)`	Returns a `std::vector` containing all the root devices from all SYCL backends available in the system which have the device type encapsulated by `deviceType`.

4.6.4.2. Device information descriptors

A device can be queried for information using the `get_info` member function of the `device` class, specifying one of the info parameters in `info::device`. The possible values for each info parameter and any restriction are defined in the specification of the SYCL backend associated with the device. All info parameters in `info::device` are specified in Table 25 and the synopsis for `info::device` is described in Section A.3.

Table 25. Device information descriptors

Device descriptors	Return type	Description
`info::device::device_type`	`info::device_type`	Returns the device type associated with the device. May not return `info::device_type::all`.
`info::device::vendor_id`	`uint32_t`	Returns a unique vendor device identifier.
`info::device::max_compute_units`	`uint32_t`	Returns the number of parallel compute units available to the device. The minimum value is 1.
`info::device::max_work_item_dimensions`	`uint32_t`	Returns the maximum dimensions that specify the global and local work-item IDs used by the data parallel execution model. The minimum value is 3 if this SYCL `device` is not of device type `info::device_type::custom`.
`info::device::max_work_item_sizes<1>`	`range<1>`	Returns the maximum number of work-items that are permitted in a work-group for a kernel running in a one-dimensional index space. The minimum value is (1) for `devices` that are not of device type `info::device_type::custom`.
`info::device::max_work_item_sizes<2>`	`range<2>`	Returns the maximum number of work-items that are permitted in each dimension of a work-group for a kernel running in a two-dimensional index space. The minimum value is $(1, 1)$ for `devices` that are not of device type `info::device_type::custom`.
`info::device::max_work_item_sizes<3>`	`range<3>`	Returns the maximum number of work-items that are permitted in each dimension of a work-group for a kernel running in a three-dimensional index space. The minimum value is $(1, 1, 1)$ for `devices` that are not of device type `info::device_type::custom`.

Device descriptors	Return type	Description
`info::device::max_work_group_size`	`size_t`	Returns the maximum number of work-items that are permitted in a work-group executing a kernel on a single compute unit. The minimum value is 1.
`info::device::max_num_sub_groups`	`uint32_t`	Returns the maximum number of sub-groups in a work-group for any kernel executed on the device. The minimum value is 1.
`info::device::sub_group_sizes`	`std::vector<size_t>`	Returns a `std::vector` of `size_t` containing the set of sub-group sizes supported by the device.

`info::device::preferred_vector_width_char`
`info::device::preferred_vector_width_short`
`info::device::preferred_vector_width_int`
`info::device::preferred_vector_width_long`
`info::device::preferred_vector_width_float`
`info::device::preferred_vector_width_double`
`info::device::preferred_vector_width_half`
	`uint32_t`	Returns the preferred native vector width size for built-in scalar types that can be put into vectors. The vector width is defined as the number of scalar elements that can be stored in the vector. Must return 0 for `info::device::preferred_vector_width_double` if the `device` does not have `aspect::fp64` and must return 0 for `info::device::preferred_vector_width_half` if the `device` does not have `aspect::fp16`.

`info::device::native_vector_width_char`
`info::device::native_vector_width_short`
`info::device::native_vector_width_int`
`info::device::native_vector_width_long`
`info::device::native_vector_width_float`
`info::device::native_vector_width_double`
`info::device::native_vector_width_half`
	`uint32_t`	Returns the native ISA vector width. The vector width is defined as the number of scalar elements that can be stored in the vector. Must return 0 for `info::device::native_vector_width_double` if the `device` does not have `aspect::fp64` and must return 0 for `info::device::native_vector_width_half` if the `device` does not have `aspect::fp16`.

`info::device::max_clock_frequency`	`uint32_t`	Returns the maximum configured clock frequency of this SYCL `device` in MHz.
`info::device::address_bits`	`uint32_t`	Returns the default compute device address space size specified as an unsigned integer value in bits. Must return either 32 or 64.

Device descriptors	Return type	Description
`info::device::max_mem_alloc_size`	`uint64_t`	Returns the maximum size of memory object allocation in bytes. The minimum value is max (1/4th of `info::device::global_mem_size`,128*1024*1024) if this SYCL `device` is not of device type `info::device_type::custom`.
`info::device::image_support`	`bool`	Deprecated. Returns the same value as `device::has(aspect::image)`.
`info::device::max_read_image_args`	`uint32_t`	Returns the maximum number of simultaneous image objects that can be read from by a kernel. The minimum value is 128 if the SYCL `device` has `aspect::image`.
`info::device::max_write_image_args`	`uint32_t`	Returns the maximum number of simultaneous image objects that can be written to by a kernel. The minimum value is 8 if the SYCL `device` has `aspect::image`.
`info::device::image2d_max_width`	`size_t`	Returns the maximum width of a 2D image or 1D image in pixels. The minimum value is 8192 if the SYCL `device` has `aspect::image`.
`info::device::image2d_max_height`	`size_t`	Returns the maximum height of a 2D image in pixels. The minimum value is 8192 if the SYCL `device` has `aspect::image`.
`info::device::image3d_max_width`	`size_t`	Returns the maximum width of a 3D image in pixels. The minimum value is 2048 if the SYCL `device` has `aspect::image`.
`info::device::image3d_max_height`	`size_t`	Returns the maximum height of a 3D image in pixels. The minimum value is 2048 if the SYCL `device` has `aspect::image`.
`info::device::image3d_max_depth`	`size_t`	Returns the maximum depth of a 3D image in pixels. The minimum value is 2048 if the SYCL `device` has `aspect::image`.
`info::device::image_max_buffer_size`	`size_t`	Returns the number of pixels for a 1D image created from a buffer object. The minimum value is 65536 if the SYCL `device` has `aspect::image`. Note that this information is intended for OpenCL interoperability only as this feature is not supported in SYCL.
`info::device::max_samplers`	`uint32_t`	Returns the maximum number of samplers that can be used in a kernel. The minimum value is 16 if the SYCL `device` has `aspect::image`.

Device descriptors	Return type	Description
`info::device::max_parameter_size`	`size_t`	Returns the maximum size in bytes of the arguments that can be passed to a kernel. The minimum value is 1024 if this SYCL `device` is not of device type `info::device_type::custom`. For this minimum value, only a maximum of 128 arguments can be passed to a kernel.
`info::device::mem_base_addr_align`	`uint32_t`	Returns the minimum value in bits of the largest supported SYCL built-in data type if this SYCL `device` is not of device type `info::device_type::custom`.
`info::device::half_fp_config`	`std::vector<info::fp_config>`	Returns a `std::vector` of `info::fp_config` describing the half precision floating-point capability of this SYCL `device`. The `std::vector` may contain zero or more of the following values: • `info::fp_config::denorm:` denorms are supported. • `info::fp_config::inf_nan:` INF and quiet NaNs are supported. • `info::fp_config::round_to_nearest:` round to nearest even rounding mode is supported. • `info::fp_config::round_to_zero:` round to zero rounding mode is supported. • `info::fp_config::round_to_inf:` round to positive and negative infinity rounding modes are supported. • `info::fp_config::fma:` IEEE754-2008 fused multiply add is supported. • `info::fp_config::correctly_rounded_divide_sqrt:` divide and sqrt are correctly rounded as defined by the IEEE754 specification. This property is deprecated. • `info::fp_config::soft_float:` basic floating-point operations (such as addition, subtraction, multiplication) are implemented in software. If half precision is supported by this SYCL `device` (i.e. the `device` has `aspect::fp16` there is no minimum floating-point capability. If half support is not supported the returned `std::vector` must be empty.

Device descriptors	Return type	Description
`info::device::single_fp_config`	`std::vector<info::fp_config>`	Returns a `std::vector` of `info::fp_config` describing the single precision floating-point capability of this SYCL `device`. The `std::vector` must contain one or more of the following values: • `info::fp_config::denorm`: denorms are supported. • `info::fp_config::inf_nan`: INF and quiet NaNs are supported. • `info::fp_config::round_to_nearest`: round to nearest even rounding mode is supported. • `info::fp_config::round_to_zero`: round to zero rounding mode is supported. • `info::fp_config::round_to_inf`: round to positive and negative infinity rounding modes are supported. • `info::fp_config::fma`: IEEE754-2008 fused multiply add is supported. • `info::fp_config::correctly_rounded_divide_sqrt`: divide and sqrt are correctly rounded as defined by the IEEE754 specification. This property is deprecated. • `info::fp_config::soft_float`: basic floating-point operations (such as addition, subtraction, multiplication) are implemented in software. If this SYCL `device` is not of type `info::device_type::custom` then the minimum floating-point capability must be: `info::fp_config::round_to_nearest` and `info::fp_config::inf_nan`.

Device descriptors	Return type	Description
`info::device::double_fp_config`	`std::vector<info::fp_config>`	Returns a `std::vector` of `info::fp_config` describing the double precision floating-point capability of this SYCL `device`. The `std::vector` may contain zero or more of the following values: • `info::fp_config::denorm:` denorms are supported. • `info::fp_config::inf_nan:` INF and NaNs are supported. • `info::fp_config::round_to_nearest:` round to nearest even rounding mode is supported. • `info::fp_config::round_to_zero:` round to zero rounding mode is supported. • `info::fp_config::round_to_inf:` round to positive and negative infinity rounding modes are supported. • `info::fp_config::fma:` IEEE754-2008 fused multiply-add is supported. • `info::fp_config::soft_float:` basic floating-point operations (such as addition, subtraction, multiplication) are implemented in software. If double precision is supported by this SYCL `device` (i.e. the `device` has `aspect::fp64` and this SYCL `device` is not of type `info::device_type::custom` then the minimum floating-point capability must be: `info::fp_config::fma`, `info::fp_config::round_to_nearest`, `info::fp_config::round_to_zero`, `info::fp_config::round_to_inf`, `info::fp_config::inf_nan` and `info::fp_config::denorm`. If double support is not supported the returned `std::vector` must be empty.
`info::device::global_mem_cache_type`	`info::global_mem_cache_type`	Returns the type of global memory cache supported.
`info::device::global_mem_cache_line_size`	`uint32_t`	Returns the size of global memory cache line in bytes.
`info::device::global_mem_cache_size`	`uint64_t`	Returns the size of global memory cache in bytes.
`info::device::global_mem_size`	`uint64_t`	Returns the size of global device memory in bytes.

Device descriptors	Return type	Description
`info::device::max_constant_buffer_size`	`uint64_t`	Deprecated in SYCL 2020. Returns the maximum size in bytes of a constant buffer allocation. The minimum value is 64 KB if this SYCL `device` is not of type `info::device_type::custom`.
`info::device::max_constant_args`	`uint32_t`	Deprecated in SYCL 2020. Returns the maximum number of constant arguments that can be declared in a kernel. The minimum value is 8 if this SYCL `device` is not of type `info::device_type::custom`.
`info::device::local_mem_type`	`info::local_mem_type`	Returns the type of local memory supported. This can be `info::local_mem_type::local` implying dedicated local memory storage such as SRAM, or `info::local_mem_type::global`. If this SYCL `device` is of type `info::device_type::custom` this can also be `info::local_mem_type::none`, indicating local memory is not supported.
`info::device::local_mem_size`	`uint64_t`	Returns the size of local memory arena in bytes. The minimum value is 32 KB if this SYCL `device` is not of type `info::device_type::custom`.
`info::device::error_correction_support`	`bool`	Returns true if the device implements error correction for all accesses to compute device memory (global and constant). Returns false if the device does not implement such error correction.
`info::device::host_unified_memory`	`bool`	Deprecated, use `device::has()` with one of the `aspect::usm_*` aspects instead. Returns true if the device and the host have a unified memory subsystem and returns false otherwise.
`info::device::atomic_memory_order_capabilities`	`std::vector<memory_order>`	Returns the set of memory orderings supported by atomic operations on the device, which is guaranteed to include `relaxed`.
`info::device::atomic_fence_order_capabilities`	`std::vector<memory_order>`	Returns the set of memory orderings supported by `atomic_fence` on the device, which is guaranteed to include `relaxed`, `acquire`, `release` and `acq_rel`.
`info::device::atomic_memory_scope_capabilities`	`std::vector<memory_scope>`	Returns the set of memory scopes supported by atomic operations on the device, which is guaranteed to include `work_group`.
`info::device::atomic_fence_scope_capabilities`	`std::vector<memory_scope>`	Returns the set of memory scopes supported by `atomic_fence` on the device, which is guaranteed to include `work_group`.

Device descriptors	Return type	Description
`info::device::profiling_timer_resolution`	`size_t`	Returns the resolution of device timer in nanoseconds.
`info::device::is_endian_little`	`bool`	Deprecated. Check the byte order of the host system instead. The host and device are required to have the same byte order. Returns true if this SYCL `device` is a little endian device and returns false otherwise.
`info::device::is_available`	`bool`	Returns true if the SYCL `device` is available and returns false if the device is not available.
`info::device::is_compiler_available`	`bool`	Deprecated. Returns the same value as `device::has(aspect::online_compiler)`.
`info::device::is_linker_available`	`bool`	Deprecated. Returns the same value as `device::has(aspect::online_linker)`.
`info::device::execution_capabilities`	`std::vector<info::execution_capability>`	Returns a `std::vector` of the `info::execution_capability` describing the supported execution capabilities. Note that this information is intended for OpenCL interoperability only as SYCL only supports `info::execution_capability::exec_kernel`.
`info::device::queue_profiling`	`bool`	Deprecated. Returns the same value as `device::has(aspect::queue_profiling)`.
`info::device::built_in_kernel_ids`	`std::vector<kernel_id>`	Returns a `std::vector` of identifiers for the built-in kernels supported by this SYCL `device`.
`info::device::built_in_kernels`	`std::vector<std::string>`	Deprecated. Use `info::device::built_in_kernel_ids` instead. Returns a `std::vector` of built-in OpenCL kernels supported by this SYCL `device`.
`info::device::platform`	`platform`	Returns the SYCL `platform` associated with this SYCL `device`.
`info::device::name`	`std::string`	Returns the device name of this SYCL `device`.
`info::device::vendor`	`std::string`	Returns the vendor of this SYCL `device`.
`info::device::driver_version`	`std::string`	Returns a vendor-defined string describing the version of the underlying backend software driver.

Device descriptors	Return type	Description
`info::device::profile`	`std::string`	Deprecated in SYCL 2020. Only supported when using the OpenCL backend (see Appendix C). Throws an `exception` with the `errc::invalid` error code if used with a device whose backend is not OpenCL. The value returned can be one of the following strings: • FULL_PROFILE - if the device supports the OpenCL specification (functionality defined as part of the core specification and does not require any extensions to be supported). • EMBEDDED_PROFILE - if the device supports the OpenCL embedded profile.
`info::device::version`	`std::string`	Returns a backend-defined device version.
`info::device::backend_version`	`std::string`	Returns a string describing the version of the SYCL backend associated with the device. The possible values are specified in the SYCL backend specification of the SYCL backend associated with the device.
`info::device::aspects`	`std::vector<aspect>`	Returns a `std::vector` of aspect values supported by this SYCL `device`.

Device descriptors	Return type	Description
`info::device::extensions`	`std::vector<std::string>`	Deprecated, use `info::device::aspects` instead. Returns a `std::vector` of extension names (the extension names do not contain any spaces) supported by this SYCL `device`. The extension names returned can be vendor supported extension names and one or more of the following Khronos approved extension names: • `cl_khr_int64_base_atomics` • `cl_khr_int64_extended_atomics` • `cl_khr_3d_image_writes` • `cl_khr_fp16` • `cl_khr_gl_sharing` • `cl_khr_gl_event` • `cl_khr_d3d10_sharing` • `cl_khr_dx9_media_sharing` • `cl_khr_d3d11_sharing` • `cl_khr_depth_images` • `cl_khr_gl_depth_images` • `cl_khr_gl_msaa_sharing` • `cl_khr_image2d_from_buffer` • `cl_khr_initialize_memory` • `cl_khr_context_abort` • `cl_khr_spir` If this SYCL `device` is an OpenCL device then following approved Khronos extension names must be returned by all device that support OpenCL C 1.2: • `cl_khr_global_int32_base_atomics` • `cl_khr_global_int32_extended_atomics` • `cl_khr_local_int32_base_atomics` • `cl_khr_local_int32_extended_atomics` • `cl_khr_byte_addressable_store` • `cl_khr_fp64` (for backward compatibility if double precision is supported) Please refer to the OpenCL 1.2 Extension Specification for a detailed description of these extensions.

Device descriptors	Return type	Description
`info::device::printf_buffer_size`	`size_t`	Deprecated in SYCL 2020. Returns the maximum size of the internal buffer that holds the output of `printf` calls from a kernel. The minimum value is 1 MB if `info::device::profile` returns true for this SYCL `device`.
`info::device::preferred_interop_user_sync`	`bool`	Deprecated in SYCL 2020. Only supported when using the OpenCL backend (see Appendix C). Throws an `exception` with the `errc::invalid` error code if used with a device whose backend is not OpenCL. Returns true if the preference for this SYCL `device` is for the user to be responsible for synchronization, when sharing memory objects between OpenCL and other APIs such as DirectX, false if the device/implementation has a performant path for performing synchronization of memory object shared between OpenCL and other APIs such as DirectX.
`info::device::parent_device`	`device`	Returns the parent SYCL `device` to which this sub-device is a child if this is a sub-device. Must throw an `exception` with the `errc::invalid` error code if this SYCL `device` is not a sub device.
`info::device::partition_max_sub_devices`	`uint32_t`	Returns the maximum number of sub-devices that can be created when this SYCL `device` is partitioned. The value returned cannot exceed the value returned by `info::device::device_max_compute_units`.
`info::device::partition_properties`	`std::vector<info::partition_property>`	Returns the partition properties supported by this SYCL `device;` a vector of `info::partition_property`. An element is returned in this vector only if the device can be partitioned into at least two sub devices along that partition property.
`info::device::partition_affinity_domains`	`std::vector<info::partition_affinity_domain>`	Returns a `std::vector` of the partition affinity domains supported by this SYCL `device` when partitioning with `info::partition_property::partition_by_affinity_domain`. An element is returned in this vector only if the device can be partitioned into at least two sub devices along that affinity domain.

Device descriptors	Return type	Description
`info::device::partition_type_property`	`info::partition_property`	Returns the partition property of this SYCL `device`. If this SYCL `device` is not a sub device then the return value must be `info::partition_property::no_partition`, otherwise it must be one of the following values: • `info::partition_property::partition_equally` • `info::partition_property::partition_by_counts` • `info::partition_property::partition_by_affinity_domain`
`info::device::partition_type_affinity_domain`	`info::partition_affinity_domain`	Returns the partition affinity domain of this SYCL `device`. If this SYCL `device` is not a sub device or the sub device was not partitioned with `info::partition_type::partition_by_affinity_domain` then the return value must be `info::partition_affinity_domain::not_applicable`, otherwise it must be one of the following values: • `info::partition_affinity_domain::numa` • `info::partition_affinity_domain::L4_cache` • `info::partition_affinity_domain::L3_cache` • `info::partition_affinity_domain::L2_cache` • `info::partition_affinity_domain::L1_cache`

4.6.4.3. Device aspects

Every SYCL device has an associated set of aspects which identify characteristics of the `device`. Aspects are defined via the `enum class aspect` enumeration:

```
namespace sycl {

enum class aspect : /* unspecified */ {
  cpu,
  gpu,
  accelerator,
  custom,
  emulated,
  host_debuggable,
  fp16,
  fp64,
  atomic64,
  image,
  online_compiler,
  online_linker,
```

```
  queue_profiling,
  usm_device_allocations,
  usm_host_allocations,
  usm_atomic_host_allocations,
  usm_shared_allocations,
  usm_atomic_shared_allocations,
  usm_system_allocations
};

} // namespace sycl
```

SYCL applications can query the aspects for a `device` via `device::has()` in order to determine whether the `device` supports any optional features. Table 26 lists the aspects that are defined in the core SYCL specification and tells which optional features correspond to each. Backends and extensions may provide additional aspects and additional optional device features. If so, the SYCL backend specification document or the extension document describes them.

Table 26. Device aspects defined by the core SYCL specification

Aspect	Description
`aspect::cpu`	A device that runs on a CPU. Devices with this `aspect` have device type `info::device_type::cpu`.
`aspect::gpu`	A device that can also be used to accelerate a 3D graphics API. Devices with this `aspect` have device type `info::device_type::gpu`.
`aspect::accelerator`	A dedicated accelerator device, usually using a peripheral interconnect for communication. Devices with this `aspect` have device type `info::device_type::accelerator`.
`aspect::custom`	A dedicated accelerator that can use the SYCL API, but programmable kernels cannot be dispatched to the device, only fixed functionality is available. See Section 3.9.7. Devices with this `aspect` have device type `info::device_type::custom`.
`aspect::emulated`	Indicates that the device is somehow emulated. A device with this aspect is not intended for performance, and instead will generally have another purpose such as emulation or profiling. The precise definition of this aspect is left open to the SYCL implementation. As an example, a vendor might support both a hardware FPGA device and a software emulated FPGA, where the emulated FPGA has all the same features as the hardware one but runs more slowly and can provide additional profiling or diagnostic information. In such a case, an application's device selector can use `aspect::emulated` to distinguish the two.

Aspect	Description
`aspect::host_debuggable`	Indicates that kernels running on this device can be debugged using standard debuggers that are normally available on the host system where the SYCL implementation resides. The precise definition of this aspect is left open to the SYCL implementation.
`aspect::fp16`	Indicates that kernels submitted to the device may use the `sycl::half` data type.
`aspect::fp64`	Indicates that kernels submitted to the device may use the `double` data type.
`aspect::atomic64`	Indicates that kernels submitted to the device may perform 64-bit atomic operations.
`aspect::image`	Indicates that the device supports images.
`aspect::online_compiler`	Indicates that the device supports online compilation of device code. Devices that have this aspect support the `build()` and `compile()` functions defined in Section 4.11.11.
`aspect::online_linker`	Indicates that the device supports online linking of device code. Devices that have this aspect support the `link()` functions defined in Section 4.11.11. All devices that have this aspect also have `aspect::online_compiler`.
`aspect::queue_profiling`	Indicates that the device supports queue profiling via `property::queue::enable_profiling`.
`aspect::usm_device_allocations`	Indicates that the device supports explicit USM allocations as described in Section 4.8.
`aspect::usm_host_allocations`	Indicates that the device can access USM memory allocated via `usm::alloc::host`. The device only supports atomic modification of a host allocation if `aspect::usm_atomic_host_allocations` is also supported. (See Section 4.8.)
`aspect::usm_atomic_host_allocations`	Indicates that the device supports USM memory allocated via `usm::alloc::host`. The host and this device may concurrently access and atomically modify host allocations. (See Section 4.8.)
`aspect::usm_shared_allocations`	Indicates that the device supports USM memory allocated via `usm::alloc::shared` on the same device. Concurrent access and atomic modification of a shared allocation is only supported if `aspect::usm_atomic_shared_allocations` is also supported. (See Section 4.8.)

Aspect	Description
`aspect::usm_atomic_shared_allocations`	Indicates that the device supports USM memory allocated via `usm::alloc::shared`. The host and other devices in the same context that also support this capability may concurrently access and atomically modify shared allocations. The allocation is free to migrate between the host and the appropriate devices. (See Section 4.8.)
`aspect::usm_system_allocations`	Indicates that the system allocator may be used instead of SYCL USM allocation mechanisms for `usm::alloc::shared` allocations on this device. (See Section 4.8.)

The implementation also provides two traits that the application can use to query aspects at compilation time. The traits `any_device_has<aspect>` and `all_devices_have<aspect>` are set according to the collection of devices *D* that can possibly execute device code, as determined by the compilation environment. The trait `any_device_has<aspect>` inherits from `std::true_type` only if at least one device in *D* has the specified aspect. The trait `all_devices_have<aspect>` inherits from `std::true_type` only if all devices in *D* have the specified aspect.

```
namespace sycl {

template <aspect Aspect> struct any_device_has;
template <aspect Aspect> struct all_devices_have;

template <aspect A>
inline constexpr bool any_device_has_v = any_device_has<A>::value;
template <aspect A>
inline constexpr bool all_devices_have_v = all_devices_have<A>::value;

} // namespace sycl
```

Applications can use these traits to reduce their code size. The following example demonstrates one way to use these traits to avoid instantiating a templated kernel for device features that are not supported by any device.

```
#include <sycl/sycl.hpp>
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

constexpr int N = 512;

template <bool HasFp16> class MyKernel {
 public:
  void operator()(id<1> i) {
    if constexpr (HasFp16) {
      // Algorithm using sycl::half type
    } else {
      // Fall back code for devices that don't support sycl::half
    }
  }
};

int main() {
```

```
18   queue myQueue;
19   myQueue.submit([&](handler& cgh) {
20     device dev = myQueue.get_device();
21     if (dev.has(aspect::fp16)) {
22       cgh.parallel_for(range { N },
23                        MyKernel<any_device_has_v<aspect::fp16>> {});
24     } else {
25       cgh.parallel_for(range { N },
26                        MyKernel<all_devices_have_v<aspect::fp16>> {});
27     }
28   });
29
30   myQueue.wait();
31 }
```

The kernel function `MyKernel` is templated to use a different algorithm depending on whether the device has the aspect `aspect::fp16`, and the call to `dev.has()` chooses the kernel function instantiation that matches the device's capabilities. However, the use of `any_device_has_v` and `all_devices_have_v` entirely avoid useless instantiations of the kernel function. For example, when the compilation environment does not support any devices with `aspect::fp16`, `any_device_has_v<aspect::fp16>` is `false`, and the kernel function is never instantiated with support for the `sycl::half` type.

Like any trait, the definitions of `any_device_has` and `all_devices_have` are uniform across all parts of a SYCL application. If an implementation uses SMCP, all compiler passes define a particular aspect's specialization of the traits the same way, regardless of whether that compiler pass' device supports the aspect. Thus, `any_device_has` and `all_devices_have` cannot be used to determine whether any particular device supports an aspect. Instead, applications must use `device::has()` or `platform::has()` for this.

An implementation could choose to provide command line options which affect the set of devices that it supports. If so, those command line options would also affect these traits. For example, if an implementation provides a command line option that disables `aspect::accelerator` devices, the trait `any_device_has<aspect::accelerator>` would inherit from `std::false_type` when that command line option was specified.

These traits only reflect the supported devices at the time the SYCL application is compiled. It's possible that unsupported devices are still visible to the application when it runs. However, if a device *D* is not supported when the application is compiled, the application will not be able to submit kernels to that device *D*.

4.6.5. Queue class

The SYCL `queue` class encapsulates a single SYCL queue which schedules kernels on a SYCL device.

A SYCL `queue` can be used to submit command groups to be executed by the SYCL runtime using the `submit` member function.

All member functions of the `queue` class are synchronous and errors are handled by throwing synchronous SYCL exceptions. The `submit` member function synchronously invokes the provided command group function object (as described in Section 3.7.1.2) in the calling thread, thereby scheduling a command group for asynchronous execution. Any error in the submission of a command group is handled by throwing a synchronous SYCL exception. Any errors from the command group after it has been submitted are handled by passing asynchronous errors at specific times to an async_handler, as described in Section 4.13.

A SYCL queue can wait for all command groups that it has submitted by calling wait or wait_and_throw.

The default constructor of the SYCL queue class will construct a queue based on the SYCL device returned from the default_selector_v (see Section 4.6.1.1). All other constructors construct a queue as determined by the parameters provided. All constructors will implicitly construct a SYCL platform, device and context in order to facilitate the construction of the queue.

Each constructor takes as the last parameter an optional SYCL property_list to provide properties to the SYCL queue.

A SYCL queue may be destroyed even when there are uncompleted commands that have been submitted to the queue. Doing so does not block. Instead, any commands that have been submitted to the queue begin execution when their requisites are satisfied, just as they would had the queue not been destroyed. Any event objects for those commands are signaled in the normal manner when the command completes. Resources associated with the queue will be freed by the time the last command completes.

The SYCL queue class provides the common reference semantics (see Section 4.5.2).

4.6.5.1. Queue interface

A synopsis of the SYCL queue class is provided below. The constructors and member functions of the SYCL queue class are listed in Table 27 and Table 28 respectively. The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively.

Some queue member functions are shortcuts to member functions of the handler class. These are listed in Section 4.6.5.2.

```
namespace sycl {
class queue {
 public:
  explicit queue(const property_list& propList = {});

  explicit queue(const async_handler& asyncHandler,
                 const property_list& propList = {});

  template <typename DeviceSelector>
  explicit queue(const DeviceSelector& deviceSelector,
                 const property_list& propList = {});

  template <typename DeviceSelector>
  explicit queue(const DeviceSelector& deviceSelector,
                 const async_handler& asyncHandler,
                 const property_list& propList = {});

  explicit queue(const device& syclDevice, const property_list& propList = {});

  explicit queue(const device& syclDevice, const async_handler& asyncHandler,
                 const property_list& propList = {});

  template <typename DeviceSelector>
  explicit queue(const context& syclContext,
                 const DeviceSelector& deviceSelector,
                 const property_list& propList = {});

  template <typename DeviceSelector>
  explicit queue(const context& syclContext,
                 const DeviceSelector& deviceSelector,
```

```
                const async_handler& asyncHandler,
                const property_list& propList = {});

explicit queue(const context& syclContext, const device& syclDevice,
                const property_list& propList = {});

explicit queue(const context& syclContext, const device& syclDevice,
                const async_handler& asyncHandler,
                const property_list& propList = {});

/* -- common interface members -- */

/* -- property interface members -- */

backend get_backend() const noexcept;

context get_context() const;

device get_device() const;

bool is_in_order() const;

template <typename Param> typename Param::return_type get_info() const;

template <typename Param>
typename Param::return_type get_backend_info() const;

template <typename T> event submit(T cgf);

template <typename T> event submit(T cgf, const queue& secondaryQueue);

void wait();

void wait_and_throw();

void throw_asynchronous();

/* -- convenience shortcuts -- */

template <typename KernelName, typename KernelType>
event single_task(const KernelType& kernelFunc);

template <typename KernelName, typename KernelType>
event single_task(event depEvent, const KernelType& kernelFunc);

template <typename KernelName, typename KernelType>
event single_task(const std::vector<event>& depEvents,
                  const KernelType& kernelFunc);

// Parameter pack acts as-if: Reductions&&... reductions, const KernelType
// &kernelFunc
template <typename KernelName, int Dims, typename... Rest>
event parallel_for(range<Dims> numWorkItems, Rest&&... rest);

// Parameter pack acts as-if: Reductions&&... reductions, const KernelType
// &kernelFunc
```

```
template <typename KernelName, int Dims, typename... Rest>
event parallel_for(range<Dims> numWorkItems, event depEvent, Rest&&... rest);

// Parameter pack acts as-if: Reductions&&... reductions, const KernelType
// &kernelFunc
template <typename KernelName, int Dims, typename... Rest>
event parallel_for(range<Dims> numWorkItems,
                   const std::vector<event>& depEvents, Rest&&... rest);

// Parameter pack acts as-if: Reductions&&... reductions, const KernelType
// &kernelFunc
template <typename KernelName, int Dims, typename... Rest>
event parallel_for(nd_range<Dims> executionRange, Rest&&... rest);

// Parameter pack acts as-if: Reductions&&... reductions, const KernelType
// &kernelFunc
template <typename KernelName, int Dims, typename... Rest>
event parallel_for(nd_range<Dims> executionRange, event depEvent,
                   Rest&&... rest);

// Parameter pack acts as-if: Reductions&&... reductions, const KernelType
// &kernelFunc
template <typename KernelName, int Dims, typename... Rest>
event parallel_for(nd_range<Dims> executionRange,
                   const std::vector<event>& depEvents, Rest&&... rest);

/* -- USM functions -- */

event memcpy(void* dest, const void* src, size_t numBytes);
event memcpy(void* dest, const void* src, size_t numBytes, event depEvent);
event memcpy(void* dest, const void* src, size_t numBytes,
             const std::vector<event>& depEvents);

template <typename T> event copy(const T* src, T* dest, size_t count);
template <typename T>
event copy(const T* src, T* dest, size_t count, event depEvent);
template <typename T>
event copy(const T* src, T* dest, size_t count,
           const std::vector<event>& depEvents);

event memset(void* ptr, int value, size_t numBytes);
event memset(void* ptr, int value, size_t numBytes, event depEvent);
event memset(void* ptr, int value, size_t numBytes,
             const std::vector<event>& depEvents);

template <typename T> event fill(void* ptr, const T& pattern, size_t count);
template <typename T>
event fill(void* ptr, const T& pattern, size_t count, event depEvent);
template <typename T>
event fill(void* ptr, const T& pattern, size_t count,
           const std::vector<event>& depEvents);

event prefetch(void* ptr, size_t numBytes);
event prefetch(void* ptr, size_t numBytes, event depEvent);
event prefetch(void* ptr, size_t numBytes,
               const std::vector<event>& depEvents);
```

```
143
144   event mem_advise(void* ptr, size_t numBytes, int advice);
145   event mem_advise(void* ptr, size_t numBytes, int advice, event depEvent);
146   event mem_advise(void* ptr, size_t numBytes, int advice,
147                    const std::vector<event>& depEvents);
148
149   /// Placeholder accessor shortcuts
150
151   // Explicit copy functions
152
153   template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt,
154             access::placeholder IsPlaceholder, typename DestT>
155   event copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsPlaceholder> src,
156              std::shared_ptr<DestT> dest);
157
158   template <typename SrcT, typename DestT, int DestDims, access_mode DestMode,
159             target DestTgt, access::placeholder IsPlaceholder>
160   event copy(std::shared_ptr<SrcT> src,
161              accessor<DestT, DestDims, DestMode, DestTgt, IsPlaceholder> dest);
162
163   template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt,
164             access::placeholder IsPlaceholder, typename DestT>
165   event copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsPlaceholder> src,
166              DestT* dest);
167
168   template <typename SrcT, typename DestT, int DestDims, access_mode DestMode,
169             target DestTgt, access::placeholder IsPlaceholder>
170   event copy(const SrcT* src,
171              accessor<DestT, DestDims, DestMode, DestTgt, IsPlaceholder> dest);
172
173   template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt,
174             access::placeholder IsSrcPlaceholder, typename DestT, int DestDims,
175             access_mode DestMode, target DestTgt,
176             access::placeholder IsDestPlaceholder>
177   event
178   copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsSrcPlaceholder> src,
179        accessor<DestT, DestDims, DestMode, DestTgt, IsDestPlaceholder> dest);
180
181   template <typename T, int Dims, access_mode Mode, target Tgt,
182             access::placeholder IsPlaceholder>
183   event update_host(accessor<T, Dim, Mode, Tgt, IsPlaceholder> acc);
184
185   template <typename T, int Dims, access_mode Mode, target Tgt,
186             access::placeholder IsPlaceholder>
187   event fill(accessor<T, Dims, Mode, Tgt, IsPlaceholder> dest, const T& src);
188 };
189 } // namespace sycl
```

Table 27. Constructors of the queue class

Constructor	Description
`explicit queue(const property_list& propList = {})`	Constructs a SYCL `queue` instance using the device constructed from the `default_selector_v`. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.
`explicit queue(const async_handler& asyncHandler, const property_list& propList = {})`	Constructs a SYCL `queue` instance with an `async_handler` using the device constructed from the `default_selector_v`. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.
`template <typename DeviceSelector> explicit queue(const DeviceSelector& deviceSelector, const property_list& propList = {})`	Constructs a SYCL `queue` instance using the device returned by the device selector provided. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.
`template <typename DeviceSelector> explicit queue(const DeviceSelector& deviceSelector, const async_handler& asyncHandler, const property_list& propList = {})`	Constructs a SYCL `queue` instance with an `async_handler` using the device returned by the device selector provided. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.
`explicit queue(const device& syclDevice, const property_list& propList = {})`	Constructs a SYCL `queue` instance using the `syclDevice` provided. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.
`explicit queue(const device& syclDevice, const async_handler& asyncHandler, const property_list& propList = {})`	Constructs a SYCL `queue` instance with an `async_handler` using the `syclDevice` provided. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.
`template <typename DeviceSelector> explicit queue(const context& syclContext, const DeviceSelector& deviceSelector, const property_list& propList = {})`	Constructs a SYCL `queue` instance that is associated with the `syclContext` provided, using the device returned by the device selector provided. Must throw an `exception` with the `errc::invalid` error code if `syclContext` does not encapsulate the SYCL `device` returned by `deviceSelector`. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.

Constructor	Description
`template <typename DeviceSelector> explicit queue(const context& syclContext, const DeviceSelector& deviceSelector, const async_handler& asyncHandler, const property_list& propList = {})`	Constructs a SYCL `queue` instance with an `async_handler` that is associated with the `syclContext` provided, using the device returned by the device selector provided. Must throw an `exception` with the `errc::invalid` error code if `syclContext` does not encapsulate the SYCL `device` returned by `deviceSelector`. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.
`explicit queue(const context& syclContext, const device& syclDevice, const property_list& propList = {})`	Constructs a SYCL `queue` instance using the `syclDevice` provided. This device must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous exception with the `errc::invalid` error code. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.
`explicit queue(const context& syclContext, const device& syclDevice, const async_handler& asyncHandler, const property_list& propList = {})`	Constructs a SYCL `queue` instance with an `async_handler` using the `syclDevice` provided. This device must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous exception with the `errc::invalid` error code. Zero or more properties can be provided to the constructed SYCL `queue` via an instance of `property_list`.

Table 28. Member functions for `queue` class

Member function	Description
`backend get_backend() const noexcept`	Returns a `backend` identifying the SYCL backend associated with this `queue`.
`context get_context() const`	Returns the SYCL queue's context. Reports errors using SYCL exception classes. The value returned must be equal to that returned by `get_info<info::queue::context>()`.

Member function	Description
`device get_device() const`	Returns the SYCL device the queue is associated with. Reports errors using SYCL exception classes. The value returned must be equal to that returned by `get_info<info::queue::device>()`.
`bool is_in_order() const`	Returns true if the SYCL `queue` was created with the `in_order` property. Equivalent to `has_property<property::queue::in_order>()`.
`void wait()`	Performs a blocking wait for the completion of all enqueued tasks in the queue. Synchronous errors will be reported through SYCL exceptions.
`void wait_and_throw()`	Performs a blocking wait for the completion of all enqueued tasks in the queue. Synchronous errors will be reported through SYCL exceptions. Any unconsumed asynchronous errors will be passed to the async_handler associated with the queue or enclosing context. If no user defined `async_handler` is associated with the queue or enclosing context, then an implementation-defined default async_handler is called to handle any errors, as described in Section 4.13.1.2.
`void throw_asynchronous()`	Checks to see if any unconsumed asynchronous errors have been produced by the queue and if so reports them by passing them to the async_handler associated with the queue or enclosing context. If no user defined `async_handler` is associated with the queue or enclosing context, then an implementation-defined default async_handler is called to handle any errors, as described in Section 4.13.1.2.
`template <typename Param> typename Param::return_type get_info() const`	Queries this SYCL `queue` for information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the info parameters in Table 30 to facilitate returning the type associated with the `Param` parameter.

Member function	Description
`template <typename T> event submit(T cgf)`	Submit a command group function object to the queue, in order to be scheduled for execution on the device.
`template <typename T> event submit(T cgf, queue& secondaryQueue)`	Submit a command group function object to the queue, in order to be scheduled for execution on the device. On a kernel error, this command group function object is then scheduled for execution on the secondary queue. Returns an event, which corresponds to the queue the command group function object is being enqueued on.
`template <typename Param> typename Param::return_type get_backend_info() const`	Queries this SYCL `queue` for SYCL backend-specific information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the SYCL backend specification. Must throw an `exception` with the `errc::backend_mismatch` error code if the SYCL backend that corresponds with `Param` is different from the SYCL backend that is associated with this `queue`.

4.6.5.2. Queue shortcut functions

Queue shortcut functions are member functions of the `queue` class that implicitly create a command group with an implicit command group `handler` consisting of a single command, a call to the member function of the handler object with the same signature (e.g. `queue::single_task` will call `handler::single_task` with the same arguments), and submit the command group. The main signature difference comes from the return type: member functions of the `handler` return `void`, whereas corresponding queue shortcut functions return an `event` object that represents the submitted command group. Queue shortcuts can additionally take a list of events to wait on, as if passing the event list to `handler::depends_on` for the implicit command group.

The full list of queue shortcuts is defined in Table 29. The list of handler member functions is defined in Table 132.

It is not allowed to capture accessors into the implicitly created command group. If a queue shortcut function launches a kernel (via `single_task` or `parallel_for`), only USM pointers are allowed inside such kernels. However, queue shortcuts that perform non-kernel operations can be provided with a valid placeholder accessor as an argument. In that case there is an additional step performed: the implicit command group `handler` calls `handler::require` on each accessor passed in as a function argument.

An example of using queue shortcuts is shown below.

```
1 class MyKernel;
2
3 queue myQueue;
```

```
auto usmPtr = malloc_device<int>(1024, myQueue); // USM pointer

int* data = /* pointer to some data */;
buffer buf { data, 1024 };
accessor acc { buf }; // Placeholder accessor

// Queue shortcut for a kernel invocation
myQueue.single_task<MyKernel>([=] {
  // Allowed to use USM pointers,
  // not allowed to use accessors
  usmPtr[0] = 0;
});

// Placeholder accessor will automatically be registered
myQueue.copy(data, acc);
```

Table 29. Queue shortcut functions

Function Definition	Function Type	Description
`template <typename KernelName, typename KernelType>` `event single_task(const KernelType& kernelFunc)`	Kernel function	Equivalent to submitting a command-group containing `handler::single_task(kernelFunc)`.
`template <typename KernelName, typename KernelType>` `event single_task(event depEvent, const KernelType& kernelFunc)`	Kernel function	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::single_task(kernelFunc)`.

`template <typename KernelName, typename KernelType>`
`event single_task(const std::vector<event>& depEvents,`
`const KernelType& kernelFunc)`
	Kernel function	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::single_task(kernelFunc)`.

`template <typename KernelName, int Dimensions, typename... Rest>` `event parallel_for(range<Dimensions> numWorkItems, Rest&&... rest)`	Kernel function	Equivalent to submitting a command-group containing `handler::parallel_for(numWorkItems, rest)`.

`template <typename KernelName, int Dimensions, typename... Rest>`
`event parallel_for(range<Dimensions> numWorkItems, event depEvent,`
`Rest&&... rest)`
	Kernel function	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::parallel_for(numWorkItems, rest)`.

Function Definition	Function Type	Description

`template <typename KernelName, int Dimensions, typename... Rest>`
`event parallel_for(range<Dimensions> numWorkItems,`
`const std::vector<event>& depEvents,`
`Rest&&... rest)`
	Kernel function	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::parallel_for(numWorkItems, rest)`.

`template <typename KernelName, int Dimensions, typename... Rest>`
`event parallel_for(nd_range<Dimensions> executionRange,`
`Rest&&... rest)`
	Kernel function	Equivalent to submitting a command-group containing `handler::parallel_for(executionRange, rest)`.

`template <typename KernelName, int Dimensions, typename... Rest>`
`event parallel_for(nd_range<Dimensions> executionRange, event depEvent,`
`Rest&&... rest)`
	Kernel function	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::parallel_for(executionRange, rest)`.

`template <typename KernelName, int Dimensions, typename... Rest>`
`event parallel_for(nd_range<Dimensions> executionRange,`
`const std::vector<event>& depEvents,`
`Rest&&... rest)`
	Kernel function	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::parallel_for(executionRange, rest)`.

`event memcpy(void* dest, const void* src, size_t numBytes)`	USM	Equivalent to submitting a command-group containing `handler::memcpy(dest, src, numBytes)`.
`event memcpy(void* dest, const void* src, size_t numBytes, event depEvent)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::memcpy(dest, src, numBytes)`.
`event memcpy(void* dest, const void* src, size_t numBytes,` `const std::vector<event>& depEvents)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::memcpy(dest, src, numBytes)`.

Function Definition	Function Type	Description
`template <typename T> event copy(const T* src, T* dest, size_t count)`	USM	Equivalent to submitting a command-group containing `handler::copy(src, dest, count)`.
`template <typename T> event copy(const T* src, T* dest, size_t count, event depEvent)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::copy(src, dest, count)`.
`template <typename T> event copy(const T* srct, T* dest, size_t count, const std::vector<event>& depEvents)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::copy(src, dest, count)`.
`event memset(void* ptr, int value, size_t numBytes)`	USM	Equivalent to submitting a command-group containing `handler::memset(ptr, value, numBytes)`.
`event memset(void* ptr, int value, size_t numBytes, event depEvent)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::memset(ptr, value, numBytes)`.
`event memset(void* ptr, int value, size_t numBytes, const std::vector<event>& depEvents)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::memset(ptr, value, numBytes)`.
`template <typename T> event fill(void* ptr, const T& pattern, size_t count)`	USM	Equivalent to submitting a command-group containing `handler::fill(ptr, pattern, count)`.
`template <typename T> event fill(void* ptr, const T& pattern, size_t count, event depEvent)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::fill(ptr, pattern, count)`.

Function Definition	Function Type	Description
`template <typename T> event fill(void* ptr, const T& pattern, size_t count, const std::vector<event>& depEvents)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::fill(ptr, pattern, count)`.
`event prefetch(void* ptr, size_t numBytes)`	USM	Equivalent to submitting a command-group containing `handler::prefetch(ptr, numBytes)`.
`event prefetch(void* ptr, size_t numBytes, event depEvent)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::prefetch(ptr, numBytes)`.
`event prefetch(void* ptr, size_t numBytes, const std::vector <event>& depEvents)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::prefetch(ptr, numBytes)`.
`event mem_advise(void* ptr, size_t numBytes, int advice)`	USM	Equivalent to submitting a command-group containing `handler::mem_advise(ptr, numBytes, advice)`.
`event mem_advise(void* ptr, size_t numBytes, int advice, event depEvent)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvent)` and `handler::mem_advise(ptr, numBytes, advice)`.
`event mem_advise(void* ptr, size_t numBytes, int advice, const std::vector<event>& depEvents)`	USM	Equivalent to submitting a command-group containing `handler::depends_on(depEvents)` and `handler::mem_advise(ptr, numBytes, advice)`.

Function Definition	Function Type	Description
`template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt, access::placeholder IsPlaceholder, typename DestT> event copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsPlaceholder> src, std::shared_ptr<DestT> dest);`	Explicit copy	Equivalent to submitting a command-group containing `handler::require(src)` and `handler::copy(src, dest)`.
`template <typename SrcT, typename DestT, int DestDims, access_mode DestMode, target DestTgt, access::placeholder IsPlaceholder> event copy(std::shared_ptr<SrcT> src, accessor<DestT, DestDims, DestMode, DestTgt, IsPlaceholder> dest);`	Explicit copy	Equivalent to submitting a command-group containing `handler::require(dest)` and `handler::copy(src, dest)`.
`template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt, access::placeholder IsPlaceholder, typename DestT> event copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsPlaceholder> src, DestT* dest);`	Explicit copy	Equivalent to submitting a command-group containing `handler::require(src)` and `handler::copy(src, dest)`.
`template <typename SrcT, typename DestT, int DestDims, access_mode DestMode, target DestTgt, access::placeholder IsPlaceholder> event copy(const SrcT* src, accessor<DestT, DestDims, DestMode, DestTgt, IsPlaceholder> dest);`	Explicit copy	Equivalent to submitting a command-group containing `handler::require(dest)` and `handler::copy(src, dest)`.
`template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt, access::placeholder IsSrcPlaceholder, typename DestT, int DestDims, access_mode DestMode, target DestTgt, access::placeholder IsDestPlaceholder> event copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsSrcPlaceholder> src, accessor<DestT, DestDims, DestMode, DestTgt, IsDestPlaceholder> dest);`	Explicit copy	Equivalent to submitting a command-group containing `handler::require(src)`, `handler::require(dest)` and `handler::copy(src, dest)`.
`template <typename T, int Dims, access_mode Mode, target Tgt, access::placeholder IsPlaceholder> event update_host(accessor<T, Dims, Mode, Tgt, IsPlaceholder> acc);`	Explicit copy	Equivalent to submitting a command-group containing `handler::require(acc)` and `handler::update_host(acc)`.

Function Definition	Function Type	Description
`template <typename T, int Dims, access_mode Mode, target Tgt, access::placeholder IsPlaceholder> event fill(accessor<T, Dims, Mode, Tgt, IsPlaceholder> dest, const T& src);`	Explicit copy	Equivalent to submitting a command-group containing `handler::require(dest)` and `handler::fill(dest, src)`.

4.6.5.3. Queue information descriptors

A queue can be queried for information using the `get_info` member function of the `queue` class, specifying one of the info parameters in `info::queue`. The possible values for each info parameter and any restriction are defined in the specification of the SYCL backend associated with the queue. All info parameters in `info::queue` are specified in Table 30 and the synopsis for `info::queue` is described in Section A.4.

Table 30. Queue information descriptors

Queue Descriptors	Return type	Description
`info::queue::context`	`context`	Returns the SYCL `context` associated with this SYCL `queue`.
`info::queue::device`	`device`	Returns the SYCL device associated with this SYCL `queue`.

4.6.5.4. Queue properties

The properties that can be provided when constructing the SYCL `queue` class are describe in Table 31.

Table 31. Properties supported by the SYCL `queue` class

Property	Description
`property::queue::enable_profiling`	The `enable_profiling` property adds the requirement that the SYCL runtime must capture profiling information for the command groups that are submitted from this SYCL `queue` and provide said information via the SYCL `event` class `get_profiling_info` member function. If the queue's associated device does not have `aspect::queue_profiling`, passing this property to the queue's constructor causes the constructor to throw a synchronous `exception` with the `errc::feature_not_supported` error code.

Property	Description
`property::queue::in_order`	The `in_order` property adds the requirement that a SYCL `queue` provides in-order semantics whereby commands submitted to said `queue` are executed in the order in which they are submitted. Commands submitted in this fashion can be viewed as-if having an implicit dependence on the previous command submitted to that `queue`. Using the `in_order` property makes no guarantees about the ordering of commands submitted to different queues with respect to each other.

The constructors of the `queue property` classes are listed in Table 32.

Table 32. Constructors of the `queue property` classes

Constructor	Description
`property::queue::enable_profiling::enable_profiling()`	Constructs a SYCL `enable_profiling` property instance.
`property::queue::in_order::in_order()`	Constructs a SYCL `in_order` property instance.

4.6.5.5. Queue error handling

Queue errors come in two forms:

- **Synchronous Errors** are those that we would expect to be reported directly at the point of waiting on an event, and hence waiting for a queue to complete, as well as any immediate errors reported by enqueuing work onto a queue. Such errors are reported through C++ exceptions.
- Asynchronous errors are those that are produced or detected after associated host API calls have returned (so can't be thrown as exceptions by the API call), and that are handled by an async_handler through which the errors are reported. Handling of asynchronous errors from a queue occurs at specific times, as described by Section 4.13.

Note that if there are asynchronous errors to be processed when a queue is destructed, the handler is called and this might delay or block the destruction, according to the behavior of the handler.

4.6.6. Event class

An event in SYCL is an object that represents the status of an operation that is being executed by the SYCL runtime.

Typically in SYCL, data dependency and execution order is handled implicitly by the SYCL runtime. However, in some circumstances developers want fine grain control of the execution, or want to retrieve properties of a command that is running.

Note that, although an event represents the status of a particular operation, the dependencies of a certain event can be used to keep track of multiple steps required to synchronize said operation.

A SYCL event is returned by the submission of a command group. The dependencies of the event

returned via the submission of the command group are the implementation-defined commands associated with the command group execution.

The SYCL event class provides the common reference semantics (see Section 4.5.2).

The constructors and member functions of the SYCL event class are listed in Table 33 and Table 34, respectively. The additional common special member functions and common member functions are listed in Table 7 and Table 8, respectively.

```
namespace sycl {

class event {
 public:
  event();

  /* -- common interface members -- */

  backend get_backend() const noexcept;

  std::vector<event> get_wait_list();

  void wait();

  static void wait(const std::vector<event>& eventList);

  void wait_and_throw();

  static void wait_and_throw(const std::vector<event>& eventList);

  template <typename Param> typename Param::return_type get_info() const;

  template <typename Param>
  typename Param::return_type get_backend_info() const;

  template <typename Param>
  typename Param::return_type get_profiling_info() const;
};

} // namespace sycl
```

Table 33. Constructors of the event class

Constructor	Description
`event()`	Constructs an `event` that is immediately ready. The `event` has no dependencies and no associated commands. Waiting on this `event` will return immediately and querying its status will return `info::event_command_status::complete`. The event is constructed as though it was created from a default-constructed `queue`. Therefore, its backend is the same as the backend from the default device.

Table 34. Member functions for the `event` class

Member function	Description
`backend get_backend() const noexcept`	Returns a `backend` identifying the SYCL backend associated with this `event`.
`std::vector<event> get_wait_list()`	Return the list of events that this event waits for in the dependence graph. Only direct dependencies are returned, and not transitive dependencies that direct dependencies wait on. Whether already completed events are included in the returned list is implementation-defined.
`void wait()`	Wait for the event and the command associated with it to complete.
`void wait_and_throw()`	Wait for the event and the command associated with it to complete. Any unconsumed asynchronous errors from any context that the event was waiting on executions from will be passed to the async_handler associated with the context. If no user defined `async_handler` is associated with the context, then an implementation-defined default async_handler is called to handle any errors, as described in Section 4.13.1.2.
`static void wait(const std::vector<event>& eventList)`	Synchronously wait on a list of events.

Member function	Description
`static void wait_and_throw(const std::vector<event>& eventList)`	Synchronously wait on a list of events. Any unconsumed asynchronous errors from any context that the event was waiting on executions from will be passed to the async_handler associated with the context. If no user defined `async_handler` is associated with the context, then an implementation-defined default async_handler is called to handle any errors, as described in Section 4.13.1.2.
`template <typename Param> typename Param::return_type get_info() const`	Queries this SYCL `event` for information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the info parameters in Table 35 to facilitate returning the type associated with the `Param` parameter.
`template <typename Param> typename Param::return_type get_backend_info() const`	Queries this SYCL `event` for SYCL backend-specific information requested by the template parameter `Param`. The type alias `Param::return_type` must be defined in accordance with the SYCL backend specification. Must throw an `exception` with the `errc::backend_mismatch` error code if the SYCL backend that corresponds with `Param` is different from the SYCL backend that is associated with this `event`.

Member function	Description
`template <typename Param> typename Param::return_type get_profiling_info() const`	Queries this SYCL `event` for profiling information requested by the parameter `Param`. If the requested profiling information is unavailable when `get_profiling_info` is called due to incompletion of command groups associated with the `event`, then the call to `get_profiling_info` will block until the requested profiling information is available. An example is asking for `info::event_profiling::command_end` when the associated command group action has yet to finish execution. Calls to `get_profiling_info` must throw an `exception` with the `errc::invalid` error code if the SYCL `queue` which submitted the command group this SYCL `event` is associated with was not constructed with the `property::queue::enable_profiling` property. The type alias `Param::return_type` must be defined in accordance with the info parameters in Table 37 to facilitate returning the type associated with the `Param` parameter.

4.6.6.1. Event information and profiling descriptors

An event can be queried for information using the `get_info` member function of the `event` class, specifying one of the info parameters in `info::event`. The possible values for each info parameter and any restrictions are defined in the specification of the SYCL backend associated with the event. All info parameters in `info::event` are specified in Table 35 and the synopsis for `info::event` is described in Section A.6.

Table 35. Event class information descriptors

Event Descriptors	Return type	Description
`info::event::command_execution_status`	`info::event_command_status`	Returns the event status of the command group and contained action (e.g. kernel invocation) associated with this SYCL `event`.

The `info::event::command_execution_status` query returns one of the values defined in Table 36.

Table 36. Event command status

Status	Description
`info::event_command_status::submitted`	Indicates that the command has been submitted to the SYCL queue but has not yet started running on the device.

Status	Description
`info::event_command_status::running`	Indicates that the command has started running on the device but has not yet completed.
`info::event_command_status::complete`	Indicates that the command has finished running on the device. Attempting to wait on such an event will not block.

An event can be queried for profiling information using the `get_profiling_info` member function of the `event` class, specifying one of the profiling info parameters enumerated in `info::event_profiling`. The possible values for each info parameter and any restrictions are defined in the specification of the SYCL backend associated with the event. All info parameters in `info::event_profiling` are specified in Table 37 and the synopsis for `info::event_profiling` is described in Section A.6.

Each profiling descriptor returns a 64-bit timestamp that represents the number of nanoseconds that have elapsed since some implementation-defined timebase. All events that share the same backend are guaranteed to share the same timebase, therefore the difference between two timestamps from the same backend yields the number of nanoseconds that have elapsed between those events.

Table 37. Profiling information descriptors for the SYCL `event` class

Event information profiling descriptor	Return type	Description
`info::event_profiling::command_submit`	`uint64_t`	Returns a timestamp telling when the associated command group was submitted to the `queue`. This is always some time after the command group function object returns and before the associated call to `queue::submit` returns.
`info::event_profiling::command_start`	`uint64_t`	Querying this profiling descriptor blocks until the event's state becomes either `info::event_command_status::running` or `info::event_command_status::complete`. The returned timestamp tells when the action associated with the command group (e.g. kernel invocation) started executing on the device. For any given event, this timestamp is always greater than or equal to the `info::event_profiling::command_submit` timestamp. Implementations are encouraged to return a timestamp that is as close as possible to the point when the action starts running on the device, but there is no specific accuracy that is guaranteed.
`info::event_profiling::command_end`	`uint64_t`	Querying this profiling descriptor blocks until the event's state becomes `info::event_command_status::complete`. The returned timestamp tells when the action associated with the command group (e.g. kernel invocation) finished executing on the device. For any given event, this timestamp is always greater than or equal to the `info::event_profiling::command_start` timestamp.

4.7. Data access and storage in SYCL

In SYCL, when using buffers and images, data storage and access are handled by separate classes. Buffers and images handle storage and ownership of the data, whereas accessors handle access to the data. Buffers and images in SYCL can be bound to more than one device or context, including across different SYCL backends. They also handle ownership of the data, while allowing exception handling for blocking and non-blocking data transfers. Accessors manage data transfers between the host and all of the devices in the system, as well as tracking of data dependencies.

Zero-sized buffers are permitted. In this case, the buffer still handles ownership as normal, but does not need to store the zero-sized data itself.

When using USM allocations, data storage is managed by USM allocation functions, and data access is via pointers. See Section 4.8 for greater detail.

4.7.1. Host allocation

A SYCL runtime may need to allocate temporary objects on the host to handle some operations (such as copying data from one context to another). Allocation on the host is managed using an allocator object, following the standard C++ allocator class definition. The default allocator for memory objects is implementation-defined, but the user can supply their own allocator class.

```
1 {
2     buffer<int, 1, UserDefinedAllocator<int>> b(d);
3 }
```

When an allocator returns a `nullptr`, the runtime cannot allocate data on the host. Note that in this case the runtime will raise an error if it requires host memory but it is not available (e.g when moving data across SYCL backend contexts).

In some cases, the implementation may retain a copy of the allocator object even after the buffer is destroyed. For example, this can happen when the buffer object is destroyed before commands using accessors to the buffer have completed. Therefore, the application must be prepared for calls to the allocator even after the buffer is destroyed.

If the application needs to know when the implementation has destroyed all copies of the allocator, it can maintain a reference count within the allocator.

The definition of allocators extends the current functionality of SYCL, ensuring that users can define allocator functions for specific hardware or certain complex shared memory mechanisms (e.g. NUMA), and improves interoperability with STL-based libraries (e.g, Intel's TBB provides an allocator).

4.7.1.1. Default allocators

A default allocator is always defined by the implementation. For allocations greater than size zero, it is guaranteed to return non-`nullptr` and new memory positions every call. The default allocator for const buffers will remove the const-ness of the type (therefore, the default allocator for a buffer of type `const int` will be an `Allocator<int>)`. This implies that host accessors will not synchronize with the pointer given by the user in the buffer/image constructor, but will use the memory returned by the `Allocator` itself for that purpose. The user can implement an allocator that returns the same address as the one passed in the buffer constructor, but it is the responsibility of the user to handle the potential race conditions.

Table 38. SYCL Default Allocators

Allocators	Description
`template <class T> buffer_allocator`	It is the default buffer allocator used by the runtime, when no allocator is defined by the user. Meets the C++ named requirement `Allocator`. A buffer of data type `const T` uses `buffer_allocator<T>` by default.
`image_allocator`	It is the default allocator used by the runtime for the SYCL `unsampled_image` and `sampled_image` classes when no allocator is provided by the user. The `image_allocator` is required to allocate in elements of `std::byte`.

See Section 4.7.5 for details on manual host-device synchronization.

4.7.2. Buffers

The `buffer` class defines a shared array of one, two or three dimensions that can be used by the SYCL kernel and has to be accessed using accessor classes. Buffers are templated on both the type of their data, and the number of dimensions that the data is stored and accessed through.

A `buffer` does not map to only one underlying backend object, and all SYCL backend memory objects may be temporary for use within a command group on a specific device.

The underlying data type of a buffer `T` must be device copyable as defined in Section 3.13.1. Some overloads of the `buffer` constructor initialize the buffer contents by copying objects from host memory while other overloads construct the buffer without copying objects from the host. For the overloads that do not copy host objects, the initial state of the objects in the buffer depends on whether `T` is an implicit-lifetime type (as defined in the C++ core language). If `T` is an implicit-lifetime type, objects of that type are implicitly created in the buffer with indeterminate values. For other types, these constructor overloads merely allocate uninitialized memory, and the application is responsible for constructing objects by calling placement-new and for destroying them later by manually calling the object's destructor.

For the overloads that do copy objects from host memory, the `hostData` pointer must point to at least *N* bytes of memory where *N* is `sizeof(T) * bufferRange.size()`. If *N* is zero, `hostData` is permitted to be a null pointer.

A SYCL `buffer` can construct an instance of a SYCL `buffer` that reinterprets the original SYCL `buffer` with a different type, dimensionality and range using the member function `reinterpret`. The reinterpreted SYCL `buffer` that is constructed must behave as though it were a copy of the SYCL `buffer` that constructed it (see Section 4.5.2) with the exception that the type, dimensionality and range of the reinterpreted SYCL `buffer` must reflect the type, dimensionality and range specified when calling the `reinterpret` member function. By extension of this, the class member types `value_type`, `reference` and `const_reference`, and the member functions `get_range()` and `size()` of the reinterpreted SYCL `buffer` must reflect the new type, dimensionality and range. The data that the original SYCL `buffer` and the reinterpreted SYCL `buffer` manage remains unaffected, though the representation of the data when accessed through the reinterpreted SYCL `buffer` may alter to reflect the new type, dimensionality and range. It is important to note that a reinterpreted SYCL `buffer` is a copy of the original SYCL `buffer` only, and not a new SYCL `buffer`. Constructing more than one SYCL `buffer` managing the same host pointer is still undefined behavior.

The SYCL `buffer` class template provides the common reference semantics (see Section 4.5.2).

4.7.2.1. Buffer interface

The constructors and member functions of the SYCL `buffer` class template are listed in Table 39 and Table 40, respectively. The additional common special member functions and common member functions are listed in Table 7 and Table 8, respectively.

Each constructor takes as the last parameter an optional SYCL `property_list` to provide properties to the SYCL `buffer`.

The SYCL `buffer` class template takes a template parameter `AllocatorT` for specifying an allocator which is used by the SYCL runtime when allocating temporary memory on the host. If no template argument is provided, then the default allocator for the SYCL `buffer` class `buffer_allocator<T>` will be used (see Section 4.7.1.1).

```
namespace sycl {
namespace property {
namespace buffer {
class use_host_ptr {
 public:
  use_host_ptr() = default;
};

class use_mutex {
 public:
  use_mutex(std::mutex& mutexRef);

  std::mutex* get_mutex_ptr() const;
};

class context_bound {
 public:
  context_bound(context boundContext);

  context get_context() const;
};
} // namespace buffer
} // namespace property

template <typename T, int Dimensions = 1,
          typename AllocatorT = buffer_allocator<std::remove_const_t<T>>>
class buffer {
 public:
  using value_type = T;
  using reference = value_type&;
  using const_reference = const value_type&;
  using allocator_type = AllocatorT;

  buffer(const range<Dimensions>& bufferRange,
         const property_list& propList = {});

  buffer(const range<Dimensions>& bufferRange, AllocatorT allocator,
         const property_list& propList = {});

  buffer(T* hostData, const range<Dimensions>& bufferRange,
         const property_list& propList = {});

```

```
buffer(T* hostData, const range<Dimensions>& bufferRange,
       AllocatorT allocator, const property_list& propList = {});

buffer(const T* hostData, const range<Dimensions>& bufferRange,
       const property_list& propList = {});

buffer(const T* hostData, const range<Dimensions>& bufferRange,
       AllocatorT allocator, const property_list& propList = {});

/* Available only if Container is a contiguous container:
     - std::data(container) and std::size(container) are well formed
     - return type of std::data(container) is convertible to T*
   and Dimensions == 1 */
template <typename Container>
buffer(Container& container, AllocatorT allocator,
       const property_list& propList = {});

/* Available only if Container is a contiguous container:
     - std::data(container) and std::size(container) are well formed
     - return type of std::data(container) is convertible to T*
   and Dimensions == 1 */
template <typename Container>
buffer(Container& container, const property_list& propList = {});

buffer(const std::shared_ptr<T>& hostData,
       const range<Dimensions>& bufferRange, AllocatorT allocator,
       const property_list& propList = {});

buffer(const std::shared_ptr<T>& hostData,
       const range<Dimensions>& bufferRange,
       const property_list& propList = {});

buffer(const std::shared_ptr<T[]>& hostData,
       const range<Dimensions>& bufferRange, AllocatorT allocator,
       const property_list& propList = {});

buffer(const std::shared_ptr<T[]>& hostData,
       const range<Dimensions>& bufferRange,
       const property_list& propList = {});

template <class InputIterator>
buffer<T, 1>(InputIterator first, InputIterator last, AllocatorT allocator,
             const property_list& propList = {});

template <class InputIterator>
buffer<T, 1>(InputIterator first, InputIterator last,
             const property_list& propList = {});

buffer(buffer& b, const id<Dimensions>& baseIndex,
       const range<Dimensions>& subRange);

/* -- common interface members -- */

/* -- property interface members -- */

range<Dimensions> get_range() const;
```

```
 99
100  size_t byte_size() const noexcept;
101
102  size_t size() const noexcept;
103
104  // Deprecated
105  size_t get_count() const;
106
107  // Deprecated
108  size_t get_size() const;
109
110  AllocatorT get_allocator() const;
111
112  template <access_mode Mode = access_mode::read_write,
113            target Targ = target::device>
114  accessor<T, Dimensions, Mode, Targ> get_access(handler& commandGroupHandler);
115
116  // Deprecated
117  template <access_mode Mode>
118  accessor<T, Dimensions, Mode, target::host_buffer> get_access();
119
120  template <access_mode Mode = access_mode::read_write,
121            target Targ = target::device>
122  accessor<T, Dimensions, Mode, Targ>
123  get_access(handler& commandGroupHandler, range<Dimensions> accessRange,
124             id<Dimensions> accessOffset = {});
125
126  // Deprecated
127  template <access_mode Mode>
128  accessor<T, Dimensions, Mode, target::host_buffer>
129  get_access(range<Dimensions> accessRange, id<Dimensions> accessOffset = {});
130
131  template <typename... Ts> auto get_access(Ts...);
132
133  template <typename... Ts> auto get_host_access(Ts...);
134
135  template <typename Destination = std::nullptr_t>
136  void set_final_data(Destination finalData = nullptr);
137
138  void set_write_back(bool flag = true);
139
140  bool is_sub_buffer() const;
141
142  template <typename ReinterpretT, int ReinterpretDim>
143  buffer<ReinterpretT, ReinterpretDim,
144         typename std::allocator_traits<AllocatorT>::template rebind_alloc<
145             ReinterpretT>>
146  reinterpret(range<ReinterpretDim> reinterpretRange) const;
147
148  // Only available when ReinterpretDim == 1
149  // or when (ReinterpretDim == Dimensions) &&
150  //         (sizeof(ReinterpretT) == sizeof(T))
151  template <typename ReinterpretT, int ReinterpretDim = Dimensions>
152  buffer<ReinterpretT, ReinterpretDim,
153         typename std::allocator_traits<AllocatorT>::template rebind_alloc<
154             ReinterpretT>>
```

```
  reinterpret() const;
};

// Deduction guides
template <class InputIterator, class AllocatorT>
buffer(InputIterator, InputIterator, AllocatorT, const property_list& = {})
    -> buffer<typename std::iterator_traits<InputIterator>::value_type, 1,
              AllocatorT>;

template <class InputIterator>
buffer(InputIterator, InputIterator, const property_list& = {})
    -> buffer<typename std::iterator_traits<InputIterator>::value_type, 1>;

template <class T, int Dimensions, class AllocatorT>
buffer(const T*, const range<Dimensions>&, AllocatorT,
       const property_list& = {}) -> buffer<T, Dimensions, AllocatorT>;

template <class T, int Dimensions>
buffer(const T*, const range<Dimensions>&, const property_list& = {})
    -> buffer<T, Dimensions>;

template <class Container, class AllocatorT>
buffer(Container&, AllocatorT, const property_list& = {})
    -> buffer<typename Container::value_type, 1, AllocatorT>;

template <class Container>
buffer(Container&, const property_list& = {})
    -> buffer<typename Container::value_type, 1>;

} // namespace sycl
```

Table 39. Constructors of the buffer class

Constructor	Description
`buffer(const range<Dimensions>& bufferRange, const property_list& propList = {})`	Construct a SYCL `buffer` instance with uninitialized memory. The constructed SYCL `buffer` will use a default constructed `AllocatorT` when allocating memory on the host. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Data is not written back to the host on destruction of the `buffer` unless the `buffer` has a valid non-null pointer specified via the member function `set_final_data()`. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description
`buffer(const range<Dimensions>& bufferRange, AllocatorT allocator, const property_list& propList = {})`	Construct a SYCL `buffer` instance with uninitialized memory. The constructed SYCL `buffer` will use the `allocator` parameter provided when allocating memory on the host. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Data is not written back to the host on destruction of the `buffer` unless the `buffer` has a valid non-null pointer specified via the member function `set_final_data()`. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.
`buffer(T* hostData, const range<Dimensions>& bufferRange, const property_list& propList = {})`	Construct a SYCL `buffer` instance with the `hostData` parameter provided. The buffer is initialized with the memory specified by `hostData`, and the buffer assumes exclusive access to this memory for the duration of its lifetime. The constructed SYCL `buffer` will use a default constructed `AllocatorT` when allocating memory on the host. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.
`buffer(T* hostData, const range<Dimensions>& bufferRange, AllocatorT allocator, const property_list& propList = {})`	Construct a SYCL `buffer` instance with the `hostData` parameter provided. The buffer is initialized with the memory specified by `hostData`, and the buffer assumes exclusive access to this memory for the duration of its lifetime. The constructed SYCL `buffer` will use the `allocator` parameter provided when allocating memory on the host. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description
`buffer(const T* hostData, const range<Dimensions>& bufferRange, const property_list& propList = {})`	Construct a SYCL `buffer` instance with the `hostData` parameter provided. The buffer assumes exclusive access to this memory for the duration of its lifetime. The constructed SYCL `buffer` will use a default constructed `AllocatorT` when allocating memory on the host. The host address is `const T`, so the host accesses can be read-only. However, the `typename T` is not const so the device accesses can be both read and write accesses. Since the `hostData` is const, this buffer is only initialized with this memory and there is no write back after its destruction, unless the `buffer` has another valid non-null final data address specified via the member function `set_final_data()` after construction of the `buffer`. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description
`buffer(const T* hostData, const range<Dimensions>& bufferRange, AllocatorT allocator, const property_list& propList = {})`	Construct a SYCL `buffer` instance with the `hostData` parameter provided. The buffer assumes exclusive access to this memory for the duration of its lifetime. The constructed SYCL `buffer` will use the `allocator` parameter provided when allocating memory on the host. The host address is `const T`, so the host accesses can be read-only. However, the `typename T` is not const so the device accesses can be both read and write accesses. Since, the `hostData` is const, this buffer is only initialized with this memory and there is no write back after its destruction, unless the `buffer` has another valid non-null final data address specified via the member function `set_final_data()` after construction of the `buffer`. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description

`template <typename Container>`
`buffer(Container& container,`
`const property_list& propList = {})`
	Construct a one dimensional SYCL `buffer` instance from the elements starting at `std::data(container)` and containing `std::size(container)` number of elements. The buffer is initialized with the contents of `container`, and the buffer assumes exclusive access to `container` for the duration of its lifetime.
	
	Data is written back to `container` before the completion of `buffer` destruction if the return type of `std::data(container)` is not `const`.
	
	The constructed SYCL `buffer` will use a default constructed `AllocatorT` when allocating memory on the host.
	
	Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.
	
	This constructor is only defined for a `buffer` parameterized with `Dimensions == 1`, and when `std::data(container)` is convertible to `T*`.

Constructor	Description

`template <typename Container>`
`buffer(Container& container, AllocatorT allocator,`
`const property_list& propList = {})`
	Construct a one dimensional SYCL `buffer` instance from the elements starting at `std::data(container)` and containing `std::size(container)` number of elements. The buffer is initialized with the contents of `container`, and the buffer assumes exclusive access to `container` for the duration of its lifetime.
	
	Data is written back to `container` before the completion of `buffer` destruction if the return type of `std::data(container)` is not `const`.
	
	The constructed SYCL `buffer` will use the `allocator` parameter provided when allocating memory on the host.
	
	Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.
	
	This constructor is only defined for a `buffer` parameterized with `Dimensions == 1`, and when `std::data(container)` is convertible to `T*`.

Constructor	Description
`buffer(const std::shared_ptr<T>& hostData, const range<Dimensions>& bufferRange, const property_list& propList = {})`	When `hostData` is not empty, construct a SYCL buffer with the contents of its stored pointer. The buffer assumes exclusive access to this memory for the duration of its lifetime. The buffer also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostData` is empty, construct a SYCL buffer with uninitialized memory. The constructed SYCL `buffer` will use a default constructed `AllocatorT` when allocating memory on the host. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description
`buffer(const std::shared_ptr<T>& hostData, const range<Dimensions>& bufferRange, AllocatorT allocator, const property_list& propList = {})`	When `hostData` is not empty, construct a SYCL buffer with the contents of its stored pointer. The buffer assumes exclusive access to this memory for the duration of its lifetime. The buffer also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostData` is empty, construct a SYCL buffer with uninitialized memory. The constructed SYCL `buffer` will use the `allocator` parameter provided when allocating memory on the host. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description
`buffer(const std::shared_ptr<T[]>& hostData, const range<Dimensions>&  bufferRange, const property_list& propList = {})`	When `hostData` is not empty, construct a SYCL buffer with the contents of its stored pointer. The buffer assumes exclusive access to this memory for the duration of its lifetime. The buffer also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostData` is empty, construct a SYCL buffer with uninitialized memory. The constructed SYCL `buffer` will use a default constructed `AllocatorT` when allocating memory on the host. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description
`buffer(const std::shared_ptr<T[]>& hostData, const range<Dimensions>& bufferRange, AllocatorT allocator, const property_list& propList = {})`	When `hostData` is not empty, construct a SYCL buffer with the contents of its stored pointer. The buffer assumes exclusive access to this memory for the duration of its lifetime. The buffer also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostData` is empty, construct a SYCL buffer with uninitialized memory. The constructed SYCL `buffer` will use the `allocator` parameter provided when allocating memory on the host. The range of the constructed SYCL `buffer` is specified by the `bufferRange` parameter provided. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.
`template <typename InputIterator> buffer(InputIterator first, InputIterator last, const property_list& propList = {})`	Create a new allocated 1D buffer initialized from the given elements ranging from `first` up to one before `last`. The data is copied to an intermediate memory position by the runtime. Data is not written back to the same iterator set provided. However, if the `buffer` has a valid non-const iterator specified via the member function `set_final_data()`, data will be copied back to that iterator. The constructed SYCL `buffer` will use a default constructed `AllocatorT` when allocating memory on the host. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description

`template <typename InputIterator>`
`buffer(InputIterator first, InputIterator last,`
`AllocatorT allocator = {},`
`const property_list& propList = {})`
	Create a new allocated 1D buffer initialized from the given elements ranging from `first` up to one before `last`. The data is copied to an intermediate memory position by the runtime. Data is not written back to the same iterator set provided. However, if the `buffer` has a valid non-const iterator specified via the member function `set_final_data()`, data will be copied back to that iterator. The constructed SYCL `buffer` will use the `allocator` parameter provided when allocating memory on the host. Zero or more properties can be provided to the constructed SYCL `buffer` via an instance of `property_list`.

Constructor	Description
`buffer(buffer& b, const id<Dimensions>& baseIndex, const range<Dimensions>& subRange)`	Create a new sub-buffer without allocation to have separate accessors later. `b` is the buffer with the real data, which must not be a sub-buffer. `baseIndex` specifies the origin of the sub-buffer inside the buffer `b`. `subRange` specifies the size of the sub-buffer. The sum of `baseIndex` and `subRange` in any dimension must not exceed the parent buffer (`b`) size (`bufferRange`) in that dimension, and an `exception` with the `errc::invalid` error code must be thrown if violated. The offset and range specified by `baseIndex` and `subRange` together must represent a contiguous region of the original SYCL `buffer`. If a non-contiguous region of a buffer is requested when constructing a sub-buffer, then an `exception` with the `errc::invalid` error code must be thrown. The origin (based on `baseIndex`) of the sub-buffer being constructed must be a multiple of the memory base address alignment of each SYCL `device` which accesses data from the buffer. This value is retrievable via the SYCL `device` class info query `info::device::mem_base_addr_align`. Violating this requirement causes the implementation to throw an `exception` with the `errc::invalid` error code from the `accessor` constructor (if the accessor is not a placeholder) or from `handler::require()` (if the accessor is a placeholder). If the accessor is bound to a command group with a secondary queue, the sub-buffer's alignment must be compatible with both the primary queue's device and the secondary queue's device, otherwise this exception is thrown. Must throw an `exception` with the `errc::invalid` error code if `b` is a sub-buffer.

Table 40. Member functions for the buffer class

Member function	Description
`range<Dimensions> get_range() const`	Return a range object representing the size of the buffer in terms of number of elements in each dimension as passed to the constructor.
`size_t size() const noexcept`	Returns the total number of elements in the buffer. Equal to `get_range()[0] * ... * get_range()[Dimensions-1]`.
`size_t get_count() const`	Returns the same value as `size()`. Deprecated.
`size_t byte_size() const noexcept`	Returns the size of the buffer storage in bytes. Equal to `size()*sizeof(T)`.
`size_t get_size() const`	Returns the same value as `byte_size()`. Deprecated.
`AllocatorT get_allocator() const`	Returns the allocator provided to the buffer.
`template <access_mode Mode = access_mode::read_write, target Targ = target::device> accessor<T, Dimensions, Mode, Targ> get_access(handler& commandGroupHandler)`	Returns a valid `accessor` to the buffer with the specified access mode and target in the command group buffer. The value of target can be `target::device` or `target::constant_buffer`.
`template <access_mode Mode> accessor<T, Dimensions, Mode, target::host_buffer> get_access()`	Deprecated in SYCL 2020. Use `get_host_access()` instead. Returns a valid host `accessor` to the buffer with the specified access mode and target.
`template <access_mode Mode = access_mode::read_write, target Targ = target::device> accessor<T, Dimensions, Mode, Targ> get_access(handler& commandGroupHandler, range <Dimensions> accessRange, id <Dimensions> accessOffset = {})`	Returns a valid `accessor` to the buffer with the specified access mode and target in the command group buffer. The accessor is a ranged accessor, where the range starts at the given offset from the beginning of the buffer. The value of target can be `target::device` or `target::constant_buffer`. Throws an `exception` with the `errc::invalid` error code if the sum of `accessRange` and `accessOffset` exceeds the range of the buffer in any dimension.

Member function	Description
`template <access_mode Mode> accessor<T, Dimensions, Mode, target::host_buffer> get_access(range<Dimensions> accessRange, id<Dimensions> accessOffset = {})`	Deprecated in SYCL 2020. Use `get_host_access()` instead. Returns a valid host `accessor` to the buffer with the specified access mode and target. The accessor is a ranged accessor, where the range starts at the given offset from the beginning of the buffer. The value of target can only be `target::host_buffer`. Throws an `exception` with the `errc::invalid` error code if the sum of `accessRange` and `accessOffset` exceeds the range of the buffer in any dimension.
`template <typename... Ts> auto get_access(Ts... args)`	Returns a valid `accessor` as if constructed via passing the buffer and all provided arguments to the `accessor` constructor. Possible implementation: `return accessor{*this, args...};`
`template <typename... Ts> auto get_host_access(Ts... args)`	Returns a valid `host_accessor` as if constructed via passing the buffer and all provided arguments to the `host_accessor` constructor. Possible implementation: `return host_accessor{*this, args...};`
`template <typename Destination = std::nullptr_t> void set_final_data(Destination finalData = nullptr)`	The `finalData` points to where the outcome of all the buffer processing is going to be copied to at destruction time, if the buffer was involved with a write accessor. Destination can be either an output iterator or a `std::weak_ptr<T>`. Note that a raw pointer is a special case of output iterator and thus defines the host memory to which the result is to be copied. In the case of a weak pointer, the output is not updated if the weak pointer has expired. If `Destination` is `std::nullptr_t`, then the copy back will not happen.

Member function	Description
`void set_write_back(bool flag = true)`	This member function allows dynamically forcing or canceling the write-back of the data of a buffer on destruction according to the value of `flag`. Forcing the write-back is similar to what happens during a normal write-back as described in Section 4.7.2.3 and Section 4.7.4. If there is nowhere to write-back, using this function does not have any effect.
`bool is_sub_buffer() const`	Returns true if this SYCL `buffer` is a sub-buffer, otherwise returns false.

`template <typename ReinterpretT, int ReinterpretDim>`
`buffer<ReinterpretT, ReinterpretDim,`
`typename std::allocator_traits<AllocatorT>::template rebind_alloc<`
`std::remove_const_t<ReinterpretT>>>`
`reinterpret(range<ReinterpretDim> reinterpretRange) const`
	Creates and returns a reinterpreted SYCL `buffer` with the type specified by `ReinterpretT`, dimensions specified by `ReinterpretDim` and range specified by `reinterpretRange`. The buffer object being reinterpreted can be a SYCL sub-buffer that was created from a SYCL `buffer` and must throw `exception` with the `errc::invalid` error code if the total size in bytes represented by the type and range of the reinterpreted SYCL `buffer` (or sub-buffer) does not equal the total size in bytes represented by the type and range of this SYCL `buffer` (or sub-buffer). Reinterpreting a sub-buffer provides a reinterpreted view of the sub-buffer only, and does not change the offset or size of the sub-buffer view (in bytes) relative to the parent `buffer`.

Member function	Description
`template <typename ReinterpretT, int ReinterpretDim = Dimensions> buffer<ReinterpretT, ReinterpretDim, typename std::allocator_traits<AllocatorT>::template rebind_alloc< std::remove_const_t<ReinterpretT>>> reinterpret() const`	Creates and returns a reinterpreted SYCL `buffer` with the type specified by `ReinterpretT` and dimensions specified by `ReinterpretDim`. Only valid when `(ReinterpretDim == 1)` or when `((ReinterpretDim == Dimensions) && (sizeof(ReinterpretT) == sizeof(T)))`. The buffer object being reinterpreted can be a SYCL sub-buffer that was created from a SYCL `buffer`. The implementation must throw an `exception` with the `errc::invalid` error code if the total size in bytes represented by this SYCL `buffer` (or sub-buffer) is not evenly divisible by `sizeof(ReinterpretT)`. Reinterpreting a sub-buffer provides a reinterpreted view of the sub-buffer only, and does not change the offset or size of the sub-buffer view (in bytes) relative to the parent `buffer`.

4.7.2.2. Buffer properties

The properties that can be provided when constructing the SYCL `buffer` class are describe in Table 41.

Table 41. Properties supported by the SYCL `buffer` class

Property	Description
`property::buffer::use_host_ptr`	The `use_host_ptr` property adds the requirement that the SYCL runtime must not allocate any memory for the SYCL `buffer` and instead uses the provided host pointer directly. This prevents the SYCL runtime from allocating additional temporary storage on the host. This property has a special guarantee for buffers that are constructed from a `hostData` pointer. If a `host_accessor` is constructed from such a buffer, then the address of the `reference` type returned from the accessor's member functions such as `operator[](id<>)` will be the same as the corresponding `hostData` address.

Property	Description
`property::buffer::use_mutex`	The `use_mutex` property is valid for the SYCL `buffer`, `unsampled_image` and `sampled_image` classes. The property adds the requirement that the memory which is owned by the SYCL `buffer` can be shared with the application via a `std::mutex` provided to the property. The mutex `m` is locked by the runtime whenever the data is in use and unlocked otherwise. Data is synchronized with `hostData`, when the mutex is unlocked by the runtime.
`property::buffer::context_bound`	The `context_bound` property adds the requirement that the SYCL `buffer` can only be associated with a single SYCL `context` that is provided to the property.

The constructors and special member functions of the buffer property classes are listed in Table 42 and Table 43 respectively.

Table 42. Constructors of the `buffer property` classes

Constructor	Description
`property::buffer::use_host_ptr::use_host_ptr()`	Constructs a SYCL `use_host_ptr` property instance.
`property::buffer::use_mutex::use_mutex(std::mutex& mutexRef)`	Constructs a SYCL `use_mutex` property instance with a reference to `mutexRef` parameter provided.
`property::buffer::context_bound::context_bound(context boundContext)`	Constructs a SYCL `context_bound` property instance with a copy of a SYCL `context`.

Table 43. Member functions of the `buffer property` classes

Member function	Description
`std::mutex* property::buffer::use_mutex::get_mutex_ptr() const`	Returns the `std::mutex` which was specified when constructing this SYCL `use_mutex` property.
`context property::buffer::context_bound::get_context() const`	Returns the `context` which was specified when constructing this SYCL `context_bound` property.

4.7.2.3. Buffer synchronization rules

Buffers are reference-counted. When a buffer value is constructed from another buffer, the two values reference the same buffer and a reference count is incremented. When a buffer value is destroyed, the reference count is decremented. Only when there are no more buffer values that reference a specific

buffer is the actual buffer destroyed and the buffer destruction behavior defined below is followed.

If any error occurs on buffer destruction, it is reported via the associated queue's asynchronous error handling mechanism.

The basic rule for the blocking behavior of a buffer destructor is that it blocks if there is some data to write back because a write accessor on it has been created, or if the buffer was constructed with attached host memory and is still in use.

More precisely:

1. A buffer can be constructed from a `range` (and without a `hostData` pointer). The memory management for this type of buffer is entirely handled by the SYCL system. The destructor for this type of buffer does not need to block, even if work on the buffer has not completed. Instead, the SYCL system frees any storage required for the buffer asynchronously when it is no longer in use in queues. The initial contents of the buffer are unspecified.
2. A buffer can be constructed from a `hostData` pointer. The buffer will use this host memory for its full lifetime, but the contents of this host memory are unspecified for the lifetime of the buffer. If the host memory is modified on the host or if it is used to construct another buffer or image during the lifetime of this buffer, then the results are undefined. The initial contents of the buffer will be the contents of the host memory at the time of construction.

   When the buffer is destroyed, the destructor will block until all work in queues on the buffer have completed, then copy the contents of the buffer back to the host memory (if required) and then return.

   a. If the type of the host data is `const`, then the buffer is read-only; only read accessors are allowed on the buffer and no-copy-back to host memory is performed (although the host memory must still be kept available for use by SYCL). When using the default buffer allocator, the const-ness of the type will be removed in order to allow host allocation of memory, which will allow temporary host copies of the data by the SYCL runtime, for example for speeding up host accesses.

      When the buffer is destroyed, the destructor will block until all work in queues on the buffer have completed and then return, as there is no copy of data back to host.

   b. If the type of the host data is not `const` but the pointer to host data is `const`, then the read-only restriction applies only on host and not on device accesses.

      When the buffer is destroyed, the destructor will block until all work in queues on the buffer have completed.

3. A buffer can be constructed using a `shared_ptr` to host data. This pointer is shared between the SYCL application and the runtime. In order to allow synchronization between the application and the runtime a `mutex` is used which will be locked by the runtime whenever the data is in use, and unlocked when it is no longer needed.

   The `shared_ptr` reference counting is used in order to prevent destroying the buffer host data prematurely. If the `shared_ptr` is deleted from the user application before buffer destruction, the buffer can continue securely because the pointer hasn't been destroyed yet. It will not copy data back to the host before destruction, however, as the application side has already deleted its copy.

   Note that since there is an implicit conversion of a `std::unique_ptr` to a `std::shared_ptr`, a `std::unique_ptr` can also be used to pass the ownership to the SYCL runtime.

4. A buffer can be constructed from a pair of iterator values. In this case, the buffer construction will copy the data from the data range defined by the iterator pair. The destructor will not copy back any data and does not need to block.
5. A buffer can be constructed from a container on which `std::data(container)` and `std::size(con-`

tainer) are well-formed. The initial contents of the buffer will be the contents of the container at the time of construction.

The buffer may use the memory within the container for its full lifetime, and the contents of this memory are unspecified for the lifetime of the buffer. If the container memory is modified by the host during the lifetime of this buffer, then the results are undefined.

When the buffer is destroyed, the destructor will block until all work in queues on the buffer have completed. If the return type of std::data(container) is not const then the destructor will also copy the contents of the buffer to the container (if required).

If set_final_data() is used to change where to write the data back to, then the destructor of the buffer will block if a write accessor on it has been created.

A sub-buffer object can be created which is a sub-range reference to a base buffer. This sub-buffer can be used to create accessors to the base buffer, which have access to the range specified at time of construction of the sub-buffer. Sub-buffers cannot be created from sub-buffers, but only from a base buffer which is not already a sub-buffer.

Sub-buffers must be constructed from a contiguous region of memory in a buffer. This requirement is potentially non-intuitive when working with buffers that have dimensionality larger than one, but maps to one-dimensional SYCL backend native allocations without performance cost due to index mapping computation. For example:

```
buffer<int, 2> parent_buffer { range<2> {
    8, 8 } }; // Create 2-d buffer with 8x8 ints

// OK: Contiguous region from middle of buffer
buffer<int, 2> sub_buf1 { parent_buffer, /*offset*/ range<2> { 2, 0 },
                          /*size*/ range<2> { 2, 8 } };

// invalid exception: Non-contiguous regions of 2-d buffer
buffer<int, 2> sub_buf2 { parent_buffer, /*offset*/ range<2> { 2, 0 },
                          /*size*/ range<2> { 2, 2 } };
buffer<int, 2> sub_buf3 { parent_buffer, /*offset*/ range<2> { 2, 2 },
                          /*size*/ range<2> { 2, 6 } };

// invalid exception: Out-of-bounds size
buffer<int, 2> sub_buf4 { parent_buffer, /*offset*/ range<2> { 2, 2 },
                          /*size*/ range<2> { 2, 8 } };
```

4.7.3. Images

The classes unsampled_image (Table 44) and sampled_image (Table 46) define shared image data of one, two or three dimensions, that can be used by kernels in queues and have to be accessed using the image accessor classes.

The constructors and member functions of the SYCL unsampled_image and sampled_image class templates are listed in Table 44, Table 45, Table 46 and Table 47, respectively. The additional common special member functions and common member functions are listed in Table 7 and Table 8, respectively.

Where relevant, it is the responsibility of the user to ensure that the format of the data matches the format described by image_format.

The allocator template parameter of the SYCL unsampled_image and sampled_image classes can be any allocator type including a custom allocator, however it must allocate in units of std::byte.

For any image that is constructed with the range $(r1, r2, r3)$ with an element type size in bytes of s, the image row pitch and image slice pitch should be calculated as follows:

$$r1 \cdot s$$

$$r1 \cdot r2 \cdot s$$

The SYCL `unsampled_image` and `sampled_image` class templates provide the common reference semantics (see Section 4.5.2).

4.7.3.1. Unsampled image interface

Each constructor of the `unsampled_image` takes an `image_format` to describe the data layout of the image data.

Each constructor additionally takes as the last parameter an optional SYCL `property_list` to provide properties to the SYCL `unsampled_image`.

The SYCL `unsampled_image` class template takes a template parameter `AllocatorT` for specifying an allocator which is used by the SYCL runtime when allocating temporary memory on the host. If no template argument is provided, the default allocator for the SYCL `unsampled_image` class `image_allocator` is used (see Section 4.7.1.1).

```
namespace sycl {

enum class image_format : /* unspecified */ {
  r8g8b8a8_unorm,
  r16g16b16a16_unorm,
  r8g8b8a8_sint,
  r16g16b16a16_sint,
  r32b32g32a32_sint,
  r8g8b8a8_uint,
  r16g16b16a16_uint,
  r32b32g32a32_uint,
  r16b16g16a16_sfloat,
  r32g32b32a32_sfloat,
  b8g8r8a8_unorm
};

template <int Dimensions = 1, typename AllocatorT = sycl::image_allocator>
class unsampled_image {
 public:
  unsampled_image(image_format format, const range<Dimensions>& rangeRef,
                  const property_list& propList = {});

  unsampled_image(image_format format, const range<Dimensions>& rangeRef,
                  AllocatorT allocator, const property_list& propList = {});

  /* Available only when: Dimensions > 1 */
  unsampled_image(image_format format, const range<Dimensions>& rangeRef,
                  const range<Dimensions - 1>& pitch,
                  const property_list& propList = {});

  /* Available only when: Dimensions > 1 */
  unsampled_image(image_format format, const range<Dimensions>& rangeRef,
                  const range<Dimensions - 1>& pitch, AllocatorT allocator,
                  const property_list& propList = {});

```

```
unsampled_image(void* hostPointer, image_format format,
                const range<Dimensions>& rangeRef,
                const property_list& propList = {});

unsampled_image(void* hostPointer, image_format format,
                const range<Dimensions>& rangeRef, AllocatorT allocator,
                const property_list& propList = {});

/* Available only when: Dimensions > 1 */
unsampled_image(void* hostPointer, image_format format,
                const range<Dimensions>& rangeRef,
                const range<Dimensions - 1>& pitch,
                const property_list& propList = {});

/* Available only when: Dimensions > 1 */
unsampled_image(void* hostPointer, image_format format,
                const range<Dimensions>& rangeRef,
                const range<Dimensions - 1>& pitch, AllocatorT allocator,
                const property_list& propList = {});

unsampled_image(std::shared_ptr<void>& hostPointer, image_format format,
                const range<Dimensions>& rangeRef,
                const property_list& propList = {});

unsampled_image(std::shared_ptr<void>& hostPointer, image_format format,
                const range<Dimensions>& rangeRef, AllocatorT allocator,
                const property_list& propList = {});

/* Available only when: Dimensions > 1 */
unsampled_image(std::shared_ptr<void>& hostPointer, image_format format,
                const range<Dimensions>& rangeRef,
                const range<Dimensions - 1>& pitch,
                const property_list& propList = {});

/* Available only when: Dimensions > 1 */
unsampled_image(std::shared_ptr<void>& hostPointer, image_format format,
                const range<Dimensions>& rangeRef,
                const range<Dimensions - 1>& pitch, AllocatorT allocator,
                const property_list& propList = {});

/* -- common interface members -- */

/* -- property interface members -- */

range<Dimensions> get_range() const;

/* Available only when: Dimensions > 1 */
range<Dimensions - 1> get_pitch() const;

size_t byte_size() const noexcept;

size_t size() const noexcept;

AllocatorT get_allocator() const;

template <typename... Ts> auto get_access(Ts... args);
```

```
92
93   template <typename... Ts> auto get_host_access(Ts... args);
94
95   template <typename Destination = std::nullptr_t>
96   void set_final_data(Destination finalData = std::nullptr);
97
98   void set_write_back(bool flag = true);
99 };
100
101 } // namespace sycl
```

Table 44. Constructors of the `unsampled_image` *class template*

Constructor	Description

`unsampled_image(image_format format,`
`const range<Dimensions>& rangeRef,`
`const property_list& propList = {})`
	Construct a SYCL `unsampled_image` instance with uninitialized memory. The constructed SYCL `unsampled_image` will use a default constructed `AllocatorT` when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the default size determined by the SYCL runtime. Unless the member function `set_final_data()` is called with a valid non-null pointer, there will be no write back on destruction. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(image_format format, const range<Dimensions>& rangeRef, AllocatorT allocator, const property_list& propList = {})`	Construct a SYCL `unsampled_image` instance with uninitialized memory. The constructed SYCL `unsampled_image` will use the `allocator` parameter provided when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the default size determined by the SYCL runtime. Unless the member function `set_final_data()` is called with a valid non-null pointer, there will be no write back on destruction. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.
`unsampled_image(image_format format, const range<Dimensions>& rangeRef, const range<Dimensions - 1>& pitch, const property_list& propList = {})`	Available only when: `Dimensions > 1`. Construct a SYCL `unsampled_image` instance with uninitialized memory. The constructed SYCL `unsampled_image` will use a default constructed `AllocatorT` when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the `pitch` parameter provided. Unless the member function `set_final_data()` is called with a valid non-null pointer, there will be no write back on destruction. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(image_format format, const range<Dimensions>& rangeRef, const range<Dimensions - 1>& pitch, AllocatorT allocator, const property_list& propList = {})`	Available only when: `Dimensions > 1`. Construct a SYCL `unsampled_image` instance with uninitialized memory. The constructed SYCL `unsampled_image` will use the `allocator` parameter provided when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the `pitch` parameter provided. Unless the member function `set_final_data()` is called with a valid non-null pointer, there will be no write back on destruction. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.
`unsampled_image(void* hostPointer, image_format format, const range<Dimensions>& rangeRef, const property_list& propList = {})`	Construct a SYCL `unsampled_image` instance with the `hostPointer` parameter provided. The `unsampled_image` assumes exclusive access to this memory for the duration of its lifetime. The constructed SYCL `unsampled_image` will use a default constructed `AllocatorT` when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the default size determined by the SYCL runtime. Unless the member function `set_final_data()` is called with a valid non-null pointer, any memory allocated by the SYCL runtime is written back to `hostPointer`. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(void* hostPointer, image_format format, const range<Dimensions>& rangeRef, AllocatorT allocator, const property_list& propList = {})`	Construct a SYCL `unsampled_image` instance with the `hostPointer` parameter provided. The `unsampled_image` assumes exclusive access to this memory for the duration of its lifetime. The constructed SYCL `unsampled_image` will use the `allocator` parameter provided when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the default size determined by the SYCL runtime. Unless the member function `set_final_data()` is called with a valid non-null pointer, any memory allocated by the SYCL runtime is written back to `hostPointer`. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(void* hostPointer, image_format format, const range<Dimensions>& rangeRef, const range<Dimensions - 1>& pitch, const property_list& propList = {})`	Available only when: `Dimensions > 1` Construct a SYCL `unsampled_image` instance with the `hostPointer` parameter provided. The `unsampled_image` assumes exclusive access to this memory for the duration of its lifetime. The constructed SYCL `unsampled_image` will use a default constructed `AllocatorT` when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the `pitch` parameter provided. Unless the member function `set_final_data()` is called with a valid non-null pointer, any memory allocated by the SYCL runtime is written back to `hostPointer`. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(void* hostPointer, image_format format, const range<Dimensions>& rangeRef, const range<Dimensions - 1>& pitch, AllocatorT allocator, const property_list& propList = {})`	Available only when: `Dimensions > 1`. Construct a SYCL `unsampled_image` instance with the `hostPointer` parameter provided. The `unsampled_image` assumes exclusive access to this memory for the duration of its lifetime. The constructed SYCL `unsampled_image` will use the `allocator` parameter provided when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the `pitch` parameter provided. Unless the member function `set_final_data()` is called with a valid non-null pointer, any memory allocated by the SYCL runtime is written back to `hostPointer`. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(std::shared_ptr<void>& hostPointer, image_format format, const range<Dimensions>& rangeRef, const property_list& propList = {})`	When `hostPointer` is not empty, construct a SYCL `unsampled_image` with the contents of its stored pointer. The `unsampled_image` assumes exclusive access to this memory for the duration of its lifetime. The `unsampled_image` also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostPointer` is empty, construct a SYCL `unsampled_image` with uninitialized memory. The constructed SYCL `unsampled_image` will use a default constructed `AllocatorT` when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the default size determined by the SYCL runtime. Unless the member function `set_final_data()` is called with a valid non-null pointer, any memory allocated by the SYCL runtime is written back to `hostPointer`. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(std::shared_ptr<void>& hostPointer, image_format format, const range<Dimensions>& rangeRef, AllocatorT allocator, const property_list& propList = {})`	When `hostPointer` is not empty, construct a SYCL `unsampled_image` with the contents of its stored pointer. The `unsampled_image` assumes exclusive access to this memory for the duration of its lifetime. The `unsampled_image` also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostPointer` is empty, construct a SYCL `unsampled_image` with uninitialized memory. The constructed SYCL `unsampled_image` will use the `allocator` parameter provided when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the default size determined by the SYCL runtime. Unless the member function `set_final_data()` is called with a valid non-null pointer, any memory allocated by the SYCL runtime is written back to `hostPointer`. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(std::shared_ptr<void>& hostPointer, image_format format, const range<Dimensions>& rangeRef, const range<Dimensions - 1>& pitch, const property_list& propList = {})`	When `hostPointer` is not empty, construct a SYCL `unsampled_image` with the contents of its stored pointer. The `unsampled_image` assumes exclusive access to this memory for the duration of its lifetime. The `unsampled_image` also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostPointer` is empty, construct a SYCL `unsampled_image` with uninitialized memory. The constructed SYCL `unsampled_image` will use a default constructed `AllocatorT` when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the `pitch` parameter provided. Unless the member function `set_final_data()` is called with a valid non-null pointer, any memory allocated by the SYCL runtime is written back to `hostPointer`. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Constructor	Description
`unsampled_image(std::shared_ptr<void>& hostPointer, image_format format, const range<Dimensions>& rangeRef, const range<Dimensions - 1>& pitch, AllocatorT allocator, const property_list& propList = {})`	When `hostPointer` is not empty, construct a SYCL `unsampled_image` with the contents of its stored pointer. The `unsampled_image` assumes exclusive access to this memory for the duration of its lifetime. The `unsampled_image` also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostPointer` is empty, construct a SYCL `unsampled_image` with uninitialized memory. The constructed SYCL `unsampled_image` will use the `allocator` parameter provided when allocating memory on the host. The element size of the constructed SYCL `unsampled_image` will be derived from the `format` parameter. The range of the constructed SYCL `unsampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `unsampled_image` will be the `pitch` parameter provided. Unless the member function `set_final_data()` is called with a valid non-null pointer, any memory allocated by the SYCL runtime is written back to `hostPointer`. Zero or more properties can be provided to the constructed SYCL `unsampled_image` via an instance of `property_list`.

Table 45. Member functions of the `unsampled_image` class template

Member function	Description
`range<Dimensions> get_range() const`	Return a range object representing the size of the image in terms of the number of elements in each dimension as passed to the constructor.
`range<Dimensions - 1> get_pitch() const`	Available only when: `Dimensions > 1`. Return a range object representing the pitch of the image in bytes.

Member function	Description
`size_t size() const noexcept`	Returns the total number of elements in the image. Equal to `get_range()[0] * ... * get_range()[Dimensions-1]`.
`size_t byte_size() const noexcept`	Returns the size of the image storage in bytes. The number of bytes may be greater than `size()*element size` due to padding of elements, rows and slices of the image for efficient access.
`AllocatorT get_allocator() const`	Returns the allocator provided to the image.
`template <typename... Ts> auto get_access(Ts... args)`	Returns a valid `unsampled_image_accessor` as if constructed via passing the image and all provided arguments to the `unsampled_image_accessor` constructor. Possible implementation: `return unsampled_image_accessor{*this, args...};`
`template <typename... Ts> auto get_host_access(Ts... args)`	Returns a valid `host_unsampled_image_accessor` as if constructed via passing the image and all provided arguments to the `host_unsampled_image_accessor` constructor. Possible implementation: `return host_unsampled_image_accessor{*this, args...};`
`template <typename Destination = std::nullptr_t>` `void set_final_data(Destination finalData = nullptr)`	The `finalData` point to where the output of all the image processing is going to be copied to at destruction time, if the image was involved with a write accessor. Destination can be either an output iterator, a `std::weak_ptr<T>`. Note that a raw pointer is a special case of output iterator and thus defines the host memory to which the result is to be copied. In the case of a weak pointer, the output is not copied if the weak pointer has expired. If `Destination` is `std::nullptr_t`, then the copy back will not happen.

Member function	Description
`void set_write_back(bool flag = true)`	This member function allows dynamically forcing or canceling the write-back of the data of an image on destruction according to the value of `flag`. Forcing the write-back is similar to what happens during a normal write-back as described in Section 4.7.3.4 and Section 4.7.4. If there is nowhere to write-back, using this function does not have any effect.

4.7.3.2. Sampled image interface

Each constructor of the `sampled_image` class requires a pointer to the host data the image will sample, an `image_format` to describe the data layout and an `image_sampler` (Section 4.7.8) to describe how to sample the image data.

Each constructor additionally takes as the last parameter an optional SYCL `property_list` to provide properties to the SYCL `sampled_image`.

```
namespace sycl {

enum class image_format : /* unspecified */ {
  r8g8b8a8_unorm,
  r16g16b16a16_unorm,
  r8g8b8a8_sint,
  r16g16b16a16_sint,
  r32b32g32a32_sint,
  r8g8b8a8_uint,
  r16g16b16a16_uint,
  r32b32g32a32_uint,
  r16b16g16a16_sfloat,
  r32g32b32a32_sfloat,
  b8g8r8a8_unorm
};

template <int Dimensions = 1, typename AllocatorT = sycl::image_allocator>
class sampled_image {
 public:
  sampled_image(const void* hostPointer, image_format format,
                image_sampler sampler, const range<Dimensions>& rangeRef,
                const property_list& propList = {});

  /* Available only when: Dimensions > 1 */
  sampled_image(const void* hostPointer, image_format format,
                image_sampler sampler, const range<Dimensions>& rangeRef,
                const range<Dimensions - 1>& pitch,
                const property_list& propList = {});

  sampled_image(std::shared_ptr<const void>& hostPointer, image_format format,
                image_sampler sampler, const range<Dimensions>& rangeRef,
```

```
32                const property_list& propList = {});
33
34  /* Available only when: Dimensions > 1 */
35  sampled_image(std::shared_ptr<const void>& hostPointer, image_format format,
36                image_sampler sampler, const range<Dimensions>& rangeRef,
37                const range<Dimensions - 1>& pitch,
38                const property_list& propList = {});
39
40  /* -- common interface members -- */
41
42  /* -- property interface members -- */
43
44  range<Dimensions> get_range() const;
45
46  /* Available only when: Dimensions > 1 */
47  range<Dimensions - 1> get_pitch() const;
48
49  size_t byte_size() const;
50
51  size_t size() const;
52
53  template <typename... Ts> auto get_access(Ts... args);
54
55  template <typename... Ts> auto get_host_access(Ts... args);
56 };
57
58 } // namespace sycl
```

Table 46. Constructors of the `sampled_image` *class template*

Constructor	Description
`sampled_image(const void* hostPointer, image_format format, image_sampler sampler, const range<Dimensions>& rangeRef, const property_list& propList = {})`	Construct a SYCL `sampled_image` instance with the `hostPointer` parameter provided. The `sampled_image` assumes exclusive access to this memory for the duration of its lifetime. The host address is `const`, so the host accesses must be read-only. Since, the `hostPointer` is `const`, this image is only initialized with this memory and there is no write after its destruction. The element size of the constructed SYCL `sampled_image` will be derived from the `format` parameter. Accessors that read the constructed SYCL `sampled_image` will use the `sampler` parameter to sample the image. The range of the constructed SYCL `sampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `sampled_image` will be the default size determined by the SYCL runtime. Zero or more properties can be provided to the constructed SYCL `sampled_image` via an instance of `property_list`.

Constructor	Description
`sampled_image(const void* hostPointer, image_format format, image_sampler sampler, const range<Dimensions>& rangeRef, const range<Dimensions - 1>& pitch, const property_list& propList = {})`	Available only when: `Dimensions > 1`. Construct a SYCL `sampled_image` instance with the `hostPointer` parameter provided. The `sampled_image` assumes exclusive access to this memory for the duration of its lifetime. The host address is `const`, so the host accesses must be read-only. Since, the `hostPointer` is `const`, this image is only initialized with this memory and there is no write after destruction. The element size of the constructed SYCL `sampled_image` will be derived from the `format` parameter. Accessors that read the constructed SYCL `sampled_image` will use the `sampler` parameter to sample the image. The range of the constructed SYCL `sampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `sampled_image` will be the `pitch` parameter provided. Zero or more properties can be provided to the constructed SYCL `sampled_image` via an instance of `property_list`.

Constructor	Description
`sampled_image(std::shared_ptr<const void>& hostPointer, image_format format, image_sampler sampler, const range<Dimensions>& rangeRef, const property_list& propList = {})`	When `hostPointer` is not empty, construct a SYCL `sampled_image` with the contents of its stored pointer. The `sampled_image` assumes exclusive access to this memory for the duration of its lifetime. The `sampled_image` also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostPointer` is empty, construct a SYCL `sampled_image` with uninitialized memory. The host address is `const`, so the host accesses must be read-only. Since, the `hostPointer` is `const`, this image is only initialized with this memory and there is no write after its destruction. The element size of the constructed SYCL `sampled_image` will be derived from the `format` parameter. Accessors that read the constructed SYCL `sampled_image` will use the `sampler` parameter to sample the image. The range of the constructed SYCL `sampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `sampled_image` will be the default size determined by the SYCL runtime. Zero or more properties can be provided to the constructed SYCL `sampled_image` via an instance of `property_list`.

Constructor	Description
`sampled_image(std::shared_ptr<const void>& hostPointer, image_format format, image_sampler sampler, const range<Dimensions>& rangeRef, const range<Dimensions - 1>& pitch, const property_list& propList = {})`	When `hostPointer` is not empty, construct a SYCL `sampled_image` with the contents of its stored pointer. The `sampled_image` assumes exclusive access to this memory for the duration of its lifetime. The `sampled_image` also creates its own internal copy of the `shared_ptr` that shares ownership of the `hostData` memory, which means the application can safely release ownership of this `shared_ptr` when the constructor returns. When `hostPointer` is empty, construct a SYCL `sampled_image` with uninitialized memory. The host address is `const`, so the host accesses can be read-only. Since, the `hostPointer` is `const`, this image is only initialized with this memory and there is no write after its destruction. The element size of the constructed SYCL `sampled_image` will be derived from the `format` parameter. Accessors that read the constructed SYCL `sampled_image` will use the `sampler` parameter to sample the image. The range of the constructed SYCL `sampled_image` is specified by the `rangeRef` parameter provided. The pitch of the constructed SYCL `sampled_image` will be the `pitch` parameter provided. Zero or more properties can be provided to the constructed SYCL `sampled_image` via an instance of `property_list`.

Table 47. Member functions of the `sampled_image` class template

Member function	Description
`range<Dimensions> get_range() const`	Return a range object representing the size of the image in terms of the number of elements in each dimension as passed to the constructor.
`range<Dimensions - 1> get_pitch() const`	Available only when: `Dimensions > 1`. Return a range object representing the pitch of the image in bytes.

Member function	Description
`size_t size() const noexcept`	Returns the total number of elements in the image. Equal to `get_range()[0] * ... * get_range()[Dimensions-1]`.
`size_t byte_size() const noexcept`	Returns the size of the image storage in bytes. The number of bytes may be greater than `size()*element size` due to padding of elements, rows and slices of the image for efficient access.
`template <typename... Ts> auto get_access(Ts... args)`	Returns a valid `sampled_image_accessor` as if constructed via passing the image and all provided arguments to the `sampled_image_accessor` constructor. Possible implementation: `return sampled_image_accessor{*this, args...};`
`template <typename... Ts> auto get_host_access(Ts... args)`	Returns a valid `host_sampled_image_accessor` as if constructed via passing the image and all provided arguments to the `host_sampled_image_accessor` constructor. Possible implementation: `return host_sampled_image_accessor{*this, args...};`

4.7.3.3. Image properties

The properties that can be provided when constructing the SYCL `unsampled_image` and `sampled_image` classes are describe in Table 48.

```
namespace sycl {
namespace property {
namespace image {
class use_host_ptr {
 public:
  use_host_ptr() = default;
};

class use_mutex {
 public:
  use_mutex(std::mutex& mutexRef);

  std::mutex* get_mutex_ptr() const;
};

class context_bound {
 public:
  context_bound(context boundContext);
```

```
19
20   context get_context() const;
21 };
22 } // namespace image
23 } // namespace property
24 } // namespace sycl
```

Table 48. Properties supported by the SYCL image classes

Property	Description
`property::image::use_host_ptr`	The `use_host_ptr` property adds the requirement that the SYCL runtime must not allocate any memory for the `image` and instead uses the provided host pointer directly. This prevents the SYCL runtime from allocating additional temporary storage on the host.
`property::image::use_mutex`	The property adds the requirement that the memory which is owned by the SYCL `image` can be shared with the application via a `std::mutex` provided to the property. The `std::mutex` is locked by the runtime whenever the data is in use and unlocked otherwise. Data is synchronized with `hostData`, when the `std::mutex` is unlocked by the runtime.
`property::image::context_bound`	The `context_bound` property adds the requirement that the SYCL `image` can only be associated with a single SYCL `context` that is provided to the property.

The constructors and member functions of the image `property` classes are listed in Table 49 and Table 50

Table 49. Constructors of the image `property` classes

Constructor	Description
`property::image::use_host_ptr::use_host_ptr()`	Constructs a SYCL `use_host_ptr` property instance.
`property::image::use_mutex::use_mutex(std::mutex& mutexRef)`	Constructs a SYCL `use_mutex` property instance with a reference to `mutexRef` parameter provided.
`property::image::context_bound::context_bound(context boundContext)`	Constructs a SYCL `context_bound` property instance with a copy of a SYCL `context`.

Table 50. Member functions of the image `property` classes

Member function	Description
`std::mutex* property::image::use_mutex::get_mutex_ptr() const`	Returns the `std::mutex` which was specified when constructing this SYCL `use_mutex` property.
`context property::image::context_bound::get_context() const`	Returns the `context` which was specified when constructing this SYCL `context_bound` property.

4.7.3.4. Image synchronization rules

The rules are similar to those described in Section 4.7.2.3.

For the lifetime of the image object, the associated host memory must be left available to the SYCL runtime and the contents of the associated host memory is unspecified until the image object is destroyed. If an image object value is copied, then only a reference to the underlying image object is copied. The underlying image object is reference-counted. Only after all image value references to the underlying image object have been destroyed is the actual image object itself destroyed.

If an image object is constructed with associated host memory, then its destructor blocks until all operations in all SYCL queues on that image object have completed. Any modifications to the image data will be copied back, if necessary, to the associated host memory. Any errors occurring during destruction are reported to any associated context's asynchronous error handler. If an image object is constructed with a storage object, then the storage object defines what synchronization or copying behavior occurs on image object destruction.

4.7.4. Sharing host memory with the SYCL data management classes

In order to allow the SYCL runtime to do memory management and allow for data dependencies, there are two classes defined, buffer and image. The default behavior for them is that a "raw" pointer is given during the construction of the data management class, with full ownership to use it until the destruction of the SYCL object.

In this section we go in greater detail on sharing or explicitly not sharing host memory with the SYCL data classes, and we will use the buffer class as an example. The same rules will apply to images as well.

4.7.4.1. Default behavior

When using a SYCL buffer, the ownership of the pointer passed to the constructor of the class is, by default, passed to SYCL runtime, and that pointer cannot be used on the host side until the buffer or image is destroyed. A SYCL application can access the contents of the memory managed by a SYCL buffer by using a `host_accessor` as defined in Section 4.7.6. However, there is no guarantee that the host accessor synchronizes with the original host address used in its constructor.

The pointer passed in is the one used to copy data back to the host, if needed, before buffer destruction. The memory pointed by host pointer will not be de-allocated by the runtime, and the data is copied back from the device if there is a need for it.

4.7.4.2. SYCL ownership of the host memory

In the case where there is host memory to be used for initialization of data but there is no intention of using that host memory after the buffer is destroyed, then the buffer can take full ownership of that host memory.

When a buffer owns the host pointer there is no copy back, by default. In this situation, the SYCL application may pass a unique pointer to the host data, which will be then used by the runtime internally to initialize the data in the device.

For example, the following could be used:

```
{
  auto ptr = std::make_unique<int>(-1234);
  buffer<int, 1> b { std::move(ptr), range { 1 } };
  // ptr is not valid anymore.
  // There is nowhere to copy data back
}
```

However, optionally the `buffer::set_final_data()` can be set to a `std::weak_ptr` to enable copying data back, to another host memory address that is going to be valid after buffer construction.

```
{
  auto ptr = std::make_unique<int>(-42);
  buffer<int, 1> b { std::move(ptr), range { 1 } };
  // ptr is not valid anymore.
  // There is nowhere to copy data back.
  // To get copy back, a location can be specified:
  b.set_final_data(std::weak_ptr<int> { .... })
}
```

4.7.4.3. Shared SYCL ownership of the host memory

When an instance of `std::shared_ptr` is passed to the buffer constructor, then the buffer object and the developer's application share the memory region. If the shared pointer is still used on the application's side then the data will be copied back from the buffer or image and will be available to the application after the buffer or image is destroyed.

If the `shared_ptr` is not empty, the contents of the referenced memory are used to initialize the buffer. If the `shared_ptr` is empty, then the buffer is created with uninitialized memory.

When the buffer is destroyed and the data have potentially been updated, if the number of copies of the shared pointer outside the runtime is 0, there is no user-side shared pointer to read the data. Therefore the data is not copied out, and the buffer destructor does not need to wait for the data processes to be finished, as the outcome is not needed on the application's side.

This behavior can be overridden using the `set_final_data()` member function of the buffer class, which will by any means force the buffer destructor to wait until the data is copied to wherever the `set_final_data()` member function has put the data (or not wait nor copy if set final data is `nullptr`).

```
{
  std::shared_ptr<int> ptr { data };
  {
    buffer<int, 1> b { ptr, range<2>{ 10, 10 } };
    // update the data
    [...]
  } // Data is copied back because there is an user side shared_ptr
}
```

```
{
  std::shared_ptr<int> ptr { data };
  {
    buffer<int, 1> b { ptr, range<2>{ 10, 10 } };
```

```
    // update the data
    [...]
    ptr.reset();
  } // Data is not copied back, there is no user side shared_ptr.
}
```

4.7.5. Synchronization primitives

When the user wants to use the `buffer` simultaneously in the SYCL runtime and their own code (e.g. a multi-threaded mechanism) and wants to use manual synchronization without using a `host_accessor`, a `std::mutex` can be passed to the `buffer` constructor via the right `property`.

The runtime promises to lock the mutex whenever the data is in use and unlock it when it no longer needs it.

```
{
  std::mutex m;
  auto shD = std::make_shared<int>(42)
  sycl::buffer b { shD, { sycl::property::buffer::use_mutex { m } } };
  {
    std::lock_guard lck { m };
    // User accesses the data
    do_something(shD);
    /* m is unlocked when lck goes out of scope, by normal end of this
       block but also if an exception is thrown for example */
  }
}
```

When the runtime releases the mutex the user is guaranteed that the data was copied back on the shared pointer --- unless the final data destination has been changed using the member function `set_final_data()`.

4.7.6. Accessors

Accessors provide three different capabilities: they provide access to the data managed by a buffer or image, they provide access to local memory on a device, and they define the **requirements** to memory objects which determine the scheduling of kernels (see Section 3.8.1).

A memory object requirement is created when an accessor is constructed, unless the accessor is a placeholder in which case the requirement is created when the accessor is bound to a command by calling `handler::require()`.

There are several different C++ classes that implement accessors:

- The `accessor` class provides access to data in a `buffer` from within a command.
- The `host_accessor` class provides access to data in a `buffer` from host code that is outside of a command. These accessors are typically used in application scope.
- The `local_accessor` class provides access to device local memory from within a SYCL kernel function.
- The `unsampled_image_accessor` and `sampled_image_accessor` classes provide access to data in an `unsampled_image` and `sampled_image` from within a command.
- The `host_unsampled_image_accessor` and `host_sampled_image_accessor` classes provide access to data in an `unsampled_image` and `sampled_image` from host code that is outside of a command. These accessors are typically used in application scope.

Accessor objects must always be constructed in host code, either in command group scope or in application scope. Whether the constructor blocks waiting for data to synchronize depends on the type of accessor. Those accessors which provide access to data within a command do not block. Instead, these accessors define a requirement which influences the scheduling of the command. Those accessors which provide access to data from host code do block until the data is available on the host.

For those accessors which provide access to data within a command, the member functions which access data should only be called from within the command. Programs which call these member functions from outside of the command are ill formed. The sections below describe exactly which member functions fall into this category.

4.7.6.1. Data type

All accessors have a `DataT` template parameter which specifies the type of each element that the accessor accesses. For `accessor` and `host_accessor`, this type must either match the type of each element in the underlying `buffer`, or it must be a `const` qualified version of that type.

For the image accessors (`unsampled_image_accessor`, `sampled_image_accessor`, `host_unsampled_image_accessor`, and `host_sampled_image_accessor`), `DataT` must be one of:

- `int4` (`vec<int32_t,4>`),
- `uint4` (`vec<uint32_t,4>`),
- `float4` (`vec<float,4>`), or
- `half4` (`vec<half,4>`)

For `local_accessor` see Section 4.7.6.11 for the allowable `DataT` types.

4.7.6.2. Access modes

Most accessors have an `AccessMode` template parameter which specifies whether the accessor can read or write the underlying data. This information is used by the runtime when defining the requirements for the associated command, and it tells the runtime whether data needs to be transferred to or from a device before data can be accessed through the accessor.

The `access_mode` enumeration, shown in Table 51, describes the potential modes of an accessor. However, not all accessor classes support all modes, so see the description of each class for more details.

```
namespace sycl {

enum class access_mode : /* unspecified */ {
  read,
  write,
  read_write,
  discard_write,      // Deprecated in SYCL 2020
  discard_read_write, // Deprecated in SYCL 2020
  atomic              // Deprecated in SYCL 2020
};

namespace access {
// The legacy type "access::mode" is deprecated.
using mode = sycl::access_mode;
} // namespace access

} // namespace sycl
```

Table 51. Enumeration of access modes available to accessors

access_mode	Description
`access_mode::read`	Read-only access.
`access_mode::write`	Write-only access.
`access_mode::read_write`	Read and write access.

4.7.6.3. Deduction tags

Some accessor constructors take a `TagT` parameter, which is used to deduce template arguments for the constructor's class. Each of the access modes in Table 51 has an associated tag, but there are additional tags which set other template parameters in addition to the access mode. The synopsis below shows the namespace scope variables that the implementation provides as possible values for the `TagT` parameter.

```
namespace sycl {

inline constexpr __unspecified__ read_only;
inline constexpr __unspecified__ read_write;
inline constexpr __unspecified__ write_only;
inline constexpr __unspecified__ read_only_host_task;
inline constexpr __unspecified__ read_write_host_task;
inline constexpr __unspecified__ write_only_host_task;

} // namespace sycl
```

The precise meaning of these tags depends on the specific accessor class that is being constructed, so they are described more fully below in the section that pertains to each of the accessor types.

4.7.6.4. Properties

All accessor constructors accept a `property_list` parameter, which affects the semantics of the accessor. Table 52 shows the set of all possible accessor properties and tells which properties are allowed when constructing each accessor class.

```
namespace sycl {
namespace property {
struct no_init {};
} // namespace property

inline constexpr property::no_init no_init;
} // namespace sycl
```

Table 52. Properties supported by accessors

Property	Allowed with	Description
property::no_init	accessor host_accessor unsampled_image_accessor host_unsampled_image_accessor	This property is useful when an application expects to write new values to all of the accessor's elements without reading their previous values. The implementation can use this information to avoid copying the accessor's data in some cases. Following is a more formal description. This property is allowed only for accessors with access_mode::write or access_mode::read_write access modes. Attempting to construct an access_mode::read accessor with this property causes an exception with the errc::invalid error code to be thrown. The usage of this property is different depending on whether the accessor's underlying data type DataT is an implicit-lifetime type (as defined in the C++ core language). If it is an implicit-lifetime type, the accessor implicitly creates objects of that type with indeterminate values. The application is not required to write values to each element of the accessor, but unwritten elements of the accessor's buffer or image receive indeterminate values, even if those buffer or image elements previously had defined values. If this is a ranged accessor, this applies only to the elements within the accessor's range. The values of unwritten elements outside of this range are preserved. If DataT is not an implicit-lifetime type, the accessor merely allocates uninitialized memory, and the application is responsible for constructing objects in that memory (e.g. by calling placement-new). The application must create an object in each element of the accessor unless the corresponding element of the underlying buffer did not previously contain an object. If this is a ranged accessor, this applies only to the elements within the accessor's range. The content of objects in the buffer outside of this range is preserved.

As stated above, the property::no_init property requires the application to construct an object for each accessor element when the element's type is not an implicit-lifetime type (except in the case when the corresponding buffer element did not previously contain an object). The reason for this requirement is to avoid the possibility of overwriting a valid object with indeterminate bytes, for example, when a command using the accessor completes. This means that the implementation can unconditionally copy memory from the device back to the host when the command completes, regardless of whether the DataT type is an implicit-lifetime type.

The constructors of the accessor property classes are listed in Table 53.

Table 53. Constructors of the accessor property classes

Constructor	Description
`property::no_init::no_init()`	Constructs a `no_init` property instance.

4.7.6.5. Read only accessors

Accessors which have an `AccessMode` template parameter can be declared as read-only by specifying `access_mode::read` for the template parameter. A read-only accessor provides read-only access to the underlying data and provides a "read" requirement for the memory object when it is constructed.

The `DataT` template parameter for a read-only accessor can optionally be `const` qualified, and the semantics of the accessor are unchanged. For example, an accessor declared with `const DataT` and `access_mode::read` has the same semantics as an accessor declared with `DataT` and `access_mode::read`.

As detailed in the sections below, some accessor types have a default value for `AccessMode`, which depends on whether the `DataT` parameter is `const` qualified. This provides a convenient way to declare a read-only accessor without explicitly specifying the access mode.

A `const` qualified `DataT` is only allowed for a read-only accessor. Programs which specify a `const` qualified `DataT` and any access mode other than `access_mode::read` are ill formed, and the implementation must issue a diagnostic in this case.

Each accessor class also provides implicit conversions between the two forms of read-only accessors. This makes it possible, for example, to assign an accessor whose type has `const DataT` and `access_mode::read` to an accessor whose type has `DataT` and `access_mode::read`, so long as the other template parameters are the same. There is also an implicit conversion from a read-write accessor to either of the forms of a read-only accessor. These implicit conversions are described in detail for each accessor class in the sections that follow.

4.7.6.6. Accessing elements of an accessor

Accessors of type `accessor`, `host_accessor`, and `local_accessor` can have zero, one, two, or three Dimensions. A zero dimension accessor provides access to a single scalar element via an implicit conversion operator to the underlying type of that element and via an overloaded copy/move assignment operators from the underlying type of the element.

One, two, or three dimensional specializations of these accessors provide access to the elements they contain in two ways. The first way is through a subscript operator that takes an instance of an `id` class which has the same dimensionality as the accessor. The second way is by passing a single `size_t` value to multiple consecutive subscript operators as specified in Section 3.11.2.

In all these cases, the reference to the contained element is of type `const DataT&` for read-only accessors and of type `DataT&` for other accessors.

Accessors of all types have a range that defines the set of indices that may be used to access elements. For buffer accessors, this is the range of the underlying buffer, unless it is a ranged accessor in which case the range comes from the accessor's constructor. For image accessors, this is the range of the underlying image. Local accessors specify the range when the accessor is constructed. Any attempt to access an element via an index that is outside of this range produces undefined behavior.

4.7.6.7. Container interface

Accessors of type `accessor`, `host_accessor`, and `local_accessor` meet the C++ requirement of `ReversibleContainer`. The exception to this is that only `local_accessor` owns the underlying data, meaning that its

destructor destroys elements and frees the memory. The `accessor` and `host_accessor` types don't destroy any elements or free the memory on destruction. The iterator for the container interface meets the C++ requirement of `LegacyRandomAccessIterator` and the underlying pointers/references correspond to the address space specified by the accessor type. For multidimensional accessors the iterator linearizes the data according to Section 3.11.1.

4.7.6.8. Ranged accessors

Accessors of type `accessor` and `host_accessor` can be constructed from a sub-range of a `buffer` by providing a range and offset to the constructor. This limits the elements that can be accessed to the specified sub-range, which allows the implementation to perform certain optimizations such as reducing the amount of memory that needs to be copied to or from a device.

If the ranged accessor is multi-dimensional, the sub-range is allowed to describe a region of memory in the underlying buffer that is not contiguous in the linear address space. It is also legal to construct several ranged accessors for the same underlying buffer, either overlapping or non-overlapping.

A ranged accessor still creates a requisite for the entire underlying buffer, even for the portions not within the range. For example, if one command writes through a ranged accessor to one region of a buffer and a second command reads through a ranged accessor from a non-overlapping region of the same buffer, the second command must still be scheduled after the first because the requisites for the two commands are on the entire buffer, not on the sub-ranges of the ranged accessors.

Most of the accessor member functions which provide a reference to the underlying buffer elements are affected by a ranged accessor's offset and range. For example, calling `operator[](0)` on a one-dimensional ranged accessor returns a reference to the element at the position specified by the accessor's offset, which is not necessarily the first element in the buffer. In addition, the accessor's iterator functions iterate only over the elements that are within the sub-range.

The only exceptions are the `get_pointer` and `get_multi_ptr` member functions, which return a pointer to the beginning of the underlying buffer regardless of the accessor's offset. Applications using these functions must take care to manually add the offset before dereferencing the pointer because accessing an element that is outside of the accessor's range results in undefined behavior.

There is no change in behavior for ranged accessors with a range of zero. It still creates a requisite for the entire underlying buffer, and an attempt to access an element produces undefined behaviour.

4.7.6.9. Buffer accessor for commands

The `accessor` class provides access to data in a `buffer` from within a SYCL kernel function or from within a host task. When used in a SYCL kernel function, it accesses the contents of the buffer via the device's global memory. These two forms of the accessor are distinguished by the `AccessTarget` template parameter as shown in Table 54. Both forms support the following values for the `AccessMode` template parameter: `access_mode::read`, `access_mode::write` and `access_mode::read_write`.

Table 54. Description of access targets for buffer accessors

Access target	Meaning
`target::device`	Access a buffer from a SYCL kernel function via device global memory.
`target::host_task`	Access a buffer from a host task.

Programs which specify the access target as `target::device` and then capture the `accessor` in a host task can only use the accessor for interoperability through the `interop_handle`, any other uses result in undefined behavior.

Programs which specify the access target as `target::host_task` and then use the `accessor` from a SYCL

kernel function result in undefined behavior.

The dimensionality of the accessor must match the underlying buffer, however, there is a special case if the buffer is one-dimensional. In this case, the accessor may either be one-dimensional or it may be zero-dimensional. A zero-dimensional accessor has access to just the first element of the buffer, whereas a one-dimensional accessor has access to the entire buffer.

Certain `accessor` constructors create a "placeholder" accessor. Such an accessor is bound to a `buffer` and its semantics such as access target and access mode are defined. However, a placeholder accessor is not yet bound to a command group. Before such an accessor can be used in a command, it must be bound by calling `handler::require()`. If a placeholder accessor is passed as an argument to a command without first being bound to a command group with `handler::require()`, the implementation throws a synchronous `exception` with the `errc::kernel_argument` error code when the command is submitted.

4.7.6.9.1. Interface for buffer command accessors

A synopsis of the `accessor` class is provided below, showing the interface when it is specialized with `target::device` or `target::host_task`. Since some of the class types and member functions have the same name and meaning as other accessors, the common types and functions are described in Section 4.7.6.12. The member types are listed in Table 79 and Table 55. The constructors are listed in Table 56, and the member functions are listed in Table 80 and Table 57.

The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively. For valid implicit conversions between accessor types refer to Section 4.7.6.9.3. Additionally, accessors of the same type must be equality comparable both in the host application and also in SYCL kernel functions.

```
namespace sycl {

enum class target : /* unspecified */ {
  device,
  host_task,
  constant_buffer,       // Deprecated
  local,                 // Deprecated
  host_buffer,           // Deprecated
  global_buffer = device // Deprecated
};

namespace access {
// The legacy type "access::target" is deprecated.
using sycl::target;

enum class placeholder : /* unspecified */ { // Deprecated
  false_t,
  true_t
};

} // namespace access

template <typename DataT, int Dimensions = 1,
          access_mode AccessMode =
              (std::is_const_v<DataT> ? access_mode::read
                                      : access_mode::read_write),
          target AccessTarget = target::device,
          access::placeholder isPlaceholder = access::placeholder::false_t>
class accessor {
```

```
public:
 using value_type = // const DataT for read-only accessors, DataT otherwise
     __value_type__;
 using reference = value_type&;
 using const_reference = const DataT&;
 template <access::decorated IsDecorated>
 using accessor_ptr =   // multi_ptr to value_type with target address space,
     __pointer_class__; //   unspecified for access_mode::host_task
 using iterator = __unspecified_iterator__<value_type>;
 using const_iterator = __unspecified_iterator__<const value_type>;
 using reverse_iterator = std::reverse_iterator<iterator>;
 using const_reverse_iterator = std::reverse_iterator<const_iterator>;
 using difference_type =
     typename std::iterator_traits<iterator>::difference_type;
 using size_type = size_t;

 accessor();

 /* Available only when: (Dimensions == 0) */
 template <typename AllocatorT>
 accessor(buffer<DataT, 1, AllocatorT>& bufferRef,
          const property_list& propList = {});

 /* Available only when: (Dimensions == 0) */
 template <typename AllocatorT>
 accessor(buffer<DataT, 1, AllocatorT>& bufferRef,
          handler& commandGroupHandlerRef, const property_list& propList = {});

 /* Available only when: (Dimensions > 0) */
 template <typename AllocatorT>
 accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
          const property_list& propList = {});

 /* Available only when: (Dimensions > 0) */
 template <typename AllocatorT, typename TagT>
 accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, TagT tag,
          const property_list& propList = {});

 /* Available only when: (Dimensions > 0) */
 template <typename AllocatorT>
 accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
          handler& commandGroupHandlerRef, const property_list& propList = {});

 /* Available only when: (Dimensions > 0) */
 template <typename AllocatorT, typename TagT>
 accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
          handler& commandGroupHandlerRef, TagT tag,
          const property_list& propList = {});

 /* Available only when: (Dimensions > 0) */
 template <typename AllocatorT>
 accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
          range<Dimensions> accessRange, const property_list& propList = {});

 /* Available only when: (Dimensions > 0) */
 template <typename AllocatorT, typename TagT>
```

```
accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
         range<Dimensions> accessRange, TagT tag,
         const property_list& propList = {});

/* Available only when: (Dimensions > 0) */
template <typename AllocatorT>
accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
         range<Dimensions> accessRange, id<Dimensions> accessOffset,
         const property_list& propList = {});

/* Available only when: (Dimensions > 0) */
template <typename AllocatorT, typename TagT>
accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
         range<Dimensions> accessRange, id<Dimensions> accessOffset, TagT tag,
         const property_list& propList = {});

/* Available only when: (Dimensions > 0) */
template <typename AllocatorT>
accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
         handler& commandGroupHandlerRef, range<Dimensions> accessRange,
         const property_list& propList = {});

/* Available only when: (Dimensions > 0) */
template <typename AllocatorT, typename TagT>
accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
         handler& commandGroupHandlerRef, range<Dimensions> accessRange,
         TagT tag, const property_list& propList = {});

/* Available only when: (Dimensions > 0) */
template <typename AllocatorT>
accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
         handler& commandGroupHandlerRef, range<Dimensions> accessRange,
         id<Dimensions> accessOffset, const property_list& propList = {});

/* Available only when: (Dimensions > 0) */
template <typename AllocatorT, typename TagT>
accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
         handler& commandGroupHandlerRef, range<Dimensions> accessRange,
         id<Dimensions> accessOffset, TagT tag,
         const property_list& propList = {});

/* -- common interface members -- */

void swap(accessor& other);

bool is_placeholder() const;

size_type byte_size() const noexcept;

size_type size() const noexcept;

size_type max_size() const noexcept;

// Deprecated
size_t get_size() const;

```

```
  // Deprecated
  size_t get_count() const;

  bool empty() const noexcept;

  /* Available only when: (Dimensions > 0) */
  range<Dimensions> get_range() const;

  /* Available only when: (Dimensions > 0) */
  id<Dimensions> get_offset() const;

  /* Available only when: (AccessMode != access_mode::atomic && Dimensions == 0) */
  operator reference() const;

  /* Available only when: (AccessMode != access_mode::atomic &&
                           AccessMode != access_mode::read && Dimensions == 0) */
  const accessor& operator=(const value_type& other) const;

  /* Available only when: (AccessMode != access_mode::atomic &&
                           AccessMode != access_mode::read && Dimensions == 0) */
  const accessor& operator=(value_type&& other) const;

  /* Available only when: (Dimensions > 0) */
  reference operator[](id<Dimensions> index) const;

  /* Available only when: (Dimensions > 1) */
  __unspecified__ operator[](size_t index) const;

  /* Available only when: (AccessMode != access_mode::atomic && Dimensions == 1)
   */
  reference operator[](size_t index) const;

  /* Deprecated
  Available only when: (AccessMode == access_mode::atomic && Dimensions ==  0)
*/
  operator cl::sycl::atomic<DataT, access::address_space::global_space>() const;

  /* Deprecated
  Available only when: (AccessMode == access_mode::atomic && Dimensions == 1) */
  cl::sycl::atomic<DataT, access::address_space::global_space>
  operator[](id<Dimensions> index) const;

  std::add_pointer_t<value_type> get_pointer() const noexcept;

  template <access::decorated IsDecorated>
  accessor_ptr<IsDecorated> get_multi_ptr() const noexcept;

  iterator begin() const noexcept;

  iterator end() const noexcept;

  const_iterator cbegin() const noexcept;

  const_iterator cend() const noexcept;

  reverse_iterator rbegin() const noexcept;
```

```
198
199   reverse_iterator rend() const noexcept;
200
201   const_reverse_iterator crbegin() const noexcept;
202
203   const_reverse_iterator crend() const noexcept;
204 };
205
206 } // namespace sycl
```

Table 55. Member types of the accessor class

Member types	Description
`template <access::decorated IsDecorated> accessor_ptr`	If `(AccessTarget == target::device)`: `multi_ptr<value_type, access::address_space::global_space, IsDecorated>`. The definition of this type is not specified when `(AccessTarget == target::host_task)`.

Table 56. Constructors of the accessor class

Constructor	Description
`accessor()`	Constructs an empty accessor which fulfills the following post-conditions: • `(empty() == true)` • All size queries return `0`. • The return values of `get_pointer()` and `get_multi_ptr()` are unspecified. • Trying to access the underlying memory is undefined behavior. A default constructed accessor can be passed to a SYCL kernel function but it is not valid to register it with the command group handler.

`template <typename AllocatorT>`
`accessor(buffer<DataT, 1, AllocatorT>& bufferRef,`
`const property_list& propList = {})`
	Available only when `(Dimensions == 0)`.
	
	Constructs a placeholder `accessor` for accessing the first element of a `buffer`. The optional `property_list` provides properties for the constructed accessor.

Constructor	Description
`template <typename AllocatorT> accessor(buffer<DataT, 1, AllocatorT>& bufferRef, handler& commandGroupHandlerRef, const property_list& propList = {})`	Available only when `(Dimensions == 0)`. Constructs an `accessor` for accessing the first element of a `buffer` within a SYCL kernel function on the `queue` associated with `commandGroupHandlerRef`. The optional `property_list` provides properties for the constructed accessor.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs a placeholder `accessor` for accessing a `buffer`. The optional `property_list` provides properties for the constructed accessor.
`template <typename AllocatorT, typename TagT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, TagT tag, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs a placeholder `accessor` for accessing a `buffer`. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.9.2. The optional `property_list` provides properties for the constructed accessor.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, handler& commandGroupHandlerRef, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs an `accessor` for accessing a `buffer` within a SYCL kernel function on the `queue` associated with `commandGroupHandlerRef`. The optional `property_list` provides properties for the constructed accessor.
`template <typename AllocatorT, typename TagT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, handler& commandGroupHandlerRef, TagT tag, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs an `accessor` for accessing a `buffer` within a SYCL kernel function on the `queue` associated with `commandGroupHandlerRef`. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.9.2. The optional `property_list` provides properties for the constructed accessor.

Constructor	Description

`template <typename AllocatorT>`
`accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,`
`range<Dimensions> accessRange, const property_list& propList = {})`
	Available only when `(Dimensions > 0)`.
	
	Constructs a placeholder `accessor` that is a ranged accessor, where the range starts at the beginning of the `buffer`. The optional `property_list` provides properties for the constructed accessor.
	
	Throws an `exception` with the `errc::invalid` error code if `accessRange` exceeds the range of `bufferRef` in any dimension.

`template <typename AllocatorT, typename TagT>`
`accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,`
`range<Dimensions> accessRange, TagT tag,`
`const property_list& propList = {})`
	Available only when `(Dimensions > 0)`.
	
	Constructs a placeholder `accessor` that is a ranged accessor, where the range starts at the beginning of the `buffer`. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.9.2. The optional `property_list` provides properties for the constructed accessor.
	
	Throws an `exception` with the `errc::invalid` error code if `accessRange` exceeds the range of `bufferRef` in any dimension.

`template <typename AllocatorT>`
`accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,`
`range<Dimensions> accessRange, id<Dimensions> accessOffset,`
`const property_list& propList = {})`
	Available only when `(Dimensions > 0)`.
	
	Constructs a placeholder `accessor` that is a ranged accessor, where the range starts at an offset from the beginning of the `buffer`. The optional `property_list` provides properties for the constructed accessor.
	
	Throws an `exception` with the `errc::invalid` error code if the sum of `accessRange` and `accessOffset` exceeds the range of `bufferRef` in any dimension.

Constructor	Description

`template <typename AllocatorT, typename TagT>`
`accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,`
`range<Dimensions> accessRange, id<Dimensions>`
`accessOffset, TagT tag,`
`const property_list& propList = {})`
	Available only when `(Dimensions > 0)`.
	
	Constructs a placeholder `accessor` that is a ranged accessor, where the range starts at an offset from the beginning of the `buffer`. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.9.2. The optional `property_list` provides properties for the constructed accessor.
	
	Throws an `exception` with the `errc::invalid` error code if the sum of `accessRange` and `accessOffset` exceeds the range of `bufferRef` in any dimension.

`template <typename AllocatorT>`
`accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,`
`handler& commandGroupHandlerRef, range<Dimensions>`
`accessRange,`
`const property_list& propList = {})`
	Available only when `(Dimensions > 0)`.
	
	Constructs an `accessor` that is a ranged accessor, where the range starts at the beginning of the `buffer`. The accessor can only be used in a SYCL kernel function on the `queue` associated with `commandGroupHandlerRef`. The optional `property_list` provides properties for the constructed accessor.
	
	Throws an `exception` with the `errc::invalid` error code if `accessRange` exceeds the range of `bufferRef` in any dimension.

Constructor	Description

`template <typename AllocatorT, typename TagT>`
`accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,`
`handler& commandGroupHandlerRef, range<Dimensions>`
`accessRange,`
`TagT tag, const property_list& propList = {})`
	Available only when `(Dimensions > 0)`.
	
	Constructs an `accessor` that is a ranged accessor, where the range starts at the beginning of the `buffer`. The accessor can only be used in a SYCL kernel function on the `queue` associated with `commandGroupHandlerRef`. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.9.2. The optional `property_list` provides properties for the constructed accessor.
	
	Throws an `exception` with the `errc::invalid` error code if `accessRange` exceeds the range of `bufferRef` in any dimension.

`template <typename AllocatorT>`
`accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,`
`handler& commandGroupHandlerRef, range<Dimensions>`
`accessRange,`
`id<Dimensions> accessOffset, const property_list&`
`propList = {})`
	Available only when `(Dimensions > 0)`.
	
	Constructs an `accessor` that is a ranged accessor, where the range starts at an offset from the beginning of the `buffer`. The accessor can only be used in a SYCL kernel function on the `queue` associated with `commandGroupHandlerRef`. The optional `property_list` provides properties for the constructed accessor.
	
	Throws an `exception` with the `errc::invalid` error code if the sum of `accessRange` and `accessOffset` exceeds the range of `bufferRef` in any dimension.

Constructor	Description

`template <typename AllocatorT, typename TagT>`
`accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,`
`handler& commandGroupHandlerRef, range<Dimensions> accessRange,`
`id<Dimensions> accessOffset, TagT tag,`
`const property_list& propList = {})`
	Available only when `(Dimensions > 0)`.
	
	Constructs an `accessor` that is a ranged accessor, where the range starts at an offset from the beginning of the `buffer`. The accessor can only be used in a SYCL kernel function on the `queue` associated with `commandGroupHandlerRef`. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.9.2. The optional `property_list` provides properties for the constructed accessor.
	
	Throws an `exception` with the `errc::invalid` error code if the sum of `accessRange` and `accessOffset` exceeds the range of `bufferRef` in any dimension.

Table 57. Member functions of the `accessor` class

Member function	Description
`void swap(accessor& other);`	Swaps the contents of the current accessor with the contents of `other`.
`bool is_placeholder() const`	Returns `true` if the accessor was constructed as a placeholder. Otherwise returns `false`.
`id<Dimensions> get_offset() const`	Available only when `(Dimensions > 0)`. If this is a ranged accessor, returns the offset that was specified when the accessor was constructed. For other accessors, returns the default constructed `id<Dimensions>{}`.
`template <access::decorated IsDecorated>` `accessor_ptr<IsDecorated> get_multi_ptr() const noexcept`	Returns a `multi_ptr` to the start of this accessor's underlying buffer, even if this is a ranged accessor whose range does not start at the beginning of the buffer. The return value is unspecified if the accessor is empty. This function may only be called from within a command.

Member function	Description
`const accessor& operator=(const value_type& other) const`	Available only when `(AccessMode != access_mode::atomic && AccessMode != access_mode::read && Dimensions == 0)`. Assignment to the single element that is accessed by this accessor. This function may only be called from within a command.
`const accessor& operator=(value_type&& other) const`	Available only when `(AccessMode != access_mode::atomic && AccessMode != access_mode::read && Dimensions == 0)`. Assignment to the single element that is accessed by this accessor. This function may only be called from within a command.

4.7.6.9.2. Deduction tags for buffer command accessors

Some `accessor` constructors take a `TagT` parameter, which is used to deduce template arguments. The permissible values for this parameter are listed in Table 58 along with the access mode and accessor target that they imply.

Table 58. Enumeration of tags available for `accessor` construction

Tag value	Access mode	Accessor target
`read_write`	`access_mode::read_write`	`target::device`
`read_only`	`access_mode::read`	`target::device`
`write_only`	`access_mode::write`	`target::device`
`read_write_host_task`	`access_mode::read_write`	`target::host_task`
`read_only_host_task`	`access_mode::read`	`target::host_task`
`write_only_host_task`	`access_mode::write`	`target::host_task`

4.7.6.9.3. Read only buffer command accessors and implicit conversions

Table 59 shows the specializations of `accessor` with `target::device` or `target::host_task` that are read-only accessors. There is an implicit conversion between any of these specializations, provided that all other template parameters are the same.

Table 59. Specializations of `accessor` that are read-only

Data type	Access mode
not const-qualified	`access_mode::read`
const-qualified	`access_mode::read`

There is also an implicit conversion from the read-write specialization shown in Table 60 to any of the read-only specializations shown in Table 59, provided that all other template parameters are the same.

Table 60. Specializations of `accessor` that are read-write

Data type	Access mode
not const-qualified	access_mode::read_write

4.7.6.9.4. Deprecated features of the accessor class

All of the features defined in this section are deprecated and will likely be removed from a future version of the specification.

4.7.6.9.4.1. Aliased names

The enumerated value target::global_buffer is an alias for target:::device. It has the same type and value as its alias.

The enumerated type access::target is an alias for target, and the enumerated type access::mode is an alias for access_mode.

4.7.6.9.4.2. Discard access modes

An accessor instance specialized with access mode access_mode::discard_write has the same behavior as an accessor instance of mode access_mode::write that is constructed with the property property::no_init.

An accessor instance specialized with access mode access_mode::discard_read_write has the same behavior as an accessor instance of mode access_mode::read_write that is constructed with the property property::no_init.

4.7.6.9.4.3. Placeholder template parameter

The accessor template parameter IsPlaceholder is allowed to be specified, but it has no bearing on whether the accessor instance is a placeholder. This is determined solely by the constructor used to create the instance.

The associated type access::placeholder is also deprecated.

4.7.6.9.4.4. Additional member functions for target::device specialization

Specializations of the accessor class with target::device have the additional member functions described in Table 61.

Table 61. Deprecated member functions of the accessor class

Member function	Description
`size_t get_size() const`	Returns the same value as byte_size().
`size_t get_count() const`	Returns the same value as size().

4.7.6.9.4.5. Accessor specialization with target::constant_buffer

The accessor class may be specialized with target target::constant_buffer, which results in an accessor that can be used within a SYCL kernel function to access the contents of a buffer through the device's constant memory.

As with other accessor specializations, the dimensionality must match the underlying buffer, however there is a special case if the buffer is one-dimensional. In this case, the accessor may either be one-dimensional or it may be zero-dimensional. A zero-dimensional accessor has access to just the first element of the buffer, whereas a one-dimensional accessor has access to the entire buffer.

This specialization of accessor is available only for the access mode access_mode::read.

This accessor type can be constructed as a "placeholder" accessor. As with other accessor specializations that are placeholders, handler::require() must be called before passing a placeholder accessor to a command. If the application neglects to call handler::require() on a placeholder accessor, the implementation throws a synchronous exception with the errc::kernel_argument error code when the command is submitted.

A synopsis for this specialization of accessor is provided below. Since some of the class types and member functions have the same name and meaning as other accessors, the common types and functions are described in Section 4.7.6.9.4.8. The member types are listed in Table 68. The constructors are listed in Table 62, and the member functions are listed in Table 69 and Table 63.

The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively. Additionally, accessors of the same type must be equality comparable.

```
namespace sycl {

template <typename DataT, int Dimensions, access_mode AccessMode,
          target AccessTarget, access::placeholder IsPlaceholder>
class accessor {
 public:
  using value_type = const DataT;
  using reference = const DataT&;
  using const_reference = const DataT&;

  /* Available only when: (Dimensions == 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, 1, AllocatorT>& bufferRef,
           const property_list& propList = {});

  /* Available only when: (Dimensions == 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, 1, AllocatorT>& bufferRef,
           handler& commandGroupHandlerRef, const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           handler& commandGroupHandlerRef, const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           range<Dimensions> accessRange, const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           range<Dimensions> accessRange, id<Dimensions> accessOffset,
```

```
            const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           handler& commandGroupHandlerRef, range<Dimensions> accessRange,
           const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           handler& commandGroupHandlerRef, range<Dimensions> accessRange,
           id<Dimensions> accessOffset, const property_list& propList = {});

  /* -- common interface members -- */

  bool is_placeholder() const;

  size_t get_size() const noexcept;

  size_t get_count() const noexcept;

  /* Available only when: (Dimensions > 0) */
  range<Dimensions> get_range() const;

  /* Available only when: (Dimensions > 0) */
  id<Dimensions> get_offset() const;

  /* Available only when: (Dimensions == 0) */
  operator reference() const;

  /* Available only when: (Dimensions > 0) */
  reference operator[](id<Dimensions> index) const;

  /* Available only when: (Dimensions > 1) */
  __unspecified__ operator[](size_t index) const;

  /* Available only when: (Dimensions == 1) */
  reference operator[](size_t index) const;

  constant_ptr<DataT> get_pointer() const noexcept;
};

} // namespace sycl
```

Table 62. Constructors of the deprecated constant accessor

Constructor	Description

`template <typename AllocatorT>`
`accessor(buffer<DataT, 1, AllocatorT>& bufferRef,`
`const property_list& propList = {})`
	Available only when `(Dimensions == 0)`.
	
	Constructs a placeholder `accessor` for accessing the first element of a `buffer`. The optional `property_list` provides properties for the constructed accessor.

Constructor	Description
`template <typename AllocatorT> accessor(buffer<DataT, 1, AllocatorT>& bufferRef, handler& commandGroupHandlerRef, const property_list& propList = {})`	Available only when (Dimensions == 0). Constructs an accessor for accessing the first element of a buffer within a SYCL kernel function on the queue associated with commandGroupHandlerRef. The optional property_list provides properties for the constructed accessor.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs a placeholder accessor for accessing a buffer. The optional property_list provides properties for the constructed accessor.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, handler& commandGroupHandlerRef, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs an accessor for accessing a buffer within a SYCL kernel function on the queue associated with commandGroupHandlerRef. The optional property_list provides properties for the constructed accessor.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, range<Dimensions> accessRange, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs a placeholder accessor that is a ranged accessor, where the range starts at the beginning of the buffer. The optional property_list provides properties for the constructed accessor. Throws an exception with the errc::invalid error code if accessRange exceeds the range of bufferRef in any dimension.

Constructor	Description
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, range<Dimensions> accessRange, id<Dimensions> accessOffset, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs a placeholder accessor that is a ranged accessor, where the range starts at an offset from the beginning of the buffer. The optional property_list provides properties for the constructed accessor. Throws an exception with the errc::invalid error code if the sum of accessRange and accessOffset exceeds the range of bufferRef in any dimension.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, handler& commandGroupHandlerRef, range<Dimensions> accessRange, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs an accessor that is a ranged accessor, where the range starts at the beginning of the buffer. The accessor can only be used in a SYCL kernel function on the queue associated with commandGroupHandlerRef. The optional property_list provides properties for the constructed accessor. Throws an exception with the errc::invalid error code if accessRange exceeds the range of bufferRef in any dimension.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, handler& commandGroupHandlerRef, range<Dimensions> accessRange, id<Dimensions> accessOffset, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs an accessor that is a ranged accessor, where the range starts at an offset from the beginning of the buffer. The accessor can only be used in a SYCL kernel function on the queue associated with commandGroupHandlerRef. The optional property_list provides properties for the constructed accessor. Throws an exception with the errc::invalid error code if the sum of accessRange and accessOffset exceeds the range of bufferRef in any dimension.

Table 63. Member functions of the deprecated constant accessor

Member function	Description
`bool is_placeholder() const`	Returns `true` if the accessor was constructed as a placeholder and returns `false` otherwise.
`id<Dimensions> get_offset() const`	Available only when `(Dimensions > 0)`. If this is a ranged accessor, returns the offset that was specified when the accessor was constructed, otherwise returns the default constructed `id<Dimensions>{}`.
`constant_ptr<DataT> get_pointer() const noexcept`	Returns a `multi_ptr` to the start of this accessor's underlying buffer, even if this is a ranged accessor whose range does not start at the beginning of the buffer. The return value is unspecified if the accessor is empty.

4.7.6.9.4.6. Accessor specialization with target::host_buffer

The accessor class may be specialized with target target::host_buffer, which results in a host accessor similar to host_accessor. This specialization provides access to data in a buffer from host code that is outside of a command, and constructors of this specialization block until the requested data is available on the host.

As with other accessor specializations, the dimensionality must match the underlying buffer, however there is a special case if the buffer is one-dimensional. In this case, the accessor may either be one-dimensional or it may be zero-dimensional. A zero-dimensional accessor has access to just the first element of the buffer, whereas a one-dimensional accessor has access to the entire buffer.

This specialization of accessor is available for all access modes except for access_mode::atomic.

A synopsis for this specialization of accessor is provided below. Since some of the class types and member functions have the same name and meaning as other accessors, the common types and functions are described in Section 4.7.6.9.4.8. The member types are listed in Table 68. The constructors are listed in Table 64, and the member functions are listed in Table 69 and Table 65.

The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively. Additionally, accessors of the same type must be equality comparable.

```
namespace sycl {

template <typename DataT, int Dimensions, access_mode AccessMode,
          target AccessTarget, access::placeholder IsPlaceholder>
class accessor {
 public:
  using value_type = // const DataT for access_mode::read, DataT otherwise
      __value_type__;
  using reference = value_type&;
  using const_reference = const DataT&;

  /* Available only when: (Dimensions == 0) */
```

```
  template <typename AllocatorT>
  accessor(buffer<DataT, 1, AllocatorT>& bufferRef,
           const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           range<Dimensions> accessRange, const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
           range<Dimensions> accessRange, id<Dimensions> accessOffset,
           const property_list& propList = {});

  /* -- common interface members -- */

  bool is_placeholder() const;

  size_t get_size() const;

  size_t get_count() const;

  /* Available only when: (Dimensions > 0) */
  range<Dimensions> get_range() const;

  /* Available only when: (Dimensions > 0) */
  id<Dimensions> get_offset() const;

  /* Available only when: (Dimensions == 0) */
  operator reference() const;

  /* Available only when: (Dimensions > 0) */
  reference operator[](id<Dimensions> index) const;

  /* Available only when: (Dimensions > 1) */
  __unspecified__ operator[](size_t index) const;

  /* Available only when: (Dimensions == 1) */
  reference operator[](size_t index) const;

  std::add_pointer_t<value_type> get_pointer() const noexcept;
};

} // namespace sycl
```

Table 64. Constructors of the deprecated host buffer accessor

Constructor	Description
`template <typename AllocatorT> accessor(buffer<DataT, 1, AllocatorT>& bufferRef, const property_list& propList = {})`	Available only when (Dimensions == 0). Constructs an accessor for accessing the first element of a buffer immediately on the host. The optional property_list provides properties for the constructed accessor.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs an accessor for accessing a buffer immediately on the host. The optional property_list provides properties for the constructed accessor.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, range<Dimensions> accessRange, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs an accessor that is a ranged accessor which accesses a buffer immediately on the host, where the range starts at the beginning of the buffer. The optional property_list provides properties for the constructed accessor. Throws an exception with the errc::invalid error code if accessRange exceeds the range of bufferRef in any dimension.
`template <typename AllocatorT> accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, range<Dimensions> accessRange, id<Dimensions> accessOffset, const property_list& propList = {})`	Available only when (Dimensions > 0). Constructs an accessor that is a ranged accessor which accesses a buffer immediately on the host, where the range starts at an offset from the beginning of the buffer. The optional property_list provides properties for the constructed accessor. Throws an exception with the errc::invalid error code if the sum of accessRange and accessOffset exceeds the range of bufferRef in any dimension.

Table 65. Member functions of the deprecated host buffer accessor

Member function	Description
`bool is_placeholder() const`	Always returns `false`.
`id<Dimensions> get_offset() const`	Available only when `(Dimensions > 0)`. If this is a ranged accessor, returns the offset that was specified when the accessor was constructed, otherwise returns the default constructed `id<Dimensions>{}`.
`std::add_pointer_t<value_type> get_pointer() const noexcept`	Returns a pointer to the start of this accessor's underlying buffer, even if this is a ranged accessor whose range does not start at the beginning of the buffer. The return value is unspecified if the accessor is empty.

4.7.6.9.4.7. Accessor specialization with target::local

The accessor class may be specialized with target target::local, which results in a local accessor that has the same semantics and restrictions as local_accessor.

This specialization of accessor is only available for access modes access_mode::read_write and access_mode::atomic.

A synopsis for this specialization of accessor is provided below. Since some of the class types and member functions have the same name and meaning as other accessors, the common types and functions are described in Section 4.7.6.9.4.8. The member types are listed in Table 68. The constructors are listed in Table 66, and the member functions are listed in Table 69 and Table 67.

The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively. Additionally, accessors of the same type must be equality comparable.

```
namespace sycl {

template <typename DataT, int Dimensions, access_mode AccessMode,
          target AccessTarget, access::placeholder IsPlaceholder>
class accessor {
 public:
  using value_type = DataT;
  using reference = DataT&;
  using const_reference = const DataT&;

  /* Available only when: (Dimensions == 0) */
  accessor(handler& commandGroupHandlerRef, const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  accessor(range<Dimensions> allocationSize, handler& commandGroupHandlerRef,
           const property_list& propList = {});

  /* -- common interface members -- */
```

```
19
20   size_t get_size() const;
21
22   size_t get_count() const;
23
24   /* Available only when: (Dimensions > 0) */
25   range<Dimensions> get_range() const;
26
27   /* Available only when: (AccessMode == access_mode::read_write && Dimensions
28    * == 0) */
29   operator reference() const;
30
31   /* Available only when: (AccessMode == access_mode::read_write && Dimensions >
32    * 0) */
33   reference operator[](id<Dimensions> index) const;
34
35   /* Available only when: (Dimensions > 1) */
36   __unspecified__ operator[](size_t index) const;
37
38   /* Available only when: (AccessMode == access_mode::read_write && Dimensions
39    * == 1) */
40   reference operator[](size_t index) const;
41
42   /* Available only when: (AccessMode == access_mode::atomic && Dimensions == 0)
43    */
44   operator atomic<DataT, access::address_space::local_space>() const;
45
46   /* Available only when: (AccessMode == access_mode::atomic && Dimensions > 0)
47    */
48   atomic<DataT, access::address_space::local_space>
49   operator[](id<Dimensions> index) const;
50
51   /* Available only when: (AccessMode == access_mode::atomic && Dimensions == 1)
52    */
53   atomic<DataT, access::address_space::local_space>
54   operator[](size_t index) const;
55
56   local_ptr<DataT> get_pointer() const noexcept;
57 };
58
59 } // namespace sycl
```

Table 66. Constructors of the deprecated local accessor

Constructor	Description
`accessor(handler& commandGroupHandlerRef, const property_list& propList = {})`	Available only when `(Dimensions == 0)`. Constructs an `accessor` instance for accessing local memory of a single `DataT` element within a SYCL kernel function on the queue associated with `commandGroupHandlerRef`. The optional `property_list` provides properties for the constructed accessor.

Constructor	Description
`accessor(range<Dimensions> allocationSize, handler& commandGroupHandlerRef, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs an `accessor` instance for accessing local memory of an array of `DataT` elements within a SYCL kernel function on the queue associated with `commandGroupHandlerRef`. The number of elements in the array is defined by `allocationSize`. The optional `property_list` provides properties for the constructed accessor.

Table 67. Member functions of the deprecated local accessor

Member function	Description
`operator atomic<DataT, access::address_space::local_space>() const`	Available only when `(AccessMode == access_mode::atomic && Dimensions == 0)`. Returns an instance of `atomic` of type `DataT` providing atomic access to the element stored within the work-group's local memory allocation that this accessor is accessing.
`atomic<DataT, access::address_space::local_space> operator[](id<Dimensions> index) const`	Available only when `(AccessMode == access_mode::atomic && Dimensions > 0)`. Returns an instance of `atomic` of type `DataT` providing atomic access to the element stored within the work-group's local memory allocation that this accessor is accessing, at the index specified by `index`.
`atomic<DataT, access::address_space::local_space> operator[](size_t index) const`	Available only when `(AccessMode == access_mode::atomic && Dimensions == 1)`. Returns an instance of `atomic` of type `DataT` providing atomic access to the element stored within the work-group's local memory allocation that this accessor is accessing, at the index specified by `index`.
`local_ptr<DataT> get_pointer() const noexcept`	Returns a `multi_ptr` to the work-group's local memory allocation that this accessor is accessing. The return value is unspecified if the accessor is empty.

4.7.6.9.4.8. Common members for deprecated accessors

Specializations of the `accessor` class with `target::constant_buffer`, `target::host_buffer` and `target::local` have many member types and member functions with the same name and meaning. Table 68 describes these common types and Table 69 describes the common member functions.

Table 68. Common member types of the deprecated accessors

Member types	Description
`value_type`	If `(AccessMode == access_mode::read)`, equal to `const DataT`, otherwise equal to `DataT`.
`reference`	Equal to `value_type&`.
`const_reference`	Equal to `const DataT&`.

Table 69. Common member functions of the deprecated accessors

Member function	Description
`size_t get_size() const noexcept`	Returns the size in bytes of the memory region this accessor may access. When `AccessTarget` is `target::constant_buffer` or `target::host_buffer`, the returned value is the size of the elements in the underlying buffer, unless this is a ranged accessor in which case it is the size of the elements within the accessor's range. When `AccessTarget` is `target::local`, the returned value is the size in bytes of the accessor's local memory allocation, per work-group.

Member function	Description
`size_t get_count() const noexcept`	Returns the number of `DataT` elements of the memory region this accessor may access. When `AccessTarget` is `target::constant_buffer` or `target::host_buffer`, the returned value is the number of elements in the underlying buffer, unless this is a ranged accessor in which case it is the number of elements within the accessor's range. When `AccessTarget` is `target::local`, the returned value is the number of elements in the accessor's local memory allocation, per work-group.
`range<Dimensions> get_range() const`	Available only when `(Dimensions > 0)`. Returns a `range` object which represents the number of elements of `DataT` per dimension that this accessor may access. When `AccessTarget` is `target::constant_buffer` or `target::host_buffer`, the returned value is the range of the underlying buffer, unless this is a ranged accessor in which case it is the range that was specified when the accessor was constructed. When `AccessTarget` is `target::local`, the returned value is the range that was specified when the accessor was constructed.
`operator reference() const`	When `AccessTarget` is `target::constant_buffer` or `target::host_buffer`, available only when `(Dimensions == 0)`. When `AccessTarget` is `target::local`, available only when `(AccessMode == access_mode::read_write && Dimensions == 0)`. Returns a reference to the single element that is accessed by this accessor.

Member function	Description
`reference operator[](id<Dimensions> index) const`	When AccessTarget is target::constant_buffer or target::host_buffer, available only when (Dimensions > 0). When AccessTarget is target::local, available only when (AccessMode == access_mode::read_write && Dimensions > 0). Returns a reference to the element at the location specified by index. If this is a ranged accessor, the element is determined by adding index to the accessor's offset.
`__unspecified__ operator[](size_t index) const`	Available only when (Dimensions > 1). Returns an instance of an undefined intermediate type representing this accessor, with the dimensionality Dimensions-1 and containing an implicit id with index Dimensions set to index. The intermediate type returned must provide all available subscript operators which take a size_t parameter defined by this accessor class that are appropriate for the type it represents (including this subscript operator). If this is a ranged accessor, the implicit id in the returned instance also includes the accessor's offset.
`reference operator[](size_t index) const`	When AccessTarget is target::constant_buffer or target::host_buffer, available only when (Dimensions == 1). When AccessTarget is target::local, available only when (AccessMode == access_mode::read_write && Dimensions == 1). Returns a reference to the element at the location specified by index. If this is a ranged accessor, the element is determined by adding index to the accessor's offset.

4.7.6.9.4.9. Accessor specialization with access_mode::atomic

The accessor class may be specialized with target target::device and access mode access_mode::atomic. This specialization provides additional member functions beyond those that are provided for other tar-

`get::device` specializations as described in Table 70.

Table 70. Deprecated atomic member functions of the `accessor` class

Member function	Description
`operator atomic<DataT, access::address_space::global_space>() const`	Available only when `(AccessMode == access_mode::atomic && Dimensions == 0)`. Returns an instance of `atomic` of type `DataT` providing atomic access to the single element that is accessed by this accessor.
`atomic<DataT, access::address_space::global_space> operator[](id<Dimensions> index) const`	Available only when `(AccessMode == access_mode::atomic && Dimensions > 0)`. Returns an instance of `atomic` of type `DataT` providing atomic access to the element stored within the accessor's buffer at the index specified by `index`. If this is a ranged accessor, the returned `atomic` instance provides access to the buffer element whose location is determined by adding the accessor's offset to `index`.
`atomic<DataT, access::address_space::global_space> operator[](size_t index) const`	Available only when `(AccessMode == access_mode::atomic && Dimensions == 1)`. Returns an instance of `atomic` of type `DataT` providing atomic access to the element stored within the accessor's buffer at the index specified by `index`. If this is a ranged accessor, the returned `atomic` instance provides access to the buffer element whose location is determined by adding the accessor's offset to `index`.

4.7.6.10. Buffer accessor for host code

The `host_accessor` class provides access to data in a `buffer` from host code that is outside of a command (i.e. do not use this class to access a buffer inside a host task).

As with `accessor`, the dimensionality of `host_accessor` must match the underlying buffer, however, there is a special case if the buffer is one-dimensional. In this case, the accessor may either be one-dimensional or it may be zero-dimensional. A zero-dimensional accessor has access to just the first element of the buffer, whereas a one-dimensional accessor has access to the entire buffer.

The `host_accessor` class supports the following access modes: `access_mode::read`, `access_mode::write` and `access_mode::read_write`.

4.7.6.10.1. Interface for buffer host accessors

A synopsis of the host_accessor class is provided below. Since some of the class types and member functions have the same name and meaning as other accessors, the common types and functions are described in Section 4.7.6.12. The member types are listed in Table 79. The constructors are listed in Table 71, and the member functions are listed in Table 80 and Table 72.

The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively. For valid implicit conversions between accessor types refer to Section 4.7.6.10.3. Additionally, accessors of the same type must be equality comparable.

```
namespace sycl {
template <typename DataT, int Dimensions = 1,
          access_mode AccessMode =
              (std::is_const_v<DataT> ? access_mode::read
                                      : access_mode::read_write)>
class host_accessor {
 public:
  using value_type = // const DataT for read-only accessors, DataT otherwise
      __value_type__;
  using reference = value_type&;
  using const_reference = const DataT&;
  using iterator = __unspecified_iterator__<value_type>;
  using const_iterator = __unspecified_iterator__<const value_type>;
  using reverse_iterator = std::reverse_iterator<iterator>;
  using const_reverse_iterator = std::reverse_iterator<const_iterator>;
  using difference_type =
      typename std::iterator_traits<iterator>::difference_type;
  using size_type = size_t;

  host_accessor();

  /* Available only when: (Dimensions == 0) */
  template <typename AllocatorT>
  host_accessor(buffer<DataT, 1, AllocatorT>& bufferRef,
                const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
                const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT, typename TagT>
  host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, TagT tag,
                const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
                range<Dimensions> accessRange,
                const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT, typename TagT>
  host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
```

```
                range<Dimensions> accessRange, TagT tag,
                const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT>
  host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
                range<Dimensions> accessRange, id<Dimensions> accessOffset,
                const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  template <typename AllocatorT, typename TagT>
  host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef,
                range<Dimensions> accessRange, id<Dimensions> accessOffset,
                TagT tag, const property_list& propList = {});

  /* -- common interface members -- */

  void swap(host_accessor& other);

  size_type byte_size() const noexcept;

  size_type size() const noexcept;

  size_type max_size() const noexcept;

  bool empty() const noexcept;

  /* Available only when: (Dimensions > 0) */
  range<Dimensions> get_range() const;

  /* Available only when: (Dimensions > 0) */
  id<Dimensions> get_offset() const;

  /* Available only when: (Dimensions == 0) */
  operator reference() const;

  /* Available only when: (AccessMode != access_mode::read && Dimensions == 0) */
  const host_accessor& operator=(const value_type& other) const;

  /* Available only when: (AccessMode != access_mode::read && Dimensions == 0) */
  const host_accessor& operator=(value_type&& other) const;

  /* Available only when: (Dimensions > 0) */
  reference operator[](id<Dimensions> index) const;

  /* Available only when: (Dimensions > 1) */
  __unspecified__ operator[](size_t index) const;

  /* Available only when: (Dimensions == 1) */
  reference operator[](size_t index) const;

  std::add_pointer_t<value_type> get_pointer() const noexcept;

  iterator begin() const noexcept;

  iterator end() const noexcept;
```

```
102
103   const_iterator cbegin() const noexcept;
104
105   const_iterator cend() const noexcept;
106
107   reverse_iterator rbegin() const noexcept;
108
109   reverse_iterator rend() const noexcept;
110
111   const_reverse_iterator crbegin() const noexcept;
112
113   const_reverse_iterator crend() const noexcept;
114 };
115 } // namespace sycl
```

Table 71. Constructors of the host_accessor class

Constructor	Description
`host_accessor()`	Constructs an empty accessor which fulfills the following post-conditions: • `(empty() == true)` • All size queries return `0`. • The return value of `get_pointer()` is unspecified. • Trying to access the underlying memory is undefined behavior.

`template <typename AllocatorT>`
`host_accessor(buffer<DataT, 1, AllocatorT>& bufferRef,`
`const property_list& propList = {})`
	Available only when `(Dimensions == 0)`.
	Constructs a `host_accessor` for accessing the first element of a `buffer` immediately on the host. The optional `property_list` provides properties for the constructed accessor.

`template <typename AllocatorT>`
`host_accessor(buffer<DataT, Dimensions, AllocatorT>&`
`bufferRef,`
`const property_list& propList = {})`
	Available only when `(Dimensions > 0)`.
	Constructs a `host_accessor` for accessing a `buffer` immediately on the host. The optional `property_list` provides properties for the constructed accessor.

Constructor	Description
`template <typename AllocatorT, typename TagT> host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, TagT tag, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs a `host_accessor` for accessing a `buffer` immediately on the host. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.10.2. The optional `property_list` provides properties for the constructed accessor.
`template <typename AllocatorT> host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, range<Dimensions> accessRange, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs a `host_accessor` that is a ranged accessor which accesses a buffer immediately on the host, where the range starts at the beginning of the `buffer`. The optional `property_list` provides properties for the constructed accessor. Throws an `exception` with the `errc::invalid` error code if `accessRange` exceeds the range of `bufferRef` in any dimension.
`template <typename AllocatorT, typename TagT> host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, range<Dimensions> accessRange, TagT tag, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs a `host_accessor` that is a ranged accessor which accesses a buffer immediately on the host, where the range starts at the beginning of the `buffer`. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.10.2. The optional `property_list` provides properties for the constructed accessor. Throws an `exception` with the `errc::invalid` error code if `accessRange` exceeds the range of `bufferRef` in any dimension.

Constructor	Description
`template <typename AllocatorT> host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, range<Dimensions> accessRange, id<Dimensions> accessOffset, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs a `host_accessor` that is a ranged accessor which accesses a buffer immediately on the host, where the range starts at an offset from the beginning of the buffer. The optional `property_list` provides properties for the constructed accessor. Throws an `exception` with the `errc::invalid` error code if the sum of `accessRange` and `accessOffset` exceeds the range of `bufferRef` in any dimension.
`template <typename AllocatorT, typename TagT> host_accessor(buffer<DataT, Dimensions, AllocatorT>& bufferRef, range<Dimensions> accessRange, id<Dimensions> accessOffset, TagT tag, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs a `host_accessor` that is a ranged accessor which accesses a buffer immediately on the host, where the range starts at an offset from the beginning of the buffer. The `tag` is used to deduce template arguments of the accessor as described in Section 4.7.6.10.2. The optional `property_list` provides properties for the constructed accessor. Throws an `exception` with the `errc::invalid` error code if the sum of `accessRange` and `accessOffset` exceeds the range of `bufferRef` in any dimension.

Table 72. Member functions of the `host_accessor` class

Member function	Description
`void swap(host_accessor& other);`	Swaps the contents of the current accessor with the contents of `other`.
`id<Dimensions> get_offset() const`	Available only when `(Dimensions > 0)`. If this is a ranged accessor, returns the offset that was specified when the accessor was constructed. For other accessors, returns the default constructed `id<Dimensions>{}`.

Member function	Description
`const host_accessor& operator=(const value_type& other) const`	Available only when `(AccessMode != access_mode::read && Dimensions == 0)`. Assignment to the single element that is accessed by this accessor.
`const host_accessor& operator=(value_type&& other) const`	Available only when `(AccessMode != access_mode::read && Dimensions == 0)`. Assignment to the single element that is accessed by this accessor.

4.7.6.10.2. Deduction tags for buffer host accessors

Some `host_accessor` constructors take a `TagT` parameter, which is used to deduce template arguments. The permissible values for this parameter are listed in Table 73 along with the access mode that they imply.

Table 73. Enumeration of tags available for `host_accessor` construction

Tag value	Access mode
`read_write`	`access_mode::read_write`
`read_only`	`access_mode::read`
`write_only`	`access_mode::write`

4.7.6.10.3. Read only buffer host accessors and implicit conversions

Table 74 shows the specializations of `host_accessor` that are read-only accessors. There is an implicit conversion between any of these specializations, provided that all other template parameters are the same.

Table 74. Specializations of `host_accessor` that are read-only

Data type	Access mode
not const-qualified	`access_mode::read`
const-qualified	`access_mode::read`

There is also an implicit conversion from the read-write `host_accessor` type shown in Table 75 to any of the read-only accessors in Table 74, provided that all other template parameters are the same.

Table 75. Specializations of `host_accessor` that are read-write

Data type	Access mode
not const-qualified	`access_mode::read_write`

4.7.6.11. Local accessor

The `local_accessor` class allocates device local memory and provides access to this memory from within a SYCL kernel function. The local memory that is allocated is shared between all work items of a work-group. If multiple work-groups execute simultaneously in an implementation, each work-group receives its own independent copy of the allocated local memory.

The underlying `DataT` type can be any C++ type that the device supports. If `DataT` is an implicit-lifetime type (as defined in the C++ core language), the local accessor implicitly creates objects of that type with indeterminate values. For other types, the local accessor merely allocates uninitialized memory, and the

application is responsible for constructing objects in that memory (e.g. by calling placement-new).

A local accessor must not be used in a SYCL kernel function that is invoked via `single_task` or via the simple form of `parallel_for` that takes a `range` parameter. In these cases submitting the kernel to a queue must throw a synchronous `exception` with the `errc::kernel_argument` error code.

4.7.6.11.1. Interface for local accessors

A synopsis of the `local_accessor` class is provided below. Since some of the class types and member functions have the same name and meaning as other accessors, the common types and functions are described in Section 4.7.6.12. The member types are listed in Table 79 and Table 76. The constructors are listed in Table 77, and the member functions are listed in Table 80 and Table 78.

The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively. For valid implicit conversions between accessor types refer to Section 4.7.6.11.2. Additionally, accessors of the same type must be equality comparable.

```
namespace sycl {
template <typename DataT, int Dimensions = 1> class local_accessor {
 public:
  using value_type = // const DataT for read-only accessors, DataT otherwise
      __value_type__;
  using reference = value_type&;
  using const_reference = const DataT&;
  template <access::decorated IsDecorated>
  using accessor_ptr =
      multi_ptr<value_type, access::address_space::local_space, IsDecorated>;
  using iterator = __unspecified_iterator__<value_type>;
  using const_iterator = __unspecified_iterator__<const value_type>;
  using reverse_iterator = std::reverse_iterator<iterator>;
  using const_reverse_iterator = std::reverse_iterator<const_iterator>;
  using difference_type =
      typename std::iterator_traits<iterator>::difference_type;
  using size_type = size_t;

  local_accessor();

  /* Available only when: (Dimensions == 0) */
  local_accessor(handler& commandGroupHandlerRef,
                 const property_list& propList = {});

  /* Available only when: (Dimensions > 0) */
  local_accessor(range<Dimensions> allocationSize,
                 handler& commandGroupHandlerRef,
                 const property_list& propList = {});

  /* -- common interface members -- */

  void swap(accessor& other);

  size_type byte_size() const noexcept;

  size_type size() const noexcept;

  size_type max_size() const noexcept;

```

```
  bool empty() const noexcept;

  range<Dimensions> get_range() const;

  /* Available only when: (Dimensions == 0) */
  operator reference() const;

  /* Available only when: (!std::is_const_v<DataT> && Dimensions == 0) */
  const local_accessor& operator=(const value_type& other) const;

  /* Available only when: (!std::is_const_v<DataT> && Dimensions == 0) */
  const local_accessor& operator=(value_type&& other) const;

  /* Available only when: (Dimensions > 0) */
  reference operator[](id<Dimensions> index) const;

  /* Available only when: (Dimensions > 1) */
  __unspecified__ operator[](size_t index) const;

  /* Available only when: (Dimensions == 1) */
  reference operator[](size_t index) const;

  std::add_pointer_t<value_type> get_pointer() const noexcept;

  template <access::decorated IsDecorated>
  accessor_ptr<IsDecorated> get_multi_ptr() const noexcept;

  iterator begin() const noexcept;

  iterator end() const noexcept;

  const_iterator cbegin() const noexcept;

  const_iterator cend() const noexcept;

  reverse_iterator rbegin() const noexcept;

  reverse_iterator rend() const noexcept;

  const_reverse_iterator crbegin() const noexcept;

  const_reverse_iterator crend() const noexcept;
};
} // namespace sycl
```

Table 76. Member types of the `local_accessor` class

Member types	Description
`template <access::decorated IsDecorated> accessor_ptr`	Equal to `multi_ptr<value_type, access::address_space::local_space, IsDecorated>`.

Table 77. Constructors of the `local_accessor` class

Constructor	Description
`local_accessor()`	Constructs an empty local accessor which fulfills the following post-conditions: • `(empty() == true)` • All size queries return `0`. • The return values of `get_pointer()` and `get_multi_ptr()` are unspecified. • Trying to access the underlying memory is undefined behavior.
`local_accessor(handler& commandGroupHandlerRef, const property_list& propList = {})`	Available only when `(Dimensions == 0)`. Constructs a `local_accessor` for accessing local memory of a single `DataT` element within a SYCL kernel function on the queue associated with `commandGroupHandlerRef`. The optional `property_list` provides properties for the constructed accessor.
`local_accessor(range<Dimensions> allocationSize, handler& commandGroupHandlerRef, const property_list& propList = {})`	Available only when `(Dimensions > 0)`. Constructs a `local_accessor` for accessing local memory of an array of `DataT` elements within a SYCL kernel function on the queue associated with `commandGroupHandlerRef`. The number of elements in the array is defined by `allocationSize`. The optional `property_list` provides properties for the constructed accessor.

Table 78. Member functions of the `local_accessor` class

Member function	Description
`void swap(local_accessor& other);`	Swaps the contents of the current accessor with the contents of `other`.
`template <access::decorated IsDecorated> accessor_ptr<IsDecorated> get_multi_ptr() const noexcept`	Returns a `multi_ptr` to the start of the accessor's local memory region which corresponds to the calling work-group. The return value is unspecified if the accessor is empty. This function may only be called from within a SYCL kernel function.

Member function	Description
`const local_accessor& operator=(const value_type& other) const`	Available only when `(!std::is_const_v<DataT> && Dimensions == 0)`. Assignment to the single element that is accessed by this accessor. This function may only be called from within a command.
`const local_accessor& operator=(const value_type&& other) const`	Available only when `(!std::is_const_v<DataT> && Dimensions == 0)`. Assignment to the single element that is accessed by this accessor. This function may only be called from within a command.

4.7.6.11.2. Read only local accessors and implicit conversions

Since `local_accessor` has no template parameter for the access mode, the only specialization for a read-only local accessor is by providing a `const` qualified `DataT` parameter. Specializations with a non-`const` qualified `DataT` parameter are read-write. There is an implicit conversion from the read-write specialization to the read-only specialization, provided that all other template parameters are the same.

4.7.6.12. Common members for buffer and local accessors

The `accessor`, `host_accessor`, and `local_accessor` classes have many member types and member functions with the same name and meaning. Table 79 describes these common types and Table 80 describes the common member functions.

Table 79. Common buffer and local accessor member types

Member types	Description
`value_type`	If the accessor is read-only, equal to `const DataT`, otherwise equal to `DataT`. See Section 4.7.6.9.3, Section 4.7.6.10.3 and Section 4.7.6.11.2 for which accessors are considered read-only.
`reference`	Equal to `value_type&`.
`const_reference`	Equal to `const DataT&`.

Member types	Description
`iterator`	Iterator that can provide ranged access. Cannot be written to if the accessor is read-only. The underlying pointer is address space qualified for `accessor` specializations with `target::device` and for `local_accessor`.
`const_iterator`	Iterator that can provide ranged access. Cannot be written to. The underlying pointer is address space qualified for `accessor` specializations with `target::device` and for `local_accessor`.
`reverse_iterator`	Iterator adaptor that reverses the direction of `iterator`.
`const_reverse_iterator`	Iterator adaptor that reverses the direction of `const_iterator`.
`difference_type`	Equal to `typename std::iterator_traits<iterator>::difference_type`.
`size_type`	Equal to `size_t`.

Table 80. Common buffer and local accessor member functions

Member function	Description
`size_type byte_size() const noexcept`	Returns the size in bytes of the memory region this accessor may access. For a buffer accessor this is the size of the underlying buffer, unless it is a ranged accessor in which case it is the size of the elements within the accessor's range. For a local accessor this is the size of the accessor's local memory allocation, per work-group.

Member function	Description
`size_type size() const noexcept`	Returns the number of `DataT` elements of the memory region this accessor may access. For a buffer accessor this is the number of elements in the underlying buffer, unless it is a ranged accessor in which case it is the number of elements within the accessor's range. For a local accessor this is the number of elements in the accessor's local memory allocation, per work-group.
`size_type max_size() const noexcept`	Returns the maximum number of elements any accessor of this type would be able to access.
`bool empty() const noexcept`	Returns `true` if `(size() == 0)`.
`range<Dimensions> get_range() const`	Available only when `(Dimensions > 0)`. Returns a `range` object which represents the number of elements of `DataT` per dimension that this accessor may access. For a buffer accessor this is the range of the underlying buffer, unless it is a ranged accessor in which case it is the range that was specified when the accessor was constructed.
`operator reference() const`	For `accessor` available only when `(AccessMode != access_mode::atomic && Dimensions == 0)`. For `host_accessor` and `local_accessor` available only when `(Dimensions == 0)`. Returns a reference to the single element that is accessed by this accessor. For `accessor` and `local_accessor`, this function may only be called from within a command.

Member function	Description
`reference operator[](id<Dimensions> index) const`	For `accessor` available only when `(AccessMode != access_mode::atomic && Dimensions > 0)`. For `host_accessor` and `local_accessor` available only when `(Dimensions > 0)`. Returns a reference to the element at the location specified by `index`. If this is a ranged accessor, the element is determined by adding `index` to the accessor's offset. For `accessor` and `local_accessor`, this function may only be called from within a command.
`__unspecified__ operator[](size_t index) const`	Available only when `(Dimensions > 1)`. Returns an instance of an undefined intermediate type representing this accessor, with the dimensionality `Dimensions-1` and containing an implicit `id` with index `Dimensions` set to `index`. The intermediate type returned must provide all available subscript operators which take a `size_t` parameter defined by this accessor class that are appropriate for the type it represents (including this subscript operator). If this is a ranged accessor, the implicit `id` in the returned instance also includes the accessor's offset. For `accessor` and `local_accessor`, this function may only be called from within a command.

Member function	Description
`reference operator[](size_t index) const`	For `accessor` available only when `(AccessMode != access_mode::atomic && Dimensions == 1)`. For `host_accessor` and `local_accessor` available only when `(Dimensions == 1)`. Returns a reference to the element at the location specified by `index`. If this is a ranged accessor, the element is determined by adding `index` to the accessor's offset. For `accessor` and `local_accessor`, this function may only be called from within a command.
`std::add_pointer_t<value_type> get_pointer() const noexcept`	Returns a pointer to the start of this accessor's memory. For a buffer accessor this is a pointer to the start of the underlying buffer, even if this is a ranged accessor whose range does not start at the beginning of the buffer. The return value is unspecified if the accessor is empty. For `accessor` and `local_accessor`, this function may only be called from within a command.
`iterator begin() const noexcept`	Returns an iterator to the first element of the memory this accessor may access. For a buffer accessor this is an iterator to the first element of the underlying buffer, unless this is a ranged accessor in which case it is an iterator to first element within the accessor's range. For `accessor` and `local_accessor`, this function may only be called from within a command.

Member function	Description
`iterator end() const noexcept`	Returns an iterator to one element past the last element of the memory this accessor may access. For a buffer accessor this is an iterator to one element past the last element in the underlying buffer, unless this is a ranged accessor in which case it is an iterator to one element past the last element within the accessor's range. For `accessor` and `local_accessor`, this function may only be called from within a command.
`const_iterator cbegin() const noexcept`	Returns a const iterator to the first element of the memory this accessor may access. For a buffer accessor this is a const iterator to the first element of the underlying buffer, unless this is a ranged accessor in which case it is a const iterator to first element within the accessor's range. For `accessor` and `local_accessor`, this function may only be called from within a command.
`const_iterator cend() const noexcept`	Returns a const iterator to one element past the last element of the memory this accessor may access. For a buffer accessor this is a const iterator to one element past the last element in the underlying buffer, unless this is a ranged accessor in which case it is a const iterator to one element past the last element within the accessor's range. For `accessor` and `local_accessor`, this function may only be called from within a command.

Member function	Description
`reverse_iterator rbegin() const noexcept`	Returns an iterator adaptor to the last element of the memory this accessor may access. For a buffer accessor this is an iterator adaptor to the last element of the underlying buffer, unless this is a ranged accessor in which case it is an iterator adaptor to the last element within the accessor's range. For `accessor` and `local_accessor`, this function may only be called from within a command.
`reverse_iterator rend() const noexcept`	Returns an iterator adaptor to one element before the first element of the memory this accessor may access. For a buffer accessor this is an iterator adaptor to one element before the first element in the underlying buffer, unless this is a ranged accessor in which case it is an iterator adaptor to one element before the first element within the accessor's range. For `accessor` and `local_accessor`, this function may only be called from within a command.
`const_reverse_iterator crbegin() const noexcept`	Returns a const iterator adaptor to the last element of the memory this accessor may access. For a buffer accessor this is a const iterator adaptor to the last element of the underlying buffer, unless this is a ranged accessor in which case it is an const iterator adaptor to last element within the accessor's range. For `accessor` and `local_accessor`, this function may only be called from within a command.

Member function	Description
`const_reverse_iterator crend() const noexcept`	Returns a const iterator adaptor to one element before the first element of the memory this accessor may access. For a buffer accessor this is a const iterator adaptor to one element before the first element in the underlying buffer, unless this is a ranged accessor in which case it is a const iterator adaptor to one element before the first element within the accessor's range. For `accessor` and `local_accessor`, this function may only be called from within a command.

4.7.6.13. Unsampled image accessors

There are two classes which implement accessors for unsampled images, `unsampled_image_accessor` and `host_unsampled_image_accessor`. The former provides access from within a SYCL kernel function or from within a host task. The latter provides access from host code that is outside of a host task.

The dimensionality of an unsampled image accessor must match the dimensionality of the underlying image to which it provides access. Both unsampled image accessor classes support the `access_mode::read` and `access_mode::write` access modes. In addition, the `host_unsampled_image_accessor` class supports `access_mode::read_write`.

The `AccessTarget` template parameter dictates how the `unsampled_image_accessor` can be used: `image_target::device` means the accessor can be used in a SYCL kernel function while `image_target::host_task` means the accessor can be used in a host task. Programs which specify this template parameter as `image_target::device` and then use the `unsampled_image_accessor` from a host task are ill formed. Likewise, programs which specify this template parameter as `image_target::host_task` and then use the `unsampled_image_accessor` from a SYCL kernel function are ill formed.

4.7.6.13.1. Interface for unsampled image accessors

A synopsis of the two unsampled image accessor classes is provided below. Both classes have member types with the same name, which are described in Table 81. The constructors for the two classes are described in Table 82 and Table 83. Both classes also have member functions with the same name, which are described in Table 84.

The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively. For valid implicit conversions between unsampled accessor types refer to Section 4.7.6.13.3.

Two `unsampled_image_accessor` objects of the same type must be equality comparable in both the host code and in SYCL kernel functions. Two `host_unsampled_image_accessor` objects of the same type must be equality comparable in the host code.

```
1 namespace sycl {
2
3 enum class image_target : /* unspecified */ { device, host_task };
4
```

```
template <typename DataT, int Dimensions, access_mode AccessMode,
          image_target AccessTarget = image_target::device>
class unsampled_image_accessor {
 public:
  using value_type = // const DataT for read-only accessors, DataT otherwise
      __value_type__;
  using reference = value_type&;
  using const_reference = const DataT&;

  template <typename AllocatorT>
  unsampled_image_accessor(unsampled_image<Dimensions, AllocatorT>& imageRef,
                           handler& commandGroupHandlerRef,
                           const property_list& propList = {});

  template <typename AllocatorT, typename TagT>
  unsampled_image_accessor(unsampled_image<Dimensions, AllocatorT>& imageRef,
                           handler& commandGroupHandlerRef, TagT tag,
                           const property_list& propList = {});

  /* -- common interface members -- */

  /* -- property interface members -- */

  size_t size() const noexcept;

  /* Available only when: AccessMode == access_mode::read
  if Dimensions == 1, CoordT = int
  if Dimensions == 2, CoordT = int2
  if Dimensions == 3, CoordT = int4 */
  template <typename CoordT> DataT read(const CoordT& coords) const noexcept;

  /* Available only when: AccessMode == access_mode::write
  if Dimensions == 1, CoordT = int
  if Dimensions == 2, CoordT = int2
  if Dimensions == 3, CoordT = int4 */
  template <typename CoordT>
  void write(const CoordT& coords, const DataT& color) const;
};

template <typename DataT, int Dimensions = 1,
          access_mode AccessMode =
              (std::is_const_v<DataT> ? access_mode::read
                                      : access_mode::read_write)>
class host_unsampled_image_accessor {
 public:
  using value_type = // const DataT for read-only accessors, DataT otherwise
      __value_type__;
  using reference = value_type&;
  using const_reference = const DataT&;

  template <typename AllocatorT>
  host_unsampled_image_accessor(
      unsampled_image<Dimensions, AllocatorT>& imageRef,
      const property_list& propList = {});

  template <typename AllocatorT, typename TagT>
```

```
  host_unsampled_image_accessor(
      unsampled_image<Dimensions, AllocatorT>& imageRef, TagT tag,
      const property_list& propList = {});

  /* -- common interface members -- */

  /* -- property interface members -- */

  size_t size() const noexcept;

  /* Available only when: (AccessMode == access_mode::read ||
                           AccessMode == access_mode::read_write)
  if Dimensions == 1, CoordT = int
  if Dimensions == 2, CoordT = int2
  if Dimensions == 3, CoordT = int4 */
  template <typename CoordT> DataT read(const CoordT& coords) const noexcept;

  /* Available only when: (AccessMode == access_mode::write ||
                           AccessMode == access_mode::read_write)
  if Dimensions == 1, CoordT = int
  if Dimensions == 2, CoordT = int2
  if Dimensions == 3, CoordT = int4 */
  template <typename CoordT>
  void write(const CoordT& coords, const DataT& color) const;
};

} // namespace sycl
```

Table 81. Member types of the unsampled image classes

Member types	Description
`value_type`	If the accessor is read-only, equal to `const DataT`, otherwise equal to `DataT`. See Section 4.7.6.13.3 for which accessors are considered read-only.
`reference`	Equal to `value_type&`.
`const_reference`	Equal to `const DataT&`.

Table 82. Constructors of the `unsampled_image_accessor` class

Constructor	Description
`template <typename AllocatorT> unsampled_image_accessor(unsampled_image<Dimensions, AllocatorT>& imageRef, handler& commandGroupHandlerRef, const property_list& propList = {})`	Constructs an `unsampled_image_accessor` for accessing an `unsampled_image` within a command on the `queue` associated with `commandGroupHandlerRef`. The optional `property_list` provides properties for the constructed object. If `AccessTarget` is `image_target::device`, throws an `exception` with the `errc::feature_not_supported` error code if the device associated with `commandGroupHandlerRef` does not have `aspect::image`.
`template <typename AllocatorT, typename TagT> unsampled_image_accessor(unsampled_image<Dimensions, AllocatorT>& imageRef, handler& commandGroupHandlerRef, TagT tag, const property_list& propList = {})`	Constructs an `unsampled_image_accessor` for accessing an `unsampled_image` within a command on the `queue` associated with `commandGroupHandlerRef`. The `tag` is used to deduce template arguments of the `unsampled_image_accessor` as described in Section 4.7.6.13.2. The optional `property_list` provides properties for the constructed object. If `AccessTarget` is `image_target::device`, throws an `exception` with the `errc::feature_not_supported` error code if the device associated with `commandGroupHandlerRef` does not have `aspect::image`.

Table 83. Constructors of the `host_unsampled_image_accessor` class

Constructor	Description
`template <typename AllocatorT> host_unsampled_image_accessor(unsampled_image<Dimensions, AllocatorT>& imageRef, const property_list& propList = {})`	Constructs a `host_unsampled_image_accessor` for accessing an `unsampled_image` immediately on the host. The optional `property_list` provides properties for the constructed object.

Constructor	Description
`template <typename AllocatorT, typename TagT> host_unsampled_image_accessor(unsampled_image<Dimensions, AllocatorT>& imageRef, TagT tag, const property_list& propList = {})`	Constructs a `host_unsampled_image_accessor` for accessing an `unsampled_image` immediately on the host. The `tag` is used to deduce template arguments of the `host_unsampled_image_accessor` as described in Section 4.7.6.13.2. The optional `property_list` provides properties for the constructed object.

Table 84. Member functions of the unsampled image classes

Member function	Description
`size_t size() const noexcept`	Returns the number of elements of the underlying `unsampled_image` that this accessor is accessing.
`template <typename CoordT> DataT read(const CoordT& coords) const`	Available only when `(AccessMode == access_mode::read || AccessMode == access_mode::read_write)`. Reads and returns an element of the `unsampled_image` at the coordinates specified by `coords`. Permitted types for `CoordT` are `int` when `Dimensions == 1`, `int2` when `Dimensions == 2` and `int4` when `Dimensions == 3`. For `unsampled_image_accessor`, this function may only be called from within a command.
`template <typename CoordT> void write(const CoordT& coords, const DataT& color) const`	Available only when `(AccessMode == access_mode::write || AccessMode == access_mode::read_write)`. Writes the value specified by `color` to the element of the image at the coordinates specified by `coords`. Permitted types for `CoordT` are `int` when `Dimensions == 1`, `int2` when `Dimensions == 2` and `int4` when `Dimensions == 3`. For `unsampled_image_accessor`, this function may only be called from within a command.

4.7.6.13.2. Deduction tags for unsampled image accessors

Some `unsampled_image_accessor` constructors take a `TagT` parameter, which is used to deduce template arguments. The permissible values for this parameter are listed in Table 85 along with the access mode and accessor target that they imply.

Table 85. Enumeration of tags available for `unsampled_image_accessor` construction

Tag value	Access mode	Accessor target
`read_only`	`access_mode::read`	`image_target::device`
`write_only`	`access_mode::write`	`image_target::device`
`read_only_host_task`	`access_mode::read`	`image_target::host_task`
`write_only_host_task`	`access_mode::write`	`image_target::host_task`

Some `host_unsampled_image_accessor` constructors also take a `TagT` parameter. The permissible values for this parameter are listed in Table 86 along with the access mode that they imply.

Table 86. Enumeration of tags available for `host_unsampled_image_accessor` construction

Tag value	Access mode
`read_only`	`access_mode::read`
`write_only`	`access_mode::write`
`read_write`	`access_mode::read_write`

4.7.6.13.3. Read only unsampled image accessors and implicit conversions

All specializations of unsampled image accessors with `access_mode::read` are read-only regardless of whether `DataT` is `const` qualified. There is an implicit conversion between the `const` qualified and non-`const` qualified specializations, provided that all other template parameters are the same.

4.7.6.14. Sampled image accessors

There are two classes which implement accessors for sampled images, `sampled_image_accessor` and `host_sampled_image_accessor`. The former provides access from within a SYCL kernel function or from within a host task. The latter provides access from host code that is outside of a host task.

The dimensionality of a sampled image accessor must match the dimensionality of the underlying image to which it provides access. Sampled image accessors are always read-only.

The `AccessTarget` template parameter dictates how the `sampled_image_accessor` can be used: `image_target::device` means the accessor can be used in a SYCL kernel function while `image_target::host_task` means the accessor can be used in a host task. Programs which specify this template parameter as `image_target::device` and then use the `sampled_image_accessor` from a host task are ill formed. Likewise, programs which specify this template parameter as `image_target::host_task` and then use the `sampled_image_accessor` from a SYCL kernel function are ill formed.

4.7.6.14.1. Interface for sampled image accessors

A synopsis of the two sampled image accessor classes is provided below. Both classes have member types with the same name, which are described in Table 87. The constructors for the two classes are described in Table 88 and Table 89. Both classes also have member functions with the same name, which are described in Table 90.

The additional common special member functions and common member functions are listed in Section 4.5.2 in Table 7 and Table 8, respectively. For valid implicit conversions between sampled accessor types refer to Section 4.7.6.14.3.

Two `sampled_image_accessor` objects of the same type must be equality comparable in both the host code and in SYCL kernel functions. Two `host_sampled_image_accessor` objects of the same type must be equality comparable in the host code.

```
1 namespace sycl {
2
3 enum class image_target : /* unspecified */ { device, host_task };
```

```
4
5  template <typename DataT, int Dimensions,
6            image_target AccessTarget = image_target::device>
7  class sampled_image_accessor {
8   public:
9    using value_type = const DataT;
10   using reference = const DataT&;
11   using const_reference = const DataT&;
12
13   template <typename AllocatorT>
14   sampled_image_accessor(sampled_image<Dimensions, AllocatorT>& imageRef,
15                          handler& commandGroupHandlerRef,
16                          const property_list& propList = {});
17
18   template <typename AllocatorT, typename TagT>
19   sampled_image_accessor(sampled_image<Dimensions, AllocatorT>& imageRef,
20                          handler& commandGroupHandlerRef, TagT tag,
21                          const property_list& propList = {});
22
23   /* -- common interface members -- */
24
25   /* -- property interface members -- */
26
27   size_t size() const noexcept;
28
29   /* if Dimensions == 1, CoordT = float
30      if Dimensions == 2, CoordT = float2
31      if Dimensions == 3, CoordT = float4 */
32   template <typename CoordT> DataT read(const CoordT& coords) const noexcept;
33 };
34
35 template <typename DataT, int Dimensions> class host_sampled_image_accessor {
36  public:
37   using value_type = const DataT;
38   using reference = const DataT&;
39   using const_reference = const DataT&;
40
41   template <typename AllocatorT>
42   host_sampled_image_accessor(sampled_image<Dimensions, AllocatorT>& imageRef,
43                               const property_list& propList = {});
44
45   /* -- common interface members -- */
46
47   /* -- property interface members -- */
48
49   size_t size() const noexcept;
50
51   /* if Dimensions == 1, CoordT = float
52      if Dimensions == 2, CoordT = float2
53      if Dimensions == 3, CoordT = float4 */
54   template <typename CoordT> DataT read(const CoordT& coords) const noexcept;
55 };
56
57 } // namespace sycl
```

Table 87. Member types of the sampled image classes

Member types	Description
`value_type`	Equal to `const DataT`.
`reference`	Equal to `const DataT&`.
`const_reference`	Equal to `const DataT&`.

Table 88. Constructors of the `sampled_image_accessor` class

Constructor	Description

`template <typename AllocatorT>`
`sampled_image_accessor(sampled_image<Dimensions, AllocatorT>& imageRef,`
`handler& commandGroupHandlerRef,`
`const property_list& propList = {})`
	Constructs a `sampled_image_accessor` for accessing a `sampled_image` within a command on the `queue` associated with `commandGroupHandlerRef`. The optional `property_list` provides properties for the constructed object.
	
	If `AccessTarget` is `image_target::device`, throws an `exception` with the `errc::feature_not_supported` error code if the device associated with `commandGroupHandlerRef` does not have `aspect::image`.

`template <typename AllocatorT, typename TagT>`
`sampled_image_accessor(sampled_image<Dimensions, AllocatorT>& imageRef,`
`handler& commandGroupHandlerRef, TagT tag,`
`const property_list& propList = {})`
	Constructs a `sampled_image_accessor` for accessing a `sampled_image` within a command on the `queue` associated with `commandGroupHandlerRef`. The `tag` is used to deduce template arguments of the `sampled_image_accessor` as described in Section 4.7.6.14.2. The optional `property_list` provides properties for the constructed object.
	
	If `AccessTarget` is `image_target::device`, throws an `exception` with the `errc::feature_not_supported` error code if the device associated with `commandGroupHandlerRef` does not have `aspect::image`.

Table 89. Constructors of the `host_sampled_image_accessor` class

Constructor	Description
`template <typename AllocatorT> host_sampled_image_accessor(sampled_image<Dimensions, AllocatorT>& imageRef, const property_list& propList = {})`	Constructs a `host_sampled_image_accessor` for accessing a `sampled_image` immediately on the host. The optional `property_list` provides properties for the constructed object.

Table 90. Member functions of the sampled image classes

Member function	Description
`size_t size() const noexcept`	Returns the number of elements of the underlying `sampled_image` that this accessor is accessing.
`template <typename CoordT> DataT read(const CoordT& coords) const`	Reads and returns a sampled element of the `sampled_image` at the coordinates specified by `coords`. Permitted types for `CoordT` are `float` when `Dimensions == 1`, `float2` when `Dimensions == 2` and `float4` when `Dimensions == 3`. For `sampled_image_accessor`, this function may only be called from within a command.

4.7.6.14.2. Deduction tags for sampled image accessors

Some `sampled_image_accessor` constructors take a `TagT` parameter, which is used to deduce template arguments. The permissible values for this parameter are listed in Table 91 along with the accessor target that they imply.

Table 91. Enumeration of tags available for `sampled_image_accessor` construction

Tag value	Accessor target
`read_only`	`image_target::device`
`read_only_host_task`	`image_target::host_task`

4.7.6.14.3. Read only sampled image accessors and implicit conversions

All specializations of sampled image accessors are read-only regardless of whether `DataT` is `const` qualified. There is an implicit conversion between the `const` qualified and non-`const` qualified specializations, provided that all other template parameters are the same.

4.7.7. Address space classes

In SYCL, there are five different address spaces: global, local, constant, private and generic. In a SYCL generic implementation, types are not affected by the address spaces. However, there are situations where users need to explicitly carry address spaces in the type. For example:

- For performance tuning and genericness. Even if the platform supports the representation of the generic address space, this may come at some performance sacrifice. In order to help the target compiler, it can be useful to track specifically which address space a pointer is addressing.
- When linking SYCL kernels with SYCL backend-specific functions. In this case, it might be necessary to specify the address space for any pointer parameters.

Direct declaration of pointers with address spaces is discouraged as the definition is implementation-defined. Users must rely on the `multi_ptr` class to handle address space boundaries and interoperability.

4.7.7.1. Multi-pointer class

The multi-pointer class is the common interface for the explicit pointer classes, defined in Section 4.7.7.2.

There are situations where a user may want to make their type address space dependent. This allows performing generic programming that depends on the address space associated with their data. An example might be wrapping a pointer inside a class, where a user may need to template the class according to the address space of the pointer the class is initialized with. In this case, the `multi_ptr` class enables users to do this in a portable and stable way.

The `multi_ptr` class exposes 3 flavors of the same interface. If the value of `access::decorated` is `access::decorated::no`, the interface exposes pointers and references type that are not decorated by an address space. If the value of `access::decorated` is `access::decorated::yes`, the interface exposes pointers and references type that are decorated by an address space. The decoration is implementation dependent and relies on device compiler extensions. The decorated type may be distinct from the non-decorated one. For interoperability with the SYCL backend, users should rely on types exposed by the decorated version. If the value of `access::decorated` is `access::decorated::legacy`, the 1.2.1 interface is exposed. This interface is deprecated.

The template traits `remove_decoration` and type alias `remove_decoration_t` retrieve the non-decorated pointer or reference from a decorated one. Using this template trait with a non-decorated type is safe and returns the same type.

It is possible to use the `void` type for the `multi_ptr` class, but in that case some functionality is disabled. `multi_ptr<void>` does not provide the `reference` or `const_reference` types, the access operators (`operator*()`, `operator->()`), the arithmetic operators or `prefetch` member function. Conversions from `multi_ptr` to `multi_ptr<void>` of the same address space are allowed, and will occur implicitly. Conversions from `multi_ptr<void>` to any other `multi_ptr` type of the same address space are allowed, but must be explicit. The same rules apply to `multi_ptr<const void>`.

An overview of the interface provided for the `multi_ptr` class follows.

```
namespace sycl {
namespace access {

enum class address_space : /* unspecified */ {
  global_space,
  local_space,
  constant_space, // Deprecated in SYCL 2020
  private_space,
  generic_space
};

enum class decorated : /* unspecified */ { no, yes, legacy };

} // namespace access

template <typename T> struct remove_decoration {
  using type = /* ... */;
};

template <typename T> using remove_decoration_t = remove_decoration<T>::type;

template <typename ElementType, access::address_space Space,
```

```
          access::decorated DecorateAddress>
class multi_ptr {
 public:
  static constexpr bool is_decorated =
      DecorateAddress == access::decorated::yes;
  static constexpr access::address_space address_space = Space;

  using value_type = ElementType;
  using pointer = std::conditional_t<is_decorated, __unspecified__*,
                                     std::add_pointer_t<value_type>>;
  using reference = std::conditional_t<is_decorated, __unspecified__&,
                                       std::add_lvalue_reference_t<value_type>>;
  using iterator_category = std::random_access_iterator_tag;
  using difference_type = std::ptrdiff_t;

  static_assert(std::is_same_v<remove_decoration_t<pointer>,
                               std::add_pointer_t<value_type>>);
  static_assert(std::is_same_v<remove_decoration_t<reference>,
                               std::add_lvalue_reference_t<value_type>>);
  // Legacy has a different interface.
  static_assert(DecorateAddress != access::decorated::legacy);

  // Constructors
  multi_ptr();
  multi_ptr(const multi_ptr&);
  multi_ptr(multi_ptr&&);
  explicit multi_ptr(
      typename multi_ptr<ElementType, Space, access::decorated::yes>::pointer);
  multi_ptr(std::nullptr_t);

  // Available only when:
  //   (Space == access::address_space::global_space ||
  //    Space == access::address_space::generic_space)
  template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder>
  multi_ptr(
      accessor<value_type, Dimensions, Mode, target::device, IsPlaceholder>);

  // Available only when:
  //   (Space == access::address_space::local_space ||
  //    Space == access::address_space::generic_space)
  template <int Dimensions> multi_ptr(local_accessor<ElementType, Dimensions>);

  // Deprecated
  // Available only when:
  //   (Space == access::address_space::local_space ||
  //    Space == access::address_space::generic_space)
  template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder>
  multi_ptr(
      accessor<value_type, Dimensions, Mode, target::local, IsPlaceholder>);

  // Assignment and access operators
  multi_ptr& operator=(const multi_ptr&);
  multi_ptr& operator=(multi_ptr&&);
  multi_ptr& operator=(std::nullptr_t);

  // Available only when:
```

```
//   (Space == access::address_space::generic_space &&
//    AS != access::address_space::constant_space)
template <access::address_space AS, access::decorated IsDecorated>
multi_ptr& operator=(const multi_ptr<value_type, AS, IsDecorated>&);

// Available only when:
//   (Space == access::address_space::generic_space &&
//    AS != access::address_space::constant_space)
template <access::address_space AS, access::decorated IsDecorated>
multi_ptr& operator=(multi_ptr<value_type, AS, IsDecorated>&&);

reference operator[](std::ptrdiff_t) const;

reference operator*() const;
pointer operator->() const;

pointer get() const;
std::add_pointer_t<value_type> get_raw() const;
__unspecified__* get_decorated() const;

// Conversion to the underlying pointer type
// Deprecated, get() should be used instead.
operator pointer() const;

// Cast to private_ptr
// Available only when: (Space == access::address_space::generic_space)
explicit operator multi_ptr<value_type, access::address_space::private_space,
                            DecorateAddress>();

// Cast to private_ptr
// Available only when: (Space == access::address_space::generic_space)
explicit operator multi_ptr<const value_type, access::address_space::private_space,
                            DecorateAddress>() const;

// Cast to global_ptr
// Available only when: (Space == access::address_space::generic_space)
explicit operator multi_ptr<value_type, access::address_space::global_space,
                            DecorateAddress>();

// Cast to global_ptr
// Available only when: (Space == access::address_space::generic_space)
explicit operator multi_ptr<const value_type, access::address_space::global_space,
                            DecorateAddress>() const;

// Cast to local_ptr
// Available only when: (Space == access::address_space::generic_space)
explicit operator multi_ptr<value_type, access::address_space::local_space,
                            DecorateAddress>();

// Cast to local_ptr
// Available only when: (Space == access::address_space::generic_space)
explicit operator multi_ptr<const value_type, access::address_space::local_space,
                            DecorateAddress>() const;

// Implicit conversion to a multi_ptr<void>.
// Available only when: (!std::is_const_v<value_type>)
```

```
template <access::decorated IsDecorated>
operator multi_ptr<void, Space, IsDecorated>() const;

// Implicit conversion to a multi_ptr<const void>.
// Available only when: (std::is_const_v<value_type>)
template <access::decorated IsDecorated>
operator multi_ptr<const void, Space, IsDecorated>() const;

// Implicit conversion to multi_ptr<const value_type, Space>.
template <access::decorated IsDecorated>
operator multi_ptr<const value_type, Space, IsDecorated>() const;

// Implicit conversion to the non-decorated version of multi_ptr.
// Available only when: (is_decorated == true)
operator multi_ptr<value_type, Space, access::decorated::no>() const;

// Implicit conversion to the decorated version of multi_ptr.
// Available only when: (is_decorated == false)
operator multi_ptr<value_type, Space, access::decorated::yes>() const;

void prefetch(size_t numElements) const;

// Arithmetic operators
friend multi_ptr& operator++(multi_ptr& mp) { /* ... */
}
friend multi_ptr operator++(multi_ptr& mp, int) { /* ... */
}
friend multi_ptr& operator--(multi_ptr& mp) { /* ... */
}
friend multi_ptr operator--(multi_ptr& mp, int) { /* ... */
}
friend multi_ptr& operator+=(multi_ptr& lhs, difference_type r) { /* ... */
}
friend multi_ptr& operator-=(multi_ptr& lhs, difference_type r) { /* ... */
}
friend multi_ptr operator+(const multi_ptr& lhs,
                           difference_type r) { /* ... */
}
friend multi_ptr operator-(const multi_ptr& lhs,
                           difference_type r) { /* ... */
}
friend reference operator*(const multi_ptr& lhs) { /* ... */
}

friend bool operator==(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator!=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator<(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator>(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator<=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator>=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
```

```
191
192   friend bool operator==(const multi_ptr& lhs, std::nullptr_t) { /* ... */
193   }
194   friend bool operator!=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
195   }
196   friend bool operator<(const multi_ptr& lhs, std::nullptr_t) { /* ... */
197   }
198   friend bool operator>(const multi_ptr& lhs, std::nullptr_t) { /* ... */
199   }
200   friend bool operator<=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
201   }
202   friend bool operator>=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
203   }
204
205   friend bool operator==(std::nullptr_t, const multi_ptr& rhs) { /* ... */
206   }
207   friend bool operator!=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
208   }
209   friend bool operator<(std::nullptr_t, const multi_ptr& rhs) { /* ... */
210   }
211   friend bool operator>(std::nullptr_t, const multi_ptr& rhs) { /* ... */
212   }
213   friend bool operator<=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
214   }
215   friend bool operator>=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
216   }
217 };
218
219 // Specialization of multi_ptr for void and const void
220 // VoidType can be either void or const void
221 template <access::address_space Space, access::decorated DecorateAddress>
222 class multi_ptr<VoidType, Space, DecorateAddress> {
223  public:
224   static constexpr bool is_decorated =
225       DecorateAddress == access::decorated::yes;
226   static constexpr access::address_space address_space = Space;
227
228   using value_type = VoidType;
229   using pointer = std::conditional_t<is_decorated, __unspecified__*,
230                                      std::add_pointer_t<value_type>>;
231   using difference_type = std::ptrdiff_t;
232
233   static_assert(std::is_same_v<remove_decoration_t<pointer>,
234                                std::add_pointer_t<value_type>>);
235   // Legacy has a different interface.
236   static_assert(DecorateAddress != access::decorated::legacy);
237
238   // Constructors
239   multi_ptr();
240   multi_ptr(const multi_ptr&);
241   multi_ptr(multi_ptr&&);
242   explicit multi_ptr(
243       typename multi_ptr<VoidType, Space, access::decorated::yes>::pointer);
244   multi_ptr(std::nullptr_t);
245
246   // Available only when:
```

```
//   (Space == access::address_space::global_space)
template <typename ElementType, int Dimensions, access_mode Mode,
          access::placeholder IsPlaceholder>
multi_ptr(
    accessor<ElementType, Dimensions, Mode, target::device, IsPlaceholder>);

// Available only when:
//   (Space == access::address_space::local_space)
template <typename ElementType, int Dimensions>
multi_ptr(local_accessor<ElementType, Dimensions>);

// Deprecated
// Available only when:
//   (Space == access::address_space::local_space)
template <typename ElementType, int Dimensions, access_mode Mode,
          access::placeholder IsPlaceholder>
multi_ptr(
    accessor<ElementType, Dimensions, Mode, target::local, IsPlaceholder>);

// Assignment operators
multi_ptr& operator=(const multi_ptr&);
multi_ptr& operator=(multi_ptr&&);
multi_ptr& operator=(std::nullptr_t);

pointer get() const;

// Conversion to the underlying pointer type
explicit operator pointer() const;

// Explicit conversion to a multi_ptr<ElementType>
// Available only when: (std::is_const_v<ElementType> || !std::is_const_v<VoidType>)
template <typename ElementType>
explicit operator multi_ptr<ElementType, Space, DecorateAddress>() const;

// Implicit conversion to the non-decorated version of multi_ptr.
// Available only when: (is_decorated == true)
operator multi_ptr<value_type, Space, access::decorated::no>() const;

// Implicit conversion to the decorated version of multi_ptr.
// Available only when: (is_decorated == false)
operator multi_ptr<value_type, Space, access::decorated::yes>() const;

// Implicit conversion to multi_ptr<const void, Space>
operator multi_ptr<const void, Space, DecorateAddress>() const;

friend bool operator==(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator!=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator<(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator>(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator<=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
}
friend bool operator>=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
```

```
303   }
304
305   friend bool operator==(const multi_ptr& lhs, std::nullptr_t) { /* ... */
306   }
307   friend bool operator!=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
308   }
309   friend bool operator<(const multi_ptr& lhs, std::nullptr_t) { /* ... */
310   }
311   friend bool operator>(const multi_ptr& lhs, std::nullptr_t) { /* ... */
312   }
313   friend bool operator<=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
314   }
315   friend bool operator>=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
316   }
317
318   friend bool operator==(std::nullptr_t, const multi_ptr& rhs) { /* ... */
319   }
320   friend bool operator!=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
321   }
322   friend bool operator<(std::nullptr_t, const multi_ptr& rhs) { /* ... */
323   }
324   friend bool operator>(std::nullptr_t, const multi_ptr& rhs) { /* ... */
325   }
326   friend bool operator<=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
327   }
328   friend bool operator>=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
329   }
330 };
331
332 // Deprecated, address_space_cast should be used instead.
333 template <typename ElementType, access::address_space Space,
334           access::decorated DecorateAddress>
335 multi_ptr<ElementType, Space, DecorateAddress> make_ptr(ElementType*);
336
337 template <access::address_space Space, access::decorated DecorateAddress,
338           typename ElementType>
339 multi_ptr<ElementType, Space, DecorateAddress> address_space_cast(ElementType*);
340
341 // Deduction guides
342 template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder,
343           class T>
344 multi_ptr(accessor<T, Dimensions, Mode, target::device, IsPlaceholder>)
345     -> multi_ptr<T, access::address_space::global_space, access::decorated::no>;
346
347 template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder,
348           class T>
349 multi_ptr(local_accessor<T, Dimensions>)
350     -> multi_ptr<T, access::address_space::local_space, access::decorated::no>;
351
352 } // namespace sycl
```

Table 92. Constructors of the SYCL `multi_ptr` class template

Constructor	Description
`multi_ptr()`	Default constructor.
`multi_ptr(const multi_ptr&)`	Copy constructor.
`multi_ptr(multi_ptr&&)`	Move constructor.
`explicit multi_ptr(multi_ptr<ElementType, Space, yes>::pointer)`	Constructor that takes as an argument a decorated pointer.
`multi_ptr(std::nullptr_t)`	Constructor from a `nullptr`.
`template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder> multi_ptr( accessor<ElementType, Dimensions, Mode, target::device, IsPlaceholder>);`	Available only when: `Space == access::address_space::global_space || Space == access::address_space::generic_space`. Constructs a `multi_ptr` from an accessor of `target::device`. This constructor may only be called from within a command.
`template <int Dimensions> multi_ptr(local_accessor<ElementType, Dimensions>)`	Available only when: `Space == access::address_space::global_space || Space == access::address_space::generic_space`. Constructs a `multi_ptr` from a `local_accessor`. This constructor may only be called from within a command.
`template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder> multi_ptr( accessor<ElementType, Dimensions, Mode, target::local, IsPlaceholder>);`	Deprecated in SYCL 2020. Use the overload with `local_accessor` instead. Available only when: `Space == access::address_space::global_space || Space == access::address_space::generic_space`. Constructs a `multi_ptr` from an accessor of `target::local`. This constructor may only be called from within a command.

Constructor	Description
`template <typename ElementType, access::address_space Space, access::decorated DecorateAddress> multi_ptr<ElementType, Space, DecorateAddress> make_ptr(ElementType* pointer)`	Deprecated in SYCL 2020. Use `address_space_cast` instead. Global function to create a `multi_ptr` instance depending on the address space of the `pointer` argument. An implementation must return `nullptr` if the run-time value of `pointer` is not compatible with `Space`, and must issue a compile-time diagnostic if the deduced address space is not compatible with `Space`.
`template <access::address_space Space, access::decorated DecorateAddress, typename ElementType> multi_ptr<ElementType, Space, DecorateAddress> address_space_cast(ElementType* pointer)`	Global function to create a `multi_ptr` instance from `pointer`, using the address space and decoration specified via the `Space` and `DecorateAddress` template arguments. An implementation must return `nullptr` if the run-time value of `pointer` is not compatible with `Space`, and must issue a compile-time diagnostic if the deduced address space for `pointer` is not compatible with `Space`.

Table 93. Operators of `multi_ptr` class

Operators	Description
`multi_ptr& operator=(const multi_ptr&)`	Copy assignment operator.
`multi_ptr& operator=(multi_ptr&&)`	Move assignment operator.
`multi_ptr& operator=(std::nullptr_t)`	Assigns `nullptr` to the `multi_ptr`.
`template <access::address_space AS, access::decorated IsDecorated> multi_ptr& operator=(const multi_ptr<value_type, AS, IsDecorated>&)`	Available only when: `(Space == access::address_space::generic_space && AS != access::address_space::constant_space)`. Assigns the value of the left hand side `multi_ptr` into the `generic_ptr`.
`template<access::address_space AS, access::decorated IsDecorated> multi_ptr& operator=(multi_ptr<value_type, AS, IsDecorated>&&)`	Available only when: `(Space == access::address_space::generic_space && AS != access::address_space::constant_space)`. Move the value of the left hand side `multi_ptr` into the `generic_ptr`.

Operators	Description
`reference operator[](std::ptrdiff_t i) const`	Available only when: `(!std::is_void_v<value_type>)`. Returns a reference to the i-th pointed value. The value i can be negative.
`pointer operator->() const`	Available only when: `(!std::is_void_v<value_type>)`. Returns the underlying pointer.
`reference operator*() const`	Available only when: `(!std::is_void_v<value_type>)`. Returns a reference to the pointed value.
`operator pointer() const`	Implicit conversion to the underlying pointer type. **Deprecated:** The member function `get` should be used instead

`template <access::decorated IsDecorated>`
`explicit`
`operator multi_ptr<value_type,`
`access::address_space::private_space,`
`IsDecorated>() const`
	Available only when: `(Space == access::address_space::generic_space)`.
	
	Conversion from `generic_ptr` to `private_ptr`. The result is undefined if the pointer does not address the private address space.

`template <access::decorated IsDecorated>`
`explicit`
`operator multi_ptr<const value_type,`
`access::address_space::private_space,`
`IsDecorated>() const`
	Available only when: `(Space == access::address_space::generic_space)`.
	
	Conversion from `generic_ptr` to `private_ptr`. The result is undefined if the pointer does not address the private address space.

`template <access::decorated IsDecorated>`
`explicit`
`operator multi_ptr<value_type,`
`access::address_space::global_space,`
`IsDecorated>() const`
	Available only when: `(Space == access::address_space::generic_space)`.
	
	Conversion from `generic_ptr` to `global_ptr`. The result is undefined if the pointer does not address the global address space.

`template <access::decorated IsDecorated>`
`explicit`
`operator multi_ptr<const value_type,`
`access::address_space::global_space,`
`IsDecorated>() const`
	Available only when: `(Space == access::address_space::generic_space)`.
	
	Conversion from `generic_ptr` to `global_ptr`. The result is undefined if the pointer does not address the global address space.

Operators	Description

`template <access::decorated IsDecorated>`
`explicit`
`operator multi_ptr<value_type,`
`access::address_space::local_space,`
`IsDecorated>() const`
	Available only when: `(Space == access::address_space::generic_space)`.
	
	Conversion from `generic_ptr` to `local_ptr`. The result is undefined if the pointer does not address the local address space.

`template <access::decorated IsDecorated>`
`explicit`
`operator multi_ptr<const value_type,`
`access::address_space::local_space,`
`IsDecorated>() const`
	Available only when: `(Space == access::address_space::generic_space)`.
	
	Conversion from `generic_ptr` to `local_ptr`. The result is undefined if the pointer does not address the local address space.

`template <access::decorated IsDecorated>` `operator multi_ptr<void, Space, IsDecorated>() const`	Available only when: `(!std::is_void_v<value_type> && !std::is_const_v<value_type>)`. Implicit conversion to a `multi_ptr` of type `void`.
`template <access::decorated IsDecorated>` `operator multi_ptr<const void, Space, IsDecorated>() const`	Available only when: `(!std::is_void_v<value_type> && std::is_const_v<value_type>)`. Implicit conversion to a `multi_ptr` of type `const void`.

`template <access::decorated IsDecorated>`
`operator multi_ptr<const value_type, Space,`
`IsDecorated>() const`
	Implicit conversion to a `multi_ptr` of type `const value_type`.

`operator multi_ptr<const value_type, Space,` `access::decorated::no>() const`	Available only when: `(is_decorated == true)`. Implicit conversion to the equivalent `multi_ptr` object that does not expose decorated pointers or references.
`operator multi_ptr<const value_type, Space,` `access::decorated::yes>() const`	Available only when: `(is_decorated == false)`. Implicit conversion to the equivalent `multi_ptr` object that exposes decorated pointers and references.

Table 94. Member functions of `multi_ptr` class

Member function	Description
`pointer get() const`	Returns the underlying pointer. Whether the pointer is decorated depends on the value of `DecorateAddress`.

Member function	Description
`__unspecified__* get_decorated() const`	Returns the underlying pointer decorated by the address space that it addresses. Note that the support involves implementation-defined device compiler extensions.
`std::add_pointer_t<value_type> get_raw() const`	Returns the underlying pointer, always undecorated.
`void prefetch(size_t numElements) const`	Available only when: `Space == access::address_space::global_space`. Prefetches a number of elements specified by `numElements` into the global memory cache. This operation is an implementation-defined optimization and does not effect the functional behavior of the SYCL kernel function.

Table 95. Hidden friend functions of the `multi_ptr` class

Hidden friend function	Description
`reference operator*(const multi_ptr& mp)`	Available only when: `(!std::is_void_v<ElementType>)`. Operator that returns a reference to the `value_type` of `mp`.
`multi_ptr& operator++(multi_ptr& mp)`	Available only when: `(!std::is_void_v<ElementType>)`. Increments `mp` by `1` and returns `mp`.
`multi_ptr operator++(multi_ptr& mp, int)`	Available only when: `(!std::is_void_v<ElementType>)`. Increments `mp` by `1` and returns a new `multi_ptr` with the value of the original `mp`.
`multi_ptr& operator--(multi_ptr& mp)`	Available only when: `(!std::is_void_v<ElementType>)`. Decrements `mp` by `1` and returns `mp`.
`multi_ptr operator--(multi_ptr& mp, int)`	Available only when: `(!std::is_void_v<ElementType>)`. Decrements `mp` by `1` and returns a new `multi_ptr` with the value of the original `mp`.

Hidden friend function	Description
`multi_ptr& operator+=(multi_ptr& lhs, difference_type r)`	Available only when: `(!std::is_void_v<ElementType>)`. Moves `mp` forward by `r` and returns `lhs`.
`multi_ptr& operator-=(multi_ptr& lhs, difference_type r)`	Available only when: `(!std::is_void_v<ElementType>)`. Moves `mp` backward by `r` and returns `lhs`.
`multi_ptr operator+(const multi_ptr& lhs, difference_type r)`	Available only when: `(!std::is_void_v<ElementType>)`. Creates a new `multi_ptr` that points `r` forward compared to `lhs`.
`multi_ptr operator-(const multi_ptr& lhs, difference_type r)`	Available only when: `(!std::is_void_v<ElementType>)`. Creates a new `multi_ptr` that points `r` backward compared to `lhs`.
`bool operator==(const multi_ptr& lhs, const multi_ptr& rhs)`	Comparison operator `==` for `multi_ptr` class.
`bool operator!=(const multi_ptr& lhs, const multi_ptr& rhs)`	Comparison operator `!=` for `multi_ptr` class.
`bool operator<(const multi_ptr& lhs, const multi_ptr& rhs)`	Comparison operator `<` for `multi_ptr` class.
`bool operator>(const multi_ptr& lhs, const multi_ptr& rhs)`	Comparison operator `>` for `multi_ptr` class.
`bool operator<=(const multi_ptr& lhs, const multi_ptr& rhs)`	Comparison operator `<=` for `multi_ptr` class.
`bool operator>=(const multi_ptr& lhs, const multi_ptr& rhs)`	Comparison operator `>=` for `multi_ptr` class.
`bool operator==(const multi_ptr& lhs, std::nullptr_t)`	Comparison operator `==` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator!=(const multi_ptr& lhs, std::nullptr_t)`	Comparison operator `!=` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator<(const multi_ptr& lhs, std::nullptr_t)`	Comparison operator `<` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator>(const multi_ptr& lhs, std::nullptr_t)`	Comparison operator `>` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator<=(const multi_ptr& lhs, std::nullptr_t)`	Comparison operator `<=` for `multi_ptr` class with a `std::nullptr_t`.

Hidden friend function	Description
`bool operator>=(const multi_ptr& lhs, std::nullptr_t)`	Comparison operator `>=` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator==(std::nullptr_t, const multi_ptr& rhs)`	Comparison operator `==` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator!=(std::nullptr_t, const multi_ptr& rhs)`	Comparison operator `!=` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator<(std::nullptr_t, const multi_ptr& rhs)`	Comparison operator `<` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator>(std::nullptr_t, const multi_ptr& rhs)`	Comparison operator `>` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator<=(std::nullptr_t, const multi_ptr& rhs)`	Comparison operator `<=` for `multi_ptr` class with a `std::nullptr_t`.
`bool operator>=(std::nullptr_t, const multi_ptr& rhs)`	Comparison operator `>=` for `multi_ptr` class with a `std::nullptr_t`.

The following is the overview of the legacy interface from 1.2.1 provided for the `multi_ptr` class.

This legacy class supports the deprecated `address_space::constant_space` address space, which can be used to represent a pointer to constant memory. Pointers to constant memory have an implementation-defined address space, and each implementation can define whether it is legal to assign such a pointer to a generic address pointer.

```
namespace sycl {

// Legacy interface, inherited from 1.2.1.
// Deprecated.
template <typename ElementType, access::address_space Space>
class [[deprecated]] multi_ptr<ElementType, Space, access::decorated::legacy> {
 public:
  using element_type = ElementType;
  using difference_type = std::ptrdiff_t;

  // Implementation defined pointer and reference types that correspond to
  // SYCL/OpenCL interoperability types for OpenCL C functions.
  using pointer_t =
      multi_ptr<ElementType, Space, access::decorated::yes>::pointer;
  using const_pointer_t =
      multi_ptr<const ElementType, Space, access::decorated::yes>::pointer;
  using reference_t =
      multi_ptr<ElementType, Space, access::decorated::yes>::reference;
  using const_reference_t =
      multi_ptr<const ElementType, Space, access::decorated::yes>::reference;

  static constexpr access::address_space address_space = Space;

  // Constructors
  multi_ptr();
  multi_ptr(const multi_ptr&);
```

```
multi_ptr(multi_ptr&&);
multi_ptr(pointer_t);
multi_ptr(ElementType*);
multi_ptr(std::nullptr_t);
~multi_ptr();

// Assignment and access operators
multi_ptr& operator=(const multi_ptr&);
multi_ptr& operator=(multi_ptr&&);
multi_ptr& operator=(pointer_t);
multi_ptr& operator=(ElementType*);
multi_ptr& operator=(std::nullptr_t);
friend ElementType& operator*(const multi_ptr& mp) { /* ... */
}
ElementType* operator->() const;

// Only if Space == global_space
template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder>
multi_ptr(
    accessor<ElementType, Dimensions, Mode, target::device, IsPlaceholder>);

// Only if Space == local_space
template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder>
multi_ptr(
    accessor<ElementType, Dimensions, Mode, target::local, IsPlaceholder>);

// Only if Space == constant_space
template <int Dimensions, access_mode Mode, access::placeholder IsPlaceholder>
multi_ptr(accessor<ElementType, Dimensions, Mode, target::constant_buffer,
                   IsPlaceholder>);

// Returns the underlying OpenCL C pointer
pointer_t get() const;

// Implicit conversion to the underlying pointer type
operator ElementType*() const;

// Implicit conversion to a multi_ptr<void>
// Only available when ElementType is not const-qualified
operator multi_ptr<void, Space, access::decorated::legacy>() const;

// Implicit conversion to a multi_ptr<const void>
// Only available when ElementType is const-qualified
operator multi_ptr<const void, Space, access::decorated::legacy>() const;

// Implicit conversion to multi_ptr<const ElementType, Space>
operator multi_ptr<const ElementType, Space, access::decorated::legacy>()
    const;

// Arithmetic operators
friend multi_ptr& operator++(multi_ptr& mp) { /* ... */
}
friend multi_ptr operator++(multi_ptr& mp, int) { /* ... */
}
friend multi_ptr& operator--(multi_ptr& mp) { /* ... */
}
```

```
  friend multi_ptr operator--(multi_ptr& mp, int) { /* ... */
  }
  friend multi_ptr& operator+=(multi_ptr& lhs, difference_type r) { /* ... */
  }
  friend multi_ptr& operator-=(multi_ptr& lhs, difference_type r) { /* ... */
  }
  friend multi_ptr operator+(const multi_ptr& lhs,
                             difference_type r) { /* ... */
  }
  friend multi_ptr operator-(const multi_ptr& lhs,
                             difference_type r) { /* ... */
  }

  void prefetch(size_t numElements) const;

  friend bool operator==(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator!=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator<(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator>(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator<=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator>=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
  }

  friend bool operator==(const multi_ptr& lhs, std::nullptr_t) { /* ... */
  }
  friend bool operator!=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
  }
  friend bool operator<(const multi_ptr& lhs, std::nullptr_t) { /* ... */
  }
  friend bool operator>(const multi_ptr& lhs, std::nullptr_t) { /* ... */
  }
  friend bool operator<=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
  }
  friend bool operator>=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
  }

  friend bool operator==(std::nullptr_t, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator!=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator<(std::nullptr_t, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator>(std::nullptr_t, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator<=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
  }
  friend bool operator>=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
  }
};

// Legacy interface, inherited from 1.2.1.
```

```
// Deprecated.
// Specialization of multi_ptr for void and const void
// VoidType can be either void or const void
template <access::address_space Space>
class [[deprecated]] multi_ptr<VoidType, Space, access::decorated::legacy> {
 public:
  using element_type = VoidType;
  using difference_type = std::ptrdiff_t;

  // Implementation defined pointer types that correspond to
  // SYCL/OpenCL interoperability types for OpenCL C functions
  using pointer_t = multi_ptr<VoidType, Space, access::decorated::yes>::pointer;
  using const_pointer_t =
      multi_ptr<const VoidType, Space, access::decorated::yes>::pointer;

  static constexpr access::address_space address_space = Space;

  // Constructors
  multi_ptr();
  multi_ptr(const multi_ptr&);
  multi_ptr(multi_ptr&&);
  multi_ptr(pointer_t);
  multi_ptr(VoidType*);
  multi_ptr(std::nullptr_t);
  ~multi_ptr();

  // Assignment operators
  multi_ptr& operator=(const multi_ptr&);
  multi_ptr& operator=(multi_ptr&&);
  multi_ptr& operator=(pointer_t);
  multi_ptr& operator=(VoidType*);
  multi_ptr& operator=(std::nullptr_t);

  // Only if Space == global_space
  template <typename ElementType, int Dimensions, access_mode Mode>
  multi_ptr(accessor<ElementType, Dimensions, Mode, target::device>);

  // Only if Space == local_space
  template <typename ElementType, int Dimensions, access_mode Mode>
  multi_ptr(accessor<ElementType, Dimensions, Mode, target::local>);

  // Only if Space == constant_space
  template <typename ElementType, int Dimensions, access_mode Mode>
  multi_ptr(accessor<ElementType, Dimensions, Mode, target::constant_buffer>);

  // Returns the underlying OpenCL C pointer
  pointer_t get() const;

  // Implicit conversion to the underlying pointer type
  operator VoidType*() const;

  // Explicit conversion to a multi_ptr<ElementType>
  // If VoidType is const, ElementType must be as well
  template <typename ElementType>
  explicit
  operator multi_ptr<ElementType, Space, access::decorated::legacy>() const;
```

```
195
196   // Implicit conversion to multi_ptr<const void, Space>
197   operator multi_ptr<const void, Space, access::decorated::legacy>() const;
198
199   friend bool operator==(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
200   }
201   friend bool operator!=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
202   }
203   friend bool operator<(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
204   }
205   friend bool operator>(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
206   }
207   friend bool operator<=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
208   }
209   friend bool operator>=(const multi_ptr& lhs, const multi_ptr& rhs) { /* ... */
210   }
211
212   friend bool operator==(const multi_ptr& lhs, std::nullptr_t) { /* ... */
213   }
214   friend bool operator!=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
215   }
216   friend bool operator<(const multi_ptr& lhs, std::nullptr_t) { /* ... */
217   }
218   friend bool operator>(const multi_ptr& lhs, std::nullptr_t) { /* ... */
219   }
220   friend bool operator<=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
221   }
222   friend bool operator>=(const multi_ptr& lhs, std::nullptr_t) { /* ... */
223   }
224
225   friend bool operator==(std::nullptr_t, const multi_ptr& rhs) { /* ... */
226   }
227   friend bool operator!=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
228   }
229   friend bool operator<(std::nullptr_t, const multi_ptr& rhs) { /* ... */
230   }
231   friend bool operator>(std::nullptr_t, const multi_ptr& rhs) { /* ... */
232   }
233   friend bool operator<=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
234   }
235   friend bool operator>=(std::nullptr_t, const multi_ptr& rhs) { /* ... */
236   }
237 };
238
239 } // namespace sycl
```

4.7.7.2. Explicit pointer aliases

SYCL provides aliases to the `multi_ptr` class template (see Section 4.7.7.1) for each specialization of `access::address_space`.

A synopsis of the SYCL `multi_ptr` class template aliases is provided below.

```
1 namespace sycl {
2
```

```
template <typename ElementType, access::address_space Space,
          access::decorated IsDecorated>
class multi_ptr;

// Template specialization aliases for different pointer address spaces

template <typename ElementType,
          access::decorated IsDecorated = access::decorated::legacy>
using global_ptr =
    multi_ptr<ElementType, access::address_space::global_space, IsDecorated>;

template <typename ElementType,
          access::decorated IsDecorated = access::decorated::legacy>
using local_ptr =
    multi_ptr<ElementType, access::address_space::local_space, IsDecorated>;

// Deprecated in SYCL 2020
template <typename ElementType>
using constant_ptr =
    multi_ptr<ElementType, access::address_space::constant_space,
              access::decorated::legacy>;

template <typename ElementType,
          access::decorated IsDecorated = access::decorated::legacy>
using private_ptr =
    multi_ptr<ElementType, access::address_space::private_space, IsDecorated>;

// Template specialization aliases for different pointer address spaces.
// The interface exposes non-decorated pointer while keeping the
// address space information internally.

template <typename ElementType>
using raw_global_ptr =
    multi_ptr<ElementType, access::address_space::global_space,
              access::decorated::no>;

template <typename ElementType>
using raw_local_ptr = multi_ptr<ElementType, access::address_space::local_space,
                                access::decorated::no>;

template <typename ElementType>
using raw_private_ptr =
    multi_ptr<ElementType, access::address_space::private_space,
              access::decorated::no>;

// Template specialization aliases for different pointer address spaces.
// The interface exposes decorated pointer.

template <typename ElementType>
using decorated_global_ptr =
    multi_ptr<ElementType, access::address_space::global_space,
              access::decorated::yes>;

template <typename ElementType>
using decorated_local_ptr =
    multi_ptr<ElementType, access::address_space::local_space,
```

```
59              access::decorated::yes>;
60
61 template <typename ElementType>
62 using decorated_private_ptr =
63     multi_ptr<ElementType, access::address_space::private_space,
64               access::decorated::yes>;
65
66 } // namespace sycl
```

Note that using global_ptr, local_ptr, constant_ptr or private_ptr without specifying the decoration is deprecated. The default argument is provided for compatibility with 1.2.1.

4.7.8. Image samplers

The SYCL image_sampler struct contains a configuration for sampling a sampled_image. The members of this struct are defined by the following tables.

```
1 namespace sycl {
2
3 enum class addressing_mode : /* unspecified */ {
4   mirrored_repeat,
5   repeat,
6   clamp_to_edge,
7   clamp,
8   none
9 };
10
11 enum class filtering_mode : /* unspecified */ { nearest, linear };
12
13 enum class coordinate_normalization_mode : /* unspecified */ {
14   normalized,
15   unnormalized
16 };
17
18 struct image_sampler {
19   addressing_mode addressing;
20   coordinate_mode coordinate;
21   filtering_mode filtering;
22 };
23
24 } // namespace sycl
```

Table 96. Addressing modes description

addressing_mode	Description
mirrored_repeat	Out of range coordinates will be flipped at every integer junction. This addressing mode can only be used with normalized coordinates. If normalized coordinates are not used, this addressing mode may generate image coordinates that are undefined.

addressing_mode	Description
`repeat`	Out of range image coordinates are wrapped to the valid range. This addressing mode can only be used with normalized coordinates. If normalized coordinates are not used, this addressing mode may generate image coordinates that are undefined.
`clamp_to_edge`	Out of range image coordinates are clamped to the extent.
`clamp`	Out of range image coordinates will return a border color.
`none`	For this addressing mode the programmer guarantees that the image coordinates used to sample elements of the image refer to a location inside the image; otherwise the results are undefined.

Table 97. Filtering modes description

filtering_mode	Description
`nearest`	Chooses a color of nearest pixel.
`linear`	Performs a linear sampling of adjacent pixels.

Table 98. Coordinate normalization modes description

coordinate_normalization_mode	Description
`normalized`	Normalizes image coordinates.
`unnormalized`	Does not normalize image coordinates.

4.8. Unified shared memory (USM)

This section describes properties and routines for pointer-based memory management interfaces in SYCL. These routines augment, rather than replace, the buffer-based interfaces in SYCL.

Unified Shared Memory (USM) provides a pointer-based alternative to the buffer programming model. USM enables:

- Easier integration into existing code bases by representing allocations as pointers rather than buffers, with full support for pointer arithmetic into allocations.
- Fine-grain control over ownership and accessibility of allocations, to optimally choose between performance and programmer convenience.
- A simpler programming model, by automatically migrating some allocations between SYCL devices

and the host.

To show the differences with the example from Section 3.2, the following source code example shows how shared memory can be used between host and device:

```
#include <iostream>
#include <sycl/sycl.hpp>
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

int main() {
  //  Create a default queue to enqueue work to the default device
  queue myQueue;

  // Allocate shared memory bound to the device and context associated to the
  // queue Replacing malloc_shared with malloc_host would yield a correct
  // program that allocated device-visible memory on the host.
  int* data = sycl::malloc_shared<int>(1024, myQueue);

  myQueue.parallel_for(1024, [=](id<1> idx) {
    // Initialize each buffer element with its own rank number starting at 0
    data[idx] = idx;
  }); // End of the kernel function

  // Explicitly wait for kernel execution since there is no accessor involved
  myQueue.wait();

  // Print result
  for (int i = 0; i < 1024; i++)
    std::cout << "data[" << i << "] = " << data[i] << std::endl;

  return 0;
}
```

By comparison, the following source code example uses less capable device memory, which requires an explicit copy between the device and the host:

```
#include <iostream>
#include <sycl/sycl.hpp>
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

int main() {
  // Create a default queue to enqueue work to the default device
  queue myQueue;

  // Allocate shared memory bound to the device and context associated to the
  // queue
  int* data = sycl::malloc_device<int>(1024, myQueue);

  myQueue.parallel_for(1024, [=](id<1> idx) {
    // Initialize each buffer element with its own rank number starting at 0
    data[idx] = idx;
  }); // End of the kernel function

  // Explicitly wait for kernel execution since there is no accessor involved
  myQueue.wait();
```

```
20
21   // Create an array to receive the device content
22   int hostData[1024];
23   // Receive the content from the device
24   myQueue.memcpy(hostData, data, 1024 * sizeof(int));
25   // Wait for the copy to complete
26   myQueue.wait();
27
28   // Print result
29   for (int i = 0; i < 1024; i++)
30     std::cout << "hostData[" << i << "] = " << hostData[i] << std::endl;
31
32   return 0;
33 }
```

4.8.1. Unified addressing

Unified Addressing guarantees that all devices will use a unified address space. Pointer values in the unified address space will always refer to the same location in memory. The unified address space encompasses the host and one or more devices. Note that this does not require addresses in the unified address space to be accessible on all devices, just that pointer values will be consistent.

4.8.2. Kinds of unified shared memory

USM is a capability that, when available, provides the ability to create allocations that are visible to both host and device(s). USM builds upon Unified Addressing to define a shared address space where pointer values in this space always refer to the same location in memory. USM defines three types of memory allocations described in Table 99.

Table 99. Type of USM allocations

USM allocation type	Description
`host`	Allocations in host memory that are accessible by a device
`device`	Allocations in device memory that are **not** accessible by the host
`shared`	Allocations in shared memory that are accessible by both host and device

The following `enum` is used to refer to the different types of allocations inside of a SYCL program:

```
1 namespace sycl {
2 namespace usm {
3
4 enum class alloc : /* unspecified */ {
5   host,
6   device,
7   shared,
8   unknown
9 };
10
11 }
12 }
```

USM is an optional feature which may not be supported by all devices, and devices that support USM may not support all types of USM allocation. A SYCL application can use the `device::has()` function to

determine the level of USM support for a device. See Table 26 in Section 4.6.4.3 for more details.

The characteristics of USM allocations are summarized in Table 100.

Table 100. Characteristics of the different kinds of USM allocation

Allocation Type	Initial Location	Accessible By		Migratable To	
`device`	`device`	`host`	No	`host`	No
		`device`	Yes	`device`	N/A
		Another `device`	Optional (P2P)	Another `device`	No
`host`	`host`	`host`	Yes	`host`	N/A
		Any `device`	Yes	`device`	No
`shared`	Unspecified	`host`	Yes	`host`	Yes
		`device`	Yes	`device`	Yes
		Another `device`	Optional	Another `device`	Optional

Each USM allocation has an associated SYCL context, and any access to that memory must use the same context. Specifically, any SYCL kernel function that dereferences a pointer to a USM allocation must be submitted to a queue that was constructed with the same context that was used to allocate that memory. The explicit memory operation commands that take USM pointers have a similar restriction. (See Section 4.9.4.3 for details.) Violations of these requirements result in undefined behavior.

There are no similar restrictions for dereferencing a USM pointer in a host task. This is legal regardless of which queue the host task was submitted to so long as the USM pointer is accessible on the host.

Each type of USM allocation has different rules for where that memory is accessible. Attempting to dereference a USM pointer on the host or on a device in violation of these rules results in undefined behavior. Passing a USM pointer to one of the explicit memory functions where the pointer is not accessible to the device generally results in undefined behavior. See Section 4.9.4.3 for the exact rules.

Device allocations are used for explicitly managing device memory. Programmers directly allocate device memory and explicitly copy data between host memory and a device allocation. Device allocations are obtained through SYCL device USM allocation routines instead of system allocation routines like `std::malloc` or C++ `new`. Device allocations are not accessible on the host, but the pointer values remain consistent on account of Unified Addressing. The size of device allocations will be limited by the amount of memory in a device. Support for device allocations on a specific device can be queried through `aspect::usm_device_allocations`.

Device allocations must be explicitly copied between the host and a device. The member functions to copy and initialize data are found in Table 28 and Table 135, and these functions may be used on device allocations if a device supports `aspect::usm_device_allocations`.

Host allocations allow devices to directly read and write host memory inside of a kernel. This can be useful for several reasons, such as when the overhead of moving a small amount of data is not worth paying over the cost of a remote access or when the size of a data set exceeds the size of a device's memory. Host allocations must also be obtained using SYCL routines instead of system allocation routines. While a device may remotely read and write a host allocation, the allocation does not migrate to the device - it remains in host memory. Users should take care to properly synchronize access to host allocations between host execution and kernels. The total size of host allocations will be limited by the amount of pinnable-memory on the host on most systems. Support for host allocations on a specific device can be queried through `aspect::usm_host_allocations`. Support for atomic modification of host allocations on a specific device can be queried through `aspect::usm_atomic_host_allocations`.

Shared allocations implicitly share data between the host and devices. Data may move to where it is being used without the programmer explicitly informing the runtime. It is up to the runtime and backends to make sure that a shared allocation is available where it is used. Shared allocations must also be obtained using SYCL allocation routines instead of the system allocator. The maximum size of a shared allocation on a specific device, and the total size of all shared allocations in a context, are implementation-defined. Support for shared allocations on a specific device can be queried through `aspect::usm_shared_allocations`.

Not all devices may support concurrent access of a shared allocation with the host. If a device does not support this, host execution and device code must take turns accessing the allocation, so the host must not access a shared allocation while a kernel is executing. Host access to a shared allocation which is also accessed by an executing kernel on a device that does not support concurrent access results in undefined behavior. If a device does support concurrent access, both the host and and the device may atomically modify the same data inside an allocation. Allocations, or pieces of allocations, are now free to migrate to different devices in the same context that also support this capability. Additionally, many devices that support concurrent access may support a working set of shared allocations larger than device memory. Users may query whether a device supports concurrent access with atomic modification of shared allocations through the aspect `aspect::usm_atomic_shared_allocations`. See Table 26 in Section 4.6.4.3 for more details.

Performance hints for shared allocations may be specified by the user by enqueueing `prefetch` operations on a device. These operations inform the SYCL runtime that the specified shared allocation is likely to be accessed on the device in the future, and that it is free to migrate the allocation to the device. More about `prefetch` is found in Table 28 and Table 135. If a device supports concurrent access to shared allocations, then `prefetch` operations may be overlapped with kernel execution.

Additionally, users may use the `mem_advise` member function to annotate shared allocations with `advice`. Valid `advice` is defined by the device and its associated backend. See Table 28 and Table 135 for more information.

In the most capable systems, users do not need to use SYCL USM allocation functions to create shared allocations. The system allocator (`malloc`/`new`) may instead be used. Likewise, `std::free` and `delete` are used instead of `sycl::free`. Note that host and device allocations are unaffected by this change and must still be allocated using their respective USM functions in order to guarantee their behavior. Users may query the device to determine if system allocations are supported for use on the device, through `aspect::usm_system_allocations`.

4.8.3. USM allocations

USM provides several allocation functions. These functions accept a `property_list` parameter, which is provided for future extensibility. The core SYCL specification does not yet define any USM allocation properties.

Some of the allocation functions take an explicit alignment parameter. Like `std::aligned_alloc`, these functions return `nullptr` if the alignment is not supported by the implementation. Some of the allocation functions are templated on the allocated type `T` and some are not. The following table specifies the alignment guarantees for each category.

Table 101. Alignment guarantees of USM allocation functions

Category	Alignment guarantee
No alignment parameter Not templated on allocation type	Pointer is suitably aligned for any object with fundamental alignment whose size is less than or equal to the requested allocation size.
No alignment parameter Templated on allocation type `T`	Pointer is suitably aligned for an object of type `T`.

Category	Alignment guarantee
Alignment parameter `alignment` specified Not templated on allocation type	Pointer is suitably aligned for any object with fundamental alignment whose size is less than or equal to the requested allocation size or it is aligned to the specified `alignment`, whichever is greater.
Alignment parameter `alignment` specified Templated on allocation type `T`	Pointer is suitably aligned for an object of type `T` or it is aligned to the specified `alignment`, whichever is greater.

4.8.3.1. C++ allocator interface

SYCL defines an allocator class named `usm_allocator` that satisfies the C++ named requirement `Allocator`. The `AllocKind` template parameter can be either `usm::alloc::host` or `usm::alloc::shared`, causing the allocator to make either host USM allocations or shared USM allocations.

There is no specialization for `usm::alloc::device` because an `Allocator` is required to allocate memory that is accessible on the host.

The `usm_allocator` class has a template argument `Alignment`, which specifies the minimum alignment for memory that it allocates. This alignment is used even if the allocator is rebound to a different type. Memory allocated by this allocator is suitably aligned for objects of its underlying `value_type` or at the alignment specified by `Alignment`, whichever is greater.

A synopsis of the `usm_allocator` class is provided below. The constructors are listed in Table 102.

```
template <typename T, usm::alloc AllocKind, size_t Alignment = 0>
class usm_allocator {
public:
  using value_type = T;
  using propagate_on_container_copy_assignment = std::true_type;
  using propagate_on_container_move_assignment = std::true_type;
  using propagate_on_container_swap = std::true_type;

public:
  template <typename U> struct rebind {
    typedef usm_allocator<U, AllocKind, Alignment> other;
  };

  usm_allocator() = delete;
  usm_allocator(const context& syclContext,
                const device& syclDevice,
                const property_list& propList = {});
  usm_allocator(const queue& syclQueue,
                const property_list& propList = {});
  usm_allocator(const usm_allocator& other);
  usm_allocator(usm_allocator&&) noexcept;
  usm_allocator& operator=(const usm_allocator&);
  usm_allocator& operator=(usm_allocator&&);

  template <class U>
  usm_allocator(usm_allocator<U, AllocKind, Alignment> const&) noexcept;

  /// Allocate memory
  T* allocate(size_t count);

  /// Deallocate memory
```

```
  void deallocate(T* Ptr, size_t count);

  /// Equality Comparison
  ///
  /// Allocators only compare equal if they are of the same USM kind, alignment,
  /// context, and device
  template <class U, usm::alloc AllocKindU, size_t AlignmentU>
  friend bool operator==(const usm_allocator<T, AllocKind, Alignment>&,
                         const usm_allocator<U, AllocKindU, AlignmentU>&);

  /// Inequality Comparison
  /// Allocators only compare unequal if they are not of the same USM kind, alignment,
  /// context, or device
  template <class U, usm::alloc AllocKindU, size_t AlignmentU>
  friend bool operator!=(const usm_allocator<T, AllocKind, Alignment>&,
                         const usm_allocator<U, AllocKindU, AlignmentU>&);
};
```

Table 102. Constructors of the usm_allocator class

Constructor	Description
`usm_allocator(const context& syclContext, const device& syclDevice, const property_list& propList = {})`	Constructs a usm_allocator instance that allocates USM for the provided context and device. If AllocKind is usm::alloc::host, this constructor throws a synchronous exception with the errc::feature_not_supported error code if no device in syclContext has aspect::usm_host_allocations. The syclDevice is ignored for this allocation kind. If AllocKind is usm::alloc::shared, this constructor throws a synchronous exception with the errc::feature_not_supported error code if the syclDevice does not have aspect::usm_shared_allocations. The syclDevice must either be contained by syclContext or it must be a descendent device of some device that is contained by that context, otherwise this constructor throws a synchronous exception with the errc::invalid error code.
`usm_allocator(const queue& syclQueue, const property_list& propList = {})`	Simplified constructor form where syclQueue provides the device and context.

4.8.3.2. Device allocation functions

The functions in Table 103 allocate device USM. On success, these functions return a pointer to the newly allocated memory, which must eventually be deallocated with sycl::free in order to avoid a memory

leak. If there are not enough resources to allocate the requested memory, these functions return `nullptr`.

When the allocation size is zero bytes (`numBytes` or `count` is zero), these functions behave in a manor consistent with C++ `std::malloc`. The value returned is unspecified in this case, and the returned pointer may not be used to access storage. If this pointer is not null, it must be passed to `sycl::free` to avoid a memory leak.

Table 103. Device USM Allocation Functions

Function	Description
`void* sycl::malloc_device(size_t numBytes, const device& syclDevice, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory, which is allocated on `syclDevice`. The allocation size is specified in bytes. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if the `syclDevice` does not have `aspect::usm_device_allocations`. The `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.
`template <typename T> T* sycl::malloc_device(size_t count, const device& syclDevice, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory, which is allocated on `syclDevice`. The allocation size is specified in number of elements of type `T`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if the `syclDevice` does not have `aspect::usm_device_allocations`. The `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.
`void* sycl::malloc_device(size_t numBytes, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `device` and `context`.
`template <typename T> T* sycl::malloc_device(size_t count, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `device` and `context`.

Function	Description
`void* sycl::aligned_alloc_device(size_t alignment, size_t numBytes, const device& syclDevice, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory, which is allocated on `syclDevice`. The allocation is specified in bytes and aligned according to `alignment`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if the `syclDevice` does not have `aspect::usm_device_allocations`. The `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.
`template <typename T> T* sycl::aligned_alloc_device(size_t alignment, size_t count, const device& syclDevice, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory, which is allocated on `syclDevice`. The allocation is specified in number of elements of type `T` and aligned according to `alignment`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if the `syclDevice` does not have `aspect::usm_device_allocations`. The `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.
`void* sycl::aligned_alloc_device(size_t alignment, size_t numBytes, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `device` and `context`.
`template <typename T> T* sycl::aligned_alloc_device(size_t alignment, size_t count, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `device` and `context`.

4.8.3.3. Host allocation functions

The functions in Table 104 allocate host USM. On success, these functions return a pointer to the newly allocated memory, which must eventually be deallocated with `sycl::free` in order to avoid a memory

leak. If there are not enough resources to allocate the requested memory, these functions return `nullptr`.

Table 104. Host USM Allocation Functions

Function	Description
`void* sycl::malloc_host(size_t numBytes, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory. This allocation is specified in bytes. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if no device in `syclContext` has `aspect::usm_host_allocations`.
`template <typename T> T* sycl::malloc_host(size_t count, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory. This allocation is specified in number of elements of type `T`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if no device in `syclContext` has `aspect::usm_host_allocations`.
`void* sycl::malloc_host(size_t numBytes, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `context`.
`template <typename T> T* sycl::malloc_host(size_t count, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `context`.
`void* sycl::aligned_alloc_host(size_t alignment, size_t numBytes, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory. This allocation is specified in bytes and aligned according to `alignment`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if no device in `syclContext` has `aspect::usm_host_allocations`.
`template <typename T> T* sycl::aligned_alloc_host(size_t alignment, size_t count, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory. This allocation is specified in elements of type `T` and aligned according to `alignment`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if no device in `syclContext` has `aspect::usm_host_allocations`.
`void* sycl::aligned_alloc_host(size_t alignment, size_t numBytes, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `context`.

Function	Description

`template <typename T>`
`void* sycl::aligned_alloc_host(size_t alignment, size_t count,`
`const queue& syclQueue,`
`const property_list& propList = {})`
	Simplified form where `syclQueue` provides the `context`.

4.8.3.4. Shared allocation functions

The functions in Table 105 allocate shared USM. On success, these functions return a pointer to the newly allocated memory, which must eventually be deallocated with `sycl::free` in order to avoid a memory leak. If there are not enough resources to allocate the requested memory, these functions return `nullptr`.

Table 105. Shared USM Allocation Functions

Function	Description

`void* sycl::malloc_shared(size_t numBytes, const device& syclDevice,`
`const context& syclContext,`
`const property_list& propList = {})`
	Returns a pointer to the newly allocated memory, which is associated with `syclDevice`. This allocation is specified in bytes. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if the `syclDevice` does not have `aspect::usm_shared_allocations`. The `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.

`template <typename T>`
`T* sycl::malloc_shared(size_t count, const device& syclDevice,`
`const context& syclContext,`
`const property_list& propList = {})`
	Returns a pointer to the newly allocated memory, which is associated with `syclDevice`. This allocation is specified in number of elements of type `T`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if the `syclDevice` does not have `aspect::usm_shared_allocations`. The `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.

Function	Description
`void* sycl::malloc_shared(size_t numBytes, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `device` and `context`.
`template <typename T> T* sycl::malloc_shared(size_t count, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `device` and `context`.
`void* sycl::aligned_alloc_shared(size_t alignment, size_t numBytes, const device& syclDevice, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory, which is associated with `syclDevice`. This allocation is specified in bytes and aligned according to `alignment`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if the `syclDevice` does not have `aspect::usm_shared_allocations`. The `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.
`template <typename T> T* sycl::aligned_alloc_shared(size_t alignment, size_t count, const device& syclDevice, const context& syclContext, const property_list& propList = {})`	Returns a pointer to the newly allocated memory, which is associated with `syclDevice`. This allocation is specified in number of elements of type `T` and aligned aligned according to `alignment`. Throws a synchronous `exception` with the `errc::feature_not_supported` error code if the `syclDevice` does not have `aspect::usm_shared_allocations`. The `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.
`void* sycl::aligned_alloc_shared(size_t alignment, size_t numBytes, const queue& syclQueue, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `device` and `context`.

Function	Description

`template <typename T>`
`T* sycl::aligned_alloc_shared(size_t alignment, size_t count,`
`const queue& syclQueue,`
`const property_list& propList = {})`
	Simplified form where `syclQueue` provides the `device` and `context`.

4.8.3.5. Parameterized allocation functions

The functions in Table 106 take a `kind` parameter that specifies the type of USM to allocate. When `kind` is `usm::alloc::device`, then the allocation device must have `aspect::usm_device_allocations`. When `kind` is `usm::alloc::host`, at least one device in the allocation context must have `aspect::usm_host_allocations`. When `kind` is `usm::alloc::shared`, the allocation device must have `aspect::usm_shared_allocations`. If these requirements are violated, the allocation function throws a synchronous `exception` with the `errc::feature_not_supported` error code.

On success, these functions return a pointer to the newly allocated memory, which must eventually be deallocated with `sycl::free` in order to avoid a memory leak. If there are not enough resources to allocate the requested memory, these functions return `nullptr`.

Table 106. Parameterized USM Allocation Functions

Function	Description

`void* sycl::malloc(size_t numBytes, const device& syclDevice,`
`const context& syclContext, usm::alloc kind,`
`const property_list& propList = {})`
	Returns a pointer to the newly allocated memory of type `kind`. This allocation size is specified in bytes. The `syclDevice` parameter is ignored if `kind` is `usm::alloc::host`. If `kind` is not `usm::alloc::host`, `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.

`template <typename T>`
`T* sycl::malloc(size_t count, const device& syclDevice,`
`const context& syclContext, usm::alloc kind,`
`const property_list& propList = {})`
	Returns a pointer to the newly allocated memory of type `kind`. This allocation size is specified in number of elements of type `T`. The `syclDevice` parameter is ignored if `kind` is `usm::alloc::host`. If `kind` is not `usm::alloc::host`, `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.

Function	Description
`void* sycl::malloc(size_t numBytes, const queue& syclQueue, usm::alloc kind, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `context` and any necessary `device`.
`template <typename T> T* sycl::malloc(size_t count, const queue& syclQueue, usm::alloc kind, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `context` and any necessary `device`.
`void* sycl::aligned_alloc(size_t alignment, size_t numBytes, const device& syclDevice, const context& syclContext, usm::alloc kind, const property_list& propList = {})`	Returns a pointer to the newly allocated memory of type `kind`. This allocation is specified in bytes and is aligned according to `alignment`. The `syclDevice` parameter is ignored if `kind` is `usm::alloc::host`. If `kind` is not `usm::alloc::host`, `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.
`template <typename T> T* sycl::aligned_alloc(size_t alignment, size_t count, const device& syclDevice, const context& syclContext, usm::alloc kind, const property_list& propList = {})`	Returns a pointer to the newly allocated memory of type `kind`. This allocation is specified in number of elements of type `T` and is aligned according to `alignment`. The `syclDevice` parameter is ignored if `kind` is `usm::alloc::host`. If `kind` is not `usm::alloc::host`, `syclDevice` must either be contained by `syclContext` or it must be a descendent device of some device that is contained by that context, otherwise this function throws a synchronous `exception` with the `errc::invalid` error code.
`void* sycl::aligned_alloc(size_t alignment, size_t numBytes, const queue& syclQueue, usm::alloc kind, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `context` and any necessary `device`.

Function	Description
`template <typename T> T* sycl::aligned_alloc(size_t alignment, size_t count, const queue& syclQueue, usm::alloc kind, const property_list& propList = {})`	Simplified form where `syclQueue` provides the `context` and any necessary `device`.

4.8.3.6. Memory deallocation functions

Table 107. USM Deallocation Functions

Function	Description
`void sycl::free(void* ptr, const context& syclContext)`	Frees an allocation. The memory pointed to by `ptr` must have been allocated using one of the USM allocation routines. `syclContext` must be the same `context` that was used to allocate the memory. The memory is freed without waiting for commands operating on it to be completed. If commands that use this memory are in-progress or are enqueued the behavior is undefined.
`void sycl::free(void* ptr, const queue& syclQueue)`	Alternate form where `syclQueue` provides the `context`.

4.8.4. Unified shared memory pointer queries

Since USM pointers look like raw C++ pointers, users cannot deduce what kind of USM allocation a given pointer may be from examining its type. However, two functions are defined that let users query the type of a USM allocation and, if applicable, the `device` on which it was allocated. These query functions are only supported on the host.

Table 108. USM Pointer Query Functions

Function	Description
`usm::alloc get_pointer_type(const void* ptr, const context& syclContext)`	Returns the USM allocation type for `ptr` if `ptr` falls inside a valid USM allocation for the context `syclContext`. Returns `usm::alloc::unknown` if `ptr` does not point within a valid USM allocation from `syclContext`.

Function	Description
`device get_pointer_device(const void* ptr, const context& syclContext)`	Returns the `device` associated with the USM allocation. If `ptr` points within a device USM allocation or a shared USM allocation for the context `syclContext`, returns the same device that was passed when allocating the memory. If `ptr` points within a host USM allocation for the context `syclContext`, returns the first device in `syclContext`. Throws a synchronous `exception` with the `errc::invalid` error code if `ptr` does not point within a valid USM allocation from `syclContext`.

4.9. Expressing parallelism through kernels

4.9.1. Ranges and index space identifiers

The data parallelism of the SYCL kernel execution model requires instantiation of a parallel execution over a range of iteration space coordinates. To achieve this, SYCL exposes types to define the range of execution and to identify a given execution instance's point in the iteration space.

The following types are defined: `range`, `nd_range`, `id`, `item`, `h_item`, `nd_item` and `group`.

When constructing multi-dimensional ids or ranges from integers, the elements are written such that the right-most element varies fastest in a linearization of the multi-dimensional space (see Section 3.11.1).

Table 109. Summary of types used to identify points in an index space, and ranges over which those points can vary

Type	Description
`id`	A point within a range
`range`	Bounds over which an `id` may vary
`item`	Pairing of an `id` (specific point) and the `range` that it is bounded by
`nd_range`	Encapsulates both global and local (work-group size) `ranges` over which work-item `ids` will vary
`nd_item`	Encapsulates two `items`, one for global `id` and `range`, and one for local `id` and `range`
`h_item`	Index point queries within hierarchical parallelism (`parallel_for_work_item`). Encapsulates physical global and local `ids` and `ranges`, as well as a logical local `id` and `range` defined by hierarchical parallelism

Type	Description
group	Work-group queries within hierarchical parallelism (parallel_for_work_group), and exposes the parallel_for_work_item construct that identifies code to be executed by each work-item. Encapsulates work-group ids and ranges

4.9.1.1. range class

range<int Dimensions> is a 1D, 2D or 3D vector that defines the iteration domain of either a single work-group in a parallel dispatch, or the overall Dimensions of the dispatch. It can be constructed from integers.

The SYCL range class template provides the common by-value semantics (see Section 4.5.3).

A synopsis of the SYCL range class is provided below. The constructors, member functions and non-member functions of the SYCL range class are listed in Table 110, Table 111 and Table 112 respectively. The additional common special member functions and common member functions are listed in Section 4.5.3 in Table 9 and Table 10 respectively.

```
namespace sycl {
template <int Dimensions = 1> class range {
 public:
  static constexpr int dimensions = Dimensions;

  /* The following constructor is only available in the range class
   * specialization where: Dimensions==1 */
  range(size_t dim0);
  /* The following constructor is only available in the range class
   * specialization where: Dimensions==2 */
  range(size_t dim0, size_t dim1);
  /* The following constructor is only available in the range class
   * specialization where: Dimensions==3 */
  range(size_t dim0, size_t dim1, size_t dim2);

  /* -- common interface members -- */

  size_t get(int dimension) const;
  size_t& operator[](int dimension);
  size_t operator[](int dimension) const;

  size_t size() const;

  // OP is: +, -, *, /, %, <<, >>, &, |, ^, &&, ||, <, >, <=, >=
  friend range operatorOP(const range& lhs, const range& rhs) { /* ... */
  }
  friend range operatorOP(const range& lhs, const size_t& rhs) { /* ... */
  }

  // OP is: +=, -=, *=, /=, %=, <<=, >>=, &=, |=, ^=
  friend range& operatorOP(range& lhs, const range& rhs) { /* ... */
  }
  friend range& operatorOP(range& lhs, const size_t& rhs) { /* ... */
```

```
  }

  // OP is: +, -, *, /, %, <<, >>, &, |, ^, &&, ||, <, >, <=, >=
  friend range operatorOP(const size_t& lhs, const range& rhs) { /* ... */
  }

  // OP is unary +, -
  friend range operatorOP(const range& rhs) { /* ... */
  }

  // OP is prefix ++, --
  friend range& operatorOP(range& rhs) { /* ... */
  }

  // OP is postfix ++, --
  friend range operatorOP(range& lhs, int) { /* ... */
  }
};

// Deduction guides
range(size_t)->range<1>;
range(size_t, size_t)->range<2>;
range(size_t, size_t, size_t)->range<3>;

} // namespace sycl
```

Table 110. Constructors of the range class template

Constructor	Description
`range(size_t dim0)`	Construct a 1D range with value dim0. Only valid when the template parameter Dimensions is equal to 1.
`range(size_t dim0, size_t dim1)`	Construct a 2D range with values dim0 and dim1. Only valid when the template parameter Dimensions is equal to 2.
`range(size_t dim0, size_t dim1, size_t dim2)`	Construct a 3D range with values dim0, dim1 and dim2. Only valid when the template parameter Dimensions is equal to 3.

Table 111. Member functions of the range class template

Member function	Description
`size_t get(int dimension) const`	Return the value of the specified dimension of the range.
`size_t& operator[](int dimension)`	Return the l-value of the specified dimension of the range.
`size_t operator[](int dimension) const`	Return the value of the specified dimension of the range.

Member function	Description
`size_t size() const`	Return the size of the range computed as dimension0*...*dimensionN.

Table 112. Hidden friend functions of the SYCL range class template

Hidden friend function	Description
`range operatorOP(const range& lhs, const range& rhs)`	Where OP is: +, -, *, /, %, <<, >>, &, |, ^, &&, ||, <, >, <=, >=. Constructs and returns a new instance of the SYCL range class template with the same dimensionality as lhs range, where each element of the new SYCL range instance is the result of an element-wise OP operator between each element of lhs range and each element of the rhs range. If the operator returns a bool, the result is the cast to size_t.
`range operatorOP(const range& lhs, const size_t& rhs)`	Where OP is: +, -, *, /, %, <<, >>, &, |, ^, &&, ||, <, >, <=, >=. Constructs and returns a new instance of the SYCL range class template with the same dimensionality as lhs range, where each element of the new SYCL range instance is the result of an element-wise OP operator between each element of this SYCL range and the rhs size_t. If the operator returns a bool, the result is the cast to size_t.
`range& operatorOP(range& lhs, const range& rhs)`	Where OP is: +=, -=,*=, /=, %=, <<=, >>=, &=, |=, ^=. Assigns each element of lhs range instance with the result of an element-wise OP operator between each element of lhs range and each element of the rhs range and returns lhs range. If the operator returns a bool, the result is the cast to size_t.

Hidden friend function	Description
`range& operatorOP(range& lhs, const size_t& rhs)`	Where OP is: +=, -=,*=, /=, %=, <<=, >>=, &=, |=, ^=. Assigns each element of lhs range instance with the result of an element-wise OP operator between each element of lhs range and the rhs size_t and returns lhs range. If the operator returns a bool, the result is the cast to size_t.
`range operatorOP(const size_t& lhs, const range& rhs)`	Where OP is: +, -, *, /, %, <<, >>, &, |, ^, &&, ||, <, >, <=, >=. Constructs and returns a new instance of the SYCL range class template with the same dimensionality as the rhs SYCL range, where each element of the new SYCL range instance is the result of an element-wise OP operator between the lhs size_t and each element of the rhs SYCL range. If the operator returns a bool, the result is the cast to size_t.
`range operatorOP(const range& rhs)`	Where OP is: unary +, unary -. Constructs and returns a new instance of the SYCL range class template with the same dimensionality as the rhs SYCL range, where each element of the new SYCL range instance is the result of an element-wise OP operator on the rhs SYCL range.
`range& operatorOP(range& rhs)`	Where OP is: prefix ++, prefix --. Assigns each element of the rhs range instance with the result of an element-wise OP operator on each element of the rhs range and returns this range.
`range operatorOP(range& lhs, int)`	Where OP is: postfix ++, postfix --. Make a copy of the lhs range. Assigns each element of the lhs range instance with the result of an element-wise OP operator on each element of the lhs range. Then return the initial copy of the range.

4.9.1.2. nd_range class

```
1 namespace sycl {
```

```
template <int Dimensions = 1> class nd_range {
 public:
  static constexpr int dimensions = Dimensions;

  /* -- common interface members -- */

  // The offset is deprecated in SYCL 2020.
  nd_range(range<Dimensions> globalSize, range<Dimensions> localSize,
           id<Dimensions> offset = id<Dimensions>());

  range<Dimensions> get_global_range() const;
  range<Dimensions> get_local_range() const;
  range<Dimensions> get_group_range() const;
  id<Dimensions> get_offset() const; // Deprecated in SYCL 2020.
};
} // namespace sycl
```

nd_range<int Dimensions> defines the iteration domain of both the work-groups and the overall dispatch. To define this the nd_range comprises two ranges: the whole range over which the kernel is to be executed, and the range of each work group.

The SYCL nd_range class template provides the common by-value semantics (see Section 4.5.3).

A synopsis of the SYCL nd_range class is provided below. The constructors and member functions of the SYCL nd_range class are listed in Table 113 and Table 114 respectively. The additional common special member functions and common member functions are listed in Section 4.5.3 in Table 9 and Table 10 respectively.

Table 113. Constructors of the nd_range class

Constructor	Description
`nd_range<Dimensions>( range<Dimensions> globalSize, range<Dimensions> localSize) id<Dimensions> offset = id<Dimensions>())`	Construct an nd_range from the local and global constituent ranges. Supplying the option offset is deprecated in SYCL 2020. If the offset is not provided it will default to no offset.

Table 114. Member functions for the nd_range class

Member function	Description
`range<Dimensions> get_global_range() const`	Return the constituent global range.
`range<Dimensions> get_local_range() const`	Return the constituent local range.
`range<Dimensions> get_group_range() const`	Return a range representing the number of groups in each dimension. This range would result from globalSize/localSize as provided on construction.
`id<Dimensions> get_offset() const // Deprecated in SYCL 2020.`	Deprecated in SYCL 2020. Return the constituent offset.

4.9.1.3. id class

id<int Dimensions> is a vector of Dimensions that is used to represent an id into a global or local range. It can be used as an index in an accessor of the same rank. The subscript operator (operator[](n)) returns the component n as a size_t.

The SYCL id class template provides the common by-value semantics (see Section 4.5.3).

A synopsis of the SYCL id class is provided below. The constructors, member functions and non-member functions of the SYCL id class are listed in Table 115, Table 116 and Table 117 respectively. The additional common special member functions and common member functions are listed in Section 4.5.3 in Table 9 and Table 10 respectively.

```
namespace sycl {
template <int Dimensions = 1> class id {
 public:
  static constexpr int dimensions = Dimensions;

  id();

  /* The following constructor is only available in the id class
   * specialization where: Dimensions==1 */
  id(size_t dim0);
  /* The following constructor is only available in the id class
   * specialization where: Dimensions==2 */
  id(size_t dim0, size_t dim1);
  /* The following constructor is only available in the id class
   * specialization where: Dimensions==3 */
  id(size_t dim0, size_t dim1, size_t dim2);

  /* -- common interface members -- */

  id(const range<Dimensions>& range);
  id(const item<Dimensions>& item);

  size_t get(int dimension) const;
  size_t& operator[](int dimension);
  size_t operator[](int dimension) const;

  // only available if Dimensions == 1
  operator size_t() const;

  // OP is: +, -, *, /, %, <<, >>, &, |, ^, &&, ||, <, >, <=, >=
  friend id operatorOP(const id& lhs, const id& rhs) { /* ... */
  }
  friend id operatorOP(const id& lhs, const size_t& rhs) { /* ... */
  }

  // OP is: +=, -=, *=, /=, %=, <<=, >>=, &=, |=, ^=
  friend id& operatorOP(id& lhs, const id& rhs) { /* ... */
  }
  friend id& operatorOP(id& lhs, const size_t& rhs) { /* ... */
  }

  // OP is: +, -, *, /, %, <<, >>, &, |, ^, &&, ||, <, >, <=, >=
  friend id operatorOP(const size_t& lhs, const id& rhs) { /* ... */
```

```
  }

  // OP is unary +, -
  friend id operatorOP(const id& rhs) { /* ... */
  }

  // OP is prefix ++, --
  friend id& operatorOP(id& rhs) { /* ... */
  }

  // OP is postfix ++, --
  friend id operatorOP(id& lhs, int) { /* ... */
  }
};

// Deduction guides
id(size_t)->id<1>;
id(size_t, size_t)->id<2>;
id(size_t, size_t, size_t)->id<3>;

} // namespace sycl
```

Table 115. Constructors of the id class template

Constructor	Description
`id()`	Construct a SYCL `id` with the value `0` for each dimension.
`id(size_t dim0)`	Construct a 1D `id` with value dim0. Only valid when the template parameter `Dimensions` is equal to 1.
`id(size_t dim0, size_t dim1)`	Construct a 2D `id` with values dim0, dim1. Only valid when the template parameter `Dimensions` is equal to 2.
`id(size_t dim0, size_t dim1, size_t dim2)`	Construct a 3D `id` with values dim0, dim1, dim2. Only valid when the template parameter `Dimensions` is equal to 3.
`id(const range<Dimensions>& range)`	Construct an `id` from the dimensions of `range`.
`id(const item<Dimensions>& item)`	Construct an `id` from `item.get_id()`.

Table 116. Member functions of the id class template

Member function	Description
`size_t get(int dimension) const`	Return the value of the `id` for dimension `Dimension`.
`size_t& operator[](int dimension)`	Return a reference to the requested dimension of the `id` object.

Member function	Description
`size_t operator[](int dimension) const`	Return the value of the requested dimension of the `id` object.
`operator size_t() const`	Available only when: `Dimensions == 1` Returns the same value as `get(0)`.

Table 117. Hidden friend functions of the `id` class template

Hidden friend function	Description
`id operatorOP(const id& lhs, const id& rhs)`	Where `OP` is: `+`, `-`, `*`, `/`, `%`, `<<`, `>>`, `&`, `|`, `^`, `&&`, `||`, `<`, `>`, `<=`, `>=`. Constructs and returns a new instance of the SYCL `id` class template with the same dimensionality as `lhs id`, where each element of the new SYCL `id` instance is the result of an element-wise `OP` operator between each element of `lhs id` and each element of the `rhs id`. If the operator returns a `bool` the result is the cast to `size_t`.
`id operatorOP(const id& lhs, const size_t& rhs)`	Where `OP` is: `+`, `-`, `*`, `/`, `%`, `<<`, `>>`, `&`, `|`, `^`, `&&`, `||`, `<`, `>`, `<=`, `>=`. Constructs and returns a new instance of the SYCL `id` class template with the same dimensionality as `lhs id`, where each element of the new SYCL `id` instance is the result of an element-wise `OP` operator between each element of `lhs id` and the `rhs size_t`. If the operator returns a `bool` the result is the cast to `size_t`.
`id& operatorOP(id& lhs, const id& rhs)`	Where `OP` is: `+=`, `-=`,`*=`, `/=`, `%=`, `<<=`, `>>=`, `&=`, `|=`, `^=`. Assigns each element of `lhs id` instance with the result of an element-wise `OP` operator between each element of `lhs id` and each element of the `rhs id` and returns `lhs id`. If the operator returns a `bool` the result is the cast to `size_t`.

Hidden friend function	Description
`id& operatorOP(id& lhs, const size_t& rhs)`	Where OP is: +=, -=,*=, /=, %=, <<=, >>=, &=, |=, ^=. Assigns each element of lhs id instance with the result of an element-wise OP operator between each element of lhs id and the rhs size_t and returns lhs id. If the operator returns a bool the result is the cast to size_t.
`id operatorOP(const size_t& lhs, const id& rhs)`	Where OP is: +, -, *, /, %, <<, >>, &, |, ^, &&, ||, <, >, <=, >=. Constructs and returns a new instance of the SYCL id class template with the same dimensionality as the rhs SYCL id, where each element of the new SYCL id instance is the result of an element-wise OP operator between the lhs size_t and each element of the rhs SYCL id. If the operator returns a bool the result is the cast to size_t.
`id operatorOP(const id& rhs)`	Where OP is: unary +, unary -. Constructs and returns a new instance of the SYCL id class template with the same dimensionality as the rhs SYCL id, where each element of the new SYCL id instance is the result of an element-wise OP operator on the rhs SYCL id.
`id& operatorOP(id& rhs)`	Where OP is: prefix ++, prefix --. Assigns each element of the rhs id instance with the result of an element-wise OP operator on each element of the rhs id and returns this id.
`id operatorOP(id& lhs, int)`	Where OP is: postfix ++, postfix --. Make a copy of the lhs id. Assigns each element of the lhs id instance with the result of an element-wise OP operator on each element of the lhs id. Then return the initial copy of the id.

4.9.1.4. item class

item identifies an instance of the function object executing at each point in a range. It is passed to a parallel_for call or returned by member functions of h_item. It encapsulates enough information to identify the work-item's range of possible values and its ID in that range. It can optionally carry the offset of the

range if provided to the parallel_for; note this is deprecated in SYCL 2020. Instances of the item class are not user-constructible and are passed by the runtime to each instance of the function object.

The SYCL item class template provides the common by-value semantics (see Section 4.5.3).

A synopsis of the SYCL item class is provided below. The member functions of the SYCL item class are listed in Table 116. The additional common special member functions and common member functions are listed in Section 4.5.3 in Table 9 and Table 10 respectively.

```
namespace sycl {
template <int Dimensions = 1, bool WithOffset = true> class item {
 public:
  static constexpr int dimensions = Dimensions;

  item() = delete;

  /* -- common interface members -- */

  id<Dimensions> get_id() const;

  size_t get_id(int dimension) const;

  size_t operator[](int dimension) const;

  range<Dimensions> get_range() const;

  size_t get_range(int dimension) const;

  // Deprecated in SYCL 2020.
  // only available if WithOffset is true
  id<Dimensions> get_offset() const;

  // only available if WithOffset is false
  operator item<Dimensions, true>() const;

  // only available if Dimensions == 1
  operator size_t() const;

  size_t get_linear_id() const;
};
} // namespace sycl
```

Table 118. Member functions for the item class

Member function	Description
`id<Dimensions> get_id() const`	Return the constituent id representing the work-item's position in the iteration space.
`size_t get_id(int dimension) const`	Return the same value as `get_id()[dimension]`.
`size_t operator[](int dimension) const`	Return the same value as `get_id(dimension)`.

Member function	Description
`range<Dimensions> get_range() const`	Returns a `range` representing the dimensions of the range of possible values of the `item`.
`size_t get_range(int dimension) const`	Return the same value as `get_range().get(dimension)`.
`id<Dimensions> get_offset() const` `// Deprecated in SYCL 2020.`	Deprecated in SYCL 2020. Returns an `id` representing the *n*-dimensional offset provided to the `parallel_for` and that is added by the runtime to the global-ID of each work-item, if this item represents a global range. For an item converted from an item with no offset this will always return an `id` of all 0 values. This member function is only available if `with_offset` is `true`.
`operator item<Dimensions, true>() const`	Available only when: `with_offset == false` Returns an `item` representing the same information as the object holds but also includes the offset set to 0. This conversion allow users to seamlessly write code that assumes an offset and still provides an offset-less `item`.
`operator size_t() const`	Available only when: `Dimensions == 1` Returns the same value as `get_id(0)`.
`size_t get_linear_id() const`	Return the id as a linear index value. Calculating a linear address from the multi-dimensional index follows Section 3.11.1.

4.9.1.5. nd_item class

`nd_item<int Dimensions>` identifies an instance of the function object executing at each point in an `nd_range<int Dimensions>` passed to a `parallel_for` call. It encapsulates enough information to identify the work-item's local and global ids, the work-group id and also provides access to the `group` and `sub_group` classes. Instances of the `nd_item<int Dimensions>` class are not user-constructible and are passed by the runtime to each instance of the function object.

The SYCL `nd_item` class template provides the common by-value semantics (see Section 4.5.3).

A synopsis of the SYCL `nd_item` class is provided below. The member functions of the SYCL `nd_item` class are listed in Table 119. The additional common special member functions and common member functions are listed in Section 4.5.3 in Table 9 and Table 10 respectively.

% interface for nd_item class

```
namespace sycl {
template <int Dimensions = 1> class nd_item {
 public:
  static constexpr int dimensions = Dimensions;

  nd_item() = delete;

  /* -- common interface members -- */

  id<Dimensions> get_global_id() const;

  size_t get_global_id(int dimension) const;

  size_t get_global_linear_id() const;

  id<Dimensions> get_local_id() const;

  size_t get_local_id(int dimension) const;

  size_t get_local_linear_id() const;

  group<Dimensions> get_group() const;

  sub_group get_sub_group() const;

  size_t get_group(int dimension) const;

  size_t get_group_linear_id() const;

  range<Dimensions> get_group_range() const;

  size_t get_group_range(int dimension) const;

  range<Dimensions> get_global_range() const;

  size_t get_global_range(int dimension) const;

  range<Dimensions> get_local_range() const;

  size_t get_local_range(int dimension) const;

  // Deprecated in SYCL 2020.
  id<Dimensions> get_offset() const;

  nd_range<Dimensions> get_nd_range() const;

  template <typename DataT>
  device_event async_work_group_copy(decorated_local_ptr<DataT> dest,
                                     decorated_global_ptr<DataT> src,
                                     size_t numElements) const;

  template <typename DataT>
  device_event async_work_group_copy(decorated_global_ptr<DataT> dest,
                                     decorated_local_ptr<DataT> src,
                                     size_t numElements) const;
```

```
56
57   template <typename DataT>
58   device_event async_work_group_copy(decorated_local_ptr<DataT> dest,
59                                      decorated_global_ptr<DataT> src,
60                                      size_t numElements,
61                                      size_t srcStride) const;
62
63   template <typename DataT>
64   device_event async_work_group_copy(decorated_global_ptr<DataT> dest,
65                                      decorated_local_ptr<DataT> src,
66                                      size_t numElements,
67                                      size_t destStride) const;
68
69   template <typename... EventTN> void wait_for(EventTN... events) const;
70 };
71 } // namespace sycl
```

Table 119. Member functions for the nd_item class

Member function	Description
`id<Dimensions> get_global_id() const`	Return the constituent global id representing the work-item's position in the global iteration space.
`size_t get_global_id(int dimension) const`	Return the constituent element of the global id representing the work-item's position in the nd-range in the given Dimension.
`size_t get_global_linear_id() const`	Return the constituent global id as a linear index value, representing the work-item's position in the global iteration space. The linear address is calculated from the multi-dimensional index by first subtracting the offset and then following Section 3.11.1.
`id<Dimensions> get_local_id() const`	Return the constituent local id representing the work-item's position within the current work-group.
`size_t get_local_id(int dimension) const`	Return the constituent element of the local id representing the work-item's position within the current work-group in the given Dimension.
`size_t get_local_linear_id() const`	Return the constituent local id as a linear index value, representing the work-item's position within the current work-group. The linear address is calculated from the multi-dimensional index following Section 3.11.1.

Member function	Description
`group<Dimensions> get_group() const`	Return the constituent work-group, `group` representing the work-group's position within the overall nd-range.
`sub_group get_sub_group() const`	Return a `sub_group` representing the sub-group to which the work-item belongs.
`size_t get_group(int dimension) const`	Return the constituent element of the group `id` representing the work-group's position within the overall `nd_range` in the given `Dimension`.
`size_t get_group_linear_id() const`	Return the group id as a linear index value. Calculating a linear address from a multi-dimensional index follows Section 3.11.1.
`range<Dimensions> get_group_range() const`	Returns the number of work groups in the iteration space.
`size_t get_group_range(int dimension) const`	Return the number of work groups for `Dimension` in the iteration space.
`range<Dimensions> get_global_range() const`	Returns a `range` representing the dimensions of the global iteration space.
`size_t get_global_range(int dimension) const`	Return the same value as `get_global_range().get(dimension)`.
`range<Dimensions> get_local_range() const`	Returns a `range` representing the dimensions of the current work-group.
`size_t get_local_range(int dimension) const`	Return the same value as `get_local_range().get(dimension)`.
`id<Dimensions> get_offset() const` `// Deprecated in SYCL 2020.`	Deprecated in SYCL 2020. Returns an `id` representing the n-dimensional offset provided to the constructor of the `nd_range` and that is added by the runtime to the global id of each work-item.
`nd_range<Dimensions> get_nd_range() const`	Returns the `nd_range` of the current execution.

Member function	Description
`template <typename DataT> device_event async_work_group_copy(decorated_local_ptr <DataT> dest, decorated_global_ptr <DataT> src, size_t numElements) const`	Permitted types for DataT are all scalar and vector types. Asynchronously copies a number of elements specified by numElements from the source pointer src to destination pointer dest and returns a SYCL device_event which can be used to wait on the completion of the copy.
`template <typename DataT> device_event async_work_group_copy(decorated_global_ptr <DataT> dest, decorated_local_ptr <DataT> src, size_t numElements) const`	Permitted types for DataT are all scalar and vector types. Asynchronously copies a number of elements specified by numElements from the source pointer src to destination pointer dest and returns a SYCL device_event which can be used to wait on the completion of the copy.
`template <typename DataT> device_event async_work_group_copy(decorated_local_ptr <DataT> dest, decorated_global_ptr <DataT> src, size_t numElements, size_t srcStride) const`	Permitted types for DataT are all scalar and vector types. Asynchronously copies a number of elements specified by numElements from the source pointer src to destination pointer dest with a source stride specified by srcStride and returns a SYCL device_event which can be used to wait on the completion of the copy.
`template <typename DataT> device_event async_work_group_copy(decorated_global_ptr <DataT> dest, decorated_local_ptr <DataT> src, size_t numElements, size_t destStride) const`	Permitted types for DataT are all scalar and vector types. Asynchronously copies a number of elements specified by numElements from the source pointer src to destination pointer dest with a destination stride specified by deststride and returns a SYCL device_event which can be used to wait on the completion of the copy.
`template <typename... EventTN> void wait_for(EventTN... events) const`	Permitted type for EventTN is device_event. Waits for the asynchronous operations associated with each device_event to complete.

4.9.1.6. h_item class

h_item<int Dimensions> identifies an instance of a group::parallel_for_work_item function object executing at each point in a local range<int Dimensions> passed to a parallel_for_work_item call or to the corresponding parallel_for_work_group call if no range is passed to the parallel_for_work_item call. It encapsulates enough information to identify the work-item's local and global items according to the information given to parallel_for_work_group (physical ids) as well as the work-item's logical local items in the logical local range. All returned items objects are offset-less. Instances of the h_item<int Dimensions> class are

not user-constructible and are passed by the runtime to each instance of the function object.

The SYCL h_item class template provides the common by-value semantics (see Section 4.5.3).

A synopsis of the SYCL h_item class is provided below. The member functions of the SYCL h_item class are listed in Table 120. The additional common special member functions and common member functions are listed in Section 4.5.3 in Table 9 and Table 10 respectively.

```
namespace sycl {
template <int Dimensions> class h_item {
 public:
  static constexpr int dimensions = Dimensions;

  h_item() = delete;

  /* -- common interface members -- */

  item<Dimensions, false> get_global() const;

  item<Dimensions, false> get_local() const;

  item<Dimensions, false> get_logical_local() const;

  item<Dimensions, false> get_physical_local() const;

  range<Dimensions> get_global_range() const;

  size_t get_global_range(int dimension) const;

  id<Dimensions> get_global_id() const;

  size_t get_global_id(int dimension) const;

  range<Dimensions> get_local_range() const;

  size_t get_local_range(int dimension) const;

  id<Dimensions> get_local_id() const;

  size_t get_local_id(int dimension) const;

  range<Dimensions> get_logical_local_range() const;

  size_t get_logical_local_range(int dimension) const;

  id<Dimensions> get_logical_local_id() const;

  size_t get_logical_local_id(int dimension) const;

  range<Dimensions> get_physical_local_range() const;

  size_t get_physical_local_range(int dimension) const;

  id<Dimensions> get_physical_local_id() const;

  size_t get_physical_local_id(int dimension) const;
```

```
49 };
50 } // namespace sycl
```

Table 120. Member functions for the h_item class

Member function	Description
`item<Dimensions, false> get_global() const`	Return the constituent global item representing the work-item's position in the global iteration space as provided upon kernel invocation.
`item<Dimensions, false> get_local() const`	Return the same value as `get_logical_local()`.
`item<Dimensions, false> get_logical_local() const`	Return the constituent element of the logical local item work-item's position in the local iteration space as provided upon the invocation of the `group::parallel_for_work_item`. If the `group::parallel_for_work_item` was called without any logical local range then the member function returns the physical local item. A physical id can be computed from a logical id by getting the remainder of the integer division of the logical id and the physical range: `get_logical_local().get() % get_physical_local.get_range() == get_physical_local().get()`.
`item<Dimensions, false> get_physical_local() const`	Return the constituent element of the physical local item work-item's position in the local iteration space as provided (by the user or the runtime) upon the kernel invocation.
`range<Dimensions> get_global_range() const`	Return the same value as `get_global().get_range()`
`size_t get_global_range(int dimension) const`	Return the same value as `get_global().get_range(dimension)`
`id<Dimensions> get_global_id() const`	Return the same value as `get_global().get_id()`
`size_t get_global_id(int dimension) const`	Return the same value as `get_global().get_id(dimension)`
`range<Dimensions> get_local_range() const`	Return the same value as `get_local().get_range()`

Member function	Description
`size_t get_local_range(int dimension) const`	Return the same value as `get_local().get_range(dimension)`
`id<Dimensions> get_local_id() const`	Return the same value as `get_local().get_id()`
`size_t get_local_id(int dimension) const`	Return the same value as `get_local().get_id(dimension)`
`range<Dimensions> get_logical_local_range() const`	Return the same value as `get_logical_local().get_range()`
`size_t get_logical_local_range(int dimension) const`	Return the same value as `get_logical_local().get_range(dimension)`
`id<Dimensions> get_logical_local_id() const`	Return the same value as `get_logical_local().get_id()`
`size_t get_logical_local_id(int dimension) const`	Return the same value as `get_logical_local().get_id(dimension)`
`range<Dimensions> get_physical_local_range() const`	Return the same value as `get_physical_local().get_range()`
`size_t get_physical_local_range(int dimension) const`	Return the same value as `get_physical_local().get_range(dimension)`
`id<Dimensions> get_physical_local_id() const`	Return the same value as `get_physical_local().get_id()`
`size_t get_physical_local_id(int dimension) const`	Return the same value as `get_physical_local().get_id(dimension)`

4.9.1.7. `group` class

The `group<int Dimensions>` encapsulates all functionality required to represent a particular work-group within a parallel execution. It is not user-constructible.

The local range stored in the group class is provided either by the programmer, when it is passed as an optional parameter to `parallel_for_work_group`, or by the runtime system when it selects the optimal work-group size. This allows the developer to always know how many work-items are in each executing work-group, even through the abstracted iteration range of the `parallel_for_work_item` loops.

The SYCL `group` class template provides the common by-value semantics (see Section 4.5.3).

A synopsis of the SYCL `group` class is provided below. The member functions of the SYCL `group` class are listed in Table 121. The additional common special member functions and common member functions are listed in Section 4.5.3 in Table 9 and Table 10 respectively.

```
1 namespace sycl {
2 template <int Dimensions = 1> class group {
3  public:
4   using id_type = id<Dimensions>;
5   using range_type = range<Dimensions>;
6   using linear_id_type = size_t;
```

```
  static constexpr int dimensions = Dimensions;
  static constexpr memory_scope fence_scope = memory_scope::work_group;

  /* -- common interface members -- */

  id<Dimensions> get_group_id() const;

  size_t get_group_id(int dimension) const;

  id<Dimensions> get_local_id() const;

  size_t get_local_id(int dimension) const;

  range<Dimensions> get_local_range() const;

  size_t get_local_range(int dimension) const;

  range<Dimensions> get_group_range() const;

  size_t get_group_range(int dimension) const;

  range<Dimensions> get_max_local_range() const;

  size_t operator[](int dimension) const;

  size_t get_group_linear_id() const;

  size_t get_local_linear_id() const;

  size_t get_group_linear_range() const;

  size_t get_local_linear_range() const;

  bool leader() const;

  template <typename WorkItemFunctionT>
  void parallel_for_work_item(const WorkItemFunctionT& func) const;

  template <typename WorkItemFunctionT>
  void parallel_for_work_item(range<Dimensions> logicalRange,
                              const WorkItemFunctionT& func) const;

  template <typename DataT>
  device_event async_work_group_copy(decorated_local_ptr<DataT> dest,
                                     decorated_global_ptr<DataT> src,
                                     size_t numElements) const;

  template <typename DataT>
  device_event async_work_group_copy(decorated_global_ptr<DataT> dest,
                                     decorated_local_ptr<DataT> src,
                                     size_t numElements) const;

  template <typename DataT>
  device_event async_work_group_copy(decorated_local_ptr<DataT> dest,
                                     decorated_global_ptr<DataT> src,
                                     size_t numElements,
```

```
63                                    size_t srcStride) const;
64
65   template <typename DataT>
66   device_event async_work_group_copy(decorated_global_ptr<DataT> dest,
67                                      decorated_local_ptr<DataT> src,
68                                      size_t numElements,
69                                      size_t destStride) const;
70
71   template <typename... EventTN> void wait_for(EventTN... events) const;
72 };
73 } // namespace sycl
```

Table 121. Member functions for the group class

Member function	Description
`id<Dimensions> get_group_id() const`	Return an id representing the index of the work-group within the global nd-range for every dimension. Since the work-items in a work-group have a defined position within the global nd-range, the returned group id can be used along with the local id to uniquely identify the work-item in the global nd-range.
`size_t get_group_id(int dimension) const`	Return the same value as `get_group_id()[dimension]`.
`id<Dimensions> get_local_id() const`	Return a SYCL `id` representing the calling work-item's position within the work-group. It is undefined behavior for this member function to be invoked from within a `parallel_for_work_item` context.
`size_t get_local_id(int dimension) const`	Return the same value as `get_local_id()[dimension]`. It is undefined behavior for this member function to be invoked from within a `parallel_for_work_item` context.
`range<Dimensions> get_local_range() const`	Return a SYCL `range` representing all dimensions of the local range. This local range may have been provided by the programmer, or chosen by the SYCL runtime.
`size_t get_local_range(int dimension) const`	Return the same value as `get_local_range()[dimension]`.
`range<Dimensions> get_group_range() const`	Return a `range` representing the number of work groups in the `nd_range`.

Member function	Description
`size_t get_group_range(int dimension) const`	Return the same value as `get_group_range()[dimension]`.
`size_t operator[](int dimension) const`	Return the same value as `get_group_id(dimension)`.
`range<Dimensions> get_max_local_range() const`	Return a `range` representing the maximum number of work-items in any work-group in the `nd_range`.
`size_t get_group_linear_id() const`	Get a linearized version of the work-group id. Calculating a linear work-group id from a multi-dimensional index follows Section 3.11.1.
`size_t get_group_linear_range() const`	Return the total number of work-groups in the `nd_range`.
`size_t get_local_linear_id() const`	Get a linearized version of the calling work-item's local id. Calculating a linear local id from a multi-dimensional index follows Section 3.11.1. It is undefined behavior for this member function to be invoked from within a `parallel_for_work_item` context.
`size_t get_local_linear_range() const`	Return the total number of work-items in the work-group.
`bool leader() const`	Return true for exactly one work-item in the work-group, if the calling work-item is the leader of the work-group, and false for all other work-items in the work-group. The leader of the work-group is determined during construction of the work-group, and is invariant for the lifetime of the work-group. The leader of the work-group is guaranteed to be the work-item with a local id of 0.

Member function	Description

`template <typename WorkItemFunctionT>`
`void parallel_for_work_item(const WorkItemFunctionT& func)`
`const`
	Launch the work-items for this work-group.
	
	`func` is a function object type with a public member function `void F::operator()(h_item<Dimensions>)` representing the work-item computation.
	
	This member function can only be invoked within a `parallel_for_work_group` context. It is undefined behavior for this member function to be invoked from within the `parallel_for_work_group` form that does not define work-group size, because then the number of work-items that should execute the code is not defined. It is expected that this form of `parallel_for_work_item` is invoked within the `parallel_for_work_group` form that specifies the size of a work-group.

Member function	Description
`template <typename WorkItemFunctionT> void parallel_for_work_item(range<Dimensions> logicalRange, const WorkItemFunctionT& func) const`	Launch the work-items for this work-group using a logical local range. The function object `func` is executed as if the kernel were invoked with `logicalRange` as the local range. This new local range is emulated and may not map one-to-one with the physical range. `logicalRange` is the new local range to be used. This range can be smaller or larger than the one used to invoke the kernel. `func` is a function object type with a public member function `void F::operator()(h_item<Dimensions>)` representing the work-item computation. Note that the logical range does not need to be uniform across all work-groups in a kernel. For example the logical range may depend on a work-group varying query (e.g. `group::get_linear_id`), such that different work-groups in the same kernel invocation execute different logical range sizes. This member function can only be invoked within a `parallel_for_work_group` context.
`template <typename DataT> device_event async_work_group_copy(decorated_local_ptr <DataT> dest, decorated_global_ptr <DataT> src, size_t numElements) const`	Permitted types for `DataT` are all scalar and vector types. Asynchronously copies a number of elements specified by `numElements` from the source pointer `src` to destination pointer `dest` and returns a SYCL `device_event` which can be used to wait on the completion of the copy.
`template <typename DataT> device_event async_work_group_copy(decorated_global_ptr <DataT> dest, decorated_local_ptr <DataT> src, size_t numElements) const`	Permitted types for `DataT` are all scalar and vector types. Asynchronously copies a number of elements specified by `numElements` from the source pointer `src` to destination pointer `dest` and returns a SYCL `device_event` which can be used to wait on the completion of the copy.

Member function	Description
`template <typename DataT> device_event async_work_group_copy(decorated_local_ptr <DataT> dest, decorated_global_ptr <DataT> src, size_t numElements, size_t srcStride) const`	Permitted types for DataT are all scalar and vector types. Asynchronously copies a number of elements specified by numElements from the source pointer src to destination pointer dest with a source stride specified by srcStride and returns a SYCL device_event which can be used to wait on the completion of the copy.
`template <typename DataT> device_event async_work_group_copy(decorated_global_ptr <DataT> dest, decorated_local_ptr <DataT> src, size_t numElements, size_t destStride) const`	Permitted types for DataT are all scalar and vector types. Asynchronously copies a number of elements specified by numElements from the source pointer src to destination pointer dest with a destination stride specified by destStride and returns a SYCL device_event which can be used to wait on the completion of the copy.
`template <typename... EventTN> void wait_for(EventTN... events) const`	Permitted type for EventTN is device_event. Waits for the asynchronous operations associated with each device_event to complete.

4.9.1.8. sub_group class

The sub_group class encapsulates all functionality required to represent a particular sub-group within a parallel execution. It is not user-constructible.

The SYCL sub_group class provides the common by-value semantics (see Section 4.5.3).

A synopsis of the SYCL sub_group class is provided below. The member functions of the SYCL sub_group class are listed in Table 122. The additional common special member functions and common member functions are listed in Section 4.5.3 in Table 9 and Table 10 respectively.

```
1  namespace sycl {
2  class sub_group {
3   public:
4    using id_type = id<1>;
5    using range_type = range<1>;
6    using linear_id_type = uint32_t;
7    static constexpr int dimensions = 1;
8    static constexpr memory_scope fence_scope = memory_scope::sub_group;
9
10   /* -- common interface members -- */
11
12   id<1> get_group_id() const;
13
14   id<1> get_local_id() const;
15
16   range<1> get_local_range() const;
```

```
17
18   range<1> get_group_range() const;
19
20   range<1> get_max_local_range() const;
21
22   uint32_t get_group_linear_id() const;
23
24   uint32_t get_local_linear_id() const;
25
26   uint32_t get_group_linear_range() const;
27
28   uint32_t get_local_linear_range() const;
29
30   bool leader() const;
31 };
32 } // namespace sycl
```

Table 122. Member functions for the sub_group class

Member function	Description
`id<1> get_group_id() const`	Return an id representing the index of the sub-group within the work-group. Since the work-items that compose a sub-group are chosen in an implementation defined way, the returned sub-group id cannot be used to identify a particular work-item in the global nd-range. Rather, the returned sub-group id is merely an abstract identifier of the sub-group containing this work-item.
`id<1> get_local_id() const`	Return a SYCL `id` representing the calling work-item's position within the sub-group.
`range<1> get_local_range() const`	Return a `range` representing the size of the sub-group. This size may be less than the value returned by `get_max_local_range()`, depending on the position of the sub-group within its parent work-group and the manner in which sub-groups are constructed by the implementation.
`range<1> get_group_range() const`	Return a `range` representing the number of sub-groups in the work-group.

Member function	Description
`range<1> get_max_local_range() const`	Return a `range` representing the maximum number of work-items permitted in a sub-group for the executing kernel. This value may have been chosen by the programmer via an attribute, or chosen by the device compiler.
`uint32_t get_group_linear_id() const`	Return the same value as `get_group_id()[0]`.
`uint32_t get_group_linear_range() const`	Return the same value as `get_group_range()[0]`.
`uint32_t get_local_linear_id() const`	Return the same value as `get_local_id()[0]`.
`uint32_t get_local_linear_range() const`	Return the same value as `get_local_range()[0]`.
`bool leader() const`	Return true for exactly one work-item in the sub-group, if the calling work-item is the leader of the sub-group, and false for all other work-items in the sub-group. The leader of the sub-group is determined during construction of the sub-group, and is invariant for the lifetime of the sub-group. The leader of the sub-group is guaranteed to be the work-item with a local id of 0.

4.9.2. Reduction variables

All functionality related to reductions is captured by the `reducer` class and the `reduction` function.

The example below demonstrates how to write a reduction kernel that performs two reductions simultaneously on the same input values, computing both the sum of all values in a buffer and the maximum value in the buffer. For each reduction variable passed to `parallel_for`, a reference to a `reducer` object is passed as a parameter to the kernel function in the same order.

```
buffer<int> valuesBuf { 1024 };
{
  // Initialize buffer on the host with 0, 1, 2, 3, ..., 1023
  host_accessor a { valuesBuf };
  std::iota(a.begin(), a.end(), 0);
}

// Buffers with just 1 element to get the reduction results
int sumResult = 0;
buffer<int> sumBuf { &sumResult, 1 };
int maxResult = 0;
buffer<int> maxBuf { &maxResult, 1 };
```

```
13
14 myQueue.submit([&](handler& cgh) {
15   // Input values to reductions are standard accessors
16   auto inputValues = valuesBuf.get_access<access_mode::read>(cgh);
17
18   // Create temporary objects describing variables with reduction semantics
19   auto sumReduction = reduction(sumBuf, cgh, plus<>());
20   auto maxReduction = reduction(maxBuf, cgh, maximum<>());
21
22   // parallel_for performs two reduction operations
23   // For each reduction variable, the implementation:
24   // - Creates a corresponding reducer
25   // - Passes a reference to the reducer to the lambda as a parameter
26   cgh.parallel_for(range<1> { 1024 }, sumReduction, maxReduction,
27                    [=](id<1> idx, auto& sum, auto& max) {
28                      // plus<>() corresponds to += operator, so sum can be
29                      // updated via += or combine()
30                      sum += inputValues[idx];
31
32                      // maximum<>() has no shorthand operator, so max can only
33                      // be updated via combine()
34                      max.combine(inputValues[idx]);
35                    });
36 });
37
38 // sumBuf and maxBuf contain the reduction results once the kernel completes
39 assert(maxBuf.get_host_access()[0] == 1023 &&
40        sumBuf.get_host_access()[0] == 523776);
```

Reductions are supported for all trivially copyable types (as defined by the C++ core language). If the reduction operator is non-associative or non-commutative, the behavior of a reduction may be non-deterministic. If multiple reductions reference the same reduction variable, or a reduction variable is accessed directly during the lifetime of a reduction (e.g. via an `accessor` or USM pointer), the behavior is undefined.

Some of the overloads for the `reduction` function take an identity value and some do not. An implementation is required to compute a correct reduction even when the application does not specify an identity value. However, the implementation may be more efficient when the identity value is either provided by the application or is known by the implementation. For reductions using standard binary operators and fundamental types (e.g. `plus` and arithmetic types), an implementation can determine the correct identity value automatically in order to avoid performance penalties.

If an implementation can identify an identity value for a given combination of accumulator type and function object type, the value is defined as a member of the `known_identity` trait class. Whether this member value exists can be tested using the `has_known_identity` trait class.

```
1 template <typename BinaryOperation, typename AccumulatorT>
2 struct known_identity {
3   static constexpr AccumulatorT value;
4 };
5
6 template <typename BinaryOperation, typename AccumulatorT>
7 inline constexpr AccumulatorT known_identity_v =
8     known_identity<BinaryOperation, AccumulatorT>::value;
9
```

```
template <typename BinaryOperation, typename AccumulatorT>
struct has_known_identity {
  static constexpr bool value;
};

template <typename BinaryOperation, typename AccumulatorT>
inline constexpr bool has_known_identity_v =
    has_known_identity<BinaryOperation, AccumulatorT>::value;
```

For each of the partial specializations listed in Table 123, known_identity exists and has the value shown.

Table 123. Known identities.

Operator	Available Only When	Identity
sycl::plus	std::is_arithmetic_v<AccumulatorT> || std::is_same_v<std::remove_cv_t<AccumulatorT>, sycl::half>	AccumulatorT{}
sycl::multiplies	std::is_arithmetic_v<AccumulatorT> || std::is_same_v<std::remove_cv_t<AccumulatorT>, sycl::half>	AccumulatorT{1}
sycl::bit_and	std::is_integral_v<AccumulatorT>	~AccumulatorT{}
sycl::bit_or	std::is_integral_v<AccumulatorT>	AccumulatorT{}
sycl::bit_xor	std::is_integral_v<AccumulatorT>	AccumulatorT{}
sycl::logical_and	std::is_same_v<std::remove_cv_t<AccumulatorT>, bool>	true
sycl::logical_or	std::is_same_v<std::remove_cv_t<AccumulatorT>, bool>	false
sycl::minimum	std::is_integral_v<AccumulatorT>	std::numeric_limits<AccumulatorT>::max()
sycl::minimum	std::is_floating_point_v<AccumulatorT> || std::is_same_v<std::remove_cv_t<AccumulatorT>, sycl::half>	std::numeric_limits<AccumulatorT>::infinity()

Operator	Available Only When	Identity
`sycl::maximum`	`std::is_integral_v<AccumulatorT>`	`std::numeric_limits<AccumulatorT>::lowest()`
`sycl::maximum`	`std::is_floating_point_v<AccumulatorT> ||` `  std::is_same_v<std::remove_cv_t<AccumulatorT>, sycl::half>`	`-std::numeric_limits<AccumulatorT>::infinity()`

The reduction interface is limited to reduction variables whose size can be determined at compile-time. As such, `buffer` and USM pointer arguments are interpreted by the reduction interface as describing a single variable. A reduction operation associated with a `span` represents an array reduction. An array reduction of size *N* is functionally equivalent to specifying *N* independent scalar reductions. The combination operations performed by an array reduction are limited to the extent of a USM allocation described by a `span`, and access to elements outside of these regions results in undefined behavior.

Since a `span` is one-dimensional, there is currently no way to describe an array reduction with more than one dimension. This is expected to change in a future version of the SYCL specification, but depends on the introduction of a multi-dimensional `span`.

4.9.2.1. `reduction` interface

The `reduction` interface is used to attach reduction semantics to a variable, by specifying: the reduction variable, the reduction operator and an optional identity value associated with the operator. The overloads of the interface are described in Table 124. The return value of the `reduction` interface is an implementation-defined object of unspecified type, which is interpreted by `parallel_for` to construct an appropriate `reducer` type as detailed in Section 4.9.2.3.

An implementation may use an unspecified number of temporary variables inside of any `reducer` objects it creates. If an identity value is supplied to a reduction, an implementation will use that value to initialize any such temporary variables.

Since the number of temporary variables is unspecified, supplying an identity value different to the identity value associated with the reduction operator may lead to unexpected results.

The initial value of the reduction variable is included in the reduction operation, unless the `property::reduction::initialize_to_identity` property was specified when the `reduction` interface was invoked.

The reduction variable is updated so as to contain the result of the reduction when the kernel finishes execution.

```
template <typename BufferT, typename BinaryOperation>
__unspecified__ reduction(BufferT vars, handler& cgh, BinaryOperation combiner,
                          const property_list& propList = {});

template <typename T, typename BinaryOperation>
__unspecified__ reduction(T* var, BinaryOperation combiner,
                          const property_list& propList = {});

```

```
template <typename T, typename Extent, typename BinaryOperation>
__unspecified__ reduction(span<T, Extent> vars, BinaryOperation combiner,
                          const property_list& propList = {});

template <typename BufferT, typename BinaryOperation>
__unspecified__
reduction(BufferT vars, handler& cgh, const BufferT::value_type& identity,
          BinaryOperation combiner, const property_list& propList = {});

template <typename T, typename BinaryOperation>
__unspecified__ reduction(T* var, const T& identity, BinaryOperation combiner,
                          const property_list& propList = {});

template <typename T, typename Extent, typename BinaryOperation>
__unspecified__ reduction(span<T, Extent> vars, const T& identity,
                          BinaryOperation combiner,
                          const property_list& propList = {});
```

Table 124. Overloads of the reduction interface

Function	Description
`reduction<BufferT, BinaryOperation>(BufferT vars, handler& cgh, BinaryOperation combiner, const property_list& propList = {})`	Construct an unspecified object representing a reduction of the variable(s) described by `vars` using the combination operation specified by `combiner`. Zero or more properties can be provided via an instance of `property_list`. Throws an `exception` with the `errc::invalid` error code if the range of the `vars` buffer is not 1.
`reduction<T, BinaryOperation>(T* var, BinaryOperation combiner, const property_list& propList = {})`	Construct an unspecified object representing a reduction of the variable described by `var` using the combination operation specified by `combiner`. Zero or more properties can be provided via an instance of `property_list`.
`reduction<T, BinaryOperation>(span<T, Extent> vars, BinaryOperation combiner, const property_list& propList = {})`	Available only when `Extent != sycl::dynamic_extent`. Construct an unspecified object representing a reduction of the variable(s) described by `vars` using the combination operation specified by `combiner`. Zero or more properties can be provided via an instance of `property_list`.

Function	Description
`reduction<BufferT, BinaryOperation>(BufferT vars, handler& cgh, const BufferT ::value_type& identity, BinaryOperation combiner, const property_list& propList = {})`	Construct an unspecified object representing a reduction of the variable(s) described by `vars` using the combination operation specified by `combiner`. The value of `identity` may be used by the implementation to initialize an unspecified number of temporary accumulation variables. Zero or more properties can be provided via an instance of `property_list`. Throws an `exception` with the `errc::invalid` error code if the range of the `vars` buffer is not 1.
`reduction<T, BinaryOperation>(T* var, const T& identity, BinaryOperation combiner, const property_list& propList = {})`	Construct an unspecified object representing a reduction of the variable described by `var` using the combination operation specified by `combiner`. The value of `identity` may be used by the implementation to initialize an unspecified number of temporary accumulation variables. Zero or more properties can be provided via an instance of `property_list`.
`reduction<T, BinaryOperation>(span<T, Extent> vars, const T& identity, BinaryOperation combiner, const property_list& propList = {})`	Available only when `Extent != sycl::dynamic_extent`. Construct an unspecified object representing a reduction of the variable(s) described by `vars` using the combination operation specified by `combiner`. The value of `identity` may be used by the implementation to initialize an unspecified number of temporary accumulation variables. Zero or more properties can be provided via an instance of `property_list`.

4.9.2.2. Reduction properties

The properties that can be provided when using the `reduction` interface are described in Table 125.

Table 125. Properties supported by the `reduction` interface

Property	Description
`property::reduction::initialize_to_identity`	The `initialize_to_identity` property adds the requirement that the SYCL runtime must initialize the `reduction` variable to the identity value passed to the reduction interface, or to the identity value determined by the `known_identity` trait if no identity value was specified. If no identity value was specified and an identity value cannot be determined by the `known_identity` trait, the compiler must raise a diagnostic. When this property is set, the original value of the reduction variable is not included in the reduction.

The constructors of the reduction property classes are listed in Table 126.

Table 126. Constructors of the `reduction property` classes

Constructor	Description
`property::reduction::initialize_to_identity::initialize_to_identity()`	Constructs an `initialize_to_identity` property instance.

4.9.2.3. `reducer` class

The `reducer` class defines the interface between a work-item and a reduction variable during the execution of a SYCL kernel, restricting access to the underlying reduction variable. The intermediate values of a reduction variable cannot be inspected during kernel execution, and the variable cannot be updated using anything other than the reduction's specified combination operation. The combination order of different reducers is unspecified, as are when and how the value of each reducer is combined with the original reduction variable.

To enable compile-time specialization of reduction algorithms, the implementation of the `reducer` class is unspecified, except for the functions and operators defined in Table 128 and Table 129. As such, developers should not specify the template arguments of a `reducer` directly, and should instead employ generic programming techniques that allow kernel functions to accept a reference to a variable of any `reducer` type. Kernels written as lambdas should employ `auto&` or `auto&...`, and kernels written as function objects should employ template parameters or template parameter packs.

An implementation must guarantee that it is safe for multiple work-items in a kernel to call the combine function of a `reducer` concurrently. An implementation is free to re-use reducer variables (e.g. across work-groups scheduled to the same compute unit) if it can guarantee that it is safe to do so.

The type aliases and constant static members of the `reducer` class are listed in Table 127 and its member functions are listed in Table 128. Additional shorthand operators may be made available for certain combinations of reduction variable type and combination operation, as described in Table 129.

```
1 // Exposition only
2 template <typename T, typename BinaryOperation, int Dimensions,
3           /* unspecified */>
4 class reducer {
```

```
public:
 using value_type = T;
 using binary_operation = BinaryOperation;
 static constexpr int dimensions = Dimensions;

 reducer(const reducer&) = delete;
 reducer(reducer&&) = delete;
 reducer& operator=(const reducer&) = delete;
 reducer& operator=(reducer&&) = delete;

 ~reducer();

 /* Only available if Dimensions == 0 */
 reducer& combine(const T& partial);

 /* Only available if Dimensions > 0 */
 __unspecified__ operator[](size_t index)

     /* Only available if identity value is known */
     T identity() const;

 /* Only available if Dimensions == 0 and either
  * BinaryOperation == plus<> or BinaryOperation == plus<T> */
 friend reducer& operator+=(reducer&, const T&) { /* ... */
 }

 /* Only available if Dimensions == 0 and either
  * BinaryOperation == multiplies<> or BinaryOperation == multiplies<T> */
 friend reducer& operator*=(reducer&, const T&) { /* ... */
 }

 /* Only available if Dimensions == 0, T is an integral type and either
  * BinaryOperation == bit_and<> or BinaryOperation == bit_and<T> */
 friend reducer& operator&=(reducer&, const T&) { /* ... */
 }

 /* Only available if Dimensions == 0, T is an integral type and either
  * BinaryOperation == bit_or<> or BinaryOperation == bit_or<T> */
 friend reducer& operator|=(reducer&, const T&) { /* ... */
 }

 /* Only available if Dimensions == 0, T is an integral type and either
  * BinaryOperation == bit_xor<> or BinaryOperation == bit_xor<T> */
 friend reducer& operator^=(reducer&, const T&) { /* ... */
 }

 /* Only available if Dimensions == 0, T is an integral type, T is not bool and
  * either BinaryOperation == plus<> or BinaryOperation == plus<T> */
 friend reducer& operator++(reducer&) { /* ... */
 }
};
```

Table 127. Member types and constants of the reducer class

Member	Description
`value_type`	The data type of the reduction variable. If this reducer object was created from a buffer type `BufferT`, this type is `BufferT::value_type`. If this reducer object was created from a USM pointer `T*` or a span `span<T, Extent>`, this type is `T`.
`binary_operation`	The type of the combiner operator `BinaryOperation` that was passed to the reduction function that created this reducer object.
`static constexpr int dimensions`	The number of dimensions of the reduction variable. If this reducer object was created from a buffer or a USM pointer, the number of dimensions is `0`. If this reducer object was created from a span, the number of dimensions is `1`.

Table 128. Member functions of the `reducer` class

Member function	Description
`reducer& combine(const T& partial)`	Available only when: `Dimensions == 0`. Combine the value of `partial` with the reduction variable associated with this `reducer`. Returns `*this`.
`__unspecified__ operator[](size_t index)`	Available only when: `Dimensions > 0`. Returns an instance of an undefined intermediate type representing a `reducer` of the same type as this `reducer`, with the dimensionality `Dimensions-1` and containing an implicit SYCL `id` with index `Dimensions` set to `index`. The intermediate type returned must provide all member functions and operators defined by the `reducer` class that are appropriate for the type it represents (including this subscript operator).
`T identity() const`	Return the identity value of the combination operation associated with this `reducer`. Only available if the identity value is known to the implementation.

Table 129. Hidden friend operators of the `reducer` class

Operator	Description
`reducer& operator+=(reducer& accum, const T& partial)`	Equivalent to calling `accum.combine(partial)`. Available only when: `Dimensions == 0 && (std::is_same_v<BinaryOperation, plus<>> || std::is_same_v<BinaryOperation, plus<T>>)`.

Operator	Description
`reducer& operator*=(reducer& accum, const T& partial)`	Equivalent to calling `accum.combine(partial)`. Available only when: `Dimensions == 0 && (std::is_same_v<BinaryOperation, multiplies<>> || std::is_same_v<BinaryOperation, multiplies<T>>)`.
`reducer& operator&=(reducer& accum, const T& partial)`	Equivalent to calling `accum.combine(partial)`. Available only when: `Dimensions == 0 && is_integral_v<T> && (std::is_same_v<BinaryOperation, bit_and<>> || std::is_same_v<BinaryOperation, bit_and<T>>)`.
`reducer& operator|=(reducer& accum, const T& partial)`	Equivalent to calling `accum.combine(partial)`. Available only when: `Dimensions == 0 && is_integral_v<T> && (std::is_same_v<BinaryOperation, bit_or<>> || std::is_same_v<BinaryOperation, bit_or<T>>)`.
`reducer& operator^=(reducer& accum, const T& partial)`	Equivalent to calling `accum.combine(partial)`. Available only when: `Dimensions == 0 && is_integral_v<T> && (std::is_same_v<BinaryOperation, bit_xor<>> || std::is_same_v<BinaryOperation, bit_xor<T>>)`.
`reducer& operator++(reducer& accum)`	Equivalent to calling `accum.combine(1)`. Available only when: `Dimensions == 0 && std::is_integral_v<T> && !std::is_same_v<T, bool> && (std::is_same_v<BinaryOperation, plus<>> || std::is_same_v<BinaryOperation, plus<T>>)`.

4.9.3. Command group scope

A command group scope, as defined in Section 3.7.1, may execute a single command such as invoking a kernel, copying memory, or executing a host task. It is legal for a command group scope to statically contain more than one call to a command function, but any single execution of the command group function object may execute no more than one command. If an application fails to do this, the function that submits the command group function object (i.e., `queue::submit`) must throw a synchronous `exception` with the `errc::invalid` error code. The statements that call commands together with the statements that define the requirements for a kernel form the command group function object. The command group function object takes as a parameter an instance of the command group handler class which encapsulates all the member functions executed in the command group scope. The member functions and objects defined in this scope will define the requirements for the kernel execution or explicit memory operation, and will be used by the SYCL runtime to evaluate if the operation is ready for execution. Host code within a command group function object (typically setting up requirements) is executed once, before the command group submit call returns. This abstraction of the kernel execution unifies the data with its processing, and consequently allows more abstraction and flexibility in the parallel program-

ming models that can be implemented on top of SYCL.

The command group function object and the handler class serve as an interface for the encapsulation of command group scope. A SYCL kernel function is defined as a function object. All the device data accesses are defined inside this group and any transfers are managed by the SYCL runtime. The rules for the data transfers regarding device and host data accesses are better described in Section 4.7, where buffers (Section 4.7.2) and accessor (Section 4.7.6) classes are described. The overall memory model of the SYCL application is described in Section 3.8.1.

It is possible for a command group function object to fail to enqueue to a queue, or for it to fail to execute correctly. A user can therefore supply a secondary queue when submitting a command group to the primary queue. If the SYCL runtime fails to enqueue or execute a command group on a primary queue, it can attempt to run the command group on the secondary queue. The circumstances in which it is, or is not, possible for a SYCL runtime to fall-back from primary to secondary queue are unspecified in the specification. Even if a command group is run on the secondary queue, the requirement that host code within the command group is executed exactly once remains, regardless of whether the fallback queue is used for execution.

The command group handler class provides the interface for all of the member functions that are able to be executed inside the command group scope, and it is also provided as a scoped object to all of the data access requests. The command group handler class provides the interface in which every command in the command group scope will be submitted to a queue.

4.9.4. Command group handler class

A command group handler object can only be constructed by the SYCL runtime. All of the accessors defined in command group scope take as a parameter an instance of the command group handler, and all the kernel invocation functions are member functions of this class.

The constructors of the SYCL handler class are described in Table 130.

It is disallowed for an instance of the SYCL handler class to be moved or copied.

```
namespace sycl {

class handler {
 private:
  // implementation defined constructor
  handler(___unspecified___);

 public:
  template <typename DataT, int Dimensions, access_mode AccessMode,
            target AccessTarget, access::placeholder IsPlaceholder>
  void require(
      accessor<DataT, Dimensions, AccessMode, AccessTarget, IsPlaceholder> acc);

  void depends_on(event depEvent);

  void depends_on(const std::vector<event>& depEvents);

  //----- Backend interoperability interface
  //
  template <typename T> void set_arg(int argIndex, T&& arg);

  template <typename... Ts> void set_args(Ts&&... args);

  //------ Kernel dispatch API
```

```
//
// Note: In all kernel dispatch functions, the template parameter
// "typename KernelName" is optional.
//
template <typename KernelName, typename KernelType>
void single_task(const KernelType& kernelFunc);

// Parameter pack acts as-if: Reductions&&... reductions, const KernelType
// &kernelFunc
template <typename KernelName, int Dimensions, typename... Rest>
void parallel_for(range<Dimensions> numWorkItems, Rest&&... rest);

// Deprecated in SYCL 2020.
template <typename KernelName, typename KernelType, int Dimensions>
void parallel_for(range<Dimensions> numWorkItems,
                  id<Dimensions> workItemOffset,
                  const KernelType& kernelFunc);

// Parameter pack acts as-if: Reductions&&... reductions, const KernelType
// &kernelFunc
template <typename KernelName, int Dimensions, typename... Rest>
void parallel_for(nd_range<Dimensions> executionRange, Rest&&... rest);

template <typename KernelName, typename WorkgroupFunctionType, int Dimensions>
void parallel_for_work_group(range<Dimensions> numWorkGroups,
                             const WorkgroupFunctionType& kernelFunc);

template <typename KernelName, typename WorkgroupFunctionType, int Dimensions>
void parallel_for_work_group(range<Dimensions> numWorkGroups,
                             range<Dimensions> workGroupSize,
                             const WorkgroupFunctionType& kernelFunc);

void single_task(const kernel& kernelObject);

template <int Dimensions>
void parallel_for(range<Dimensions> numWorkItems, const kernel& kernelObject);

template <int Dimensions>
void parallel_for(nd_range<Dimensions> ndRange, const kernel& kernelObject);

//------ USM functions
//

void memcpy(void* dest, const void* src, size_t numBytes);

template <typename T> void copy(const T* src, T* dest, size_t count);

void memset(void* ptr, int value, size_t numBytes);

template <typename T> void fill(void* ptr, const T& pattern, size_t count);

void prefetch(void* ptr, size_t numBytes);

void mem_advise(void* ptr, size_t numBytes, int advice);

//------ Explicit memory operation APIs
```

```
  //
  template <typename SrcT, int SrcDim, access_mode SrcMode, target SrcTgt,
            access::placeholder IsPlaceholder, typename DestT>
  void copy(accessor<SrcT, SrcDim, SrcMode, SrcTgt, IsPlaceholder> src,
            std::shared_ptr<DestT> dest);

  template <typename SrcT, typename DestT, int DestDim, access_mode DestMode,
            target DestTgt, access::placeholder IsPlaceholder>
  void copy(std::shared_ptr<SrcT> src,
            accessor<DestT, DestDim, DestMode, DestTgt, IsPlaceholder> dest);

  template <typename SrcT, int SrcDim, access_mode SrcMode, target SrcTgt,
            access::placeholder IsPlaceholder, typename DestT>
  void copy(accessor<SrcT, SrcDim, SrcMode, SrcTgt, IsPlaceholder> src,
            DestT* dest);

  template <typename SrcT, typename DestT, int DestDim, access_mode DestMode,
            target DestTgt, access::placeholder IsPlaceholder>
  void copy(const SrcT* src,
            accessor<DestT, DestDim, DestMode, DestTgt, IsPlaceholder> dest);

  template <typename SrcT, int SrcDim, access_mode SrcMode, target SrcTgt,
            access::placeholder SrcIsPlaceholder, typename DestT, int DestDim,
            access_mode DestMode, target DestTgt,
            access::placeholder DestIsPlaceholder>
  void
  copy(accessor<SrcT, SrcDim, SrcMode, SrcTgt, SrcIsPlaceholder> src,
       accessor<DestT, DestDim, DestMode, DestTgt, DestIsPlaceholder> dest);

  template <typename T, int Dim, access_mode Mode, target Tgt,
            access::placeholder IsPlaceholder>
  void update_host(accessor<T, Dim, Mode, Tgt, IsPlaceholder> acc);

  template <typename T, int Dim, access_mode Mode, target Tgt,
            access::placeholder IsPlaceholder>
  void fill(accessor<T, Dim, Mode, Tgt, IsPlaceholder> dest, const T& src);

  void
  use_kernel_bundle(const kernel_bundle<bundle_state::executable>& execBundle);

  template <auto& SpecName>
  void set_specialization_constant(
      typename std::remove_reference_t<decltype(SpecName)>::value_type value);

  template <auto& SpecName>
  typename std::remove_reference_t<decltype(SpecName)>::value_type
  get_specialization_constant();
};
} // namespace sycl
```

Table 130. Constructors of the handler class

Constructor	Description
`handler(___unspecified___)`	Unspecified implementation-defined constructor.

4.9.4.1. SYCL functions for adding requirements

When an accessor is created from a command group handler, a **requirement** is implicitly added to the command group for the accessor's data. However, this does not happen when creating a placeholder accessor. In order to create a **requirement** for a placeholder accessor, code must call the `handler::require()` member function.

SYCL events may also be used to create requirements for a command group. Such requirements state that the actions represented by the events must complete before the command group may execute. Such requirements are added when code calls the `handler::depends_on()` member function.

Table 131. Member functions of the `handler` class

Member function	Description
`template <typename DataT, int Dimensions, access_mode AccessMode, target AccessTarget, access::placeholder IsPlaceholder> void require( accessor<DataT, Dimensions, AccessMode, AccessTarget, IsPlaceholder> acc)`	Requires access to the memory object associated with the accessor. The command group now has a **requirement** to gain access to the given memory object before executing the kernel. If the accessor has already been registered with the command group, calling this function has no effect. Throws `exception` with the `errc::invalid` error code if `(acc.empty() == true)`.
`void depends_on(event depEvent)`	The command group now has a **requirement** that the action represented by `depEvent` must complete before executing this command-group's action.
`void depends_on(const std::vector<event>& depEvents)`	The command group now has a **requirement** that the actions represented by each event in `depEvents` must complete before executing this command-group's action.

4.9.4.2. SYCL functions for invoking kernels

Kernels can be invoked as single tasks, basic data-parallel kernels, nd-range in work groups, or hierarchical parallelism.

Each function takes an optional kernel name template parameter. The user may optionally provide a kernel name, otherwise an implementation-defined name will be generated for the kernel.

All the functions for invoking kernels are member functions of the command group `handler` class (Section 4.9.4), which is used to encapsulate all the member functions provided in a command group scope. Table 132 lists all the members of the `handler` class related to the kernel invocation.

Table 132. Member functions of the `handler` class

Member function	Description
`template <typename T> void set_arg(int argIndex, T&& arg)`	This function must only be used to set arguments for a kernel that was constructed using a backend specific interoperability function or for a device built-in kernel. Attempting to use this function to set arguments for other kernels results in undefined behavior. The precise semantics of this function are defined by each SYCL backend specification.
`template <typename... Ts> void set_args(Ts&&... args)`	Set all arguments for a given kernel, as if each argument in `args` was passed to `set_arg` in the same order and with an increasing index starting at 0.
`template <typename KernelName, typename KernelType>` `void single_task(const KernelType& kernelFunc)`	Defines and invokes a SYCL kernel function as a lambda function or a named function object type. Specification of a kernel name (`typename KernelName`), as described in Section 4.9.4.2, is optional. The callable `KernelType` can optionally take a `kernel_handler` in which case the SYCL runtime will construct an instance of `kernel_handler` and pass it to `KernelType`.

Member function	Description
`template <typename KernelName, int Dimensions, typename... Rest>` `void parallel_for(range<Dimensions> numWorkItems, Rest&&... rest)`	Defines and invokes a SYCL kernel function as a lambda function or a named function object type, for the specified range and given an item or integral type (e.g `int`, `size_t`), if range is 1-dimensional, for indexing in the indexing space defined by range. Generic kernel functions are permitted, in that case the argument type is an `item`. Specification of a kernel name (`typename KernelName`), as described in Section 4.9.4.2, is optional. The `rest` parameter pack consists of 0 or more objects created by the `reduction` function, followed by a callable. For each object in `rest`, the kernel function must take an additional reference parameter corresponding to that object's `reducer` type, in the same order. The callable can optionally take a `kernel_handler` as its last parameter, in which case the SYCL runtime will construct an instance of `kernel_handler` and pass it to the callable.

Member function	Description

`template <typename KernelName, int Dimensions, typename... Rest>`
`void parallel_for(range<Dimensions> numWorkItems, id <Dimensions> workItemOffset,`
`const KernelType& kernelFunc)`
`// Deprecated in SYCL 2020.`
	Deprecated in SYCL 2020. Defines and invokes a SYCL kernel function as a lambda function or a named function object type, for the specified range and offset and given an item or integral type (e.g `int`, `size_t`), if range is 1-dimensional, for indexing in the indexing space defined by range. Generic kernel functions are permitted, in that case the argument type is an `item`. Specification of a kernel name (`typename KernelName`), as described in Section 4.9.4.2, is optional. The `rest` parameter pack consists of 0 or more objects created by the `reduction` function, followed by a callable. For each object in `rest`, the kernel function must take an additional reference parameter corresponding to that object's `reducer` type, in the same order. The callable can optionally take a `kernel_handler` as its last parameter, in which case the SYCL runtime will construct an instance of `kernel_handler` and pass it to the callable.

Member function	Description
`template <typename KernelName, int Dimensions, typename... Rest>` `void parallel_for(nd_range<Dimensions> executionRange, Rest&&... rest)`	Defines and invokes a SYCL kernel function as a lambda function or a named function object type, for the specified nd-range and given an nd-item for indexing in the indexing space defined by the nd-range. Generic kernel functions are permitted, in that case the argument type is an nd-item. Specification of a kernel name (`typename KernelName`), as described in Section 4.9.4.2, is optional. The `rest` parameter pack consists of 0 or more objects created by the `reduction` function, followed by a callable. For each object in `rest`, the kernel function must take an additional reference parameter corresponding to that object's `reducer` type, in the same order. The callable can optionally take a `kernel_handler` as its last parameter, in which case the SYCL runtime will construct an instance of `kernel_handler` and pass it to the callable. Throws an `exception` with the `errc::nd_range` error code if the global size defined in the associated `executionRange` defines a non-zero index space which is not evenly divisible by the local size in each dimension.

`template <typename KernelName, typename WorkgroupFunctionType, int Dimensions>`
`void parallel_for_work_group(range<Dimensions> numWorkGroups,`
`const WorkgroupFunctionType& kernelFunc)`
	Defines and invokes a hierarchical kernel as a lambda function or a named function object type, encoding the body of each work-group to launch. Generic kernel functions are permitted, in that case the argument type is a `group`. May contain multiple calls to `parallel_for_work_item(..)` member functions representing the execution on each work-item. Launches `num_work_groups` work-groups of runtime-defined size. Described in detail in Section 4.9.4.2. The callable `WorkgroupFunctionType` can optionally take a `kernel_handler` as it's last parameter, in which case the SYCL runtime will construct an instance of `kernel_handler` and pass it to `WorkgroupFunctionType`.

Member function	Description
`template <typename KernelName, typename WorkgroupFunctionType, int Dimensions> void parallel_for_work_group(range<Dimensions> numWorkGroups, range<Dimensions> workGroupSize, const WorkgroupFunctionType& kernelFunc)`	Defines and invokes a hierarchical kernel as a lambda function or a named function object type, encoding the body of each work-group to launch. Generic kernel functions are permitted, in that case the argument type is a `group`. May contain multiple calls to `parallel_for_work_item` member functions representing the execution on each work-item. Launches `num_work_groups` work-groups of `work_group_size` work-items each. Described in detail in Section 4.9.4.2. The callable `WorkgroupFunctionType` can optionally take a `kernel_handler` as it's last parameter, in which case the SYCL runtime will construct an instance of `kernel_handler` and pass it to `WorkgroupFunctionType`.
`void single_task(const kernel& kernelObject)`	This function must only be used to invoke a kernel that was constructed using a backend specific interoperability function or to invoke a device built-in kernel. Attempting to use this function to invoke other kernels throws a synchronous `exception` with the `errc::invalid` error code. The precise semantics of this function are defined by each SYCL backend specification, but the intent is that the kernel should execute exactly once. This invocation function ignores any `kernel_bundle` that was bound to this command group handler via `handler::use_kernel_bundle()` and instead implicitly uses the kernel bundle that contains the `kernelObject`. Throws an `exception` with the `errc::kernel_not_supported` error code if the `kernelObject` is not compatible with either the device associated with the primary queue of the command group or with the device associated with the secondary queue (if specified).

Member function	Description
`template <int Dimensions> void parallel_for(range<Dimensions> numWorkItems, const kernel& kernelObject)`	This function must only be used to invoke a kernel that was constructed using a backend specific interoperability function or to invoke a device built-in kernel. Attempting to use this function to invoke other kernels throws a synchronous `exception` with the `errc::invalid` error code. The precise semantics of this function are defined by each SYCL backend specification, but the intent is that the kernel should be invoked for the specified range of index values. This invocation function ignores any `kernel_bundle` that was bound to this command group handler via `handler::use_kernel_bundle()` and instead implicitly uses the kernel bundle that contains the `kernelObject`. Throws an `exception` with the `errc::kernel_not_supported` error code if the `kernelObject` is not compatible with either the device associated with the primary queue of the command group or with the device associated with the secondary queue (if specified).

Member function	Description

`template <int Dimensions>`
`void parallel_for(nd_range<Dimensions> executionRange,`
`const kernel& kernelObject)`
	This function must only be used to invoke a kernel that was constructed using a backend specific interoperability function or to invoke a device built-in kernel. Attempting to use this function to invoke other kernels throws a synchronous exception with the errc::invalid error code. The precise semantics of this function are defined by each SYCL backend specification, but the intent is that the kernel should be invoked for the specified executionRange.
	
	Throws an exception with the errc::nd_range error code if the global size defined in the associated executionRange defines a non-zero index space which is not evenly divisible by the local size in each dimension.
	
	This invocation function ignores any kernel_bundle that was bound to this command group handler via handler::use_kernel_bundle() and instead implicitly uses the kernel bundle that contains the kernelObject. Throws an exception with the errc::kernel_not_supported error code if the kernelObject is not compatible with either the device associated with the primary queue of the command group or with the device associated with the secondary queue (if specified).

4.9.4.2.1. single_task invoke

SYCL provides a simple interface to enqueue a kernel that will be sequentially executed on a device. Only one instance of the kernel will be executed. This interface is useful as a primitive for more complicated parallel algorithms, as it can easily create a chain of sequential tasks on a SYCL device with each of them managing its own data transfers.

This function can only be called inside a command group using the handler object created by the runtime. Any accessors that are used in a kernel should be defined inside the same command group.

Local accessors are disallowed for single task invocations.

```
1 myQueue.submit([&](handler& cgh) {
2 cgh.single_task(
3     [=] () {
4     // [kernel code]
```

```
5     }));
6 });
```

For single tasks, the kernel member function takes no parameters, as there is no need for index space classes in a unary index space.

A kernel_handler can optionally be passed as a parameter to the SYCL kernel function that is invoked by single_task for the purpose explained in Section 4.9.5.3.

```
1 myQueue.submit([&](handler& cgh) {
2 cgh.single_task(
3     [=] (kernel_handler kh) {
4     // [kernel code]
5     }));
6 });
```

4.9.4.2.2. parallel_for invoke

The parallel_for member function of the SYCL handler class provides an interface to define and invoke a SYCL kernel function in a command group, to execute in parallel execution over a 3 dimensional index space. There are three overloads of the parallel_for member function which provide variations of this interface, each with a different level of complexity and providing a different set of features.

For the simplest case, users need only provide the global range (the total number of work-items in the index space) via a SYCL range parameter. In this case the function object that represents the SYCL kernel function must take one of: 1) a single SYCL item parameter, 2) a single generic parameter (template parameter or auto) that will be treated as an item parameter, 3) any other type implicitly converted from SYCL item, representing the currently executing work-item within the range specified by the range parameter.

Case 3) above allows the kernel function to take an argument of type id because item is implicitly convertible to id. It also allows a 1-D kernel function to take an integral argument (e.g. int or size_t) because a 1-D item is implicitly convertible to these types. Finally, it allows the kernel function to take a user-defined argument type that can be constructed from item, enabling users to layer their own abstractions on top of SYCL.

The execution of the kernel function is the same whether the parameter to the SYCL kernel function is a SYCL id or a SYCL item. What differs is the functionality that is available to the SYCL kernel function via the respective interfaces.

Below is an example of invoking a SYCL kernel function with parallel_for using a lambda function, and passing a SYCL id parameter. In this case, only the global id is available. This variant of parallel_for is designed for when it is not necessary to query the global range of the index space being executed across.

```
1 myQueue.submit([&](handler& cgh) {
2   accessor acc { myBuffer, cgh, write_only };
3
4   cgh.parallel_for(range<1>(numWorkItems),
5                    [=](id<1> index) { acc[index] = 42.0f; });
6 });
```

Below is an example of invoking a SYCL kernel function with parallel_for using a lambda function and passing a SYCL item parameter. In this case, both the global id and global range are queryable. This variant of parallel_for is designed for when it is necessary to query the global range of the index space

being executed across.

```
myQueue.submit([&](handler& cgh) {
  accessor acc { myBuffer, cgh, write_only };

  cgh.parallel_for(range<1>(numWorkItems), [=](item<1> item) {
    // kernel argument type is item
    size_t index = item.get_linear_id();
    acc[index] = index;
  });
});
```

Below is an example of invoking a SYCL kernel function with `parallel_for` using a lambda function and passing `auto` parameter, treated as `item`. In this case, both the global id and global range are queryable. The same effect can be achieved using class with templatized `operator()`. This variant of `parallel_for` is designed for when it is necessary to query the global range within which the global id will vary.

```
myQueue.submit([&](handler& cgh) {
  auto acc = myBuffer.get_access<access_mode::write>(cgh);

  cgh.parallel_for(range<1>(numWorkItems), [=](auto item) {
    // kernel argument type is auto treated as an item
    size_t index = item.get_linear_id();
    acc[index] = index;
  });
});
```

Below is an example of invoking a SYCL kernel function with `parallel_for` using a lambda function and passing an integral type parameter. This example is only valid when calling `parallel_for` with `range<1>`. In this case only the global id is available. This variant of `parallel_for` is designed for when it is not necessary to query the global range of the index space being executed across.

```
myQueue.submit([&](handler& cgh) {
  auto acc = myBuffer.get_access<access_mode::write>(cgh);

  cgh.parallel_for(range<1>(numWorkItems), [=](size_t index) {
    // kernel argument type is size_t
    acc[index] = index;
  });
});
```

The `parallel_for` overload without an offset can be called with either a number or a `braced-init-list` with 1-3 elements. In that case the following calls are equivalent:

- `parallel_for(N, some_kernel)` has same effect as `parallel_for(range<1>(N), some_kernel)`
- `parallel_for({N}, some_kernel)` has same effect as `parallel_for(range<1>(N), some_kernel)`
- `parallel_for({N1, N2}, some_kernel)` has same effect as `parallel_for(range<2>(N1, N2), some_kernel)`
- `parallel_for({N1, N2, N3}, some_kernel)` has same effect as `parallel_for(range<3>(N1, N2, N3), some_kernel)`

Below is an example of invoking `parallel_for` with a number instead of an explicit `range` object.

```
myQueue.submit([&](handler& cgh) {
  auto acc = myBuffer.get_access<access_mode::write>(cgh);

  // parallel_for may be called with number (with numWorkItems)
  cgh.parallel_for(numWorkItems, [=](auto item) {
    size_t index = item.get_linear_id();
    acc[index] = index;
  });
});
```

For SYCL kernel functions invoked via the above described overload of the parallel_for member function, it is disallowed to use local accessors or to use a work-group barrier.

The following two examples show how a kernel function object can be launched over a 3D grid, with 3 elements in each dimension. In the first case work-item ids range from 0 to 2 inclusive, and in the second case work-item ids run from 1 to 3.

```
myQueue.submit([&](handler& cgh) {
  cgh.parallel_for(range<3>(3, 3, 3), // global range
                   [=](item<3> it) {
                     //[kernel code]
                   });
});

// This form of parallel_for with the "offset" parameter is deprecated in SYCL
// 2020
myQueue.submit([&](handler& cgh) {
  cgh.parallel_for(range<3>(3, 3, 3), // global range
                   id<3>(1, 1, 1),    // offset
                   [=](item<3> it) {
                     //[kernel code]
                   });
});
```

The last case of a parallel_for invocation enables low-level functionality of work-items and work-groups. This becomes valuable when an execution requires groups of work-items that communicate and synchronize. These are exposed in SYCL through parallel_for (nd_range,...) and the nd_item class. In this case, the developer needs to define the nd_range that the kernel will execute on in order to have fine grained control of the enqueuing of the kernel. This variation of parallel_for expects an nd_range, specifying both local and global ranges, defining the global number of work-items and the number in each cooperating work-group. The function object that represents the SYCL kernel function must take one of: 1) a single SYCL nd_item parameter, 2) a single generic parameter (template parameter or auto) that will be treated as an nd_item parameter, 3) any other type converted from SYCL nd_item, representing the currently executing work-item within the range specified by the nd_range parameter. The nd_item parameter makes all information about the work-item and its position in the range available, and provides access to functions enabling the use of a work-group barrier to synchronize between the work-items in the work-group.

Case 3) above includes user-defined types that can be constructed from nd_item, enabling users to layer their own abstractions on top of SYCL.

The following example shows how sixty-four work-items may be launched in a three-dimensional grid with four in each dimension, and divided into eight work-groups. Each group of work-items synchronizes with a work-group barrier.

```
myQueue.submit([&](handler& cgh) {
  cgh.parallel_for(nd_range<3>(range<3>(4, 4, 4), range<3>(2, 2, 2)),
                   [=](nd_item<3> item) {
                     //[kernel code]
                     // Internal synchronization
                     group_barrier(item.get_group());
                     //[kernel code]
                   });
});
```

In all of these cases the underlying nd-range will be created and the kernel defined as a function object will be created and enqueued as part of the command group scope.

Some forms of `parallel_for` accept an offset parameter of type `id<Dimensions>`, where the number of dimensions of the `id` is the same as the number of dimensions of the `range` that determines the iteration space. These forms of `parallel_for` execute the same number of iterations as the form with no offset. The difference is that the `id` or `item` parameter passed to the kernel function has the value of `offset` implicitly added. This offset parameter is deprecated in SYCL 2020.

An offset can also be passed to the forms of `parallel_for` that accept an `nd_range` via the third parameter to the `nd_range` constructor. These forms of `parallel_for` also execute the same number of iterations as if no offset was specified. The difference is that the `nd_item` parameter passed to the kernel function has the value of the offset implicitly added to the constituent global id. This offset parameter is deprecated in SYCL 2020.

A `kernel_handler` can optionally be passed as a parameter to the SYCL kernel function that is invoked by both variants of `parallel_for`.

```
myQueue.submit([&](handler& cgh) {
  cgh.parallel_for(range<3>(3, 3, 3), // global range
                   [=](item<3> it, kernel_handler kh) {
                     //[kernel code]
                   });
});

// This form of parallel_for with the "offset" parameter is deprecated in SYCL
// 2020
myQueue.submit([&](handler& cgh) {
  cgh.parallel_for(range<3>(3, 3, 3), // global range
                   id<3>(1, 1, 1),    // offset
                   [=](item<3> it, kernel_handler kh) {
                     //[kernel code]
                   });
});
```

4.9.4.2.3. Parallel for hierarchical invoke

The hierarchical parallel kernel execution interface provides the same functionality as is available from the nd-range interface, but exposed differently. To execute the same sixty-four work-items in sixteen work-groups that we saw in the previous example, we execute an outer `parallel_for_work_group` call to create the groups. The member function `handler::parallel_for_work_group` is parameterized by the number of work-groups, such that the size of each group is chosen by the runtime, or by the number of work-groups and number of work-items for users who need more control.

The body of the outer `parallel_for_work_group` call consists of a lambda function or function object. The

body of this function object contains code that is executed only once for the entire work-group. If the code has no side-effects and the compiler heuristic suggests that it is more efficient to do so, this code will be executed for each work-item.

Within this region any variable declared will have the semantics of local memory, shared between all work items in the work-group. If the device compiler can prove that an array of such variables is accessed only by a single work-item throughout the lifetime of the work-group, for example if access is derived from the id of the work-item with no transformation, then it can allocate the data in private memory or registers instead.

To guarantee use of private per-work-item memory, the `private_memory` class can be used to wrap the data. This class simply constructs private data for a given group across the entire group. The id of the current work-item is passed to any access to grab the correct data.

The `private_memory` class has the following interface:

Listing 1. Private memory class

```
namespace sycl {
template <typename T, int Dimensions = 1> class private_memory {
 public:
  // Construct based directly off the number of work-items
  private_memory(const group<Dimensions>&);

  // Access the instance for the current work-item
  T& operator()(const h_item<Dimensions>& id);
};
} // namespace sycl
```

Table 133. Constructor of the `private_memory` class

Constructor	Description
`private_memory(const group<Dimensions>&)`	Place an object of type `T` in the underlying private memory of each work items. The type `T` must be default constructible. The underlying constructor will be called for each work-item.

Table 134. Member functions of the `private_memory` class

Member functions	Description
`T& operator()(const h_item<Dimensions>& id)`	Retrieve a reference to the object for the work items.

Private memory is allocated per underlying work-item, not per iteration of the `parallel_for_work_item` loop. The number of instances of a private memory object is only under direct control if a work-group size is passed to the `parallel_for_work_group` call. If the underlying work-group size is chosen by the runtime, the number of private memory instances is opaque to the program. Explicit private memory declarations should therefore be used with care and with a full understanding of which instances of a `parallel_for_work_item` loop will share the same underlying variable.

Also within the lambda body can be a sequence of calls to `parallel_for_work_item`. At the edges of these inner parallel executions the work-group synchronizes. As a result the pair of `parallel_for_work_item` calls in the code below is equivalent to the parallel execution with a work-group barrier in the earlier example.

```
myQueue.submit([&](handler& cgh) {
  // Issue 8 work-groups of 8 work-items each
  cgh.parallel_for_work_group(
      range<3>(2, 2, 2), range<3>(2, 2, 2), [=](group<3> myGroup) {
        //[workgroup code]
        int myLocal; // this variable is shared between workitems
        // this variable will be instantiated for each work-item separately
        private_memory<int> myPrivate(myGroup);

        // Issue parallel work-items.  The number issued per work-group is
        // determined by the work-group size range of parallel_for_work_group.
        // In this case, 8 work-items will execute the parallel_for_work_item
        // body for each of the 8 work-groups, resulting in 64 executions
        // globally/total.
        myGroup.parallel_for_work_item([&](h_item<3> myItem) {
          //[work-item code]
          myPrivate(myItem) = 0;
        });

        // Implicit work-group barrier

        // Carry private value across loops
        myGroup.parallel_for_work_item([&](h_item<3> myItem) {
          //[work-item code]
          output[myItem.get_global_id()] = myPrivate(myItem);
        });
        //[workgroup code]
      });
});
```

It is valid to use more flexible dimensions of the work-item loops. In the following example we issue 8 work-groups but let the runtime choose their size, by not passing a work-group size to the `parallel_for_work_group` call. The `parallel_for_work_item` loops may also vary in size, with their execution ranges unrelated to the dimensions of the work-group, and the compiler generating an appropriate iteration space to fill the gap. In this case, the `h_item` provides access to local ids and ranges that reflect both kernel and `parallel_for_work_item` invocation ranges.

```
myQueue.submit([&](handler& cgh) {
  // Issue 8 work-groups.  The work-group size is chosen by the runtime because
  // unspecified
  cgh.parallel_for_work_group(range<3>(2, 2, 2), [=](group<3> myGroup) {
    // Launch a set of work-items for each work-group.  The number of work-items
    // is chosen by the runtime because the work-group size was not specified to
    // parallel_for_work_group and a logical range is not specified to
    // parallel_for_work_item.
    myGroup.parallel_for_work_item([=](h_item<3> myItem) {
      //[work-item code]
    });

    // Implicit work-group barrier

    // Launch 512 logical work-items that will be executed by the underlying
    // work-group size chosen by the runtime.  myItem allows the logical and
    // physical work-item IDs to be queried.  512 logical work-items will
```

```
    // execute for each work-group, and the parallel_for body will therefore be
    // executed 8*512 = 4096 times globally/total.
    myGroup.parallel_for_work_item(range<3>(8, 8, 8), [=](h_item<3> myItem) {
      //[work-item code]
    });
    //[workgroup code]
  });
});
```

This interface offers a more intuitive way for tiling parallel programming paradigms. In summary, the hierarchical model allows a developer to distinguish the execution at work-group level and at work-item level using the `parallel_for_work_group` and the nested `parallel_for_work_item` functions. It also provides this visibility to the compiler without the need for difficult loop fission such that host execution may be more efficient.

A `kernel_handler` can optionally be passed as a parameter to the SYCL kernel function that is invoked by any variant of `parallel_for_work_group`.

```
myQueue.submit([&](handler& cgh) {
  // Issue 8 work-groups of 8 work-items each
  cgh.parallel_for_work_group(
      range<3>(2, 2, 2), range<3>(2, 2, 2),
      [=](group<3> myGroup, kernel_handler kh) {
        //[workgroup code]
        int myLocal; // this variable is shared between workitems
        // this variable will be instantiated for each work-item separately
        private_memory<int> myPrivate(myGroup);

        // Issue parallel work-items.  The number issued per work-group is
        // determined by the work-group size range of parallel_for_work_group.
        // In this case, 8 work-items will execute the parallel_for_work_item
        // body for each of the 8 work-groups, resulting in 64 executions
        // globally/total.
        myGroup.parallel_for_work_item([&](h_item<3> myItem) {
          //[work-item code]
          myPrivate(myItem) = 0;
        });

        // Implicit work-group barrier

        // Carry private value across loops
        myGroup.parallel_for_work_item([&](h_item<3> myItem) {
          //[work-item code]
          output[myItem.get_global_id()] = myPrivate(myItem);
        });
        //[workgroup code]
      });
});
```

4.9.4.3. SYCL functions for explicit memory operations

In addition to kernels, command group objects can also be used to perform manual operations on host and device memory by using the copy API of the command group handler. Manual copy operations can be seen as specialized kernels executing on the device, except that typically this operations will be implemented using a host API that exists as part of a backend (e.g, OpenCL enqueue copy operations).

These explicit copy operations have a source and a destination. When an accessor is the *source* of the operation, the destination can be a host pointer or another accessor. The *source* accessor must have either `access_mode::read` or `access_mode::read_write` access mode. When an accessor is the *destination* of the explicit copy operation, the source can be a host pointer or another accessor. The *destination* accessor must have either `access_mode::write`, `access_mode::read_write`, `access_mode::discard_write` or `access_mode::discard_read_write` access mode.

When an accessor is used as a parameter to one of these explicit copy operations, the target must be either `target::device` or `target::constant_buffer`.

When accessors are both the source and the destination, the operation is executed on objects controlled by the SYCL runtime. The SYCL runtime is allowed to not perform an explicit in-copy operation if a different path to update the data is available according to the SYCL application memory model.

The most recent copy of the memory object may reside on any context controlled by the SYCL runtime, or on the host in a pointer controlled by the SYCL runtime. The SYCL runtime will ensure that data is copied to the destination once the command group has completed execution.

Whenever a host pointer is used as either the source or the destination of these explicit memory operations, it is the responsibility of the user for that pointer to have at least as much memory allocated as the accessor is giving access to, e.g: if an accessor accesses a range of 10 elements of `int` type, the host pointer must at least have `10 * sizeof(int)` bytes of memory allocated.

A special case is the `update_host` member function. This member function only requires an accessor, and instructs the runtime to update the internal copy of the data in the host, if any. This is particularly useful when users use manual synchronization with host pointers, e.g. via mutex objects on the `buffer` constructors.

Table 135 describes the interface for the explicit copy operations.

Table 135. Member functions of the `handler` class

Member function	Description
`template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt, typename DestT, access::placeholder IsPlaceholder> void copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsPlaceholder> src, std::shared_ptr<DestT> dest)`	Copies the contents of the memory object accessed by `src` into the memory pointed to by `dest`. `dest` must be a host pointer and must have at least as many bytes as the range accessed by `src`.
`template <typename SrcT, typename DestT, int DestDims, access_mode DestMode, target DestTgt, access::placeholder IsPlaceholder> void copy(std::shared_ptr<SrcT> src, accessor<DestT, DestDims, DestMode, DestTgt, IsPlaceholder> dest)`	Copies the contents of the memory pointed to by `src` into the memory object accessed by `dest`. `src` must be a host pointer and must have at least as many bytes as the range accessed by `dest`.

Member function	Description
`template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt, typename DestT, access::placeholder IsPlaceholder> void copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsPlaceholder> src, DestT* dest)`	Copies the contents of the memory object accessed by `src` into the memory pointed to by `dest`. `dest` must be a host pointer and must have at least as many bytes as the range accessed by `src`.
`template <typename SrcT, typename DestT, int DestDims, access_mode DestMode, target DestTgt, access::placeholder IsPlaceholder> void copy(const SrcT* src, accessor<DestT, DestDims, DestMode, DestTgt, IsPlaceholder> dest)`	Copies the contents of the memory pointed to by `src` into the memory object accessed by `dest`. `src` must be a host pointer and must have at least as many bytes as the range accessed by `dest`.
`template <typename SrcT, int SrcDims, access_mode SrcMode, target SrcTgt, access::placeholder IsSrcPlaceholder, typename DestT, int DestDims, access_mode DestMode, target DestTgt, access::placeholder IsDestPlaceholder> void copy(accessor<SrcT, SrcDims, SrcMode, SrcTgt, IsSrcPlaceholder> src, accessor<DestT, DestDims, DestMode, DestTgt, IsDestPlaceholder> dest)`	Copies the contents of the memory object accessed by `src` into the memory object accessed by `dest`. The size of the `src` accessor determines the number of bytes that are copied, and `dest` must have at least this many bytes. If the size of `dest` is too small, the implementation throws a synchronous `exception` with the `errc::invalid` error code.
`template <typename T, int Dims, access_mode Mode, target Tgt, access::placeholder IsPlaceholder> void update_host(accessor<T, Dims, Mode, Tgt, IsPlaceholder> acc)`	The contents of the memory object accessed via `acc` on the host are guaranteed to be up-to-date after this command group object execution is complete.
`template <typename T, int Dims, access_mode Mode, target Tgt, access::placeholder IsPlaceholder> void fill(accessor<T, Dims, Mode, Tgt, IsPlaceholder> dest, const T& src)`	Replicates the value of `src` into the memory object accessed by `dest`.

Member function	Description
`void memcpy(void* dest, const void* src, size_t numBytes)`	Copies `numBytes` of data from the pointer `src` to the pointer `dest`. The `dest` and `src` parameters must each either be a host pointer or a pointer within a USM allocation that is accessible on the handler's device. If a pointer is to a USM allocation, that allocation must have been created from the same context as the handler's queue. For more detail on USM, please see Section 4.8.
`template <typename T> void copy(const T* src, T* dest, size_t count)`	Copies `count` elements of type `T` from the pointer `src` to the pointer `dest`. The `dest` and `src` parameters must each either be a host pointer or a pointer within a USM allocation that is accessible on the handler's device. If a pointer is to a USM allocation, that allocation must have been created from the same context as the handler's queue. For more detail on USM, please see Section 4.8.
`void memset(void* ptr, int value, size_t numBytes)`	Fills `numBytes` bytes of memory beginning at address `ptr` with `value`. The `ptr` must point within a USM allocation from the same context as the handler's queue, and the pointer must be accessible from the queue's device. Note that `value` is interpreted as an `unsigned char`. For more detail on USM, please see Section 4.8.
`template <typename T> void fill(void* ptr, const T& pattern, size_t count)`	Replicates the provided `pattern` into the memory at address `ptr`. The `ptr` must point within a USM allocation from the same context as the handler's queue, and the pointer must be accessible from the queue's device. The `pattern` is filled `count` times. For more detail on USM, please see Section 4.8.
`void prefetch(void* ptr, size_t numBytes)`	Enqueues a prefetch of `num_bytes` of data starting at address `ptr`. The `ptr` must point within a USM allocation from the same context as the handler's queue, and the pointer must be accessible from the queue's device. For more detail on USM, please see Section 4.8.

Member function	Description
`void mem_advise(void* ptr, size_t numBytes, int advice)`	Enqueues a command that provides information to the implementation about a region of USM starting at `ptr` and extending for `numBytes` bytes. The `ptr` must point within a USM allocation from the same context as the handler's queue, and the pointer must be accessible from the queue's device. The values for `advice` are vendor- or backend-specific, with the exception of the value `0` which reverts the advice for `ptr` to the default behavior. For more detail on USM, please see Section 4.8.

The listing below illustrates how to use explicit copy operations in SYCL. The example copies half of the contents of a `std::vector` into the device, leaving the rest of the contents of the buffer on the device unchanged.

```
1 const size_t nElems = 10u;
2
3 // Create a vector and fill it with values 0, 1, 2, 3, 4, 5, 6, 7, 8, 9
4 std::vector<int> v { nElems };
5 std::iota(std::begin(v), std::end(v), 0);
6
7 // Create a buffer with no associated user storage
8 sycl::buffer<int, 1> b { range<1>(nElems) };
9
10 // Create a queue
11 queue myQueue;
12
13 myQueue.submit([&](handler& cgh) {
14   // Retrieve a ranged write accessor to a global buffer with access to the
15   // first half of the buffer
16   accessor acc { b, cgh, range<1>(nElems / 2), id<1>(0), write_only };
17   // Copy the first five elements of the vector into the buffer associated with
18   // the accessor
19   cgh.copy(v.data(), acc);
20 });
```

4.9.4.4. Functions for using a kernel bundle

```
1 void use_kernel_bundle(
2     const kernel_bundle<bundle_state::executable>& execBundle);
```

Effects: The command group associated with the `handler` will use device images of the `kernel_bundle` `execBundle` in any of its kernel invocation commands. If the `kernel_bundle` contains multiple device images that are compatible with the device to which the kernel is submitted, then the device image chosen is implementation-defined.

If the command group attempts to invoke a kernel that is not contained by a compatible device image in

execBundle, the kernel invocation command throws a synchronous exception with the errc::kernel_not_supported error code. If the command group has a secondary queue, then the execBundle must contain a kernel that is compatible with both the primary queue's device and the secondary queue's device, otherwise the kernel invocation command throws this exception.

Since the handler method for setting specialization constants is incompatible with the kernel bundle method, applications should not call this function if handler::set_specialization_constant() has been previously called for this same command group.

Throws:

- An exception with the errc::invalid error code if the context associated with the command group handler via its associated primary queue or the context associated with the secondary queue (if provided) is different from the context associated with the kernel bundle specified by execBundle.
- An exception with the errc::invalid error code if handler::set_specialization_constant() has been called for this command group.

4.9.5. Specialization constants

Device code can make use of specialization constants which represent constants whose values can be set dynamically during execution of the SYCL application. The values of these constants are fixed when a SYCL kernel function is invoked, and they do not change during the execution of the kernel. However, the application is able to set a new value for a specialization constant each time a kernel is invoked, so the values can be tuned differently for each invocation.

There are two methods for an application to use specialization constants, one method requires creating a kernel_bundle object and the other does not. The syntax for both methods is mostly the same. Both methods declare specialization constants in the same way, and kernels read their values in the same way. The main difference is whether their values are set via handler::set_specialization_constant() or via kernel_bundle::set_specialization_constant(). These two methods are incompatible with one another, so they may not both be used by the same command group.

Implementations that support online compilation of kernel bundles will likely implement both methods of specialization constants using kernel bundles. Therefore, applications should expect that there is some overhead associated with invoking a kernel with new values for its specialization constants. A typical implementation records the values of specialization constants set via handler::set_specialization_constant() and remembers these values until a kernel is invoked (e.g. via parallel_for()). At this point, the implementation determines the bundle that contains the invoked kernel. If that bundle has already been compiled for the handler's device and compiled with the correct values for the specialization constants, the kernel is scheduled for invocation. Otherwise, the implementation compiles the bundle before scheduling the kernel for invocation. Therefore, applications that frequently change the values of specialization constants may see an overhead associated with recompilation of the kernel's bundle.

4.9.5.1. Declaring a specialization constant

Specialization constants must be declared using the specialization_id class with the following restrictions:

- the template parameter T must be a device copyable type;
- the specialization_id variable must be declared as constexpr;
- the specialization_id variable must be declared in either namespace scope or in class scope;
- if the specialization_id variable is declared in class scope, it must have public accessibility when referenced from namespace scope;

- the specialization_id variable may not be shadowed by another identifier X which has the same name and is declared in an inline namespace, such that the specialization_id variable is no longer accessible after the declaration of X;
- if the specialization_id variable is declared in a namespace, none of the enclosing namespace names N may be shadowed by another identifier X which has the same name as N and is declared in an inline namespace, such that N is no longer accessible after the declaration of X.

The expectation is that some implementations may conceptually insert code at the end of a translation unit which references each specialization_id variable that is declared in that translation unit. The restrictions listed above make this possible by ensuring that these variables are accessible at the end of the translation unit.

The following example illustrates some of these restrictions:

```
#include <sycl/sycl.hpp>
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

struct Compound {
  int i;
  float f;
};

constexpr specialization_id<int> a { 1 };            // OK
constexpr specialization_id<Compound> b { 2, 3.14 }; // OK
inline constexpr specialization_id<int> c { 3 };     // OK
static constexpr specialization_id<int> d { 4 };     // OK
specialization_id<int> e { 5 };                      // ILLEGAL: not constexpr

struct Bar {
  static constexpr specialization_id<int> f { 6 }; // OK
};
struct Baz {
  struct Inner {
    static constexpr specialization_id<int> g { 7 }; // OK
  };
};
class Boo {
  static constexpr specialization_id<int> h { 8 }; // ILLEGAL: not public member
};

void Func() {
  static constexpr specialization_id<int> i { 9 }; // ILLEGAL: not at namespace
                                                   // or class scope
  /* ... */
}

constexpr specialization_id<int> same_name { 10 }; // OK
namespace foo {
constexpr specialization_id<int> same_name { 11 }; // OK
}
namespace {
constexpr specialization_id<int> same_name { 12 }; // OK
}
inline namespace other {
int same_name; // ILLEGAL: shadows "specialization_id" variable with same name in
```

```
42                // enclosing namespace scope
43 }
44 inline namespace other2 {
45 namespace foo { // ILLEGAL: namespace name shadows "::foo" namespace which contains
46                 // "specialization_id" variable.
47 } // namespace foo
48 } // namespace
```

A synopsis of this class is shown below.

```
1 namespace sycl {
2
3 template <typename T> class specialization_id {
4  public:
5   using value_type = T;
6
7   template <class... Args> explicit constexpr specialization_id(Args&&... args);
8
9   specialization_id(const specialization_id& rhs) = delete;
10  specialization_id(specialization_id&& rhs) = delete;
11  specialization_id& operator=(const specialization_id& rhs) = delete;
12  specialization_id& operator=(specialization_id&& rhs) = delete;
13 };
14
15 } // namespace sycl
```

4.9.5.1.1. Constructors

```
template <class... Args> explicit constexpr specialization_id(Args&&... args);
```

Constraints: Available only when `std::is_constructible_v<T, Args...>` evaluates to `true`.

Effects: Constructs a `specialization_id` containing an instance of `T` initialized with `args...`, which represents the specialization constant's default value.

4.9.5.1.2. Special member functions

```
specialization_id(const specialization_id& rhs) = delete;            // (1)
specialization_id(specialization_id&& rhs) = delete;                 // (2)
specialization_id& operator=(const specialization_id& rhs) = delete; // (3)
specialization_id& operator=(specialization_id&& rhs) = delete;      // (4)
```

1. Deleted copy constructor.
2. Deleted move constructor.
3. Deleted copy assignment operator.
4. Deleted move assignment operator.

4.9.5.2. Setting and getting the value of a specialization constant

If the application uses specialization constants without creating a `kernel_bundle` object, it can set and get their values from command group scope by calling member functions of the `handler` class. These member functions have a template parameter `SpecName` whose value must be a reference to a variable of type

specialization_id, which defines the type and default value of the specialization constant.

When not using a kernel bundle, the value of a specialization constant that is used in a kernel invoked from a command group is affected by calls to set its value from that same command group, but it is not affected by calls from other command groups even if those calls are from another invocation of the same command group function object.

```
template <auto& SpecName>
void set_specialization_constant(
    typename std::remove_reference_t<decltype(SpecName)>::value_type value);
```

Effects: Sets the value of the specialization constant whose address is SpecName for this handler's command group. If the specialization constant's value was previously set in this same command group, the value is overwritten.

This function may be called even if the specialization constant SpecName isn't used by the kernel that is invoked by this handler's command group. Doing so has no effect on the invoked kernel.

Throws:

- An exception with the errc::invalid error code if a kernel bundle has been bound to the handler via use_kernel_bundle().

```
template <auto& SpecName>
typename std::remove_reference_t<decltype(SpecName)>::value_type
get_specialization_constant();
```

Returns: The value of the specialization constant whose address is SpecName for this handler's command group. If the value was previously set in this handler's command group, that value is returned. Otherwise, the specialization constant's default value is returned.

Throws:

- An exception with the errc::invalid error code if a kernel bundle has been bound to the handler via use_kernel_bundle().

4.9.5.3. Reading the value of a specialization constant from device code

In order to read the value of a specialization constant from device code, the SYCL kernel function must be declared to take an object of type kernel_handler as its last parameter. The SYCL runtime constructs this object, which has a member function for reading the specialization constant's value. A synopsis of this class is shown below.

```
namespace sycl {

class kernel_handler {
 public:
  template <auto& SpecName>
  typename std::remove_reference_t<decltype(SpecName)>::value_type
  get_specialization_constant();
};

} // namespace sycl
```

4.9.5.3.1. Member functions

```
template<auto& SpecName>
typename std::remove_reference_t<decltype(SpecName)>::value_type
get_specialization_constant();
```

Returns: The value of the specialization constant whose address is SpecName. For a kernel invoked from a command group that was not bound to a kernel bundle, the value is the same as what would have been returned if handler::get_specialization_constant() was called immediately before invoking the kernel. For a kernel invoked from a command group that was bound to a kernel bundle, the value is the same as what would be returned if kernel_bundle::get_specialization_constant() was called on the bound bundle.

4.9.5.4. Example usage

The following example performs a convolution and uses specialization constants to set the values of the coefficients.

```
#include <sycl/sycl.hpp>
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

using coeff_t = std::array<std::array<float, 3>, 3>;

// Read coefficients from somewhere.
coeff_t get_coefficients();

// Identify the specialization constant.
constexpr specialization_id<coeff_t> coeff_id;

void do_conv(buffer<float, 2> in, buffer<float, 2> out) {
  queue myQueue;

  myQueue.submit([&](handler& cgh) {
    accessor in_acc { in, cgh, read_only };
    accessor out_acc { out, cgh, write_only };

    // Set the coefficient of the convolution as constant.
    // This will build a specific kernel the coefficient available as literals.
    cgh.set_specialization_constant<coeff_id>(get_coefficients());

    cgh.parallel_for<class Convolution>(in.get_range(), [=](item<2> item_id,
                                                            kernel_handler h) {
      float acc = 0;
      coeff_t coeff = h.get_specialization_constant<coeff_id>();
      for (int i = -1; i <= 1; i++) {
        if (item_id[0] + i < 0 || item_id[0] + i >= in_acc.get_range()[0])
          continue;
        for (int j = -1; j <= 1; j++) {
          if (item_id[1] + j < 0 || item_id[1] + j >= in_acc.get_range()[1])
            continue;
          // The underlying JIT can see all the values of the array returned
          // by coeff.get().
          acc += coeff[i + 1][j + 1] * in_acc[item_id[0] + i][item_id[1] + j];
        }
      }
```

```
38       out_acc[item_id] = acc;
39     });
40   });
41
42   myQueue.wait();
43 }
```

4.10. Host tasks

4.10.1. Overview

A host task is a native C++ callable which is scheduled by the SYCL runtime. A host task is submitted to a queue via a command group by a host task command.

When a host task command is submitted to a queue it is scheduled based on its data dependencies with other commands including kernel invocation commands and asynchronous copies, resolving any requisites created by accessors attached to the command group as defined in Section 3.8.1.

Since a host task is invoked directly by the SYCL runtime rather than being compiled as a SYCL kernel function, it does not have the same restrictions as a SYCL kernel function, and can therefore contain any arbitrary C++ code.

Capturing accessors in a host task is allowed, however, capturing or using any other SYCL class that has reference semantics (see Section 4.5.2) is undefined behavior.

A host task can be enqueued on any queue and the callable will be invoked directly by the SYCL runtime, regardless of which device the queue is associated with.

A host task is enqueued on a queue via the `host_task` member function of the `handler` class. The event returned by the submission of the associated command group enters the completed state (corresponding to a status of `info::event_command_status::complete`) once the invocation of the provided C++ callable has returned. Any uncaught exception thrown during the execution of a host task will be turned into an asynchronous error that can be handled as described in Section 4.13.1.1.

A host task can optionally be used to interoperate with the native backend objects associated with the queue executing the host task, the context that the queue is associated with, the device that the queue is associated with and the accessors that have been captured in the callable, via an optional `interop_handle` parameter.

This allows host tasks to be used for two purposes: either as a task which can perform arbitrary C++ code within the scheduling of the SYCL runtime or as a task which can perform interoperability at a point within the scheduling of the SYCL runtime.

For the former use case, construct a buffer accessor with `target::host_task` or an image accessor with `image_target::host_task`. This makes the buffer or image available on the host during execution of the host task.

For the latter case, construct a buffer accessor with `target::device` or `target::constant_buffer`, or construct an image accessor with `image_target::device`. This makes the buffer or image available on the device that is associated with the queue used to submit the host task, so that it can be accessed via interoperability member functions provided by the `interop_handle` class.

Local accessors cannot be used within a host task.

```
1 namespace sycl {
2
```

```
class interop_handle {
 private:
  interop_handle(__unspecified__);

 public:
  interop_handle() = delete;

  backend get_backend() const noexcept;

  template <backend Backend, typename DataT, int Dims, access_mode AccessMode,
            target AccessTarget, access::placeholder isPlaceholder>
  backend_return_t<Backend, buffer<DataT, Dims>>
  get_native_mem(const accessor<DataT, Dims, AccessMode, AccessTarget,
                                isPlaceholder>& bufferAccessor) const;

  template <backend Backend, typename DataT, int Dims, access_mode AccMode>
  backend_return_t<Backend, unsampled_image<Dims>> get_native_mem(
      const unsampled_image_accessor<DataT, Dims, AccMode,
                                     image_target::device>& imageAcc) const;

  template <backend Backend, typename DataT, int Dims>
  backend_return_t<Backend, sampled_image<Dims>> get_native_mem(
      const sampled_image_accessor<DataT, Dims, image_target::device>& imageAcc)
      const;

  template <backend Backend>
  backend_return_t<Backend, queue> get_native_queue() const;

  template <backend Backend>
  backend_return_t<Backend, device> get_native_device() const;

  template <backend Backend>
  backend_return_t<Backend, context> get_native_context() const;
};

class handler {
  ...

      public
      :

      template <typename T>
      void
      host_task(T&& hostTaskCallable);

  ...
};

} // namespace sycl
```

4.10.2. Class interop_handle

The interop_handle class is an abstraction over the queue which is being used to invoke the host task and its associated device and context. It also represents the state of the SYCL runtime dependency model at the point the host task is invoked.

The interop_handle class provides access to the native backend object associated with the queue, device, context and any buffers or images that are captured in the callable being invoked in order to allow a host task to be used for interoperability purposes.

An interop_handle cannot be constructed by user-code, only by the SYCL runtime.

```
class interop_handle;
```

4.10.2.1. Constructors

```
private:
interop_handle(__unspecified__); // (1)

public:
interop_handle() = delete; // (2)
```

1. Private implementation-defined constructor with unspecified arguments so that the SYCL runtime can construct a interop_handle.
2. Explicitly deleted default constructor.

4.10.2.2. Member functions

```
backend get_backend() const noexcept;
```

1. *Returns:* Returns a backend identifying the SYCL backend associated with the queue associated with this interop_handle.

4.10.2.3. Template member functions get_native_*

```
    // SPDX-License-Identifier: MIT

    template <backend Backend, typename DataT, int Dims, access_mode AccMode,
              target AccTarget, access::placeholder IsPlaceholder>
    backend_return_t<Backend, buffer<DataT, Dims>>
    get_native_mem(const accessor<DataT, Dims, AccMode, AccTarget, // (1)
                                  IsPlaceholder>& bufferAcc) const;

template <backend Backend, typename DataT, int Dims, access_mode AccMode>
backend_return_t<Backend, unsampled_image<Dims>> get_native_mem( // (2)
    const unsampled_image_accessor<DataT, Dims, AccMode, image_target::device>&
        imageAcc) const;

template <backend Backend, typename DataT, int Dims>
backend_return_t<Backend, sampled_image<Dims>> get_native_mem( // (3)
    const sampled_image_accessor<DataT, Dims, image_target::device>& imageAcc)
    const;

template <backend Backend>
backend_return_t<Backend, queue> get_native_queue() const; // (4)

template <backend Backend>
backend_return_t<Backend, device> get_native_device() const; // (5)
```

```
24
25 template <backend Backend>
26 backend_return_t<Backend, context> get_native_context() const; // (6)
```

1. *Constraints:* Available only if the optional interoperability function get_native taking a buffer is available and if accTarget is target::device.

   Returns: The native backend object associated with the underlying buffer of accessor bufferAcc. The native backend object returned must be in a state where it represents the memory in its current state within the SYCL runtime dependency model and is capable of being used in a way appropriate for the associated SYCL backend. It is undefined behavior to use the native backend object outside of the scope of the host task.

   Throws: An exception with the errc::invalid error code if the accessor bufferAcc was not registered with the command group which contained the host task. Must throw an exception with the errc::backend_mismatch error code if Backend != get_backend().

2. *Constraints:* Available only if the optional interoperability function get_native taking an unsampled_image is available.

   Returns: The native backend object associated with with the underlying unsampled_image of accessor imageAcc. The native backend object returned must be in a state where it represents the memory in its current state within the SYCL runtime dependency model and is capable of being used in a way appropriate for the associated SYCL backend. It is undefined behavior to use the native backend object outside of the scope of the host task.

   Throws: An exception with the errc::invalid error code if the accessor imageAcc was not registered with the command group which contained the host task.

3. *Constraints:* Available only if the optional interoperability function get_native taking an sampled_image is available.

   Returns: The native backend object associated with with the underlying sampled_image of accessor imageAcc. The native backend object returned must be in a state where it represents the memory in its current state within the SYCL runtime dependency model and is capable of being used in a way appropriate for the associated SYCL backend. It is undefined behavior to use the native backend object outside of the scope of the host task.

   Throws: An exception with the errc::invalid error code if the accessor imageAcc was not registered with the command group which contained the host task. Must throw an exception with the errc::backend_mismatch error code if Backend != get_backend().

4. *Constraints:* Available only if the optional interoperability function get_native taking a queue is available.

   Returns: The native backend object associated with the queue that the host task was submitted to. If the command group was submitted with a secondary queue and the fall-back was triggered, the queue that is associated with the interop_handle must be the fall-back queue. The native backend object returned must be in a state where it is capable of being used in a way appropriate for the associated SYCL backend. It is undefined behavior to use the native backend object outside of the scope of the host task.

   Throws: Must throw an exception with the errc::backend_mismatch error code if Backend != get_backend().

5. *Constraints:* Available only if the optional interoperability function get_native taking a device is available.

Returns: The native backend object associated with the device that is associated with the queue that the host task was submitted to. The native backend object returned must be in a state where it is capable of being used in a way appropriate for the associated SYCL backend. It is undefined behavior to use the native backend object outside of the scope of the host task.

Throws: Must throw an exception with the errc::backend_mismatch error code if Backend != get_backend().

6. *Constraints:* Available only if the optional interoperability function get_native taking a context is available.

   Returns: The native backend object associated with the context that is associated with the queue that the host task was submitted to. The native backend object returned must be in a state where it is capable of being used in a way appropriate for the associated SYCL backend. It is undefined behavior to use the native backend object outside of the scope of the host task.

   Throws: Must throw an exception with the errc::backend_mismatch error code if Backend != get_backend().

4.10.3. Additions to the handler class

This section describes member functions in the command group handler class that are used with host tasks.

```
1 class handler {
2   ...
3
4       public
5       : template <typename T>
6         void
7         host_task(T&& hostTaskCallable); // (1)
8
9   ...
10 };
```

1. *Effects:* Enqueues an implementation-defined command to the SYCL runtime to invoke hostTaskCallable exactly once. The scheduling of the invocation of hostTaskCallable in relation to other commands enqueued to the SYCL runtime must be in accordance with the dependency model described in Section 3.8.1. Initializes an interop_handle object and passes it to hostTaskCallable when it is invoked if std::is_invocable_v<T, interop_handle> evaluates to true, otherwise invokes hostTaskCallable as a nullary function.

4.11. Kernel bundles

Kernel bundles provide several features to a SYCL application. For implementations that support an online compiler, they provide fine grained control over the online compilation of device code. For example, an application can use a kernel bundle to compile its kernels at a specific time during the application's execution (such as during its initialization), rather than relying on the implementation's default behavior (which may not compile kernels until they are submitted).

Kernel bundles also provide a way for the application to set the values of specialization constants in many kernels before any of them are submitted to a device, which could potentially be more efficient in some cases.

Kernel bundles provide a way for the application to introspect its kernels. For example, an application can use a bundle to query a kernel's work-group size when it is run on a specific device.

Finally, kernel bundles provide an extension point to interoperate with backend and device specific features. Some examples of this include invocation of device specific built-in kernels, online compilation of kernel code with vendor specific options, or interoperation with kernels created with backend APIs.

4.11.1. Overview

A kernel bundle is a high-level abstraction which represents a set of kernels that are associated with a context and can be executed on a number of devices, where each device is associated with that same context. Depending on how a bundle is obtained, it could represent all of the SYCL kernel functions in the SYCL application, or a certain subset of them.

A kernel bundle is composed of one or more device images, where each device image is an indivisible unit of compilation and/or linking. When the SYCL runtime compiles or links one of the kernels represented by the device image, it must also compile or link any other kernels the device image represents. Once a device image is compiled and linked, any of the other kernels which that device image represents may be invoked without further compilation or linking.

Each SYCL kernel function a bundle represents must reside in at least one of the bundle's device images. However, it is not necessary for each device image to contain all of the kernel functions that the bundle represents. The granularity in which kernel functions are grouped into device images is an implementation detail.

To illustrate the intent of device images, a hypothetical implementation could represent an application's kernel functions in both the SPIR-V format and also in a native device code format. The implementation's ahead-of-time compiler in this example produces device images with native code for certain devices and also produces SPIR-V device images for use with other devices. Note that in such an implementation, a particular kernel function could be represented in more than one device image.

An implementation could choose to have all kernel functions from all translation units grouped together in a single device image, to have each kernel function represented in its own device image, or to group kernel functions in some other way.

Each device associated with a kernel bundle must have at least one compatible device image, meaning that the implementation can either invoke the image's kernel functions directly on the device or that the implementation can translate the device image into a format that allows it to invoke the kernel functions.

An outcome of this definition is that each kernel function in a bundle must be invocable on at least one of the devices associated with the bundle. However, it is not necessary for every kernel function in the bundle to be invocable on every associated device.

One common reason why a kernel function might not be invocable on every device associated with a bundle is if the kernel uses optional device features. It's possible that these features are available to only some devices in the bundle.

The use of optional device features could affect how the implementation groups kernels into device images, depending on how these features are represented. For example, consider an implementation where the optional feature is represented in SPIR-V but translation of that SPIR-V into native code will fail if the target device does not support the feature. In such an implementation, kernels that use optional features should not be grouped into the same device image as kernels that do not use these features. Since a device image is an indivisible unit of compilation, doing so would cause a compilation failure if a kernel K1 is invoked on a device D1 if K1 happened to reside in the same device image as another kernel K2 that used a feature which is not supported on device D1.

> See Section 5.7 for more about optional device features.

A SYCL application can obtain a kernel bundle by calling one of the overloads of the `get_kernel_bundle()` free function. Certain backends may provide additional mechanisms for obtaining bundles with other representations. If this is supported, the backend specification document will describe the details.

Once a kernel bundle has been obtained there are a number of free functions for performing compilation, linking and joining. Once a bundle is compiled and linked, the application can invoke kernels from the bundle by calling `handler::use_kernel_bundle()` as described in Section 4.9.4.4.

4.11.2. Synopsis

```
namespace sycl {

enum class bundle_state : /* unspecified */ { input, object, executable };

class kernel_id { /* ... */
};

template <bundle_state State> class kernel_bundle { /* ... */
};

template <typename KernelName> kernel_id get_kernel_id();

std::vector<kernel_id> get_kernel_ids();

template <bundle_state State>
kernel_bundle<State> get_kernel_bundle(const context& ctxt);

template <bundle_state State>
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<kernel_id>& kernelIds);

template <typename KernelName, bundle_state State>
kernel_bundle<State> get_kernel_bundle(const context& ctxt);

template <bundle_state State>
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<device>& devs);

template <bundle_state State>
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<device>& devs,
                                       const std::vector<kernel_id>& kernelIds);

template <typename KernelName, bundle_state State>
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<device>& devs);

template <bundle_state State, typename Selector>
kernel_bundle<State> get_kernel_bundle(const context& ctxt, Selector selector);

template <bundle_state State, typename Selector>
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<device>& devs,
                                       Selector selector);
```

```
45
46 template <bundle_state State> bool has_kernel_bundle(const context& ctxt);
47
48 template <bundle_state State>
49 bool has_kernel_bundle(const context& ctxt,
50                        const std::vector<kernel_id>& kernelIds);
51
52 template <typename KernelName, bundle_state State>
53 bool has_kernel_bundle(const context& ctxt);
54
55 template <bundle_state State>
56 bool has_kernel_bundle(const context& ctxt, const std::vector<device>& devs);
57
58 template <bundle_state State>
59 bool has_kernel_bundle(const context& ctxt, const std::vector<device>& devs,
60                        const std::vector<kernel_id>& kernelIds);
61
62 template <typename KernelName, bundle_state State>
63 bool has_kernel_bundle(const context& ctxt, const std::vector<device>& devs);
64
65 bool is_compatible(const std::vector<kernel_id>& kernelIds, const device& dev);
66
67 template <typename KernelName> bool is_compatible(const device& dev);
68
69 template <bundle_state State>
70 kernel_bundle<State> join(const std::vector<kernel_bundle<State>>& bundles);
71
72 kernel_bundle<bundle_state::object>
73 compile(const kernel_bundle<bundle_state::input>& inputBundle,
74         const property_list& propList = {});
75
76 kernel_bundle<bundle_state::object>
77 compile(const kernel_bundle<bundle_state::input>& inputBundle,
78         const std::vector<device>& devs, const property_list& propList = {});
79
80 kernel_bundle<bundle_state::executable>
81 link(const kernel_bundle<bundle_state::object>& objectBundle,
82      const property_list& propList = {});
83
84 kernel_bundle<bundle_state::executable>
85 link(const std::vector<kernel_bundle<bundle_state::object>>& objectBundles,
86      const property_list& propList = {});
87
88 kernel_bundle<bundle_state::executable>
89 link(const kernel_bundle<bundle_state::object>& objectBundle,
90      const std::vector<device>& devs, const property_list& propList = {});
91
92 kernel_bundle<bundle_state::executable>
93 link(const std::vector<kernel_bundle<bundle_state::object>>& objectBundles,
94      const std::vector<device>& devs, const property_list& propList = {});
95
96 kernel_bundle<bundle_state::executable>
97 build(const kernel_bundle<bundle_state::input>& inputBundle,
98       const property_list& propList = {});
99
100 kernel_bundle<bundle_state::executable>
```

```
101 build(const kernel_bundle<bundle_state::input>& inputBundle,
102       const std::vector<device>& devs, const property_list& propList = {});
103
104 } // namespace sycl
```

4.11.3. Fixed-function built-in kernels

SYCL allows a SYCL backend to expose fixed functionality as non-programmable built-in kernels. The availability and behavior of these built-in kernels are backend specific and are not required to follow the SYCL execution and memory models. However, the basic interface is common to all backends.

4.11.4. Bundle states

A kernel bundle can be in one of three different bundle states which are represented by an enum class called `bundle_state`. Table 136 describes the semantics of these three states.

The states form a progression. A bundle in `bundle_state::input` can be translated into `bundle_state::object` by online compilation of the bundle. A bundle in `bundle_state::object` can be translated into `bundle_state::executable` by online linking.

Each implementation is free to define the "online compilation" and "online linking" operations as it sees fit, so long as this progression of bundle states is preserved and so long as the bundles in each state behave as specified.

There is no requirement that an implementation must expose kernels in `bundle_state::input` or `bundle_state::object`. In fact, an implementation could expose some kernels in these states but not others. For example, this behavior could be controlled by implementation specific options to the ahead-of-time compiler. Kernels that are not exposed in these states cannot be online compiled or online linked by the application.

All kernels defined in the SYCL application, however, must be exposed in `bundle_state::executable` because this is the only state that allows a kernel to be invoked on a device. Device built-in kernels are also exposed in `bundle_state::executable`.

If an application exposes a bundle in `bundle_state::input` for a device D, then the implementation must also provide an online compiler for device D. Therefore, an application need not explicitly test for `aspect::online_compiler` if it successfully obtains a bundle in `bundle_state::input` for that device. Likewise, an implementation must provide an online linker for device D if it exposes a bundle in `bundle_state::object` for device D.

Table 136. Enumeration of possible bundle states

Bundle State	Description
`bundle_state::input`	The device images in the kernel bundle have a format that must be compiled and linked before their kernels can be invoked. For example, an implementation could use this state for device images that are stored in an intermediate language format or for device images that are stored as source code strings.
`bundle_state::object`	The device images in the kernel bundle have a format that must be linked before their kernels can be invoked.
`bundle_state::executable`	The device images in the kernel bundle are in a format that allows them to be invoked on a device. For example, an implementation could use this state for device images that have been compiled into the device's native code.

4.11.5. Kernel identifiers

Some of the functions related to kernel bundles take an input parameter of type `kernel_id` which identifies a kernel. A synopsis of the `kernel_id` class is shown below along with a description of its member functions. Additionally, this class provides the common special member functions and common member functions that are listed in Section 4.5.2 in Table 7 and Table 8, respectively.

As with all SYCL objects that have the common reference semantics, kernel identifiers are equality comparable. Two `kernel_id` objects compare equal if and only if they refer to the same application kernel or to the same device built-in kernel.

There is no public default constructor for this class.

```
namespace sycl {

class kernel_id {
 public:
  kernel_id() = delete;

  const char* get_name() const noexcept;
};

} // namespace sycl
```

```
const char* get_name() const noexcept;
```

Returns: An implementation-defined null-terminated string containing the name of the kernel. There is no guarantee that this name is unique amongst all the kernels, nor is there a guarantee that the name is stable from one run of the application to another. The lifetime of the memory containing the name is unspecified.

In practice, the lifetime of the memory containing the name will typically extend until the application terminates, unless the kernel associated with the name comes from a dynamic library. In this case, the lifetime of the memory may end if the dynamic library is unloaded.

4.11.6. Obtaining a kernel identifier

An application can obtain an identifier for a kernel that is defined in the application by calling one of the following free functions, or it may obtain an identifier for a device's built-in kernels by querying the device with `info::device::built_in_kernel_ids`.

```
template <typename KernelName> kernel_id get_kernel_id();
```

Preconditions: The template parameter `KernelName` must be the type kernel name of a kernel that is defined in the SYCL application. Since lambda functions have no standard type name, kernels defined as lambda functions must specify a `KernelName` in their kernel invocation command in order to obtain their identifier via this function. Applications which call `get_kernel_id()` for a `KernelName` that is not defined are ill formed, and the implementation must issue a diagnostic in this case.

Returns: The identifier of the kernel associated with `KernelName`.

```
std::vector<kernel_id> get_kernel_ids();
```

Returns: A vector with the identifiers for all kernels defined in the SYCL application. This does not include identifiers for any device built-in kernels.

4.11.7. Obtaining a kernel bundle

A SYCL application can obtain a kernel bundle by calling one of the overloads of the free function `get_kernel_bundle()`. The implementation may return a bundle that consists of device images that were created by the ahead-of-time compiler, or it may call the online compiler or linker to create the bundle's device images in the requested state. A bundle may also contain device images that represent a device's built-in kernels.

When `get_kernel_bundle()` is used to obtain a kernel bundle in `bundle_state::object` or `bundle_state::executable`, any specialization constants in the bundle will have their default values.

```
template <bundle_state State>
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<device>& devs);
```

Returns: A kernel bundle in state `State` which contains all of the kernels in the application which are compatible with at least one of the devices in `devs`. This does not include any device built-in kernels. The bundle's set of associated devices is `devs` (with any duplicate devices removed).

Since the implementation may not represent all kernels in `bundle_state::input` or `bundle_state::object`, calling this function with one of those states may return a bundle that is missing some of the application's kernels.

Throws:

- An `exception` with the `errc::invalid` error code if any of the devices in `devs` is not one of devices contained by the context `ctxt` or is not a descendent device of some device in `ctxt`.
- An `exception` with the `errc::invalid` error code if the `devs` vector is empty.
- An `exception` with the `errc::invalid` error code if `State` is `bundle_state::input` and any device in `devs` does not have `aspect::online_compiler`.
- An `exception` with the `errc::invalid` error code if `State` is `bundle_state::object` and any device in `devs` does not have `aspect::online_linker`.
- An `exception` with the `errc::build` error code if `State` is `bundle_state::object` or `bundle_state::executable`, if the implementation needs to perform an online compile or link, and if the online compile or link fails.

```
template <bundle_state State>
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<device>& devs,
                                       const std::vector<kernel_id>& kernelIds);
```

Returns: A kernel bundle in state `State` which contains all of the device images that are compatible with at least one of the devices in `devs`, further filtered to contain only those device images that contain at least one of the kernels with the given identifiers. These identifiers may represent kernels that are defined in the application, device built-in kernels, or a mixture of the two. Since the device images may group many kernels together, the returned bundle may contain additional kernels beyond those that are requested in `kernelIds`. The bundle's set of associated devices is `devs` (with duplicate devices removed).

Since the implementation may not represent all kernels in `bundle_state::input` or `bundle_state::object`, calling this function with one of those states may return a bundle that is missing some of the kernels in `kernelIds`. The application can test for this via `kernel_bundle::has_kernel()`.

Throws:

- An `exception` with the `errc::invalid` error code if any of the kernels identified by `kernelIds` are incompatible with all devices in `devs`.
- An `exception` with the `errc::invalid` error code if any of the devices in `devs` is not one of devices contained by the context `ctxt` or is not a descendent device of some device in `ctxt`.
- An `exception` with the `errc::invalid` error code if the `devs` vector is empty.
- An `exception` with the `errc::invalid` error code if `State` is `bundle_state::input` and any device in `devs` does not have `aspect::online_compiler`.
- An `exception` with the `errc::invalid` error code if `State` is `bundle_state::object` and any device in `devs` does not have `aspect::online_linker`.
- An `exception` with the `errc::build` error code if `State` is `bundle_state::object` or `bundle_state::executable`, if the implementation needs to perform an online compile or link, and if the online compile or link fails.

```
template <bundle_state State, typename Selector>
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<device>& devs,
                                       Selector selector);
```

Preconditions: The `selector` must be a unary predicate whose return value is convertible to `bool` and whose parameter is `const device_image<State>&`.

Effects: The predicate function `selector` is called once for every device image in the application of state `State` which is compatible with at least one of the devices in `devs`. The function's return value determines whether a device image is included in the new kernel bundle. The `selector` is called only for device images that contain kernels defined in the application, not for device images that contain device built-in kernels.

Returns: A kernel bundle in state `State` which contains all of the device images for which the `selector` returns `true`. The bundle's set of associated devices is `devs` (with duplicate devices removed).

Throws:

- An `exception` with the `errc::invalid` error code if any of the devices in `devs` is not one of devices contained by the context `ctxt` or is not a descendent device of some device in `ctxt`.
- An `exception` with the `errc::invalid` error code if the `devs` vector is empty.
- An `exception` with the `errc::invalid` error code if `State` is `bundle_state::input` and any device in `devs` does not have `aspect::online_compiler`.
- An `exception` with the `errc::invalid` error code if `State` is `bundle_state::object` and any device in `devs` does not have `aspect::online_linker`.

This function is intended to be used in conjunction with backend specific APIs that allow the application to choose device images based on backend specific criteria.

This function does not call the online compiler or linker to translate device images into state `State`. If the application wants to select specific device images and also compile or link them into the desired state, it can do this by calling `compile()` or `link()` and then optionally joining several bundles together with `join()`.

```
template <bundle_state State> // (1)
kernel_bundle<State> get_kernel_bundle(const context& ctxt);

template <bundle_state State> // (2)
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<kernel_id>& kernelIds);

template <bundle_state State, typename Selector> // (3)
kernel_bundle<State> get_kernel_bundle(const context& ctxt, Selector selector);
```

1. Equivalent to `get_kernel_bundle<State>(ctxt, ctxt.get_devices())`.
2. Equivalent to `get_kernel_bundle<State>(ctxt, ctxt.get_devices(), kernelIds)`.
3. Equivalent to `get_kernel_bundle<State>(ctxt, ctxt.get_devices(), selector)`.

```
template <typename KernelName, bundle_state State> // (1)
kernel_bundle<State> get_kernel_bundle(const context& ctxt);

template <typename KernelName, bundle_state State> // (2)
kernel_bundle<State> get_kernel_bundle(const context& ctxt,
                                       const std::vector<device>& devs);
```

Preconditions: The template parameter `KernelName` must be the type kernel name of a kernel that is defined in the SYCL application. Since lambda functions have no standard type name, kernels defined as lambda functions must specify a `KernelName` in their kernel invocation command in order to use these functions. Applications which call these functions for a `KernelName` that is not defined are ill formed, and the implementation must issue a diagnostic in this case.

1. Equivalent to `get_kernel_bundle<State>(ctxt, ctxt.get_devices(), {get_kernel_id<KernelName>()})`.
2. Equivalent to `get_kernel_bundle<State>(ctxt, devs, {get_kernel_id<KernelName>()})`.

4.11.8. Querying if a kernel bundle exists

Most overloads of `get_kernel_bundle()` have a matching overload of the free function `has_kernel_bundle()` which checks to see if a kernel bundle with the requested characteristics exists.

```
template <bundle_state State>
bool has_kernel_bundle(const context& ctxt, const std::vector<device>& devs);
```

Returns: `true` only if all of the following are true:

- The application defines at least one kernel that is compatible with at least one of the devices in `devs`, and that kernel can be represented in a device image of state `State`.
- If `State` is `bundle_state::input`, all devices in `devs` have `aspect::online_compiler`.
- If `State` is `bundle_state::object`, all devices in `devs` have `aspect::online_linker`.

Throws:

- An `exception` with the `errc::invalid` error code if any of the devices in `devs` is not one of devices contained by the context `ctxt` or is not a descendent device of some device in `ctxt`.
- An `exception` with the `errc::invalid` error code if the `devs` vector is empty.

```
template <bundle_state State>
bool has_kernel_bundle(const context& ctxt, const std::vector<device>& devs,
                       const std::vector<kernel_id>& kernelIds);
```

Returns: `true` only if all of the following are true:

- Each of the kernels in `kernelIds` can be represented in a device image of state `State`.
- Each of the kernels in `kernelIds` is compatible with at least one of the devices in `devs`.
- If `State` is `bundle_state::input`, all devices in `devs` have `aspect::online_compiler`.
- If `State` is `bundle_state::object`, all devices in `devs` have `aspect::online_linker`.

Throws:

- An `exception` with the `errc::invalid` error code if any of the devices in `devs` is not one of devices contained by the context `ctxt` or is not a descendent device of some device in `ctxt`.
- An `exception` with the `errc::invalid` error code if the `devs` vector is empty.

```
template <bundle_state State> // (1)
bool has_kernel_bundle(const context& ctxt);

template <bundle_state State> // (2)
bool has_kernel_bundle(const context& ctxt,
                       const std::vector<kernel_id>& kernelIds);
```

1. Equivalent to `has_kernel_bundle(ctxt, ctxt.get_devices())`.
2. Equivalent to `has_kernel_bundle<State>(ctxt, ctxt.get_devices(), kernelIds)`.

```
template <typename KernelName, bundle_state State> // (1)
bool has_kernel_bundle(const context& ctxt);

template <typename KernelName, bundle_state State> // (2)
bool has_kernel_bundle(const context& ctxt, const std::vector<device>& devs);
```

Preconditions: The template parameter `KernelName` must be the type kernel name of a kernel that is defined in the SYCL application. Since lambda functions have no standard type name, kernels defined as lambda functions must specify a `KernelName` in their kernel invocation command in order to use these functions. Applications which call these functions for a `KernelName` that is not defined are ill formed, and the implementation must issue a diagnostic in this case.

1. Equivalent to `has_kernel_bundle<State>(ctxt, {get_kernel_id<KernelName>()})`.
2. Equivalent to `has_kernel_bundle<State>(ctxt, devs, {get_kernel_id<KernelName>()})`.

4.11.9. Querying if a kernel is compatible with a device

The following free functions allow an application to test whether a particular kernel is compatible with a device. A kernel that is defined in the application is compatible with a device unless:

- It uses optional features which are not supported on the device, as described in Section 5.7; or
- It is decorated with a `[[sycl::device_has()]]` C++ attribute that lists an aspect that is not supported by the device, as described in Section 5.8.1.

A device built-in kernel is only compatible with the device for which it is built-in.

```
bool is_compatible(const std::vector<kernel_id>& kernelIds, const device& dev);
```

Returns: `true` if all of the kernels identified by `kernelIds` are compatible with the device `dev`.

```
template <typename KernelName> bool is_compatible(const device& dev);
```

Preconditions: The template parameter `KernelName` must be the type kernel name of a kernel that is defined in the SYCL application. Since lambda functions have no standard type name, kernels defined as lambda functions must specify a `KernelName` in their kernel invocation command in order to use this function. Applications which call this function for a `KernelName` that is not defined are ill formed, and the implementation must issue a diagnostic in this case.

Equivalent to `is_compatible<State>({get_kernel_id<KernelName>()}, dev)`.

4.11.10. Joining kernel bundles

Two or more kernel bundles of the same state may be joined together into a single composite bundle. Joining bundles together is not the same as online compiling or linking because it produces a new bundle in the same state as its inputs. Rather, joining creates the union of all the devices images from the input bundles, eliminates duplicate copies of the same device image, and creates a new bundle from the result.

```
template <bundle_state State>
kernel_bundle<State> join(const std::vector<kernel_bundle<State>>& bundles);
```

Returns: A new kernel bundle that contains a copy of all the device images in the input `bundles` with duplicates removed. The new bundle has the same associated context and the same set of associated devices as those in `bundles`.

Throws:

- An `exception` with the `errc::invalid` error code if the bundles in `bundles` do not all have the same associated context or do not all have the same set of associated devices.

4.11.11. Online compiling and linking

If the implementation provides an online compiler or linker, a SYCL application can use the free functions defined in this section to transform a kernel bundle from `bundle_state::input` into a bundle of state `bundle_state::object` or to transform a bundle from `bundle_state::object` into a bundle of state `bundle_state::executable`.

An application can query whether the implementation provides an online compiler or linker by querying a device for `aspect::online_compiler` or `aspect::online_linker`.

All of the functions in this section accept a `property_list` parameter, which can affect the semantics of the compilation or linking operation. The core SYCL specification does not currently define any such properties, but vendors may specify these properties as an extension.

```
kernel_bundle<bundle_state::object>
compile(const kernel_bundle<bundle_state::input>& inputBundle,
        const std::vector<device>& devs, const property_list& propList = {});
```

Effects: The device images from `inputBundle` are translated into one or more new device images of state `bundle_state::object`, and a new kernel bundle is created to contain these new device images. The new bundle represents all of the kernels in `inputBundles` that are compatible with at least one of the devices in `devs`. Any remaining kernels (those that are not compatible with any of the devices `devs`) are not compiled and not represented in the new kernel bundle.

The new bundle has the same associated context as `inputBundle`, and the new bundle's set of associated devices is `devs` (with duplicate devices removed).

Returns: The new kernel bundle.

Throws:

- An `exception` with the `errc::invalid` error code if any of the devices in `devs` are not in the set of associated devices for `inputBundle` (as defined by `kernel_bundle::get_devices()`) or if the `devs` vector is empty.
- An `exception` with the `errc::build` error code if the online compile operation fails.

```
kernel_bundle<bundle_state::executable>
link(const std::vector<kernel_bundle<bundle_state::object>>& objectBundles,
     const std::vector<device>& devs, const property_list& propList = {});
```

Effects: Duplicate device images from `objectBundles` are eliminated as though they were joined via `join()`, then the remaining device images are translated into one or more new device images of state `bundle_state::executable`, and a new kernel bundle is created to contain these new device images. The new bundle represents all of the kernels in `objectBundles` that are compatible with at least one of the devices in `devs`. Any remaining kernels (those that are not compatible with any of the devices in `devs`) are not linked and not represented in the new bundle.

The new bundle has the same associated context as those in `objectBundles`, and the new bundle's set of associated devices is `devs` (with duplicate devices removed).

Returns: The new kernel bundle.

Throws:

- An `exception` with the `errc::invalid` error code if the bundles in `objectBundles` do not all have the same associated context.
- An `exception` with the `errc::invalid` error code if any of the devices in `devs` are not in the set of associated devices for any of the bundles in `objectBundles` (as defined by `kernel_bundle::get_devices()`) or if the `devs` vector is empty.
- An `exception` with the `errc::build` error code if the online link operation fails.

```
kernel_bundle<bundle_state::executable>
build(const kernel_bundle<bundle_state::input>& inputBundle,
      const std::vector<device>& devs, const property_list& propList = {});
```

Effects: This function performs both an online compile and link operation, translating a kernel bundle of state `bundle_state::input` into a bundle of state `bundle_state::executable`. The device images from `inputBundle` are translated into one or more new device images of state `bundle_state::executable`, and a new bundle is created to contain these new device images. The new bundle represents all of the kernels in `inputBundle` that are compatible with at least one of the devices in `devs`. Any remaining kernels (those that are not compatible with any of the devices `devs`) are not compiled or linked and are not represented in the new bundle.

The new bundle has the same associated context as inputBundle, and the new bundle's set of associated devices is devs (with duplicate devices removed).

Returns: The new kernel bundle.

Throws:

- An exception with the errc::invalid error code if any of the devices in devs are not in the set of associated devices for inputBundle (as defined by kernel_bundle::get_devices()) or if the devs vector is empty.
- An exception with the errc::build error code if the online compile or link operations fail.

```
kernel_bundle<bundle_state::object> // (1)
compile(const kernel_bundle<bundle_state::input>& inputBundle,
        const property_list& propList = {});

kernel_bundle<bundle_state::executable> // (2)
link(const kernel_bundle<bundle_state::object>& objectBundle,
     const std::vector<device>& devs, const property_list& propList = {});

kernel_bundle<bundle_state::executable> // (3)
link(const std::vector<kernel_bundle<bundle_state::object>>& objectBundles,
     const property_list& propList = {});

kernel_bundle<bundle_state::executable> // (4)
link(const kernel_bundle<bundle_state::object>& objectBundle,
     const property_list& propList = {});

kernel_bundle<bundle_state::executable> // (5)
build(const kernel_bundle<bundle_state::input>& inputBundle,
      const property_list& propList = {});
```

1. Equivalent to compile(inputBundle, inputBundle.get_devices(), propList).
2. Equivalent to link({objectBundle}, devs, propList).
3. Equivalent to link(objectBundles, devs, propList), where devs is the intersection of associated devices in common for all bundles in objectBundles.
4. Equivalent to link({objectBundle}, objectBundle.get_devices(), propList).
5. Equivalent to build(inputBundle, inputBundle.get_devices(), propList).

4.11.12. The kernel_bundle class

A synopsis of the kernel_bundle class is shown below. Additionally, this class provides the common special member functions and common member functions that are listed in Section 4.5.2 in Table 7 and Table 8, respectively.

As with all SYCL objects that have the common reference semantics, kernel bundles are equality comparable. Two bundles of the same bundle state are considered to be equal if they are associated with the same context, have the same set of associated devices, and contain the same set of device images.

There is no public default constructor for this class.

```
1 namespace sycl {
2
3 class kernel { /* ... */
```

```
};

template <bundle_state State> class kernel_bundle {
 public:
  using device_image_iterator = __unspecified__;

  kernel_bundle() = delete;

  bool empty() const noexcept;

  backend get_backend() const noexcept;

  context get_context() const noexcept;

  std::vector<device> get_devices() const noexcept;

  bool has_kernel(const kernel_id& kernelId) const noexcept;

  bool has_kernel(const kernel_id& kernelId, const device& dev) const noexcept;

  template <typename KernelName> bool has_kernel() const noexcept;

  template <typename KernelName>
  bool has_kernel(const device& dev) const noexcept;

  std::vector<kernel_id> get_kernel_ids() const;

  /* Available only when: (State == bundle_state::executable) */
  kernel get_kernel(const kernel_id& kernelId) const;

  /* Available only when: (State == bundle_state::executable) */
  template <typename KernelName> kernel get_kernel() const;

  bool contains_specialization_constants() const noexcept;

  bool native_specialization_constant() const noexcept;

  template <auto& SpecName> bool has_specialization_constant() const noexcept;

  /* Available only when: (State == bundle_state::input) */
  template <auto& SpecName>
  void set_specialization_constant(
      typename std::remove_reference_t<decltype(SpecName)>::value_type value);

  template <auto& SpecName>
  typename std::remove_reference_t<decltype(SpecName)>::value_type
  get_specialization_constant() const;

  device_image_iterator begin() const;

  device_image_iterator end() const;
};

} // namespace sycl
```

4.11.12.1. Queries

The following member functions provide various queries for a kernel bundle.

```
bool empty() const noexcept;
```

Returns: `true` only if the kernel bundle contains no device images.

```
backend get_backend() const noexcept;
```

Returns: The backend that is associated with the kernel bundle.

```
context get_context() const noexcept;
```

Returns: The context that is associated with the kernel bundle.

```
std::vector<device> get_devices() const noexcept;
```

Returns: The set of devices that is associated with the kernel bundle.

```
bool has_kernel(const kernel_id& kernelId) const noexcept; // (1)
bool has_kernel(const kernel_id& kernelId,
                const device& dev) const noexcept; // (2)
```

1. *Returns:* `true` only if the kernel bundle contains the kernel identified by `kernelId`.
2. *Returns:* `true` only if the kernel bundle contains the kernel identified by `kernelId` and if that kernel is compatible with the device `dev`.

```
template <typename KernelName> bool has_kernel() const noexcept; // (1)

template <typename KernelName>
bool has_kernel(const device& dev) const noexcept; // (2)
```

Preconditions: The template parameter `KernelName` must be the type kernel name of a kernel that is defined in the SYCL application. Since lambda functions have no standard type name, kernels defined as lambda functions must specify a `KernelName` in their kernel invocation command in order to use these functions. Applications which call these functions for a `KernelName` that is not defined are ill formed, and the implementation must issue a diagnostic in this case.

1. *Returns:* `true` only if the kernel bundle contains the kernel identified by `KernelName`.
2. *Returns:* `true` only if the kernel bundle contains the kernel identified by `KernelName` and if that kernel is compatible with the device `dev`.

```
std::vector<kernel_id> get_kernel_ids() const;
```

Returns: A vector of the identifiers for all kernels that are contained in the kernel bundle.

```
kernel get_kernel(const kernel_id& kernelId) const;
```

Preconditions: This member function is only available if the kernel bundle's state is `bundle_state::executable`.

Returns: A `kernel` object representing the kernel identified by `kernelId`, which resides in the bundle.

Throws:

- An `exception` with the `errc::invalid` error code if the kernel bundle does not contain the kernel identified by `kernelId`.

```
template <typename KernelName> kernel get_kernel() const;
```

Preconditions: This member function is only available if the kernel bundle's state is `bundle_state::executable`. The template parameter `KernelName` must be the type kernel name of a kernel that is defined in the SYCL application. Since lambda functions have no standard type name, kernels defined as lambda functions must specify a `KernelName` in their kernel invocation command in order to use this function. Applications which call this function for a `KernelName` that is not defined are ill formed, and the implementation must issue a diagnostic in this case.

Returns: A `kernel` object representing the kernel identified by `KernelName`, which resides in the bundle.

Throws:

- An `exception` with the `errc::invalid` error code if the kernel bundle does not contain the kernel identified by `KernelName`.

4.11.12.2. Specialization constant support

The following member functions allow an application to manipulate specialization constants that are used in the device images of a kernel bundle. Applications can set the value of specialization constants in a kernel bundle whose state is `bundle_state::input` and then online compile that bundle into `bundle_state::object` or `bundle_state::executable`. The value of the specialization constants then become fixed in the compiled bundle and cannot be changed. Specialization constants that have not had their values set by the time the bundle is compiled take their default values.

It is expected that many implementations will use an intermediate language representation for a bundle in state `bundle_state::input` such as SPIR-V, and the intermediate language will have native support for specialization constants. However, implementations that do not have such native support must still support specialization constants in some other way.

```
bool contains_specialization_constants() const noexcept;
```

Returns: `true` only if the kernel bundle contains at least one device image which uses a specialization constant.

```
bool native_specialization_constant() const noexcept;
```

Returns: `true` only if the kernel bundle contains at least one device image which uses a specialization constant and all specialization constants used in all of the bundle's device images are native specialization constants.

```
template <auto& SpecName> bool has_specialization_constant() const noexcept;
```

Returns: `true` if any device image in the kernel bundle uses the specialization constant whose address is `SpecName`.

```
template <auto& SpecName>
void set_specialization_constant(
    typename std::remove_reference_t<decltype(SpecName)>::value_type value);
```

Preconditions: This member function is only available if the kernel bundle's state is `bundle_state::input`.

Effects: Sets the value of the specialization constant whose address is `SpecName` for this bundle. If the specialization constant's value was previously set in this bundle, the value is overwritten.

The new value applies to all device images in the bundle. It is allowed to set the value of a specialization constant even if no device image in the bundle uses it; doing so has no effect on the execution of kernels from that bundle.

```
template <auto& SpecName>
typename std::remove_reference_t<decltype(SpecName)>::value_type
get_specialization_constant() const;
```

Returns: The value of the specialization constant whose address is `SpecName` for this kernel bundle. The value returned is as follows:

- If the value of this specialization constant was previously set in this bundle, that value is returned. Otherwise,
- If this bundle is the result of compiling, linking or joining another bundle and this specialization constant was set in that other bundle prior to compiling, linking or joining; then that value is returned. Otherwise,
- The specialization constant's default value is returned.

4.11.12.3. Device image support

The following member type and functions allow iteration over the device images contained by the kernel bundle.

```
using device_image_iterator = __unspecified__;
```

An iterator type that satisfies the C++ requirements of `LegacyForwardIterator`. The iterator's referenced type is `const device_image<State>`, where `State` is the same state as the containing `kernel_bundle`.

```
device_image_iterator begin() const; // (1)
device_image_iterator end() const;   // (2)
```

1. *Returns:* An iterator to the first device image contained by the kernel bundle.
2. *Returns:* An iterator to one past the last device image contained by the kernel bundle.

4.11.13. The `kernel` class

A synopsis of the `kernel` class is shown below. Additionally, this class provides the common special member functions and common member functions that are listed in Section 4.5.2 in Table 7 and Table 8, respectively.

There is no public default constructor for this class.

```
namespace sycl {

class kernel {
 public:
  kernel() = delete;

  backend get_backend() const noexcept;

  context get_context() const;

  kernel_bundle<bundle_state::executable> get_kernel_bundle() const;

  template <typename Param> typename Param::return_type get_info() const;

  template <typename Param>
  typename Param::return_type get_info(const device& dev) const;

  template <typename Param>
  typename Param::return_type get_backend_info() const;
};

} // namespace sycl
```

4.11.13.1. Queries

The following member functions provide various queries for a kernel.

```
backend get_backend() const noexcept;
```

Returns: The backend associated with this kernel.

```
context get_context() const;
```

Returns: The context associated with this kernel.

```
kernel_bundle<bundle_state::executable> get_kernel_bundle() const;
```

Returns: The kernel bundle that contains this kernel.

```
template <typename Param> typename Param::return_type get_info() const;
```

Preconditions: The `Param` must be one of the `info::kernel` descriptors defined in Table 137, and the type alias `Param::return_type` must be defined in accordance with that table.

Returns: Information about the kernel that is not specific to the device on which it is invoked.

```
template <typename Param>
typename Param::return_type get_info(const device& dev) const;
```

Preconditions: The `Param` must be one of the `info::kernel_device_specific` descriptors defined in Table 138, and the type alias `Param::return_type` must be defined in accordance with that table.

Returns: Information about the kernel that applies when the kernel is invoked on the device `dev`.

Throws:

- An `exception` with the `errc::invalid` error code if the kernel is not compatible with device `dev` (as defined by `is_compatible()`).

```
template <typename Param> typename Param::return_type get_backend_info() const;
```

Preconditions: The `Param` must be one of a descriptor defined by a SYCL backend specification.

Returns: Backend specific information about the kernel that is not specific to the device on which it is invoked.

Throws:

- An `exception` with the `errc::backend_mismatch` error code if the SYCL backend that corresponds with `Param` is different from the SYCL backend that is associated with this kernel bundle.

4.11.13.2. Kernel information descriptors

A kernel can be queried for information using the `get_info()` member function, specifying one of the info parameters in `info::kernel`. All info parameters in `info::kernel` are specified in Table 137 and the synopsis for `info::kernel` is described in Section A.5.

Table 137. Kernel class information descriptors

Kernel Descriptors	Return type	Description
`info::kernel::num_args`	`uint32_t`	This descriptor may only be used to query a kernel that resides in a kernel bundle that was constructed using a backend specific interoperability function or to query a device built-in kernel, and the semantics of this descriptor are defined by each SYCL backend specification. Attempting to use this descriptor for other kernels throws an `exception` with the `errc::invalid` error code.
`info::kernel::attributes`	`std::string`	Return any attributes specified on a kernel function (as defined in Section 5.8).

A kernel can also be queried for device specific information using the `get_info()` member function, specifying one of the info parameters in `info::kernel_device_specific`. All info parameters in `info::kernel_device_specific` are specified in Table 138. The synopsis for `info::kernel_device_specific` is described in Section A.5.

Table 138. Device-specific kernel information descriptors

Device-specific Kernel Information Descriptors	Return type	Description
`info::kernel_device_specific::global_work_size`	`range<3>`	This descriptor may only be used if the device type is `device_type::custom` or if the kernel is a built-in kernel. The exact semantics of this descriptor are defined by each SYCL backend specification, but the intent is to return the kernel's maximum global work size. Attempting to use this descriptor for other devices or kernels throws an `exception` with the `errc::invalid` error code.
`info::kernel_device_specific::work_group_size`	`size_t`	Returns the maximum number of work-items in a work-group that can be used to execute a kernel on a specific device.
`info::kernel_device_specific::compile_work_group_size`	`range<3>`	Returns the work-group size specified by the device compiler if applicable, otherwise returns `{0,0,0}`.
`info::kernel_device_specific::preferred_work_group_size_multiple`	`size_t`	Returns a value, of which work-group size is preferred to be a multiple, for executing a kernel on a particular device. This is a performance hint. The value must be less than or equal to that returned by `info::kernel_device_specific::work_group_size`.
`info::kernel_device_specific::private_mem_size`	`size_t`	Returns the minimum amount of private memory, in bytes, used by each work-item in the kernel. This value may include any private memory needed by an implementation to execute the kernel, including that used by the language built-ins and variables declared inside the kernel in the private address space.
`info::kernel_device_specific::max_num_sub_groups`	`uint32_t`	Returns the maximum number of sub-groups for this kernel.
`info::kernel_device_specific::compile_num_sub_groups`	`uint32_t`	Returns the number of sub-groups specified by the kernel, or 0 (if not specified).
`info::kernel_device_specific::max_sub_group_size`	`uint32_t`	Returns the maximum sub-group size for this kernel.
`info::kernel_device_specific::compile_sub_group_size`	`uint32_t`	Returns the required sub-group size specified by the kernel, or 0 (if not specified).

4.11.14. The device_image class

A synopsis of the device_image class is shown below. Additionally, this class provides the common special member functions and common member functions that are listed in Section 4.5.2 in Table 7 and Table 8, respectively.

```
namespace sycl {

template <bundle_state State> class device_image {
 public:
  device_image() = delete;

  bool has_kernel(const kernel_id& kernelId) const noexcept;

  bool has_kernel(const kernel_id& kernelId, const device& dev) const noexcept;
};

} // namespace sycl
```

There is no public constructor for this class.

```
bool has_kernel(const kernel_id& kernelId) const noexcept; // (1)
bool has_kernel(const kernel_id& kernelId,
                const device& dev) const noexcept; // (2)
```

1. *Returns:* true only if the device image contains the kernel identified by kernelId.
2. *Returns:* true only if the device image contains the kernel identified by kernelId and if that kernel is compatible with the device dev.

4.11.15. Example usage

This section provides some examples showing typical use cases for kernel bundles. These examples are intended to clarify the definition of the kernel bundle interfaces, but the content of this section is non-normative.

4.11.15.1. Controlling the timing of online compilation

In some cases an application may want to pre-compile its kernels before submitting them to a device. This gives the application control over when the overhead of online compilation happens, rather than relying on the default behavior (which may cause the online compilation to happen at the point when the kernel is submitted to a device). The following example shows how this can be achieved.

```
#include <sycl/sycl.hpp>
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

int main() {
  queue myQueue;
  auto myContext = myQueue.get_context();

  // This call to get_kernel_bundle() forces an online compilation of all the
  // application's kernels for the device in "myContext", unless those kernels
  // were already compiled for that device by the ahead-of-time compiler.
  auto myBundle = get_kernel_bundle<bundle_state::executable>(myContext);
```

```
12
13   myQueue.submit([&](handler& cgh) {
14     // Calling use_kernel_bundle() causes the parallel_for() below to use the
15     // pre-compiled kernel from "myBundle".
16     cgh.use_kernel_bundle(myBundle);
17
18     cgh.parallel_for(range { 1024 }, ([=](item index) {
19                         // kernel code
20                       }));
21   });
22
23   myQueue.wait();
24 }
```

4.11.15.2. Specialization constants

An application can use a kernel bundle to set the values of specialization constants in several kernels before any of them are submitted for execution.

```
1  #include <sycl/sycl.hpp>
2  using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names
3
4  // Forward declare names for our two kernels.
5  class MyKernel1;
6  class MyKernel2;
7
8  extern int get_width();
9  extern int get_height();
10
11 // Declare specialization constants used in our kernels.
12 constexpr specialization_id<int> width;
13 constexpr specialization_id<int> height;
14
15 int main() {
16   queue myQueue;
17   auto myContext = myQueue.get_context();
18
19   // Get the identifiers for our kernels, then get an input kernel bundle that
20   // contains our two kernels.
21   auto kernelIds = { get_kernel_id<MyKernel1>(), get_kernel_id<MyKernel2>() };
22   auto inputBundle =
23       get_kernel_bundle<bundle_state::input>(myContext, kernelIds);
24
25   // Set the values of the specialization constants.
26   inputBundle.set_specialization_constant<width>(get_width());
27   inputBundle.set_specialization_constant<height>(get_height());
28
29   // Build the kernel bundle into an executable form.  The values of the
30   // specialization constants are compiled in.
31   auto exeBundle = build(inputBundle);
32
33   myQueue.submit([&](handler& cgh) {
34     // Use the kernel bundle we built in this command group.
35     cgh.use_kernel_bundle(exeBundle);
36     cgh.parallel_for<MyKernel1>(
```

```
37        range { 1024 }, ([=](item index, kernel_handler kh) {
38          // Read the value of the specialization constant.
39          int w = kh.get_specialization_constant<width>();
40          // ...
41        }));
42  });
43
44  myQueue.submit([&](handler& cgh) {
45    // This command group uses the same kernel bundle.
46    cgh.use_kernel_bundle(exeBundle);
47    cgh.parallel_for<MyKernel2>(
48        range { 1024 }, ([=](item index, kernel_handler kh) {
49          int h = kh.get_specialization_constant<height>();
50          // ...
51        }));
52  });
53
54  myQueue.wait();
55 }
```

4.11.15.3. Kernel introspection

Applications can use kernel bundles to introspect its kernels and use that information to tune the arguments passed when invoking it.

```
1  #include <sycl/sycl.hpp>
2  using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names
3
4  class MyKernel; // Forward declare the name of our kernel.
5
6  int main() {
7    size_t N = 1024;
8    queue myQueue;
9    auto myContext = myQueue.get_context();
10   auto myDev = myQueue.get_device();
11
12   // Get an executable kernel bundle containing our kernel.
13   kernel_id kernelId = get_kernel_id<MyKernel>();
14   auto myBundle =
15       get_kernel_bundle<bundle_state::executable>(myContext, { kernelId });
16
17   // Get the kernel's maximum work group size when running on our device.
18   kernel myKernel = myBundle.get_kernel(kernelId);
19   size_t maxWgSize =
20       myKernel.get_info<info::kernel_device_specific::work_group_size>(myDev);
21
22   // Compute a good ND-range to use for iteration in the kernel
23   // based on the maximum work group size.
24   std::array<size_t, 11> divisors = { 1024, 512, 256, 128, 64, 32,
25                                       16,   8,   4,   2,   1 };
26   size_t wgSize = *std::find_if(divisors.begin(), divisors.end(),
27                                 [=](auto d) { return (d <= maxWgSize); });
28   nd_range myRange { range { N }, range { wgSize } };
29
30   myQueue.submit([&](handler& cgh) {
```

```
    // Use the kernel bundle we queried, so we are sure the queried work-group
    // size matches the kernel we run.
    cgh.use_kernel_bundle(myBundle);
    cgh.parallel_for<MyKernel>(myRange, ([=](nd_item<1> index) {
                                  // kernel code
                                }));
  });

  myQueue.wait();
}
```

4.11.15.4. Invoking a device built-in kernel

An application can use kernel bundles to invoke a device's built-in kernels.

```
#include <sycl/sycl.hpp>
using namespace sycl; // (optional) avoids need for "sycl::" before SYCL names

int main() {
  queue myQueue;
  auto myContext = myQueue.get_context();
  auto myDevice = myQueue.get_device();

  const std::vector<kernel_id> builtinKernelIds =
      myDevice.get_info<info::device::built_in_kernel_ids>();

  // Get an executable kernel_bundle containing all the built-in kernels
  // supported by the device.
  kernel_bundle<bundle_state::executable> myBundle =
      get_kernel_bundle(myContext, { myDevice }, builtinKernelIds);

  // Retrieve a kernel object that can be used to query for more information
  // about the built-in kernel or to submit it to a command group.  We assume
  // here that the device supports at least one built-in kernel.
  kernel builtinKernel = myBundle.get_kernel(builtinKernelIds[0]);

  // Submit the built-in kernel.
  myQueue.submit([&](handler& cgh) {
    // Setting the arguments depends on the backend and the exact kernel used.
    cgh.set_args(...);
    cgh.parallel_for(range { 1024 }, builtinKernel);
  });

  myQueue.wait();
}
```

4.12. Defining kernels

In SYCL, functions that are executed on a SYCL device are referred to as SYCL kernel functions. A kernel containing such a SYCL kernel function is enqueued on a device queue in order to be executed on that particular device.

The return type of the SYCL kernel function is `void`, and all memory accesses between host and device are through accessors or through USM pointers.

There are two ways of defining kernels: as named function objects or as lambda functions. A backend may also provide interoperability interfaces for defining kernels.

4.12.1. Defining kernels as named function objects

A kernel can be defined as a named function object type. These function objects provide the same functionality as any C++ function object, with the restriction that they need to follow SYCL rules to be device copyable. The kernel function can be templated via templating the kernel function object type. For details on restrictions for kernel naming, please refer to Section 5.2.

The `operator()` member function must be const-qualified, and it may take different parameters depending on the data accesses defined for the specific kernel. If the `operator()` function writes to any of the member variables, the behavior is undefined.

The following example defines a SYCL kernel function, *RandomFiller*, which initializes a buffer with a random number. The random number is generated during the construction of the function object while processing the command group. The `operator()` member function of the function object receives an `item` object. This member function will be called for each work item of the execution range. The value of the random number will be assigned to each element of the buffer. In this case, the accessor and the scalar random number are members of the function object and therefore will be arguments to the device kernel. Usual restrictions of passing arguments to kernels apply.

```
class RandomFiller {
 public:
  RandomFiller(accessor<int> ptr)
      : ptr_ { ptr } {
    std::random_device hwRand;
    std::uniform_int_distribution<> r { 1, 100 };
    randomNum_ = r(hwRand);
  }
  void operator()(item<1> item) const { ptr_[item.get_id()] = get_random(); }
  int get_random() { return randomNum_; }

 private:
  accessor<int> ptr_;
  int randomNum_;
};

void workFunction(buffer<int, 1>& b, queue& q, const range<1> r) {
  myQueue.submit([&](handler& cgh) {
    accessor ptr { buf, cgh };
    RandomFiller filler { ptr };

    cgh.parallel_for(r, filler);
  });
}
```

4.12.2. Defining kernels as lambda functions

In C++, function objects can be defined using lambda functions. Kernels may be defined as lambda functions in SYCL. The name of a lambda function in SYCL may optionally be specified by passing it as a template parameter to the invoking member function, and in that case, the lambda name is a C++ typename which must be forward declarable at namespace scope. If the lambda function relies on template arguments, then if specified, the name of the lambda function must contain those template arguments which must also be forward declarable at namespace scope. The class used for the name of a lambda function

is only used for naming purposes and is not required to be defined. For details on restrictions for kernel naming, please refer to Section 5.2.

The kernel function for the lambda function is the lambda function itself. The kernel lambda must use copy for all of its captures (i.e. `[=]`), and the lambda must not use the `mutable` specifier.

```
// Explicit kernel names can be optionally forward declared at namespace scope
class MyKernel;

myQueue.submit([&](handler& h) {
  // Explicitly name kernel with previously forward declared type
  h.single_task<MyKernel>([=] {
    // [kernel code]
  });

  // Explicitly name kernel without forward declaring type at
  // namespace scope.  Must still be forward declarable at
  // namespace scope, even if not declared at that scope
  h.single_task<class MyOtherKernel>([=] {
    // [kernel code]
  });
});
```

Explicit lambda naming is shown in the following code example, including an illegal case that uses a class within the kernel name which is not forward declarable (`std::complex`).

```
// Explicit kernel names can be optionally forward declared at namespace scope
class MyForwardDeclName;

template <typename T> class MyTemplatedKernelName;

// Define and launch templated kernel
template <typename T> void templatedFunction() {
  queue myQueue;

  // Launch A: No explicit kernel name
  myQueue.submit([&](handler& h) {
    h.single_task([=] {
      // [kernel code that depends on type T]
    });
  });

  // Launch B: Name the kernel when invoking (this is optional)
  myQueue.submit([&](handler& h) {
    h.single_task<MyTemplatedKernelName<T>>([=] {
      // The provided kernel name (MyTemplatedKernelName<T>) depends on T
      // because the kernel does.  T must also be forward declarable at
      // namespace scope.

      // [kernel code that depends on type T]
    });
  });
}

int main() {
```

```
30   queue myQueue;
31
32   myQueue.submit([&](handler& h) {
33     // Declare MyKernel within this kernel invocation.  Legal because
34     // forward declaration at namespace scope is optional
35     h.single_task<class MyKernel>([=] {
36       // [kernel code]
37     });
38   });
39
40   myQueue.submit([&](handler& h) {
41     // Use kernel name that was forward declared at namespace scope
42     h.single_task<MyForwardDeclName>([=] {
43       // [kernel code]
44     });
45   });
46
47   templatedFunction<int>(); // OK
48
49   templatedFunction<std::complex<float>>(); // Launch A is OK, Launch B illegal
50   // because std::complex is not forward declarable according to C++, and was
51   // used in an explicit kernel name which must be forward declarable.
52 }
```

4.12.3. is_device_copyable type trait

```
namespace sycl {
    template<typename T>
    struct is_device_copyable;

    template<typename T>
    inline constexpr bool is_device_copyable_v = is_device_copyable<T>::value;
};
```

is_device_copyable is a user specializable class template to indicate that a type T is device copyable.

- is_device_copyable must meet the Cpp17UnaryTrait requirements.
- If is_device_copyable is specialized such that is_device_copyable_v<T> == true on a T that does not satisfy all the requirements of a device copyable type, the results are unspecified.

If the application defines a type UDT that satisfies the requirements of a device copyable type (as defined in Section 3.13.1) but the type is not implicitly device copyable as defined in that section, then the application must provide a specialization of is_device_copyable that derives from std:true_type in order to use that type in a context that requires a device copyable type. Such a specialization can be declared like this:

```
template<>
struct sycl::is_device_copyable<UDT> : std::true_type {};
```

It is legal to provide this specialization even if the implementation does not define SYCL_DEVICE_COPYABLE to 1, but the type cannot be used as a device copyable type in that case and the specialization is ignored.

4.12.4. Rules for parameter passing to kernels

A SYCL application passes parameters to a kernel in different ways depending on whether the kernel is a named function object or a lambda function. If the kernel is a named function object, the `operator()` member function (or other member functions that it calls) may reference member variables inside the same named function object. Any such member variables become parameters to the kernel. If the kernel is a lambda function, any variables captured by the lambda become parameters to the kernel.

Regardless of how the parameter is passed, the following rules define the allowable types for a kernel parameter:

- Any device copyable type is a legal parameter type.
- The following SYCL types are legal parameter types:
  - `accessor` when templated with `target::device`;
  - `accessor` when templated with any of the deprecated parameters: `target::global_buffer`, `target::constant_buffer`, or `target::local`;
  - `local_accessor`;
  - `unsampled_image_accessor` when templated with `image_target::device`;
  - `sampled_image_accessor` when templated with `image_target::device`;
  - `stream`;
  - `id`;
  - `range`;
  - `marray<T, NumElements>` when `T` is device copyable;
  - `vec<T, NumElements>`.
- An array of element types `T` is a legal parameter type if `T` is a legal parameter type.
- A class type `S` with a non-static member variable of type `T` is a legal parameter type if `T` is a legal parameter type and if `S` would otherwise be a legal parameter type aside from this member variable.
- A class type `S` with a non-virtual base class of type `T` is a legal parameter type if `T` is a legal parameter type and if `S` would otherwise be a legal parameter type aside from this base class.

Pointer types are trivially copyable, so they may be passed as kernel parameters. However, only the pointer value itself is passed to the kernel. Dereferencing the pointer on the kernel results in undefined behavior unless the pointer points to an address within a USM memory region that is accessible on the device.

Reference types are not trivially copyable, so they may not be passed as kernel parameters.

The `reducer` class is a special type of kernel parameter which is passed to a kernel in a different way. Section 4.9.2 describes how this parameter type is used.

4.13. Error handling

4.13.1. Error handling rules

Error handling in a SYCL application (host code) uses C++ exceptions. If an error occurs, it will be thrown by the API function call and may be caught by the user through standard C++ exception handling mechanisms.

SYCL applications are asynchronous in the sense that host and device code executions are decoupled

from one another except at specific points. For example, device code executions often begin when dependencies in the SYCL task graph are satisfied, which occurs asynchronously from host code execution. As a result of this the errors that occur on a device cannot be thrown directly from a host API call, because the call enqueueing a device action has typically already returned by the time that the error occurs. Such errors are not detected until the error-causing task executes or tries to execute, and we refer to these as asynchronous errors.

4.13.1.1. Asynchronous error handler

The queue and context classes can optionally take an asynchronous handler object async_handler on construction, which is a callable such as a function class or lambda, with an `exception_list` as a parameter. Invocation of an async_handler may be triggered by the queue member functions `queue::wait_and_throw()` or `queue::throw_asynchronous()`, by the event member function `event::wait_and_throw()`, or automatically on destruction of a queue or context that contains unconsumed asynchronous errors. When invoked, an async_handler is called and receives an `exception_list` argument containing a list of exception objects representing any unconsumed asynchronous errors associated with the queue or context.

When an asynchronous error instance has been passed to an async_handler, then that instance of the error has been consumed for handling and is not reported on any subsequent invocations of the async_handler.

The async_handler may be a named function object type, a lambda function or a `std::function`. The `exception_list` object passed to the async_handler is constructed by the SYCL runtime.

4.13.1.2. Behavior without an async_handler

If an asynchronous error occurs in a queue or context that has no user-supplied asynchronous error handler object async_handler, then an implementation-defined default async_handler is called to handle the error in the same situations that a user-supplied async_handler would be, as defined in Section 4.13.1.1. The default async_handler must in some way report all errors passed to it, when possible, and must then invoke `std::terminate` or equivalent.

4.13.1.3. Priorities of async handlers

If the SYCL runtime can associate an asynchronous error with a specific queue, then:

- If the queue was constructed with an async_handler, that handler is invoked to handle the error.
- Otherwise if the context enclosed by the queue was constructed with an async_handler, that handler is invoked to handle the error.
- Otherwise when no handler was passed to either queue or context on construction, then a default handler is invoked to handle the error, as described by Section 4.13.1.2.
- All handler invocations in this list occur at times as defined by Section 4.13.1.1.

If the SYCL runtime cannot associate an asynchronous error with a specific queue, then:

- If the context in which the error occurred was constructed with an async_handler, then that handler is invoked to handle the error.
- Otherwise when no handler was passed to the associated context on construction, then a default handler is invoked to handle the error, as described by Section 4.13.1.2.
- All handler invocations in this list occur at times as defined by Section 4.13.1.1.

4.13.1.4. Asynchronous errors with a secondary queue

If an asynchronous error occurs when running or enqueuing a command group which has a secondary queue specified, then the command group may be enqueued to the secondary queue instead of the pri-

mary queue. The error handling in this case is also configured using the async_handler provided for both queues. If there is no async_handler given on any of the queues, then the asynchronous error handling proceeds through the contexts associated with the queues, and if they were also constructed without async_handlers, then the default handler will be used. If the primary queue fails and there is an async_handler given at this queue's construction, which populates the exception_list parameter, then any errors will be added and can be thrown whenever the user chooses to handle those exceptions. Since there were errors on the primary queue and a secondary queue was given, then the execution of the kernel is re-scheduled to the secondary queue and any error reporting for the kernel execution on that queue is done through that queue, in the same way as described above. The secondary queue may fail as well, and the errors will be thrown if there is an async_handler and either wait_and_throw() or throw() are called on that queue. If no async_handler was specified, then the one associated with the queue's context will be used and if the context was also constructed without an async_handler, then the default handler will be used. The command group function object event returned by that function will be relevant to the queue where the kernel has been enqueued.

Below is an example of catching a SYCL exception and printing out the error message.

```
void catch_any_errors(sycl::context const& ctx) {
  try {
    do_something_to_invoke_error(ctx);
  } catch (sycl::exception const& e) {
    std::cerr << e.what();
  }
}
```

Below is an example of catching a SYCL exception with the errc::invalid error code and printing out the error message.

```
void catch_invalid_errors(sycl::context const& ctx) {
  try {
    do_something_to_invoke_error(ctx);
  } catch (sycl::exception const& e) {
    if (e.code() == sycl::errc::invalid) {
      std::cerr << "Invalid error: " << e.what();
    } else {
      throw;
    }
  }
}
```

Below is an example of catching a SYCL exception, checking for the SYCL backend by inspecting the category and handling the OpenCL SYCL backend error codes if the category is that of the OpenCL SYCL backend otherwise checking the standard error code.

```
void catch_backend_errors(sycl::context const& ctx) {
  try {
    do_something_to_invoke_error(ctx);
  } catch (sycl::exception const& e) {
    if (e.category() == sycl::error_category_for<sycl::backend::opencl>()) {
      switch (e.code().value()) {
      case CL_INVALID_PROGRAM:
        std::cerr << "OpenCL invalid program error: " << e.what();
        /* ...*/
      }
```

```
      else {
        throw;
      }
    } else {
      if (e.code() == sycl::errc::invalid) {
        std::cerr << "Invalid error: " << e.what();
      } else {
        throw;
      }
    }
  }
}
```

4.13.2. Exception class interface

```
namespace sycl {

using async_handler = std::function<void(sycl::exception_list)>;

class exception : public virtual std::exception {
 public:
  exception(std::error_code ec, const std::string& what_arg);
  exception(std::error_code ec, const char* what_arg);
  exception(std::error_code ec);
  exception(int ev, const std::error_category& ecat,
            const std::string& what_arg);
  exception(int ev, const std::error_category& ecat, const char* what_arg);
  exception(int ev, const std::error_category& ecat);

  exception(context ctx, std::error_code ec, const std::string& what_arg);
  exception(context ctx, std::error_code ec, const char* what_arg);
  exception(context ctx, std::error_code ec);
  exception(context ctx, int ev, const std::error_category& ecat,
            const std::string& what_arg);
  exception(context ctx, int ev, const std::error_category& ecat,
            const char* what_arg);
  exception(context ctx, int ev, const std::error_category& ecat);

  const std::error_code& code() const noexcept;
  const std::error_category& category() const noexcept;

  const char* what() const;

  bool has_context() const noexcept;
  context get_context() const;
};

class exception_list {
  // Used as a container for a list of asynchronous exceptions
 public:
  using value_type = std::exception_ptr;
  using reference = value_type&;
  using const_reference = const value_type&;
  using size_type = std::size_t;
  using iterator = /*unspecified*/;
```

```
41   using const_iterator = /*unspecified*/;
42
43   size_type size() const;
44   iterator begin() const; // first asynchronous exception
45   iterator end() const;   // refer to past-the-end last asynchronous exception
46 };
47
48 enum class errc : /* unspecified */ {
49   success = 0,
50   runtime,
51   kernel,
52   accessor,
53   nd_range,
54   event,
55   kernel_argument,
56   build,
57   invalid,
58   memory_allocation,
59   platform,
60   profiling,
61   feature_not_supported,
62   kernel_not_supported,
63   backend_mismatch
64 };
65
66 template <backend b> using errc_for = typename backend_traits<b>::errc;
67
68 std::error_code make_error_code(errc e) noexcept;
69
70 const std::error_category& sycl_category() noexcept;
71
72 template <backend b> const std::error_category& error_category_for() noexcept;
73
74 } // namespace sycl
75
76 namespace std {
77
78 template <> struct is_error_code_enum</* see below */> : true_type {};
79
80 } // namespace std
```

The SYCL `exception_list` class is also available in order to provide a list of synchronous and asynchronous exceptions.

Errors can occur both in the SYCL library and SYCL host side, or may come directly from a SYCL backend. The member functions on these exceptions provide the corresponding information. SYCL backends can provide additional exception class objects as long as they derive from `sycl::exception` object, or any of its derived classes.

A specialization of `std::is_error_code_enum` must be defined for `sycl::errc` and `backend_traits<Backend>::errc` inheriting from `std::true_type` for each `Backend`, where `backend` is each enumeration of the enum class `backend`.

Table 139. Member functions of the SYCL `exception` class

Member function	Description
`exception(std::error_code ec, const std::string& what_arg)`	Constructs an `exception`. The string returned by `what()` is guaranteed to contain `what_arg` as a substring.
`exception(std::error_code ec, const char* what_arg)`	Constructs an `exception`. The string returned by `what()` is guaranteed to contain `what_arg` as a substring.
`exception(std::error_code ec)`	Constructs an `exception`.
`exception(int ev, const std::error_category& ecat, const std::string& what_arg)`	Constructs an `exception` with the error code ev and the underlying error category `ecat`. The string returned by `what()` is guaranteed to contain `what_arg` as a substring.
`exception(int ev, const std::error_category& ecat, const char* what_arg)`	Constructs an `exception` with the error code ev and the underlying error category `ecat`. The string returned by `what()` is guaranteed to contain `what_arg` as a substring.
`exception(int ev, const std::error_category& ecat)`	Constructs an `exception` with the error code ev and the underlying error category `ecat`.
`exception(context ctx, std::error_code ec, const std::string& what_arg)`	Constructs an `exception` with an associated SYCL context `ctx`. The string returned by `what()` is guaranteed to contain `what_arg` as a substring.
`exception(context ctx, std::error_code ec, const char* what_arg)`	Constructs an `exception` with an associated SYCL context `ctx`. The string returned by `what()` is guaranteed to contain `what_arg` as a substring.
`exception(context ctx, std::error_code ec)`	Constructs an `exception` with an associated SYCL context `ctx`.
`exception(context ctx, int ev, const std::error_category& ecat, const std::string& what_arg)`	Constructs an `exception` with an associated SYCL context `ctx`, the error code ev and the underlying error category `ecat`. The string returned by `what()` is guaranteed to contain `what_arg` as a substring.
`exception(context ctx, int ev, const std::error_category& ecat, const char* what_arg)`	Constructs an `exception` with an associated SYCL context `ctx`, the error code ev and the underlying error category `ecat`. The string returned by `what()` is guaranteed to contain `what_arg` as a substring.

Member function	Description
`exception(context ctx, int ev, const std::error_category& ecat)`	Constructs an `exception` with an associated SYCL context `ctx`, the error code ev and the underlying error category `ecat`.
`const std::error_code& code() const noexcept`	Returns the error code stored inside the exception.
`const std::error_category& category() const noexcept`	Returns the error category of the error code stored inside the exception.
`const char* what() const`	Returns an implementation-defined non-null constant C-style string that describes the error that triggered the exception.
`bool has_context() const noexcept`	Returns `true` if this SYCL `exception` has an associated SYCL `context` and `false` if it does not.
`context get_context() const`	Returns the SYCL `context` that is associated with this SYCL `exception` if one is available. Must throw an `exception` with the `errc::invalid` error code if this SYCL `exception` does not have a SYCL `context`.

Table 140. Member functions of the `exception_list`

Member function	Description
`size_t size() const`	Returns the size of the list
`iterator begin() const`	Returns an iterator to the beginning of the list of asynchronous exceptions.
`iterator end() const`	Returns an iterator to the end of the list of asynchronous exceptions.

Table 141. Values of the SYCL `errc` enum

Standard SYCL Error Codes	Description
`success`	The implementation never throws an exception with this error code, but it is defined to ensure that no other error code has the value zero. An application can construct an `std::error_code` with this code to indicate "not an error".
`runtime`	Generic runtime error.

Standard SYCL Error Codes	Description
`kernel`	Error that occurred before or while enqueuing the SYCL kernel.
`nd_range`	Error regarding the SYCL `nd_range` specified for the SYCL kernel
`accessor`	Error regarding the SYCL accessor objects defined.
`event`	Error regarding associated SYCL `event` objects.
`kernel_argument`	The application has passed an invalid argument to a SYCL kernel function. This includes captured variables if the SYCL kernel function is a lambda function.
`build`	Error from an online compile or link operation when compiling, linking, or building a kernel bundle for a device.
`invalid`	A catchall error which is used when the application passes an invalid value as a parameter to a SYCL API function or calls a SYCL API function in some invalid way.
`memory_allocation`	Error on memory allocation on the SYCL device for a SYCL kernel.
`platform`	The SYCL platform will trigger this exception on error.
`profiling`	The SYCL runtime will trigger this error if there is an error when profiling info is enabled.
`feature_not_supported`	Exception thrown when host code uses an optional feature that is not supported by a device.
`kernel_not_supported`	Exception thrown when a kernel uses an optional feature that is not supported on the device to which it is enqueued. This exception is also thrown if a command group is bound to a kernel bundle, and the bundle does not contain the kernel invoked by the command group.

Standard SYCL Error Codes	Description
`backend_mismatch`	The application has called a backend interoperability function with mismatched backend information. For example, requesting information specific to backend A from a SYCL object that comes from backend B causes this error.

Table 142. SYCL error code helper functions

SYCL Error Code Helpers	Description
`const std::error_category& sycl_category() noexcept;`	Obtains a reference to the static error category object for SYCL errors. This object overrides the virtual function `error_category::name()` to return a pointer to the string `"sycl"`. When the implementation throws an `sycl::exception` object `ex` with this category, the error code value contained by the exception (`ex.code().value()`) is one of the enumerated values in `sycl::errc`.
`std::error_code make_error_code(errc e) noexcept;`	Constructs an error code using `e` and `sycl_category()`.

4.14. Data types

SYCL as a C++ programming model supports the C++ core language data types, and it also provides the ability for all SYCL applications to be executed on SYCL compatible devices. The scalar and vector data types that are supported by the SYCL system are defined below. More details about the SYCL device compiler support for fundamental and backend interoperability types are found in Section 5.5.

4.14.1. Scalar data types

The fundamental C++ data types which are supported in SYCL are described in Table 184. Note these types are fundamental and therefore do not exist within the `sycl` namespace.

Additional scalar data types which are supported by SYCL within the `sycl` namespace are described in Table 143.

Table 143. Additional scalar data types supported by SYCL

Scalar data type	Description
`byte`	An unsigned 8-bit integer. This is deprecated in SYCL 2020 since C++17 `std::byte` can be used instead.

Scalar data type	Description
`half`	A 16-bit floating-point. The half data type must conform to the IEEE 754-2008 half precision storage format. This type is only supported on devices that have `aspect::fp16`. `std::numeric_limits` must be specialized for the half data type.

4.14.2. Vector types

SYCL provides a cross-platform class template that works efficiently on SYCL devices as well as in host C++ code. This type allows sharing of vectors between the host and its SYCL devices. The vector supports member functions that allow construction of a new vector from a swizzled set of component elements.

`vec<typename DataT, int NumElements>` is a vector type that compiles down to a SYCL backend built-in vector types on SYCL devices, where possible, and provides compatible support on the host or when it is not possible. The `vec` class is templated on its number of elements and its element type. The number of elements parameter, *NumElements*, can be one of: 1, 2, 3, 4, 8 or 16. Any other value shall produce a compilation failure. The element type parameter, *DataT*, must be one of the basic scalar types supported in device code.

The SYCL `vec` class template provides interoperability with the underlying vector type defined by `vector_t` which is available only when compiled for the device. The SYCL `vec` class can be constructed from an instance of `vector_t` and can implicitly convert to an instance of `vector_t` in order to support interoperability with native SYCL backend functions from a SYCL kernel function.

An instance of the SYCL `vec` class template can also be implicitly converted to an instance of the data type when the number of elements is `1` in order to allow single element vectors and scalars to be convertible with each other.

4.14.2.1. Vec interface

The constructors, member functions and non-member functions of the SYCL `vec` class template are listed in Table 144, Table 145 and Table 146 respectively.

```
namespace sycl {

enum class rounding_mode : /* unspecified */ { automatic, rte, rtz, rtp, rtn };

struct elem {
  static constexpr int x = 0;
  static constexpr int y = 1;
  static constexpr int z = 2;
  static constexpr int w = 3;
  static constexpr int r = 0;
  static constexpr int g = 1;
  static constexpr int b = 2;
  static constexpr int a = 3;
  static constexpr int s0 = 0;
  static constexpr int s1 = 1;
  static constexpr int s2 = 2;
  static constexpr int s3 = 3;
  static constexpr int s4 = 4;
  static constexpr int s5 = 5;
```

```
  static constexpr int s6 = 6;
  static constexpr int s7 = 7;
  static constexpr int s8 = 8;
  static constexpr int s9 = 9;
  static constexpr int sA = 10;
  static constexpr int sB = 11;
  static constexpr int sC = 12;
  static constexpr int sD = 13;
  static constexpr int sE = 14;
  static constexpr int sF = 15;
};

template <typename DataT, int NumElements> class vec {
 public:
  using element_type = DataT;

#ifdef __SYCL_DEVICE_ONLY__
  using vector_t = __unspecified__;
#endif

  vec();

  explicit constexpr vec(const DataT& arg);

  template <typename... ArgTN> constexpr vec(const ArgTN&... args);

  constexpr vec(const vec<DataT, NumElements>& rhs);

#ifdef __SYCL_DEVICE_ONLY__
  vec(vector_t nativeVector);

  operator vector_t() const;
#endif

  // Available only when: NumElements == 1
  operator DataT() const;

  static constexpr size_t byte_size() noexcept;

  static constexpr size_t size() noexcept;

  // Deprecated
  size_t get_size() const;

  // Deprecated
  size_t get_count() const;

  template <typename ConvertT,
            rounding_mode RoundingMode = rounding_mode::automatic>
  vec<ConvertT, NumElements> convert() const;

  template <typename AsT> AsT as() const;

  template <int... swizzleIndexes> __swizzled_vec__ swizzle() const;

  // Available only when NumElements <= 4.
```

```
  // XYZW_ACCESS is: x, y, z, w, subject to NumElements.
  __swizzled_vec__ XYZW_ACCESS() const;

  // Available only NumElements == 4.
  // RGBA_ACCESS is: r, g, b, a.
  __swizzled_vec__ RGBA_ACCESS() const;

  // INDEX_ACCESS is: s0, s1, s2, s3, s4, s5, s6, s7, s8, s9, sA, sB, sC, sD,
  // sE, sF, subject to NumElements.
  __swizzled_vec__ INDEX_ACCESS() const;

#ifdef SYCL_SIMPLE_SWIZZLES
  // Available only when NumElements <= 4.
  // XYZW_SWIZZLE is all permutations with repetition of: x, y, z, w, subject to
  // NumElements.
  __swizzled_vec__ XYZW_SWIZZLE() const;

  // Available only when NumElements == 4.
  // RGBA_SWIZZLE is all permutations with repetition of: r, g, b, a.
  __swizzled_vec__ RGBA_SWIZZLE() const;

#endif // #ifdef SYCL_SIMPLE_SWIZZLES

  // Available only when: NumElements > 1.
  __swizzled_vec__ lo() const;
  __swizzled_vec__ hi() const;
  __swizzled_vec__ odd() const;
  __swizzled_vec__ even() const;

  // load and store member functions
  template <access::address_space AddressSpace, access::decorated IsDecorated>
  void load(size_t offset,
            multi_ptr<const DataT, AddressSpace, IsDecorated> ptr);
  template <access::address_space AddressSpace, access::decorated IsDecorated>
  void store(size_t offset,
             multi_ptr<DataT, AddressSpace, IsDecorated> ptr) const;

  // subscript operator
  DataT& operator[](int index);
  const DataT& operator[](int index) const;

  // OP is: +, -, *, /, %
  /* If OP is %, available only when: DataT != float && DataT != double
  && DataT != half. */
  friend vec operatorOP(const vec& lhs, const vec& rhs) { /* ... */
  }
  friend vec operatorOP(const vec& lhs, const DataT& rhs) { /* ... */
  }

  // OP is: +=, -=, *=, /=, %=
  /* If OP is %=, available only when: DataT != float && DataT != double
  && DataT != half. */
  friend vec& operatorOP(vec& lhs, const vec& rhs) { /* ... */
  }
  friend vec& operatorOP(vec& lhs, const DataT& rhs) { /* ... */
  }
```

```
132
133   // OP is prefix ++, --
134   // Available only when: DataT != bool
135   friend vec& operatorOP(vec& rhs) { /* ... */
136   }
137
138   // OP is postfix ++, --
139   // Available only when: DataT != bool
140   friend vec operatorOP(vec& lhs, int) { /* ... */
141   }
142
143   // OP is unary +, -
144   friend vec operatorOP(const vec& rhs) { /* ... */
145   }
146
147   // OP is: &, |, ^
148   /* Available only when: DataT != float && DataT != double
149   && DataT != half. */
150   friend vec operatorOP(const vec& lhs, const vec& rhs) { /* ... */
151   }
152   friend vec operatorOP(const vec& lhs, const DataT& rhs) { /* ... */
153   }
154
155   // OP is: &=, |=, ^=
156   /* Available only when: DataT != float && DataT != double
157   && DataT != half. */
158   friend vec& operatorOP(vec& lhs, const vec& rhs) { /* ... */
159   }
160   friend vec& operatorOP(vec& lhs, const DataT& rhs) { /* ... */
161   }
162
163   // OP is: &&, ||
164   friend vec<RET, NumElements> operatorOP(const vec& lhs, const vec& rhs) {
165     /* ... */ }
166     friend vec<RET, NumElements> operatorOP(const vec& lhs, const DataT& rhs) {
167     /* ... */ }
168
169     // OP is: <<, >>
170     /* Available only when: DataT != float && DataT != double
171     && DataT != half. */
172     friend vec operatorOP(const vec& lhs, const vec& rhs) { /* ... */
173     }
174     friend vec operatorOP(const vec& lhs, const DataT& rhs) { /* ... */
175     }
176
177     // OP is: <<=, >>=
178     /* Available only when: DataT != float && DataT != double
179     && DataT != half. */
180     friend vec& operatorOP(vec& lhs, const vec& rhs) { /* ... */
181     }
182     friend vec& operatorOP(vec& lhs, const DataT& rhs) { /* ... */
183     }
184
185     // OP is: ==, !=, <, >, <=, >=
186     friend vec<RET, NumElements> operatorOP(const vec& lhs, const vec& rhs) {
187     /* ... */ }
```

```
    friend vec<RET, NumElements> operatorOP(const vec& lhs, const DataT& rhs) {
    /* ... */ }

    vec& operator=(const vec<DataT, NumElements>& rhs);
    vec& operator=(const DataT& rhs);

    /* Available only when: DataT != float && DataT != double
    && DataT != half. */
    friend vec operator~(const vec& v) { /* ... */
    }
    friend vec<RET, NumElements> operator!(const vec& v) { /* ... */
    }

    // OP is: +, -, *, /, %
    /* operator% is only available when: DataT != float && DataT != double &&
    DataT != half. */
    friend vec operatorOP(const DataT& lhs, const vec& rhs) { /* ... */
    }

    // OP is: &, |, ^
    /* Available only when: DataT != float && DataT != double
    && DataT != half. */
    friend vec operatorOP(const DataT& lhs, const vec& rhs) { /* ... */
    }

    // OP is: &&, ||
    friend vec<RET, NumElements> operatorOP(const DataT& lhs, const vec& rhs) {
    /* ... */ }

    // OP is: <<, >>
    /* Available only when: DataT != float && DataT != double
    && DataT != half. */
    friend vec operatorOP(const DataT& lhs, const vec& rhs) { /* ... */
    }

    // OP is: ==, !=, <, >, <=, >=
    friend vec<RET, NumElements> operatorOP(const DataT& lhs, const vec& rhs) {
    /* ... */ }
};

// Deduction guides
// Available only when: (std::is_same_v<T, U> && ...)
template <class T, class... U> vec(T, U...) -> vec<T, sizeof...(U) + 1>;

} // namespace sycl
```

Table 144. Constructors of the SYCL vec class template

Constructor	Description
`vec()`	Default construct a vector with element type DataT and with NumElements dimensions by default construction of each of its elements.

Constructor	Description
`explicit constexpr vec(const DataT& arg)`	Construct a vector of element type `DataT` and `NumElements` dimensions by setting each value to `arg` by assignment.
`template <typename... ArgTN> constexpr vec(const ArgTN&... args)`	Construct a SYCL `vec` instance from any combination of scalar and SYCL `vec` parameters of the same element type, providing the total number of elements for all parameters sum to `NumElements` of this `vec` specialization.
`constexpr vec(const vec<DataT, NumElements>& rhs)`	Construct a vector of element type `DataT` and number of elements `NumElements` by copy from another similar vector.
`vec(vector_t nativeVector)`	Available only when: compiled for the device. Constructs a SYCL `vec` instance from an instance of the underlying backend-native vector type defined by `vector_t`.

Table 145. Member functions for the SYCL `vec` class template

Member function	Description
`operator vector_t() const`	Available only when: compiled for the device. Converts this SYCL `vec` instance to the underlying backend-native vector type defined by `vector_t`.
`operator DataT() const`	Available only when: `NumElements == 1`. Converts this SYCL `vec` instance to an instance of `DataT` with the value of the single element in this SYCL `vec` instance. The SYCL `vec` instance shall be implicitly convertible to the same data types, to which `DataT` is implicitly convertible. Note that conversion operator shall not be templated to allow standard conversion sequence for implicit conversion.
`static constexpr size_t size() noexcept`	Returns the number of elements of this SYCL `vec`.

Member function	Description
`size_t get_count() const`	Returns the same value as `size()`. Deprecated.
`static constexpr size_t byte_size() noexcept`	Returns the size of this SYCL `vec` in bytes. 3-element vector size matches 4-element vector size to provide interoperability with OpenCL vector types. The same rule applies to vector alignment as described in Section 4.14.2.6.
`size_t get_size() const`	Returns the same value as `byte_size()`. Deprecated.
`template <typename ConvertT, rounding_mode RoundingMode = rounding_mode ::automatic> vec<ConvertT, NumElements> convert() const`	Converts this SYCL `vec` to a SYCL `vec` of a different element type specified by `ConvertT` using the rounding mode specified by `RoundingMode`. The new SYCL `vec` type must have the same number of elements as this SYCL `vec`. The different rounding modes are described in Table 147.
`template <typename asT> asT as() const`	Bitwise reinterprets this SYCL `vec` as a SYCL `vec` of a different element type and number of elements specified by `asT`. The new SYCL `vec` type must have the same storage size in bytes as this SYCL `vec`.
`template <int... swizzleIndexes> __swizzled_vec__ swizzle() const`	Return an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4.
`__swizzled_vec__ XYZW_ACCESS() const`	Available only when: `NumElements <= 4`. Returns an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. Where `XYZW_ACCESS` is: `x` for `NumElements == 1`, `x, y` for `NumElements == 2`, `x, y, z` for `NumElements == 3` and `x, y, z, w` for `NumElements == 4`.

Member function	Description
`__swizzled_vec__ RGBA_ACCESS() const`	Available only when: `NumElements == 4`. Returns an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. Where `RGBA_ACCESS` is: `r, g, b, a`.
`__swizzled_vec__ INDEX_ACCESS() const`	Returns an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. Where `INDEX_ACCESS` is: `s0` for `NumElements == 1`, `s0, s1` for `NumElements == 2`, `s0, s1, s2` for `NumElements == 3`, `s0, s1, s2, s3` for `NumElements == 4`, `s0, s1, s2, s3, s4, s5, s6, s7, s8` for `NumElements == 8` and `s0, s1, s2, s3, s4, s5, s6, s7, s8, s9, sA, sB, sC, sD, sE, sF` for `NumElements == 16`.
`__swizzled_vec__ XYZW_SWIZZLE() const`	Available only when: `NumElements <= 4`, and when the macro `SYCL_SIMPLE_SWIZZLES` is defined before including `<sycl/sycl.hpp>`. Returns an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. Where XYZW_SWIZZLE is all permutations with repetition, of any subset with length greater than 1, of `x, y` for `NumElements == 2`, `x, y, z` for `NumElements == 3` and `x, y, z, w` for `NumElements == 4`. For example a four element `vec` provides permutations including `xzyw`, `xyyy` and `xz`.

Member function	Description
`__swizzled_vec__ RGBA_SWIZZLE() const`	Available only when: `NumElements == 4`, and when the macro `SYCL_SIMPLE_SWIZZLES` is defined before including `<sycl/sycl.hpp>`. Returns an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. Where RGBA_SWIZZLE is all permutations with repetition, of any subset with length greater than `1`, of `r, g, b, a`. For example a four element `vec` provides permutations including `rbga`, `rggg` and `rb`.
`__swizzled_vec__ lo() const`	Available only when: `NumElements > 1`. Return an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence made up of the lower half of this SYCL vec which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. When `NumElements == 3`, this SYCL `vec` is treated as though `NumElements == 4` with the fourth element undefined.
`__swizzled_vec__ hi() const`	Available only when: `NumElements > 1`. Return an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence made up of the upper half of this SYCL vec which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. When `NumElements == 3`, this SYCL `vec` is treated as though `NumElements == 4` with the fourth element undefined.

Member function	Description
`__swizzled_vec__ odd() const`	Available only when: `NumElements > 1`. Return an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence made up of the odd indexes of this SYCL vec which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. When `NumElements == 3`, this SYCL `vec` is treated as though `NumElements == 4` with the fourth element undefined.
`__swizzled_vec__ even() const`	Available only when: `NumElements > 1`. Return an instance of the implementation-defined intermediate class template `__swizzled_vec__` representing an index sequence made up of the even indexes of this SYCL vec which can be used to apply the swizzle in a valid expression as described in Section 4.14.2.4. When `NumElements == 3`, this SYCL `vec` is treated as though `NumElements == 4` with the fourth element undefined.
`template <access::address_space AddressSpace, access::decorated IsDecorated>` `void load(size_t offset, multi_ptr<const DataT, AddressSpace, IsDecorated> ptr)`	Loads the values at the address of `ptr` offset in elements of type `DataT` by `NumElements * offset`, into the components of this SYCL `vec`.
`template <access::address_space AddressSpace, access::decorated IsDecorated>` `void store(size_t offset, multi_ptr<DataT, AddressSpace, IsDecorated> ptr) const`	Stores the components of this SYCL `vec` into the values at the address of `ptr` offset in elements of type `DataT` by `NumElements * offset`.
`DataT& operator[](int index)`	Returns a reference to the element stored within this SYCL `vec` at the index specified by `index`.
`const DataT& operator[](int index) const`	Returns a const reference to the element stored within this SYCL `vec` at the index specified by `index`.
`vec& operator=(const vec& rhs)`	Assign each element of the `rhs` SYCL `vec` to each element of this SYCL `vec` and return a reference to this SYCL `vec`.

Member function	Description
`vec& operator=(const DataT& rhs)`	Assign each element of the `rhs` scalar to each element of this SYCL `vec` and return a reference to this SYCL `vec`.

Table 146. Hidden friend functions of the `vec` class template

Hidden friend function	Description
`vec operatorOP(const vec& lhs, const vec& rhs)`	If `OP` is `%`, available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as `lhs vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` arithmetic operation between each element of `lhs vec` and each element of the `rhs` SYCL `vec`. Where `OP` is: `+`, `-`, `*`, `/`, `%`.
`vec operatorOP(const vec& lhs, const DataT& rhs)`	If `OP` is `%`, available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as `lhs vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` arithmetic operation between each element of `lhs vec` and the `rhs` scalar. Where `OP` is: `+`, `-`, `*`, `/`, `%`.
`vec& operatorOP(vec& lhs, const vec& rhs)`	If `OP` is `%=`, available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` arithmetic operation between each element of `lhs vec` and each element of the `rhs` SYCL `vec` and return `lhs vec`. Where `OP` is: `+=`, `-=`, `*=`, `/=`, `%=`.

Hidden friend function	Description
`vec& operatorOP(vec& lhs, const DataT& rhs)`	If `OP` is `%=`, available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` arithmetic operation between each element of `lhs vec` and `rhs` scalar and return `lhs vec`. Where `OP` is: `+=`, `-=`, `*=`, `/=`, `%=`.
`vec& operatorOP(vec& v)`	Available only when: `DataT != bool`. Perform an in-place element-wise `OP` prefix arithmetic operation on each element of `lhs vec`, assigning the result of each element to the corresponding element of `lhs vec` and return `lhs vec`. Where `OP` is: `++`, `--`.
`vec operatorOP(vec& v, int)`	Available only when: `DataT != bool`. Perform an in-place element-wise `OP` postfix arithmetic operation on each element of `lhs vec`, assigning the result of each element to the corresponding element of `lhs vec` and returns a copy of `lhs vec` before the operation is performed. Where `OP` is: `++`, `--`.
`vec operatorOP(const vec& v)`	Construct a new instance of the SYCL `vec` class template with the same template parameters as this SYCL `vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` unary arithmetic operation on each element of this SYCL `vec`. Where `OP` is: `+`, `-`.

Hidden friend function	Description
`vec operatorOP(const vec& lhs, const vec& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as `lhs vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` bitwise operation between each element of `lhs vec` and each element of the `rhs` SYCL `vec`. Where `OP` is: `&`, `|`, `^`.
`vec operatorOP(const vec& lhs, const DataT& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as `lhs vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` bitwise operation between each element of `lhs vec` and the `rhs` scalar. Where `OP` is: `&`, `|`, `^`.
`vec& operatorOP(vec& lhs, const vec& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` bitwise operation between each element of `lhs vec` and the `rhs` SYCL `vec` and return `lhs vec`. Where `OP` is: `&=`, `|=`, `^=`.
`vec& operatorOP(vec& lhs, const DataT& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` bitwise operation between each element of `lhs vec` and the `rhs` scalar and return a `lhs vec`. Where `OP` is: `&=`, `|=`, `^=`.

Hidden friend function	Description
`vec<RET, NumElements> operatorOP(const vec& lhs, const vec& rhs)`	Construct a new instance of the SYCL `vec` class template with the same template parameters as `lhs vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` logical operation between each element of `lhs vec` and each element of the `rhs` SYCL `vec`. The `DataT` template parameter of the constructed SYCL `vec`, `RET`, varies depending on the `DataT` template parameter of this SYCL `vec`. For a SYCL `vec` with `DataT` of type `int8_t` or `uint8_t` `RET` must be `int8_t`. For a SYCL `vec` with `DataT` of type `int16_t`, `uint16_t` or `half` `RET` must be `int16_t`. For a SYCL `vec` with `DataT` of type `int32_t`, `uint32_t` or `float` `RET` must be `int32_t`. For a SYCL `vec` with `DataT` of type `int64_t`, `uint64_t` or `double` `RET` must be `int64_t`. Where `OP` is: `&&`, `||`.
`vec<RET, NumElements> operatorOP(const vec& lhs, const DataT& rhs)`	Construct a new instance of the SYCL `vec` class template with the same template parameters as this SYCL `vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` logical operation between each element of `lhs vec` and the `rhs` scalar. The `DataT` template parameter of the constructed SYCL `vec`, `RET`, varies depending on the `DataT` template parameter of this SYCL `vec`. For a SYCL `vec` with `DataT` of type `int8_t` or `uint8_t` `RET` must be `int8_t`. For a SYCL `vec` with `DataT` of type `int16_t`, `uint16_t` or `half` `RET` must be `int16_t`. For a SYCL `vec` with `DataT` of type `int32_t`, `uint32_t` or `float` `RET` must be `int32_t`. For a SYCL `vec` with `DataT` of type `int64_t`, `uint64_t` or `double` `RET` must be `uint64_t`. Where `OP` is: `&&`, `||`.

Hidden friend function	Description
`vec operatorOP(const vec& lhs, const vec& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as `lhs vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` bitshift operation between each element of `lhs vec` and each element of the `rhs` SYCL `vec`. If `OP` is `>>`, `DataT` is a signed type and `lhs vec` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<`, `>>`.
`vec operatorOP(const vec& lhs, const DataT& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as `lhs vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` bitshift operation between each element of `lhs vec` and the `rhs` scalar. If `OP` is `>>`, `DataT` is a signed type and `lhs vec` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<`, `>>`.

Hidden friend function	Description
`vec& operatorOP(vec& lhs, const vec& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` bitshift operation between each element of `lhs vec` and the `rhs` SYCL `vec` and returns `lhs vec`. If `OP` is `>>=`, `DataT` is a signed type and `lhs vec` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<=`, `>>=`.
`vec& operatorOP(vec& lhs, const DataT& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` bitshift operation between each element of `lhs vec` and the `rhs` scalar and returns a reference to this SYCL `vec`. If `OP` is `>>=`, `DataT` is a signed type and `lhs vec` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<=`, `>>=`.

Hidden friend function	Description
`vec<RET, NumElements> operatorOP(const vec& lhs, const vec& rhs)`	Construct a new instance of the SYCL `vec` class template with the element type `RET` with each element of the new SYCL `vec` instance the result of an element-wise `OP` relational operation between each element of `lhs` `vec` and each element of the `rhs` SYCL `vec`. Each element of the SYCL `vec` that is returned must be `-1` if the operation results in `true` and `0` if the operation results in `false`. The `==`, `<`, `>`, `<=` and `>=` operations result in `false` if either the `lhs` element or the `rhs` element is a NaN. The `!=` operation results in `true` if either the `lhs` element or the `rhs` element is a NaN. The `DataT` template parameter of the constructed SYCL `vec`, `RET`, varies depending on the `DataT` template parameter of this SYCL `vec`. For a SYCL `vec` with `DataT` of type `int8_t` or `uint8_t` `RET` must be `int8_t`. For a SYCL `vec` with `DataT` of type `int16_t`, `uint16_t` or `half` `RET` must be `int16_t`. For a SYCL `vec` with `DataT` of type `int32_t`, `uint32_t` or `float` `RET` must be `int32_t`. For a SYCL `vec` with `DataT` of type `int64_t`, `uint64_t` or `double` `RET` must be `uint64_t`. Where `OP` is: `==`, `!=`, `<`, `>`, `<=`, `>=`.

Hidden friend function	Description
`vec<RET, NumElements> operatorOP(const vec& lhs, const DataT& rhs)`	Construct a new instance of the SYCL `vec` class template with the `DataT` parameter of `RET` with each element of the new SYCL `vec` instance the result of an element-wise `OP` relational operation between each element of `lhs` `vec` and the `rhs` scalar. Each element of the SYCL `vec` that is returned must be `-1` if the operation results in `true` and `0` if the operation results in `false`. The `==`, `<`, `>`, `<=` and `>=` operations result in `false` if either the `lhs` element or the `rhs` is a NaN. The `!=` operation results in `true` if either the `lhs` element or the `rhs` is a NaN. The `DataT` template parameter of the constructed SYCL `vec`, `RET`, varies depending on the `DataT` template parameter of this SYCL `vec`. For a SYCL `vec` with `DataT` of type `int8_t` or `uint8_t` `RET` must be `int8_t`. For a SYCL `vec` with `DataT` of type `int16_t`, `uint16_t` or `half` `RET` must be `int16_t`. For a SYCL `vec` with `DataT` of type `int32_t`, `uint32_t` or `float` `RET` must be `int32_t`. For a SYCL `vec` with `DataT` of type `int64_t`, `uint64_t` or `double` `RET` must be `uint64_t`. Where `OP` is: `==`, `!=`, `<`, `>`, `<=`, `>=`.
`vec operatorOP(const DataT& lhs, const vec& rhs)`	If `OP` is `%`, available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as the `rhs` SYCL `vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` arithmetic operation between the `lhs` scalar and each element of the `rhs` SYCL `vec`. Where `OP` is: `+`, `-`, `*`, `/`, `%`.

Hidden friend function	Description
`vec operatorOP(const DataT& lhs, const vec& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as the `rhs` SYCL `vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` bit-wise operation between the `lhs` scalar and each element of the `rhs` SYCL `vec`. Where `OP` is: `&`, `|`, `^`.
`vec<RET, NumElements> operatorOP(const DataT& lhs, const vec& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as the `rhs` SYCL `vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` logical operation between the `lhs` scalar and each element of the `rhs` SYCL `vec`. The `DataT` template parameter of the constructed SYCL `vec`, `RET`, varies depending on the `DataT` template parameter of this SYCL `vec`. For a SYCL `vec` with `DataT` of type `int8_t` or `uint8_t` `RET` must be `int8_t`. For a SYCL `vec` with `DataT` of type `int16_t`, `uint16_t` or `half` `RET` must be `int16_t`. For a SYCL `vec` with `DataT` of type `int32_t`, `uint32_t` or `float` `RET` must be `int32_t`. For a SYCL `vec` with `DataT` of type `int64_t`, `uint64_t` or `double` `RET` must be `int64_t`. Where `OP` is: `&&`, `||`.

Hidden friend function	Description
`vec operatorOP(const DataT& lhs, const vec& rhs)`	Construct a new instance of the SYCL `vec` class template with the same template parameters as the `rhs` SYCL `vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` bit-shift operation between the `lhs` scalar and each element of the `rhs` SYCL `vec`. If `OP` is `>>`, `DataT` is a signed type and this SYCL `vec` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<`, `>>`.
`vec<RET, NumElements> operatorOP(const DataT& lhs, const vec& rhs)`	Construct a new instance of the SYCL `vec` class template with the element type `RET` with each element of the new SYCL `vec` instance the result of an element-wise `OP` relational operation between the `lhs` scalar and each element of the `rhs` SYCL `vec`. Each element of the SYCL `vec` that is returned must be `-1` if the operation results in `true` and `0` if the operation results in `false`. The `==`, `<`, `>`, `<=` and `>=` operations result in `false` if either the `lhs` or the `rhs` element is a NaN. The `!=` operation results in `true` if either the `lhs` or the `rhs` element is a NaN. The `DataT` template parameter of the constructed SYCL `vec`, `RET`, varies depending on the `DataT` template parameter of this SYCL `vec`. For a SYCL `vec` with `DataT` of type `int8_t` or `uint8_t` `RET` must be `int8_t`. For a SYCL `vec` with `DataT` of type `int16_t`, `uint16_t` or `half` `RET` must be `int16_t`. For a SYCL `vec` with `DataT` of type `int32_t`, `uint32_t` or `float` `RET` must be `int32_t`. For a SYCL `vec` with `DataT` of type `int64_t`, `uint64_t` or `double` `RET` must be `int64_t`. Where `OP` is: `==`, `!=`, `<`, `>`, `<=`, `>=`.

Hidden friend function	Description
`vec& operator~(const vec& v)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `vec` class template with the same template parameters as `v vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` bitwise operation on each element of `v vec`.
`vec<RET, NumElements> operator!(const vec& v)`	Construct a new instance of the SYCL `vec` class template with the same template parameters as `v vec` with each element of the new SYCL `vec` instance the result of an element-wise `OP` logical operation on each element of `v vec`. Each element of the SYCL `vec` that is returned must be `-1` if the operation results in `true` and `0` if the operation results in `false` or this SYCL `vec` is a NaN. The `DataT` template parameter of the constructed SYCL `vec`, `RET`, varies depending on the `DataT` template parameter of this SYCL `vec`. For a SYCL `vec` with `DataT` of type `int8_t` or `uint8_t` `RET` must be `int8_t`. For a SYCL `vec` with `DataT` of type `int16_t`, `uint16_t` or `half` `RET` must be `int16_t`. For a SYCL `vec` with `DataT` of type `int32_t`, `uint32_t` or `float` `RET` must be `int32_t`. For a SYCL `vec` with `DataT` of type `int64_t`, `uint64_t` or `double` `RET` must be `int64_t`.

4.14.2.2. Aliases

The SYCL programming API provides all permutations of the type alias:

```
using <type><elems> = vec<<storage-type>, <elems>>
```

where `<elems>` is `2`, `3`, `4`, `8` and `16`, and pairings of `<type>` and `<storage-type>` for integral types are `char` and `int8_t`, `uchar` and `uint8_t`, `short` and `int16_t`, `ushort` and `uint16_t`, `int` and `int32_t`, `uint` and `uint32_t`, `long` and `int64_t`, `ulong` and `uint64_t`, and for floating point types are both `half`, `float` and `double`.

For example `uint4` is the alias to `vec<uint32_t, 4>` and `float16` is the alias to `vec<float, 16>`.

4.14.2.3. Swizzles

Swizzle operations can be performed in two ways. Firstly by calling the `swizzle` member function template, which takes a variadic number of integer template arguments between `0` and `NumElements-1`, speci-

fying swizzle indexes. Secondly by calling one of the simple swizzle member functions defined in Table 145 as XYZW_SWIZZLE and RGBA_SWIZZLE. Note that the simple swizzle functions are only available for up to 4 element vectors and are only available when the macro SYCL_SIMPLE_SWIZZLES is defined before including <sycl/sycl.hpp>.

In both cases the return type is always an instance of __swizzled_vec__, an implementation-defined temporary class representing a swizzle of the original SYCL vec instance. Both kinds of swizzle member functions must not perform the swizzle operation themselves, instead the swizzle operation must be performed by the returned instance of __swizzled_vec__ when used within an expression, meaning if the returned __swizzled_vec__ is never used in an expression no swizzle operation is performed.

Both the swizzle member function template and the simple swizzle member functions allow swizzle indexes to be repeated.

A series of static constexpr values are provided within the elem struct to allow specifying named swizzle indexes when calling the swizzle member function template.

4.14.2.4. Swizzled vec class

The __swizzled_vec__ class must define an unspecified temporary which provides the entire interface of the SYCL vec class template, including swizzled member functions, with the additions and alterations described below:

- The __swizzled_vec__ class template must be readable as an r-value reference on the RHS of an expression. In this case the swizzle operation is performed on the RHS of the expression and then the result is applied to the LHS of the expression.
- The __swizzled_vec__ class template must be assignable as an l-value reference on the LHS of an expression. In this case the RHS of the expression is applied to the original SYCL vec which the __swizzled_vec__ represents via the swizzle operation. Note that a __swizzled_vec__ that is used in an l-value expression may not contain any repeated element indexes.

  For example: f4.xxxx() = fx.wzyx() would not be valid.
- The __swizzled_vec__ class template must be convertible to an instance of SYCL vec with the type DataT and number of elements specified by the swizzle member function, if NumElements > 1, and must be convertible to an instance of type DataT, if NumElements == 1.
- The __swizzled_vec__ class template must be non-copyable, non-moveable, non-user constructible and may not be bound to a l-value or escape the expression it was constructed in. For example auto x = f4.x() would not be valid.
- The __swizzled_vec__ class template should return __swizzled_vec__& for each operator inherited from the vec class template interface which would return vec<DataT, NumElements>&.

4.14.2.5. Rounding modes

The various rounding modes that can be used in the as member function template are described in Table 147.

Table 147. Rounding modes for the SYCL vec class template

Rounding mode	Description
automatic	Default rounding mode for the SYCL vec class element type. rtz (round toward zero) for integer types and rte (round to nearest even) for floating-point types.

Rounding mode	Description
`rte`	Round to nearest even.
`rtz`	Round toward zero.
`rtp`	Round toward positive infinity.
`rtn`	Round toward negative infinity.

4.14.2.6. Memory layout and alignment

The elements of an instance of the SYCL `vec` class template are stored in memory sequentially and contiguously and are aligned to the size of the element type in bytes multiplied by the number of elements:

$$sizeof(DataT) \cdot NumElements$$

The exception to this is when the number of element is three in which case the SYCL `vec` is aligned to the size of the element type in bytes multiplied by four:

$$sizeof(DataT) \cdot 4$$

This is true for both host and device code in order to allow for instances of the `vec` class template to be passed to SYCL kernel functions.

4.14.2.7. Performance note

The usage of the subscript `operator[]` may not be efficient on some devices.

4.14.3. Math array types

SYCL provides an `marray<typename DataT, std::size_t NumElements>` class template to represent a contiguous fixed-size container. This type allows sharing of containers between the host and its SYCL devices.

The `marray` class is templated on its element type and number of elements. The number of elements parameter, `NumElements`, is a positive value of the `std::size_t` type. The element type parameter, `DataT`, must be a *numeric type* as it is defined by C++ standard.

An instance of the `marray` class template can also be implicitly converted to an instance of the data type when the number of elements is `1` in order to allow single element arrays and scalars to be convertible with each other.

Logical and comparison operators for `marray` class template return `marray<bool, NumElements>`.

4.14.3.1. Math array interface

The constructors, member functions and non-member functions of the SYCL `marray` class template are listed in Table 148, Table 149 and Table 150 respectively.

```
1 namespace sycl {
2
3 template <typename DataT, std::size_t NumElements> class marray {
4  public:
```

```
using value_type = DataT;
using reference = DataT&;
using const_reference = const DataT&;
using iterator = DataT*;
using const_iterator = const DataT*;

marray();

explicit constexpr marray(const DataT& arg);

template <typename... ArgTN> constexpr marray(const ArgTN&... args);

constexpr marray(const marray<DataT, NumElements>& rhs);
constexpr marray(marray<DataT, NumElements>&& rhs);

// Available only when: NumElements == 1
operator DataT() const;

static constexpr std::size_t size() noexcept;

// subscript operator
reference operator[](std::size_t index);
const_reference operator[](std::size_t index) const;

marray& operator=(const marray<DataT, NumElements>& rhs);
marray& operator=(const DataT& rhs);

// iterator functions
iterator begin();
const_iterator begin() const;

iterator end();
const_iterator end() const;

// OP is: +, -, *, /, %
/* If OP is %, available only when: DataT != float && DataT != double && DataT
 * != half. */
friend marray operatorOP(const marray& lhs, const marray& rhs) { /* ... */
}
friend marray operatorOP(const marray& lhs, const DataT& rhs) { /* ... */
}

// OP is: +=, -=, *=, /=, %=
/* If OP is %=, available only when: DataT != float && DataT != double &&
 * DataT != half. */
friend marray& operatorOP(marray& lhs, const marray& rhs) { /* ... */
}
friend marray& operatorOP(marray& lhs, const DataT& rhs) { /* ... */
}

// OP is prefix ++, --
friend marray& operatorOP(marray& v) { /* ... */
}

// OP is postfix ++, --
friend marray operatorOP(marray& v, int) { /* ... */
```

```
}

// OP is unary +, -
friend marray operatorOP(marray& v) { /* ... */
}

// OP is: &, |, ^
/* Available only when: DataT != float && DataT != double && DataT != half. */
friend marray operatorOP(const marray& lhs, const marray& rhs) { /* ... */
}
friend marray operatorOP(const marray& lhs, const DataT& rhs) { /* ... */
}

// OP is: &=, |=, ^=
/* Available only when: DataT != float && DataT != double && DataT != half. */
friend marray& operatorOP(marray& lhs, const marray& rhs) { /* ... */
}
friend marray& operatorOP(marray& lhs, const DataT& rhs) { /* ... */
}

// OP is: &&, ||
friend marray<bool, NumElements> operatorOP(const marray& lhs,
                                            const marray& rhs) {
/* ... */ }
friend marray<bool, NumElements> operatorOP(const marray& lhs,
                                            const DataT& rhs) {
/* ... */ }

// OP is: <<, >>
/* Available only when: DataT != float && DataT != double && DataT != half.
 */
friend marray operatorOP(const marray& lhs, const marray& rhs) { /* ... */
}
friend marray operatorOP(const marray& lhs, const DataT& rhs) { /* ... */
}

// OP is: <<=, >>=
/* Available only when: DataT != float && DataT != double && DataT != half.
 */
friend marray& operatorOP(marray& lhs, const marray& rhs) { /* ... */
}
friend marray& operatorOP(marray& lhs, const DataT& rhs) { /* ... */
}

// OP is: ==, !=, <, >, <=, >=
friend marray<bool, NumElements> operatorOP(const marray& lhs,
                                            const marray& rhs) {
/* ... */ }
friend marray<bool, NumElements> operatorOP(const marray& lhs,
                                            const DataT& rhs) {
/* ... */ }

/* Available only when: DataT != float && DataT != double && DataT != half.
 */
friend marray operator~(const marray& v) { /* ... */
}
```

```
117
118   // OP is: +, -, *, /, %
119   /* operator% is only available when: DataT != float && DataT != double &&
120    * DataT != half. */
121   friend marray operatorOP(const DataT& lhs, const marray& rhs) { /* ... */
122   }
123
124   // OP is: &, |, ^
125   /* Available only when: DataT != float && DataT != double
126   && DataT != half. */
127   friend marray operatorOP(const DataT& lhs, const marray& rhs) { /* ... */
128   }
129
130   // OP is: &&, ||
131   friend marray<bool, NumElements> operatorOP(const DataT& lhs,
132                                               const marray& rhs) {
133   /* ... */ }
134
135   // OP is: <<, >>
136   /* Available only when: DataT != float && DataT != double && DataT != half.
137    */
138   friend marray operatorOP(const DataT& lhs, const marray& rhs) { /* ... */
139   }
140
141   // OP is: ==, !=, <, >, <=, >=
142   friend marray<bool, NumElements> operatorOP(const DataT& lhs,
143                                               const marray& rhs) {
144   /* ... */ }
145
146   friend marray<bool, NumElements> operator!(const marray& v) { /* ... */
147   }
148 };
149
150 } // namespace sycl
```

Table 148. Constructors of the SYCL `marray` class template

Constructor	Description
`marray()`	Default construct an array with element type `DataT` and with `NumElements` dimensions by default construction of each of its elements.
`explicit constexpr marray(const DataT& arg)`	Construct an array of element type `DataT` and `NumElements` dimensions by setting each value to `arg` by assignment.
`template <typename... ArgTN> constexpr marray(const ArgTN &... args)`	Construct a SYCL `marray` instance from any combination of scalar and SYCL `marray` parameters of the same element type, providing the total number of elements for all parameters sum to `NumElements` of this `marray` specialization.

Constructor	Description
`constexpr marray(const marray<DataT, NumElements>& rhs)`	Construct an array of element type `DataT` and number of elements `NumElements` by copy from another similar vector.
`constexpr marray(marray<DataT, NumElements>&& rhs)`	Construct an array of element type `DataT` and number of elements `NumElements` by moving from another similar vector.

Table 149. Member functions for the SYCL `marray` class template

Member function	Description
`operator DataT() const`	Available only when: `NumElements == 1`. Converts this SYCL `marray` instance to an instance of `DataT` with the value of the single element in this SYCL `marray` instance. The SYCL `marray` instance shall be implicitly convertible to the same data types, to which `DataT` is implicitly convertible. Note that conversion operator shall not be templated to allow standard conversion sequence for implicit conversion.
`static constexpr std::size_t size() noexcept`	Returns the size of this SYCL `marray` in bytes.
`DataT& operator[](std::size_t index)`	Returns a reference to the element stored within this SYCL `marray` at the index specified by `index`.
`const DataT& operator[](std::size_t index) const`	Returns a const reference to the element stored within this SYCL `marray` at the index specified by `index`.
`marray& operator=(const marray& rhs)`	Assign each element of the `rhs` SYCL `marray` to each element of this SYCL `marray` and return a reference to this SYCL `marray`.
`marray& operator=(const DataT& rhs)`	Assign each element of the `rhs` scalar to each element of this SYCL `marray` and return a reference to this SYCL `marray`.
`iterator begin()`	Returns an iterator referring to the first element stored within the `v marray`.

Member function	Description
`const_iterator begin() const`	Returns a const iterator referring to the first element stored within the `v marray`.
`iterator end()`	Returns an iterator referring to the one past the last element stored within the `v marray`.
`const_iterator end() const`	Returns a const iterator referring to the one past the last element stored within the `v marray`.

Table 150. Hidden friend functions of the `marray` class template

Hidden friend function	Description
`marray operatorOP(const marray& lhs, const marray& rhs)`	If `OP` is `%`, available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as `lhs marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` arithmetic operation between each element of `lhs marray` and each element of the `rhs` SYCL `marray`. Where `OP` is: `+`, `-`, `*`, `/`, `%`.
`marray operatorOP(const marray& lhs, const DataT& rhs)`	If `OP` is `%`, available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as `lhs marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` arithmetic operation between each element of `lhs marray` and the `rhs` scalar. Where `OP` is: `+`, `-`, `*`, `/`, `%`.
`marray& operatorOP(marray& lhs, const marray& rhs)`	If `OP` is `%=`, available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` arithmetic operation between each element of `lhs marray` and each element of the `rhs` SYCL `marray` and return `lhs marray`. Where `OP` is: `+=`, `-=`, `*=`, `/=`, `%=`.

Hidden friend function	Description
`marray& operatorOP(marray& lhs, const DataT& rhs)`	If `OP` is `%=`, available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` arithmetic operation between each element of `lhs marray` and `rhs` scalar and return `lhs marray`. Where `OP` is: `+=`, `-=`, `*=`, `/=`, `%=`.
`marray& operatorOP(marray& v)`	Perform an in-place element-wise `OP` prefix arithmetic operation on each element of `v marray`, assigning the result of each element to the corresponding element of `v marray` and return `v marray`. Where `OP` is: `++`, `--`.
`marray operatorOP(marray& v, int)`	Perform an in-place element-wise `OP` postfix arithmetic operation on each element of `v marray`, assigning the result of each element to the corresponding element of `v marray` and returns a copy of `v marray` before the operation is performed. Where `OP` is: `++`, `--`.
`marray operatorOP(marray& v)`	Construct a new instance of the SYCL `marray` class template with the same template parameters as this SYCL `marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` unary arithmetic operation on each element of this SYCL `marray`. Where `OP` is: `+`, `-`.
`marray operatorOP(const marray& lhs, const marray& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as `lhs marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` bitwise operation between each element of `lhs marray` and each element of the `rhs` SYCL `marray`. Where `OP` is: `&`, `|`, `^`.

Hidden friend function	Description
`marray operatorOP(const marray& lhs, const DataT& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as `lhs marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` bit-wise operation between each element of `lhs marray` and the `rhs` scalar. Where `OP` is: `&`, `|`, `^`.
`marray& operatorOP(marray& lhs, const marray& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` bitwise operation between each element of `lhs marray` and the `rhs` SYCL `marray` and return `lhs marray`. Where `OP` is: `&=`, `|=`, `^=`.
`marray& operatorOP(marray& lhs, const DataT& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` bitwise operation between each element of `lhs marray` and the `rhs` scalar and return a `lhs marray`. Where `OP` is: `&=`, `|=`, `^=`.
`marray<bool, NumElements> operatorOP(const marray& lhs, const marray& rhs)`	Construct a new instance of the `marray` class template with `DataT = bool` and same NumElements as `lhs marray` with each element of the new `marray` instance the result of an element-wise `OP` logical operation between each element of `lhs marray` and each element of the `rhs marray`. Where `OP` is: `&&`, `||`.

Hidden friend function	Description
`marray<bool, NumElements> operatorOP(const marray& lhs, const DataT& rhs)`	Construct a new instance of the `marray` class template with `DataT = bool` and same NumElements as `lhs marray` with each element of the new `marray` instance the result of an element-wise `OP` logical operation between each element of `lhs marray` and the `rhs` scalar. Where `OP` is: `&&`, `||`.
`marray operatorOP(const marray& lhs, const marray& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as `lhs marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` bit-shift operation between each element of `lhs marray` and each element of the `rhs` SYCL `marray`. If `OP` is `>>`, `DataT` is a signed type and `lhs marray` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<`, `>>`.
`marray operatorOP(const marray& lhs, const DataT& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as `lhs marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` bit-shift operation between each element of `lhs marray` and the `rhs` scalar. If `OP` is `>>`, `DataT` is a signed type and `lhs marray` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<`, `>>`.

Hidden friend function	Description
`marray& operatorOP(marray& lhs, const marray& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` bitshift operation between each element of `lhs marray` and the `rhs` SYCL `marray` and returns `lhs marray`. If `OP` is `>>=`, `DataT` is a signed type and `lhs marray` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<=`, `>>=`.
`marray& operatorOP(marray& lhs, const DataT& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Perform an in-place element-wise `OP` bitshift operation between each element of `lhs marray` and the `rhs` scalar and returns a reference to this SYCL `marray`. If `OP` is `>>=`, `DataT` is a signed type and `lhs marray` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<=`, `>>=`.
`marray<bool, NumElements> operatorOP(const marray& lhs, const marray& rhs)`	Construct a new instance of the `marray` class template with `DataT = bool` and same NumElements as `lhs marray` with each element of the new `marray` instance is the result of an element-wise `OP` relational operation between each element of `lhs marray` and each element of the `rhs marray`. The `==`, `<`, `>`, `<=` and `>=` operations result in `false` if either the `lhs` element or the `rhs` element is a NaN. The `!=` operation results in `true` if either the `lhs` element or the `rhs` element is a NaN. Where `OP` is: `==`, `!=`, `<`, `>`, `<=`, `>=`.

Hidden friend function	Description
`marray<bool, NumElements> operatorOP(const marray& lhs, const DataT& rhs)`	Construct a new instance of the `marray` class template with `DataT = bool` and same NumElements as `lhs` `marray` with each element of the new `marray` instance the result of an element-wise `OP` relational operation between each element of `lhs` `marray` and the `rhs` scalar. The `==`, `<`, `>`, `<=` and `>=` operations result in `false` if either the `lhs` element or the `rhs` is a NaN. The `!=` operation results in `true` if either the `lhs` element or the `rhs` is a NaN. Where `OP` is: `==`, `!=`, `<`, `>`, `<=`, `>=`.
`marray operatorOP(const DataT& lhs, const marray& rhs)`	If `OP` is `%`, available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as the `rhs` SYCL `marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` arithmetic operation between the `lhs` scalar and each element of the `rhs` SYCL `marray`. Where `OP` is: `+`, `-`, `*`, `/`, `%`.
`marray operatorOP(const DataT& lhs, const marray& rhs)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as the `rhs` SYCL `marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` bitwise operation between the `lhs` scalar and each element of the `rhs` SYCL `marray`. Where `OP` is: `&`, `|`, `^`.

Hidden friend function	Description
`marray<bool, NumElements> operatorOP(const DataT& lhs, const marray& rhs)`	Construct a new instance of the `marray` class template with `DataT = bool` and same NumElements as `rhs marray` with each element of the new `marray` instance the result of an element-wise `OP` logical operation between the `lhs` scalar and each element of the `rhs marray`. Where `OP` is: `&&`, `||`.
`marray operatorOP(const DataT& lhs, const marray& rhs)`	Construct a new instance of the SYCL `marray` class template with the same template parameters as the `rhs` SYCL `marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` bitshift operation between the `lhs` scalar and each element of the `rhs` SYCL `marray`. If `OP` is `>>`, `DataT` is a signed type and this SYCL `marray` has a negative value any vacated bits viewed as an unsigned integer must be assigned the value `1`, otherwise any vacated bits viewed as an unsigned integer must be assigned the value `0`. Where `OP` is: `<<`, `>>`.
`marray<bool, NumElements> operatorOP(const DataT& lhs, const marray& rhs)`	Construct a new instance of the `marray` class template with `DataT = bool` and same NumElements as `rhs marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` relational operation between the `lhs` scalar and each element of the `rhs marray`. The `==`, `<`, `>`, `<=` and `>=` operations result in `false` if either the `lhs` or the `rhs` element is a NaN. The `!=` operation results in `true` if either the `lhs` or the `rhs` element is a NaN. Where `OP` is: `==`, `!=`, `<`, `>`, `<=`, `>=`.

Hidden friend function	Description
`marray& operator~(const marray& v)`	Available only when: `DataT != float && DataT != double && DataT != half`. Construct a new instance of the SYCL `marray` class template with the same template parameters as `v` `marray` with each element of the new SYCL `marray` instance the result of an element-wise `OP` bit-wise operation on each element of `v` `marray`.
`marray<bool, NumElements> operator!(const marray& v)`	Construct a new instance of the `marray` class template with `DataT = bool` and same NumElements as `v` `marray` with each element of the new `marray` instance the result of an element-wise logical `!` operation on each element of `v` `marray`.

4.14.3.2. Aliases

The SYCL programming API provides all permutations of the type alias:

```
using m<type><elems> = marray<<storage-type>, <elems>>
```

where `<elems>` is `2`, `3`, `4`, `8` and `16`, and pairings of `<type>` and `<storage-type>` for integral types are `char` and `int8_t`, `uchar` and `uint8_t`, `short` and `int16_t`, `ushort` and `uint16_t`, `int` and `int32_t`, `uint` and `uint32_t`, `long` and `int64_t`, `ulong` and `uint64_t`, for floating point types are both `half`, `float` and `double`, and for boolean type `bool`.

For example `muint4` is the alias to `marray<uint32_t, 4>` and `mfloat16` is the alias to `marray<float, 16>`.

4.14.3.3. Memory layout and alignment

The elements of an instance of the `marray` class template as if stored in `std::array<DataT, NumElements>`.

4.15. Synchronization and atomics

The available features are:

- Accessor classes: Accessor classes specify acquisition and release of buffer and image data structures to provide points at which underlying queue synchronization primitives must be generated.
- Atomic operations: SYCL devices support a restricted subset of C++ atomics and SYCL uses the library syntax from the next C++ specification to make this available.
- Fences: Fence primitives are made available to order loads and stores. They are exposed through the `atomic_fence` function. Fences can have acquire semantics, release semantics or both.
- Barriers: Barrier primitives are made available to synchronize sets of work-items within individual groups. They are exposed through the `group_barrier` function.
- Hierarchical parallel dispatch: In the hierarchical parallelism model of describing computations, synchronization within the work-group is made explicit through multiple instances of the `parallel_for_work_item` function call, rather than through the use of explicit work-group barrier operations.
- Device event: they are used inside SYCL kernel functions to wait for asynchronous operations within

a SYCL kernel function to complete.

4.15.1. Barriers and fences

A group barrier or mem-fence provides memory ordering semantics over both the local address space and global address space. A mem-fence provides control over the re-ordering of memory load and store operations, subject to the associated memory `order` and memory `scope`, when paired with synchronization through an atomic object.

```
namespace sycl {

void atomic_fence(memory_order order, memory_scope scope);

} // namespace sycl
```

The effects of a call to `atomic_fence` depend on the value of the `order` parameter:

- `memory_order::relaxed`: No effect
- `memory_order::acquire`: Acquire fence
- `memory_order::release`: Release fence
- `memory_order::acq_rel`: Both an acquire fence and a release fence
- `memory_order::seq_cst`: A sequentially consistent acquire and release fence

A group barrier acts as both an acquire fence and a release fence: all work-items in the group execute a release fence prior to synchronizing at the barrier, and all work-items in the group execute an acquire fence afterwards. A group barrier provides implicit atomic synchronization as if through an internal atomic object, such that the acquire and release fences associated with the barrier synchronize with each other, without an explicit atomic operation being required on an atomic object to synchronize the fences.

4.15.2. `device_event` class

The SYCL `device_event` class encapsulates a single SYCL device event which is available only within SYCL kernel functions and can be used to wait for asynchronous operations within a SYCL kernel function to complete.

All member functions of the `device_event` class must not throw a SYCL exception.

A synopsis of the SYCL `device_event` class is provided below. The constructors and member functions of the SYCL `device_event` class are listed in Table 152 and Table 151 respectively.

```
namespace sycl {
class device_event {

  device_event(__unspecified__);

 public:
  void wait() noexcept;
};
} // namespace sycl
```

Table 151. Member functions of the SYCL `device_event` class

Member function	Description
`void wait() noexcept`	Waits for the asynchronous operation associated with this SYCL `device_event` to complete.

Table 152. Constructors of the `device_event` class

Constructor	Description
`device_event(___unspecified___)`	Unspecified implementation-defined constructor.

4.15.3. Atomic references

The `sycl::atomic_ref` class provides the ability to perform atomic operations in device code with a syntax similar to the C++ standard `std::atomic_ref`. The `sycl::atomic_ref` class must not be used in host code.

Unlike `std::atomic_ref`, `sycl::atomic_ref` does not provide a default memory ordering for its operations. Instead, the application must specify a default ordering via the `DefaultOrder` template parameter. This ordering is used as a default for most of the atomic operations, but most member functions also provide an optional parameter that allows the application to override this default. The set of supported orderings is specific to a device, but every device is guaranteed to support at least `memory_order::relaxed`. If the default order is set to `memory_order::relaxed`, all memory order arguments default to `memory_order::relaxed`. If the default order is set to `memory_order::acq_rel`, memory order arguments default to `memory_order::acquire` for load operations, `memory_order::release` for store operations and `memory_order::acq_rel` for read-modify-write operations. If the default order is set to `memory_order::seq_cst`, all memory order arguments default to `memory_order::seq_cst`.

The `sycl::atomic_ref` class has a template parameter `DefaultScope`, which allows the application to define a default memory scope for the atomic operations. Most member functions also provide an optional parameter that allows the application to override this default.

The `sycl::atomic_ref` class also has a template parameter `AddressSpace`, which allows the application to make an assertion about the address space of the object of type `T` that it references. The default value for this parameter is `access::address_space::generic_space`, which indicates that the object could be in either the global or local address spaces. If the application knows the address space, it can set this template parameter to either `access::address_space::global_space` or `access::address_space::local_space` as an assertion to the implementation. Specifying the address space via this template parameter may allow the implementation to perform certain optimizations. Specifying an address space that does not match the object's actual address space results in undefined behavior.

The template parameter `T` must be one of the following types:

- `int`,
- `unsigned int`,
- `long`,
- `unsigned long`,
- `long long`,
- `unsigned long long`,
- `float`, or
- `double`.

In addition, the type `T` must satisfy one of the following conditions:

- `sizeof(T) == 4`, or
- `sizeof(T) == 8` and the code containing this `atomic_ref` was submitted to a device that has `aspect::atomic64`.

For floating-point types, the member functions of the `atomic_ref` class may be emulated, and they may use a different floating-point environment from those defined by `info::device::single_fp_config` and `info::device::double_fp_config` (i.e. floating-point atomics may use different rounding modes and may have different exception behavior).

The atomic types are defined as follows.

```
namespace sycl {

// Exposition only
template <memory_order ReadModifyWriteOrder> struct memory_order_traits;

template <> struct memory_order_traits<memory_order::relaxed> {
  static constexpr memory_order read_order = memory_order::relaxed;
  static constexpr memory_order write_order = memory_order::relaxed;
};

template <> struct memory_order_traits<memory_order::acq_rel> {
  static constexpr memory_order read_order = memory_order::acquire;
  static constexpr memory_order write_order = memory_order::release;
};

template <> struct memory_order_traits<memory_order::seq_cst> {
  static constexpr memory_order read_order = memory_order::seq_cst;
  static constexpr memory_order write_order = memory_order::seq_cst;
};

template <typename T, memory_order DefaultOrder, memory_scope DefaultScope,
          access::address_space AddressSpace = access::address_space::generic_space>
class atomic_ref {
 public:
  using value_type = T;
  static constexpr size_t required_alignment = /* implementation-defined */;
  static constexpr bool is_always_lock_free = /* implementation-defined */;
  static constexpr memory_order default_read_order =
      memory_order_traits<DefaultOrder>::read_order;
  static constexpr memory_order default_write_order =
      memory_order_traits<DefaultOrder>::write_order;
  static constexpr memory_order default_read_modify_write_order = DefaultOrder;
  static constexpr memory_scope default_scope = DefaultScope;

  bool is_lock_free() const noexcept;

  explicit atomic_ref(T&);
  atomic_ref(const atomic_ref&) noexcept;
  atomic_ref& operator=(const atomic_ref&) = delete;

  void store(T operand, memory_order order = default_write_order,
             memory_scope scope = default_scope) const noexcept;

  T operator=(T desired) const noexcept;

```

```
  T load(memory_order order = default_read_order,
         memory_scope scope = default_scope) const noexcept;

  operator T() const noexcept;

  T exchange(T operand, memory_order order = default_read_modify_write_order,
             memory_scope scope = default_scope) const noexcept;

  bool compare_exchange_weak(T& expected, T desired, memory_order success,
                             memory_order failure,
                             memory_scope scope = default_scope) const noexcept;

  bool
  compare_exchange_weak(T& expected, T desired,
                        memory_order order = default_read_modify_write_order,
                        memory_scope scope = default_scope) const noexcept;

  bool
  compare_exchange_strong(T& expected, T desired, memory_order success,
                          memory_order failure,
                          memory_scope scope = default_scope) const noexcept;

  bool
  compare_exchange_strong(T& expected, T desired,
                          memory_order order = default_read_modify_write_order,
                          memory_scope scope = default_scope) const noexcept;
};

// Partial specialization for integral types
template <memory_order DefaultOrder, memory_scope DefaultScope,
          access::address_space AddressSpace = access::address_space::generic_space>
class atomic_ref<Integral, DefaultOrder, DefaultScope, AddressSpace> {

  /* All other members from atomic_ref<T> are available */

  using difference_type = value_type;

  Integral fetch_add(Integral operand,
                     memory_order order = default_read_modify_write_order,
                     memory_scope scope = default_scope) const noexcept;

  Integral fetch_sub(Integral operand,
                     memory_order order = default_read_modify_write_order,
                     memory_scope scope = default_scope) const noexcept;

  Integral fetch_and(Integral operand,
                     memory_order order = default_read_modify_write_order,
                     memory_scope scope = default_scope) const noexcept;

  Integral fetch_or(Integral operand,
                    memory_order order = default_read_modify_write_order,
                    memory_scope scope = default_scope) const noexcept;

  Integral fetch_xor(Integral operand,
                     memory_order order = default_read_modify_write_order,
                     memory_scope scope = default_scope) const noexcept;
```

```
102
103   Integral fetch_min(Integral operand,
104                      memory_order order = default_read_modify_write_order,
105                      memory_scope scope = default_scope) const noexcept;
106
107   Integral fetch_max(Integral operand,
108                      memory_order order = default_read_modify_write_order,
109                      memory_scope scope = default_scope) const noexcept;
110
111   Integral operator++(int) const noexcept;
112   Integral operator--(int) const noexcept;
113   Integral operator++() const noexcept;
114   Integral operator--() const noexcept;
115   Integral operator+=(Integral) const noexcept;
116   Integral operator-=(Integral) const noexcept;
117   Integral operator&=(Integral) const noexcept;
118   Integral operator|=(Integral) const noexcept;
119   Integral operator^=(Integral) const noexcept;
120 };
121
122 // Partial specialization for floating-point types
123 template <memory_order DefaultOrder, memory_scope DefaultScope,
124           access::address_space AddressSpace = access::address_space::generic_space>
125 class atomic_ref<Floating, DefaultOrder, DefaultScope, AddressSpace> {
126
127   /* All other members from atomic_ref<T> are available */
128
129   using difference_type = value_type;
130
131   Floating fetch_add(Floating operand,
132                      memory_order order = default_read_modify_write_order,
133                      memory_scope scope = default_scope) const noexcept;
134
135   Floating fetch_sub(Floating operand,
136                      memory_order order = default_read_modify_write_order,
137                      memory_scope scope = default_scope) const noexcept;
138
139   Floating fetch_min(Floating operand,
140                      memory_order order = default_read_modify_write_order,
141                      memory_scope scope = default_scope) const noexcept;
142
143   Floating fetch_max(Floating operand,
144                      memory_order order = default_read_modify_write_order,
145                      memory_scope scope = default_scope) const noexcept;
146
147   Floating operator+=(Floating) const noexcept;
148   Floating operator-=(Floating) const noexcept;
149 };
150
151 // Partial specialization for pointers
152 template <typename T, memory_order DefaultOrder, memory_scope DefaultScope,
153           access::address_space AddressSpace = access::address_space::generic_space>
154 class atomic_ref<T*, DefaultOrder, DefaultScope, AddressSpace> {
155
156   using value_type = T*;
157   using difference_type = ptrdiff_t;
```

```
static constexpr size_t required_alignment = /* implementation-defined */;
static constexpr bool is_always_lock_free = /* implementation-defined */;
static constexpr memory_order default_read_order =
    memory_order_traits<DefaultOrder>::read_order;
static constexpr memory_order default_write_order =
    memory_order_traits<DefaultOrder>::write_order;
static constexpr memory_order default_read_modify_write_order = DefaultOrder;
static constexpr memory_scope default_scope = DefaultScope;

bool is_lock_free() const noexcept;

explicit atomic_ref(T*&);
atomic_ref(const atomic_ref&) noexcept;
atomic_ref& operator=(const atomic_ref&) = delete;

void store(T* operand, memory_order order = default_write_order,
           memory_scope scope = default_scope) const noexcept;

T* operator=(T* desired) const noexcept;

T* load(memory_order order = default_read_order,
        memory_scope scope = default_scope) const noexcept;

operator T*() const noexcept;

T* exchange(T* operand, memory_order order = default_read_modify_write_order,
            memory_scope scope = default_scope) const noexcept;

bool compare_exchange_weak(T*& expected, T* desired, memory_order success,
                           memory_order failure,
                           memory_scope scope = default_scope) const noexcept;

bool
compare_exchange_weak(T*& expected, T* desired,
                      memory_order order = default_read_modify_write_order,
                      memory_scope scope = default_scope) const noexcept;

bool
compare_exchange_strong(T*& expected, T* desired, memory_order success,
                        memory_order failure,
                        memory_scope scope = default_scope) const noexcept;

bool
compare_exchange_strong(T*& expected, T* desired,
                        memory_order order = default_read_modify_write_order,
                        memory_scope scope = default_scope) const noexcept;

T* fetch_add(difference_type,
             memory_order order = default_read_modify_write_order,
             memory_scope scope = default_scope) const noexcept;

T* fetch_sub(difference_type,
             memory_order order = default_read_modify_write_order,
             memory_scope scope = default_scope) const noexcept;

T* operator++(int) const noexcept;
```

```
214   T* operator--(int) const noexcept;
215   T* operator++() const noexcept;
216   T* operator--() const noexcept;
217   T* operator+=(difference_type) const noexcept;
218   T* operator-=(difference_type) const noexcept;
219 };
220
221 } // namespace sycl
```

The constructors and member functions for instances of the SYCL `atomic_ref` class using any compatible type are listed in Table 153 and Table 154 respectively. Additional member functions for integral, floating-point and pointer types are listed in Table 155, Table 156 and Table 157 respectively.

The static member `required_alignment` describes the minimum required alignment in bytes of an object that can be referenced by an `atomic_ref<T>`, which must be at least `alignof(T)`.

The static member `is_always_lock_free` is true if all atomic operations for type `T` are always lock-free. A SYCL implementation is not guaranteed to support atomic operations that are not lock-free.

The static members `default_read_order`, `default_write_order` and `default_read_modify_write_order` reflect the default memory order values for each type of atomic operation, consistent with the `DefaultOrder` template.

The atomic operations and member functions behave as described in the C++ specification, barring the restrictions discussed above.

Care must be taken when using atomics for work-item coordination, because work-items are not required to provide stronger than weakly parallel forward progress guarantees. Operations that block a work-item, such as continuously checking the value of an atomic variable until some condition holds, or using atomic operations that are not lock-free, may prevent overall progress.

Table 153. Constructors of the SYCL `atomic_ref` class template

Constructor	Description
`atomic_ref(T& ref)`	Constructs an instance of SYCL `atomic_ref` which is associated with the reference `ref`.

Table 154. Member functions available on any object of type `atomic_ref<T>`

Member function	Description
`bool is_lock_free() const`	Return `true` if the atomic operations provided by this `atomic_ref` are lock-free.
`void store(T operand, memory_order order = default_write_order, memory_scope scope = default_scope) const`	Atomically stores `operand` to the object referenced by this `atomic_ref`. The memory order of this atomic operation must be `memory_order::relaxed`, `memory_order::release` or `memory_order::seq_cst`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

Member function	Description
`T operator=(T desired) const`	Equivalent to `store(desired)`. Returns `desired`.
`T load(memory_order order = default_read_order memory_scope scope = default_scope) const`	Atomically loads the value of the object referenced by this `atomic_ref`. The memory order of this atomic operation must be `memory_order::relaxed`, `memory_order::acquire`, or `memory_order::seq_cst`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`operator T() const`	Equivalent to `load()`.
`T exchange(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically replaces the value of the object referenced by this `atomic_ref` with value `operand` and returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`bool compare_exchange_weak(T& expected, T desired, memory_order success, memory_order failure, memory_scope scope = default_scope) const`	Atomically compares the value of the object referenced by this `atomic_ref` against the value of `expected`. If the values are equal, attempts to replace the value of the referenced object with the value of `desired`; otherwise assigns the original value of the referenced object to `expected`. Returns `true` if the comparison operation and replacement operation were successful. The `failure` memory order of this atomic operation must be `memory_order::relaxed`, `memory_order::acquire` or `memory_order::seq_cst`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`bool compare_exchange_weak(T& expected, T desired, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Equivalent to `compare_exchange_weak(expected, desired, order, order, scope)`.

Member function	Description
`bool compare_exchange_strong(T& expected, T desired, memory_order success, memory_order failure, memory_scope scope = default_scope) const`	Atomically compares the value of the object referenced by this `atomic_ref` against the value of `expected`. If the values are equal, replaces the value of the referenced object with the value of `desired`; otherwise assigns the original value of the referenced object to `expected`. Returns `true` if the comparison operation was successful. The `failure` memory order of this atomic operation must be `memory_order::relaxed`, `memory_order::acquire` or `memory_order::seq_cst`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`bool compare_exchange_strong( T& expected, T desired, memory_order order = default_read_modify_write_order) const`	Equivalent to `compare_exchange_strong(expected, desired, order, order, scope)`.

Table 155. Additional member functions available on an object of type `atomic_ref<T>` for integral `T`

Member function	Description
`T fetch_add(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically adds `operand` to the value of the object referenced by this `atomic_ref` and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T operator+=(T operand) const`	Equivalent to `fetch_add(operand) + operand`.
`T operator++(int) const`	Equivalent to `fetch_add(1)`.
`T operator++() const`	Equivalent to `fetch_add(1) + 1`.

Member function	Description
`T fetch_sub(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically subtracts `operand` from the value of the object referenced by this `atomic_ref` and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T operator-=(T operand) const`	Equivalent to `fetch_sub(operand) - operand`.
`T operator--(int) const`	Equivalent to `fetch_sub(1)`.
`T operator--() const`	Equivalent to `fetch_sub(1) - 1`.
`T fetch_and(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically performs a bitwise AND between `operand` and the value of the object referenced by this `atomic_ref`, and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T operator&=(T operand) const`	Equivalent to `fetch_and(operand) & operand`.
`T fetch_or(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically performs a bitwise OR between `operand` and the value of the object referenced by this `atomic_ref`, and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T operator|=(T operand) const`	Equivalent to `fetch_or(operand) | operand`.

Member function	Description
`T fetch_xor(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically performs a bitwise XOR between `operand` and the value of the object referenced by this `atomic_ref`, and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T operator^=(T operand) const`	Equivalent to `fetch_xor(operand) ^ operand`.
`T fetch_min(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically computes the minimum of `operand` and the value of the object referenced by this `atomic_ref`, and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T fetch_max(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically computes the maximum of `operand` and the value of the object referenced by this `atomic_ref`, and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

Table 156. Additional member functions available on an object of type `atomic_ref<T>` for floating-point `T`

Member function	Description
`T fetch_add(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically adds `operand` to the value of the object referenced by this `atomic_ref` and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T operator+=(T operand) const`	Equivalent to `fetch_add(operand) + operand`.

Member function	Description
`T fetch_sub(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically subtracts `operand` from the value of the object referenced by this `atomic_ref` and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T operator-=(T operand) const`	Equivalent to `fetch_sub(operand) - operand`.
`T fetch_min(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically computes the minimum of `operand` and the value of the object referenced by this `atomic_ref`, and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T fetch_max(T operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically computes the maximum of `operand` and the value of the object referenced by this `atomic_ref`, and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

Table 157. Additional member functions available on an object of type `atomic_ref<T*>`

Member function	Description
`T* fetch_add(ptrdiff_t operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically adds `operand` to the value of the object referenced by this `atomic_ref` and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit pointers on devices that have `aspect::atomic64`.
`T* operator+=(ptrdiff_t operand) const`	Equivalent to `fetch_add(operand) + operand`.
`T* operator++(int) const`	Equivalent to `fetch_add(1)`.

Member function	Description
`T* operator++() const`	Equivalent to `fetch_add(1) + 1`.
`T* fetch_sub(ptrdiff_t operand, memory_order order = default_read_modify_write_order, memory_scope scope = default_scope) const`	Atomically subtracts `operand` from the value of the object referenced by this `atomic_ref` and assigns the result to the value of the referenced object. Returns the original value of the referenced object. This function is only supported for 64-bit pointers on devices that have `aspect::atomic64`.
`T* operator-=(ptrdiff_t operand) const`	Equivalent to `fetch_sub(operand) - operand`.
`T* operator--(int) const`	Equivalent to `fetch_sub(1)`.
`T* operator--() const`	Equivalent to `fetch_sub(1) - 1`.

4.15.4. Atomic types (deprecated)

The atomic types and operations on atomic types provided by SYCL 1.2.1 are deprecated in SYCL 2020, and will be removed in a future version of SYCL. The types and operations are made available in the `cl::sycl::` namespace for backwards compatibility.

The constructors and member functions for the `cl::sycl::atomic` class are listed in Table 158 and Table 159 respectively.

```
namespace cl {
namespace sycl {

/* Deprecated in SYCL 2020 */
enum class memory_order : /* unspecified */ { relaxed };

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace =
                          access::address_space::global_space>
class atomic {
 public:
  template <typename PointerT, access::decorated IsDecorated>
  atomic(multi_ptr<PointerT, AddressSpace, IsDecorated> ptr);

  void store(T operand, memory_order memoryOrder = memory_order::relaxed);

  T load(memory_order memoryOrder = memory_order::relaxed) const;

  T exchange(T operand, memory_order memoryOrder = memory_order::relaxed);

  /* Available only when: T != float */
  bool compare_exchange_strong(
      T& expected, T desired,
```

```
      memory_order successMemoryOrder = memory_order::relaxed,
      memory_order failMemoryOrder = memory_order::relaxed);

  /* Available only when: T != float */
  T fetch_add(T operand, memory_order memoryOrder = memory_order::relaxed);

  /* Available only when: T != float */
  T fetch_sub(T operand, memory_order memoryOrder = memory_order::relaxed);

  /* Available only when: T != float */
  T fetch_and(T operand, memory_order memoryOrder = memory_order::relaxed);

  /* Available only when: T != float */
  T fetch_or(T operand, memory_order memoryOrder = memory_order::relaxed);

  /* Available only when: T != float */
  T fetch_xor(T operand, memory_order memoryOrder = memory_order::relaxed);

  /* Available only when: T != float */
  T fetch_min(T operand, memory_order memoryOrder = memory_order::relaxed);

  /* Available only when: T != float */
  T fetch_max(T operand, memory_order memoryOrder = memory_order::relaxed);
};

} // namespace sycl
} // namespace cl
```

The global functions are as follows and described in Table 160.

```
namespace cl {
namespace sycl {
/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
void atomic_store(atomic<T, AddressSpace> object, T operand,
                  memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
T atomic_load(atomic<T, AddressSpace> object,
              memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
T atomic_exchange(atomic<T, AddressSpace> object, T operand,
                  memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
bool atomic_compare_exchange_strong(
    atomic<T, AddressSpace> object, T& expected, T desired,
    memory_order successMemoryOrder = memory_order::relaxed,
    memory_order failMemoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
```

```
template <typename T, access::address_space AddressSpace>
T atomic_fetch_add(atomic<T, AddressSpace> object, T operand,
                   memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
T atomic_fetch_sub(atomic<T, AddressSpace> object, T operand,
                   memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
T atomic_fetch_and(atomic<T, AddressSpace> object, T operand,
                   memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
T atomic_fetch_or(atomic<T, AddressSpace> object, T operand,
                  memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
T atomic_fetch_xor(atomic<T, AddressSpace> object, T operand,
                   memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
T atomic_fetch_min(atomic<T, AddressSpace> object, T operand,
                   memory_order memoryOrder = memory_order::relaxed);

/* Deprecated in SYCL 2020 */
template <typename T, access::address_space AddressSpace>
T atomic_fetch_max(atomic<T, AddressSpace> object, T operand,
                   memory_order memoryOrder = memory_order::relaxed);
} // namespace sycl
} // namespace cl
```

Table 158. Constructors of the `cl::sycl::atomic` class template

Constructor	Description
`template <typename pointerT> atomic(multi_ptr<pointerT, AddressSpace> ptr)`	Deprecated in SYCL 2020. Permitted data types for `pointerT` are any valid scalar data type which is the same size in bytes as `T`. Constructs an instance of SYCL `atomic` which is associated with the pointer `ptr`, converted to a pointer of data type `T`.

Table 159. Member functions available on an object of type `cl::sycl::atomic<T>`

Member function	Description
`void store(T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Atomically stores the value `operand` at the address of the `multi_ptr` associated with this SYCL `atomic`. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T load(memory_order memoryOrder = memory_order::relaxed) const`	Deprecated in SYCL 2020. Atomically loads the value at the address of the `multi_ptr` associated with this SYCL `atomic`. Returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T exchange(T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Atomically replaces the value at the address of the `multi_ptr` associated with this SYCL `atomic` with value `operand` and returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

Member function	Description

`bool compare_exchange_strong(`
`  T& expected, T desired,`
`  memory_order successMemoryOrder = memory_order::`
`relaxed,`
`  memory_order failMemoryOrder = memory_order::relaxed)`
	Deprecated in SYCL 2020.
	
	Available only when: `T != float`.
	
	Atomically compares the value at the address of the `multi_ptr` associated with this SYCL `atomic` against the value of `expected`. If the values are equal, replaces value at address of the `multi_ptr` associated with this SYCL `atomic` with the value of `desired`; otherwise assigns the original value at the address of the `multi_ptr` associated with this SYCL `atomic` to `expected`. Returns `true` if the comparison operation was successful. The memory order of this atomic operation must be `memory_order::relaxed` for both success and fail. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

`T fetch_add(T operand, memory_order memoryOrder =` `memory_order::relaxed)`	Deprecated in SYCL 2020. Available only when: `T != float`. Atomically adds the value `operand` to the value at the address of the `multi_ptr` associated with this SYCL `atomic` and assigns the result to the value at the address of the `multi_ptr` associated with this SYCL `atomic`. Returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

Member function	Description
`T fetch_sub(T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Available only when: `T != float`. Atomically subtracts the value `operand` to the value at the address of the `multi_ptr` associated with this SYCL `atomic` and assigns the result to the value at the address of the `multi_ptr` associated with this SYCL `atomic`. Returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T fetch_and(T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Available only when: `T != float`. Atomically performs a bitwise AND between the value `operand` and the value at the address of the `multi_ptr` associated with this SYCL `atomic` and assigns the result to the value at the address of the `multi_ptr` associated with this SYCL `atomic`. Returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

Member function	Description
`T fetch_or(T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Available only when: `T != float`. Atomically performs a bitwise OR between the value `operand` and the value at the address of the `multi_ptr` associated with this SYCL `atomic` and assigns the result to the value at the address of the `multi_ptr` associated with this SYCL `atomic`. Returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T fetch_xor(T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Available only when: `T != float`. Atomically performs a bitwise XOR between the value `operand` and the value at the address of the `multi_ptr` associated with this SYCL `atomic` and assigns the result to the value at the address of the `multi_ptr` associated with this SYCL `atomic`. Returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

Member function	Description
`T fetch_min(T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Available only when: `T != float`. Atomically computes the minimum of the value `operand` and the value at the address of the `multi_ptr` associated with this SYCL `atomic` and assigns the result to the value at the address of the `multi_ptr` associated with this SYCL `atomic`. Returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.
`T fetch_max(T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Available only when: `T != float`. Atomically computes the maximum of the value `operand` and the value at the address of the `multi_ptr` associated with this SYCL `atomic` and assigns the result to the value at the address of the `multi_ptr` associated with this SYCL `atomic`. Returns the value at the address of the `multi_ptr` associated with this SYCL `atomic` before the call. The memory order of this atomic operation must be `memory_order::relaxed`. This function is only supported for 64-bit data types on devices that have `aspect::atomic64`.

Table 160. Global functions available on atomic types

Functions	Description

`template <typename T, access::address_space AddressSpace>`
`T atomic_load(atomic<T, AddressSpace> object,`
`memory_order memoryOrder = memory_order::relaxed)`
	Deprecated in SYCL 2020.
	
	Equivalent to calling `object.load(memoryOrder)`.

Functions	Description
`template <typename T, access::address_space AddressSpace> void atomic_store(atomic<T, AddressSpace> object, T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.store(operand, memoryOrder)`.
`template <typename T, access::address_space AddressSpace> T atomic_exchange(atomic<T, AddressSpace> object, T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.exchange(operand, memoryOrder)`.
`template <typename T, access::address_space AddressSpace> bool atomic_compare_exchange_strong( atomic<T, AddressSpace> object, T& expected, T desired, memory_order successMemoryOrder = memory_order::relaxed memory_order failMemoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.compare_exchange_strong(expected, desired, successMemoryOrder, failMemoryOrders)`.
`template <typename T, access::address_space AddressSpace> T atomic_fetch_add(atomic<T, AddressSpace> object, T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.fetch_add(operand, memoryOrder)`.
`template <typename T, access::address_space AddressSpace> T atomic_fetch_sub(atomic<T, AddressSpace> object, T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.fetch_sub(operand, memoryOrder)`.
`template <typename T, access::address_space AddressSpace> T atomic_fetch_and(atomic<T> operand, T object, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.fetch_add(operand, memoryOrder)`.
`template <typename T, access::address_space AddressSpace> T atomic_fetch_or(atomic<T, AddressSpace> object, T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.fetch_or(operand, memoryOrder)`.

Functions	Description
`template <typename T, access::address_space AddressSpace> T atomic_fetch_xor(atomic<T, AddressSpace> object, T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.fetch_xor(operand, memoryOrder)`.
`template <typename T, access::address_space AddressSpace> T atomic_fetch_min(atomic<T, AddressSpace> object, T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.fetch_min(operand, memoryOrder)`.
`template <typename T, access::address_space AddressSpace> T atomic_fetch_max(atomic<T, AddressSpace> object, T operand, memory_order memoryOrder = memory_order::relaxed)`	Deprecated in SYCL 2020. Equivalent to calling `object.fetch_max(operand, memoryOrder)`.

4.15.5. Interaction with host code

When a kernel runs on a device that has either `aspect::usm_atomic_host_allocations` or `aspect::usm_atomic_shared_allocations`, the device code and the host code can concurrently access the same memory. This has a ramification on the atomic operations because it is possible for device code and host code to perform atomic operations on the same object *M* in this shared memory. It also has a ramification on the fence operations because the C++ core language defines the semantics of these fence operations in relation to atomic operations on some shared object *M*. The following paragraphs specify the guarantees that the SYCL implementation provides when the application performs atomic or fence operations in device code using the memory scope `memory_scope::system`.

Atomic operations in device code using `sycl::atomic_ref` on an object *M* are guaranteed to be atomic with respect to atomic operations in host code using `std::atomic_ref` on that same object *M*.

Fence operations in device code using `sycl::atomic_fence` synchronize with fence operations in host code using `std::atomic_thread_fence` if the fence operations shared the same atomic object *M* and follow the rules for fence synchronization defined in the C++ core language.

Fence operations in device code using `sycl::atomic_fence` synchronize with atomic operations in host code using `std::atomic_ref` if the operations share the same atomic object *M* and follow the rules for fence synchronization defined in the C++ core language.

Atomic operations in device code using `sycl::atomic_ref` synchronize with fence operations in host code using `std::atomic_thread_fence` if the operations share the same atomic object *M* and follow the rules for fence synchronization defined in the C++ core language.

4.16. Stream class

The SYCL `stream` class is a buffered output stream that allows outputting the values of built-in, vector and SYCL types to the console. The implementation of how values are streamed to the console is left as an implementation detail.

The way in which values are output by an instance of the SYCL `stream` class can also be altered using a

range of manipulators.

There are two limits that are relevant for the `stream` class. The `totalBufferSize` limit specifies the maximum size of the overall character stream that can be output during a kernel invocation, and the `workItemBufferSize` limit specifies the maximum size of the character stream that can be output within a work item before a flush must be performed. Both of these limits are specified in bytes. The `totalBufferSize` limit must be sufficient to contain the characters output by all stream statements during execution of a kernel invocation (the aggregate of outputs from all work items), and the `workItemBufferSize` limit must be sufficient to contain the characters output within a work item between stream flush operations.

If the `totalBufferSize` or `workItemBufferSize` limits are exceeded, it is implementation-defined whether the streamed characters exceeding the limit are output, or silently ignored/discarded, and if output it is implementation-defined whether those extra characters exceeding the `workItemBufferSize` limit count toward the `totalBufferSize` limit. Regardless of this implementation defined behavior of output exceeding the limits, no undefined or erroneous behavior is permitted of an implementation when the limits are exceeded. Unused characters within `workItemBufferSize` (any portion of the `workItemBufferSize` capacity that has not been used at the time of a stream flush) do not count toward the `totalBufferSize` limit, in that only characters flushed count toward the `totalBufferSize` limit.

The SYCL `stream` class provides the common reference semantics (see Section 4.5.2).

4.16.1. Stream class interface

The constructors and member functions of the SYCL `stream` class are listed in Table 163, Table 164, and Table 165 respectively. The additional common special member functions and common member functions are listed in Table 7 and Table 8, respectively.

The operand types that are supported by the SYCL `stream` class `operator<<()` operator are listed in Table 161.

The manipulators that are supported by the SYCL `stream` class `operator<<()` operator are listed in Table 162.

```
namespace sycl {

enum class stream_manipulator : /* unspecified */ {
  flush,
  dec,
  hex,
  oct,
  noshowbase,
  showbase,
  noshowpos,
  showpos,
  endl,
  fixed,
  scientific,
  hexfloat,
  defaultfloat
};

const stream_manipulator flush = stream_manipulator::flush;

const stream_manipulator dec = stream_manipulator::dec;

const stream_manipulator hex = stream_manipulator::hex;

```

```
const stream_manipulator oct = stream_manipulator::oct;

const stream_manipulator noshowbase = stream_manipulator::noshowbase;

const stream_manipulator showbase = stream_manipulator::showbase;

const stream_manipulator noshowpos = stream_manipulator::noshowpos;

const stream_manipulator showpos = stream_manipulator::showpos;

const stream_manipulator endl = stream_manipulator::endl;

const stream_manipulator fixed = stream_manipulator::fixed;

const stream_manipulator scientific = stream_manipulator::scientific;

const stream_manipulator hexfloat = stream_manipulator::hexfloat;

const stream_manipulator defaultfloat = stream_manipulator::defaultfloat;

__precision_manipulator__ setprecision(int precision);

__width_manipulator__ setw(int width);

class stream {
 public:
  stream(size_t totalBufferSize, size_t workItemBufferSize,
         handler& cgh, const property_list& propList = {});

  /* -- common interface members -- */

  /* -- property interface members -- */

  size_t size() const noexcept;

  // Deprecated
  size_t get_size() const;

  size_t get_work_item_buffer_size() const;

  /* get_max_statement_size() has the same functionality as
     get_work_item_buffer_size(), and is provided for backward compatibility.
     get_max_statement_size() is a deprecated query. */
  size_t get_max_statement_size() const;
};

template <typename T> const stream& operator<<(const stream& os, const T& rhs);

} // namespace sycl
```

Table 161. Operand types supported by the `stream` class

Stream operand type	Description
`char`, `signed char`, `unsigned char`, `int`, `unsigned int`, `short`, `unsigned short`, `long int`, `unsigned long int`, `long long int`, `unsigned long long int`	Outputs the value as a stream of characters.
`float`, `double`, `half`	Outputs the value according to the precision of the current statement as a stream of characters.
`char*`, `const char*`	Outputs the string.
`T*`, `const T*`, `multi_ptr`	Outputs the address of the pointer as a stream of characters.
`vec`	Outputs the value of each component of the vector as a stream of characters.
`id`, `range`, `item`, `nd_item`, `group`, `nd_range`, `h_item`	Outputs the value of each component of each id or range as a stream of characters.

Table 162. Manipulators supported by the `stream` class

Stream manipulator	Description
`flush`	Triggers a flush operation, which synchronizes the work item stream buffer with the global stream buffer, and then empties the work item stream buffer. After a flush, the full `workItemBufferSize` is available again for subsequent streaming within the work item.
`endl`	Outputs a new-line character and then triggers a flush operation.
`dec`	Outputs any subsequent values in the current statement in decimal base.
`hex`	Outputs any subsequent values in the current statement in hexadecimal base.
`oct`	Outputs any subsequent values in the current statement in octal base.
`noshowbase`	Outputs any subsequent values without the base prefix.
`showbase`	Outputs any subsequent values with the base prefix.

Stream manipulator	Description
`noshowpos`	Outputs any subsequent values without a plus sign if the value is positive.
`showpos`	Outputs any subsequent values with a plus sign if the value is positive.
`setw(int)`	Sets the field width of any subsequent values in the current statement.
`setprecision(int)`	Sets the precision of any subsequent values in the current statement.
`fixed`	Outputs any subsequent floating-point values in the current statement in fixed notation.
`scientific`	Outputs any subsequent floating-point values in the current statement in scientific notation.
`hexfloat`	Outputs any subsequent floating-point values in the current statement in hexadecimal notation.
`defaultfloat`	Outputs any subsequent floating-point values in the current statement in the default notation.

Table 163. Constructors of the `stream` class

Constructor	Description
`stream(size_t totalBufferSize, size_t workItemBufferSize, handler& cgh, const property_list& propList = {})`	Constructs a SYCL `stream` instance associated with the command group specified by `cgh`, with a maximum buffer size in bytes per kernel invocation specified by the parameter `totalBufferSize`, and a maximum stream size that can be buffered by a work item between stream flushes specified by the parameter `workItemBufferSize`. Zero or more properties can be provided to the constructed SYCL `stream` via an instance of `property_list`.

Table 164. Member functions of the `stream` class

Member function	Description
`size_t size() const noexcept`	Returns the total buffer size, in bytes.

Member function	Description
`size_t get_size() const`	Returns the same value as `size()`. Deprecated.
`size_t get_work_item_buffer_size() const`	Returns the buffer size per work item, in bytes.
`size_t get_max_statement_size() const`	Deprecated query with same functionality as `get_work_item_buffer_size()`.

Table 165. Global functions of the `stream` class

Global function	Description
`template <typename T> const stream& operator<<(const stream& os, const T& rhs)`	Outputs any valid values (see Table 161) as a stream of characters and applies any valid manipulator (see Table 162) to the current stream.

4.16.2. Synchronization

An instance of the SYCL `stream` class is required to synchronize with the host, and must output everything that is streamed to it via the `operator<<()` operator before a flush operation (that doesn't exceed the `workItemBufferSize` or `totalBufferSize` limits) within a SYCL kernel function by the time that the event associated with a command group submission enters the completed state. The point at which this synchronization occurs and the member function by which this synchronization is performed are implementation-defined. For example it is valid for an implementation to use `printf()`.

The SYCL `stream` class is required to output the content of each stream, between flushes (up to `workItemBufferSize)`, without mixing with content from the same stream in other work items. There are no other output order guarantees between work items or between streams. The stream flush operation therefore delimits the unit of output that is guaranteed to be displayed without mixing with other work items, with respect to a single stream.

4.16.3. Implicit flush

There is guaranteed to be an implicit flush of each stream used by a kernel, at the end of kernel execution, from the perspective of each work item. There is also an implicit flush when the endl stream manipulator is executed. No other implicit flushes are permitted in an implementation.

4.16.4. Performance note

The usage of the `stream` class is designed for debugging purposes and is therefore not recommended for performance critical applications.

4.17. SYCL built-in functions for SYCL host and device

SYCL kernels may execute on any SYCL device, which requires the functions used in the kernels to be compiled and linked for both device and host. In the SYCL programming model, the built-ins are available for the entire SYCL application within the `sycl` namespace, although their semantics may be different. This section follows the OpenCL 1.2 specification document ch. 6.12 - except that for SYCL, all functions are located within the `sycl` namespace - and describes the behavior of these functions for SYCL host and device. The expected precision and any other semantic requirements are defined in the backend specification.

The SYCL built-in functions are available throughout the SYCL application, and depending on where they execute, they are either implemented using their host implementation or the device implementation. The SYCL system guarantees that all of the built-in functions fulfill the same requirements for both host and device.

4.17.1. Description of the built-in types available for SYCL host and device

All of the OpenCL built-in types are available in the namespace `sycl`. For the purposes of this document we use generic type names for describing sets of valid SYCL types. The generic type names themselves are not valid SYCL types, but they represent a set of valid types, as defined in Table 166. Each generic type within a section is comprised of a combination of scalar, SYCL `vec` and/or `marray` class specializations. The letters `{n}` and `{N}` define valid sizes for class specializations, where `{n}` means 2,3,4,8,16 and `{N}` means any positive value of size_t type. Note that any reference to the base type refers to the type of a scalar or the element type of a SYCL `vec` or `marray` specialization.

Table 166. Generic type name description, which serves as a description for all valid types of parameters to kernel functions.

Generic type name	Description
`floatn`	`float{n}`, `mfloat{n}`, `marray<{N},float>`
`genfloatf`	`float`, `floatn`
`doublen`	`double{n}`, `mdouble{n}`, `marray<{N},double>`
`genfloatd`	`double`, `doublen`
`halfn`	`half{n}`, `mhalf{n}`, `marray<{N},half>`
`genfloath`	`half`, `halfn`
`genfloat`	`genfloatf`, `genfloatd`, `genfloath`
`sgenfloat`	`float`, `double`, `half`
`vgenfloat`	`float{n}`, `double{n}`, `half{n}`
`mgenfloat`	`marray<float,{N}>`, `marray<double,{N}>`, `marray<half,{N}>`
`gengeofloat`	`float`, `float2`, `float3`, `float4`, `mfloat2`, `mfloat3`, `mfloat4`
`gengeodouble`	`double`, `double2`, `double3`, `double4`, `mdouble2`, `mdouble3`, `mdouble4`

Generic type name	Description
charn	char{n}, mchar{n}, marray<{N},char>
scharn	schar{n}, mschar{n}, marray<{N},signed char>
ucharn	uchar{n}, muchar{n}, marray<{N},unsigned char>
igenchar	signed char, scharn
ugenchar	unsigned char, ucharn
genchar	char, charn, igenchar, ugenchar
shortn	short{n}, mshort{n}, marray<{N},short>
genshort	short, shortn
ushortn	ushort{n}, mushort{n}, marray<{N},unsigned short>
ugenshort	unsigned short, ushortn
uintn	uint{n}, muint{n}, marray<{N},unsigned int>
ugenint	unsigned int, uintn
intn	int{n}, mint{n}, marray<{N},int>
genint	int, intn
ulongn	ulong{n}, mulong{n}, marray<{N},unsigned long int>
ugenlong	unsigned long int, ulongn
longn	long{n}, mlong{n}, marray<{N},long int>
genlong	long int, longn

Generic type name	Description
ulonglongn	ulonglong{n}, mulonglong{n}, marray<{N},unsigned long long int>
ugenlonglong	unsigned long long int, ulonglongn
longlongn	longlong{n}, mlonglong{n}, marray<{N},long long int>
genlonglong	long long int, longlongn
igenlonginteger	genlong, genlonglong
ugenlonginteger	ugenlong, ugenlonglong
geninteger	genchar, genshort, ugenshort, genint, ugenint, igenlonginteger, ugenlonginteger
genintegerNbit	All types within geninteger whose base type are *N* bits in size, where *N* = 8, 16, 32, 64.
igeninteger	igenchar, genshort, genint, igenlonginteger
igenintegerNbit	All types within igeninteger whose base type are *N* bits in size, where *N* = 8, 16, 32, 64.
sigeninteger	signed char, short, int, long int, long long int
vigeninteger	schar{n}, short{n}, int{n}, long{n}, longlong{n}
migeninteger	marray<signed char,{N}>, marray<short,{N}>, marray<int,{N}>, marray<long,{N}>, marray<long long,{N}>
ugeninteger	ugenchar, ugenshort, ugenint, ugenlonginteger
ugenintegerNbit	All types within ugeninteger whose base type are *N* bits in size, where *N* = 8, 16, 32, 64.
sugeninteger	unsigned char, unsigned short, unsigned int, unsigned long int, unsigned long long int
vugeninteger	uchar{n}, ushort{n}, uint{n}, ulong{n}, ulonglong{n}

Generic type name	Description
mugeninteger	marray<unsigned char,{N}>, marray<unsigned short,{N}>, marray<unsigned int,{N}>, marray<unsigned long int,{N}>, marray<unsigned long long int,{N}>
sgeninteger	char, sigeninteger, sugeninteger
vgeninteger	char{n}, vigeninteger, vugeninteger
mgeninteger	marray<char,{N}>, migeninteger, mugeninteger
gentype	genfloat, geninteger
sgentype	sgenfloat, sgeninteger
vgentype	vgenfloat, vgeninteger
mgentype	mgenfloat, mgeninteger
genfloatptr	All permutations of multi_ptr<DataT, AddressSpace, IsDecorated> where DataT is all types within genfloat, AddressSpace is access::address_space::global_space, access::address_space::local_space and access::address_space::private_space and IsDecorated is access::decorated::yes and access::decorated::no.
genintptr	All permutations of multi_ptr<DataT, AddressSpace, IsDecorated> where DataT is all types within genint, AddressSpace is access::address_space::global_space, access::address_space::local_space and access::address_space::private_space and IsDecorated is access::decorated::yes and access::decorated::no.
booln	marray<{N},bool>
genbool	bool, booln

4.17.2. Function objects

SYCL provides a number of function objects in the `sycl` namespace on host and device. All function objects obey C++ conversion and promotion rules. Each function object is additionally specialized for `void` as a *transparent* function object that deduces its parameter types and return type.

```
namespace sycl {

template <typename T = void> struct plus {
  T operator()(const T& x, const T& y) const;
};

template <typename T = void> struct multiplies {
  T operator()(const T& x, const T& y) const;
};

template <typename T = void> struct bit_and {
  T operator()(const T& x, const T& y) const;
};

template <typename T = void> struct bit_or {
  T operator()(const T& x, const T& y) const;
};

template <typename T = void> struct bit_xor {
  T operator()(const T& x, const T& y) const;
};

template <typename T = void> struct logical_and {
  T operator()(const T& x, const T& y) const;
};

template <typename T = void> struct logical_or {
  T operator()(const T& x, const T& y) const;
};

template <typename T = void> struct minimum {
  T operator()(const T& x, const T& y) const;
};

template <typename T = void> struct maximum {
  T operator()(const T& x, const T& y) const;
};

} // namespace sycl
```

Table 167. Member functions for the `plus` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the sum of its arguments, equivalent to `x + y`.

Table 168. Member functions for the `multiplies` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the product of its arguments, equivalent to `x * y`.

Table 169. Member functions for the `bit_and` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the bitwise AND of its arguments, equivalent to `x & y`.

Table 170. Member functions for the `bit_or` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the bitwise OR of its arguments, equivalent to `x | y`.

Table 171. Member functions for the `bit_xor` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the bitwise XOR of its arguments, equivalent to `x ^ y`.

Table 172. Member functions for the `logical_and` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the logical AND of its arguments, equivalent to `x && y`.

Table 173. Member functions for the `logical_or` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the logical OR of its arguments, equivalent to `x || y`.

Table 174. Member functions for the `minimum` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the smaller value. Returns the first argument when the arguments are equivalent.

Table 175. Member functions for the `maximum` function object

Member function	Description
`T operator()(const T& x, const T& y) const`	Returns the larger value. Returns the first argument when the arguments are equivalent.

4.17.3. Group functions

SYCL provides a number of functions that expose functionality tied to groups of work-items (such as group barriers and collective operations). These group functions act as synchronization points and must be encountered in converged control flow by all work-items in the group. If one work-item in a group

calls a group function, then all work-items in that group must call exactly the same function under the same set of conditions --- calling the same function under different conditions (e.g. in different iterations of a loop, or different branches of a conditional statement) results in undefined behavior. Additionally, restrictions may be placed on the arguments passed to each function in order to ensure that all work-items in the group agree on the operation that is being performed. Any such restrictions on the arguments passed to a function are defined within the descriptions of those functions. Violating these restrictions results in undefined behavior.

All group functions are supported for the fundamental scalar types supported by SYCL (see Table 184) and instances of the SYCL `vec` and `marray` classes.

Using a group function inside of a kernel may introduce additional limits on the resources available to user code inside the same kernel. The behavior of these limits is implementation-defined, but must be reflected by calls to kernel querying functions (such as `kernel::get_info`) as described in Section 4.11.13.1.

It is undefined behavior for any group function to be invoked within a `parallel_for_work_group` or `parallel_for_work_item` context.

4.17.3.1. Group type trait

```
1 namespace sycl {
2 template <class T> struct is_group;
3
4 template <class T> inline constexpr bool is_group_v = is_group<T>::value;
5 } // namespace sycl
```

The `is_group` type trait is used to determine which types of groups are supported by group functions, and to control when group functions participate in overload resolution.

`is_group<T>` inherits from `std::true_type` if `T` is the type of a standard SYCL group (`group` or `sub_group`) and it inherits from `std::false_type` otherwise. A SYCL implementation may introduce additional specializations of `is_group<T>` for implementation-defined group types, if the interface of those types supports all member functions and static members common to the `group` and `sub_group` classes.

4.17.3.2. `group_broadcast`

The `group_broadcast` function communicates a value held by one work-item to all other work-items in the group.

```
1 template <typename Group, typename T> T group_broadcast(Group g, T x); // (1)
2
3 template <typename Group, typename T>
4 T group_broadcast(Group g, T x, Group::linear_id_type local_linear_id); // (2)
5
6 template <typename Group, typename T>
7 T group_broadcast(Group g, T x, Group::id_type local_id); // (3)
```

1. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true and `T` is a trivially copyable type.

   Returns: The value of `x` from the work-item with the smallest linear id within group `g`.

2. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true and `T` is a trivially copyable type.

Preconditions: local_linear_id must be the same for all work-items in the group and must be in the range [0, get_local_linear_range()).

Returns: The value of x from the work-item with the specified linear id within group g.

3. *Constraints:* Available only if sycl::is_group_v<std::decay_t<Group>> is true and T is a trivially copyable type.

   Preconditions: local_id must be the same for all work-items in the group, and its dimensionality must match the dimensionality of the group. The value of local_id in each dimension must be greater than or equal to 0 and less than the value of get_local_range() in the same dimension.

   Returns: The value of x from the work-item with the specified id within group g.

4.17.3.3. group_barrier

The group_barrier function synchronizes all work-items in a group, using a group barrier.

```
1 template <typename Group>
2 void group_barrier(Group g,
3                    memory_scope fence_scope = Group::fence_scope); // (1)
```

1. *Constraints:* Available only if sycl::is_group_v<std::decay_t<Group>> is true.

   Effects: Synchronizes all work-items in group g. The current work-item will wait at the barrier until all work-items in group g have reached the barrier. In addition, the barrier performs mem-fence operations ensuring that memory accesses issued before the barrier are not re-ordered with those issued after the barrier: all work-items in group g execute a release fence prior to synchronizing at the barrier, all work-items in group g execute an acquire fence afterwards, and there is an implicit synchronization of these fences as if provided by an explicit atomic operation on an atomic object.

   By default, the scope of these fences is set to the narrowest scope including all work-items in group g (as reported by Group::fence_scope). This scope may be optionally overridden with a broader scope, specified by the fence_scope argument.

4.17.4. Group algorithms library

SYCL provides an algorithms library based on the functions described in Section 28 of the C++17 specification. The first argument to each function is a group, and data ranges can be described using pointers, iterators or instances of the multi_ptr class. The functions defined in this section are free functions available in the sycl namespace.

Any restrictions from the standard algorithms library apply. Some of the functions in the SYCL algorithms library introduce additional restrictions in order to maximize portability across different devices and to minimize the chances of encountering unexpected behavior.

All algorithms are supported for the fundamental scalar types supported by SYCL (see Table 184) and instances of the SYCL vec and marray classes.

The group argument to a SYCL algorithm denotes that it should be performed collaboratively by the work-items in the specified group. All algorithms act as group functions (as defined in Section 4.17.3), inheriting all restrictions of group functions. Unless the description of a function says otherwise, how the elements of a range are processed by the work-items in a group is undefined.

SYCL provides separate functions for algorithms which use the work-items in a group to execute an operation over a range of iterators and algorithms which are applied to data held directly by the work-items in a group. An example of the usage of these functions is given below:

Listing 2. Using the group algorithms library to perform a work-group reduce

```
buffer<int> inputBuf { 1024 };
buffer<int> outputBuf { 2 };
{
  // Initialize buffer on the host with 0, 1, 2, 3, ..., 1023
  host_accessor a { inputBuf };
  std::iota(a.begin(), a.end(), 0);
}

myQueue.submit([&](handler& cgh) {
  accessor inputValues { inputBuf, cgh, read_only };
  accessor outputValues { outputBuf, cgh, write_only, no_init };

  cgh.parallel_for(nd_range<1>(range<1>(16), range<1>(16)), [=](nd_item<1> it) {
    // Apply a group algorithm to any number of values, described by an iterator
    // range. The work-group reduces all inputValues and each work-item works on
    // part of the range.
    int* first = inputValues.get_pointer();
    int* last = first + 1024;
    int sum = joint_reduce(it.get_group(), first, last, plus<>());
    outputValues[0] = sum;

    // Apply a group algorithm to a set of values held directly by work-items.
    // The work-group reduces a number of values equal to the size of the group
    // and each work-item provides one value.
    int partial_sum = reduce_over_group(
        it.get_group(), inputValues[it.get_global_linear_id()], plus<>());
    outputValues[1] = partial_sum;
  });
});

host_accessor a { outputBuf };
assert(a[0] == 523776 && a[1] == 120);
```

4.17.4.1. any_of, all_of and none_of

The any_of, all_of and none_of functions from standard C++ test whether Boolean conditions hold for any of, all of or none of the values in a range, respectively.

SYCL provides two sets of similar algorithms:

1. joint_any_of, joint_all_of and joint_none_of use the work-items in a group to execute the corresponding algorithm in parallel.
2. any_of_group, all_of_group and none_of_group test Boolean conditions applied to data held directly by the work-items in a group.

```
template <typename Group, typename Ptr, typename Predicate>
bool joint_any_of(Group g, Ptr first, Ptr last, Predicate pred); // (1)

template <typename Group, typename T, typename Predicate>
bool any_of_group(Group g, T x, Predicate pred); // (2)

template <typename Group> bool any_of_group(Group g, bool pred); // (3)
```

1. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true and `Ptr` is a pointer.

   Preconditions: `first` and `last` must be the same for all work-items in group `g`, and `pred` must be an immutable callable with the same type and state for all work-items in group `g`.

   Returns: true if `pred` returns true when applied to the result of dereferencing any iterator in the range `[first, last)`.

2. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true.

   Preconditions: `pred` must be an immutable callable with the same type and state for all work-items in group `g`.

   Returns: true if `pred(x)` returns true for any work-item in group `g`.

3. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true.

   Returns: true if `pred` is true for any work-item in group `g`.

```
template <typename Group, typename Ptr, typename Predicate>
bool joint_all_of(Group g, Ptr first, Ptr last, Predicate pred); // (1)

template <typename Group, typename T, typename Predicate>
bool all_of_group(Group g, T x, Predicate pred); // (2)

template <typename Group> bool all_of_group(Group g, bool pred); // (3)
```

1. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true and `Ptr` is a pointer.

   Preconditions: `first` and `last` must be the same for all work-items in group `g`, and `pred` must be an immutable callable with the same type and state for all work-items in group `g`.

   Returns: true if `pred` returns true when applied to the result of dereferencing all iterators in the range `[first, last)`.

2. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true.

   Preconditions: `pred` must be an immutable callable with the same type and state for all work-items in group `g`.

   Returns: true if `pred(x)` returns true for all work-items in group `g`.

3. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true.

   Returns: true if `pred` is true for all work-items in group `g`.

```
template <typename Group, typename Ptr, typename Predicate>
bool joint_none_of(Group g, Ptr first, Ptr last, Predicate pred); // (1)

template <typename Group, typename T, typename Predicate>
bool none_of_group(Group g, T x, Predicate pred); // (2)

template <typename Group> bool none_of_group(Group g, bool pred); // (3)
```

1. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true and `Ptr` is a pointer.

   Preconditions: `first` and `last` must be the same for all work-items in group `g`, and `pred` must be an immutable callable with the same type and state for all work-items in group `g`.

Returns: true if `pred` returns false when applied to the result of dereferencing all iterators in the range `[first, last)`.

2. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true.

   Preconditions: `pred` must be an immutable callable with the same type and state for all work-items in group `g`.

   Returns: true if `pred(x)` returns false for all work-items in group `g`.

3. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true.

   Returns: true if `pred` is false for all work-items in group `g`.

4.17.4.2. shift_left and shift_right

The `shift_left` and `shift_right` functions from standard C++ move values in a range down (to the left) or up (to the right) respectively.

SYCL provides similar algorithms compatible with the `sub_group` class:

1. `shift_group_left` and `shift_group_right` move values held by the work-items in a group directly to another work-item in group `g`, by shifting values a fixed number of work-items to the left or right.

```
1 template <typename Group, typename T>
2 T shift_group_left(Group g, T x, Group::linear_id_type delta = 1); // (1)
3
4 template <typename Group, typename T>
5 T shift_group_right(Group g, T x, Group::linear_id_type delta = 1); // (2)
```

1. *Constraints:* Available only if `std::is_same_v<std::decay_t<Group>, sub_group>` is true and `T` is a trivially copyable type.

   Preconditions: `delta` must be the same for all work-items in the group.

   Returns: the value of `x` from the work-item whose group local id (`id`) is `delta` larger than that of the calling work-item. `id + delta` may be greater than or equal to the group's linear size, but the value returned in this case is unspecified.

2. *Constraints:* Available only if `std::is_same_v<std::decay_t<Group>, sub_group>` is true and `T` is a trivially copyable type.

   Preconditions: `delta` must be the same for all work-items in the group.

   Returns: the value of `x` from the work-item whose group local id (`id`) is `delta` smaller than that of the calling work-item. `id - delta` may be less than 0, but the value returned in this case is unspecified.

4.17.4.3. permute

SYCL provides an algorithm to permute the values held by work-items in a sub-group:

1. `permute_group_by_xor` permutes values by exchanging values held by pairs of work-items identified by computing the bitwise exclusive OR of the work-item id and some fixed mask.

```
1 template <typename Group, typename T>
2 T permute_group_by_xor(Group g, T x, Group::linear_id_type mask); // (1)
```

1. *Constraints:* Available only if `std::is_same_v<std::decay_t<Group>, sub_group>` is true and `T` is a trivially copyable type.

   Preconditions: `mask` must be the same for all work-items in the group.

   Returns: the value of `x` from the work-item whose group local id is equal to the bitwise exclusive OR of the calling work-item's group local id and `mask`. The result of the exclusive OR may be greater than or equal to the group's linear size, but the value returned in this case is unspecified.

4.17.4.4. select

SYCL provides an algorithm to directly exchange the values held by work-items in a sub-group:

1. `select_from_group` allows work-items to obtain a copy of a value held by any other work-item in group `g`.

```
1 template <typename Group, typename T>
2 T select_from_group(Group g, T x, Group::id_type remote_local_id); // (1)
```

1. *Constraints:* Available only if `std::is_same_v<std::decay_t<Group>, sub_group>` is true and `T` is a trivially copyable type.

   Returns: the value of `x` from the work-item with the group local id specified by `remote_local_id`. The value of `remote_local_id` may be outside of the group, but the value returned in this case is unspecified.

4.17.4.5. reduce

The `reduce` function from standard C++ combines the values in a range in an unspecified order using a binary operator.

SYCL provides two similar algorithms that compute the same generalized sum as defined by standard C++:

1. `joint_reduce` uses the work-items in a group to execute a `reduce` operation in parallel.
2. `reduce_over_group` combines values held directly by the work-items in a group.

The result of a call to these functions is non-deterministic if the binary operator is not commutative and associative. Only the binary operators defined in Section 4.17.2 are supported by the `reduce` functions in SYCL 2020, but the standard C++ syntax is used for forward compatibility with future SYCL versions.

```
1 template <typename Group, typename Ptr, typename BinaryOperation>
2 std::iterator_traits<Ptr>::value_type
3 joint_reduce(Group g, Ptr first, Ptr last, BinaryOperation binary_op); // (1)
4
5 template <typename Group, typename Ptr, typename T, typename BinaryOperation>
6 T joint_reduce(Group g, Ptr first, Ptr last, T init,
7                BinaryOperation binary_op); // (2)
8
9 template <typename Group, typename T, typename BinaryOperation>
10 T reduce_over_group(Group g, T x, BinaryOperation binary_op); // (3)
11
12 template <typename Group, typename V, typename T, typename BinaryOperation>
13 T reduce_over_group(Group g, V x, T init, BinaryOperation binary_op); // (4)
```

1. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `Ptr` is a pointer to a fun-

damental type, and BinaryOperation is a SYCL function object type.

Mandates: binary_op(*first, *first) must return a value of type std::iterator_traits<Ptr>::value_type.

Preconditions: first, last and the type of binary_op must be the same for all work-items in group g. binary_op must be an instance of a SYCL function object.

Returns: The result of combining the values resulting from dereferencing all iterators in the range [first, last) using the operator binary_op, where the values are combined according to the generalized sum defined in standard C++.

2. *Constraints:* Available only if sycl::is_group_v<std::decay_t<Group>> is true, Ptr is a pointer to a fundamental type, T is a fundamental type, and BinaryOperation is a SYCL function object type.

   Mandates: binary_op(init, *first) must return a value of type T.

   Preconditions: first, last, init and the type of binary_op must be the same for all work-items in group g. binary_op must be an instance of a SYCL function object.

   Returns: The result of combining the values resulting from dereferencing all iterators in the range [first, last) and the initial value init using the operator binary_op, where the values are combined according to the generalized sum defined in standard C++.

3. *Constraints:* Available only if sycl::is_group_v<std::decay_t<Group>> is true, T is a fundamental type and BinaryOperation is a SYCL function object type.

   Mandates: binary_op(x, x) must return a value of type T.

   Preconditions: binary_op must be an instance of a SYCL function object.

   Returns: The result of combining all the values of x specified by each work-item in group g using the operator binary_op, where the values are combined according to the generalized sum defined in standard C++.

4. *Constraints:* Available only if sycl::is_group_v<std::decay_t<Group>> is true, V and T are fundamental types, and BinaryOperation is a SYCL function object type.

   Mandates: binary_op(init, x) must return a value of type T.

   Preconditions: binary_op must be an instance of a SYCL function object.

   Returns: The result of combining all the values of x specified by each work-item in group g and the initial value init using the operator binary_op, where the values are combined according to the generalized sum defined in standard C++.

4.17.4.6. exclusive_scan and inclusive_scan

The exclusive_scan and inclusive_scan functions in standard C++ compute a prefix sum using a binary operator. For a scan of elements $[x_0, ..., x_n]$, the i th result in an exclusive scan is the generalized noncommutative sum of all elements preceding x_i (excluding x_i itself), whereas the i th result in an inclusive scan is the generalized noncommutative sum of all elements preceding x_i (including x_i itself).

SYCL provides two similar sets of algorithms that compute the same prefix sums using the generalized noncommutative sum as defined by standard C++:

1. joint_exclusive_scan and joint_inclusive_scan use the work-items in a group to execute the corresponding algorithm in parallel, and intermediate partial prefix sums are written to memory as in standard C++.
2. exclusive_scan_over_group and inclusive_scan_over_group perform a scan over values held directly by

the work-items in a group, and the result returned to each work-item represents a partial prefix sum.

The result of a call to a scan is non-deterministic if the binary operator is not associative. Only the binary operators defined in Section 4.17.2 are supported by the scan functions in SYCL 2020, but the standard C++ syntax is used for forward compatibility with future SYCL versions.

```
template <typename Group, typename InPtr, typename OutPtr,
          typename BinaryOperation>
OutPtr joint_exclusive_scan(Group g, InPtr first, InPtr last, OutPtr result,
                            BinaryOperation binary_op); // (1)

template <typename Group, typename InPtr, typename OutPtr, typename T,
          typename BinaryOperation>
OutPtr joint_exclusive_scan(Group g, InPtr first, InPtr last, OutPtr result,
                            T init, BinaryOperation binary_op); // (2)

template <typename Group, typename T, typename BinaryOperation>
T exclusive_scan_over_group(Group g, T x, BinaryOperation binary_op); // (3)

template <typename Group, typename V, typename T, typename BinaryOperation>
T exclusive_scan_over_group(Group g, V x, T init,
                            BinaryOperation binary_op); // (4)
```

1. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `InPtr` and `OutPtr` are pointers to fundamental types, and `BinaryOperation` is a SYCL function object type.

   Mandates: `binary_op(*first, *first)` must return a value of type `std::iterator_traits<OutPtr>::value_type`.

   Preconditions: `first`, `last`, `result` and the type of `binary_op` must be the same for all work-items in group `g`. `binary_op` must be an instance of a SYCL function object.

   Note that `first` may be equal to `result`.

   Effects: The value written to `result` + *i* is the exclusive scan of the values resulting from dereferencing the first *i* values in the range `[first, last)` and the identity value of `binary_op` (as identified by `sycl::known_identity`), using the operator `binary_op`. The scan is computed using a generalized noncommutative sum as defined in standard C++.

   Returns: A pointer to the end of the output range.

2. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `InPtr` and `OutPtr` are pointers to fundamental types, `T` is a fundamental type, and `BinaryOperation` is a SYCL function object type.

   Mandates: `binary_op(init, *first)` must return a value of type `T`.

   Preconditions: `first`, `last`, `result`, `init` and the type of `binary_op` must be the same for all work-items in group `g`. `binary_op` must be an instance of a SYCL function object.

   Note that `first` may be equal to `result`.

   Effects: The value written to `result` + *i* is the exclusive scan of the values resulting from dereferencing the first *i* values in the range `[first, last)` and an initial value specified by `init`, using the operator `binary_op`. The scan is computed using a generalized noncommutative sum as defined in standard C++.

Returns: A pointer to the end of the output range.

3. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `T` is a fundamental type, and `BinaryOperation` is a SYCL function object type.

   Mandates: `binary_op(x, x)` must return a value of type `T`.

   Preconditions: `binary_op` must be an instance of a SYCL function object.

   Returns: The value returned on work-item *i* is the exclusive scan of the first *i* values in group `g` and the identity value of `binary_op` (as identified by `sycl::known_identity`), using the operator `binary_op`. The scan is computed using a generalized noncommutative sum as defined in standard C++. For multi-dimensional groups, the order of work-items in group `g` is determined by their linear id.

4. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `V` and `T` are fundamental types, and `BinaryOperation` is a SYCL function object type.

   Mandates: `binary_op(init, x)` must return a value of type `T`.

   Preconditions: `binary_op` must be an instance of a SYCL function object.

   Returns: The value returned on work-item *i* is the exclusive scan of the first *i* values in group `g` and an initial value specified by `init`, using the operator `binary_op`. The scan is computed using a generalized noncommutative sum as defined in standard C++. For multi-dimensional groups, the order of work-items in group `g` is determined by their linear id.

```
template <typename Group, typename InPtr, typename OutPtr,
          typename BinaryOperation>
OutPtr joint_inclusive_scan(Group g, InPtr first, InPtr last, OutPtr result,
                            BinaryOperation binary_op); // (1)

template <typename Group, typename InPtr, typename OutPtr, typename T,
          typename BinaryOperation>
OutPtr joint_inclusive_scan(Group g, InPtr first, InPtr last, OutPtr result,
                            BinaryOperation binary_op, T init); // (2)

template <typename Group, typename T, typename BinaryOperation>
T inclusive_scan_over_group(Group g, T x, BinaryOperation binary_op); // (3)

template <typename Group, typename V, typename T, typename BinaryOperation>
T inclusive_scan_over_group(Group g, V x, BinaryOperation binary_op,
                            T init); // (4)
```

1. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `InPtr` and `OutPtr` are pointers to fundamental types, and `BinaryOperation` is a SYCL function object type.

   Mandates: `binary_op(*first, *first)` must return a value of type `std::iterator_traits<OutPtr>::value_type`.

   Preconditions: `first`, `last`, `result` and the type of `binary_op` must be the same for all work-items in group `g`. `binary_op` must be an instance of a SYCL function object.

   Note that `first` may be equal to `result`.

   Effects: The value written to `result` + *i* is the inclusive scan of the values resulting from dereferencing the first *i* values in the range `[first, last)`, using the operator `binary_op`. The scan is computed using a generalized noncommutative sum as defined in standard C++.

Returns: A pointer to the end of the output range.

2. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `InPtr` and `OutPtr` are pointers to fundamental types, `BinaryOperation` is a SYCL function object type, and `T` is a fundamental type.

   Mandates: `binary_op(init, *first)` must return a value of type `T`.

   Preconditions: `first`, `last`, `result`, `init` and the type of `binary_op` must be the same for all work-items in group `g`. `binary_op` must be an instance of a SYCL function object.

   Note that `first` may be equal to `result`.

   Effects: The value written to `result` + *i* is the inclusive scan of the values resulting from dereferencing the first *i* values in the range `[first, last)` and an initial value specified by `init`, using the operator `binary_op`. The scan is computed using a generalized noncommutative sum as defined in standard C++.

   Returns: A pointer to the end of the output range.

3. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `T` is a fundamental type, and `BinaryOperation` is a SYCL function object type.

   Mandates: `binary_op(x, x)` must return a value of type `T`.

   Preconditions: `binary_op` must be an instance of a SYCL function object.

   Returns: The value returned on work-item *i* is the inclusive scan of the first *i* values in group `g`, using the operator `binary_op`. The scan is computed using a generalized noncommutative sum as defined in standard C++. For multi-dimensional groups, the order of work-items in group `g` is determined by their linear id.

4. *Constraints:* Available only if `sycl::is_group_v<std::decay_t<Group>>` is true, `V` is a fundamental type, `BinaryOperation` is a SYCL function object type, and `T` is a fundamental type.

   Mandates: `binary_op(init, x)` must return a value of type `T`.

   Preconditions: `binary_op` must be an instance of a SYCL function object.

   Returns: The value returned on work-item *i* is the inclusive scan of the first *i* values in group `g` and an initial value specified by `init`, using the operator `binary_op`. The scan is computed using a generalized noncommutative sum as defined in standard C++. For multi-dimensional groups, the order of work-items in group `g` is determined by their linear id.

4.17.5. Math functions

In SYCL the OpenCL math functions are available in the namespace `sycl` on host and device with the same precision guarantees as defined in the OpenCL 1.2 specification document ch. 7 for host and device. For a SYCL platform the numerical requirements for host need to match the numerical requirements of the OpenCL math built-in functions. The built-in functions can take as input float or optionally double and their `vec` and `marray` counterparts, for all supported dimensions including dimension 1.

The built-in functions available for SYCL host and device, with the same precision requirements for both host and device, are described in Table 176.

Table 176. Math functions which work on SYCL host and device. They correspond to Table 6.8 of the OpenCL 1.2 specification.

Math Function	Description
`genfloat acos(genfloat x)`	Inverse cosine function.
`genfloat acosh(genfloat x)`	Inverse hyperbolic cosine.
`genfloat acospi(genfloat x)`	Compute $\frac{\arccos(x)}{\pi}$
`genfloat asin(genfloat x)`	Inverse sine function.
`genfloat asinh(genfloat x)`	Inverse hyperbolic sine.
`genfloat asinpi(genfloat x)`	Compute $\frac{\arcsin(x)}{\pi}$
`genfloat atan(genfloat y_over_x)`	Inverse tangent function.
`genfloat atan2(genfloat y, genfloat x)`	Compute $\arctan(\frac{y}{x})$.
`genfloat atanh(genfloat x)`	Hyperbolic inverse tangent.
`genfloat atanpi(genfloat x)`	Compute $\frac{\arctan(x)}{\pi}$.
`genfloat atan2pi(genfloat y, genfloat x)`	Compute $\frac{(y,\ x)}{\pi}$.
`genfloat cbrt(genfloat x)`	Compute cube-root.
`genfloat ceil(genfloat x)`	Round to integral value using the round to positive infinity rounding mode.
`genfloat copysign(genfloat x, genfloat y)`	Returns x with its sign changed to match the sign of y.
`genfloat cos(genfloat x)`	Compute cosine.
`genfloat cosh(genfloat x)`	Compute hyperbolic cosine.
`genfloat cospi(genfloat x)`	Compute $\cos(\pi x)$.
`genfloat erfc(genfloat x)`	Complementary error function.

Math Function	Description
`genfloat erf(genfloat x)`	Error function encountered in integrating the normal distribution.
`genfloat exp(genfloat x)`	Compute the base-*e* exponential of x.
`genfloat exp2(genfloat x)`	Exponential base 2 function.
`genfloat exp10(genfloat x)`	Exponential base 10 function.
`genfloat expm1(genfloat x)`	Compute $e^x - 1.0$.
`genfloat fabs(genfloat x)`	Compute absolute value of a floating-point number.
`genfloat fdim(genfloat x, genfloat y)`	$x - y$ if $x>y$, +0 if x is less than or equal to y.
`genfloat floor(genfloat x)`	Round to integral value using the round to negative infinity rounding mode.
`genfloat fma(genfloat a, genfloat b, genfloat c)`	Returns the correctly rounded floating-point representation of the sum of c with the infinitely precise product of a and b. Rounding of intermediate products shall not occur. Edge case behavior is per the IEEE 754-2008 standard.
`genfloat fmax(genfloat x, genfloat y)` `genfloat fmax(genfloat x, sgenfloat y)`	Returns y if $x<y$, otherwise it returns x. If one argument is a NaN, fmax() returns the other argument. If both arguments are NaNs, fmax() returns a NaN.
`genfloat fmin(genfloat x, genfloat y)` `genfloat fmin(genfloat x, sgenfloat y)`	Returns y if $y<x$, otherwise it returns x. If one argument is a NaN, fmin() returns the other argument. If both arguments are NaNs, fmin() returns a NaN.
`genfloat fmod(genfloat x, genfloat y)`	Modulus. Returns $x - y \cdot \text{trunc}(x / y)$.
`genfloat fract(genfloat x, genfloatptr iptr)`	Returns fmin(x - floor(x), nextafter(genfloat(1.0), genfloat(0.0))). floor(x) is returned in iptr.

Math Function	Description
`genfloat frexp(genfloat x, genintptr exp)`	Extract mantissa and exponent from x. For each component the mantissa returned is a float with magnitude in the interval [1/2, 1) or 0. Each component of x equals mantissa returned $\times 2^{exp}$.
`genfloat hypot(genfloat x, genfloat y)`	Compute the value of the square root of $x^2 + y^2$ without undue overflow or underflow.
`genint ilogb(genfloat x)`	Compute the integral part of logr (|x|) and return the result as an integer, where r is the value returned by `std::numeric_limits<genfloat>::radix`.
`genfloat ldexp(genfloat x, genint k)` `genfloat ldexp(genfloat x, int k)`	Multiply x by 2^k.
`genfloat lgamma(genfloat x)`	Log gamma function. Returns the natural logarithm of the absolute value of the gamma function.
`genfloat lgamma_r(genfloat x, genintptr signp)`	Log gamma function. Returns the natural logarithm of the absolute value of the gamma function. The sign of the gamma function is returned in the signp argument of `lgamma_r`.
`genfloat log(genfloat x)`	Compute natural logarithm.
`genfloat log2(genfloat x)`	Compute a base 2 logarithm.
`genfloat log10(genfloat x)`	Compute a base 10 logarithm.
`genfloat log1p(genfloat x)`	Compute $\log_e(1.0 + x)$.
`genfloat logb(genfloat x)`	Compute the integral part of logr (|x|), where r is the value returned by `std::numeric_limits<genfloat>::radix`.
`genfloat mad(genfloat a, genfloat b, genfloat c)`	mad approximates a * b + c. Whether or how the product of a * b is rounded and how supernormal or subnormal intermediate products are handled is not defined. mad is intended to be used where speed is preferred over accuracy.

Math Function	Description
`genfloat maxmag(genfloat x, genfloat y)`	Returns x if $\|x\|>\|y\|$, y if $\|y\|>\|x\|$, otherwise fmax(x, y).
`genfloat minmag(genfloat x, genfloat y)`	Returns x if $\|x\|<\|y\|$, y if $\|y\|<\|x\|$, otherwise fmin(x, y).
`genfloat modf(genfloat x, genfloatptr iptr)`	Decompose a floating-point number. The modf function breaks the argument x into integral and fractional parts, each of which has the same sign as the argument. It stores the integral part in the object pointed to by iptr.
`genfloatf nan(ugenint nancode)` `genfloatd nan(ugenlonginteger nancode)`	Returns a quiet NaN. The nancode may be placed in the significand of the resulting NaN.
`genfloat nextafter(genfloat x, genfloat y)`	Computes the next representable single-precision floating-point value following x in the direction of y. Thus, if y is less than x, nextafter() returns the largest representable floating-point number less than x.
`genfloat pow(genfloat x, genfloat y)`	Compute x to the power y.
`genfloat pown(genfloat x, genint y)`	Compute x to the power y, where y is an integer.
`genfloat powr(genfloat x, genfloat y)`	Compute x to the power y, where $x \geq 0$.
`genfloat remainder(genfloat x, genfloat y)`	Compute the value r such that r = x - n*y, where n is the integer nearest the exact value of x/y. If there are two integers closest to x/y, n shall be the even one. If r is zero, it is given the same sign as x.
`genfloat remquo(genfloat x, genfloat y, genintptr quo)`	The remquo function computes the value r such that r = x - k*y, where k is the integer nearest the exact value of x/y. If there are two integers closest to x/y, k shall be the even one. If r is zero, it is given the same sign as x. This is the same value that is returned by the remainder function. remquo also calculates the lower seven bits of the integral quotient x/y, and gives that value the same sign as x/y. It stores this signed value in the object pointed to by quo.

Math Function	Description
`genfloat rint(genfloat x)`	Round to integral value (using round to nearest even rounding mode) in floating-point format. Refer to section 7.1 of the OpenCL 1.2 specification document for description of rounding modes.
`genfloat rootn(genfloat x, genint y)`	Compute x to the power 1/y.
`genfloat round(genfloat x)`	Return the integral value nearest to x rounding halfway cases away from zero, regardless of the current rounding direction.
`genfloat rsqrt(genfloat x)`	Compute inverse square root.
`genfloat sin(genfloat x)`	Compute sine.
`genfloat sincos(genfloat x, genfloatptr cosval)`	Compute sine and cosine of x. The computed sine is the return value and computed cosine is returned in `cosval`.
`genfloat sinh(genfloat x)`	Compute hyperbolic sine.
`genfloat sinpi(genfloat x)`	Compute *sin(π x)*.
`genfloat sqrt(genfloat x)`	Compute square root.
`genfloat tan(genfloat x)`	Compute tangent.
`genfloat tanh(genfloat x)`	Compute hyperbolic tangent.
`genfloat tanpi(genfloat x)`	Compute *tan(π x)*.
`genfloat tgamma(genfloat x)`	Compute the gamma function.
`genfloat trunc(genfloat x)`	Round to integral value using the round to zero rounding mode.

In SYCL the implementation-defined precision math functions are defined in the namespace `sycl::native`. The functions that are available within this namespace are specified in Table 177.

Table 177. Native math functions

Native Math Function	Description
`genfloatf cos(genfloatf x)`	Compute cosine over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf divide(genfloatf x, genfloatf y)`	Compute x / y over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf exp(genfloatf x)`	Compute the base- e exponential of x over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf exp2(genfloatf x)`	Compute the base- 2 exponential of x over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf exp10(genfloatf x)`	Compute the base- 10 exponential of x over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf log(genfloatf x)`	Compute natural logarithm over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf log2(genfloatf x)`	Compute a base 2 logarithm over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf log10(genfloatf x)`	Compute a base 10 logarithm over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf powr(genfloatf x, genfloatf y)`	Compute x to the power y, where $x \geq 0$. The range of x and y are implementation-defined. The maximum error is implementation-defined.
`genfloatf recip(genfloatf x)`	Compute reciprocal over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf rsqrt(genfloatf x)`	Compute inverse square root over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf sin(genfloatf x)`	Compute sine over an implementation-defined range. The maximum error is implementation-defined.

Native Math Function	Description
`genfloatf sqrt(genfloatf x)`	Compute square root over an implementation-defined range. The maximum error is implementation-defined.
`genfloatf tan(genfloatf x)`	Compute tangent over an implementation-defined range. The maximum error is implementation-defined.

In SYCL the half precision math functions are defined in `sycl::half_precision`. The functions that are available within this namespace are specified in Table 178. These functions are implemented with a minimum of 10-bits of accuracy i.e. the maximum error is less than or equal to 8192 ulp.

Table 178. Half precision math functions

Half Math function	Description
`genfloatf cos(genfloatf x)`	Compute cosine. x must be in the range -216 to +216.
`genfloatf divide(genfloatf x, genfloatf y)`	Compute x / y.
`genfloatf exp(genfloatf x)`	Compute the base- e exponential of x.
`genfloatf exp2(genfloatf x)`	Compute the base- 2 exponential of x.
`genfloatf exp10(genfloatf x)`	Compute the base- 10 exponential of x.
`genfloatf log(genfloatf x)`	Compute natural logarithm.
`genfloatf log2(genfloatf x)`	Compute a base 2 logarithm.
`genfloatf log10(genfloatf x)`	Compute a base 10 logarithm.
`genfloatf powr(genfloatf x, genfloatf y)`	Compute x to the power y, where $x \geq 0$.
`genfloatf recip(genfloatf x)`	Compute reciprocal.
`genfloatf rsqrt(genfloatf x)`	Compute inverse square root.
`genfloatf sin(genfloatf x)`	Compute sine. x must be in the range -216 to +216.
`genfloatf sqrt(genfloatf x)`	Compute square root.

Half Math function	Description
`genfloatf tan(genfloatf x)`	Compute tangent. x must be in the range -216 to +216.

4.17.6. Integer functions

Integer math functions are available in SYCL in the namespace `sycl` on host and device. The built-in functions can take as input `char`, `unsigned char`, `short`, `unsigned short`, `int`, `unsigned int`, `long long int`, `unsigned long long int` and their `vec` and `marray` counterparts. The supported integer math functions are described in Table 179.

Table 179. Integer functions which work on SYCL host and device, are available in the `sycl` namespace

Integer Function	Description
`geninteger abs(geninteger x)`	Returns $\|x\|$.
`ugeninteger abs_diff(geninteger x, geninteger y)`	Returns $\|x - y\|$ without modulo overflow.
`geninteger add_sat(geninteger x, geninteger y)`	Returns $x + y$ and saturates the result.
`geninteger hadd(geninteger x, geninteger y)`	Returns $(x + y)>>1$. The intermediate sum does not modulo overflow.
`geninteger rhadd(geninteger x, geninteger y)`	Returns $(x + y + 1)>>1$. The intermediate sum does not modulo overflow.
`geninteger clamp(geninteger x, geninteger minval, geninteger maxval)` `geninteger clamp(geninteger x, sgeninteger minval, sgeninteger maxval)`	Returns min(max(x, minval), maxval). Results are undefined if $minval>maxval$.
`geninteger clz(geninteger x)`	Returns the number of leading 0-bits in x, starting at the most significant bit position. If x is 0, returns the size in bits of the type of x or component type of x, if x is a vector type.
`geninteger ctz(geninteger x)`	Returns the count of trailing 0-bits in x. If x is 0, returns the size in bits of the type of x or component type of x, if x is a vector type.
`geninteger mad_hi(geninteger a, geninteger b, geninteger c)`	Returns `mul_hi(a, b)+c`.
`geninteger mad_sat(geninteger a, geninteger b, geninteger c)`	Returns `a * b + c` and saturates the result.

Integer Function	Description
`geninteger max(geninteger x, geninteger y)` `geninteger max(geninteger x, sgeninteger y)`	Returns y if $x<y$, otherwise it returns x.
`geninteger min(geninteger x, geninteger y)` `geninteger min(geninteger x, sgeninteger y)`	Returns y if $y<x$, otherwise it returns x.
`geninteger mul_hi(geninteger x, geninteger y)`	Computes `x * y` and returns the high half of the product of x and y.
`geninteger rotate(geninteger v, geninteger i)`	For each element in v, the bits are shifted left by the number of bits given by the corresponding element in i (subject to usual shift modulo rules described in the OpenCL 1.2 specification section 6.3). Bits shifted off the left side of the element are shifted back in from the right.
`geninteger sub_sat(geninteger x, geninteger y)`	Returns $x-y$ and saturates the result.
`ugeninteger16bit upsample(ugeninteger8bit hi, ugeninteger8bit lo)`	`result[i] = ((ushort)hi[i] << 8) | lo[i]`
`igeninteger16bit upsample(igeninteger8bit hi, ugeninteger8bit lo)`	`result[i] = ((short)hi[i] << 8) | lo[i]`
`ugeninteger32bit upsample(ugeninteger16bit hi, ugeninteger16bit lo)`	`result[i] = ((uint)hi[i] << 16) | lo[i]`
`igeninteger32bit upsample(igeninteger16bit hi, ugeninteger16bit lo)`	`result[i] = ((int)hi[i] << 16) | lo[i]`
`ugeninteger64bit upsample(ugeninteger32bit hi, ugeninteger32bit lo)`	`result[i] = ((ulonglong)hi[i] << 32) | lo[i]`
`igeninteger64bit upsample(igeninteger32bit hi, ugeninteger32bit lo)`	`result[i] = ((longlong)hi[i] << 32) | lo[i]`
`geninteger popcount(geninteger x)`	Returns the number of non-zero bits in x.

Integer Function	Description
`geninteger32bit mad24(geninteger32bit x, geninteger32bit y, geninteger32bit z)`	Multiply two 24-bit integer values x and y and add the 32-bit integer result to the 32-bit integer z. Refer to definition of mul24 to see how the 24-bit integer multiplication is performed.
`geninteger32bit mul24(geninteger32bit x, geninteger32bit y)`	Multiply two 24-bit integer values x and y. x and y are 32-bit integers but only the low 24-bits are used to perform the multiplication. mul24 should only be used when values in x and y are in the range $[-2^{23}, 2^{23}-1]$ if x and y are signed integers and in the range $[0, 2^{24}-1]$ if x and y are unsigned integers. If x and y are not in this range, the multiplication result is implementation-defined.

4.17.7. Common functions

In SYCL the OpenCL common functions are available in the namespace `sycl` on host and device as defined in the OpenCL 1.2 specification document par. 6.12.4. They are described here in Table 180. The built-in functions can take as input `float` or optionally `double` and their `vec` and `marray` counterparts.

Table 180. Common functions which work on SYCL host and device, are available in the `sycl` namespace. They correspond to Table 6.12 of the OpenCL 1.2 specification.

Common Function	Description

`genfloat clamp(genfloat x, genfloat minval, genfloat maxval)`
`genfloatf clamp(genfloatf x, float minval, float maxval)`
`genfloatd clamp(genfloatd x, double minval, double maxval)`
	Returns fmin(fmax(x, minval), maxval). Results are undefined if minval>maxval.

`genfloat degrees(genfloat radians)`	Converts radians to degrees, i.e. $\frac{180}{\pi} \times radians$.

`genfloat max(genfloat x, genfloat y)`
`genfloatf max(genfloatf x, float y)`
`genfloatd max(genfloatd x, double y)`
	Returns y if $x<y$, otherwise it returns x. If x or y are infinite or NaN, the return values are undefined.

`genfloat min(genfloat x, genfloat y)`
`genfloatf min(genfloatf x, float y)`
`genfloatd min(genfloatd x, double y)`
	Returns y if $y<x$, otherwise it returns x. If x or y are infinite or NaN, the return values are undefined.

`genfloat mix(genfloat x, genfloat y, genfloat a)`
`genfloatf mix(genfloatf x, genfloatf y, float a)`
`genfloatd mix(genfloatd x, genfloatd y, double a)`
	Returns the linear blend of x and y implemented as: $x + (y - x) \times a$. a must be a value in the range 0.0 ... 1.0. If a is not in the range 0.0 ... 1.0, the return values are undefined.

Common Function	Description
`genfloat radians(genfloat degrees)`	Converts degrees to radians, i.e. $(\pi / 180) \times degrees$.

`genfloat step(genfloat edge, genfloat x)`
`genfloatf step(float edge, genfloatf x)`
`genfloatd step(double edge, genfloatd x)`
	Returns 0.0 if $x<edge$, otherwise it returns 1.0.

`genfloat smoothstep (genfloat edge0,`
`genfloat edge1, genfloat x)`
`genfloatf smoothstep (float edge0,`
`float edge1, genfloatf x)`
`genfloatd smoothstep (double edge0,`
`double edge1, genfloatd x)`
	Returns 0.0 if $x \leq edge0$ and 1.0 if $x \geq edge1$ and performs smooth Hermite interpolation between 0 and 1 when $edge0<x<edge1$. This is useful in cases where you would want a threshold function with a smooth transition.
	This is equivalent to:
	`gentype t;`
	`t = clamp((x - edge0) /`
	`(edge1 - edge0), 0, 1);`
	`return t * t * (3 - 2 * t);`
	Results are undefined if $edge0>=edge1$ or if x, edge0 or edge1 is a NaN.

`genfloat sign(genfloat x)`	Returns 1.0 if $x>0$, -0.0 if $x=-0.0$, +0.0 if $x=+0.0$, or -1.0 if $x<0$. Returns 0.0 if x is a NaN.

4.17.8. Geometric functions

In SYCL the OpenCL geometric functions are available in the namespace `sycl` on host and device as defined in the OpenCL 1.2 specification document par. 6.12.5. The built-in functions can take as input float or optionally double and their `vec` and `marray` counterparts, for dimensions 2, 3 and 4. On the host the vector types use the `vec` class and on an SYCL device use the corresponding native SYCL backend vector types. All of the geometric functions use round-to-nearest-even rounding mode. Table 181 contains the definitions of supported geometric functions.

Table 181. Geometric functions which work on SYCL host and device, are available in the `sycl` namespace. They correspond to Table 6.13 of the OpenCL 1.2 specification.

Geometric Function	Description

`float4 cross(float4 p0, float4 p1)`
`float3 cross(float3 p0, float3 p1)`
`double4 cross(double4 p0, double4 p1)`
`double3 cross(double3 p0, double3 p1)`
	Returns the cross product of p0.xyz and p1.xyz. The *w* component of `float4` result returned will be 0.0.

Geometric Function	Description

`mfloat4 cross(mfloat4 p0, mfloat4 p1)`
`mfloat3 cross(mfloat3 p0, mfloat3 p1)`
`mdouble4 cross(mdouble4 p0, mdouble4 p1)`
`mdouble3 cross(mdouble3 p0, mdouble3 p1)`
	Returns the cross product of first 3 components of p0 and p1. The 4th component of result returned will be 0.0.

`float dot(gengeofloat p0, gengeofloat p1)` `double dot(gengeodouble p0, gengeodouble p1)`	Compute dot product.
`float distance(gengeofloat p0, gengeofloat p1)` `double distance(gengeodouble p0, gengeodouble p1)`	Returns the distance between p0 and p1. This is calculated as `length(p0 - p1)`.
`float length(gengeofloat p)` `double length(gengeodouble p)`	Return the length of vector p, i.e., $\sqrt{p.x^2 + p.y^2 + \ldots}$
`gengeofloat normalize(gengeofloat p)` `gengeodouble normalize(gengeodouble p)`	Returns a vector in the same direction as p but with a length of 1.
`float fast_distance(gengeofloat p0, gengeofloat p1)`	Returns `fast_length(p0 - p1)`.
`float fast_length(gengeofloat p)`	Returns the length of vector p computed as: `sqrt((half)(pow(p.x,2) + pow(p.y,2) + ...))`

Geometric Function	Description

`gengeofloat fast_normalize(gengeofloat p)`	Returns a vector in the same direction as p but with a length of 1. fast_normalize is computed as:
	`p*rsqrt((half)(pow(p.x,2) + pow(p.y,2) + ... ))`
	The result shall be within 8192 ulps error from the infinitely precise result of
	`if (all(p == 0.0f))`
	`  result = p;`
	`else`
	`  result = p / sqrt(pow(p.x, 2) + pow(p.y, 2) + ...);`
	with the following exceptions:
	1. If the sum of squares is greater than `FLT_MAX` then the value of the floating-point values in the result vector are undefined.
	2. If the sum of squares is less than `FLT_MIN` then the implementation may return back p.
	3. If the device is in "denorms are flushed to zero" mode, individual operand elements with magnitude less than `sqrt(FLT_MIN)` may be flushed to zero before proceeding with the calculation.

4.17.9. Relational functions

The follow free functions are defined in the `sycl` namespace and are available on both host and device. These functions perform various relational comparisons on `vec`, `marray`, and scalar types.

The comparisons performed by `isequal`, `isgreater`, `isgreaterequal`, `isless`, `islessequal`, and `islessgreater` are false when one or both operands are NaN. The comparison performed by `isnotequal` is true when one or both operands are NaN.

The `vec` versions of these functions follow the definitions in the OpenCL 1.2 specification document par. 6.12.6. Unless otherwise specified, these functions return a vector component of -1 (i.e. all bits set) when the comparison is true and 0 when the comparison is false.

Table 182 shows the functions that are available for the `vec` type.

Table 182. Relational functions for the `vec` template class.

Relational Function	Description

`vec<int16_t, { n }> isequal(half { n } x, half { n } y)`
`vec<int32_t, { n }> isequal(float { n } x, float { n } y)`
`vec<int64_t, { n }> isequal(double { n } x, double { n } y)`
	Returns the component-wise compare of `x == y`.

`vec<int16_t, { n }> isnotequal(half { n } x, half { n } y)`
`vec<int32_t, { n }> isnotequal(float { n } x, float { n } y)`
`vec<int64_t, { n }> isnotequal(double { n } x, double { n } y)`
	Returns the component-wise compare of `x != y`.

`vec<int16_t, { n }> isgreater(half { n } x, half { n } y)`
`vec<int32_t, { n }> isgreater(float { n } x, float { n } y)`
`vec<int64_t, { n }> isgreater(double { n } x, double { n } y)`
	Returns the component-wise compare of `x > y`.

`vec<int16_t, { n }> isgreaterequal(half { n } x, half { n } y)`
`vec<int32_t, { n }> isgreaterequal(float { n } x, float { n } y)`
`vec<int64_t, { n }> isgreaterequal(double { n } x, double { n } y)`
	Returns the component-wise compare of `x >= y`.

`vec<int16_t, { n }> isless(half { n } x, half { n } y)`
`vec<int32_t, { n }> isless(float { n } x, float { n } y)`
`vec<int64_t, { n }> isless(double { n } x, double { n } y)`
	Returns the component-wise compare of `x < y`.

`vec<int16_t, { n }> islessequal(half { n } x, half { n } y)`
`vec<int32_t, { n }> islessequal(float { n } x, float { n } y)`
`vec<int64_t, { n }> islessequal(double { n } x, double { n } y)`
	Returns the component-wise compare of `x <= y`.

`vec<int16_t, { n }> islessgreater(half { n } x, half { n } y)`
`vec<int32_t, { n }> islessgreater(float { n } x, float { n } y)`
`vec<int64_t, { n }> islessgreater(double { n } x, double { n } y)`
	Returns the component-wise compare of `(x < y) || (x > y)`.

`vec<int16_t, { n }> isfinite(half { n } x)`
`vec<int32_t, { n }> isfinite(float { n } x)`
`vec<int64_t, { n }> isfinite(double { n } x)`
	Test for finite value.

Relational Function	Description

`vec<int16_t, { n }> isinf(half { n } x)`
`vec<int32_t, { n }> isinf(float { n } x)`
`vec<int64_t, { n }> isinf(double { n } x)`
	Test for infinity value (positive or negative) .

`vec<int16_t, { n }> isnan(half { n } x)`
`vec<int32_t, { n }> isnan(float { n } x)`
`vec<int64_t, { n }> isnan(double { n } x)`
	Test for a NaN.

`vec<int16_t, { n }> isnormal(half { n } x)`
`vec<int32_t, { n }> isnormal(float { n } x)`
`vec<int64_t, { n }> isnormal(double { n } x)`
	Test for a normal value.

`vec<int16_t, { n }> isordered(half { n } x, half { n } y)`
`vec<int32_t, { n }> isordered(float { n } x, float { n } y)`
`vec<int64_t, { n }> isordered(double { n } x, double { n } y)`
	Test if arguments are ordered. `isordered()` takes arguments `x` and `y`, and returns the result `isequal(x, x) && isequal(y, y)`.

`vec<int16_t, { n }> isunordered(half { n } x, half { n } y)`
`vec<int32_t, { n }> isunordered(float { n } x, float { n } y)`
`vec<int64_t, { n }> isunordered(double { n } x, double { n } y)`
	Test if arguments are unordered. `isunordered()` takes arguments `x` and `y`, returning non-zero if `x` or `y` is NaN, and zero otherwise.

`vec<int16_t, { n }> signbit(half { n } x)`
`vec<int32_t, { n }> signbit(float { n } x)`
`vec<int64_t, { n }> signbit(double { n } x)`
	Test for sign bit. Returns the following for each component in `x`: -1 (i.e all bits set) if the sign bit in the component value is set else returns 0.

`int any(vigeninteger x)`	Returns 1 if the most significant bit in any component of `x` is set; otherwise returns 0.
`int all(vigeninteger x)`	Returns 1 if the most significant bit in all components of `x` is set; otherwise returns 0.
`vgentype bitselect(vgentype a, vgentype b, vgentype c)`	Each bit of the result is the corresponding bit of `a` if the corresponding bit of `c` is 0. Otherwise it is the corresponding bit of `b`.
`vgentype select(vgentype a, vgentype b, vigeninteger c)` `vgentype select(vgentype a, vgentype b, vugeninteger c)`	For each component of a vector type: `result[i] = (MSB of c[i] is set) ? b[i] : a[i]`. `vigeninteger` and `vugeninteger` must have the same number of elements and bits as `vgentype`.

Table 183 shows the functions that are available for the `marray` type and for scalar data types.

Table 183. Relational functions for the `maray` template class and for scalar data types.

Relational Function	Description
`bool isequal(sgenfloat x, sgenfloat y)` `marray<bool, { N }> isequal(mgenfloat x, mgenfloat y)`	Returns the component-wise compare of `x == y`.
`bool isnotequal(sgenfloat x, sgenfloat y)` `marray<bool, { N }> isnotequal(mgenfloat x, mgenfloat y)`	Returns the component-wise compare of `x != y`.
`bool isgreater(sgenfloat x, sgenfloat y)` `marray<bool, { N }> isgreater(mgenfloat x, mgenfloat y)`	Returns the component-wise compare of `x > y`.
`bool isgreaterequal(sgenfloat x, sgenfloat y)` `marray<bool, { N }> isgreaterequal(mgenfloat x, mgenfloat y)`	Returns the component-wise compare of `x >= y`.
`bool isless(sgenfloat x, sgenfloat y)` `marray<bool, { N }> isless(mgenfloat x, mgenfloat y)`	Returns the component-wise compare of `x < y`.
`bool islessequal(sgenfloat x, sgenfloat y)` `marray<bool, { N }> islessequal(mgenfloat x, mgenfloat y)`	Returns the component-wise compare of `x <= y`.
`bool islessgreater(sgenfloat x, sgenfloat y)` `marray<bool, { N }> islessgreater(mgenfloat x, mgenfloat y)`	Returns the component-wise compare of `(x < y) || (x > y)`.
`bool isfinite(sgenfloat x)` `marray<bool, { N }> isfinite(mgenfloat x)`	Test for finite value.
`bool isinf(sgenfloat x)` `marray<bool, { N }> isinf(mgenfloat x)`	Test for infinity value (positive or negative) .
`bool isnan(sgenfloat x)` `marray<bool, { N }> isnan(mgenfloat x)`	Test for a NaN.
`bool isnormal(sgenfloat x)` `marray<bool, { N }> isnormal(mgenfloat x)`	Test for a normal value.
`bool isordered(sgenfloat x, sgenfloat y)` `marray<bool, { N }> isordered(mgenfloat x, mgenfloat y)`	Test if arguments are ordered. `isordered()` takes arguments `x` and `y`, and returns the result `isequal(x, x) && isequal(y, y)`.

Relational Function	Description
`bool isunordered(sgenfloat x, sgenfloat y)` `marray<bool, { N }> isunordered(mgenfloat x, mgenfloat y)`	Test if arguments are unordered. `isunordered()` takes arguments `x` and `y`, returning `true` if `x` or `y` is NaN, and `false` otherwise.
`bool signbit(sgenfloat x)` `marray<bool, { N }> signbit(mgenfloat x)`	Test for sign bit, returning `true` if the sign bit in `x` is set, and `false` otherwise.
`bool any(sgeninteger x)` `bool any(migeninteger x)`	Returns `true` if the most significant bit in any component of `x` is set; otherwise returns `false`.
`bool all(sgeninteger x)` `bool all(migeninteger x)`	Returns `true` if the most significant bit in all components of `x` is set; otherwise returns `false`.
`sgentype bitselect(sgentype a, sgentype b, sgentype c)` `mgentype bitselect(mgentype a, mgentype b, mgentype c)`	Each bit of the result is the corresponding bit of `a` if the corresponding bit of `c` is 0. Otherwise it is the corresponding bit of `b`.
`sgentype select(sgentype a, sgentype b, bool c)` `mgentype select(mgentype a, mgentype b, marray<bool, { N }> c)`	Returns the component-wise `result = c ? b : a`.

Chapter 5. SYCL Device Compiler

This section specifies the requirements of the SYCL device compiler. Most features described in this section relate to underlying SYCL backend capabilities of target devices and limiting the requirements of device code to ensure portability.

5.1. Offline compilation of SYCL source files

There are two alternatives for a SYCL device compiler: a single-source device compiler and a device compiler that supports the technique of SMCP.

A SYCL device compiler takes in a C++ source file, extracts only the SYCL kernels and outputs the device code in a form that can be enqueued from host code by the associated SYCL runtime. How the SYCL runtime invokes the kernels is implementation-defined, but a typical approach is for a device compiler to produce a header file with the compiled kernel contained within it. By providing a command-line option to the host compiler, it would cause the implementation's SYCL header files to `#include` the generated header file. The SYCL specification has been written to allow this as an implementation approach in order to allow SMCP. However, any of the mechanisms needed from the SYCL compiler, the SYCL runtime and build system are implementation-defined, as they can vary depending on the platform and approach.

A SYCL single-source device compiler takes in a C++ source file and compiles both host and device code at the same time. This specification specifies how a SYCL single-source device compiler sees and outputs device code for kernels, but does not specify the host compilation.

5.2. Naming of kernels

SYCL kernels are extracted from C++ source files and stored in an implementation-defined format. In the case of the shared-source compilation model, the kernels have to be uniquely identified by both host and device compiler. This is required in order for the host runtime to be able to load the kernel by using a backend-specific host runtime interface.

From this requirement the following rules apply for naming the kernels:

- The kernel name is a C++ typename.
- The kernel name must be forward declarable at namespace scope (including global namespace scope) and may not be forward declared other than at namespace scope. If it isn't forward declared but is specified as a template argument in a kernel invoking interface, as described in Section 4.9.4.2, then it may not conflict with a name in any enclosing namespace scope.

The requirement that a kernel name be forward declarable makes some types for kernel names illegal, such as anything declared in the `std` namespace (adding a declaration to namespace `std` leads to undefined behavior).

- If the kernel is defined as a named function object type, the name can be the typename of the function object as long as it is either declared at namespace scope, or does not conflict with any name in an enclosing namespace scope.
- If the kernel is defined as a lambda, a typename can optionally be provided to the kernel invoking interface as described in Section 4.9.4.2, so that the developer can control the kernel name for purposes such as debugging or referring to the kernel when applying build options.
- If a kernel function relies on template parameters, then those template parameters must be contained by the kernel name. If such a kernel name is specified as a template argument in a kernel invoking interface, then the template parameters on which the kernel depends must be forward declarable at namespace scope.

In both single-source and shared-source implementations, a device compiler should detect the kernel invocations (e.g. `parallel_for<kernelname>)` in the source code and compile the enclosed kernels, storing them with their associated type name.

The format of the kernel and the compilation techniques are details of an implementation and not specified. The interface between the compiler and the runtime for extracting and executing SYCL kernels on the device is a detail of an implementation and not specified.

5.3. Compilation of functions

The SYCL device compiler parses an entire C++ source file supplied by the user, including any header files referenced via `#include` directives. From this source file, the SYCL device compiler must compile kernels for the device, as well as any functions that the kernels call.

The device compiler identifies kernels by looking for calls to Kernel invocation commands such as `parallel_for`. One of the parameters is a function object which is known as a SYCL kernel function, and this function must always return `void`. Any function called by the SYCL kernel function is also compiled for the device, and these functions together with the SYCL kernel functions are known as device functions. The device compiler searches recursively for any functions called from a device function, and these functions are also compiled for the device and known as device functions.

To illustrate, the following source code shows three functions and a kernel invoke with comments explaining which functions need to be compiled for the device.

```
1 void f(handler& cgh) {
2   // Function "f" is not compiled for device
3
4   cgh.single_task([=] {
5     // This code is compiled for device
6     g(); // This line forces "g" to be compiled for device
7   });
8 }
9
10 void g() {
11   // Called from kernel, so "g" is compiled for device
12 }
13
14 void h() {
15   // Not called from a device function, so not compiled for device
16 }
```

In order for the SYCL device compiler to correctly compile device functions, all functions in the source file, whether device functions or not, must be syntactically correct functions according to this specification. A syntactically correct function adheres to at least the minimum required C++ version defined in Section 3.9.1.

5.4. Language restrictions for device functions

Device functions must abide by certain restrictions. The full set of C++ features are not available to these functions. Following is a list of these restrictions:

- Pointers and objects containing pointers may be shared. However, when a pointer is passed between SYCL devices or between the host and a SYCL device, dereferencing that pointer on the device produces undefined behavior unless the device supports USM and the pointer is an address within a USM memory region (see Section 4.8).

- Memory storage allocation is not allowed in kernels. All memory allocation for the device is done on the host using accessor classes or using USM as explained in Section 4.8. Consequently, the default allocation `operator new` overloads that allocate storage are disallowed in a SYCL kernel. The placement `new` operator and any user-defined overloads that do not allocate storage are permitted.
- Kernel functions must always have a `void` return type. A kernel lambda trailing-return-type that is not `void` is therefore illegal, as is a return statement (that would return from the kernel function) with an expression that does not convert to `void`.
- The odr-use of polymorphic classes and classes with virtual inheritance is allowed. However, no virtual member functions are allowed to be called in a device function.
- No function pointers or references are allowed to be called in a device function.
- RTTI is disabled inside device functions.
- No variadic functions are allowed to be called in a device function.
- Exception-handling cannot be used inside a device function. `noexcept` is allowed.
- Recursion is not allowed in a device function.
- Variables with thread storage duration (`thread_local` storage class specifier) are not allowed to be odr-used in a device function.
- Variables with static storage duration that are odr-used inside a device function, must be `const` or `constexpr` and zero-initialized or constant-initialized.

Amongst other things, this restriction makes it illegal for a device function to access a global variable that isn't `const` or `constexpr`.

- The rules for kernels apply to both the kernel function objects themselves and all functions, operators, member functions, constructors and destructors called by the kernel. This means that kernels can only use library functions that have been adapted to work with SYCL. Implementations are not required to support any library routines in kernels beyond those explicitly mentioned as usable in kernels in this spec. Developers should refer to the SYCL built-in functions in Section 4.17 to find functions that are specified to be usable in kernels.
- Interacting with a special SYCL runtime class (e.g. SYCL `accessor` or `stream`) that is stored within a C++ union is undefined behavior.
- Any variable or function that is odr-used from a device function must be defined in the same translation unit as that use. However, a function may be defined in another translation unit if the implementation defines the `SYCL_EXTERNAL` macro as described in Section 5.10.1.

5.5. Built-in scalar data types

In a SYCL device compiler, the device definition of all standard C++ fundamental types from Table 184 must match the host definition of those types, in both size and alignment. A device compiler may have this preconfigured so that it can match them based on the definitions of those types on the platform, or there may be a necessity for a device compiler command-line option to ensure the types are the same.

The standard C++ fixed width types, e.g. `int8_t`, `int16_t`, `int32_t`,`int64_t`, should have the same size as defined by the C++ standard for host and device.

Table 184. Fundamental data types supported by SYCL

Fundamental data type	Description
`bool`	A conditional data type which can be either true or false. The value true expands to the integer constant 1 and the value false expands to the integer constant 0.
`char`	A signed or unsigned 8-bit integer, as defined by the C++ core language
`signed char`	A signed 8-bit integer, as defined by the C++ core language
`unsigned char`	An unsigned 8-bit integer, as defined by the C++ core language
`short int`	A signed integer of at least 16-bits, as defined by the C++ core language
`unsigned short int`	An unsigned integer of at least 16-bits, as defined by the C++ core language
`int`	A signed integer of at least 16-bits, as defined by the C++ core language
`unsigned int`	An unsigned integer of at least 16-bits, as defined by the C++ core language
`long int`	A signed integer of at least 32-bits, as defined by the C++ core language
`unsigned long int`	An unsigned integer of at least 32-bits, as defined by the C++ core language
`long long int`	An integer of at least 64-bits, as defined by the C++ core language
`unsigned long long int`	An unsigned integer of at least 64-bits, as defined by the C++ core language
`float`	A 32-bit floating-point. The float data type must conform to the IEEE 754 single precision storage format.
`double`	A 64-bit floating-point. The double data type must conform to the IEEE 754 double precision storage format. This type is only supported on devices that have `aspect::fp64`.

5.6. Preprocessor directives and macros

The standard C++ preprocessing directives and macros are supported. The following preprocessor macros must be defined by all conformant implementations:

- `SYCL_LANGUAGE_VERSION` substitutes an integer reflecting the version number and revision of the SYCL language being supported by the implementation. The version of SYCL defined in this document will have `SYCL_LANGUAGE_VERSION` substitute the integer `2020`, composed with the general SYCL version followed by 2 digits representing the revision number;
- `SYCL_DEVICE_COPYABLE` is defined to 1 if the implementation supports explicitly specified device copyable types as described in Section 3.13.1. Otherwise, the implementation's definition of device copyable falls back to C++ trivially copyable and `sycl::is_device_copyable` is ignored;
- `__SYCL_DEVICE_ONLY__` is defined to 1 if the source file is being compiled with a SYCL device compiler which does not produce host binary;
- `__SYCL_SINGLE_SOURCE__` is defined to 1 if the source file is being compiled with a SYCL single-source compiler which produces host as well as device binary;
- `SYCL_FEATURE_SET_FULL` is defined to 1 if the SYCL implementation supports the full feature set and is not defined otherwise. For more details see Appendix B;
- `SYCL_FEATURE_SET_REDUCED` is defined to 1 if the SYCL implementation supports the reduced feature set and not the full feature set, otherwise it is not defined. For more details see Appendix B;
- `SYCL_EXTERNAL` is an optional macro which enables external linkage of SYCL functions and member functions to be included in a SYCL kernel. The macro is only defined if the implementation supports external linkage. For more details see Section 5.10.1.

In addition, for each SYCL backend supported, the preprocessor macros described in Section 4.1 must be defined by all conformant implementations.

5.7. Optional kernel features

A number of kernel features defined by this SYCL specification are optional; they may be supported on some devices but not on other devices. As described in Section 4.6.4.3, an application can test whether a device supports these features by testing whether the device has an associated aspect. The following aspects are those that correspond to optional kernel features:

- `fp16`
- `fp64`
- `atomic64`

In addition, the following C++ attributes from Section 5.8.1 also correspond to optional kernel features because they force the kernel to be compiled in a way that might not run on all devices:

- `reqd_work_group_size()`
- `reqd_sub_group_size()`

In order to guarantee source code portability of SYCL applications that use optional kernel features, all SYCL implementations must be able to compile device code that uses these optional features regardless of whether the implementation supports the features on any of its devices.

Of course, applications that make use of optional kernel features should ensure that a kernel using such a feature is submitted only to a device that supports the feature. If the application submits a command group using a secondary queue, then any kernel submitted from the command group should use only features that are supported by both the primary queue's device and the secondary queue's device. If an application fails to do this, the implementation must throw a synchronous exception with the `errc::ker-`

nel_not_supported error code from the kernel invocation command (e.g. parallel_for()).

It is legal for a SYCL application to define several kernels in the same translation unit even if they use different optional features, as shown in the following example:

```
queue q1(dev1);
if (dev1.has(aspect::fp16)) {
  q1.submit([&](handler& cgh) {
    cgh.parallel_for<KernelA>(range { N }, [=](id i) {
      half fpShort = 1.0;
      /* ... */
    });
  });
}

queue q2(dev2);
if (dev2.has(aspect::atomic64)) {
  q2.submit([&](handler& cgh) {
    cgh.parallel_for<KernelB>(range { N }, [=](id i) {
      /* ... */
      sycl::atomic_ref longAtomic(longValue);
      longAtomic.fetch_add(1);
    });
  });
}
```

An implementation may not raise a compile time diagnostic or a run time exception merely due to speculative compilation of a kernel for a device when the application does not actually submit the kernel to that device. To illustrate using the example above, assume that device dev1 does not have aspect::atomic64 and device dev2 doe not have aspect::fp16. An implementation cannot raise a diagnostic due to compilation of KernelA for device dev2 or for compilation of KernelB for device dev1 because the application does not submit these kernels to those devices.

It is expected that this requirement will have an impact on the way an implementation bundles kernels into device images. For example, naively bundling KernelA and KernelB into the same device image could run afoul of this requirement if the implementation compiles the entire device image when KernelA is submitted to device dev1.

5.8. Attributes for device code

C++ attributes may be used to decorate kernels and device functions in order to influence the code generated by the device compiler. These attributes are all defined in the [[sycl::]] namespace.

If one of the attributes defined in this section is applied to a kernel or device function, it must be applied to the first declaration of that kernel or device function in the translation unit. Programs which fail to do this are ill formed and the compiler must issue a diagnostic. Redeclarations of the kernel or device function in the same translation unit may optionally have the same attribute applied (so long as the attribute arguments are the same between the declarations), but this is not required. The attribute remains in effect regardless of whether it appears in the redeclaration.

Unless an attribute's description specifically allows it, a kernel or device function may not be declared with the more than one instance of the same attribute unless all instances have the same attribute arguments. The compiler must issue a diagnostic for programs which violate this requirement. When two or more instances of the same attribute appear on the declaration of a kernel or device function, the effect is as though a single instance appeared (assuming that all instances have the same attribute arguments).

If a kernel or device function is declared with an attribute in one translation unit and the same kernel or device function is declared without the same attribute (and its same attribute arguments) in another translation unit, the program is ill formed and no diagnostic is required.

If any of these attributes are applied to a device function that is also compiled for the host, they have no effect when the function is compiled for the host.

Applying these attributes to any language construct other than those specified in this section has implementation-defined effect.

5.8.1. Kernel attributes

The attributes listed in Table 185 have a different position depending on whether the kernel is defined as a lambda function or as a named function object. If the kernel is a named function object, the attribute is applied to the declarator-id in the function declaration. However, if the kernel is a lambda function, the attribute is applied to the lambda declarator.

The reason for the different positions is because the C++ core language does not currently define a position for attributes to appertain to the lambda's corresponding function operator or operator template, only to the corresponding *type* of the function operator or operator template. This is expected to be remedied in a future version of the C++ core language specification.

The example below demonstrates these attribute positions using the `[[sycl::reqd_work_group_size(16)]]` attribute. Note that the C++ core language allows two possible positions for kernels that are defined as a named function object.

```
// Kernel defined as a lambda
myQueue.submit([&](handler& h) {
  h.parallel_for(range<1>(16),
                 [=](item<1> it) [[sycl::reqd_work_group_size(16)]] {
                   //[kernel code]
                 });
});

// Kernel defined as a named function object
class KernelFunctor1 {
 public:
  [[sycl::reqd_work_group_size(16)]] void operator()(item<1> it) const {
    //[kernel code]
  };
};

// Kernel defined as a named function object
class KernelFunctor2 {
 public:
  void operator() [[sycl::reqd_work_group_size(16)]] (item<1> it) const {
    //[kernel code]
  };
};
```

Table 185. Attributes for kernel functions

SYCL attribute	Description

`reqd_work_group_size(dim0)`
`reqd_work_group_size(dim0, dim1)`
`reqd_work_group_size(dim0, dim1, dim2)`
	Indicates that the kernel must be launched with the specified work-group size. The number of arguments must match the dimensionality of the work-group used to invoke the kernel, and the order of the arguments matches the order of the dimension extents to the `range` constructor. Each argument must be an integral constant expression.
	
	Kernels that are decorated with this attribute may not call functions that are defined in another translation unit via the `SYCL_EXTERNAL` macro.
	
	Each device may have limitations on the work group sizes that it supports. If a kernel is decorated with this attribute and then submitted to a device that does not support the work group size, the implementation must throw a synchronous `exception` with the `errc::kernel_not_supported` error code. If the kernel is submitted to a device that does support the work group size, but the application provides an `nd_range` that does not match the size from the attribute, then the implementation must throw a synchronous `exception` with the `errc::nd_range` error code.

`work_group_size_hint(dim0)`
`work_group_size_hint(dim0, dim1)`
`work_group_size_hint(dim0, dim1, dim2)`
	Provides a hint to the compiler about the work-group size most likely to be used when launching the kernel at runtime. The number of arguments must match the dimensionality of the work-group used to invoke the kernel, and the order of the arguments matches the order of the dimension extents to the `range` constructor. Each argument must be an integral constant expression. The effect of this attribute, if any, is implementation-defined.

SYCL attribute	Description
`vec_type_hint(<type>)`	Hint to the compiler on the vector computational width of of the kernel. The argument must be one of the vector types defined in Section 4.14.2. The effect of this attribute, if any, is implementation-defined. This attribute is deprecated (available for use, but will likely be removed in a future version of the specification and is not recommended for use in new code).
`reqd_sub_group_size(dim)`	Indicates that the kernel must be compiled and executed with the specified sub-group size. The argument to the attribute must be an integral constant expression. Kernels that are decorated with this attribute may not call functions that are defined in another translation unit via the `SYCL_EXTERNAL` macro. Each device supports only certain sub-group sizes as defined by `info::device::sub_group_sizes`. In addition, some device features may be incompatible with certain sub-group sizes. If a kernel is decorated with this attribute and then submitted to a device that does not support the sub-group size or if the kernel uses a feature that the device does not support with this sub-group size, the implementation must throw a synchronous `exception` with the `errc::kernel_not_supported` error code.

SYCL attribute	Description
`device_has(aspect, ...)`	This attribute may be used to decorate either the declaration of a kernel function that is defined in the current translation unit or to decorate the declaration of a non-kernel device function. The following description applies when the attribute decorates a kernel function. The parameter list to the `sycl::device_has()` attribute consists of zero or more integral constant expressions, where each integer is interpreted as one of the enumerated values in the `sycl::aspect` enumeration type. Specifying this attribute on a kernel has two effects. First, it causes the kernel invocation command to throw a synchronous exception with the `errc::kernel_not_supported` error code if the kernel is submitted to a device that does not have one of the listed aspects. (This includes the device associated with the secondary queue if the kernel is submitted from a command group that has a secondary queue.) Second, it causes the compiler to issue a diagnostic if the kernel (or any of the functions it calls) uses an optional feature that is associated with an aspect that is not listed in the attribute. The value of each parameter to this attribute must be equal to one of the values in the `sycl::aspect` enumeration type (including any extended values the implementation may provide). If it does not, the program is ill formed and the compiler must issue a diagnostic. See Listing 3 for an example of this attribute.

Listing 3. Example of the `sycl::device_has()` attribute

```
1 class KernelFunctor {
2  public:
3   [[sycl::device_has(aspect::fp16)]] void operator()(item<1> it) const {
4     foo();
```

```
    bar();
  };

 private:
  void foo() const {
    half fp = 1.0; // No compiler diagnostic here
  }

  void bar() const {
    sycl::atomic_ref longAtomic(longValue);
    longAtomic.fetchAdd(1); // ERROR: Compiler issues diagnostic because
                            // "aspect::atomic64" missing from "device_has()"
  }
};

// Using "sycl::device_has()" does not provide any guarantee that the device
// actually supports the required features.  Therefore, the host code should
// still check the device's aspects before submitting the kernel.
if (myQueue.get_device().has(aspect::fp16)) {
  myQueue.submit(
      [&](handler& h) { h.parallel_for(range { 16 }, KernelFunctor {}); });
}
```

5.8.2. Device function attributes

The attributes in Table 186 are applied to the declaration of a non-kernel device function. The position of the attribute is the same as for the kernel function attributes defined above in Section 5.8.1.

Table 186. Attributes for non-kernel device functions

SYCL attribute	Description
`device_has(aspect, ...)`	This attribute may be used to decorate either the declaration of a kernel function that is defined in the current translation unit or to decorate the declaration of a non-kernel device function. The following description applies when the attribute decorates a non-kernel device function declaration. The syntax of this attribute's parameter list is the same as the syntax for the form of `sycl::device_has()` that is specified on a kernel function (see Table 185). This attribute is required when a non-kernel device function that uses optional device features is called in one translation unit and defined in another translation unit via the `SYCL_EXTERNAL` macro. When this attribute appears in a translation unit that calls the decorated device function, it is an assertion that the device function uses optional features that correspond to the aspects listed in the attribute. The program is ill formed if the called device function uses optional features that do not correspond to any of the aspects listed in the attribute, or if the function uses optional features and the attribute is not specified. No diagnostic is required in this case. When this attribute appears in a translation unit that defines the decorated device function, it causes the compiler to issue a diagnostic if the device function (or any of the functions it calls) uses an optional feature that is associated with an aspect that is not listed in the attribute.

5.9. Address-space deduction

C++ has no type-level support to represent address spaces. As a consequence, the SYCL generic programming model does not directly affect the C++ type of unannotated pointers and references.

Source level guarantees about address spaces in the SYCL generic programming model can only be achieved using pointer classes (instances of `multi_ptr`), which are regular classes that represent pointers to data stored in the corresponding address spaces.

In SYCL, the address space of pointer and references are derived from:

- Accessors that give access to shared data. They can be bound to a memory object in a command group and passed into a kernel. Accessors are used in scheduling of kernels to define ordering. Accessors to buffers have a compile-time address space based on their access mode.
- Explicit pointer classes (e.g. `global_ptr`) holds a pointer which is known to be addressing the address space represented by the `access::address_space`. This allows the compiler to determine whether the pointer references global, local, constant or private memory and generate code accordingly.
- Raw C++ pointer and reference types (e.g. `int*`) are allowed within SYCL kernels. They can be constructed from the address of local variables, explicit pointer classes, or accessors.

5.9.1. Address space assignment

In order to understand where data lives, the device compiler is expected to assign address spaces while lowering types for the underlying target based on the context. Depending on the SYCL backends and mode, address space deducing rules differ slightly.

If the target of the SYCL backend can represent the generic address space, then the "common address space deduction rules" in Section 5.9.2 and the "generic as default address space rules" in Section 5.9.3 apply. If the target of the SYCL backend cannot represent the generic address space, then the "common address space deduction rules" in Section 5.9.2 and the "inferred address space rules" in Section 5.9.4 apply.

SYCL address space does not affect the type, address space shall be understood as memory segment in which data is allocated. For instance, if `int i;` is allocated to the global address space, then `decltype(&i)` shall evaluate to `int*`.

5.9.2. Common address space deduction rules

The variable declarations get assigned to an address space depending on their scope and storage class:

- Namespace scope
  - If the type is `const`, the address space the declaration is assigned to is implementation-defined. If the target of the SYCL backend can represent the generic address space, then the assigned address space must be compatible with the generic address space.

Namespace scope non-`const` declarations cannot be used within a kernel, as restricted in Section 5.4. This means that non-`const` global variables cannot be accessed by any device kernel or code called by the device kernel.

- Block scope and function parameter scope
  - Declarations with static storage duration are treated the same way as variables in namespace scope
  - Otherwise the declaration is assigned to the local address space if declared in a hierarchical context
  - Otherwise the declaration is assigned to the private address space
- Class scope
  - Static data members are treated the same way as for variable in namespace scope

The result of a prvalue-to-xvalue conversion is assigned to the local address space if it happens in a hierarchical context or to the private address space otherwise.

5.9.3. Generic as default address space

For SYCL backends that can represent the generic address space (see Section 5.9.1), unannotated pointers and references are considered to be pointing to the generic address space.

5.9.4. Inferred address space

Note for this version

The address space deduction feature described next is inherited from the SYCL 1.2.1 specifications. This section will be changed in a future version to better align with addition of generic address space and generic as default address space.

For SYCL backends that cannot represent the generic address space (see Section 5.9.1), inside kernels the SYCL device compiler will need to auto-deduce the memory region of unannotated pointer and reference types during the lowering of types from C++ to the underlying representation.

If a kernel function or device function contains a pointer or reference type, then the address space deduction must be attempted using the following rules:

- If an explicit pointer class is converted into a C++ pointer value, then the C++ pointer value will point to same address space as the one represented by the explicit pointer class.
- If a variable is declared as a pointer type, but initialized in its declaration to a pointer value with an already-deduced address space, then that variable will have the same address space as its initializer.
- If a function parameter is declared as a pointer type, and the argument is a pointer value with a deduced address space, then the function will be compiled as if the parameter had the same address space as its argument. It is legal for a function to be called in different places with different address spaces for its arguments: in this case the function is said to be “duplicated” and compiled multiple times. Each duplicated instance of the function must compile legally in order to have defined behavior.
- If a function return type is declared as a pointer type and return statements use address space deduced expressions, then the function will be compiled as if the return type had the same address space. To compile legally, all return expressions must deduce to the same address space.
- The rules for pointer types also apply to reference types. i.e. a reference variable takes its address space from its initializer. A function with a reference parameter takes its address space from its argument.
- If no other rule above can be applied to a declaration of a pointer, then it is assumed to be in the private address space.

It is illegal to assign a pointer value addressing one address space to a pointer variable addressing a different address space.

5.10. SYCL offline linking

5.10.1. SYCL functions and member functions linkage

By default, any function that is odr-used from a device function must be defined in the same translation unit as that use. However, this restriction is relaxed if both of the following conditions are met:

- The implementation defines the `SYCL_EXTERNAL` macro;
- The translation unit that calls the function declares the function with `SYCL_EXTERNAL` as described

below.

When a function is declared with SYCL_EXTERNAL, that macro must be used on the first declaration of that function in the translation unit. Redeclarations of the function in the same translation unit may optionally use SYCL_EXTERNAL, but this is not required.

When a function is declared with SYCL_EXTERNAL, that function must also be defined in some translation unit, where the function is declared with SYCL_EXTERNAL.

A function may only be declared with SYCL_EXTERNAL if it has external linkage by normal C++ rules.

A function declared with SYCL_EXTERNAL may be called from both host and device code. The macro has no effect when the function is called from host code.

In order to declare a function with SYCL_EXTERNAL, the macro name SYCL_EXTERNAL must appear before the function declaration. If the function is also decorated with C++ attributes that appear before the declaration, the SYCL_EXTERNAL may appear before, after, or between these attributes. The following example demonstrates the use of SYCL_EXTERNAL.

```
#include <sycl/sycl.hpp>

SYCL_EXTERNAL void Foo();

SYCL_EXTERNAL void Bar() { /* ... */
}

SYCL_EXTERNAL extern void Baz();

[[nodiscard]] SYCL_EXTERNAL void Important();

SYCL_EXTERNAL [[nodiscard]] void AlsoImportant();
```

Functions that are declared using SYCL_EXTERNAL have the following additional restrictions beyond those imposed on other device functions:

- If the SYCL backend does not support the generic address space then the function cannot use raw pointers as parameter or return types. Explicit pointer classes must be used instead;
- The function cannot call group::parallel_for_work_item;
- The function cannot be called from a parallel_for_work_group scope.

Chapter 6. SYCL Extensions

This chapter describes the mechanism by which the core SYCL specification can be extended. Some parts of this chapter are requirements that all implementations must follow if they extend the core SYCL specification, while other parts of the chapter are merely guidelines. Unless a requirement is specifically stated as normative, all content in this chapter is a non-normative guideline.

An extension can be either of two flavors: an extension ratified by the Khronos SYCL group or a vendor supplied extension. In both cases, an extension is an optional feature set which an implementation need not implement in order to be conformant with the core SYCL specification.

Vendors may choose to define extensions in order to expose custom features or to gather feedback on an API that is not yet ready for inclusion in the core SYCL specification. Once a vendor extension has stabilized, the vendor is encouraged to promote it to a future version of the core SYCL specification or to a ratified Khronos extension. Thus, vendor extensions can be viewed as a pipeline of features for consideration in future SYCL versions.

The Khronos SYCL group may define extensions for features that are not yet ready for the core SYCL specification but are implemented by more than one vendor. These extensions also may be considered for inclusion in a future version of the core SYCL specification.

This chapter does not describe any particular extension to SYCL. Rather, it describes the *mechanism* for defining an extension. Each extension is defined by its own separate document. If an extension is ratified by the Khronos SYCL group, that group will release a document describing the extension. If a vendor defines an extension, the vendor is responsible for releasing its documentation.

6.1. Definition of an extension

An extension can take many possible forms. Some examples include:

- adding new types or free functions to the SYCL runtime;
- modifying existing SYCL classes, structs, or enumeration types by adding new members, member functions, or enumerated values;
- adding new overloads for existing free functions or member functions;
- defining new specializations for existing SYCL templates;
- adding new C++ attributes;
- adding new predefined macros;
- adding new keywords to the language;
- adding a new backend.

An extension may also broaden the definition of existing functions defined in the core SYCL specification by defining semantics for cases that are left unspecified by the core SYCL specification.

6.2. Requirements for an extension

This section is normative. All vendors which provide an extension must abide by the requirements described here.

An extension may not change the definition of existing functions defined by the core SYCL specification in a way that changes their specified behavior. Also, an extension may not remove any feature defined by the core SYCL specification.

The vendor must choose at least one `<vendorstring>` which uniquely identifies the vendor's SYCL imple-

mentation. The Khronos SYCL group does not provide any registry of the strings, so each vendor is responsible for choosing its own. One way to choose a unique string is to use the vendor's company name or a marketing name that is associated with the vendor's implementation. Ultimately, it is each vendor's responsibility to choose a string that is unique. The strings "khr" and "KHR" are reserved for the Khronos SYCL group for its own extensions, so vendors may not use these as a `<vendorstring>`.

The implementation must predefine at least one macro of the form `SYCL_IMPLEMENTATION_<vendorstring>` which allows applications to test whether they are being compiled with that vendor's implementation. For example, the Acme vendor could predefine a macro whose name is `SYCL_IMPLEMENTATION_ACME`.

6.3. Guidelines for portable extensions

Vendors who want to ensure that their extension does not collide with other vendors' extensions or with future versions of the core SYCL specification should follow the additional rules specified in this section. However, this is not a requirement for conformance.

6.3.1. Extension namespace

If an extension adds new types or free functions, it should avoid adding these directly in the `sycl::` namespace since future versions of the core SYCL specification may also add new identifiers in this namespace. The namespace `sycl::ext::<vendorstring>` is reserved for use by extensions. For example, the Acme vendor could define extended types and free functions in the namespace `sycl::ext::acme`, and this would guarantee that they will not collide with definitions in other vendors' extensions or with future versions of the core SYCL specification.

6.3.2. Names for extensions to existing classes or enumerations

An extension may add new members or member functions to existing SYCL classes or new values to existing SYCL enumeration types. To ensure these extensions do not collide, vendors are encouraged to name them with the prefix `ext_<vendorstring>_`. For example, the Acme vendor could add a new member function to the `sycl::device` class named `device::ext_acme_fancy()` or a new value to the `sycl::aspect` enumeration named `aspect::ext_acme_fancier`.

In some cases, an extension does not have the freedom to choose a specific function name. For example, this could happen if the extension adds a new constructor overload for an existing SYCL class. In cases like this, the extension should ensure that one of the function parameters has a type that is defined in the extension's namespace. For example, the Acme vendor could add a new constructor for `sycl::context` with the signature `context(ext::acme::frobber&)`.

A similar situation can occur if an existing SYCL template is specialized with an extended enumerated value. Obviously, the extension cannot rename the template in this case. Instead, it is sufficient that the template is specialized with an extended enumerated value, and this guarantees that the extended specialization will not collide.

Vendors are encouraged to use the `ext_<vendorstring>_` prefix form when possible for additions to existing SYCL classes because this form makes the extension's vendor name apparent. People reading application code will immediately know that a member function is an extension, and they will immediately know which vendor's documentation to consult.

6.3.3. Feature test macros

Vendors are encouraged to group a related set of extensions together into a "feature" and to predefine a feature-test macro when the implementation supports the extensions in that feature. The feature-test macro should have the following form to ensure it is unique: `SYCL_EXT_<vendorstring>_<featurename>`. For

example, the Acme vendor might define a feature-test macro named SYCL_EXT_ACME_FANCYFEATURE. This allows applications to protect code using the extension with #ifdef, so that the code is skipped when compiled with an implementation that doesn't support the feature.

Since the interface to an extension might change from one release to another, vendors are also encouraged to predefine the macro's value to the version of the extension. Vendors should use a numerical value that monotonically increases for each revision of the extension API.

Of course, an extension may also predefine other macros. In order to ensure that these macro names do not collide with other extensions or future versions of the core SYCL specification, the name should start with the prefix SYCL_EXT_<vendorstring> or SYCL_IMPLEMENTATION_<vendorstring>.

6.3.4. Attribute namespace

An extension may define new C++ attributes. The attribute namespace sycl:: is reserved for the core SYCL specification, so vendors should choose a different namespace for any attributes they add.

6.3.5. Include file paths

An extension may define new #include files under the "sycl" path. The path prefix "sycl/ext/<vendorstring>" is reserved for this purpose. For example, the Acme vendor could add a header file "sycl/ext/acme/fancy.h" and be guaranteed that it would not conflict with other extensions or with future versions of the core SYCL specification.

6.3.6. Optional kernel features

An extension may also add new optional kernel features — features which are supported on some devices but not on others. Vendors are encouraged to follow the same mechanism outlined in Section 5.7. Therefore, an extended optional kernel feature should have a matching extension to the sycl::aspect enumerated type.

6.3.7. Adding a backend

An extension may also add a new backend. If it does, the naming of the backend APIs follows the normal guidelines for extensions and also follows the naming pattern for backends that are defined in the core SYCL specification. To illustrate:

- The extension should add a new value to the sycl::backend enumeration type using a naming scheme like ext_<vendorstring>_<backendname>. For example, if the Acme vendor adds a backend named "foo", it would add an enumerated value named sycl::backend::ext_acme_foo.
- The extension should define the backend's interop API in a namespace named sycl::ext::<vendorstring>::<backendname>. For our hypothetical Acme example, this would be a namespace named sycl::ext::acme::foo.
- If the backend interop API is available through a separate header file, that header should be named "sycl/ext/<vendorstring>/backend/<backendname>.hpp". For our hypothetical Acme example this would be "sycl/ext/acme/backend/foo.hpp".
- The extension should predefine a macro for the backend when it is "active". The name of this macro should be SYCL_EXT_<vendorstring>_BACKEND_<backendname>. For our hypothetical Acme example this would be SYCL_EXT_ACME_BACKEND_FOO.

Appendix A: Information descriptors

This appendix contains the definitions of all the SYCL information descriptors introduced in Chapter 4.

A.1. Platform information descriptors

The following interface includes all the information descriptors for the `platform` class as described in Table 18.

```
namespace sycl {
namespace info {
namespace platform {

struct profile;
struct version;
struct name;
struct vendor;
struct extensions; // Deprecated

} // namespace platform
} // namespace info
} // namespace sycl
```

A.2. Context information descriptors

The following interface includes all the information descriptors for the `context` class as described in Table 21.

```
namespace sycl {
namespace info {
namespace context {

struct platform;
struct devices;
struct atomic_memory_order_capabilities;
struct atomic_fence_order_capabilities;
struct atomic_memory_scope_capabilities;
struct atomic_fence_scope_capabilities;

} // namespace context
} // namespace info
} // namespace sycl
```

A.3. Device information descriptors

The following interface includes all the information descriptors for the `device` class as described in Table 25.

```
namespace sycl {
namespace info {
namespace device {
```

```
 4
 5 struct device_type;
 6 struct vendor_id;
 7 struct max_compute_units;
 8 struct max_work_item_dimensions;
 9 template <int Dimensions = 3> struct max_work_item_sizes;
10 struct max_work_group_size;
11 struct preferred_vector_width_char;
12 struct preferred_vector_width_short;
13 struct preferred_vector_width_int;
14 struct preferred_vector_width_long;
15 struct preferred_vector_width_float;
16 struct preferred_vector_width_double;
17 struct preferred_vector_width_half;
18 struct native_vector_width_char;
19 struct native_vector_width_short;
20 struct native_vector_width_int;
21 struct native_vector_width_long;
22 struct native_vector_width_float;
23 struct native_vector_width_double;
24 struct native_vector_width_half;
25 struct max_clock_frequency;
26 struct address_bits;
27 struct max_mem_alloc_size;
28 struct image_support; // Deprecated
29 struct max_read_image_args;
30 struct max_write_image_args;
31 struct image2d_max_height;
32 struct image2d_max_width;
33 struct image3d_max_height;
34 struct image3d_max_width;
35 struct image3d_max_depth;
36 struct image_max_buffer_size;
37 struct max_samplers;
38 struct max_parameter_size;
39 struct mem_base_addr_align;
40 struct half_fp_config;
41 struct single_fp_config;
42 struct double_fp_config;
43 struct global_mem_cache_type;
44 struct global_mem_cache_line_size;
45 struct global_mem_cache_size;
46 struct global_mem_size;
47 struct max_constant_buffer_size; // Deprecated
48 struct max_constant_args;        // Deprecated
49 struct local_mem_type;
50 struct local_mem_size;
51 struct error_correction_support;
52 struct host_unified_memory;
53 struct atomic_memory_order_capabilities;
54 struct atomic_fence_order_capabilities;
55 struct atomic_memory_scope_capabilities;
56 struct atomic_fence_scope_capabilities;
57 struct profiling_timer_resolution;
58 struct is_endian_little;
59 struct is_available;
```

```
struct is_compiler_available; // Deprecated
struct is_linker_available;   // Deprecated
struct execution_capabilities;
struct queue_profiling;  // Deprecated
struct built_in_kernels; // Deprecated
struct built_in_kernel_ids;
struct platform;
struct name;
struct vendor;
struct driver_version;
struct profile;
struct version;
struct backend_version;
struct aspects;
struct extensions; // Deprecated
struct printf_buffer_size;
struct preferred_interop_user_sync;
struct parent_device;
struct partition_max_sub_devices;
struct partition_properties;
struct partition_affinity_domains;
struct partition_type_property;
struct partition_type_affinity_domain;

} // namespace device

enum class device_type : /* unspecified */ {
  cpu,         // Maps to OpenCL CL_DEVICE_TYPE_CPU
  gpu,         // Maps to OpenCL CL_DEVICE_TYPE_GPU
  accelerator, // Maps to OpenCL CL_DEVICE_TYPE_ACCELERATOR
  custom,      // Maps to OpenCL CL_DEVICE_TYPE_CUSTOM
  automatic,   // Maps to OpenCL CL_DEVICE_TYPE_DEFAULT
  host,
  all // Maps to OpenCL CL_DEVICE_TYPE_ALL
};

enum class partition_property : /* unspecified */ {
  no_partition,
  partition_equally,
  partition_by_counts,
  partition_by_affinity_domain
};

enum class partition_affinity_domain : /* unspecified */ {
  not_applicable,
  numa,
  L4_cache,
  L3_cache,
  L2_cache,
  L1_cache,
  next_partitionable
};

enum class local_mem_type : /* unspecified */ { none, local, global };

enum class fp_config : /* unspecified */ {
```

```
  denorm,
  inf_nan,
  round_to_nearest,
  round_to_zero,
  round_to_inf,
  fma,
  correctly_rounded_divide_sqrt,
  soft_float
};

enum class global_mem_cache_type : /* unspecified */ {
  none,
  read_only,
  read_write
};

enum class execution_capability : /* unspecified */ {
  exec_kernel,
  exec_native_kernel
};

} // namespace info
} // namespace sycl
```

A.4. Queue information descriptors

The following interface includes all the information descriptors for the `queue` class as described in Table 30.

```
namespace sycl {
namespace info {
namespace queue {

struct context;
struct device;

} // namespace queue
} // namespace info
} // namespace sycl
```

A.5. Kernel information descriptors

The following interface includes all the information descriptors that apply to kernels as described in Table 137.

```
namespace sycl {
namespace info {
namespace kernel {

struct num_args;
struct attributes;

} // namespace kernel
```

```
 9
10 namespace kernel_device_specific {
11
12 struct global_work_size;
13 struct work_group_size;
14 struct compile_work_group_size;
15 struct preferred_work_group_size_multiple;
16 struct private_mem_size;
17 struct max_num_sub_groups;
18 struct compile_num_sub_groups;
19 struct max_sub_group_size;
20 struct compile_sub_group_size;
21
22 } // namespace kernel_device_specific
23
24 } // namespace info
25 } // namespace sycl
```

A.6. Event information descriptors

The following interface includes all the information descriptors for the `event` class as described in Table 35 and Table 37.

```
 1 namespace sycl {
 2 namespace info {
 3 namespace event {
 4
 5 struct command_execution_status;
 6
 7 } // namespace event
 8
 9 enum class event_command_status : /* unspecified */ {
10   submitted,
11   running,
12   complete
13 };
14
15 namespace event_profiling {
16
17 struct command_submit;
18 struct command_start;
19 struct command_end;
20
21 } // namespace event_profiling
22 } // namespace info
23 } // namespace sycl
```

Appendix B: Feature sets

As of SYCL 2020 there are now two distinct feature sets which a SYCL implementation can conform to, in order to better fit the requirements of different domains, such as embedded, mobile, and safety critical, which may have limitations because of the toolchains used.

A SYCL implementation can choose to conform to either the full feature set or the reduced feature set.

B.1. Full feature set

The full feature set includes all features specified in the core SYCL specification with no exceptions.

B.2. Reduced feature set

The reduced feature set makes certain features optional or restricted to specific forms. The following list defines all the differences between the reduced feature set and the full feature set.

1. **Un-named SYCL kernel functions:** SYCL kernel functions which are defined using a lambda expression and therefore have no standard name are required to be provided a name via the kernel name template parameter of kernel invocation functions such as `parallel_for`. This overrides the core SYCL specification rules for SYCL kernel function naming as specified in Section 4.9.4.2.
2. **Address space mode:** The address space assignment mode used in the reduced feature set is not required to be generic address space, regardless of SYCL backend in use. Instead the inferred address space mode may always be used.
3. **Declarations:** In addition to the requirements specified in Section 5.9.2, the reduced feature set does not require support for odr-use inside device functions of variables declared `const` or `constexpr` with static storage duration.

B.3. Compatibility

In order to avoid introducing any kind of divergence the reduced and full feature sets are defined such that the full feature set is a subsumption of the reduced feature set. This means that any applications which are developed for the reduced feature set will be compatible with both a SYCL reduced implementation and a SYCL full implementation.

B.4. Conformance

One of the reasons for having this be defined in the specification is that hardware vendors which wish to support SYCL on their platform(s) want to be able to demonstrate their support for it by passing conformance. However, if passing conformance means adopting features which they do not believe to be necessary at an additional development effort then this may deter them.

Each feature set has its own route for passing conformance allowing adopters of SYCL to specify the feature set they wish to test conformance against. The conformance test suite would then alter or disable the tests within the test suite according to how the feature sets are differentiated above.

Appendix C: OpenCL backend specification

This chapter describes how the SYCL general programming model is mapped on top of OpenCL, and how the SYCL generic interoperability interface must be implemented by vendors providing SYCL for OpenCL implementations to ensure SYCL applications written for the OpenCL backend are interoperable.

C.1. SYCL application interoperability native backend objects

For each SYCL runtime class which supports SYCL application interoperability, specializations of `backend_traits::input_type` and `backend_traits::return_type` must be defined as the type of SYCL application interoperability native backend object associated with `SyclType` for the SYCL backend.

The types of the native backend objects for SYCL application interoperability are described in Table 191.

C.2. Kernel function interoperability native backend objects

For each SYCL runtime class which supports kernel function interoperability, a specialization of `backend_traits::return_type` must be defined as the type of kernel function interoperability native backend object associated with `SyclType` for the SYCL backend.

The types of the native backend objects for kernel function interoperability are described in Table 187.

Table 187. Types of native backend objects kernel function interoperability

SyclType	backend_return_t<backend::opencl, SyclType>
accessor<T, Dims, Mode, target::device>	__global T*
accessor<T, Dims, Mode, target::constant_buffer>	__constant T*
accessor<T, Dims, Mode, target::local>	__local T*
local_accessor<T, Dims>	__local T*
sampled_image_accessor<T, 1, Mode, image_target::device>	sampler_1dimage_pair_t
sampled_image_accessor<T, 2, Mode, image_target::device>	sampler_2dimage_pair_t
sampled_image_accessor<T, 3, Mode, image_target::device>	sampler_3dimage_pair_t
unsampled_image_accessor<T, 1, Mode, image_target::device>	image1d_t
unsampled_image_accessor<T, 2, Mode, image_target::device>	image2d_t
unsampled_image_accessor<T, 3, Mode, image_target::device>	image3d_t
stream	__global cl_char*
device_event	event_t

The `sampler_1dimage_pair_t`, `sampler_1dimage_pair_t` and `sampler_1dimage_pair_t` types must be implemented as described below.

```
1 struct sampler_1dimage_pair_t {
2   sampler_t sampler;
3   image1d_t image;
4 }
5
6 struct sampler_2dimage_pair_t {
7   sampler_t sampler;
```

```
 8   image2d_t image;
 9 }
10
11 struct sampler_3dimage_pair_t {
12   sampler_t sampler;
13   image3d_t image;
14 }
```

C.3. Destruction of interop constructed objects with reference semantics

On destruction of the last copy of an instance of a SYCL class which is specified to have reference semantics as described in Section 4.5.2 that was constructed using one of the SYCL backend interoperability `make_*` functions specified in Section 4.5.1.3 additional lifetime related operations may be performed which are required for the underlying native backend object.

The additional behavior performed by the OpenCL SYCL backend for each SYCL class is described in Table 188.

Table 188. Destructor behavior of interop constructed objects with reference semantics

SYCL object	Destructor behavior
accessor	No additional behavior is performed.
buffer	`clReleaseMemObject` will be called on the native `cl_mem` object provided during construction.
context	`clReleaseContext` will be called on the native `cl_context` object provided during construction.
device	`clReleaseDevice` will be called on the native `cl_device` object provided during construction.
event	`clReleaseEvent` will be called on the native `cl_event` object provided during construction.
kernel	`clReleaseKernel` will be called on the native `cl_kernel` objects provided during construction.
kernel_bundle	`clReleaseProgram` will be called on the native `cl_program` objects provided during construction.
platform	No additional behavior is performed.
queue	`clReleaseCommandQueue` will be called on the native `cl_command_queue` object provided during construction.
sampled_image	`clReleaseMemObject` will be called on the native `cl_mem` object provided during construction.
unsampled_image	`clReleaseMemObject` will be called on the native `cl_mem` object provided during construction.

C.4. SYCL for OpenCL framework

The SYCL framework allows applications to use a host and one or more OpenCL devices as a single heterogeneous parallel computer system. The framework contains the following components:

- SYCL C++ template library: The template library provides a set of C++ templates and classes which

provide the programming model to the user. It enables the creation of runtime classes such as SYCL queues, buffers and images, as well as access to some underlying OpenCL runtime object, such as contexts, platforms, devices and program objects.

- SYCL runtime: The SYCL runtime interfaces with the underlying OpenCL implementations and handles scheduling of commands in queues, moving of data between host and devices, manages contexts, programs, kernel compilation and memory management.
- OpenCL Implementation(s): The SYCL system assumes the existence of one or more OpenCL implementations available on the host machine.
- SYCL device compilers: The SYCL device compilers compile SYCL C++ kernels into a format which can be executed on an OpenCL device at runtime. There may be more than one SYCL device compiler in a SYCL implementation. The format of the compiled SYCL kernels is not defined. A SYCL device compiler may, or may not, also compile the host parts of the program.

The OpenCL backend is enabled using the `sycl::backend::opencl` value of `enum class backend`. That means that when the OpenCL backend is active, the value of `sycl::is_backend_active<sycl::backend::opencl>::value` will be `true`.

C.5. Mapping of SYCL programming model on top of OpenCL

The SYCL programming model was originally designed as a high-level model for the OpenCL API, hence the mapping of SYCL on the OpenCL API is mostly straightforward.

When the OpenCL backend is active on a SYCL application, all visible OpenCL platforms are exported as SYCL platforms.

When a SYCL implementation executes kernels on an OpenCL device, it achieves this by enqueuing OpenCL **commands** to execute computations on the processing elements within a device. The processing elements within an OpenCL compute unit may execute a single stream of instructions as ALUs within a SIMD unit (which execute in lockstep with a single stream of instructions), as independent SPMD units (where each PE maintains its own program counter) or as some combination of the two.

C.5.1. Backend specific information descriptors

Some of the SYCL information descriptors are backend-defined. For the OpenCL backend these information descriptors map directly to OpenCL properties as described in the table below:

Table 189. Mapping of SYCL information descriptors to OpenCL properties

SYCL	OpenCL
`info::platform::version`	`CL_PLATFORM_VERSION`
`info::device::version`	`CL_DEVICE_VERSION`

C.5.2. OpenCL memory model

The memory model for SYCL devices running on OpenCL platforms follows the memory model of the OpenCL version they conform to.

In addition to global memory , local memory and private memory memory, the OpenCL backend permits the use of constant memory space in SYCL:

- Constant-memory is a region of memory that remains constant during the execution of a kernel. A

pointer to the generic address space cannot represent an address to this memory region.

Work-items executing in a kernel have access to four distinct memory regions, with the mapping between SYCL and OpenCL described in Table 190.

Table 190. Mapping of SYCL memory regions into OpenCL memory regions

SYCL	OpenCL
Global	Global memory
Constant	Constant memory
Local	Local memory
Private	Private memory

C.5.3. OpenCL interface for buffer command accessors

The enumerator `target::constant_buffer` is deprecated, but will remain a part of the OpenCL backend as an extension. This enables SYCL kernel functions to access the contents of a buffer through the OpenCL device's constant memory.

C.5.4. OpenCL resources managed by SYCL application

In OpenCL, a developer must create a context to be able to execute commands on a device. Creating a context involves choosing a platform and a list of devices. In SYCL, contexts, platforms and devices all exist, but the user can choose whether to specify them or have the SYCL implementation create them automatically. The minimum required object for submitting work to devices in SYCL is the queue, which contains references to a platform, device and context internally.

The resources managed by SYCL are:

1. Platforms: all features of OpenCL are implemented by platforms. A platform can be viewed as a given hardware vendor's runtime and the devices accessible through it. Some devices will only be accessible to one vendor's runtime and hence multiple platforms may be present. SYCL manages the different platforms for the user. In SYCL, a platform resource is accessible through a `sycl::platform` object.
2. Contexts: any OpenCL resource that is acquired by the user is attached to a context. A context contains a collection of devices that the host can use and manages memory objects that can be shared between the devices. Data movement between devices within a context may be efficient and hidden by the underlying OpenCL runtime while data movement between contexts may involve the host. A given context can only wrap devices owned by a single platform. In SYCL, a context resource is accessible through a `sycl::context` object.
3. Devices: platforms provide one or more devices for executing kernels. In SYCL, a device is accessible through a `sycl::device` object.
4. Kernel bundles: OpenCL objects that store implementation data for the SYCL kernels. These objects are only required for advanced use in SYCL and are encapsulated in the `sycl::kernel_bundle` class.
5. Queues: SYCL kernels execute in command queues. The user must create a queue, which references an associated context, platform and device. The context, platform and device may be chosen automatically, or specified by the user. In SYCL, command queues are accessible through `sycl::queue` objects.

C.6. Interoperability with the OpenCL API

The OpenCL backend for SYCL ensures maximum compatibility between SYCL and OpenCL kernels and API. This includes supporting devices with different capabilities and support for different versions of the OpenCL C language, in addition to supporting SYCL kernels written in C++.

SYCL runtime classes which encapsulate an OpenCL opaque type such as SYCL `context` or SYCL `queue` must provide an interoperability constructor taking an instance of the OpenCL opaque type. When the OpenCL object supports reference counting, these constructors must retain that instance to increase the reference count of the OpenCL resource. Likewise, the destructor for the SYCL runtime classes which encapsulate a reference counted OpenCL opaque type must release that instance to decrease the reference count of the OpenCL resource. Since the OpenCL `platform_id` is not reference counted, the encapsulating SYCL `platform` class neither retains nor releases this OpenCL resource.

Note that an instance of a SYCL runtime class which encapsulates an OpenCL opaque type can encapsulate any number of instances of the OpenCL type, unless it was constructed via the interoperability constructor, in which case it can encapsulate only a single instance of the OpenCL type.

The lifetime of a SYCL runtime class that encapsulates an OpenCL opaque type and the instance of that opaque type retrieved via the `get_native()` free function are not tied in either direction given correct usage of OpenCL reference counting. For example if a user were to retrieve a `cl_command_queue` instance from a SYCL `queue` instance and then immediately destroy the SYCL `queue` instance, the `cl_command_queue` instance is still valid. Or if a user were to construct a SYCL `queue` instance from a `cl_command_queue` instance and then immediately release the `cl_command_queue` instance, the SYCL `queue` instance is still valid.

Note that a SYCL runtime class that encapsulates an OpenCL opaque type is not responsible for any incorrect use of OpenCL reference counting outside of the SYCL runtime. For example if a user were to retrieve a `cl_command_queue` instance from a SYCL `queue` instance and then release the `cl_command_queue` instance more than once without any prior retain then the SYCL `queue` instance that the `cl_command_queue` instance was retrieved from is now undefined.

Note that an instance of the SYCL `buffer` or SYCL `image` class templates constructed via the interoperability constructor is free to copy from the `cl_mem` into another memory allocation within the SYCL runtime to achieve normal SYCL semantics, for as long as the SYCL `buffer` or SYCL `image` instance is alive.

Table 191 relates SYCL objects to their OpenCL native type in the SYCL application.

Table 191. List of native types per SYCL object in the OpenCL backend

SyclType	backend_input_t<backend::opencl, SyclType>	backend_return_t<backend::opencl, SyclType>	**Description**
`platform`	`cl_platform_id`	`cl_platform_id`	A SYCL platform object encapsulates an OpenCL platform ID.
`device`	`cl_device_id`	`cl_device_id`	A SYCL device object encapsulates an OpenCL device ID.
`context`	`cl_context`	`cl_context`	A SYCL context object encapsulates an OpenCL context object.
`queue`	`cl_command_queue`	`cl_command_queue`	A SYCL queue object encapsulates an OpenCL queue object.
`kernel`	`cl_kernel`	`cl_kernel`	A SYCL kernel object encapsulates an OpenCL kernel object.

SyclType	backend_input_t<backend::opencl, SyclType>	backend_return_t<backend::opencl, SyclType>	Description
template <bundle_state State> kernel_bundle<State>	cl_program	std::vector<cl_program>	A SYCL kernel bundle can encapsulate one or more OpenCL program objects. It can also encapsulate one or more OpenCL kernel objects which can be retrieved using the appropriate kernel object.
event	std::vector<cl_event>	std::vector<cl_event>	A SYCL event can encapsulate one or multiple OpenCL events, representing a number of dependencies in the same or different contexts, that must be satisfied for the SYCL event to be complete.
buffer	cl_mem	std::vector<cl_mem>	SYCL buffers containing OpenCL memory objects can handle multiple cl_mem objects in the same or different context. The interoperability interface will return a list of active buffers in the SYCL runtime.
sampled_image	cl_mem	std::vector<cl_mem>	SYCL sampled images containing OpenCL image objects can handle multiple underlying cl_mem objects at the same time in the same or different OpenCL contexts. The interoperability interface will return a list of active images in the SYCL runtime.
unsampled_image	cl_mem	std::vector<cl_mem>	SYCL unsampled images containing OpenCL image objects can handle multiple underlying cl_mem objects at the same time in the same or different OpenCL contexts. The interoperability interface will return a list of active images in the SYCL runtime.

Inside the SYCL kernel, the SYCL API offers interoperability with OpenCL device types. Table 192 describes the mapping of kernel types.

Table 192. List of native types per SYCL object on kernel code

SYCL kernel native types in OpenCL	Description
multi_ptr::get_decorated()	Returns a pointer in the OpenCL address space corresponding to the type of multi pointer object

When a buffer or image is allocated on more than one OpenCL device, if these devices are on separate contexts then multiple cl_mem objects may be allocated for the memory object, depending on whether the object has actively been used on these devices yet or not.

The OpenCL C function qualifier __kernel and the access qualifiers: __read_only, __write_only and __read_write are not exposed in SYCL via keywords, but are instead encapsulated in SYCL's parameter passing system inside accessors. Users wishing to achieve the OpenCL equivalent of these qualifiers in SYCL should instead use SYCL accessors with equivalent semantics.

Any OpenCL C function included in a pre-built OpenCL library can be defined as an extern "C" function and the OpenCL program has to be linked against any SYCL program that contains kernels using the external function. In this case, the data types used have to comply with the interoperability aliases defined in Table 194.

C.7. Programming interface

The following section describes the OpenCL-specific API.

C.7.1. Construct SYCL objects from OpenCL ones

The OpenCL backend provides the following specializations of the `make_{sycl_class}` template functions which are defined in Section 4.5.1.3. These functions are in the `sycl` namespace.

OpenCL interoperability function	Description
`context make_context(const cl_context& clContext, const async_handler& asyncHandler = {})`	Constructs a SYCL `context` instance from an OpenCL `cl_context` in accordance with the requirements described in Section 4.5.1.
`event make_event(const std::vector<cl_event>& clEvents, const context& syclContext)`	Constructs a SYCL `event` instance from a vector of OpenCL `cl_event` objects in accordance with the requirements described in Section 4.5.1.
`device make_device(const cl_device_id& clDeviceId)`	Constructs a SYCL `device` instance from an OpenCL `cl_device_id` in accordance with the requirements described in Section 4.5.1.
`platform make_platform(const cl_platform_id& clPlatformId)`	Constructs a SYCL `platform` instance from an OpenCL `cl_platform_id` in accordance with the requirements described in Section 4.5.1.
`queue make_queue(const cl_command_queue& clQueue, const context& syclContext, const async_handler& asyncHandler = {})`	Constructs a SYCL `queue` instance with an optional `async_handler` from an OpenCL `cl_command_queue` in accordance with the requirements described in Section 4.5.1.
`template <typename T, int Dimensions = 1, typename AllocatorT = buffer_allocator<std::remove_const_t<T>>> buffer<T, Dimensions, AllocatorT> make_buffer(const cl_mem& clMemObject, const context& syclContext, event availableEvent)`	Available only when: `Dimensions == 1`. Constructs a SYCL `buffer` instance from an OpenCL `cl_mem` in accordance with the requirements described in Section 4.5.1. The instance of the SYCL `buffer` class template being constructed must wait for the SYCL `event` parameter, `availableEvent` to signal that the `cl_mem` instance is ready to be used. The SYCL `context` parameter `syclContext` is the context associated with the memory object.

OpenCL interoperability function	Description
`template <typename T, int Dimensions = 1, typename AllocatorT = buffer_allocator<std::remove_const_t<T>>> buffer<T, Dimensions, AllocatorT> make_buffer(const cl_mem& clMemObject, const context& syclContext)`	Available only when: `Dimensions == 1`. Constructs a SYCL `buffer` instance from an OpenCL `cl_mem` in accordance with the requirements described in Section 4.5.1.
`template <int Dimensions = 1, typename AllocatorT = image_allocator> sampled_image<Dimensions, AllocatorT> make_sampled_image(const cl_mem& clMemObject, const context& syclContext, image_sampler syclImageSampler, event availableEvent)`	Constructs a SYCL `sampled_image` instance from an OpenCL `cl_mem` in accordance with the requirements described in Section 4.5.1. The instance of the SYCL `image` class template being constructed must wait for the SYCL `event` parameter, `availableEvent` to signal that the `cl_mem` instance is ready to be used. The SYCL `context` parameter `syclContext` is the context associated with the memory object.
`template <int Dimensions = 1, typename AllocatorT = image_allocator> sampled_image<Dimensions, AllocatorT> make_sampled_image(const cl_mem& clMemObject, const context& syclContext, image_sampler syclImageSampler)`	Constructs a SYCL `sampled_image` instance from an OpenCL `cl_mem` in accordance with the requirements described in Section 4.5.1. The SYCL `context` parameter `syclContext` is the context associated with the memory object.
`template <int Dimensions = 1, typename AllocatorT = image_allocator> unsampled_image<Dimensions, AllocatorT> make_unsampled_image(const cl_mem& clMemObject, const context& syclContext, event availableEvent)`	Constructs a SYCL `unsampled_image` instance from an OpenCL `cl_mem` in accordance with the requirements described in Section 4.5.1. The instance of the SYCL `image` class template being constructed must wait for the SYCL `event` parameter, `availableEvent` to signal that the `cl_mem` instance is ready to be used. The SYCL `context` parameter `syclContext` is the context associated with the memory object.

OpenCL interoperability function	Description
`template <int Dimensions = 1, typename AllocatorT = image_allocator> unsampled_image<Dimensions, AllocatorT> make_unsampled_image(const cl_mem& clMemObject, const context& syclContext)`	Constructs a SYCL `unsampled_image` instance from an OpenCL `cl_mem` in accordance with the requirements described in Section 4.5.1.
`kernel make_kernel(const cl_kernel& clKernel, const context& syclContext);`	Constructs a SYCL `kernel` instance from an OpenCL kernel object.
`template <bundle_state State> kernel_bundle<State> make_kernel_bundle(const cl_program& clProgram, const context& syclContext)`	Constructs a SYCL `kernel_bundle` instance from an OpenCL `cl_program` for the devices in `syclContext` in accordance with the requirements described in Section 4.5.1. The SYCL `context` must represent the same underlying OpenCL context associated with the OpenCL program object. The `state` specifies the expected `kernel_bundle` state. The mapping between the `kernel_bundle` state and OpenCL program state (`CL_PROGRAM_BINARY_TYPE`) is as follows: • `bundle_state::input` - `CL_PROGRAM_BINARY_TYPE_NONE` • `bundle_state::object` - `CL_PROGRAM_BINARY_TYPE_COMPILED_OBJECT` or `CL_PROGRAM_BINARY_TYPE_INTERMEDIATE` or `CL_PROGRAM_BINARY_TYPE_LIBRARY`. • `bundle_state::executable` - `CL_PROGRAM_BINARY_TYPE_EXECUTABLE` If the internal state of the OpenCL program doesn't match `state`, the kernel bundle will be compiled and linked as necessary. If the OpenCL program is already an executable binary, but the specified `state` is not `bundle_state::executable`, an `exception` with the `errc::invalid` error code is thrown. If the specified `state` is `bundle_state::input`, but the OpenCL program already has a binary associated with it, an `exception` with the `errc::invalid` error code is thrown. Throws an `exception` with the `errc::invalid` error code if any error is produced by the SYCL backend.

C.7.2. Extension query

Platforms and devices with an OpenCL backend may support extensions. For convenience, the extensions supported by a platform or device can be queried through the following functions provided in the `sycl::opencl` namespace.

Extension query	Description
`bool has_extension(const sycl::platform& syclPlatform, const std::string& extension)`	Returns true if the OpenCL platform associated with `syclPlatform` supports the extension identified by `extension`, otherwise it returns false. If `syclPlatform.get_backend() != sycl::backend::opencl` an `exception` with the `errc::backend_mismatch` error code is thrown.
`bool has_extension(const sycl::device& syclDevice, const std::string& extension)`	Returns true if the OpenCL device associated with `syclDevice` supports the extension identified by `extension`, otherwise it returns false. If `syclDevice.get_backend() != sycl::backend::opencl` an `exception` with the `errc::backend_mismatch` error code is thrown.

C.7.3. Reference counting

Most OpenCL objects are reference counted. The SYCL general programming model doesn't require that native objects are reference counted. However, for convenience, the following function is provided in the `sycl::opencl` namespace.

Reference counting	Description
`template <typename openCLT> cl_uint get_reference_count (openCLT obj)`	Returns the reference count of the given object

C.7.4. Errors and limitations

If there is an OpenCL error associated with an exception triggered, then the OpenCL error code can be obtained by the free function `cl_int sycl::opencl::get_error_code(sycl::exception&)`. In the case where there is no OpenCL error associated with the exception triggered, the OpenCL error code will be `CL_SUCCESS`.

C.7.5. Interoperability with kernel bundles

In OpenCL any kernel function that is enqueued over an nd-range is represented by a `cl_kernel` and must be compiled and linked via a `cl_program` using `clBuildProgram`, `clCompileProgram` and `clLinkProgram`.

For OpenCL SYCL backend this detail is abstracted away by kernel bundles and a `kernel_bundle` object containing all SYCL kernel functions is retrieved by calling the free function `get_kernel_bundle`.

The OpenCL SYCL backend specification provides additional free functions which provide convenience functions for constructing kernel bundles from OpenCL specific objects.

```
namespace sycl::opencl {

template <bundle_state State>
kernel_bundle<State> create_bundle(const context& ctxt,
                                   const std::vector<device>& devs,
                                   const std::vector<cl_program>& clPrograms);

kernel_bundle<bundle_state::executable>
create_bundle(const context& ctxt, const std::vector<device>& devs,
              const std::vector<cl_kernel>& clKernels);
```

```
11
12 } // namespace sycl::opencl
```

```
1 template <bundle_state State>
2 kernel_bundle<State> create_bundle(const context& ctxt,
3                                    const std::vector<device>& devs,
4                                    const std::vector<cl_program>& clPrograms)
```

1. *Preconditions:* The context specified by `ctxt` must be associated with the OpenCL SYCL backend. All devices in `devs` must be associated with `ctxt`. All OpenCL programs in `clPrograms` must be associated with `ctxt`.

   Effects: Constructs a kernel bundle in the specified `bundle_state` from the provided list of OpenCL programs and associated with the context specified by `syclContext` by invoking the necessary OpenCL APIs. Follows the same rules as calling `make_kernel_bundle` on a single OpenCL program, except that the rules apply to all OpenCL programs in `clPrograms`. Multiple programs will be linked together into a single one if required by the requested `State`. The constructed `kernel_bundle` will retain all provided OpenCL programs and will also release them on destruction.

   Throws: An `exception` with the `errc::build` error code if any error is produced by invoking the OpenCL APIs.

```
1 kernel_bundle<bundle_state::executable>
2 create_bundle(const context& ctxt, const std::vector<device>& devs,
3               const std::vector<cl_kernel>& clKernels)
```

1. *Preconditions:* The context specified by `ctxt` must be associated with the OpenCL SYCL backend. All devices in `devs` must be associated with `ctxt`. All OpenCL kernels in `clKernels` must be associated with `ctxt`.

   Effects: Constructs an executable kernel bundle from the provided list of OpenCL kernels and associated with the context specified by `syclContext` by invoking the necessary OpenCL APIs. `cl_kernel` objects might be associated with different `cl_program` objects, the kernel bundle will encapsulate all of them.

   Throws: An `exception` with the `errc::build` error code if any error is produced by invoking the OpenCL APIs.

C.7.6. Interoperability with kernels

A `kernel_bundle` object contains one or multiple OpenCL programs and one or multiple OpenCL kernels. Calling `kernel_bundle::get_kernel` returns a `kernel` object which can be invoked by any of kernel invocation commands such as `parallel_for` which take a `kernel` but not SYCL kernel function.

Calling `make_kernel` must trigger a call to `clRetainKernel` and the resulting `kernel` object must call `clReleaseKernel` on destruction.

It is also possible to construct a kernel bundle from previously created OpenCL `cl_kernel` objects by calling the free function `create_bundle` as described in Section C.7.5.

The kernel arguments for the OpenCL C kernel kernel can either be set prior to creating the `kernel` object or by calling `set_arg` or `set_args` member functions of the `handler` class.

If kernel arguments are set prior to creating the `kernel` object the SYCL runtime is not responsible for managing the data of these arguments.

C.7.7. OpenCL kernel conventions and SYCL

OpenCL and SYCL use opposite conventions for the unit stride dimension. SYCL aligns with C++ conventions, which is important to understand from a performance perspective when porting code to SYCL. The unit stride dimension, at least for data, is implicit in the linearization equations in SYCL (Section 3.11.1) and OpenCL. SYCL aligns with C++ array subscript ordering `arr[a][b][c]`, in that range constructor dimension ordering used to launch a kernel (e.g. `range<3> R{a,b,c}`) and range and ID queries within a kernel, are ordered in the same way as the C++ multi-dimensional subscript operators (unit stride on the right).

When specifying a `range` as the global or local size in a `parallel_for` that invokes an OpenCL interop kernel (through `cl_kernel` interop), the highest dimension of the range in SYCL will map to the lowest dimension within the OpenCL kernel. That statement applies to both an underlying enqueue operation such as `clEnqueueNDRangeKernel` in OpenCL, and also ID and size queries within the OpenCL kernel. For example, a 3D global range specified in SYCL as:

```
range<3> R { r0, r1, r2 };
```

maps to an `clEnqueueNDRangeKernel global_work_size` argument of:

```
size_t cl_interop_range[3] = { r2, r1, r0 };
```

Likewise, a 2D global range specified in SYCL as:

```
range<2> R { r0, r1 };
```

maps to an `clEnqueueNDRangeKernel global_work_size` argument of:

```
size_t cl_interop_range[2] = { r1, r0 };
```

The mapping of highest dimension in SYCL to lowest dimension in OpenCL applies to all operations where a multi-dimensional construct must be mapped, such as when mapping SYCL explicit memory operations to OpenCL APIs like `clEnqueueCopyBufferRect`.

Work-item and work-group ID and range queries have the same reversed convention for unit stride dimension between SYCL and OpenCL. For example, with three, two, or one dimensional SYCL global ranges, OpenCL and SYCL kernel code queries relate to the range as shown in Table 193. The "SYCL kernel query" column applies for SYCL-defined kernels, and the "OpenCL kernel query" column applies for kernels defined through OpenCL interop.

Table 193. Example range mapping from SYCL enqueued three dimensional global `range` to OpenCL and SYCL queries

SYCL kernel query	OpenCL kernel query	Returned Value
With enqueued 3D SYCL global `range` of `range<3> R{r0,r1,r2}`		
nd_item::get_global_range(0) / item::get_range(0)	get_global_size(2)	`r0`
nd_item::get_global_range(1) / item::get_range(1)	get_global_size(1)	`r1`
nd_item::get_global_range(2) / item::get_range(2)	get_global_size(0)	`r2`
nd_item::get_global_id(0) / item::get_id(0)	get_global_id(2)	Value in range 0..(`r0-1`)}

SYCL kernel query	OpenCL kernel query	Returned Value
nd_item::get_global_id(1) / item::get_id(1)	get_global_id(1)	Value in range 0..(r1-1)}
nd_item::get_global_id(2) / item::get_id(2)	get_global_id(0)	Value in range 0..(r2-1)}
With enqueued 2D SYCL global range of range<2> R{r0,r1}		
nd_item::get_global_range(0) / item::get_range(0)	get_global_size(1)	r0
nd_item::get_global_range(1) / item::get_range(1)	get_global_size(0)	r1
nd_item::get_global_id(0) / item::get_id(0)	get_global_id(1)	Value in range 0..(r0-1)}
nd_item::get_global_id(1) / item::get_id(1)	get_global_id(0)	Value in range 0..(r1-1)}
With enqueued 1D SYCL global range of range<1> R{r0}		
nd_item::get_global_range(0) / item::get_range(0)	get_global_size(0)	r0
nd_item::get_global_id(0) / item::get_id(0)	get_global_id(0)	Value in range 0..(r0-1)}

C.7.8. Data types

The OpenCL C language standard Section 6.11 defines its own built-in scalar data types, and these have additional requirements in terms of size and signedness on top of what is guaranteed by ISO C++. For the purpose of interoperability and portability, SYCL defines a set of aliases to C++ types within the sycl::opencl namespace using the cl_ prefix. These aliases are described in Table 194.

Table 194. Scalar data type aliases supported by SYCL OpenCL backend

Scalar data type alias	Description
cl_bool	Alias to a conditional data type which can be either true or false. The value true expands to the integer constant 1 and the value false expands to the integer constant 0.
cl_char	Alias to a signed 8-bit integer, as defined by the C++ core language.
cl_uchar	Alias to an unsigned 8-bit integer, as defined by the C++ core language.
cl_short	Alias to a signed 16-bit integer, as defined by the C++ core language.
cl_ushort	Alias to an unsigned 16-bit integer, as defined by the C++ core language.
cl_int	Alias to a signed 32-bit integer, as defined by the C++ core language.
cl_uint	Alias to an unsigned 32-bit integer, as defined by the C++ core language.

Scalar data type alias	Description
`cl_long`	Alias to a signed 64-bit integer, as defined by the C++ core language.
`cl_ulong`	Alias to an unsigned 64-bit integer, as defined by the C++ core language.
`cl_float`	Alias to a 32-bit floating-point. The float data type must conform to the IEEE 754 single precision storage format.
`cl_double`	Alias to a 64-bit floating-point. The double data type must conform to the IEEE 754 double precision storage format.
`cl_half`	Alias to a 16-bit floating-point. The half data type must conform to the IEEE 754-2008 half precision storage format. Kernels using this type are only supported on devices that have `aspect::fp16`, as described in Section 5.7.

C.8. Preprocessor directives and macros

- `SYCL_BACKEND_OPENCL` substitutes to `1` if the OpenCL SYCL backend is active while building the SYCL application.

C.8.1. Offline linking with OpenCL C libraries

SYCL supports linking SYCL kernel functions with OpenCL C libraries during offline compilation or during online compilation by the SYCL runtime within a SYCL application.

Linking with OpenCL C kernel functions offline is an optional feature and is unspecified. Linking with OpenCL C kernel functions online is performed by using the SYCL `kernel_bundle` class to compile and link an OpenCL C source; using the `compile_with_source` or `build_with_source` member functions.

OpenCL C functions that are linked with, using either offline or online compilation, must be declared as `extern "C"` function declarations. The function parameters of these function declarations must be defined as the OpenCL C interoperability aliases; `pointer` of the `multi_ptr` class template, `vector_t` of the `vec` class template and scalar data type aliases described in Table 194.

C.9. SYCL support of non-core OpenCL features

In addition to the OpenCL core features, SYCL also provides support for OpenCL extensions which provide features in OpenCL via khr extensions.

Some extensions are natively supported within the SYCL interface, however some can only be used via the OpenCL interoperability interface. The SYCL interface required for native extensions must be available. However if the respective extension is not supported by the executing SYCL `device`, the SYCL runtime must throw an `exception` with the `errc::feature_not_supported` or `errc::kernel_not_supported` error codes.

The OpenCL backend exposes some khr extensions to SYCL applications through the `sycl::aspect` enumerated type. Therefore, applications can query for the existence of these khr extensions by calling the `device::has()` or `platform::has()` member functions.

All OpenCL extensions are available through the OpenCL interoperability interface, but some can also be used through core SYCL APIs. Table 195 shows which these are. Table 195 also shows the mapping from each OpenCL extension name to its associated SYCL device `aspect` when one is available.

Table 195. SYCL support for OpenCL 1.2 extensions

SYCL Aspect	OpenCL Extension	Core SYCL API
aspect::atomic64	cl_khr_int64_base_atomics	Yes
aspect::atomic64	cl_khr_int64_extended_atomics	Yes
aspect::fp16	cl_khr_fp16	Yes
-	cl_khr_3d_image_writes	Yes
-	cl_khr_gl_sharing	No
-	cl_apple_gl_sharing	No
-	cl_khr_d3d10_sharing	No
-	cl_khr_d3d11_sharing	No
-	cl_khr_dx9_media_sharing	No

C.9.1. Half precision floating-point

The half scalar data type: `half` and the half vector data types: `half1`, `half2`, `half3`, `half4`, `half8` and `half16` must be available at compile-time. However a kernel using these types is only supported on devices that have `aspect::fp16`, as described in Section 5.7.

The conversion rules for half precision types follow the same rules as in the OpenCL 1.2 extensions specification par. 9.5.1.

The math functions for half precision types follow the same rules as in the OpenCL 1.2 extensions specification par. 9.5.2, 9.5.3, 9.5.4, 9.5.5. The allowed error in ULP(Unit in the Last Place) is less than 8192, corresponding to Table 6.9 of the OpenCL 1.2 specification.

C.9.2. Writing to 3D image memory objects

The `unsampled_image_accessor` class in SYCL supports member functions for writing 3D image memory objects, but this functionality is only allowed on a device if the extension `cl_khr_3d_image_writes` is supported on that device.

C.9.3. Interoperability with OpenGL

Interoperability between SYCL and OpenGL is not directly provided by the SYCL interface, however can be achieved via the SYCL OpenCL interoperability interface.

C.10. Correspondence of some OpenCL features to SYCL

This section describes the correspondence between some OpenCL features and features in the core SYCL specification that provide similar functionality. All content in this section is non-normative.

C.10.1. Work-item functions

The OpenCL 1.2 specification document ch. 6.12.1 in Table 6.7 defines work-item functions that tell various information about the currently executing work item in an OpenCL kernel. SYCL provides equivalent functionality through the item and group classes that are defined in Section 4.9.1.4, Section 4.9.1.5 and Section 4.9.1.7.

C.10.2. Vector data load and store functions

The functionality from the OpenCL functions as defined in the OpenCL 1.2 specification document par. 6.12.7 is available in SYCL through the `vec` class in Section 4.14.2.

C.10.3. Synchronization functions

In SYCL the OpenCL synchronization functions are available through the `nd_item` class (Section 4.9.1.5), as they are applied to work-items for local or global address spaces. Please see Table 119.

C.10.4. `printf` function

The functionality of the `printf` function is covered by the `stream` class (Section 4.16), which has the capability to print to standard output all of the SYCL classes and primitives, and covers the capabilities defined in the OpenCL 1.2 specification document par. 6.12.13.

Appendix D: What has changed from previous versions

D.1. What has changed from SYCL 1.2.1 to SYCL 2020

The SYCL runtime moved from namespace `cl::sycl` provided by `#include <CL/sycl.hpp>` to namespace `sycl` provided by `#include <sycl/sycl.hpp>` as explained in Section 4.3. The old header file is still available for compatibility with SYCL 1.2.1 applications.

The SYCL specification is now based on the core language of C++17, as described in Section 3.9.1. Features of C++17 are now enabled within the specification, such as deduction guides for class template argument deduction.

Naming of lambda functions passed to kernel invocations is now optional.

Changes to buffers, images and accessors:

- The `image` class has been removed. There are now new classes `unsampled_image` and `sampled_image` which represent sampled and unsampled images. The `sampler` class has been removed and replaced with the new `image_sampler` structure.
- Support for image arrays has been removed.
- The type name `access::target` has been deprecated and replaced with the type `target`.
- The type name `access::mode` has been deprecated and replaced with the type `access_mode`.
- The name of the `accessor` target `target::global_buffer` has been deprecated and replaced with `target::device`.
- Support for the `accessor` target `target::host_buffer` has been deprecated. There is now a new accessor class `host_accessor` which provides equivalent functionality.
- The `buffer` member functions which return an `accessor` of type `target::host_buffer` have been deprecated. A new member function `get_host_access()` has been added which returns a `host_accessor`.
- The `buffer` class has a new variadic overload of the `get_access()` member function which allows construction of an `accessor` with various parameters.
- Support for the `accessor` target `target::local` has been deprecated. There is now a new accessor class `local_accessor` which provides equivalent functionality.
- Support for the `accessor` targets `target::image` and `target::host_image` have been removed. There are now new accessor classes for sampled and unsampled images: `sampled_image_accessor`, `host_sampled_image_accessor`, `unsampled_image_accessor` and `host_unsampled_image_accessor`.
- A new `accessor` target `target::host_task` has been added, which allows access to a `buffer` from a host task.
- Support for the `accessor` modes `access_mode::discard_write` and `access_mode::discard_read_write` has been deprecated. Accessors can now be constructed with a property list, and the new property `property::no_init` provides equivalent functionality.
- Support for the `accessor` mode `access_mode::atomic` and the member functions that return an instance of the `atomic` class have been deprecated in favor of using the new `atomic_ref` class instead.
- Support for the `accessor` template parameter `isPlaceholder` has been deprecated, and the value of this parameter no longer has any bearing on whether the accessor is a placeholder. The enumerated type `access::placeholder` is also deprecated. A placeholder accessor can now be constructed by calling the appropriate constructor, without regard to the template parameter.
- The return type of `accessor::is_placeholder()` is no longer `constexpr`.

- The member function `handler::require()` may now be called on any `accessor` with target `target::device`, `target::constant_buffer` or `target::host_task`, regardless of whether it is a placeholder.
- New `accessor` constructors have been added which take a type tag parameter, which allows the class template parameters to be inferred via C++ class template argument deduction (CTAD).
- The `buffer` member function `get_access()` now has a default value for the `target` template parameter, so it is no longer necessary to provide any template parameters in order to get a `access_mode::read_write` accessor.
- The `accessor` template parameters `Dimensions` and `AccessMode` now have default values, so the only required template parameter is `DataT`. Moreover, the default access mode is either `access_mode::read_write` or `access_mode::read`, depending on the constness of the `DataT` type. This makes it possible to declare a read-only accessor by simply using a `const` qualified type.
- Implicit conversions have been added between the two forms of read-only `accessor` (one form has `const DataT` and `access_mode::read` and the other has non-const `DataT` and `access_mode::read`). There is also an implicit conversion from a read-write `accessor` to either of the read-only forms.
- Member functions of `accessor` which return a reference to an element have been changed to return a `const` reference for read-only accessors. The `get_pointer()` member function has also been changed to return a `const` pointer for read-only accessors. The `value_type` and `reference` member types of `accessor` have been changed to be `const` types for read-only accessors.
- The `accessor` member function `get_pointer()` now returns a raw pointer. The `get_multi_ptr()` member function was introduced which returns the `multi_ptr` class to the appropriate space.
- The `accessor` class now meets the C++ requirement of `ReversibleContainer`. This includes (but is not limited to) returning `begin` and `end` iterators, specifying a default constructible accessor that can be passed to a kernel but not dereferenced, and making them equality comparable.
- Many of the `accessor` member functions have been marked `noexcept`.
- A ranged accessor is no longer allowed to read elements that are outside of its range; attempting to do so produces undefined behavior.
- The semantics of the subscript operator have been changed for a ranged accessor which has an offset. Calling `operator[](0)` now returns a reference to the first element in the range, rather than a reference to the first element in the underlying buffer.
- The behavior of buffers and accessors with a zero-sized range has been clarified.

Constant memory no longer appears in the SYCL device memory model in SYCL 2020.

The C++ attributes that decorate kernels are now better described, and their position has changed so that they are applied directly to the kernel function. (Previously, they were applied to a device function that the kernel calls, and the implementation needed to propagate the information up to the enclosing kernel.) The old C++ attribute form is no longer included in the SYCL specification.

The list of built-in integer math functions was extended with `ctz()` in Table 179. Specification of `clz()` was extended with the case of argument is 0.

The classes `vector_class`, `string_class`, `function_class`, `mutex_class`, `shared_ptr_class`, `weak_ptr_class`, `hash_class` and `exception_ptr_class` have been removed from the API and the standard classes `std::vector`, `std::string`, `std::function`, `std::mutex`, `std::shared_ptr`, `std::weak_ptr`, `std::hash` and `std::exception_ptr` are used instead.

The specific `sycl::buffer` API taking `std::unique_ptr` has been removed. The behavior is the same as in SYCL 1.2.1 but with a simplified API. Since there is still the API taking `std::shared_ptr` and there is an implicit conversion from a `std::unique_ptr` prvalue to a `std::shared_ptr`, the API can still be used as before with a `std::unique_ptr` to give away memory ownership.

Offsets to `parallel_for`, `nd_range`, `nd_item` and `item` classes have been deprecated. As such, the parallel iteration spaces all begin at `(0,0,0)` and developers are now required to handle any offset arithmetic

themselves. The behavior of `nd_item.get_global_linear_id()` and `nd_item.get_local_linear_id()` has been clarified accordingly.

Unified Shared Memory (USM), in Section 4.8, has been added as a pointer-based strategy for data management. It defines several types of allocations with various accessibility rules for host and devices. USM is meant to complement buffers, not replace them.

The `queue` class received a new `property` that requires in-order semantics for a queue where operations are executed in the order in which they are submitted.

The `queue` class received several new member functions to invoke kernels directly on a queue objects instead of inside a command group handler in the `submit` member function.

The `queue` constructor overloads that accept both a `context` and a `device` parameter have been broadened to allow the device to be either a device that is in the context or a descendent device of a device that is in the context.

The `program` class has been removed and replaced with a new class `kernel_bundle`, which provides similar functionality in a type-safe and thread-safe way. The `kernel` class has changed, and some member functions have been removed.

Support has been added for specialization-constants, which allow a SYCL kernel function to use constant variables whose values aren't known until the kernel is invoked. A SYCL kernel function can now take an optional parameter of type `kernel_handler`, which allows the kernel to read the values of specialization-constants.

The constructors for SYCL `context` and `queue` are made `explicit` to prevent ambiguities in the selected constructor resulting from implicit type conversion.

The requirement for C++ standard layout for data shared between host and devices has been relaxed. SYCL now requires data shared between host and devices to be device copyable as defined Section 3.13.1.

The concept of a group of work items was generalized to include work groups and sub groups. A work-group is represented by the `sycl::group` class as in SYCL 1.2.1, and a sub-group is represented by the new `sycl::sub_group` class.

The `host_task` member function for the `queue` has been introduced for en-queueing host tasks on a queue to schedule the SYCL runtime to invoke native C++ functions, conforming to the SYCL memory model. Host-tasks also support interoperability with the native SYCL backend objects associated at that point in the DAG using the optional `interop_handle` class.

A library of algorithms based on the C++17 algorithms library was introduced in Section 4.17.4. These algorithms provide a simple way for developers to apply common parallel algorithms using the work-items of a group.

The definition of the `sycl::group` class was modified to support the new group functions in Section 4.17.3. New member types and variables were added to enable generic programming, and member functions were updated to encapsulate all functionality tied to work groups in the `sycl::group` class. See Table 121 for details.

The `barrier` and `mem_fence` member functions of the `nd_item` class have been removed. The `barrier` member function has been replaced by the `group_barrier()` function, which can be used to synchronize either work groups or sub-groups. The `mem_fence` member function has been replaced by the `atomic_fence` function, which is more closely aligned with `std::atomic_thread_fence` and offers control over memory ordering and scope.

Changes in the SYCL `vec` class described in Section 4.14.2:

- `operator[]` was added;
- unary `operator+()` and `operator-()` were added;

The device selection now relies on a simpler API based on ranking functions used as device selectors described in Section 4.6.1.1.

A new device selector utility has been added to Section 4.6.1.1, the `aspect_selector`, which returns a selector object that only selects devices that have all the requested aspects.

The device query `info::fp_config::correctly_rounded_divide_sqrt` has been deprecated.

A new reduction library consisting of the `reduction` function and `reducer` class was introduced to simplify the expression of variables with reduction semantics in SYCL kernels. See Section 4.9.2.

The `atomic` class from SYCL 1.2.1 was deprecated in favor of a new `atomic_ref` interface.

The SYCL exception class hierarchy has been condensed into a single exception type: `exception`. `exception` now derives from `std::exception`. The variety of errors are now provided via error codes, which aligns with the C++ error code mechanism.

The new error code mechanism now also generalizes the previous `get_cl_code` interface to provide a generic interface way for querying backend-specific error codes.

Default asynchronous error handling behavior is now defined, so that asynchronous errors will cause abnormal program termination even if a user-defined asynchronous handler function is not defined. This prevents asynchronous errors from being silently lost during early stages of application development.

Kernel invocation functions, such as `parallel_for`, now take kernel functions by `const` reference. Kernel functions must now have a `const`-qualified `operator()`, and are allowed to be copied zero or more times by an implementation. These clarifications allow implementations to have flexibility for specific devices, and define what users should expect with kernel functors. Specifically, kernel functors can not be marked as `mutable`, and sharing of data between work-items should not be attempted through state stored within a kernel functor.

A new concept called device aspects has been added, which tells the set of optional features a device supports. This new mechanism replaces the `has_extension()` function and some uses of `get_info()`.

There is a new Chapter 6 which describes how extensions to the SYCL language can be added by vendors and by the Khronos Group.

A `queue` constructor has been added that takes both a `device` and `context`, to simplify interfacing with libraries.

The `parallel_for` interface has been simplified in some forms to accept a braced initializer list in place of a `range`, and to always take `item` arguments. Kernel invocation functions have also been modified to accept generic lambda expressions. Implicit conversions from one-dimensional `item` and one-dimensional `id` to scalar types have been defined. All of these modifications lead to simpler SYCL code in common use cases.

The behaviour of executing a kernel over a `range` or `nd_range` with index space of zero has been clarified.

Some device-specific queries have been renamed to more clearly be “device-specific kernel” `get_info` queries (`info::kernel_device_specific`) instead of “work-group” (`get_workgroup_info`) and sub-group (`get_sub_group_info`) queries.

A new math array type `marray` has been defined to begin disambiguation of the multiple possible interpretations of how `sycl::vec` should be interpreted and implemented.

Changes in SYCL address spaces:

- the address space meaning has been significantly improved;
- the generic address space was introduced;
- the constant address space was deprecated;
- behavior of unannotated pointer/reference (raw pointer/reference) is now dependent on the compilation mode. The compiler can either interpret unannotated pointer/reference has addressing the generic address space or to be deduced;
- some ambiguities in the address space deduction were clarified. Notably that deduced type does not affect the user-provided type.

Changes in `multi_ptr` interface:

- addition of `access::address_space::generic_space` to represent the generic address space;
- deprecation of `access::address_space::constant_space`;
- an extra template parameter to allow to select a flavor of the `multi_ptr` interface. There are now 3 different interfaces:
  - interface exposing undecorated types. Returned pointer and reference are not annotated by an address space;
  - interface exposing decorated types. Returned pointer and reference are annotated by an address space;
  - legacy 1.2.1 interface (deprecated).
- deprecation of the 1.2.1 interface;
- deprecation of `constant_ptr`;
- `global_ptr`, `local_ptr` and `private_ptr` alias take the new extra parameter;
- addition of the `address_space_cast` free function to cast undecorated pointer to `multi_pointer`;
- addition of construction/conversion operator for the generic address space;
- removal of the constructor and assignment operator taking an unannotated pointer;
- implicit conversion to a pointer is now deprecated. `get` should be used instead;
- the return type of the member function `get` now depends on the selected interface.
- addition of the member function `get_raw` which returns the underlying pointer as an unannotated pointer;
- addition of the member function `get_decorated` which returns the underlying pointer as an annotated pointer;
- addition of the subscript operator providing random access.

The `cl::sycl::byte` has been deprecated and now the C++17 `std::byte` should be used instead.

A SYCL implementation is no longer required to provide a host device. Instead, an implementation is only required to provide at least one device. Implementations are still allowed to provide devices that are implemented on the host, but it is no longer required. The specification no longer defines any special semantics for a "host device" and APIs specific to the host device have been removed.

The default constructors for the `device` and `platform` classes have been changed to construct a copy of the default device and a copy of the platform containing the default device. Previously, they returned a copy of the host device and a copy of the platform containing the host device. The default constructor for the `event` class has also been changed to construct an event that comes from a default-constructed `queue`. Previously, it constructed an event that used the host backend.

Explicit copy functions of the handler class have also been introduced to the queue class as shortcuts for

the handler ones. This is enabled by the improved placeholder accessors to help reduce code verbosity in certain cases because the shortcut functions implicitly create a command group and call `handler::require`.

Information query descriptors have been changed to structures under namespaces named accordingly. `param_traits` has been removed and the return type of an information query is now contained in the descriptor. The `sycl::info::device::max_work_item_sizes` is now a template that takes a dimension parameter corresponding to the number of dimensions of the work-item size maxima.

Changes to retrieving size information:

- all `get_size()` member functions have been deprecated and replaced with `byte_size()`, which is marked `noexcept`;
- all `get_count()` member functions have been deprecated and replaced with `size()`, which is marked `noexcept`;
- in the `vec` class the functions `byte_size()` and `size()` are now static member functions;
- in the `stream` class `get_size()` has been deprecated in favor of `size()`, whereas `stream::byte_size()` is not available;
- accessors for sampled and unsampled images only define `size()` and not `byte_size()`.

The device descriptors `info::device::max_constant_buffer_size` and `info::device::max_constant_args` are deprecated in SYCL 2020.

The `buffer_allocator` is now templated on the data type and follows the C++ named requirement `Allocator`.

The SYCL `id` and `range` have now unary `+` and `-` operations, prefix `++` and `--` operations, postfix `++` and `--` operations which were forgotten in SYCL 1.2.1.

In SYCL 1.2.1, the `handler::copy()` overload with two `accessor` parameters did not clearly specify which accessor's size determines the amount of memory that is copied. The spec now clarifies that the `src` accessor's size is used.

Appendix E: References

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Glossary

accessor

An accessor is a class which allows a command to access data managed by a buffer or image class or allows a SYCL kernel function to access local memory on a device. Accessors are also used to express the dependencies among the different command groups. For the full description please refer to Section 4.7.6

application scope

The application scope starts with the construction first SYCL runtime class object and finishes with the destruction of the last one. Application refers to the C++ SYCL application and not the SYCL runtime.

aspect

A characteristic of a device which determines whether it supports some optional feature. Aspects are always boolean, so a device either has or does not have an aspect.

asynchronous error

A SYCL asynchronous error is an error occurring after the host API call invoking the error causing action has returned, such that the error cannot be thrown as a typical C++ exception from a host API call. Such errors are typically generated from device kernel invocations which are executed when SYCL task graph dependencies are satisfied, which occur asynchronously from host code execution. For the full description and associated asynchronous error handling mechanisms, please refer to Section 4.13.

async_handler

An asynchronous error handler object is a function class instance providing necessary code for handling all the asynchronous errors triggered from the execution of command groups on a queue, within a context or an associated event. For the full description please refer to Section 4.13.2.

barrier

A barrier is either a command queue barrier, or a kernel execution group barrier depending on whether it is a synchronization point on the command queue or on a group of work-items in a kernel execution.

blocking accessor

A blocking accessor is an accessor which provides immediate access and continues to provide access until it is destroyed. For the full description please refer to Section 4.7.6

buffer

The buffer class manages data for the SYCL C++ host application and the SYCL device kernels. The buffer class may acquire ownership of some host pointers passed to its constructors according to the constructor kind.

The buffer class, together with the accessor class, is responsible for tracking memory transfers and guaranteeing data consistency among the different kernels. The SYCL runtime manages the memory allocations on both the host and the device within the lifetime of the buffer object. For the full description please refer to Section 4.7.2.

bundle state

A SYCL bundle state represents the state of a kernel bundle and therefore its capabilities in the SYCL programming API. Possible states are input, object or executable.

command

A request to execute work that is submitted to a queue such as the invocation of a SYCL kernel function, the invocation of a host task or an asynchronous copy.

command group

In SYCL, the operations required to process data on a device are represented using a command group function object. Each command group function object is given a unique command group handler object to perform all the necessary work required to correctly process data on a device using a kernel. In this way, the group of commands for transferring and processing data is enqueued as a command group on a device for execution. A command group is submitted atomically to a SYCL queue.

command group function object

A type which is callable with `operator()` that takes a reference to a command group handler, that defines a command group which can be submitted by a queue. The function object can be a named type, lambda function or `std::function`.

command group handler

The command group handler class provides the interface for the commands that can be executed inside the command group scope. It is provided as a scoped object to all of the data access requests within the command group scope. For the full description please refer to Section 4.9.4.

command group scope

The command group scope is the function scope defined by the command group function object. The command group command group handler object lifetime is restricted to the command group scope. For more details see Section 4.9.3.

command queue barrier

The SYCL API provides two variants for functions that force synchronization on a SYCL command queue. The `sycl::queue::wait()` and `sycl::queue::wait_and_throw()` functions force the SYCL command queue to wait for the execution of the command group function object before it is able to continue executing.

constant memory

A region of memory that remains constant during the execution of a kernel. The SYCL runtime allocates and initializes memory objects placed into constant memory.

context

A context represents the runtime data structures and state required by a SYCL backend API to interact with a group of devices associated with a platform. The context is defined as the `sycl::context` class, for further details please see Section 4.6.3.

control flow

When all work-items in a group are executing the same sequence of statements, they are said to be executing under *converged* control flow. Control flow *diverges* when different work-items in a group execute a different sequence of statements, typically as a result of evaluating conditions differently (e.g. in selection statements or loops).

core SYCL specification

The text of the SYCL language specification (this document), excluding the text of any backend specifications and excluding the text for any extensions.

descendent device

The descendent devices of device *D* include all of the sub-devices of *D*, all of the sub-devices of those devices, etc.

device

A SYCL device is an abstraction of a piece of hardware that can execute SYCL kernels.

device compiler

A SYCL device compiler is a compiler that produces device binaries from a valid SYCL application. For

the full description please refer to Chapter 5.

device copyable

Data that is shared between the host and the devices must generally have a type that abides by the restrictions listed in Section 3.13.1 for a device copyable type.

device function

A device function is any function in a SYCL application that can be run on a device. This includes SYCL kernel functions and, recursively, functions they call.

device image

A device image is a representation of one or more kernels in an implementation-defined format. A device image could be a compiled version of the kernels in an intermediate language representation which needs to be translated at runtime into a form that can be invoked on a device, it could be a compiled version of the kernels in a native code format that is ready to be invoked without further translation, or it could be a source code representation which needs to be compiled before it can be invoked. Other representations are possible too.

device selector

A way to select a device used in various places. This is a callable object taking a device reference and returning an integer rank. One of the device with the highest non-negative value is selected. See Section 4.6.1.1 for more details.

event

A SYCL object that represents the status of an operation that is being executed by the SYCL runtime.

executable

A state which a kernel bundle can be in, representing SYCL kernel functions as an executable.

generic memory

Generic memory is a virtual memory region which can represent global memory, local memory and private memory region.

global id

As in OpenCL, a global ID is used to uniquely identify a work-item and is derived from the number of global work items specified when executing a kernel. A global ID is a one, two or three-dimensional value that starts at 0 per dimension.

global memory

Global memory is a memory region accessible to all work items executing on a device.

group

A group of work-items within the index space of a SYCL kernel execution, such as a work-group or sub-group.

group barrier

A synchronization function within a group of work items. All the work items of a group must execute the barrier construct before any work-item continues execution beyond the barrier. Additionally all work-items in the group execute a release mem-fence prior to synchronizing at the barrier, all work-items in the group execute an acquire mem-fence after synchronizing at the barrier, and there is an implicit synchronization between these acquire and release fences as if through an atomic operation on an atomic object internal to the barrier implementation.

h-item

A unique identifier representing a single work-item within the index space of a SYCL kernel hierarchical execution. Can be one, two or three dimensional. In the SYCL interface a h-item is represented by

the `h_item` class (see Section 4.9.1.6).

host

Host is the system that executes the C++ application including the SYCL API.

host pointer

A pointer to memory on the host. Cannot be accessed directly from a device.

host task

A command which invokes a native C++ callable, scheduled conforming to SYCL dependency rules.

host task command

A type of command that can be used inside a command group in order to schedule a native C++ function.

id

It is a unique identifier of an item in an index space. It can be one, two or three dimensional index space, since the SYCL kernel execution model is an nd-range. It is one of the index space classes. For the full description please refer to Section 4.9.1.3.

image

Images in SYCL, like buffers, are abstractions of multidimensional structured arrays. Image can refer to `unsampled_image` and `sampled_image`. For the full description please refer to Section 4.7.3.

implementation-defined

Behavior that is explicitly allowed to vary between conforming implementations of SYCL. A SYCL implementer is required to document the implementation-defined behavior.

index space classes

Like in OpenCL, the kernel execution model defines an nd-range index space. The SYCL runtime class that defines an nd-range is the `sycl::nd_range`, which takes as input the sizes of global and local work-items, represented using the `sycl::range` class. The kernel library classes for indexing in the defined nd-range are the following classes:

- `sycl::id` : The basic index class representing an id;
- `sycl::item` : The item index class that contains the global id and local id;
- `sycl::nd_item` : The nd-item index class that contains the global id, local id and the work-group id;
- `sycl::group` : The group class that contains the work-group id and the member functions on a work-group.

input

A state which a kernel bundle can be in, representing SYCL kernel functions as a source or intermediate representation

item

An item id is an interface used to retrieve the global id, work-group id and local id. For further details see Section 4.9.1.4.

kernel

A kernel represents a SYCL kernel function that has been compiled for a device, including all of the device functions it calls. A kernel is implicitly created when a SYCL kernel function is submitted to a device via a kernel invocation command. However, a kernel can also be created manually by pre-compiling a kernel bundle (see Section 4.11).

kernel bundle

A kernel bundle is a collection of device images that are associated with the same context and with a

set of devices. Kernel bundles have one of three states: input, object or executable. Kernel bundles in the executable state are ready to be invoked on a device, whereas bundles in the other states need to be translated into the executable state before they can be invoked.

kernel handler

A representation of a SYCL kernel function being invoked that is available to the kernel scope.

kernel invocation command

A type of command that can be used inside a command group in order to schedule a SYCL kernel function, includes `single_task`, all variants of `parallel_for` and `parallel_for_workgroup`.

kernel name

A kernel name is a class type that is used to assign a name to the kernel function, used to link the host system with the kernel object output by the device compiler. For details on naming kernels please see Section 5.2.

kernel scope

The function scope of the `operator()` on a SYCL kernel function. Note that any function or member function called from the kernel is also compiled in kernel scope. The kernel scope allows C++ language extensions as well as restrictions to reflect the capabilities of devices. The extensions and restrictions are defined in the SYCL device compiler specification.

local id

A unique identifier of a work-item among other work-items of a work-group.

local memory

Local memory is a memory region associated with a work-group and accessible only by work-items in that work-group.

native backend object

An opaque object defined by a specific backend that represents a high-level SYCL object on said backend. There is no guarantee of having native backend objects for all SYCL types.

native-specialization constant

A specialization constant in a device image whose value can be used by an online compiler as an immediate value during the compilation.

nd-item

A unique identifier representing a single work-item and work-group within the index space of a SYCL kernel execution. Can be one, two or three dimensional. In the SYCL interface a nd-item is represented by the `nd_item` class (see Section 4.9.1.5).

nd-range

A representation of the index space of a SYCL kernel execution, the distribution of work items within into work groups. Contains a range specifying the number of global work items, a range specifying the number of local work items and a id specifying the global offset. Can be one, two or three dimensional. The minimum size of range within the nd-range is 0 per dimension; where any dimension is set to zero, the index space in all dimensions will be zero. In the SYCL interface an nd-range is represented by the `nd_range` class (see Section 4.9.1.2).

mem-fence

A memory fence provides control over re-ordering of memory load and store operations when coupled with an atomic operation that synchronizes two fences with each other (or when the fences are part of a group barrier in which case there is implicit synchronization as if an atomic operation has synchronized the fences). The `sycl::atomic_fence` function acts as a fence across all work-items and devices specified by a `memory_scope` argument.

object

A state which a kernel bundle can be in, representing SYCL kernel functions as a non-executable object.

platform

A collection of devices managed by a single backend.

private memory

A region of memory private to a work-item. Variables defined in one work-item's private memory are not visible to another work-item. The `sycl::private_memory` class provides access to the work-item's private memory for the hierarchical API as it is described at Listing 1.

queue

A SYCL command queue is an object that holds command groups to be executed on a SYCL device. SYCL provides a heterogeneous platform integration using device queue, which is the minimum requirement for a SYCL application to run on a SYCL device. For the full description please refer to Section 4.6.5.

range

A representation of a number of work items or work-group within the index space of a SYCL kernel execution. Can be one, two or three dimensional. In the SYCL interface a work-group is represented by the `group` class (see Section 4.9.1.7).

ranged accessor

A ranged accessor is a host or buffer accessor that was constructed with a non-zero offset into the data buffer or with an access range smaller than the range of the data buffer, or both. Please refer to Section 4.7.6.8 for more info.

reduction

An operation that produces a single value by combining multiple values in an unspecified order using a binary operator. If the operator is non-associative or non-commutative, the behavior of a reduction may be non-deterministic.

root device

A device that is not a sub-device. The function `device::get_devices()` returns a vector of all the root devices.

rule of five

For a given class, if at least one of the copy constructor, move constructor, copy assignment operator, move assignment operator or destructor is explicitly declared, all of them should be explicitly declared.

rule of zero

For a given class, if the copy constructor, move constructor, copy assignment operator, move assignment operator and destructor would all be inlined, public and defaulted, none of them should be explicitly declared.

SMCP

The single-source multiple compiler-passes (SMCP) technique allows a single-source file to be parsed by multiple compilers for building native programs per compilation target. For example, a standard C++ CPU compiler for targeting host will parse the SYCL file to create the C++ SYCL application which offloads parts of the computation to other devices. A SYCL device compiler will parse the same source file and target only SYCL kernels. For the full description please refer to Section 3.12.1. See SSCP for another approach.

specialization constant

A constant variable where the value is not known until compilation of the SYCL kernel function.

specialization id

An identifier which represents a reference to a specialization constant both in the SYCL application for setting the value prior to the compilation of a kernel bundle and in a SYCL kernel function for retrieving the value during invocation.

SSCP

The single-source single compiler-pass (SSCP) technique allows a single-source file to be parsed only once by a single compiler. For example, the SYCL compiler will parse the SYCL file once. Then, from this single intermediate representation, for each kind of device architecture a compilation flow will generate the binary for each kernel and another compilation flow will generate the host code of the C++ SYCL application. For the full description please refer to Section 3.12.2. See SMCP for another approach.

string kernel name

The name of a SYCL kernel function in string form, this can be the name of a kernel function created via interop or a string form of a type kernel name.

sub-group

The SYCL sub-group (`sycl::sub_group` class) is a representation of a collection of related work-items within a work-group. For further details for the `sycl::sub_group` class see Section 4.9.1.8.

sub-group barrier

A group barrier for all work items in a sub-group.

sub-group mem-fence

A mem-fence for all work items in a sub-group.

SYCL application

A SYCL application is a C++ application which uses the SYCL programming model in order to execute kernels on devices.

SYCL backend

An implementation of the SYCL programming model using an heterogeneous programming API. A SYCL backend exposes one or multiple SYCL platforms. For example, the OpenCL backend, via the ICD loader, can expose multiple OpenCL platforms.

SYCL backend API

The exposed API for writing SYCL code against a given SYCL backend.

SYCL C++ template library

The template library is a set of C++ templated classes which provide the programming interface to the SYCL developer.

SYCL file

A SYCL C++ source file that contains SYCL API calls.

SYCL kernel function

A type which is callable with `operator()` that takes an id, item, nd-item or work-group, and an optional `kernel_handler` as its last parameter. This type can be passed to kernel enqueue member functions of the command group handler. A SYCL kernel function defines an entry point to a kernel. The function object can be a named device copyable type or lambda function.

SYCL runtime

A SYCL runtime is an implementation of the SYCL API specification. The SYCL runtime manages the different platforms, devices, contexts as well as memory handling of data between host and SYCL backend contexts to enable semantically correct execution of SYCL programs.

type kernel name

The name of a SYCL kernel function in type form, this can be either a kernel name provided to a kernel invocation command or the type of a function object use as a SYCL kernel function.

USM

Unified Shared Memory (USM) provides a pointer-based alternative to the buffer programming model. USM enables:

- easier integration into existing code bases by representing allocations as pointers rather than buffers, with full support for pointer arithmetic into allocations;
- fine-grain control over ownership and accessibility of allocations, to optimally choose between performance and programmer convenience;
- a simpler programming model, by automatically migrating some allocations between SYCL devices and the host.

See Section 4.8

work-group

The SYCL work-group (`sycl::group` class) is a representation of a collection of related work items that execute on a single compute unit. The work items in the group execute the same kernel-instance and share local memory and work-group functions. For further details for the `sycl::group` class see Section 4.9.1.7.

work-group barrier

A group barrier for all work items in a work-group.

work-group mem-fence

A mem-fence for all work items in a work-group.

work-group id

As in OpenCL, SYCL kernels execute in work groups. The group ID is the ID of the work-group that a work-item is executing within. A group ID is an one, two or three dimensional value that starts at 0 per dimension.

work-group range

A group range is the size of the work-group for every dimension.

work-item

The SYCL work-item is a representation of a work-item among a collection of parallel executions of a kernel invoked on a device by a command. A work-item is executed by one or more processing elements as part of a work-group executing on a compute unit. A work-item is distinguished from other work items by its global id or the combination of its work-group id and its local id within a work-group.