Abstract

UPC++ is a C++11 library providing classes and functions that support Partitioned Global Address Space (PGAS) programming. The key communication facilities in UPC++ are one-sided Remote Memory Access (RMA) and Remote Procedure Call (RPC). All communication operations are syntactically explicit and default to non-blocking; asynchrony is managed through the use of futures, promises and continuation callbacks, enabling the programmer to construct a graph of operations to execute asynchronously as high-latency dependencies are satisfied. A global pointer abstraction provides system-wide addressability of shared memory, including host and accelerator memories. The parallelism model is primarily process-based, but the interface is thread-safe and designed to allow efficient and expressive use in multi-threaded applications. The interface is designed for extreme scalability throughout, and deliberately avoids design features that could inhibit scalability.

Funding Acknowledgments

This research was supported by the Exascale Computing Project (17-SC-20-SC), a collaborative effort of the U.S. Department of Energy Office of Science and the National Nuclear Security Administration. Early development of UPC++ was supported by the Director, Office of Science, Office of Advanced Scientific Computing Research, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Authorship Acknowledgments

The UPC++ library is the result of collaboration between many individuals. The UPC++ library specification is developed by the Pagoda group at Lawrence Berkeley National Laboratory.

The current authors and maintainers of the UPC++ specification are:

      Dan Bonachea, Amir Kamil

Other current members of the Pagoda group include:

      Max Grossman, Paul H. Hargrove, Colin A. MacLean, Daniel Waters

The following people have made significant contributions to prior revisions of this specification:

      John Bachan, Scott B. Baden, Steven Hofmeyr, Mathias Jacquelin,
      Brian van Straalen

The UPC++ project has benefited from ideas and feedback from numerous members of the community. This notably includes:

      Hadia Ahmed, Rob Egan, Khaled Ibrahim, Bryce Adelstein Leibach,
      Hongzhang Shan, Samuel Williams

The predecessor library, UPC++ v0.1 [5], was designed and developed by:

      Amir Kamil, Katherine Yelick, Yili Zheng
Recent Changes

The UPC++ library continues to evolve and improve in response to stakeholder requirements and feedback.

The memory kinds changes that first appeared in the 2020.11.0 draft revision, relative to the 2020.10.0 revision are as follows:

1. `device_allocator` construction is now a collective operation with user-level progress. Although the call is collective, the arguments need not be single-valued, allowing processes to differ in the size or existence of the device segment they construct.

2. Relax the restriction that a given CUDA device identifier could only be opened once per process using `cuda_device`. The same CUDA hardware device may now be simultaneously opened multiple times by a given process, for example to support modularity of layered software.

3. Add a `device_allocator<Device>::is_active()` query, and use it to simplify/clarify in various places.

4. Restrict the use of `device_allocator<Device>::device_id()` to `global_ptr` arguments with affinity to the calling process.

5. Specify that resource exhaustion failures encountered while allocating a device segment now throw `upcxx::bad_segment_alloc`, a new subclass of `std::bad_alloc`.

6. Clarify that zero-length device segments are prohibited.

Other major changes, relative to the 2020.10.0 revision are as follows:

1. Specify that remote completion semantically implies source completion. This ensures that `rput` operations requesting only remote completion are well-formed, as they can establish implied source completion via separate synchronization.

2. Specify that serialization of arguments to `rpc`, `rpc_ff` and `remote_cx::as_rpc` is now always performed synchronously before return from the communication-injection call, regardless of asynchronously `source_cx` completions (which are now deprecated for `rpc` and `rpc_ff`).

3. Specify `shared_segment_{size,used}` functions for querying shared heap status.

4. Specify a stream-insertion operator for `dist_id`

5. Disallow array types as the element type to `new_` and `new_array`. 
6. Clarify that notification of asynchronous event completion is delivered during user-level progress with the target persona at the top of the active persona stack.

7. Clarify that bit-field members are prohibited in `UPCXX_SERIALIZED_FIELDS`.

8. Clarify that futures and promises are not TriviallySerializable and thus should not be captured by copy in lambda expressions passed to communication calls.

9. Clarify the requirements on collective operations to prohibit dependency cycles across processes.

The UPC++ 2021.3.0 software release implements all the changes described above. For details on the implementation, please consult https://upcxx.lbl.gov

Providing Feedback

Readers are encouraged to provide feedback and comments on this specification via one of the following channels:

1. Enter a new issue in the UPC++ Specification issue tracker, located at: https://upcxx-bugs.lbl.gov

2. Send email to upcxx-spec@googlegroups.com – this is a semi-public forum for maintainers of UPC++ and other interested parties.

3. Real-time video chat meetings with the Pagoda group’s specification developers can be arranged upon request to: pagoda@lbl.gov
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Chapter 1

Overview and Scope

1.1 Preliminaries

1 UPC++ is a C++11 library providing classes and functions that support Partitioned Global Address Space (PGAS) programming. The project began in 2012 with a prototype AKA V0.1, described in the IPDPS14 paper by Zheng et al. [5]. This document describes a production version, V1.0, with the addition of several features and a new asynchronous API. For a peer-reviewed overview of the new version, see the IPDPS19 paper [4].

2 Under the PGAS model, a distributed memory parallel computer is viewed abstractly as a collection of processing elements, an individual computing resource, each with local memory (see Fig. 1.1). A processing element is called a process in UPC++. The execution model of UPC++ is SPMD and the number of UPC++ processes is fixed during program execution.

3 As with conventional C++ threads programming, processes can access their respective local memory via a pointer. However, the PGAS abstraction supports a global address space, which is allocated in shared segments distributed over the processes. A global pointer enables the UPC++ programmer to reference objects in the shared segments between processes as shown in Fig. 1.2. As with threads programming, accesses to shared objects made via global pointers may be subject to race conditions, and appropriate synchronization must be employed.

4 UPC++ global pointers are fundamentally different from conventional C-style pointers. A global pointer refers to a location in a shared segment. It cannot be dereferenced using the * operator, and it cannot be constructed by the address-of operator. Rather, there are more syntactically explicit methods for accomplishing these tasks. On the other hand,
**UPC++ v1.0 Specification, Revision 2021.3.0**

**Figure 1.1:** Abstract Machine Model of a PGAS program memory

**Figure 1.2:** Global pointers and shared memory objects in a PGAS model

**UPC++** global pointers *do* support some properties of a regular C pointer, such as pointer arithmetic and passing a pointer by value.

Notably, global pointers are used in *one-sided* communication: Remote Memory Access (RMA) operations similar to `memcpy` but across processes (Ch. 8), and in Remote Procedure Calls (RPC, Ch. 9). RPC enables the programmer to move computation to other processes, which is useful in managing irregular distributed data structures. These processes can push or pull data via global pointers. *Futures* and *Promises* (Ch. 5) are used to determine completion of communication or to schedule callbacks that respond to completion. Wherever possible, **UPC++** engages low-level hardware support for communication and this capability is crucial to **UPC++**’s support of *lightweight communication*.

**UPC++**’s design philosophy is to encourage writing scalable, high-performance applications. **UPC++** imposes certain restrictions in order to meet this goal. In particular, non-blocking communication is the default for nearly all operations defined in the API, and all communication is explicit. These two restrictions encourage the programmer to write code that is performant and make it more difficult to write code that is not. Conversely, **UPC++** relaxes some restrictions found in models such as MPI; in particular, it does not impose an in-order...
delivery requirement between separate communication operations. The added flexibility increases the possibility of overlapping communication and scheduling it appropriately.

UPC++ also avoids non-scalable constructs found in models such as UPC. For example, it does not support shared distributed arrays or shared scalars. Instead, it provides distributed objects, which can be used for similar purposes (Ch. 14). Distributed objects are useful in solving the bootstrapping problem, whereby processes need to distribute their local copies of global pointers to other processes. Though UPC++ does not directly provide multidimensional arrays, applications that use UPC++ may define them. To this end, UPC++ supports non-contiguous data transfers for regular, irregular and strided data (Ch. 15).

UPC++ does not create internal threads to manage progress. Therefore, UPC++ must manage all progress inside active calls to the library. The strengths of this approach include improved user-visibility into the resource requirements of UPC++ and better interoperability with software packages and their possibly restrictive threading requirements. The consequence, however, is that the user must be conscientious to balance the need for making progress against the application’s need for CPU cycles. Chapter 10 discusses subtleties of managing progress and how an application can arrange for UPC++ to advance the state of asynchronous communication.

Processes may be grouped into teams (Ch. 11). A team can participate in collective operations. Teams are also the interface that UPC++ uses to advertise the shared memory capabilities of the underlying hardware and operating system. This enables a programmer to reason about hierarchical processor-memory organization, allowing an application to reduce its memory footprint. UPC++ supports remote atomic memory operations (Ch. 13). Atomics are useful in managing distributed queues, hash tables, and so on. However, UPC++ remote atomic operations are explicitly split-phased and handled somewhat differently from the process-scope atomics provided in C++11 std::atomic.

UPC++ supports memory kinds (Ch. 16), whereby the programmer can identify regions of memory requiring different access methods or having different performance properties, such as device memory. Global pointers can reference device memory, and UPC++ supports seamless data motion between any combination of host or device memory, whether local or remote.

### 1.2 Execution Model

The UPC++ state for each process contains internal unordered queues that are managed for the user. The UPC++ progress engine scans these queues for operations initiated by this process, as well as externally generated operations that target this process. The progress
engine is active inside UPC++ calls only and is quiescent at other times, as there are no threads or background processes executing inside UPC++. This passive stance permits UPC++ to be driven by any other execution model a user might choose. This universality does place a small burden on the user: calling into the progress function. UPC++ relies on the user to make periodic calls into the progress function to ensure that UPC++ operations are completed. progress is the mechanism by which the user loans UPC++ a thread of execution to perform operations that target the given process. The user can determine that a specific operation completes by checking the status of its associated future, or by attaching a completion handler to the operation.

2 UPC++ presents a thread-aware programming model. With a few exceptions, it generally assumes that only one thread of execution is interacting with any given library object at a time. The abstraction for thread-awareness in UPC++ is the persona. A future produced by a thread of execution is associated with its persona, and transferring the future to another thread must be accompanied by transferring the underlying persona. Each process has a master persona, initially attached to the thread that calls init. Some UPC++ operations, such as barrier, require a thread to have exclusive access to the master persona to call them. Thus, the programmer is responsible for ensuring synchronized access to both personas and memory.

1.3 Memory Model

1 The UPC++ memory model differs from that of C++11 (and beyond) in that all updates are split-phased: every communication operation has a distinct initiate and wait step. Thus, RMA operations execute over a time interval, and the time intervals of successive operations that target the same datum must not overlap, or a data race will result.

2 UPC++ differs from message passing in MPI in that it doesn’t guarantee in-order delivery. For example, if we overlap two successive RMA operations involving the same source and destination process, there are no guarantees regarding which will complete first. The same lack of implicit point-to-point ordering holds for all asynchronous operations (including RMA, RPC, remote atomics, etc). The only way to guarantee ordering is to apply explicit synchronization, e.g. issue a wait on a prior operation before initiating any dependent operation.

1 MPI supports RMA, which is also unordered.
1.4 Common Requirements

Unless explicitly stated otherwise, the requirements in [res.on.arguments] in the C++ standard apply to UPC++ functions as well. In particular, if a local or global pointer passed to a UPC++ function is invalid for its intended use, the behavior of the function is undefined.

UPC++ functions may call into user code, including invoking constructors and destructors and running user-provided callbacks. If an exception propagates from user code into a UPC++ function specified as noexcept, the behavior is undefined. As indicated in §1.6, UPC++ functions are implicitly declared noexcept unless specified otherwise. Thus, if user-provided code throws an exception that propagates outward into any UPC++ function whose specification does not include an Exceptions clause explicitly allowing this, the behavior is undefined.

For UPC++ functions with a Precondition(s) clause, violation of the preconditions results in undefined behavior.

1.5 Organization of this Document

This specification is intended to be a normative reference, not a tutorial on learning to use the library. A Programmer’s Guide is available from https://upcxx.lbl.gov and is a good tutorial to gain a working understanding of the library.

The organization for the rest of the document is as follows. Chapter 2 discusses the process of starting up and closing down UPC++. Global pointers (Ch. 3) are fundamental to the PGAS model, and Chapter 4 discusses shared heap storage management. UPC++ supports aggressively asynchronous communication and provides futures and promises (Ch. 5) to manage asynchronous operations and control flow. Chapter 6 discusses how C++ objects are serialized for communication. Chapter 7 describes the different completion models available for UPC++ communication operations. Chapters 8 and 9 describe two core forms of asynchronous one-sided communication, RMA and RPC, respectively. Chapter 10 discusses progress. Chapter 11 discusses teams, which are a means of organizing UPC++ processes, and Chapter 12 describes collective communication operations. Chapter 13 discusses atomic operations on shared memory. Chapter 14 discusses distributed objects. Chapter 15 discusses non-contiguous one-sided RMA transfers. Chapter 16 discusses memory kinds for device memory.

This differs from standard C++, which specifies that std::terminate is called if an exception reaches the outermost block of a non-throwing function.
1.6 Conventions

1. All entities are declared by the header `upcxx/upcxx.hpp`, unless otherwise specified.
2. All library identifiers are in the `upcxx` namespace, unless otherwise qualified.
3. All functions are declared `noexcept` unless specifically called out.
4. The notation `cq` represents an optional `const` qualifier.

1.7 Glossary

1. **Affinity.** A binding of each location in a shared or device segment to a particular process (generally the process which allocated that shared object). Every byte of shared memory has affinity to exactly one process (at least logically).

2. **C++ Concepts.** E.g. TriviallyCopyable. This document references C++ Concepts as defined in the C++14 standard [3] when specifying the semantics of types. However, compliant implementations are still possible within a compiler adhering to the earlier C++11 standard [2].

3. **Collective.** A constraint placed on some language operations which requires evaluation of such operations to be matched across all participating processes. The behavior of collective operations is undefined unless all processes execute the same sequence of collective operations.

4. A collective operation need not provide any actual synchronization between processes, unless otherwise noted. The collective requirement simply states a relative ordering property of calls to collective operations that must be maintained in the parallel execution trace for all executions of any valid program. Some implementations may include unspecified synchronization between processes within collective operations, but programs must not rely upon the presence or absence of such unspecified synchronization for correctness.

5. **Collective object.** (16) A semantic binding of objects constructed and destroyed collectively by the processes in a team.

6. **Device.** (16) A physical device with storage that is distinct from main memory.

7. **Device segment.** (16) A region of storage associated with a device that is used to allocate objects that are accessible by any process.
8 **Futures (and Promises).** (5) The primary mechanisms by which a UPC++ application interacts with non-blocking operations. The semantics of futures and promises in UPC++ differ from those of standard C++. While futures in C++ facilitate communicating between threads, the intent of UPC++ futures is solely to provide an interface for managing and composing non-blocking operations, and they cannot be used directly to communicate between threads or processes. A future is the interface through which the status of the operation can be queried and the results retrieved, and multiple future objects may be associated with the same promise. A future thus represents the consumer side of a non-blocking operation. A promise represents the producer side of the operation, and it is through the promise that the results of the operation are supplied and its dependencies fulfilled.

9 **Global pointer.** (3) The primary way to address memory in a shared memory segment of a UPC++ program. Global pointers can themselves be stored in shared memory or otherwise passed between processes and retain their semantic meaning to any process.

10 **Local.** (11.2) Refers to an object or reference with affinity to a process in the local team.

11 **Operation completion.** (7) The condition where a communication operation is complete with respect to the initiating process, such that its effects are visible and that resources, such as source and destination memory regions, are no longer in use by UPC++.

12 **Persona.** (10.4) The abstraction for thread-awareness in UPC++. A UPC++ persona object represents a collection of UPC++-internal state usually attributed to a single thread. By making it a proper construct, UPC++ allows a single OS thread to switch between multiple application-defined roles for processing notifications. Personas act as the receivers for notifications generated by the UPC++ runtime.

13 **Private object.** An object outside the shared space that can be accessed only by the process that owns it (e.g. an object on the program stack).

14 **Process.** (1) An OS process with associated system resources that is a member of a UPC++ parallel job execution. UPC++ uses a SPMD execution model, and the number of processes is fixed during a given program execution. The placement of processes across physical processors or NUMA domains is implementation-defined.

15 **Progress.** (10) The means by which the application allows the UPC++ runtime to advance the state of outstanding operations initiated by this or other processes, to ensure they eventually complete.

16 **Rank.** (11) An integer index that identifies a unique UPC++ process within a UPC++ team.
17 **Referentially transparent.** A routine that is a pure function, where inputs alone determine the value returned by the function. For the same inputs, repeated calls to a referentially transparent function will always return the same result.

18 **Remote.** Refers to an object or reference whose affinity is not local to the current process.

19 **Remote Procedure Call.** A communication operation that injects a function call invocation into the execution stream of another process. These injections are one-sided, meaning the target process need not explicitly expect the incoming operation or perform any specific action to receive it, aside from invoking **UPC++** progress.

20 **Serializable.** (6) A C++ type that is either TriviallySerializable, or that implements the **UPC++** class serialization interface.

21 **Source completion.** The condition where a communication operation initiated by the current process has advanced to a point where serialization of the local source memory regions for the operation has occurred, and the contents of those regions can be safely overwritten or reclaimed without affecting the behavior of the ongoing operation. Source completion does not generally imply operation completion, and other effects of the operation (e.g., updating destination memory regions, or delivery to a remote process) may still be in-progress.

22 **Shared segment.** A region of storage associated with a particular process that is used to allocate shared objects that are accessible by any process.

23 **Team.** (11) A **UPC++** object representing an ordered set of processes. Each process in a team has a unique 0-based rank index.

24 **Thread (or OS thread).** An independent stream of executing instructions with private state. A process may contain many threads (created by the application), and each is associated with at least one persona.

25 **TriviallySerializable.** (6) A C++ type that is valid to serialize by making a byte copy of an object.
Chapter 2

Init and Finalize

2.1 Overview

1 The init function must be called before any other UPC++ function can be invoked. This can happen anywhere in the program, so long as it appears before any UPC++ calls that require the library to be in an initialized state. The call is collective, meaning every process in the parallel job must enter this function if any are to participate in UPC++ operations. While init can be called more than once by each process in a program, only the first invocation will initialize UPC++, and the rest will merely increment the internal count of how many times init has been called. For each init call, a matching finalize call must eventually be made. init and finalize are not re-entrant and must be called by only a single thread of execution in each process. The thread that calls init has the master persona attached to it (see section 10.5.1 for more details of threading behavior). After the number of calls to finalize matches the number of calls to init, no UPC++ function that requires the library to be in an initialized state can be invoked until UPC++ is reinitialized by a subsequent call to init.

2 All UPC++ operations require the library to be in an initialized state unless otherwise specified, and violating this requirement results in undefined behavior. Member functions, constructors, and destructors are included in the set of operations that require UPC++ to be initialized, unless explicitly stated otherwise.
```cpp
#include <upcxx/upcxx.hpp>
#include <iostream>

int main (int argc, char *argv[])
{
  upcxx::init(); // initialize UPC++

  std::cout << "Hello World"
             << " ranks:" << upcxx::rank_n() // how many processes?
             << " my rank: " << upcxx::rank_me() // which process am I?
             << std::endl;

  upcxx::finalize(); // finalize UPC++
  return 0;
}
```

Figure 2.1: *HelloWorld.cpp* program

## 2.2 Hello World

A UPC++ installation should be able to compile and execute the simple *Hello World* program shown in Figure 2.1. The output of *Hello World*, however, is platform-dependent and may vary between different runs, since there is no synchronization to order the output between processes. Depending on the nature of the buffering protocol of `stdout`, output from different processes may even be interleaved.

## 2.3 API Reference

```cpp
void init();
```

*Precondition:* Called collectively by all processes in the parallel job. Calling thread must have the master persona (§10.5.1) if UPC++ is in an already-initialized state.

If there have been no previous calls to `init`, or if all previous calls to `init` have had matching calls to `finalize`, then this routine initializes the UPC++ library. Otherwise, leaves the library’s state as is. Upon return, the calling thread will be attached to the master persona (§10.5.1).

*This function may be called when UPC++ is in the uninitialized state.*
bool initialized();

Returns whether or not UPC++ is in the initialized state. UPC++ is initialized if there has been at least one previous call to init that has not had a matching call to finalize.

This function may be called when UPC++ is in the uninitialized state.

void finalize();

Precondition: Called collectively by all processes in the parallel job. Calling thread must have the master persona (§10.5.1), and UPC++ must be in an already-initialized state.

If this call matches the call to init that placed UPC++ in an initialized state, then this call uninitializes the UPC++ library. Otherwise, this function does not alter the library’s state.

Before uninitializing the UPC++ library, finalize shall execute a (blocking) barrier() over team world(). If this call uninitializes the UPC++ library while there are any asynchronous operations still in-flight (after the barrier), behavior is undefined. An operation is defined as in-flight if it was initiated but still requires internal-level or user-level progress from any persona on any process in the job before it can complete. It is left to the application to define and implement their own specific approach to ensuring quiescence of in-flight operations. A potential quiescence API is being considered for future versions and feedback is encouraged.

UPC++ progress level: user

#define UPCXX_SPEC_VERSION 20210300L

A macro definition to an integer literal identifying the version of this specification. Implementations complying to this specification shall define the value shown above. It is intended that future versions of this specification will replace the value of this macro with a greater value.

#define UPCXX_VERSION /* implementation-defined */

A macro definition to an integer literal identifying the version of the implementation. Values are implementation-defined, but are recommended to be monotonically non-decreasing for subsequent revisions of the same implementation.
The `getenv_console` function searches an environment list, provided by the host environment, for a string that matches the string pointed to by `env_var`. The function returns a pointer to a string associated with the matched list member. The string pointed to shall not be modified by the program, but may be overwritten by a subsequent call to the `getenv_console` function. If the specified name cannot be found, a null pointer is returned.

It is unspecified whether and how functions that modify the POSIX environment (`std::setenv`, `std::unsetenv`, `std::putenv`, etc.) affect the return values of this function.

Advice to users: On some platforms, environment variables provided by the spawning console might not be propagated to the POSIX environment of all UPC++ processes. This function’s semantics are the same as `std::getenv()`, except that if `env_var` was set in the environment of the spawning console, that value is instead returned. UPC++ programs are recommended to use this function instead of `std::getenv()` to help ensure portability.

Note: As with most library functions, this function requires UPC++ to be in an already-initialized state.

UDP++ progress level: none
Chapter 3

Global Pointers

3.1 Overview

1 The UPC++ global_ptr is the primary way to address memory in a remote shared memory segment of a UPC++ program. The next chapter discusses how memory in the shared segment is allocated to the user.

2 As mentioned in Chapter 1, a global pointer is a handle that may not be dereferenced. This restriction follows from the design decision to prohibit implicit communication. Logically, a global pointer has two parts: a raw C++ pointer and an associated affinity, which is a binding of each location in a shared or device (Ch. 16) segment to a particular process (generally the process which allocated that shared object). In cases where the use of a global_ptr executes in a process that has direct load/store access to the memory of the global_ptr (i.e. is_local is true), we may extract the raw pointer component, and benefit from the reduced cost of employing a local reference rather than a global one. To this end, UPC++ provides the local() function, which returns a raw C++ pointer. Calling local() on a global_ptr that references an address in a remote shared segment or a device location to which the caller does not have load/store access results in undefined behavior.

3 Global pointers have the following guarantees:

   1. A global_ptr<T, Kind> is only valid if it is the null global pointer, it references a valid object, or it represents one element past the end of a valid array or non-array object.
2. Two global pointers compare equal if and only if they reference the same object, one 
past the end of the same array or non-array object, or are both null.

3. Equality of global pointers corresponds to observational equality, meaning that two 
global pointers which compare equal will produce equivalent behavior when inter-
changed.

4 These facts become important given that UPC++ allows two processes which are local to 
each other to map the same memory into their own virtual address spaces but possibly 
with different virtual addresses. They also ensure that a global pointer can be viewed from 
any process to mean the same thing without need for translation.

5 Global pointers are parameterized by the kind of memory they can refer to. A global 
pointer of type `global_ptr<T, Kind>` can only refer to memory on devices described by 
Kind, and the referenced memory may be located on a device attached to a local or remote 
process. The default global pointer, `global_ptr<T, memory_kind::host>`, can only refer 
to host memory on a local or remote process. A `global_ptr<T, memory_kind::any>` can 
refer to either host memory or memory on any device associated with a local or remote 
process.

6 Most UPC++ communication operations only operate on host memory, working on the de-
default `global_ptr<T>` . Functions that work with device memory are additionally parame-
terized by memory kind, working with general types such as `global_ptr<T, Kind>`.

7 The type `global_ptr<T, Kind>` is implicitly convertible to `global_ptr<const T, Kind>`, 
even in contexts that require template deduction. Thus, a `global_ptr<T, Kind>` may be 
passed to any UPC++ operation that requires a `global_ptr<const T, Kind>`.

8 On the other hand, an object of type `global_ptr<const T, Kind>` can only be converted 
to a `global_ptr<T, Kind>` by a call to `const_pointer_cast<T>()`.

## 3.2 API Reference

1 `using intrank_t = /* implementation-defined */;`

2 An implementation-defined signed integer type that represents a UPC++ rank 
ID.

March 31, 2021 – LBNL-2001388
enum class memory_kind {
    any = /* unspecified */,  
    host = /* unspecified */,  
    cuda_device = /* unspecified */
};

Constants used with a global pointer to specify the kind of memory (Ch. 16) 
that may be referenced by the global pointer.

template<typename T, memory_kind Kind = memory_kind::host>
struct global_ptr : global_ptr<const T, Kind>;

template<typename T, memory_kind Kind>
struct global_ptr<const T, Kind>;

C++ Concepts: DefaultConstructible, TriviallyCopyable, TriviallyDestructible, 
EqualityComparable, LessThanComparable, hashable

UPC++ Concepts: TriviallySerializable

T must not be qualified with volatile: std::is_volatile<T>::value must 
be false.

T must not be a reference type: std::is_reference<T>::value must be false.

T may be an incomplete type, but some member functions are specified to 
require T to be a complete type at invocation.

template<typename T, memory_kind Kind>
struct global_ptr {
    using element_type = T;
    using pointer_type = T*;
    // ...
};

Member type aliases for the template parameter T and the underlying raw 
pointer type.

template<typename T, memory_kind Kind>
[static] const memory_kind global_ptr<T, Kind>::kind = Kind;

Constant that has the same value as the Kind template parameter.
template<typename T, memory_kind Kind>
global_ptr<T, Kind>::global_ptr(std::nullptr_t = nullptr);

Constructs a global pointer corresponding to a null pointer.

This function may be called when UPC++ is in the uninitialized state.

UPC++ progress level: none

template<typename T>

template<typename Kind>
global_ptr<T, memory_kind::any>::global_ptr(
    global_ptr<T, Kind> other);

Constructs a global pointer with kind memory_kind::any from an existing
global pointer.

UPC++ progress level: none

template<typename T, memory_kind Kind>
global_ptr<T, Kind>::~global_ptr();

Trivial destructor. Does not delete or otherwise reclaim the raw pointer that
this global pointer is referencing.

This function may be called when UPC++ is in the uninitialized state.

UPC++ progress level: none

template<typename T>
global_ptr<T> to_global_ptr(T* ptr);

Precondition: ptr is a null pointer, or a valid pointer to host memory such
that the expression *ptr on the calling process yields a (possibly uninitialized)
object of type T that resides within the shared segment of a process in the local
team (§11.2) of the caller

Constructs a global pointer corresponding to the given raw pointer.

UPC++ progress level: none
CHAPTER 3. GLOBAL POINTERS

30 template<typename T>
global_ptr<T> try_global_ptr(T* ptr);

Precondition: ptr is a null pointer, or a valid pointer to host memory such that the expression *ptr on the calling process yields a (possibly uninitialized) object of type T.

32 If the object referenced by *ptr resides within the shared segment of a process in the local team (§11.2) of the caller, returns a global pointer referencing that object. Otherwise returns a null pointer.

UPC++ progress level: none

34 template<typename T, memory_kind Kind>
memory_kind global_ptr<T, Kind>::dynamic_kind() const;

If !is_null(), returns the actual memory kind associated with the memory referenced by this pointer.

If is_null(), the result is unspecified.

UPC++ progress level: none

38 template<typename T, memory_kind Kind>
bool global_ptr<T, Kind>::is_local() const;

Returns whether or not the calling process has load/store access to the memory referenced by this pointer. Returns true if this is a null pointer, regardless of the context in which this query is called. Otherwise, the result is unspecified if this pointer targets device memory (i.e. dynamic_kind() != memory_kind::host).

UPC++ progress level: none

41 template<typename T, memory_kind Kind>
bool global_ptr<T, Kind>::is_null() const;

Returns whether or not this global pointer corresponds to the null value, meaning that it references no memory. This query is purely a function of the global pointer instance, it is not affected by the context in which it is called.

UPC++ progress level: none
44 template< typename T, memory_kind Kind >
   [explicit] bool global_ptr<T, Kind>::operator bool() const;

Explicit conversion operator that returns !is_null().

UPC++ progress level: none

47 template< typename T, memory_kind Kind >
   T* global_ptr<T, Kind>::local() const;

Precondition: this->is_local()

Converts this global pointer into a raw pointer.

UPC++ progress level: none

51 template< typename T, memory_kind Kind >
   intrank_t global_ptr<T, Kind>::where() const;

Returns the rank in team world() of the process with affinity to the T object pointed-to by this global pointer. The return value for where() on a null global pointer is an implementation-defined value.

For a non-null device pointer (dynamic_kind() != memory_kind::host), returns the rank in team world() of the process that allocated the memory referenced by this pointer. The result is undefined if this pointer references unallocated memory.

This query is purely a function of the global pointer instance, it is not affected by the context in which it is called.

UPC++ progress level: none

56 template< typename T, memory_kind Kind >
   global_ptr<T, Kind>
   global_ptr<T, Kind>::operator+(std::ptrdiff_t diff) const;

template< typename T, memory_kind Kind >
   operator+(std::ptrdiff_t diff, global_ptr<T, Kind> ptr);

template< typename T, memory_kind Kind >
   global_ptr<T, Kind>&
   global_ptr<T, Kind>::operator+=(std::ptrdiff_t diff);
Precondition: \( T \) must be a complete type. Either \( \text{diff} = 0 \), or the global pointer is pointing to the \( i \)th element of an array of \( N \) elements, where \( i \) may be equal to \( N \), representing a one-past-the-end pointer. At least one of the indices \( i+\text{diff} \) or \( i+\text{diff}-1 \) must be a valid element of the same array. A pointer to a non-array object is treated as a pointer to an array of size 1.

If \( \text{diff} = 0 \), returns a copy of the global pointer. Otherwise produces a pointer that references the element that is at \( \text{diff} \) positions greater than the current element, or a one-past-the-end pointer if the last element of the array is at \( \text{diff}-1 \) positions greater than the current.

operator+= modifies the \texttt{global_ptr} in-place and returns a reference to this pointer after the operation.

These routines are purely functions of their arguments, they are not affected by the context in which they are called.

\textit{UPC++ progress level: none}

\begin{verbatim}
  template<typename T, memory_kind Kind>
  global_ptr<T, Kind>::operator-(std::ptrdiff_t diff) const;

  template<typename T, memory_kind Kind>
  global_ptr<T, Kind>&
  global_ptr<T, Kind>::operator-=(std::ptrdiff_t diff);
\end{verbatim}

Precondition: \( T \) must be a complete type. Either \( \text{diff} = 0 \), or the global pointer is pointing to the \( i \)th element of an array of \( N \) elements, where \( i \) may be equal to \( N \), representing a one-past-the-end pointer. At least one of the indices \( i-\text{diff} \) or \( i-\text{diff}-1 \) must be a valid element of the same array. A pointer to a non-array object is treated as a pointer to an array of size 1.

If \( \text{diff} = 0 \), returns a copy of the global pointer. Otherwise produces a pointer that references the element that is at \( \text{diff} \) positions less than the current element, or a one-past-the-end pointer if the last element of the array is at \( \text{diff}+1 \) positions less than the current.

operator-= modifies the \texttt{global_ptr} in-place and returns a reference to this pointer after the operation.

These routines are purely a function of their arguments, they are not affected by the context in which they are called.

\textit{UPC++ progress level: none}
template<typename T, memory_kind Kind>
std::ptrdiff_t global_ptr<T, Kind>::operator -(const T, Kind> rhs) const;

Precondition: T must be a complete type. Either *this == rhs, or this global pointer is pointing to the ith element of an array of N elements, and rhs is pointing at the jth element of the same array. Either pointer may also point one past the end of the array, so that i or j is equal to N. A pointer to a non-array object is treated as a pointer to an array of size 1.

If *this == rhs, results in 0. Otherwise, returns i-j.

This routine is purely a function of its arguments, it is not affected by the context in which it is called.

UPC++ progress level: none

template<typename T, memory_kind Kind>
global_ptr<T, Kind>& global_ptr<T, Kind>::operator ++();
template<typename T, memory_kind Kind>
global_ptr<T, Kind> global_ptr<T, Kind>::operator ++(int);
template<typename T, memory_kind Kind>
global_ptr<T, Kind>& global_ptr<T, Kind>::operator --();
template<typename T, memory_kind Kind>
global_ptr<T, Kind> global_ptr<T, Kind>::operator --(int);

Precondition: T must be a complete type. In the first two variants, the global pointer must be pointing to an element of an array or to a non-array object. In the third and fourth variants, the global pointer must either be pointing to the ith element of an array, where i >= 1, or one element past the end of an array or a non-array object.

Modifies this pointer to have the value *this + 1 in the first two variants and *this - 1 in the third and fourth variants.

The first and third variants return a reference to this pointer. The second and fourth variants return a copy of the original pointer.

This routine is purely a function of its instance, it is not affected by the context in which it is called.

UPC++ progress level: none
Returns the result of comparing two global pointers. Two global pointers compare equal if they both represent null pointers, or if they represent the same memory address with affinity to the same process. All other global pointers compare unequal.

If Kind == memory_kind::any, then two non-null global pointers compare equal only if the memory locations they reference have affinity to the same process and represent the same memory address on the same device.

A pointer to a non-array object is treated as a pointer to an array of size one. If two global pointers point to different elements of the same array, or to subobjects of two different elements of the same array, then the pointer to the element at the higher index compares greater than the pointer to the element at the lower index. If one pointer points to an element of an array or to a subobject of an element of an array, and the other pointer points one past the end of the array, then the latter compares greater than the former.

If global pointers p and q compare equal, then p == q, p <= q, and p >= q all result in true while p != q, p < q, and p > q all result in false. If p and q do not compare equal, then p != q is true while p == q is false.

If p compares greater than q, then p > q, p >= q, q < p, and q <= p all result in true while p < q, p <= q, q > p, and q >= p all result in false.

All other comparisons result in an unspecified value.
These routines are purely functions of their arguments, they are not affected by the context in which they are called.

\textit{UPC++ progress level: none}

\begin{verbatim}
namespace std {
    template <typename T, memory_kind Kind>
    struct less<global_ptr<T, Kind>>;
    template <typename T, memory_kind Kind>
    struct less_equal<global_ptr<T, Kind>>;
    template <typename T, memory_kind Kind>
    struct greater<global_ptr<T, Kind>>;
    template <typename T, memory_kind Kind>
    struct greater_equal<global_ptr<T, Kind>>;
    template <typename T, memory_kind Kind>
    struct hash<global_ptr<T, Kind>>;
}
\end{verbatim}

Specializations of STL function objects for performing comparisons and computing hash values on global pointers. The specializations of \texttt{std::less}, \texttt{std::less_equal}, \texttt{std::greater}, and \texttt{std::greater_equal} all produce a strict total order over global pointers, even if the comparison operators do not. This strict total order is consistent with the partial order defined by the comparison operators.

\textit{UPC++ progress level: none}

\begin{verbatim}
template <typename T, memory_kind Kind>
std::ostream& operator <<(std::ostream &os,
    global_ptr<T, Kind> ptr);
\end{verbatim}

Inserts an unspecified character representation of \texttt{ptr} into the output stream \texttt{os}. The textual representation of two objects of type \texttt{global_ptr<T, Kind>} is identical if and only if the two global pointers compare equal.

\textit{UPC++ progress level: none}
CHAPTER 3. GLOBAL POINTERS

93  template<typename T, typename U, memory_kind Kind>
    global_ptr<T, Kind>
    static_pointer_cast(global_ptr<U, Kind> ptr);
    template<typename T, typename U, memory_kind Kind>
    global_ptr<T, Kind>
    reinterpret_pointer_cast(global_ptr<U, Kind> ptr);
    template<typename T, typename U, memory_kind Kind>
    global_ptr<T, Kind>
    const_pointer_cast(global_ptr<U, Kind> ptr);

    Precondition: The expression static_cast<T*>((U*)nullptr) must be well-
                  formed for the first variant; reinterpret_cast<T*>((U*)nullptr) must be
                  well-formed for the second variant; const_cast<T*>((U*)nullptr) must be
                  well-formed for the third variant.

    Constructs a global pointer whose underlying raw pointer is obtained by using
    a cast expression on that of ptr. The affinity of the result is the same as that
    of ptr.

    If rp is the raw pointer of ptr, then the raw pointer of the result is constructed
    by static_cast<T*>(rp) for the first variant, reinterpret_cast<T*>(rp) for
    the second variant, and const_cast<T*>(rp) for the third.

    UPC++ progress level: none

98  template<memory_kind ToKind, typename T, memory_kind FromKind>
    global_ptr<T, ToKind>
    static_kind_cast(global_ptr<T, FromKind> ptr);
    template<memory_kind ToKind, typename T, memory_kind FromKind>
    global_ptr<T, ToKind>
    dynamic_kind_cast(global_ptr<T, FromKind> ptr);

    Precondition: ptr.is_null() || ToKind == memory_kind::any ||
                  ptr.dynamic_kind() == ToKind for the first variant

    Constructs a global pointer with kind ToKind from an existing global pointer
    with kind FromKind. It is an error if ToKind != FromKind and neither ToKind
    nor FromKind is memory_kind::any.

    In the second variant, the result is a null pointer if
    ptr.dynamic_kind() != ToKind and ToKind != memory_kind::any.

    UPC++ progress level: none
template <typename T, memory_kind Kind>
global_ptr<MType, Kind> upcxx_memberof(global_ptr<T, Kind> ptr, member_designator MEMBER)

Precondition: T must be a complete type. ptr is a pointer to a (possibly uninitialized) object of type T. T must be a standard-layout type. MEMBER is a member designator such that the expression offsetof(T, MEMBER) (using the standard library macro from <cstddef>) is well-formed and valid in the calling context.

Evaluates to a global pointer referencing the specified member of the object referenced by ptr. If MEMBER specifies a member object with array type, then this invocation evaluates to a global pointer referencing the first element of the array rather than the array itself.

The type parameter MType of the returned global pointer preserves constness in the same manner as access to MEMBER through a raw pointer of type T*. Thus, if the expression std::addressof(std::declval<T*>()->MEMBER) has the type U*, where U is not an array type, then MType is the same as U. If U is an array type W[Dim1]...[DimN], then MType is W.

The result of applying the upcxx_memberof macro to a static data member or a function member is undefined.

UPC++ progress level: none

template <typename T, memory_kind Kind>
future<global_ptr<MType, Kind>> upcxx_memberof_general(global_ptr<T, Kind> ptr, member_designator MEMBER)

Precondition: T must be a complete type. ptr is a pointer to an object of type T. MEMBER is a member designator such that given a valid T* lp referencing the target object, the expression lp->MEMBER is well-formed and valid in the calling context. The expression lp->MEMBER must not have reference type.

Computes a global pointer referencing the specified member of the object referenced by ptr, using the most efficient mechanism available, and evaluates to a future encapsulating that pointer. If the result is determined using purely local information, then the progress level is none and the result is a readied future.
Otherwise, the progress level is internal and the resulting future will be readied during a subsequent user-level progress for the calling persona.

If MEMBER specifies a member object with array type, then this invocation evaluates to a global pointer referencing the first element of the array rather than the array itself.

The type parameter MType of the global pointer encapsulated in the returned future is as described in the specification of upcxx_memberof.

The result of applying the upcxx_memberof_general macro to a static data member or a function member is undefined.

Advice to users: The preconditions of this macro may prohibit applying it to objects residing in storage allocated from a cuda_device whose type hierarchy includes virtual base classes, due to restrictions of the CUDA model.

Advice to users: The preconditions of this macro prohibit MEMBER from specifying an array element. Instead, a pointer to an array element ARRAY[idx] can be constructed by using upcxx_memberof_general to access the array itself, producing a pointer to the base element of the array, and then adding the offset of the desired element:

```cpp
upcxx_memberof_general(ptr, ARRAY).then(
   [=](global_ptr<ElementType> gp) {
      return gp + idx;
   })
```

UPC++ progress level: none or internal
Chapter 4

Storage Management

4.1 Overview

1 UPC++ provides several flavors of storage allocation involving the shared segment:

2 • The pair of functions new_ and delete_ respectively allocate and deallocate space for one object with dynamic storage duration in the shared segment of the calling process and respectively invoke the object constructor/destructor. These are the shared segment analog of C++’s traditional new and delete operators for non-array types.

3 • The functions new_array and delete_array respectively allocate and deallocate space for a typed array of objects with dynamic storage duration in the shared segment of the calling process. Array elements allocated by new_array are default initialized, and delete_array invokes destructors on the elements. These are the shared segment analog of C++’s traditional new and delete operators for array types.

4 • The functions allocate and deallocate allocate and deallocate memory with dynamic storage duration from the shared segment of the calling process, but do not initialize the memory or invoke C++ constructors/destructors. Callers are responsible for initializing the memory and invoking any constructors (for example, via placement new) and destructors. These are the shared segment analog of std::malloc and std::free.
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4.2 API Reference

```cpp
class bad_shared_alloc : public std::bad_alloc;
```

An exception type derived from `std::bad_alloc` that is thrown by some shared heap allocation functions to indicate failure to allocate shared storage.

```cpp
template<typename T, typename ...Args>
global_ptr<T> new_(Args &...args);
```

*Precondition:* `T(args...)` must be a valid call to a constructor for `T`. `T` must not be an array type.

Allocates space for an object of type `T` from the shared segment of the calling process. If the allocation succeeds, returns a pointer to the start of the allocated memory, and the object is initialized by invoking the constructor `T(args...)`. If the allocation fails, throws `upcxx::bad_shared_alloc`.

*Exceptions:* May throw `upcxx::bad_shared_alloc` or any exception thrown by the call `T(args...)`.

*UPC++ progress level:* none

```cpp
template<typename T, typename ...Args>
global_ptr<T> new_(const std::nothrow_t &tag, Args &...args);
```

*Precondition:* `T(args...)` must be a valid call to a constructor for `T`. `T` must not be an array type.

Allocates space for an object of type `T` from the shared segment of the calling process. If the allocation succeeds, returns a pointer to the start of the allocated memory, and the object is initialized by invoking the constructor `T(args...)`. If the allocation fails, returns a null pointer.

*Exceptions:* May throw any exception thrown by the call `T(args...)`.

*UPC++ progress level:* none
\texttt{template<typename \ T>}
\texttt{global\_ptr<\ T> new\_array(size\_t \ n);}

\textit{Precondition:} \ T \text{ must be DefaultConstructible.} \ T \text{ must not be an array type.}

Allocates space for an array of \ n \ objects of type \ T \ from the shared segment of the calling process. If the allocation succeeds, returns a pointer to the start of the allocated memory, and the objects are default initialized\textsuperscript{1}. If the allocation fails, throws \texttt{upcxx::bad\_shared\_alloc}.

\textit{Exceptions:} May throw \texttt{upcxx::bad\_shared\_alloc} or any exception thrown by the call \texttt{T().} If an exception is thrown by the constructor for \ T, then previously initialized elements are destroyed in reverse order of construction.

\textit{UPC++ progress level: none}

\texttt{template<typename \ T>}
\texttt{global\_ptr<\ T> new\_array(size\_t \ n, const std::nothrow_t &tag);}

\textit{Precondition:} \ T \text{ must be DefaultConstructible.} \ T \text{ must not be an array type.}

Allocates space for an array of \ n \ objects of type \ T \ from the shared segment of the calling process. If the allocation succeeds, returns a pointer to the start of the allocated memory, and the objects are default initialized. If the allocation fails, returns a null pointer.

\textit{Exceptions:} May throw any exception thrown by the call \texttt{T().} If an exception is thrown by the constructor for \ T, then previously initialized elements are destroyed in reverse order of construction.

\textit{UPC++ progress level: none}

\textsuperscript{1}This behavior is analogous to C++ operator \texttt{new} for array types, and should not be be confused with value initialization. Default initialization implies that when \ T \ is a class type, the elements will have their default constructors invoked, but when \ T \ is a non-class type, the elements are not initialized and will have indeterminate values.
template<typename T>
void delete_(global_ptr<T> g);

Precondition: T must be Destructible. g must be either a null pointer or a
non-deallocated pointer that resulted from a call to new_<T, Args...> on the
calling process, for some value of Args....

If g is not a null pointer, invokes the destructor on the given object and deal-
locates the storage allocated to it. Does nothing if g is a null pointer.

Exceptions: May throw any exception thrown by the the destructor for T.

UPC++ progress level: none

template<typename T>
void delete_array(global_ptr<T> g);

Precondition: T must be Destructible. g must be either a null pointer or a non-
deallocated pointer that resulted from a call to new_array<T> on the calling
process.

If g is not a null pointer, invokes the destructor on each object in the given
array and deallocates the storage allocated to it. Does nothing if g is a null pointer.

Exceptions: May throw any exception thrown by the the destructor for T.

UPC++ progress level: none

void* allocate(size_t size,
        size_t alignment = alignof(std::max_align_t));

Precondition: alignment is a valid alignment. size must be an integral mul-
tiple of alignment.

Allocates size bytes of memory from the shared segment of the calling process,
with alignment as specified by alignment. If the allocation succeeds, returns
a pointer to the start of the allocated memory, and the allocated memory is
uninitialized. If the allocation fails, returns a null pointer.

UPC++ progress level: none
template<typename T>
global_ptr<T> allocate(size_t n = 1,
        size_t alignment = alignof(T));

Precondition: alignment is a valid alignment.

Allocates enough space for \( n \) objects of type \( T \) from the shared segment of the calling process, with the memory aligned as specified by \( \text{alignment} \). If the allocation succeeds, returns a pointer to the start of the allocated memory, and the allocated memory is uninitialized. If the allocation fails, returns a null pointer.

\textit{UPC++ progress level: none}

void deallocate(void* p);

Precondition: \( p \) must be either a null pointer or a non-deallocated pointer that resulted from a call to the first form of \texttt{allocate} on the calling process.

Deallocates the storage previously allocated by a call to \texttt{allocate}. Does nothing if \( p \) is a null pointer.

\textit{UPC++ progress level: none}

template<typename T>
void deallocate(global_ptr<T> g);

Precondition: \( g \) must be either a null pointer or a non-deallocated pointer that resulted from a call to \texttt{allocate}\( <T, \text{alignment}\rangle \) on the calling process, for some value of \texttt{alignment}.

Deallocates the storage previously allocated by a call to \texttt{allocate}. Does nothing if \( g \) is a null pointer. Does not invoke the destructor for \( T \).

\textit{UPC++ progress level: none}
49 std::int64_t shared_segment_size();

Requests a snapshot of the total size of the shared segment for the calling process.

Implementations are permitted to return unspecified negative values, which indicate the query is unsupported or encountered some other error.

Otherwise, a positive return value indicates the current total size, in bytes, of the shared segment for the calling process. This total size reflects an upper bound on the sum of space consumed by all shared objects allocated but not yet deallocated by the calling process, space available for servicing subsequent such requests, and unspecified implementation overheads (including but not limited to, padding around allocated objects and objects allocated by the implementation).

Return values may vary across processes or across calls on a given process in unspecified ways.

UPC++ progress level: none

55 std::int64_t shared_segment_used();

Requests a snapshot of the occupied size of the shared segment for the calling process.

Implementations are permitted to return unspecified negative values, which indicate the query is unsupported or encountered some other error.

Otherwise, a positive return value indicates the current occupied size, in bytes, of the shared segment for the calling process. This occupied size reflects an upper bound on the sum of space consumed by all shared objects allocated but not yet deallocated by the calling process and unspecified implementation overheads (including but not limited to, padding around allocated objects and objects allocated by the implementation).

Return values may vary across processes or across calls on a given process in unspecified ways.

UPC++ progress level: none
Chapter 5

Futures and Promises

5.1 Overview

1 In UPC++, the primary mechanisms by which a programmer interacts with non-blocking operations are futures and promises.1 These two mechanisms, usually bound together under the umbrella concept of futures, are present in the C++11 standard. However, while we borrow some of the high-level concepts of C++’s futures, many of the semantics of upcxx::future and upcxx::promise differ from those of std::future and std::promise. In particular, while futures in C++ facilitate communicating between threads, the intent of UPC++ futures is solely to provide an interface for managing and composing non-blocking operations, and they cannot be used directly to communicate between threads or processes.

2 A non-blocking operation is associated with a state that encapsulates both the status of the operation as well as any result values. Each such operation has associated promise objects, which can either be explicitly created by the user or implicitly by the runtime when a non-blocking operation is invoked. A promise represents the producer side of the operation, and it is through a promise that the results of the operation are supplied and its dependencies fulfilled. A future is the interface through which the status of the operation can be queried and the results retrieved, and multiple future and promise objects may be associated with the same underlying operation. A future thus represents the consumer side of a non-blocking operation.

---

1 Another mechanism, persona-targeted callbacks, is discussed in §10.4.
5.2 The Basics of Asynchronous Communication

1 A programmer can invoke a non-blocking operation to be serviced by another process, such as a one-sided get operation (Ch. 8) or a remote procedure call (Ch. 9). Such an operation creates an implicit promise and returns an associated future object to the user. When the operation completes, the future becomes ready, and it can be used to access the results. The following demonstrates an example using a remote get (see Ch. 10 on how to make progress with UPC++):

```cpp
1 global_ptr<double> ptr = /* obtain some remote pointer */;
2 future<double> fut = rget(ptr); // initiate a remote get
3 // ...call into upcxx::progress() elided...
4 if (fut.ready()) {
5    double value = fut.result(); // retrieve result
6    std::cout << "got: " << value << '\n'; // use result
7 }
```

2 In general, a non-blocking operation will not complete immediately, so if a user needs to wait on the readiness of a future, they must do so in a loop. To facilitate this, we provide the wait member function, which waits on a future to complete while ensuring that sufficient progress (Ch. 10) is made on internal and user-level state:

```cpp
1 global_ptr<double> ptr = /* obtain some remote pointer */;
2 future<double> fut = rget(ptr); // initiate a remote get
3 double value = fut.wait(); // wait for completion and retrieve result
4 std::cout << "got: " << value << '\n'; // use result
```

3 An alternative to waiting for completion of a future is to attach a callback or completion handler to the future, to be executed when the future completes. This callback can be any function object, including lambda (anonymous) functions, that can be called on the results of the future, and is attached using then.

```cpp
1 global_ptr<double> ptr = /* obtain some remote pointer */;
2 auto fut =
3     rget(ptr).then( // initiate a remote get and register a callback
4                     // lambda callback function
5                     [](double value) {
6             std::cout << "got: " << value << '\n'; // use result
7         }
8     );
```
The return value of `then` is another future representing the results of the callback, if any. This permits the specification of a sequence of operations, each of which depends on the results of the previous one.

A future can also represent the completion of a combination of several non-blocking operations. Unlike the standard C++ future, `upcxx::future` is a variadic template, encapsulating an arbitrary number of result values that can come from different operations. The following example constructs a future that represents the results of two existing futures:

```cpp
future<double> fut1 = /* one future */;
future<int> fut2 = /* another future */;
future<double, int> combined = when_all(fut1, fut2);
```

Here, `combined` represents the state and results of two futures, and it will be ready when both `fut1` and `fut2` are ready. The results of `combined` are a `std::tuple` whose components are the results of the source futures.

### 5.3 Working with Promises

In addition to the implicit promises created by non-blocking operations, a user may explicitly create a promise object, obtain associated future objects, and then register non-blocking operations on the promise. This is useful in several cases, such as when a future is required before a non-blocking operation can be initiated, or where a single promise is used to count dependencies.

A promise can also be used to count *anonymous dependencies*, keeping track of operations that complete without producing a value. Upon creation, a promise has a dependency count of one, representing the unfulfilled results or, if there are none, an anonymous dependency. Further anonymous dependencies can then be registered on the promise. When registration is complete, the original dependency can then be fulfilled to signal the end of registration. The following example keeps track of several remote put operations with a single promise:

```cpp
global_ptr<int> ptrs[10] = /* some remote pointers */;
// create a promise with no results
// the dependency count starts at one
promise<> prom;

// do 10 puts, registering each of them on the promise
for (int k = 0; k < 10; k++) {
    // rput implicitly registers itself on the given promise
    rput(k, ptrs[k], operation_cx::as_promise(prom));
}
5.4 Advanced Callbacks

Polling for completion of a future allows simple overlap of communication and computation operations. However, it introduces the need for synchronization, and this requirement can diminish the benefits of overlap. To this end, many programs can benefit from the use of callbacks. Callbacks avoid the need for an explicit wait and enable reactive control flow: future completion triggers a callback. Callbacks allow operations to occur as soon as they are capable of executing, rather than artificially waiting for an unrelated operation to complete before being initiated.

Futures are the core abstraction for obtaining asynchronous results, and an API that supports asynchronous behavior can work with futures rather than values directly. Such an API can also work with immediately available values by having the caller wrap the values into a ready future using the `make_future` function template, as in this example that creates a future for an ordered pair of a `double` and an `int`:

```cpp
void consume(future<int, double> fut);
consume(make_future(3, 4.1));
```

Given a future, we can attach a callback to be executed at some subsequent point when the future is ready using the `then` member function:

```cpp
future<int, double> source = /* obtain a future */;
future<double> result = source.then(
    [](int x, double y) {
    return x + y;
    });
```

In this example, `source` is a future representing an `int` and a `double` value. The argument of the call to `then` must be a function object that can be called on these values. Here, we use a lambda function that takes in an `int` and a `double`. The call to `then` returns a future that represents the result of calling the argument of `then` on the values contained
in source. Since the lambda function above returns a double, the result of then is a future<double> that will hold the double's value when it is ready.

Instead of returning a plain value, the callback function passed to then may directly return a future. In this case, the future returned by then has the same type as the future returned by the callback, and both futures represent the same set of results. The future returned by then will be readied when two conditions are met: the invocation of the callback function has completed, and the future returned by the callback has itself been readied.

```
future<int, double> source = /* obtain a future */;
future<double> result = source.then(
    [](int x, double y) {
        // return a future<double> that is ready
        return make_future(x + y);
    });
// result may not be ready, since the callback will not be executed
// until source is ready
```

In the example above, the future returned by then is readied as soon as the callback completes its execution, since the callback returns a ready future. The future returned by then encapsulates the values passed to make_future.

A callback may also initiate new asynchronous work and return a future representing the completion of that work:

```
global_ptr<int> remote_array = /* some remote array */;

// retrieve remote_array[0]
future<int> elt0 = rget(remote_array);

// retrieve remote_array[remote_array[0]]
future<int> elt_indirect = elt0.then(
    [=](int index) {
        return rget(remote_array + index);
    });
```

In this example, a callback is chained onto the result of the first call to rget. The future returned by the callback only becomes ready after the operation initiated by the rget contained within the callback completes. Thus, elt_indirect will be made ready after all of the following:
• The operation initiated by the first `rget` completes, producing the value to be passed to the callback.

• The invocation of the callback completes, returning a future that represents the eventual results of the second `rget`.

• The operation initiated by the second `rget` completes, producing the final `int` value.

The final `int` value is the result encapsulated by `elt_indirect`. This example demonstrates how the UPC++ programmer can chain the results of one asynchronous operation into the inputs of the next, to arbitrary degree of nesting.

The `then` member function is a combinator for constructing pipelines of transformations over futures. Given a future and a function that transforms that future’s value into another value, `then` produces a future representing the transformed value. For example, we can transform, via a future, the value of `elt_indirect` above as follows:

```cpp
future<int> elt_indirect_squared = elt_indirect.then(
    [](int value) {
        return value * value;
    }
);
```

As the examples above demonstrate, the `then` member function allows a callback to depend on the result of another future. A more general pattern is for an operation to depend on the results of multiple futures. The `when_all` function template enables this by constructing a single future that combines the results of multiple futures. We can then register a callback on the combined future:

```cpp
future<int> value1 = /* ... */;
future<double> value2 = /* ... */;
future<int, double> combined = when_all(value1, value2);
future<double> result = combined.then(
    [](int x, double y) {
        return x + y;
    }
);
```

In the more general case, we may need to combine heterogeneous mixtures of future and non-future types. The `when_all` function template also permits non-future values to be passed in as arguments. Thus, we can use `when_all` to construct a single future that represents the combination of both future and non-future values:
future<int> value1 = /* ... */;
double value2 = /* ... */;

future<int, double> combined = when_all(value1, value2);
future<double> result = combined.then(
    [](int x, double y) {
        return x + y;
    }
);

5.5 Execution Model

While some software frameworks provide thread-level parallelism by considering each callback to be a task that can be run in an arbitrary worker thread, this is not the case in UPC++. In order to maximize performance, our approach to futures is purposefully ambivalent to issues of concurrency. A UPC++ implementation is allowed to take action as if the current thread is the only one that needs to be accounted for. This restriction gives rise to a natural execution policy: callbacks registered against futures are always executed as soon as possible by the thread that discovers them. There are exactly two scenarios in which this may happen:

1. When a promise is fulfilled.
2. A callback is registered onto a ready future using the then member function.
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2 Fulfilling a promise (via fulfill_result, fulfill_anonymous or finalize) is the only operation that can change an associated future from a non-ready to a ready state, enabling callbacks that depend on it to execute. Thus, promise fulfillment is an obvious place for discovering and executing such callbacks. Whenever a thread calls a fulfillment function on a promise, the user must anticipate that any newly available callbacks will be executed by the current thread before the fulfillment call returns.

3 The other place in which a callback will execute immediately is during the invocation of then on a future that is already in its ready state. In this case, the callback provided will fire immediately during the call to then.

4 There are some common programming contexts where it is not safe for a callback to execute during fulfillment of a promise. For example, it is generally unsafe to execute a callback that modifies a data structure while a thread is traversing the data structure. In such a situation, it is the user’s responsibility to ensure that a conflicting callback will not execute. One solution is create a promise that represents a thread reaching its safe-to-execute context, and then adding it to the dependency list of any conflicting callback.

```cpp
future<int> value = /* ... */;
// create a promise representing a safe-to-execute state
// dependency count is initially 1
promise<> safe_state;
// create a future that depends on both value and safe_state
future<int> combined = when_all(value, safe_state.get_future());
auto fut = // register a callback on the combined future
combined.then(/* some callback that requires a safe state */);
// do some work, potentially fulfilling value’s promise...
// signify a safe state
safe_state.finalize();
// callback can now execute
```

5 As demonstrated above, the user can wait to fulfill the promise until it is safe to execute the callback, which will then allow it to execute.

5.6 Fulfilling Promises

1 As demonstrated previously, promises can be used to both supply values as well as signal completion of events that do not produce a value. As such, a promise is a unified abstraction for tracking the completion of asynchronous operations, whether the operations produce a value or not. A promise represents at most one dependency that produces a value, but it can track any number of anonymous dependencies that do not result in a value.
When created, a promise starts with an initial dependency count of 1. For an empty promise (\texttt{promise<>>}), this is necessarily an anonymous dependency, since an empty promise does not hold a value. For a non-empty promise, the initial count represents the sole dependency that produces a value. Further anonymous dependencies can be explicitly registered on a promise with the \texttt{require\_anonymous} member function:

\begin{verbatim}
 promise<int, double> pro; // initial dependency count is 1
 pro.require_anonymous(10); // dependency count is now 11
\end{verbatim}

The argument to \texttt{require\_anonymous} must be nonnegative and the promise’s current dependency count must be greater than zero, so that a call to \texttt{require\_anonymous} never causes the dependency count to reach zero, which would put the promise in the fulfilled state. In the example above, the argument must be greater than -1, and the given argument of 10 is valid.

Anonymous dependencies can be fulfilled by calling the \texttt{fulfill\_anonymous} member function:

\begin{verbatim}
 for (int k = 0; k < 5; i++) {
   pro.fulfill_anonymous(k);
 } // dependency count is now 1
\end{verbatim}

A non-anonymous dependency is fulfilled by calling \texttt{fulfill\_result} with the produced values:

\begin{verbatim}
 pro.fulfill_result(3, 4.1); // dependency count is now 0
 assert(pro.get_future().ready());
\end{verbatim}

Both empty and non-empty promises can be used to track anonymous dependencies. A \texttt{UPC++} operation that operates on a promise \textit{always} increments its dependency count upon invocation, as if by calling \texttt{require\_anonymous(1)} on the promise. After the operation completes\footnote{The notification will occur during user-level progress of the persona that initiates the operation. See Ch. 10 for more details.}, if the completion produces values of type \texttt{T...}, then the values are supplied to the promise through a call to \texttt{fulfill\_result}. Otherwise, the completion is signaled by fulfilling an anonymous dependency through a call to \texttt{fulfill\_anonymous(1)}.

The rationale for this behavior is to free the user from having to manually increment the dependency count before calling an operation on a promise; instead, \texttt{UPC++} will implicitly perform this increment. This leads to the pattern, shown at the beginning of this chapter, of registering operations on a promise and then finalizing the promise to take it out of registration mode:
global_ptr<int> ptrs[10] = /* some remote pointers */;
promise<> prom; // dependency count is 1

for (int i = 0; i < 10; i++) {
    rput(i, ptrs[i],
        operation_cx::as_promise(prom)); // increment count
} // dependency count is now 11

future<> fut = prom.finalize(); // decrement count, making it 10

// wait for the 10 rput operations to complete
fut.wait();

A user familiar with UPC++ V0.1 will observe that empty promises subsume the capabilities of events in UPC++ V0.1. In addition, they can take part in all the machinery of promises, futures, and callbacks, providing a much richer set of capabilities than were available in V0.1.

5.7 Lifetime and Thread Safety

Understanding the lifetime of objects in the presence of asynchronous control flow can be tricky. Objects must outlive the last callback that references them, which in general does not follow the scoped lifetimes of the call stack. For this reason, UPC++ automatically manages the state represented by futures and promises, and the state persists for as long as there is a future, promise, or dependent callback that references it. Thus, a user can construct intricate webs of callbacks over futures without worrying about explicitly managing the state representing the callbacks’ dependencies or results.

Though UPC++ does not prescribe a specific management strategy, the semantics of futures and promises are analogous to those of standard C++11 smart pointers. As with std::shared_ptr, futures and promises may be freely copied, and both the original and the copy represent the same state and are associated with the same underlying set of dependencies and callbacks. Thus, if one copy of a future becomes ready, then so will the other copies, and if a dependency is fulfilled on one copy of a promise, it is fulfilled on the others as well.

Given that UPC++ futures and promises are already thread-unaware to allow the execution strategy to be straightforward and efficient, UPC++ also makes no thread safety guarantees about internal state management. This enables creation of copies of a future or promise to be a very cheap operation. For example, a future or promise can be captured by value by
a lambda function\(^3\) or passed by value without any performance penalties. On the other hand, the lack of thread safety means that sharing a future or promise between threads must be handled with great caution. Even a simple operation such as making a copy of a future or promise, as when passing it by value to a function, is unsafe if another thread is concurrently accessing an identical future or promise, since the act of copying it can modify the internal management state. Thus, a mutex or other synchronization is required to ensure exclusive access to a future or promise when performing any operation on it.

Fulfilling a promise gives rise to an even more stringent demand, since it can set off a cascade of callback execution. Before fulfilling a promise, the user must ensure that the thread has the exclusive right to mutate not just the future associated with the promise, but all other futures that are directly or indirectly dependent on fulfillment of the promise. Thus, when crafting their code, the user must properly manage exclusivity for islands of disjoint futures. We say that two futures are in disjoint islands if there is no dependency, direct or indirect, between them.

A reader having previous experience with futures will note that UPC++’s formulation is a significant departure from many other software packages. Futures are commonly used to pass data between threads, like a channel that a producing thread can supply a value into, notifying a consuming thread of its availability. UPC++, however, is intended for high-performance computing, and supporting concurrently shareable futures would require synchronization that would significantly degrade performance. As such, futures in UPC++ are not intended to directly facilitate communication between threads. Rather, they are designed for a single thread to manage the non-determinism of reacting to the events delivered by concurrently executing agents, be they other threads or the network hardware.

### 5.8 API Reference

1. **UPC++ progress level for all functions in this chapter (unless otherwise noted) is: none**

2. In this and subsequent API-reference sections, \texttt{FType} denotes a future type, and \texttt{EType} denotes a non-future type derived from the element types of a future. The actual types denoted by \texttt{FType} and \texttt{EType} differ between uses and are explained in the API descriptions in which they are used.

3. Futures and promises are not TriviallySerializable (or even Serializable) (Ch. 6), so they cannot be captured by copy in a lambda expression that is passed to a remote procedure call (Ch. 9) or an RPC completion (Ch. 7).
5.8.1 future

```cpp
template<typename ...T>
class future;

C++ Concepts: DefaultConstructible, CopyConstructible, CopyAssignable, Destructible

The types in T must be complete types (and not void). Several member functions impose stricter requirements on T.

```cpp
template<typename ...T>
future<T...>::future();
```

Constructs a future that will never become ready.

This function may be called when UPC++ is in the uninitialized state.

```cpp
template<typename ...T>
future<T...>::~future();
```

Destructs this future object.

This function may be called when UPC++ is in the uninitialized state.

```cpp
template<typename ...T>
future<T...> make_future(T ...results);
```

Precondition: Each component of T must be MoveConstructible.

Constructs a trivially ready future from the given values.

```cpp
template<typename ...T>
bool future<T...>::ready() const;
```

Returns true if the future’s result values have been supplied to it.

```cpp
template<typename ...T>
std::tuple<T...> future<T...>::result_tuple() const;
```

Precondition: this->ready(). Each component of T must be CopyConstructible.

Retrieves the tuple of result values for this future.
template<typename ...T>
template<int I=-1>
EType future<T...>::result() const;

Precondition: this->ready(). If EType is non-void, each component of EType
must be CopyConstructible.

If I is in the range [0, sizeof...(T)), retrieves the I\textsuperscript{th} component from the
future’s results tuple. The return type EType is the I\textsuperscript{th} component of T.

If I is -1, returns the following:

- void if T is empty
- if T has one element, the single component of the future’s results tuple;
  the return type is T
- if T has multiple elements, the tuple of result values for the future; the
  return type is std::tuple<T...>

The return type is void if I is outside the range [-1, sizeof...(T)).

template<typename ...T>
template<int I=-1>
EType future<T...>::result_reference() const;

Precondition: this->ready()

If I is in the range [0, sizeof...(T)), retrieves the I\textsuperscript{th} component from the
future’s results tuple as a reference. If the I\textsuperscript{th} component of T has type U, the
return type of this function is:

- U if U is of reference type
- const U& if U is of non-reference type

If I is -1, returns the following:

- void if T is empty
- if T has one element, the single component of the future’s results tuple as
  a reference; if the component has type U, the return type of this function
  is:
  - U if U is of reference type
  - const U& if U is of non-reference type
• if \( T \) has multiple elements, the tuple of result values for the future as references; the return type is \( \text{std::tuple<V...>} \), where if the \( n^{\text{th}} \) component of \( T \) has type \( U \), then the \( n^{\text{th}} \) component of \( V \) has type:
  
  - \( U \) if \( U \) is of reference type
  
  - \( \text{const } U\& \) if \( U \) is of non-reference type

The return type is \textit{void} if \( I \) is outside the range \([-1, \text{sizeof...}(T))\).

\[
\text{template<typename ...T>}
\text{template<typename Func>}
\text{FType future<T...>::then(Func \&\&func) const;}
\]

\textbf{Preconditions:}

• If \( \text{Func}\&\& \) is an rvalue-reference type, the underlying decayed type \((\text{std::decay<Func}\&\&):\text{type})\) must be \text{MoveConstructible}.

• If \( \text{Func}\&\& \) is an lvalue-reference type, the underlying decayed type \((\text{std::decay<Func}\&\&):\text{type})\) must be \text{CopyConstructible}.

• \( \text{func} \) must be invokable on a sequence of \( \text{sizeof...}(T) \) arguments, where if the \( n^{\text{th}} \) component of \( T \) has type \( U \), then the \( n^{\text{th}} \) argument provided to \( \text{func} \) has type:

  - \( U \) if \( U \) is of reference type

  - \( \text{const } U\& \) if \( U \) is of non-reference type

• If the return type \( \text{RetType} \) of \( \text{func} \) is of non-reference or rvalue-reference type, the underlying decayed type \((\text{std::decay<RetType>}:\text{type})\) must be \text{MoveConstructible}.

• The invocation of \( \text{func} \) must not throw an exception.

Returns a new future representing the return value of the given function object \( \text{func} \) when invoked on the results of this future as its argument list. The return type \( \text{FType} \) and return value are as follows:

• If \( \text{func} \) returns a future type \( \text{future<U...>} \), then \( \text{FType} \) is also \( \text{future<U...>} \). The future returned by \text{then} encapsulates the same set of results as the future returned by \( \text{func} \). The future returned by \text{then} is readied when both the invocation of \( \text{func} \) has completed and the future returned by that invocation has been made ready.
If \( \text{func} \) returns a non-future, non-
void type \( U \), then \( \text{FType} \) is \( \text{future}<U> \).
The future returned by \( \text{then} \) encapsulates the result of \( \text{func} \), and it is readied upon completion of
the invocation of \( \text{func} \).

If \( \text{func} \) has void return type, then \( \text{FType} \) is \( \text{future}<\> \). The future returned
by \( \text{then} \) encapsulates whether or not the invocation of \( \text{func} \) has completed,
and it is readied upon completion of that invocation.

The function object will be invoked in one of two situations:

- Immediately before \( \text{then} \) returns if this future is in the ready state.
- During a promise fulfillment which would directly or indirectly make this future transition to the ready state.

```
template<typename ...T>
std::tuple<T...> future<T...>::wait_tuple() const;
```

*Precondition:* Each component of \( T \) must be CopyConstructible.

Blocks until the future is ready, while making UPC++ user-level progress. See Ch. 10 for a discussion of progress. The return value is the same as that produced by calling \( \text{result_tuple}() \) on the future.

*This function may not be invoked from the restricted context (§10.2).*

*UPC++ progress level: user*

```
template<typename ...T>
template<int I=-1>
EType future<T...>::wait() const;
```

*Precondition:* If \( \text{EType} \) is non-void, each component of \( \text{EType} \) must be Copy-
Constructible.

Blocks until the future is ready, while making UPC++ user-level progress. See Ch. 10 for a discussion of progress. The return value is the same as that produced by calling \( \text{result}<I>() \) on the future.

*This function may not be invoked from the restricted context (§10.2).*

*UPC++ progress level: user*
template <typename ...T>
    template <int I = -1>
    EType future<T...>::wait_reference() const;

Blocks until the future is ready, while making UPC++ user-level progress. See Ch. 10 for a discussion of progress. The return value is the same as that produced by calling result_reference<I>() on the future.

This function may not be invoked from the restricted context (§10.2).

UPC++ progress level: user

template <typename ...T>
    future<ETypes...> when_all(T&& ...futures_or_values);

Precondition: For any future type future<U...> in T, each argument type U must be CopyConstructible. Each non-future type in T must be MoveConstructible.

Given a variadic list of arguments consisting of futures and non-future values, constructs a future representing the readiness of all arguments. The results tuple of this future will consist of the concatenation of the results or non-future values represented by each argument. The type parameters of the returned object (ETypes...) is the ordered concatenation of the following over each component of T:

- U... if the n<sup>th</sup> component of T is a future type or a reference to a future type future<U...>
- U if the n<sup>th</sup> component of T is a non-future type or a reference to a non-future type U

If T... is empty, then the result is a trivially ready future<>.

template <typename T>
    future<ETypes...> to_future(T future_or_value);

Precondition: T must be MoveConstructible if it is a non-future type.

Constructs a future that encapsulates the value represented by future_or_value. If T is of type future<U...>, then ETypes... is the same as U..., and the returned future is a copy of future_or_value. If T is not a future, then the call to_future(arg) is semantically equivalent to make_future(arg). In this case, ETypes... is T, and the function returns a ready future whose encapsulated value is future_or_value.
5.8.2 promise

1 template<typename ...T>
   class promise;

2 C++ Concepts: DefaultConstructible, CopyConstructible, CopyAssignable, Destructible

3 The types in T must be complete types (and not void). Several member functions impose stricter requirements on T.

4 template<typename ...T>
   promise<T...>::promise(std::intptr_t dependency_count=1);

5 Precondition: dependency_count >= 1

6 Constructs a promise with its results uninitialized and the given initial dependency count. The state of the resulting promise is independent of all existing promises.

7 This function may be called when UPC++ is in the uninitialized state.

8 template<typename ...T>
   promise<T...>::~promise();

9 Destructs this promise object.

10 This function may be called when UPC++ is in the uninitialized state.

11 template<typename ...T>
   void promise<T...>::require_anonymous(std::intptr_t count) const;

12 Precondition: count is nonnegative. The dependency count of this promise is greater than 0.

13 Adds count to this promise’s dependency count.
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14 \texttt{template<typename \ldots T>}
\texttt{template<typename \ldots U>}
\texttt{void promise<T\ldots>::fulfill_result(U \&\ldots results) const;}

15 \textit{Precondition:} fulfill\_result has not been called on this promise or a copy of this promise before, and the dependency count of this promise is greater than zero. T and U must have the same number of components, and each component of T must be constructible from the corresponding component of U (i.e., std::is\_constructible<std::tuple<T\ldots>, U&&\ldots>::value must be true).

16 Initializes the promise’s result tuple with the given values and decrements the dependency counter by 1. If the dependency counter reaches zero as a result of this call, the associated future is set to ready, and callbacks that are waiting on the future are executed on the calling thread before this function returns.

17 \texttt{template<typename \ldots T>}
\texttt{void promise<T\ldots>::fulfill_anonymous(std::intptr\_t count) const;}

18 \textit{Precondition:} count is nonnegative. The dependency count of this promise is greater than zero and greater than or equal to count. If the dependency count is equal to count and T is not empty, then the results of this promise must have been previously supplied by a call to fulfill\_result.

19 Subtracts count from the dependency counter. If this produces a zero counter value, the associated future is set to ready, and callbacks that are waiting on the future are executed on the calling thread before this function returns.

20 \texttt{template<typename \ldots T>}
\texttt{future<T\ldots> promise<T\ldots>::get_future() const;}

21 Returns the future representing this promise being fulfilled. Repeated calls to get\_future return equivalent futures with the guarantee that no additional memory allocation is performed.

22 \texttt{template<typename \ldots T>}
\texttt{future<T\ldots> promise<T\ldots>::finalize() const;}

23 Equivalent to calling this->fulfill\_anonymous(1) and then returning the result of this->get\_future.
Chapter 6

Serialization

As a communication library, UPC++ needs to send C++ objects between processes that might be separated by a network interface. The underlying GASNet networking interface sends and receives bytes, thus, UPC++ needs to be able to convert C++ objects to and from bytes.

UPC++ communication operations such as remote procedure calls (Ch. 9) serialize C++ objects, converting them to raw bytes, before sending the data to the destination. Upon receiving the data at the destination, the library deserializes the raw bytes back into C++ objects. We refer to the data channel between the sender and receiver of an operation as a byte stream; the sender writes data sequentially to the stream, and the receiver sequentially reads data out of it.

6.1 Serialization Concepts

UPC++ defines the concepts TriviallySerializable and Serializable that describe what form of serialization a C++ type supports. Figure 6.1 helps summarize the relationship of these concepts.

A type T is TriviallySerializable if it is semantically valid to copy an object by copying its underlying bytes. UPC++ serializes such types by making a byte copy.

A type T is considered TriviallySerializable if either of the following holds:

- T is TriviallyCopyable (i.e. std::is_trivially_copyable<T>::value is true), and
- (if T is of class type) T does not implement any class serialization interface described in §6.2
• `upcxx::is_trivially_serializable<T>` is specialized to provide a member constant value that is `true`.

5 In the latter case, UPC++ treats the type T as if it were TriviallyCopyable for the purposes of serialization. Thus, UPC++ will serialize an object of type T by making a byte copy, and it will assume T is TriviallyDestructible when destroying a deserialized object of type T.

6 A type T is considered Serializable if one of the following holds:

• T is TriviallySerializable

7 The type trait `upcxx::is_trivially_serializable<T>` provides a member constant value that is `true` if T is TriviallySerializable and `false` otherwise. This trait may be specialized for user types (types that are not defined by the C++ or UPC++ standards).

11 The type trait `upcxx::is_serializable<T>` provides a member constant value that is `true` if T is Serializable and `false` otherwise. This trait may not be specialized by the user for any types.

12 Several UPC++ communication operations require that the objects to be transferred are of TriviallySerializable type. The C++ standard allows implementations to determine whether or not lambda function objects are TriviallyCopyable, so whether or not such objects are TriviallySerializable is implementation-dependent.

13 Serializability of a type T does not imply that objects of type T are meaningful on another process. In particular, C++ pointer-to-object and pointer-to-function types are Trivially-Serializable, but it is generally invalid to dereference a local pointer that originated from

14...
another process. More generally, objects that represent local process resources (e.g., file descriptors) are usually not meaningful on other processes, whether their types are Serializable or not.

Implementations of serialization may require moving deserialized objects after constructing them. It is an error to serialize an object of type $T$ if its deserialized counterpart \texttt{deserialized\_type\_t\langle T \rangle} (§6.2.6) is not MoveConstructible.

### 6.2 Class Serialization Interface

1. For a class $T$ that requires nontrivial serialization, UPC++ provides several different mechanisms for specifying how serialization and deserialization are to be performed.
   
   1. Declare which member variables of $T$ to serialize with \texttt{UPCXX\_SERIALIZED\_FIELDS}. UPC++ automatically generates the required serialization logic.
   
   2. Specify expressions for computing the data to be serialized with \texttt{UPCXX\_SERIALIZED\_VALUES}. UPC++ automatically generates logic to evaluate the expressions in serialization and invoke a constructor with the resulting values in deserialization.
   
   3. Define a public, nested $T$::\texttt{upcxx\_serialization} member type with public \texttt{serialize} and \texttt{deserialize} member-function templates.
   
   4. Define a specialization of \texttt{upcxx::serialization\langle T \rangle} with public \texttt{serialize} and \texttt{deserialize} member-function templates.

2. If any of these mechanisms is used on a type $T$, then $T$ is Serializable but not TriviallySerializable, unless \texttt{upcxx::is\_trivially\_serializable\langle T \rangle} is specialized to provide a member constant \texttt{value} that is \texttt{true}.

3. It is an error if more than one of the first three mechanisms (\texttt{UPCXX\_SERIALIZED\_FIELDS}, \texttt{UPCXX\_SERIALIZED\_VALUES}, or a nested \texttt{upcxx\_serialization} class) is used directly by the same class $T$.

4. It is an error if both an explicit specialization of \texttt{upcxx::serialization\langle T \rangle} is defined and \texttt{upcxx::is\_trivially\_serializable\langle T \rangle} is specialized to provide a member constant \texttt{value} that is \texttt{true}.

5. An explicit specialization of \texttt{serialization\langle T \rangle} or \texttt{is\_trivially\_serializable\langle T \rangle} takes precedence over the mechanisms that are nested within a class (\texttt{UPCXX\_SERIALIZED\_FIELDS}, \texttt{UPCXX\_SERIALIZED\_VALUES}, or a nested \texttt{upcxx\_serialization} class).
6.2.1 UPCXX_SERIALIZED_FIELDS

If serialization of a type $T$ can be accomplished by recursively serializing a fixed subset of its member variables, the variadic **UPCXX_SERIALIZED_FIELDS** macro may be used to declare this subset. **UPC++** will then automatically generate the code to serialize and deserialize objects of type $T$.

The following is an example of using **UPCXX_SERIALIZED_FIELDS**:

```cpp
struct UserType {
    U a;
    V b;
    W c;
    UPCXX_SERIALIZED_FIELDS(a, b, c);
};
```

The macro **UPCXX_SERIALIZED_FIELDS** must be invoked directly within a class definition in a context that has public access level. The macro arguments must name non-static member variables of the class or an application of **UPCXX_SERIALIZED_BASE** (§6.2.5). A bit-field data member may not be used as an argument. In addition, the following must hold:

- The class must have a default constructor; the default constructor may have any access level.
- Each argument to **UPCXX_SERIALIZED_FIELDS** must be of a non-array type $T$, or of a (possibly multidimensional) array of elements of type $T$, where:
  - $T$ must not be qualified with `const`
  - $T$ must be Serializable and Destructible
  - $T$ and `deserialized_type_t<T>` (§6.2.6) must be the same type

**UPC++** serializes an object of a type $T$ that invokes **UPCXX_SERIALIZED_FIELDS** by serializing each member variable that is an argument to the macro in some unspecified order. Deserialization starts by default constructing an object of type $T$. Then each member variable listed in **UPCXX_SERIALIZED_FIELDS** is destructed and overwritten by an object deserialized from the byte stream, in the same order as serialization. Member variables elided from **UPCXX_SERIALIZED_FIELDS** are not overwritten; they retain their initial values as determined by the default constructor for $T$.
6.2.2 UPCXX_SERIALIZED_VALUES

If serialization of a type \( T \) consists of computing values to be inserted into the byte stream and using those values in deserialization to reconstruct the object, the variadic UPCXX_SERIALIZED_VALUES macro may be used. Each argument to the macro must be an expression that can be evaluated from the body of a non-static, \texttt{const} member function or an application of UPCXX_SERIALIZED_BASE (§6.2.5), and \( T \) must have a constructor that can be invoked with the resulting rvalues from the body of a static member function. The expressions provided to UPCXX_SERIALIZED_VALUES are evaluated in an unspecified order, and the types of the values must be Serializable.

The following is an example that uses UPCXX_SERIALIZED_VALUES to serialize a type using single-precision rather than the original double-precision floating-point values:

```cpp
struct Point {
  double x;
  double y;
  Point(float a, float b) : x(a), y(b) {}
  UPCXX_SERIALIZED_VALUES(float(x), float(y))
};
```

The macro UPCXX_SERIALIZED_VALUES must be invoked directly within a class definition in a context that has \texttt{public} access level.

6.2.3 Custom Serialization

Serialization for a class \( T \) may be customized by directly writing subobjects to a byte stream and reading them back out in deserialization. The following is an example of specifying custom serialization for a class:

```cpp
struct UserType {
  U a;
  V b;
  W c;

  struct upcxx_serialization {
    // Write a UserType into the given writer.
    template<typename Writer>
    static void serialize(Writer& writer, UserType const& object) {
      writer.write(object.a);
    }
  }
};
```
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```cpp
writer.write(object.c);
}

// Read a UserType from the given reader into the provided // storage.
template<typename Reader>
static UserType* deserialize(Reader& reader, void* storage) {
  // Order of these matters, which is why they can't be done // inline in the constructor call below (argument-evaluation // order is unspecified in C++).
  U a = reader.template read<U>();
  W c = reader.template read<W>();
  return ::new (storage) UserType{std::move(a), V{},
      std::move(c)};
}
};
```

A Writer is an object of an opaque type that provides an interface for writing to a byte stream. Writers provide the following member-function templates:

- **write(item)** writes a single object to the byte stream. *item* must be Serializable or a (possibly multidimensional) array of Serializable element type.

- **write_sequence(begin, end)** writes a sequence of objects to the byte stream and returns the number of objects in the sequence. *begin* and *end* must be ForwardIterators of the same type *Iter*, and *std::iterator_traits<Iter>::value_type* must be Serializable. **write_sequence** is semantically equivalent to separate calls to **write** on the elements of a sequence in order, but it may provide better performance.

- **write_sequence(begin, end, num_items)** provides the same behavior as **write_sequence(begin, end)**, but is more efficient when *begin* and *end* are not RandomAccessIterators. *num_items* must be the distance between *begin* and *end*.

- **reserve<T>()** reserves space in the byte stream for a single object of type *T* and returns a handle to the location in the stream. *T* must be TriviallySerializable. The location is written by calling **commit(handle, object)**, where *object* has type *T*. It is an error if **commit** is not called on a handle before the return of the function that calls **reserve** to create the handle.

The combination of **reserve**, **write_sequence**, and **commit** can be used to write a sequence of unknown length, prefixing the sequence with the actual length:
A Reader is an object of an opaque type that provides an interface for reading from a byte stream. Readers provide the following member-function templates:

- `read<T>()` reads and returns a single object from the byte stream. `T` must be Serializable.

- `read_into<T>(storage)` reads a single object from the byte stream, places it into the memory denoted by `storage`, and returns the address of the resulting object. `storage` must point to a location with appropriate space and alignment for the object. `T` must be Serializable or a (possibly multidimensional) array of Serializable element type.

- `read_sequence_into<T>(storage, num_items)` reads a sequence of `num_items` objects from the byte stream and places them into an array at the memory denoted by `storage`. `storage` must point to a location with appropriate space and alignment for the objects. `read_sequence_into` is semantically equivalent to a sequence of calls to `read_into`, but it may provide better performance.

For each of these function templates, `T` must be the same type of the original objects written in serialization by `write`, `write_sequence`, or `commit`. However, the objects constructed in deserialization may have a different type.

Serialization and deserialization for a class `T` may be customized by defining either a public, nested, member type `T::upcxx_serialization` or an explicit specialization of `upcxx::serialization<T>`. The nested class or specialization must define the following public member-function templates:

```cpp
template< typename Writer >
static void serialize(Writer& writer, T const& object);

template< typename Reader >
static U* deserialize(Reader& reader, void* storage);
```

1Note that due to C++ typechecking rules, invocations of these member-function templates must be explicitly instantiated using a `template` keyword, eg: `reader.template read<int>()`
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It is an error if either \texttt{T::upcxx_serialization} or an explicit specialization of \texttt{upcxx::serialization\langle T\rangle} is defined without the required public member-function templates.

UPC++ invokes \texttt{serialize(writer, object)} to serialize \texttt{object} into a byte stream, where \texttt{object} has type \texttt{T}. Similarly, \texttt{deserialize(reader, storage)} is invoked to deserialize an object of type \texttt{T}. The return type of \texttt{deserialize} must be a pointer \texttt{U*}, where \texttt{U} is the type of the resulting object, which may be distinct from the type \texttt{T} passed to serialization. \texttt{storage} points to a location with appropriate storage and alignment for an object of type \texttt{U}. \texttt{deserialize} must use placement \texttt{new} to construct the resulting object in the provided \texttt{storage} and return a pointer to the object.

As described in §6.2.6, the types \texttt{serialization_traits\langle T\rangle::deserialized_type} and \texttt{deserialized_type_t\langle T\rangle} are defined as aliases for the type \texttt{U}, where \texttt{U*} is the return type of \texttt{deserialize}.

### 6.2.4 Restrictions on Class Serialization

There are restrictions on which actions serialization/deserialization routines and expressions may perform. The following restrictions apply to constructors and destructors invoked when deserializing an object that uses \texttt{UPCXX_SERIALIZED_FIELDS}, expressions passed to \texttt{UPCXX_SERIALIZED_VALUES} and the constructor invoked upon deserialization, and all statements executed within any call to the member-function templates \texttt{serialize} and \texttt{deserialize} (§6.2.3):

1. Serialization/deserialization may not call any UPC++ routine with a progress level other than \texttt{none}.

2. If multiple application threads in the same process may concurrently invoke serialization/deserialization, the expressions or routines must be thread-safe and permit concurrent invocation from multiple threads.

Serialization/deserialization is only invoked by UPC++ functions with a progress level of internal or user. Calls to \texttt{write} and \texttt{write_sequence} on a writer synchronously invoke serialization on the argument objects, and calls to \texttt{read}, \texttt{read_into}, and \texttt{read_sequence_into} on a reader synchronously invoke deserialization to construct the resulting objects.
6.2.5 Serialization and Inheritance

1 Serialization mechanisms that are defined within a class T (UPCXX_SERIALIZED_FIELDS, UPCXX_SERIALIZED_VALUES, or a nested upcxx_serialization class) are inherited by the derived classes of T. The resulting behavior differs depending on which mechanism is inherited:

2 • If a derived class U inherits a nested upcxx_serialization class, then serializing an object of type U and deserializing produces an object of base type T. Thus, deserialized_type_t<U> (§6.2.6) is T.

3 • If a derived class U inherits serialization defined using UPCXX_SERIALIZED_FIELDS or UPCXX_SERIALIZED_VALUES, then serializing an object of type U and deserializing produces an object of type U. Thus, deserialized_type_t<U> (§6.2.6) is U.

4 If a derived class U inherits serialization defined using UPCXX_SERIALIZED_FIELDS or UPCXX_SERIALIZED_VALUES, the constructors required by those mechanisms must be members of U, and these constructors must additionally have public access level.

5 A derived class U may provide its own serialization by directly defining one of these mechanisms itself, or by specializing serialization<U> or is_trivially_serializable<U>.

6 Specializations of serialization<T> or is_trivially_serializable<T> do not affect serialization of derived classes of T.

7 A derived class U may disable serialization, when it would otherwise be inherited, by invoking the UPCXX_SERIALIZED_DELETE macro. The macro must be invoked directly within the definition of U in a context that has public access level, and it is subsequently inherited by derived classes of U. The following is an example of using UPCXX_SERIALIZED_DELETE:

1 struct Derived : Base {
2    UPCXX_SERIALIZED_DELETE();
3};

8 UPC++ serialization does not perform dynamic dispatch. Thus, the call writer.write(object) uses the static type of object to determine how to serialize object, regardless of the actual runtime type of the object.

9 Class serialization for a derived class U may explicitly serialize each of its base subobjects.

10 • The expression UPCXX_SERIALIZED_BASE(B) may be passed as an argument to UPCXX_SERIALIZED_FIELDS to serialize the subobject of base type B. B must be Serializable and Destructible. B must be neither polymorphic nor abstract.
Since the order in which the arguments to `UPCXX_SERIALIZED_FIELDS` are serialized and deserialized is unspecified, the behavior is undefined if both `UPCXX_SERIALIZED_BASE(B)` and a member variable inherited from B are passed to `UPCXX_SERIALIZED_FIELDS`.

- The expression `UPCXX_SERIALIZED_BASE(B)` may be passed as an argument to `UPCXX_SERIALIZED_VALUES` to serialize the subobject of base type B. B must be Serializable and must not be abstract. The constructor of U invoked by deserialization must accept an rvalue of type B as the corresponding argument.

- Custom serialization may serialize a base subobject by casting the object to a base class and writing the result. The base type must be Serializable. Deserialization requires reading a base-type object into a temporary before passing it to a derived-class constructor. The following is an example:

```cpp
struct Derived : Base {
    X d;

    Derived(Base&& base, X&& x)
    : Base(std::forward(base)), d(std::forward(x)) {}

    struct upcxx_serialization {
        template<typename Writer>
        static void serialize(Writer& writer, Derived const& object) {
            writer.write(static_cast<Base const&>(object));
            writer.write(object.d);
        }

        template<typename Reader>
        static Derived* deserialize(Reader& reader, void* storage) {
            Base base = reader.template read<Base>();
            X x = reader.template read<X>();
            return ::new(storage) Derived(std::move(base), std::move(x));
        }
    };
```
6.2.6 Serialization Traits

As mentioned in §6.2.3, custom UPC++ deserialization may produce an object of a different type than that of the original serialized object. UPC++ provides the serialization_traits class template that enables a user to determine the type of the deserialized object: serialization_traits<T>::deserialized_type is an alias for the type resulting from deserializing an object of type T. The top-level alias template deserialized_type_t is an alias for serialization_traits<T>::deserialized_type.

The serialization_traits template also provides a static member function that converts an object to its deserialized counterpart. The call serialization_traits<T>::deserialized_value(object) returns a value of type serialization_traits<T>::deserialized_type. The latter must be Movable, and object must not be a view (§6.7).

6.3 Standard-Library Containers

UPC++ supports serialization of several standard-library container types.

The following fixed-size containers are TriviallySerializable when the element types T, T1 and T2, or T... are all TriviallySerializable. They are Serializable when the element types are all Serializable:

- std::array<T, N>
- std::pair<T1, T2>
- std::tuple<T...>

UPC++ treats std::pair<T1, T2> and std::tuple<T...> as TriviallySerializable when T1, T2, and T... are TriviallySerializable even when the C++ implementation does not consider the pair or tuple to be TriviallyCopyable.

The following sequence container types are Serializable when the template parameters (T and Allocator) are all Serializable:

- std::vector<T, Allocator>
- std::deque<T, Allocator>
- std::list<T, Allocator>
The following set container types are Serializable when the template parameters (Key, Compare, Hash, KeyEqual, and Allocator) are all Serializable:

- `std::set<Key, Compare, Allocator>`
- `std::multiset<Key, Compare, Allocator>`
- `std::unordered_set<Key, Hash, KeyEqual, Allocator>`
- `std::unordered_multiset<Key, Hash, KeyEqual, Allocator>`

The following map container types are Serializable when the template parameters (Key, T, Compare, Hash, KeyEqual, and Allocator) are all Serializable:

- `std::map<Key, T, Compare, Allocator>`
- `std::multimap<Key, T, Compare, Allocator>`
- `std::unordered_map<Key, T, Hash, KeyEqual, Allocator>`
- `std::unordered_multimap<Key, T, Hash, KeyEqual, Allocator>`

The type `std::basic_string<CharT, Traits, Allocator>` is Serializable when the template parameter Allocator is Serializable.

The following types are also Serializable:

- `std::allocator<T>`
- Standard specializations of `std::hash<T>`

Typical library implementations of `std::equal_to<T>`, `std::not_equal_to<T>`, `std::greater<T>`, `std::less<T>`, `std::greater_equal<T>`, and `std::less_equal<T>` are TriviallyCopyable and thus TriviallySerializable.

When serializing a container that has a template parameter of Compare, Hash, KeyEqual, or Allocator, UPC++ invokes the corresponding observer member function (e.g., `key_comp()` or `get_allocator()`), serializes the resulting object, and passes the deserialized object as an argument to the constructor when deserializing the container.

UPC++ allows the template arguments (e.g., T and Key in the types above) of containers to produce different types upon deserialization. For example, the sequence `vector<T, Allocator>` is deserialized as `vector<deserialized_type_t<T>, deserialized_type_t<Allocator>>`, and the map `map<Key, T, Compare, Allocator>` is deserialized as `map<deserialized_type_t<Key>, deserialized_type_t<T>, deserialized_type_t<Compare>, deserialized_type_t<Allocator>>`. 
6.4 References, Arrays, and CV-Qualified Types

1 A reference type \texttt{cq} \texttt{T} & or \texttt{cq} \texttt{T} && is Serializable when \texttt{T} is Serializable. Such a type is serialized by serializing the referent, and deserialization produces an object of non-reference type \texttt{deserialized_type_t<T>}. Thus, \texttt{deserialized_type_t<cq} \texttt{T} &\texttt{>} and \texttt{deserialized_type_t<cq} \texttt{T} &&\texttt{>} are both the same as \texttt{deserialized_type_t<T>}.  

2 A reference type is never TriviallySerializable.

3 An array type is never Serializable. However, an array may be passed to \texttt{UPCXX\_SERIALIZED\_FIELDS} or the \texttt{write} member-function template of a Writer if the element type of the array is Serializable. Such an array type may also be used with the \texttt{read\_into} member-function template of a Reader to read an entire array into a given memory location.

4 The type \texttt{T const} is Serializable when \texttt{T} is Serializable, and it is TriviallySerializable when \texttt{T} is TriviallySerializable. Deserialization preserves the original \texttt{const} qualifier. Thus, an RPC (§9) of a function whose return type is \texttt{T const} by default produces a future (§5) whose type is \texttt{future<deserialized_type_t<T> const>}. Similarly, deserialization of a std::pair\texttt{T1 const, T2 const} produces an object of type std::pair\texttt{<deserialized_type_t<T1> const, deserialized_type_t<T2> const>}.  

5 The types \texttt{T volatile} and \texttt{T const volatile} are not Serializable.

6 It is an error to define an explicit specialization \texttt{is\_trivially\_serializable<T>} or \texttt{serialization<T>} if \texttt{T} is a reference, array, or cv-qualified type.

6.5 Functions

1 In Chapter 7 (Completion) and Chapter 9 (Remote Procedure Calls) there are several cases where a C++ FunctionObject is expected to execute on a destination process. In these cases the function arguments are serialized as described in this chapter. The FunctionObject itself (i.e. the \texttt{func} argument to \texttt{rpc}, \texttt{rpc\_ff}, or \texttt{as\_rpc}) is converted to a function pointer offset from a known sentinel in the source program’s code segment. The details of the implementation are not described here but typical allowed FunctionObjects are

2 • C functions

3 • C++ global and file-scope functions

4 • Class static functions
• lambda expressions

Objects captured by copy in a lambda expression are transferred to the destination by making a byte copy. The behavior is undefined if the type of an object captured by copy is not TriviallySerializable.

6.6 Special Handling in Remote Procedure Calls

Remote procedure calls, whether standalone (§9) or completion based (§7), perform special handling on certain non-Serializable UPC++ data structures. Arguments that are either a reference to dist_object type (see §14 Distributed Objects) or a team (see §11 Teams) are transferred by their dist_id or team_id respectively. Execution of the RPC is deferred until all of the id’s have a corresponding instance constructed on the recipient. When that occurs, func is enlisted for execution during user-level progress of the recipient’s master persona (see §10 Progress), and it will be called with the recipient’s instance references in place of those supplied at the send site. The behavior is undefined if the recipient’s instance of a dist_object or team argument is destroyed before the RPC executes.

6.7 View-Based Serialization

UPC++ also provides a mechanism for serializing the elements of a sequence, without explicitly serializing an enclosing container type. The following is an example of transferring a sequence with rpc:

```cpp
std::list<double> items = /* fill with elements */;
auto fut = rpc_ff(1, [] (view<double> packedlist) {
    // target side gets object containing iterators
    for (double elem : packedlist) { // traverse network buffer
        process(elem); // process each element
    }
}, make_view(items.begin(), items.end()));
```

In this example, a std::list<double> contains the elements to be transferred. Calling make_view on its begin and end iterators results in a view, which can then be passed to a remote procedure call. The elements in the sequence are serialized and transferred as part of the RPC, and the target receives a view over the elements stored in the network buffer. The RPC can then iterate over the view to obtain each element.
There is an asymmetry in the `view` types at the initiator and target of an RPC, reflecting the difference in how the underlying sequences are stored in memory. In the example above, the type of the value returned by `make_view` is `view<double, std::list<double>::iterator>`, since the initiator supplies iterators associated with a list. The target of the RPC, however, receives a `view<double, view_default_iterator_t<double>>`, with the `view_default_iterator_t<T>` type representing an iterator over a network buffer. The latter is the default argument for the second template parameter of `view`, so that a user can specify `view<T>` rather than `view<T, view_default_iterator_t<T>>`.

UPC++ provides different handling of `view<T>` based on whether the element type `T` is TriviallySerializable or not. For TriviallySerializable element type, deserialization is a no-op, and the `view<T>` on the recipient is a direct view over a network buffer, providing both random access and access to the buffer itself. The corresponding `view_default_iterator_t<T>` is an alias for `T*`. On the other hand, if the view element type is not TriviallySerializable, then an element must be nontrivially deserialized before it can be accessed by the user. In such a case, the `view<T>` only provides access through an InputIterator, which deserializes and returns elements by value, and `view_default_iterator_t<T>` is an alias for `deserializing_iterator<T>`.

A `deserializing_iterator<T>` also provides the `deserialize_into` member function to deserialize an object directly into user-provided storage. This avoids constructing a `deserialized_type_t<T>` on the stack and returning it by value, which can be inefficient for large types or types that are costly to move. The following is an example of using a `view` and `deserialize_into` to transfer a single object of a large, non-TriviallySerializable type:

```cpp
BigObject *ptr = /* ... */;
future<> = rpc( target_rank,
    [](view<BigObject> item) {
        auto storage =
            new typename std::aligned_storage<
                sizeof(BigObject),
                alignof(BigObject)>::type;
        BigObject *ptr = item.begin().deserialize_into(storage);
        /* consume the object */
        delete ptr;
    },
make_view(ptr, ptr+1));
```
6 The result of deserializing a `view<T, Iter>` is always `view<T>`, even if `deserialized_type_t<T>` is some type `U` that is distinct from `T`\(^2\). In such a case, `T` is necessarily not TriviallySerializable, and `deserializing_iterator<T>` invokes the `deserialize` routine for `T` to produce an element of type `U`. The type `deserializing_iterator<T>::value_type` is an alias for the element type produced by `deserializing_iterator<T>`, and it is equivalent to `deserialized_type_t<T>`.

7 As a non-owning interface, `view` only provides `const` access to the elements in the underlying sequence, analogous to C++17 `string_view`. However, in the case of a `view<T>` that is received by the target of an RPC, where `T` is TriviallySerializable, the underlying elements are stored directly in a network buffer as indicated above. There is no external owning container, so UPC++ permits a user to perform a `const_cast` conversion on an element and modify it.

8 The lifetime of the underlying data buffer and all view iterators on the target in both the TriviallySerializable and non-TriviallySerializable cases is restricted by default to the duration of the RPC. In this case, the elements must be processed or copied elsewhere before the RPC returns. However, if the RPC returns a future, then the lifetime of the buffer and view iterators is extended until that future is readied. This allows an RPC to initiate an asynchronous operation to consume the elements, and as long as the resulting future is returned from the RPC, the underlying buffer will remain valid until the asynchronous operation is complete and the future readied. Lifetime extension applies to all RPC variants, including `rpc_ff` and `as_rpc` where the return value is not made available to user code.

9 While UPC++ manages the lifetime of the data underlying a `view` when it is an argument to an RPC, the library does not support a `view` as the return type of an RPC due to the lifetime issues it raises. Thus, an RPC is prohibited from returning a `view` even though it is classified as Serializable.

10 The behavior is unspecified when a `view<T, IterType>` is passed to `rpc`, `rpc_ff`, or `as_rpc` if the type `T` is itself a `view`.

---

\(^2\) Note this differs from the behavior of standard-library containers, where for example, `deserialized_type_t<std::vector<T>>` is `std::vector<deserialized_type_t<T>>`, and objects of the latter type are completely deserialized before being passed to RPC callbacks or completion events. The difference arises because the `view<T>` object passed to an RPC callback is a non-owning container over the serialized representation, and its `deserializing_iterator` performs deserialization on-demand using the deserialization code provided by `T`. 

6.8 API Reference

1 template<typename T>
   struct is_trivially_serializable;

Provides a member constant `value` that is `true` if `T` is TriviallySerializable and `false` otherwise. This trait may be specialized for user types.

3 template<typename T>
   struct is_serializable;

Provides a member constant `value` that is `true` if `T` is Serializable and `false` otherwise. This trait may not be specialized. However, its value may be indirectly influenced by specializing `is_trivially_serializable<T>`, or implementing a class serialization interface for `T` (§6.2), as appropriate.

6.8.1 Views

1 template<typename T>
   class deserializing_iterator {
   public:
     // types
     using iterator_category = std::input_iterator_tag;
     using value_type = deserialized_type_t<T>;
     using difference_type = std::ptrdiff_t;
     using pointer = value_type *;
     using reference = value_type;

     deserializing_iterator();

     value_type operator*() const;
     pointer_type deserialize_into(void* storage) const;

     deserializing_iterator& operator++();
     deserializing_iterator  operator++(int);
   };

   // comparisons
   template<typename T>
   bool operator==(const deserializing_iterator& x, const deserializing_iterator& y);
template<typename T>
bool operator!=(const deserializing_iterator& x,
const deserializing_iterator& y);

C++ Concepts: InputIterator
T must be Serializable.

An iterator over elements stored in a network buffer. Dereferencing the iterator causes the element to be deserialized and returned by value (i.e. deserializing_iterator<T>::reference is an alias for deserializing_iterator<T>::value_type).

While this iterator is classified as an InputIterator, it does not support operator->, as the underlying element must be materialized on demand and its lifetime would not extend beyond the application of the operator.

UPC++ progress level for all functions above: none

template<typename T>
deserialized_type_t<T>*
deserializing_iterator<T>::deserialize_into(void* storage) const;

Precondition: This iterator must be pointing to a valid element. storage must point to a location with appropriate size and alignment for an object of type deserialized_type_t<T>.

Reads the serialized representation of an object of type T referenced by this iterator and deserializes it into the memory denoted by storage. Returns a pointer to the newly constructed object.

UPC++ progress level: none

template<typename T>
using view_default_iterator_t = /* ... */;

A type alias that is equivalent to T* if T is TriviallySerializable (i.e. upcxx::is_trivially_serializable<T>::value is true), and deserializing_iterator<T> otherwise.
template <typename T, typename IterType = view_default_iterator_t<T>>
class view {
public:
    // types
    using iterator = IterType;
    using size_type = std::size_t;

    // iterators
    iterator begin();
    iterator end();

    // capacity
    size_type size() const;
};

C++ Concepts: DefaultConstructible, CopyConstructible, CopyAssignable, De-
structible

UPC++ Concepts: Serializable

A class template representing a view over an underlying sequence of elements
of type T, delimited by begin() and end().

UPC++ progress level for all member functions of view: none

template <typename T>
class view<T, T*> {
public:
    // types
    using value_type = T;
    using pointer = T*;
    using const_pointer = const T*;
    using reference = T&;
    using const_reference = const T&;
    using const_iterator = const T*;
    using iterator = const_iterator;
    using const_reverse_iterator =
        std::reverse_iterator<const_iterator>;
    using reverse_iterator = const_reverse_iterator;
    using size_type = std::size_t;
    using difference_type = std::ptrdiff_t;

    // no explicit construct/copy/destroy for non-owning type
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// iterators
const_iterator begin () const;
const_iterator cbegin () const;
const_iterator end () const;
const_iterator cend () const;
const_reverse_iterator rbegin () const;
const_reverse_iterator crbegin () const;
const_reverse_iterator rend () const;
const_reverse_iterator crend () const;

// capacity
bool empty () const;
size_type size () const;

// element access
const_reference operator [] (size_type n) const;
const_reference at (size_type n) const;
const_reference front () const;
const_reference back () const;

const_pointer data () const;

C++ Concepts: DefaultConstructible, CopyConstructible, CopyAssignable, De-
destructible

UPC++ Concepts: Serializable

A template specialization representing a view over a network buffer of elements
of type T, delimited by begin() and end().

Exceptions: at(n) throws std::out_of_range if n is not in the range
[0, size()).

UPC++ progress level for all member functions of view: none

template<typename T, typename IterType>
view<T, IterType>::view();

Precondition: IterType must satisfy the ForwardIterator C++ concept. The
type std::iterator_traits<IterType>::value_type must be the same as
T. T must be Serializable.

Initializes this view to represent an empty sequence.
template <typename IterType>
view<typename std::iterator_traits<IterType>::value_type, IterType>
make_view(IterType begin, IterType end,
typename std::iterator_traits<IterType>::difference_type
size = std::distance(begin, end));

Precondition: IterType must satisfy the ForwardIterator C++ concept. The underlying element type (std::iterator_traits<IterType>::value_type) must be Serializable. The value of size must be equal to the number of elements in [begin, end).

Constructs a view over the sequence delimited by begin and end.

UPC++ progress level: none

template <typename Container>
view<typename Container::value_type, typename Container::const_iterator>
make_view(const Container &container);

Precondition: Container must satisfy the Container C++ concept. The underlying element type (Container::value_type) must be Serializable.

Constructs a view over the sequence delimited by container.cbegin() and container.cend().

UPC++ progress level: none

6.8.2 Class Serialization

template <typename T>
struct serialization_traits;

Precondition: T must be Serializable

Provides a member type alias deserialized_type that is the type resulting from deserializing an object that was serialized as the type T.

template <typename T>
using deserialized_type_t =
typename serialization_traits<T>::deserialized_type;

Type alias for serialization_traits<T>::deserialized_type.
template<typename T>
    [static] deserialized_type_t<T>
        serialization_traits<T>::deserialized_value(T const& object);

Precondition: T must be Serializable and must not be a view.
deserialized_type_t<T> must be Movable.

Returns a value that is the deserialized counterpart of object. Equivalent to
serializing object into temporary storage and deserializing the result.

UPC++ progress level: none

#define UPCXX_SERIALIZED_FIELDS(...) /* implementation-defined */

A variadic macro for specifying a subset of member variables to be automatically
serialized by UPC++, as described in §6.2.1.

#define UPCXX_SERIALIZED_VALUES(...) /* implementation-defined */

A variadic macro for specifying a set of values to be used by UPC++ to serialize
an object, as described in §6.2.2.

#define UPCXX_SERIALIZED_DELETE() /* implementation-defined */

A macro for disabling serialization of a derived class when the derived class
would otherwise inherit a serialization mechanism from a base class (§6.2.5).

#define UPCXX_SERIALIZED_BASE(base) /* implementation-defined */

A macro for specifying serialization of a base subobject of type base, as de-
scribed in §6.2.5.

template<typename T>
    struct serialization;

A class template that can be specialized to customize serialization and deseri-
alization for a type T, as described in §6.2.3.

template<typename T>
    void [Writer]::write(T const &object);

Precondition: T must be Serializable

Writes a serialized representation of object to the given writer.

UPC++ progress level: none
template<typename IterType>
std::size_t [Writer]::write_sequence(IterType begin, IterType end);

**Precondition:** IterType must satisfy the ForwardIterator C++ concept. The underlying element type (std::iterator_traits<IterType>::value_type) must be Serializable.

Writes serialized representations of the objects in the sequence delimited by begin and end to the given writer and returns the number of objects written. This is semantically equivalent to separate calls to write on the elements of the sequence in order, but it may provide better performance.

**UPC++ progress level:** none

```cpp
template<typename IterType>
std::size_t [Writer]::write_sequence(IterType begin, IterType end,
                                   std::size_t num_items);
```

**Precondition:** IterType must satisfy the ForwardIterator C++ concept. The underlying element type (std::iterator_traits<IterType>::value_type) must be Serializable. num_items must be equal to the number of elements in [begin, end).

Writes serialized representations of the objects in the sequence delimited by begin and end to the given writer and returns the number of objects written. This is semantically equivalent to write_sequence(begin, end), but it may provide better performance when IterType is not a RandomAccessIterator.

**UPC++ progress level:** none

```cpp
template<typename T>
struct [Writer]::reserve_handle;
```

**C++ Concepts:** Movable, Destructible

Represents a reserved location in a writer where an object of type T is to be written.
**template<typename T>**

```cpp
typename [Writer]::reserve_handle<T> [Writer]::reserve();
```

*Precondition:* $T$ must be TriviallySerializable

Reserves space in the given writer for an object of type $T$ and returns a handle to the resulting location. The handle must be written by a call to `commit` prior to the return of the function that invoked `reserve` to create the handle.

**UPC++ progress level:** none

---

**template<typename T>**

```cpp
void [Writer]::commit(
  typename [Writer]::reserve_handle<T> && handle,
  T const & object);
```

*Precondition:* $T$ must be TriviallySerializable. `handle` must have been constructed through a call to `reserve` on this writer, and it must not previously have had `commit` called on it.

Writes a representation of `object` to the location in the writer denoted by `handle`. Invalidates `handle`.

**UPC++ progress level:** none

---

**template<typename T>**

```cpp
deserialized_type_t<T> [Reader]::read();
```

*Precondition:* The current position of the reader must be a location where an object of $T$ was written.

Reads a serialized representation of an object of type $T$ and returns a deserialized object of type `deserialized_type_t<T>`.

**UPC++ progress level:** none
template< typename T>
  deserialized_type_t<T>* [Reader]::read_into( void* storage);

Precondition: The current position of the reader must be a location where an object of T was written. storage must point to a location with appropriate space and alignment for an object of type deserialized_type_t<T>.

Reads a serialized representation of an object of type T and constructs a deserialized object of type deserialized_type_t<T> in the memory denoted by storage. Returns a pointer to the newly constructed object.

UPC++ progress level: none

template< typename T>
  deserialized_type_t<T>*
  [Reader]::read_sequence_into( void* storage,
                               std::size_t num_items);

Precondition: The current position of the reader must be a location where num_items objects of T were written. storage must point to a location with appropriate space and alignment for an array of num_items objects of type deserialized_type_t<T>.

Reads serialized representations of num_items objects of type T and constructs an array of deserialized objects of type deserialized_type_t<T> in the memory denoted by storage. Returns a pointer to the first newly constructed object in the array.

UPC++ progress level: none
Chapter 7

Completion

7.1 Overview

Data movement operations come with the concept of completion, meaning that the effect of the operation is now visible on the source or target process and that resources, such as memory on the source and destination sides, are no longer in use by UPC++. A single UPC++ call may have several completion events associated with it, indicating completion of different stages of a communication operation. These events are categorized as follows:

- **Source completion**: The source-side resources of a communication operation are no longer in use by UPC++, and the application is now permitted to modify or reclaim them.

- **Remote completion**: The data have been deposited on the remote target process, and they can be consumed by the target.

- **Operation completion**: The operation is complete from the viewpoint of the initiator. The transferred data can now be read by the initiator, resulting in the values that were written to the target locations.

A completion event may be associated with some values produced by the communication operation, or it may merely signal completion of an action. Each communication operation specifies the set of completion events it provides, as well as the values that a completion event produces. Unless otherwise indicated, a completion event does not produce a value.

UPC++ provides several alternatives for how completion can be signaled to the program:
• **Future:** The communication call returns a future, which will be readied when the completion event occurs. This is the default notification mode for communication operations. If the completion event is associated with some values of type \(T, \ldots\), then the returned future will have type `future<T, \ldots>`.

If no value is associated with the completion, then the future will have type `future<>`.

• **Promise:** The user provides a promise when requesting notification of a completion event, and that promise will have one of its dependencies fulfilled when the event occurs. The promise must have a non-zero dependency count. If the completion event is associated with some values of type \(T, \ldots\), then it must be valid to call `fulfill_result()` on the promise with values of type \(T, \ldots\), and the promise must not have had `fulfill_result()` called on it. The promise will then have `fulfill_result()` called on it with the associated values when the completion event occurs. If no value is associated with the completion, then the promise may have any type. It will have an anonymous dependency fulfilled upon the completion event.

• **Local-Procedure Call (LPC):** The user provides a target persona and a callback function object when requesting notification of a completion event. If the completion is associated with some values of type \(T, \ldots\), then the callback must be invokable with a sequence of `sizeof...(T)` arguments, where if the \(n\)th component of \(T\) has type \(U\), then the \(n\)th argument provided to the callback has type:

- \(U\) if \(U\) is of reference type
- \(U&&\) if \(U\) is of non-reference type

If the completion is not associated with any values, the callback must be invokable with no arguments. The callback, together with the associated completion values if any, is enlisted for execution during user-level progress of the given persona when the completion event occurs.

• **Remote-Procedure Call (RPC):** The user provides a function object that is either Serializable or one of the allowed FunctionObjects in §6.5 when requesting notification of a completion event, as well as the arguments on which the function object should be invoked. Each argument must either be Serializable, a `cq dist_object<T>&`, or `cq team&`. The result of serializing and deserializing the function object must be invokable on the values that result from serializing and deserializing the arguments, and the invocation must not throw an exception. Specifically, if an argument is of type `cq dist_object<T>&` or `cq team&`, the function object must accept a value of `dist_object<T>&` or `team&`, respectively, for the associated parameter. If the argument is of some other type \(T\), the function object must accept a value of type `deserialized_type_t<T>&&` for the respective parameter. The function object and arguments are transferred as part of the communication operation, and the invocation...
is enlisted for execution during user-level progress of the master persona of the target
process when the completion event occurs.

The result from invoking the function object is discarded. However, the return value
affects the lifetime of the deserialized objects that the UPC++ runtime constructs\(^1\) and
passes to the function object. If the return value is a non-future value or a ready future, the
deserialized objects are destructed immediately after the invocation returns. On the other hand,
if the return value is a non-ready future, destruction of the deserialized objects is deferred
until after the future becomes ready, allowing the function object to safely initiate further
asynchronous computation that operates on those objects.

- **Buffered**: The communication call consumes the source-side resources of the operation
before the call returns, allowing the application to immediately modify or reclaim them.
This delays the return of the call until after the source-completion event. The implementation
may internally buffer the source-side resources or block until network resources are available to inject the data directly.

- **Blocking**: This is similar to buffered completion, except that the implementation is
required to block until network resources are available to inject the data directly.

Future, promise, and LPC completions are only valid for completion events that occur
at the initiator of a communication call, namely source and operation completion. RPC
completion is only valid for a completion event that occurs at the target of a communication
operation, namely remote completion. Buffered and blocking completion are only valid for
source completion. More details on futures and promises are in Ch. 5, while LPC and
RPC callbacks are discussed in Ch. 10.

If a completion event is associated with some values, the UPC++ runtime is permitted to pass
separate copies of those values to each notification registered on that completion event. If
multiple notifications are registered on an event that produces values, their respective types
must be CopyConstructible. Otherwise, the respective types must be MoveConstructible.

Notification of completion only happens during user-level progress of the initiator or target
process. Even if an operation completes early, including before the initiation operation
returns, the application cannot learn this fact without entering user progress. For futures
and promises, only when the initiating thread (persona actually) enters user-level progress
will the future or promise be eligible for taking on a readied or fulfilled state. LPC callbacks
will execute once a thread enters user progress of the designated persona. See Ch. 10 for
the full discussion on user progress and personas.

\(^1\)This excludes \texttt{team\&} and \texttt{dist\_object<T>\&} arguments, where the underlying objects are not con-
structed by the UPC++ runtime in deserialization.
If buffered or blocking completion is requested, then the source-completion event occurs before the communication call returns. However, source-completion notifications, such as signaling a future or executing an LPC, are still delayed until the next user-level progress. Similarly, source-completion notifications for empty data transfers (e.g. `rput` with a size of zero) are delayed until the next user-level progress.

Operation completion implies both source and remote completion. However, it does not imply that notifications associated with source and remote completion have occurred. Similarly, remote completion implies source completion, but it does not imply that notifications associated with source completion have occurred.

### 7.2 Completion Objects

The UPC++ mechanism for requesting notification of completion is through opaque completion objects, which associate notification actions with completion events. Completion objects are CopyConstructible, CopyAssignable, and Destructible, and the same completion object may be passed to multiple communication calls. A simple completion object is constructed by a call to a static member function of the `source_cx`, `remote_cx`, or `operation_cx` class, providing notification for the corresponding event. The member functions `as_future`, `as_promise`, `as_lpc`, and `as_rpc` request notification through a future, promise, LPC, or RPC, respectively. Only the member functions that correspond to valid means of signaling notification of an event are defined in the class associated with that event.

The following is an example of a simple completion object:

```cpp
1       global_ptr<int> gp1 = /* some global pointer */;
2       promise<int> pro1;
3       auto cxs = operation_cx::as_promise(pro1);
4       rget(gp1, cxs);
5       pro1.finalize(); // fulfill the initial anonymous dependency
```

The `rget` function, when provided just a `global_ptr<int>`, transfers a single `int` from the given location to the initiator. Thus, operation completion is associated with an `int` value, and the promise used for signaling that event must have type compatible with an `int` value, e.g. `promise<int>`. The user constructs a completion object that requests operation notification on the promise `pro1` by calling `operation_cx::as_promise(pro1)`. Since a completion object is opaque, the `auto` keyword is used to deduce the type of the completion object. The resulting completion object can then be passed to `rget`, which fulfills the promise with the transferred value upon operation completion.
A user can request notification of multiple completion events, as well as multiple notifications of a single completion event. The pipe (|) operator can be used to combine completion objects to construct a union of the operands. The following is an example:

```c
int foo() {
    return 0;
}

int bar(int x) {
    return x;
}

void do_comm(double *src, size_t count) {
    global_ptr<double> dest = /* some global pointer */;
    promise<> pro1;
    persona &per1 = /* some persona */;
    auto cx = (operation_cx::as_promise(pro1) |
                source_cx::as_future() |
                operation_cx::as_future() |
                operation_cx::as_future() |
                source_cx::as_lpc(per1, foo) |
                remote_cx::as_rpc(bar, 3));
    std::tuple<future<>, future<>, future<>> result =
        rput(src, dest, count, cx);
    pro1.finalize().wait(); // finalize promise, wait on its future
}
```

This code initiates an `rput` operation, which provides source-, remote-, and operation-completion events. A unified completion object is constructed by applying the pipe operator to individual completion objects. When `rput` is invoked with the resulting unified completion object, it returns a tuple of futures corresponding to the individual future completions requested. The ordering of futures in this tuple matches the order of application of the pipe operator (this operator is associative but not commutative). In the example above, the first future in the tuple would correspond to source completion, and the second and third would be for operation completion. If no future-based notification is requested, then the return type of the communication call would be `void` rather than a tuple.

When multiple notifications are requested for a single event, the order in which those notifications occur is unspecified. In the code above, the order in which `pro1` is fulfilled and the two futures for operation completion are readied is indeterminate. Similarly, if both source and operation completion occur before the next user-level progress, the order...
in which the notifications occur is unspecified, so that operation-completion requests may be notified before source-completion requests.

Unlike a direct call to the rpc function (Ch. 9), but like a call to rpc_ff, an RPC completion callback does not return a result to the initiator. Thus, the value returned by the RPC invocation of bar above is discarded.

Arguments to remote_cx::as_rpc are serialized at an unspecified time between the invocation of as_rpc and the return from the invocation of a communication operation that accepts the resulting completion object. If multiple communication operations use a single completion object resulting from as_rpc, then the arguments may be serialized multiple times. For lvalue arguments, the user must ensure that they remain valid until the return from the invocation of all communication operations that use the associated completion object. Rvalue arguments are guaranteed to be “consumed” before the remote_cx::as_rpc factory function returns the completion object, meaning they are move-constructed into an internal location and/or fully serialized.

### 7.2.1 Restrictions

1. The API reference for a UPC++ call that supports the completion interface lists the completion events that the call provides, as well as the types of values associated with each event, if any. The result is undefined if a completion object is passed to a call and the object contains a request for an event that the call does not support. Passing a completion object that contains a request whose type does not match the types provided by the corresponding completion event, as described in §7.1, also results in undefined behavior.

2. If a UPC++ call provides both operation and remote completion, then at least one must be requested by the provided completion object. If a call provides operation but not remote completion, then operation completion must be requested. The behavior of the program is undefined if neither operation nor remote completion is requested from a call that supports one or both of operation or remote completion.

3. A promise object associated with a promise-based completion request must have a dependency count greater than zero when the completion object is passed to a UPC++ operation. The result is undefined if the same promise object is used in multiple requests for notifications that produce values.
7.2.2 Completion and Return Types

In subsequent API-reference sections, the opaque type of a completion object is denoted by \texttt{CType}. Similarly, \texttt{RType} denotes a return type that is dependent on the completion object passed to a \texttt{UPC++} call. This return type is as follows:

\begin{itemize}
  \item \texttt{void}, if no future-based completions are requested
  \item \texttt{future<\ldots>}, if a single future-based completion is requested, where \texttt{T\ldots} is the sequence of types associated with the given completion event
  \item \texttt{std::tuple<future<\ldots>\ldots>}, if multiple future-based completions are requested, where each future’s arguments \texttt{T\ldots} is the sequence of types associated with the corresponding completion event
\end{itemize}

Type deduction, such as with \texttt{auto}, is recommended when working with completion objects and return types.

7.2.3 Default Completions

If a completion object is not explicitly provided to a communication call, then a default completion object is used. For most calls, the default is \texttt{operation_cx::as_future()}. However, for \texttt{rpc_ff}, the default completion is \texttt{source_cx::as_buffered()}, and for \texttt{rpc}, it is \texttt{source_cx::as_buffered() | operation_cx::as_future()}. The default completion of a \texttt{UPC++} communication call is listed in its API reference.

7.3 API Reference

\begin{verbatim}
struct source_cx;
struct remote_cx;
struct operation_cx;
\end{verbatim}

Types that contain static member functions for constructing completion objects for source, remote, and operation completion.
[static] CType source_cx::as_future();

[static] CType operation_cx::as_future();

Constructs a completion object that represents notification of source or operation completion with a future.

UPC++ progress level: none

template<typename ...T>
[static] CType source_cx::as.promise(promise<T...> pro);

template<typename ...T>
[static] CType operation_cx::as.promise(promise<T...> pro);

Precondition: pro must have a dependency count greater than zero.

Constructs a completion object that represents signaling the given promise upon source or operation completion.

UPC++ progress level: none

template<typename Func>
[static] CType source_cx::as_lpc(persona &target, Func &&func);

template<typename Func>
[static] CType operation_cx::as_lpc(persona &target, Func &&func);

Precondition: Func must be a function-object type, and the underlying decayed type (std::decay<Func&&>::type) must be CopyConstructible. func must not throw an exception when invoked.

Constructs a completion object that represents the enqueuing of func on the given local persona upon source or operation completion.

UPC++ progress level: none
template<typename Func, typename ... Args>
    CType remote_cx::as_rpc(Func &&func, Args... &&args);

Preconditions:

• Func must be a function-object type.

• If Func&& is an rvalue-reference type, the underlying decayed type
  (std::decay<Func&&>::type) must be CopyConstructible.

• Func must either be Serializable or one of the FunctionObjects listed in
  §6.5.

• Each of Args... must either be a Serializable type, or cq
  dist_object<T>&, or cq team&.

• If a type Arg in Args&&... is an rvalue-reference type, the underlying
  decayed type (std::decay<Arg>::type) must be CopyConstructible.

• The invocation of the deserialized function object on the deserialized ar-
  guments must not throw an exception.

Constructs a completion object that represents the enqueuing of func on a
target process upon remote completion.

UPC++ progress level: none

[static] CType source_cx::as_buffered();

Constructs a completion object that represents buffering source-side resources
or blocking until they are consumed before a communication call returns, de-
laying the return until the source-completion event occurs.

UPC++ progress level: none

[static] CType source_cx::as_blocking();

Constructs a completion object that represents blocking until source-side re-
sources are consumed before a communication call returns, delaying the return
until the source-completion event occurs.

UPC++ progress level: none
template< typename CTypeA, CTypeB >
CType operator |(CTypeA &&a, CTypeB &&b);

Precondition: CTypeA and CTypeB must be completion types.

Constructs a completion object that is the union of the completions in a and b. Future-based completions in the result are ordered the same as in a and b, with those in a preceding those in b.

UPC++ progress level: none
Chapter 8

One-Sided Communication

8.1 Overview

The main one-sided communication functions for UPC++ are `rput` and `rget`. Where possible, the underlying transport layer will use RDMA techniques to provide the lowest-latency transport possible. The type T used by `rput` or `rget` needs to be `TriviallySerializable`, as described in Chapter 6 (Serialization).

8.2 API Reference

8.2.1 Remote Puts

```
1 template<typename T, typename Cx=/*unspecified*/>
2 RType rput(T value, global_ptr<T> dest,
3            Cx &completions=operation_cx::as_future());
```

1 *Precondition:* T must be `TriviallySerializable`.
2 Initiates a transfer of `value` that will store it in the memory referenced by `dest`.
3 Remote-completion operations execute on the master persona of the process associated with the destination (i.e. `dest.where()`).
Completions:

- **Remote**: Indicates completion of the transfer of `value`.

- **Operation**: Indicates completion of all aspects of the operation: the transfer and remote stores are complete.

**C++ Memory Ordering**: The writes to `dest` will have a `happens-before` relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment) and remote-completion actions (RPC enlistment). For LPC and RPC completions, all evaluations `sequenced-before` this call will have a `happens-before` relationship with the execution of the completion function.

**UPC++ Progress Level**: `internal`

```cpp
template<typename T, typename Cx=/*unspecified*/>
RType rput(T const *src, global_ptr<T> dest, std::size_t count, 
           Cx &&completions=operation_cx::as_future());
```

**Precondition**: `T` must be TriviallySerializable. The source and destination memory regions must not overlap. `src` and `dest` must not be null pointers, even if `count` is zero.

Initiates an operation to transfer and store the `count` items of type `T` beginning at `src` to the memory beginning at `dest`. The values referenced in the `[src, src+count)` interval must not be modified until either source or operation completion is indicated.

Remote-completion operations execute on the master persona of the process associated with the destination (i.e. `dest.where()`).

Completions:

- **Source**: Indicates completion of injection or internal buffering of the source values, signifying that the `src` buffer may be modified.

- **Remote**: Indicates completion of the transfer of the values, implying readiness of the target buffer `[dest, dest+count)`.

- **Operation**: Indicates completion of all aspects of the operation: the transfer and remote stores are complete.
C++ memory ordering: The reads of src will have a happens-before relationship with the source-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). The writes to dest will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment) and remote-completion actions (RPC enlistment). For LPC and RPC completions, all evaluations sequenced-before this call will have a happens-before relationship with the execution of the completion function.

UPC++ progress level: internal

8.2.2 Remote Gets

template<
typename T, typename Cx=/*unspecified*/>
RTYPE rget(global_ptr<const T> src,
Cx &&completions=operation_cx::as_future());

Precondition: T must be TriviallySerializable.

Initiates a transfer to this process of a single value of type T located at src. The value will be transferred to the calling process and delivered in the operation-completion notification.

Completions:

- Operation: Indicates completion of all aspects of the operation, including transfer and readiness of the resulting value. This completion produces a value of type T.

C++ memory ordering: The read of src will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). All evaluations sequenced-before this call will have a happens-before relationship with the invocation of any LPC associated with operation completion.

UPC++ progress level: internal
template<typename T, typename Cx=/*unspecified*/>
RType rget(global_ptr<const T> src, T *dest, std::size_t count,
Cx &&completions=operation_cx::as_future());

Precondition: T must be TriviallySerializable. The source and destination memory regions must not overlap. src and dest must not be null pointers, even if count is zero.

Initiates a transfer of count values of type T beginning at src and stores them in the locations beginning at dest. The source values must not be modified until operation completion is notified.

Completions:

- Operation: Indicates completion of all aspects of the operation, including transfer and readiness of the resulting values.

C++ memory ordering: The reads of src and writes to dest will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). All evaluations sequenced-before this call will have a happens-before relationship with the invocation of any LPC associated with operation completion.

UPC++ progress level: internal
Chapter 9

Remote Procedure Call

9.1 Overview

1 **UPC++** provides remote procedure calls (RPCs) for injecting function calls into other processes. These injections are one-sided, meaning the recipient is not required to explicitly acknowledge which functions are expected. Concurrent with a process’s execution, incoming RPCs accumulate in an internal queue managed by **UPC++**. The only control a process has over inbound RPCs is when it would like to check its inbox for arrived function calls and execute them. Draining the RPC inbox is one of the many responsibilities of the progress API (see Ch. 10, *Progress*).

2 There are two main flavors of RPC in **UPC++**: *fire-and-forget* \( \text{rpc}_{\text{ff}} \) and *round trip* \( \text{rpc} \). Each takes a function \( \text{Func} \) together with variadic arguments \( \text{Args} \).

3 The \( \text{rpc}_{\text{ff}} \) call serializes the given function and arguments into a message destined for the recipient, and guarantees that this function call will be placed eventually in the recipient’s inbox. The round-trip \( \text{rpc} \) call does the same, but also forces the recipient to reply to the sender of the RPC with a message containing the return value of the function, providing the value for operation completion of the sender’s invocation of \( \text{rpc} \). Thus, when the future is ready, the sender knows the recipient has executed the function call. Additionally, if the return value of \( \text{func} \) is a future, the recipient will wait for that future to become ready before sending its result back to the sender.

4 There are important restrictions on what the permissible types for \( \text{func} \) and its bound arguments can be for RPC functions. First, the \( \text{Func} \) type must be a function object (has a publicly accessible overload of the function call operator, \( \text{operator}() \)). Second, \( \text{Func} \) must either be Serializable or one of the FunctionObject types listed in §6.5, and
all Arg types must be Serializable (see Ch. 6, Serialization), a cq dist_object<T>&, or cq team&. Third, the result of serializing and deserializing the function object (a value of type deserialized_type_t<Func>) must be invokable on the values that result from serializing and deserializing the arguments. Specifically, if an argument is of type cq dist_object<T>& or cq team&, the function object must accept a value of dist_object<T>& or team&, respectively, for the associated parameter. If the argument is of some other type T, the function object must accept a value of type deserialized_type_t<T>&& for the respective parameter. Lastly, the invocation must not throw an exception.

9.2 Remote Hello World Example

Figure 9.1 shows a simple alternative Hello World example where each process issues an rpc to its neighbor, where the last rank wraps around to 0.

```cpp
#include <upcxx/upcxx.hpp>
#include <iostream>

void hello_world(intrank_t num) {
    std::cout << "Rank " << num << " told rank " << upcxx::rank_me() << " to say Hello World" << std::endl;
}

int main(int argc, char** argv[]){
    upcxx::init();  // Start UPC++ state
    intrank_t remote = (upcxx::rank_me()+1)%upcxx::rank_n();
    auto f = upcxx::rpc(remote, hello_world, upcxx::rank_me());
    f.wait();
    upcxx::finalize();  // Close down UPC++ state
    return 0;
}
```

Figure 9.1: HelloWorld with Remote Procedure Call

---

1 The parameter type may be any of U, const U&, or U&&, where U is deserialized_type_t<T>, as all three parameter types accept an argument value of type U&&. The parameter type may not be U&, as that does not accept an argument value of type U&&. The parameter types const U& and U&& are recommended over U to minimize copy/move costs at invocation.
9.3 API Reference

```cpp
#include <cq/cq_team.hpp>
#include <cq/cq_dist_object.hpp>
#include <cq/cq_profile.hpp>

1 template <typename Func, typename ...Args>
void rpc_ff(intrank_t recipient,
            Func &&func, Args &&...args);

2 template <typename Cx, typename Func, typename ...Args>
RType rpc_ff(intrank_t recipient,
             Cx &&completions,
             Func &&func, Args &&...args);

3 template <typename Func, typename ...Args>
void rpc_ff(const team &team, intrank_t recipient,
            Func &&func, Args &&...args);

4 template <typename Cx, typename Func, typename ...Args>
RType rpc_ff(const team &team, intrank_t recipient,
             Cx &&completions,
             Func &&func, Args &&...args);
```

**Preconditions:**

2 • Func must be a function-object type.

3 • Func must either be Serializable or one of the FunctionObjects listed in §6.5.

4 • If Func&& is an rvalue-reference type, the underlying decayed type (std::decay<Func&&>::type) must be MoveConstructible.

5 • Each of Args... must be a Serializable type, or cq dist_object<T> &, or cq team&.

6 • If a type Arg in Args&&... is an rvalue-reference type, the underlying decayed type (std::decay<Arg>::type) must be MoveConstructible.

7 • The invocation of the deserialized function object on the deserialized arguments must not throw an exception.

8 In all variants, the func and args... are serialized and internally buffered before the call returns, regardless of what source-completion notifications are requested. In other words, the source-completion event always occurs before the invocation of rpc_ff returns. However, source-completion notifications (signaling a future, executing an LPC, or fulfilling a promise) are delayed until the next user-level progress. Requesting a notification other than buffered or blocking for source completion is deprecated, and it may be prohibited in subsequent revisions.
The call `rpc_ff(rank, func, args...)` is equivalent to:

```
rpc_ff(rank,
    source_cx::as_buffered(),
    func, args...)
```

Similarly, the call `rpc_ff(team, rank, func, args...)` is equivalent to

```
rpc_ff(team, rank,
    source_cx::as_buffered(),
    func, args...)
```

In the first two variants, the target of the RPC is the process whose rank is `recipient` in the world team (Ch. 11). In the latter two variants, the target is the process whose rank is `recipient` relative to the given team.

After their receipt on the target, the data are deserialized and the invocation of the deserialized function object on the deserialized arguments is enlisted for execution during user-level progress of the master persona. So long as the sending persona continues to make internal-level progress it is guaranteed that the message will eventually arrive at the recipient. See §10.5.3 `progress_required` for an understanding of how much internal-progress is necessary.

The result from invoking the function object is discarded. However, the return value affects the lifetime of the deserialized objects that the UPC++ runtime constructs and passes to the function object. If the return value is a non-future value or a ready future, the deserialized objects are destructed immediately after the invocation returns. On the other hand, if the return value is a non-ready future, destruction of the deserialized objects is deferred until after the future becomes ready, allowing the function object to safely initiate further asynchronous computation that operates on those objects.

The function object and arguments are always serialized and deserialized, even if the target is the same as the calling process. The invocation of the deserialized function object on the deserialized arguments is never performed synchronously, even if the target is the same as the calling process and `rpc_ff` is invoked during user-level progress.

Special handling is applied to those members of `args` which are either a reference to `dist_object` type or a `team`, as described in §6.6.

---

2 This excludes `team&` and `dist_object<T>&` arguments, where the underlying objects are not constructed by the UPC++ runtime in deserialization.
CHAPTER 9. REMOTE PROCEDURE CALL

Completions:

- **Source**: Indicates completion of serialization of the function object and arguments.

**C++ memory ordering**: All evaluations sequenced-before this call will have a happens-before relationship with the source-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment) and the recipient’s invocation of the function object.

**UPC++ progress level**: internal

```cpp
template< typename Func, typename ... Args >
RType rpc(intrank_t recipient,
        Func &&func, Args &&... args);

template< typename Cx, typename Func, typename ... Args >
RType rpc(intrank_t recipient,
        Cx &&completions,
        Func &&func, Args &&... args);

template< typename Func, typename ... Args >
RType rpc(const team &team, intrank_t recipient,
        Func &&func, Args &&... args);

template< typename Cx, typename Func, typename ... Args >
RType rpc(const team &team, intrank_t recipient,
        Cx &&completions,
        Func &&func, Args &&... args);
```

**Preconditions:**

- **Func** must be a function-object type.
- **Func** must either be Serializable or one of the FunctionObjects listed in §6.5.
- If **Func&&** is an rvalue-reference type, the underlying decayed type (std::decay<Func&&>::type) must be MoveConstructible.
- Each of **Args...** must be a Serializable type, or cq dist_object<T>&, or cq team&.
- If a type **Arg** in **Args&&...** is an rvalue-reference type, the underlying decayed type (std::decay<Arg>::type) must be MoveConstructible.
• The result of applying the deserialized function object to the deserialized arguments must either be of a Serializable type that is not view\langle U, IterType\rangle, or it must be future\langle T...\rangle, where each type in T... must be Serializable but not view\langle U, IterType\rangle.

• If the return type RetType of the function object is of non-reference or rvalue-reference type, the underlying decayed type (std::decay\langle RetType\rangle::type) must be MoveConstructible.

• The invocation of the deserialized function object on the deserialized arguments must not throw an exception.

Similar to rpc_ff, this call sends func and args... to be executed remotely, but additionally provides an operation-completion event. This event produces the value returned from the remote invocation of the deserialized function object on its deserialized arguments, if it is non-void.

In all variants, the func and args... are serialized and internally buffered before the call returns, regardless of what source-completion notifications are requested. In other words, the source-completion event always occurs before the invocation of rpc returns. However, source-completion notifications (signaling a future, executing an LPC, or fulfilling a promise) are delayed until the next user-level progress. Requesting a notification other than buffered or blocking for source completion is deprecated, and it may be prohibited in subsequent revisions.

The call rpc(rank, func, args...) is equivalent to:

```cpp
rpc(rank,
    source_cx::as_buffered() | operation_cx::as_future(),
    func, args...)
```

Similarly, the call rpc(team, rank, func, args...) is equivalent to:

```cpp
rpc(team, rank,
    source_cx::as_buffered() | operation_cx::as_future(),
    func, args...)
```

In the first two variants, the target of the RPC is the process whose rank is recipient in the world team (Ch. 11). In the latter two variants, the target is the process whose rank is recipient relative to the the given team.

After their receipt on the target, the data are deserialized and the invocation is enlisted for execution during user-level progress of the master persona.
In the first variant, the returned future is readied upon operation completion.

For futures provided by an operation-completion request, or promises used in promise-based operation-completion requests, the type of the future or promise must correspond to the return type of the invocation of the function object as follows:

- If the return type is of the form `future<T...>`, then a future provided by operation completion has type `future<deserialized_type_t<T>...>` and promises used in operation-completion requests must permit invocation of `fulfill_result` with values of type `deserialized_type_t<T>...`.

- If the return type is some other non-void type `T`, then a future provided by operation completion has type `future<deserialized_type_t<T>>`, and promises used in operation-completion requests must permit invocation of `fulfill_result` with a value of type `deserialized_type_t<T>`.

- If the return type is `void`, then a future provided by operation completion has type `future<>`, and promises used in operation-completion requests may have any type `promise<T...>`.

Within user-progress of the recipient’s master persona, the result from invoking the function object will be immediately serialized if the result is a non-future value or a ready future. If the result is a non-ready future, the encapsulated value will be serialized when the future becomes ready. In both cases, the deserialized objects that the UPC++ runtime constructs and passes to the function object are destructed after serialization of the result is complete. This allows the function object to safely initiate further asynchronous computation that operates on the deserialized objects or return a result that contain references to those objects. The serialized value is eventually sent back to the initiating process. Upon receipt, it will be deserialized, and operation-completion notifications will take place during subsequent user-progress of the initiating persona.

The function object and arguments are always serialized and deserialized, even if the target is the same as the calling process. The invocation of the deserialized function object on the deserialized arguments is never performed synchronously, even if the target is the same as the calling process and `rpc` is invoked during user-level progress.

---

³This excludes `team&` and `dist_object<T>&` arguments, where the underlying objects are not constructed by the UPC++ runtime in deserialization.
The same special handling applied to `dist_object&` and `team&` arguments by `rpc_ff` is also done by `rpc`.

**Completions:**

- **Source:** Indicates completion of serialization of the function object and arguments.
- **Operation:** Indicates completion of all aspects of the operation: serialization, deserialization, remote invocation, transfer of any result, and destruction of any internally managed values are complete. This completion produces a value as described above.

**C++ memory ordering:** All evaluations *sequenced-before* this call will have a *happens-before* relationship with the invocation of the function object. The return from the invocation of the function object will have a *happens-before* relationship with the operation-completion actions (future readying, promise fulfillment, or persona LPC enlistment). For LPC completions, all evaluations *sequenced-before* this call will have a *happens-before* relationship with the execution of the completion function.

**UPC++ progress level:** internal
Chapter 10

Progress

10.1 Overview

1 UPC++ presents a highly-asynchronous interface, but guarantees that user-provided call-
backs will only ever run on user threads during calls to the library. This guarantees a good
user-visibility of the resource requirements of UPC++, while providing a better interoper-
ability with other software packages which may have restrictive threading requirements.
However, such a design choice requires the application developer to be conscientious about
providing UPC++ access to CPU cycles.

2 Progress in UPC++ refers to how the calling application allows the UPC++ internal runtime to
advance the state of its outstanding asynchronous operations. Any asynchronous operation
initiated by the user may require the application to give UPC++ access to the execution
thread periodically until the operation reports its completion. Such access is granted by
simply making calls into UPC++. Each UPC++ function’s contract to the user contains its
progress guarantee level. This is described by the members of the upcxx::progress_level
enumerated type:

3 progress_level::user UPC++ may advance its internal state as well as signal completion
of user-initiated operations. This may entail the firing of remotely injected procedure
calls (RPCs), or readying/fulfillment of futures/promises and the ensuing callback
cascade.

4 progress_level::internal UPC++ may advance its internal state, but no notifications
will be delivered to the application. Thus, an application has very limited ways to
“observe” the effects of such progress.
Progress level: none

UPC++ will not attempt to advance the progress of asynchronous operations. (Note this level does not have an explicit entry in the `progress_level` enumerated type).

The most common progress guarantee made by UPC++ functions is `progress_level::internal`. This ensures the delivery of notifications to remote processes (or other threads) making user-level progress in a timely manner. In order to avoid having the user contend with the cost associated with callbacks and RPCs being run anytime a UPC++ function is entered, `progress_level::user` is purposefully not the common case.

`progress` is the notable function enabling the application to make user-level progress. Its sole purpose is to look for ready operations involving this process or thread and run the associated RPC/callback code:

```cpp
upcxx::progress(progress_level lev = progress_level::user)
```

UPC++ execution phases which leverage asynchrony heavily tend to follow a particular program structure. First, initial communications are launched. Their completion callbacks might then perform a mixture of compute or further UPC++ communication with similar, cascading completion callbacks. Then, the application spins on `upcxx::progress()`, checking some designated application state which monitors the amount of pending outgoing/incoming/local work to be done. For the user, understanding which functions perform these progress spins becomes crucial, since any invocation of user-level progress may execute RPCs or callbacks.

10.2 Restricted Context

During user-level progress made by UPC++, callbacks may be executed. Such callbacks are subject to restrictions on how they may further invoke UPC++ themselves. We designate such restricted execution of callbacks as being in the restricted context. The general restriction is stated as:

```
User code running in the restricted context must assume that for the duration of the context all other attempts at making user-level progress, from any thread on any process, may result in a no-op every time.
```

The immediate implication is that a thread which is already in the restricted context should assume no-op behavior from further attempts at making progress. This makes it pointless to try and wait for UPC++ notifications from within restricted context since there is no viable mechanism to make the notifications visible to the user. Thus, calling any routine which spins on user-level progress until some notification occurs will likely hang the thread.
A thread running in the restricted context shall not initiate any `UPC++` collective operation that has a progress level of `user`.

Initiating a collective operation with a progress level of `internal` or `none` from within the restricted context is deprecated behavior, and it may be prohibited in subsequent revisions.

The `in_progress` function can be used to query whether the calling thread is currently running in the restricted context.

## 10.3 Attentiveness

Many `UPC++` operations have a mechanism to signal completion to the application. However, a performance-oriented application will need to be aware of an additional asynchronous operation status indicator called `progress-required`. This status indicates that for a particular operation further advancements of the current process or thread’s `internal-level progress are necessary so that completion regarding remote entities (e.g. notification of delivery) can be reached. Once an operation has left the progress-required state, `UPC++` guarantees that remote entities will see their side of the operations' completion without any further progress by the current compute resource. Applications will need to leverage this information for performance, as it is inadvisable for a compute resource to become inattentive to `UPC++` progress (e.g. long bouts of arithmetic-heavy computation) while other entities depend on operations that require further servicing.

As said previously, nearly all `UPC++` operations track their completion individually. However, it is not possible for the programmer to query `UPC++` if individual operations no longer require further progress. Instead, the user may ask `UPC++` when operations initiated by this thread have reached a state at which they no longer require internal progress to reach their destinations. So for example, one may ask whether `rpc` or `rput` operations previously initiated by this thread and destined for a remote process have been handed off to the network hardware (but not necessarily delivered/completed).

This is achieved by using the following functions:

```cpp
bool upcxx::progress_required();
void upcxx::discharge();
```

The `progress_required` function reports whether this thread requires internal progress on outgoing operations, allowing the application to know that there are still pending outgoing operations that will not achieve remote completion without further advancements to internal progress. This is of particular importance before a thread enters a lapse of inat-
tentiveness (for instance, performing expensive computations) in order to prevent slowing down remote entities.

5 The **discharge** function allows a thread to ensure that **UPC++** no longer requires internal progress to deliver operations outgoing from this thread. It is equivalent to the following:

6 ```
void upcxx::discharge(persona_scope &ps = top_persona_scope()) {
    while(upcxx::progress_required(ps))
        upcxx::progress(upcxx::progress_level::internal);
}
```

A well-behaved **UPC++** application is encouraged to call **discharge** before any long lapse of attentiveness to progress.

### 10.4 Thread Personas/Notification Affinity

1 As explained in Chapter 5 *Futures and Promises*, futures require careful consideration when used in the presence of thread concurrency. It is crucial that **UPC++** is very explicit about how a multi-threaded application can safely use futures returned by **UPC++** calls.

2 The most important thing an application has to be aware of is which thread **UPC++** will use to signal completion of a given future. It is therefore extremely important to know that **UPC++** will use the same thread to which the future was returned by the **UPC++** operation (i.e. the thread which invoked the operation in the first place). This means that the thread which invoked a future-returning operation will be the only one able to see that operation’s completion. As **UPC++** triggers futures only during a call which makes user-level progress, the invoking thread must continue to make such progress calls until the future is satisfied. This requirement has the drawback of banning the application from doing the following: initiating a future-returning operation on one thread, allowing that thread to terminate or become permanently inattentive (e.g. sleeping in a thread pool), and expecting a different thread to receive the future’s completion. This section will focus on two ways the application can still attain this use-case.

3 The notion of “thread” has been used in a loose fashion throughout this document, the natural interpretation being an operating system (OS) thread. More precisely, this document uses the notion of “thread” to denote an **UPC++** device referred to as **thread persona** which generalizes the notion of operating system threads.

---

1Actually, this only applies to non-master personas held by this thread; see the API reference for detailed semantics. Personas are discussed in the next section.
A UPC++ thread persona is a collection of UPC++-internal state usually attributed to a single thread. By making it a proper construct, UPC++ allows a single OS thread to switch between multiple application-defined roles for processing notifications. Personas act as the receivers for notifications generated by the UPC++ runtime.

Values of type upcxx::persona are non-copyable, non-movable objects which the application can instantiate as desired. For each OS thread, UPC++ internally maintains a stack of active persona references. The top of this stack is the current persona. All asynchronous UPC++ operations will have their notification events (signaling of futures or promises) sent to the current persona of the OS thread invoking the operation. Calls that make user-level progress will process notifications destined to any of the active personas of the invoking thread. For the duration of a notification’s processing, its target persona is placed at the top of the persona stack of the OS thread associated with that persona.

The initial state of the persona stack consists of a single entry pointing to a persona created by UPC++ which is dedicated to the current OS thread. Therefore, if the application never makes any use of the persona API, notifications will be processed solely by the OS thread that initiates the operation.

Pushing and popping personas from the persona stack (hence changing the current persona) is done with the upcxx::persona_scope type. For example:

```cpp
persona scheduler_persona;
std::mutex scheduler_lock;

{ // Scope block delimits domain of persona Scope instance.
  auto scope = persona_scope(scheduler_lock, scheduler_persona);

  // All following upcxx actions will use 'scheduler_persona' as current.
  // ...

  // 'scope' destructs:
  // - 'scheduler_persona' dropped from active set if it wasn't active before the scope's construction.
  // - Previously current persona revived.
  // - Lock released.
}
```

Since UPC++ will assume an OS thread has exclusive access to all of its active personas, it is the user’s responsibility to ensure that no OS threads share an active persona concur-
rently. The use of the `persona_scope` constructor, which takes a lock-like synchronization primitive, is strongly encouraged to facilitate in enforcing this invariant.

There are two ways that asynchronous operations can be initiated by a given OS thread but retired in another. The first solution is simple:

1. The user defines a persona `P`.
2. Thread 1 activates `P`, initiates the asynchronous operation, and releases `P`.
3. Thread 1 synchronizes with Thread 2, indicating the operation has been initiated.
4. Thread 2 activates `P`, spins on `progress` until the operation completes.

Care must be taken that any futures created by phase 2 are never altered (uttered) concurrently. The same synchronization that was used to enforce exclusivity of persona acquisition can be leveraged to protect the future as well.

While this technique achieves our goal of different threads initiating and resolving asynchronous operations, it fails a different but also desirable property. It is often desirable to allow multiple threads to issue communication *concurrently* while delegating a separate thread to handle the notifications. To achieve this, it is clear that multiple personas are needed. Indeed, the exclusivity of a persona being current to only one OS thread prevents the application from concurrent initiation of communication.

In order to issue operations and concurrently retire them in a different thread, the user is strongly encouraged to use the LPC completion mechanism described in Chapter 7, as opposed to the future or promise variants. An example of such a call is:

```
rget(gptr_src, operation_cx::as_lpc(some_persona, callback_func));
```

In addition to the arguments necessary for the particular operation, the `as_lpc` completion mechanism takes a persona reference and a C++ function object (lambda, etc.) such that upon completion of the operation, the designated persona shall execute the function object during its user-level progress. Using this mechanism, it is simple to have multiple threads initiating communication concurrently with a designated thread receiving the completion notifications. To achieve this, each operation is initiated by a thread using the agreed-upon persona of the receiver thread together with a callback that will incorporate knowledge of completion into the receiver’s state.
## 10.5 API Reference

```cpp
enum class progress_level {
    /* none, -- not an actual member, conceptual only*/
    internal,
    user
};

void progress(progress_level lev = progress_level::user);

This call will always attempt to advance internal progress.

If `lev == progress_level::user` then this thread is also used to execute any available user actions for the personas currently active. Actions include:

1. Either future-readying or promise-fulfilling completion notifications for asynchronous operations initiated by one of the active personas. By the execution model of futures and promises this can induce callback cascade.

2. Continuation-style completion notifications from operations initiated by any persona but designating one of the active personas as the completion recipient.

3. RPCs destined for this process but only if the master persona is among the active set.

4. lpc’s destined for any of the active personas.

UPC++ progress level: internal or user

bool in_progress();

Returns true if and only if the calling thread is currently executing in the restricted context (§10.2), in other words, within the dynamic scope of user-level progress.

UPC++ progress level: none
10.5.1 persona

```cpp
1 class persona;
2
3 persona::persona();

Constructs a persona object with no enqueued operations.

4 This function may be called when UPC++ is in the uninitialized state.
5
6 UPC++ progress level: none

7 persona::~persona();

Destructs this persona object. If this persona is a member of any thread’s persona stack, the result of this call is undefined. If any operations are currently enqueued on this persona, or if any operations initiated by this persona require further progress, the result of this call is undefined.

8 This function may be called when UPC++ is in the uninitialized state.
9
10 UPC++ progress level: none
```

```cpp
11 template<typename Func>
12 void persona::lpc_ff(Func &&func);

Preconditions:
```
13   • Func must be a function-object type that can be invoked on zero arguments.
14   • If Func&& is an rvalue-reference type, the underlying decayed type (std::decay<Func&&>::type) must be MoveConstructible.
15   • If Func&& is an lvalue-reference type, the underlying decayed type (std::decay<Func&&>::type) must be CopyConstructible.
16   • The call func() must not throw an exception.
```
std::forward's func into an unordered collection of type-erased function objects to be executed during user-level progress of the targeted (this) persona. This function is thread-safe, so it may be called from any thread to enqueue work for this persona.

The execution of func is never performed synchronously, even if the target persona is a member of the caller’s persona stack and this function is invoked during user-level progress.

C++ memory ordering: All evaluations sequenced-before this call will have a happens-before relationship with the invocation of func.

UPC++ progress level: none

template<typename Func>
FType persona::lpc(Func &&func);

Preconditions:

• Func must be a function-object type that can be invoked on zero arguments.

• If Func&& is an rvalue-reference type, the underlying decayed type (std::decay<Func&&>::type) must be MoveConstructible.

• If Func&& is an lvalue-reference type, the underlying decayed type (std::decay<Func&&>::type) must be CopyConstructible.

• The call func() must not throw an exception.

• If the return type RetType of Func is of non-reference or rvalue-reference type, the underlying decayed type (std::decay<RetType>::type) must be MoveConstructible.

std::forward's func into an unordered collection of type-erased function objects to be executed during user-level progress of the targeted (this) persona. The return value of func is asynchronously returned to the currently active persona in a future. If the return value of func is a future, then the targeted persona will wait for that future before signaling the future returned by lpc with its value. This function is thread-safe, so it may be called from any thread to enqueue work for this persona. Note that the future returned by lpc is considered to be owned by the currently active persona, the future returned by func (if any) will be considered owned by the target (this) persona.
If the return type \( U \) of \( \text{Func} \) is an lvalue reference, then \( \text{FType} \) is \( \text{future}<U> \). Otherwise, \( \text{FType} \) is \( \text{future<typename std::decay<U>::type>} \).

The execution of \( \text{func} \) is never performed synchronously, even if the target persona is a member of the caller’s persona stack and this function is invoked during user-level progress.

\( C++ \) memory ordering: All evaluations sequenced-before this call will have a happens-before relationship with the invocation of \( \text{func} \), and the invocation of \( \text{func} \) will have a happens-before relationship with evaluations sequenced after the signaling of the final future.

\( UPC++ \) progress level: none

```cpp
bool persona::active_with_caller() const;
```

Returns true if and only if this persona is a member of the calling OS thread’s persona stack.

\( UPC++ \) progress level: none

```cpp
persona& master_persona();
```

Returns a reference to the master persona automatically instantiated by the \( UPC++ \) runtime. The thread that executes \text{upcxx::init} \) implicitly acquires this persona as its current persona. The master persona is special in that it is the only one which will execute RPCs destined for this process. Additionally, some \( UPC++ \) functions may only be called by a thread with the master persona in its active stack.

\( UPC++ \) progress level: none

```cpp
persona& current_persona();
```

Returns a reference to the persona on the top of the thread’s active persona stack.

\( UPC++ \) progress level: none

```cpp
persona& default_persona();
```

Returns a reference to the persona instantiated automatically and uniquely for this OS thread. The default persona is always the bottom of and can never be removed from its designated OS thread’s active stack.

\( UPC++ \) progress level: none
void liberate_master_persona()

Precondition: This thread must be the one which called upcxx::init, it must have not altered its persona stack since calling init, and it must not have called this function already since calling init.

The thread which invokes upcxx::init implicitly has the master persona at the top of its active stack, yet the user has no persona_scope to drop to allow other threads to acquire the persona. Thus, if the user intends for other threads to acquire the master persona, they should have the init-calling thread release the persona with this function so that it can be claimed by persona_scope’s. Generally, if this function is ever called, it is done soon after init and then the master persona should be reacquired by a persona_scope.

UPC++ progress level: none

10.5.2 persona_scope

class persona_scope;

C++ Concepts: Destructible, MoveConstructible

persona_scope::persona_scope(persona &p);

Precondition: Excluding this thread, p is not a member of any other thread’s active stack.

Pushes p onto the top of the calling OS thread’s active persona stack.

UPC++ progress level: none

template<typename Mutex>
persona_scope::persona_scope(Mutex &mutex, persona &p);

C++ Concepts of Mutex: Mutex

Precondition: p will only be a member of some thread’s active stack if that thread holds mutex in a locked state.

Invokes mutex.lock(), then pushes p onto the OS thread’s active persona stack.

UPC++ progress level: none
12 persona_scope::~persona_scope();

13 Precondition: All persona_scope’s constructed on this thread since the construction of this instance have since destructed.

14 The persona supplied to this instance’s constructor is popped from this thread’s active stack. If this instance was constructed with the mutex constructor, then that mutex is unlocked.

15 This function may be called when UPC++ is in the uninitialized state.

16 UPC++ progress level: none

17 persona_scope& top_persona_scope();

18 Reference to the most recently constructed but not destructed persona_scope for this thread. Every thread begins with an implicitly instantiated scope pointing to its default persona that survives for the duration of the thread’s lifetime.

19 UPC++ progress level: none

20 persona_scope& default_persona_scope();

21 Every thread begins with an implicitly instantiated scope pointing to its default persona that survives for the duration of the thread’s lifetime. This function returns a reference to that bottommost persona_scope for the calling thread, which points at the calling thread’s default_persona().

22 UPC++ progress level: none

10.5.3 Outgoing Progress

1 bool progress_required(persona_scope &ps = top_persona_scope());

2 Precondition: ps has been constructed by this thread.

3 For the set of personas included in this thread’s active stack section bounded inclusively between ps and the current top, nearly answers if any UPC++ operations initiated by those personas require further advancement of internal-progress of their respective personas before their completion events will be eventually available to user-level progress on the destined processes. The exact meaning of the return value depends on which personas are selected by ps:
• If ps does not include the master persona: A return value of true means that one or more of the personas indicated by ps requires further internal-progress to achieve completion of its outgoing operations. A value of false means that none of the personas indicated by ps require internal-progress, but internal-progress of the master persona might still be required.

• If ps does include the master persona: A return value of true means that one or more of the personas indicated by ps requires further internal-progress to achieve completion of its outgoing operations. A return value of false means that none of the non-master personas indicated by ps requires further internal-progress, but the master persona may or may not require further internal-progress.

**UPC++ progress level:** none

```cpp
void discharge(persona_scope &ps = top_persona_scope());
```

Advances internal-progress enough to ensure that `progress_required(ps)` returns false.

*Note:* discharge() only ensures that internal progress has been advanced sufficiently to guarantee that outgoing operations initiated by non-master personas held by this thread will eventually reach their destinations. In particular, it does not guarantee anything about communication arrival at other processes or acknowledgements to those operations, for example acknowledgements that trigger operation completion events.

**UPC++ progress level:** internal
Chapter 11

Teams

11.1 Overview

UPC++ provides *teams* as a means of grouping processes. UPC++ uses *teams* for collective operations (Ch. 12). *team* construction is collective and should be considered moderately expensive and done as part of the set-up phase of a calculation. *teams* are similar to MPI_Groups and the default *team* is *world()*.*teams* are considered special when it comes to serialization. Each *team* has a unique *team_id* that is equal across the *team* and acts as an opaque handle. Any process that is a member of the *team* can retrieve the *team* object with the *team_id::here()* function. Hence, coordinating processes can reference specific *teams* by their *team_id*.

While a process within a UPC++ SPMD program can have multiple *intrank_t* values that represent their relative placement in several *teams*, it is the *intrank_t* in the *world()* team that is used in most UPC++ functions, unless otherwise specifically noted. For example, *broadcast* takes a rank relative to the specific *team* over which it operates.

11.2 Local Teams

The local team is an ordered set of processes where heap storage in the shared segment allocated by any process in the team is local to all members. Any process can obtain a reference to the local team by calling *local_team* and global pointers behave accordingly:
1. `global_ptr`'s referencing objects allocated in the shared segment of processes that are members of this team will report `is_local() == true` and `local()` will return a valid `T*` referencing the corresponding object.

2. The `global_ptr` `where()` function will report the rank in team `world()` of the process that originally acquired the referenced object using the functions in chapter 4.

It is not guaranteed that the `T*`'s obtained by different processes to the same shared object will have bit-wise identical pointer values. In the general case, peers may have different virtual addresses for the same physical memory.

### 11.3 API Reference

#### 11.3.1 team

```cpp
class team;

// C++ Concepts: MoveConstructible, Destructible
constexpr intrank_t team::color_none;

A constant used to specify that the calling process of `split()` will not be a member of any subteam. This constant is guaranteed to have a negative value.

intrank_t team::rank_n() const;

Returns the number of ranks in the given team.

UPC++ progress level: none

intrank_t team::rank_me() const;

Returns the rank of the calling process in the given team.

UPC++ progress level: none

intrank_t team::operator[](intrank_t peer_index) const;

Precondition: `peer_index >= 0` and `peer_index < rank_n()`.

Returns the rank in the `world()` team of the process with rank `peer_index` in this team.

UPC++ progress level: unspecified between `none` and `internal`
```
intrank_t team::from_world(intrank_t world_index) const;
intrank_t team::from_world(intrank_t world_index, intrank_t otherwise) const;

Precondition: world_index >= 0 and world_index < world().rank_n(). For the single-argument overload, the process with rank world_index in the world() team must be a member of this team.

Returns the rank in this team of the process with rank world_index in the world() team. For the two-argument overload, if that process is not a member of this team then the value of otherwise is returned.

UPC++ progress level: unspecified between none and internal

team team::split(intrank_t color, intrank_t key) const;

This function is collective (§12.1) over this (i.e. the parent) team, and it must be called by the thread that has the master persona (§10.5.1).

Precondition: color >= 0 || color == team::color_none

Splits the given team into subteams based on the color and key arguments. If color == team::color_none, the return value is an invalid team that cannot be used in any UPC++ operation except ~team. Otherwise, all processes that call the function with the same color value will be separated into the same subteam. Ranks in the same subteam will be numbered according to their position in the sequence of sorted key values. If two callers specify the same combination of color and key, their relative ordering in the subteam will be the same as in the parent team. The return value is the team representing the calling process’s new subteam.

This call will invoke user-level progress, so the caller may expect incoming RPCs to fire before it returns.

C++ memory ordering: With respect to all threads participating in this collective, all evaluations which are sequenced-before their respective thread’s invocation of this call will have a happens-before relationship with all evaluations sequenced after the call.

UPC++ progress level: user
team::team(team &&other);

Precondition: Calling thread must have the master persona. No operation on this team, nor any UPC++ operation with a progress level other than none, may have been invoked by the calling process between the creation of other and this call.

Makes this instance the calling process’s representative of the team associated with other, transferring all state from other. Invalidates other, and any subsequent operations on other, except for destruction, produce undefined behavior.

UPC++ progress level: none

void team::destroy(entry_barrier lev = entry_barrier::user);

This function is collective (§12.1) over this team, and it must be called by the thread that has the master persona (§10.5.1).

Precondition: This instance must not have been invalidated by being passed to the move constructor, and it must not be an invalid team that resulted from a call to split(). lev must be single-valued (Ch. 12). After the entry barrier specified by lev completes, or upon entry if lev == entry_barrier::none, the operations on this team must not require internal-level or user-level progress from any persona before they can complete.

Destroys the calling process’s state associated with the team. Further lookups on this process using the team_id corresponding to this team will have undefined behavior.

C++ memory ordering: If lev != entry_barrier::none, with respect to all threads participating in this collective, all evaluations which are sequenced-before their respective thread’s invocation of this call will have a happens-before relationship with all evaluations sequenced after the call.

UPC++ progress level: user if lev == entry_barrier::user, internal otherwise
team::~team();

Precondition: Either UPC++ must have been uninitialized since the team’s creation, or the team must either have had destroy() called on it, been invalidated by being passed to the move constructor, or be an invalid team that resulted from a call to split().

Destructs this team object.

This function may be called when UPC++ is in the uninitialized state.

UPC++ progress level: none

team_id team::id() const;

Returns the universal name that uniquely identifies this team.

UPC++ progress level: none

### 11.3.2 team_id

class team_id;

cpp Concepts: DefaultConstructible, TriviallyCopyable, StandardLayoutType, EqualityComparable, LessThanComparable, hashable

UPC++ Concepts: TriviallySerializable

A universal name that uniquely identifies a team.

team_id::team_id();

Initializes this name to be the invalid ID. All default-constructed team_id objects will receive the same, unique invalid identifier. This enables use of team_id() as a placeholder ID for naming the absence of a team. Note this unique value may differ from the result of team::id() on destroyed or otherwise invalid teams.

UPC++ progress level: none
precondition: This name must be a valid ID. The calling process must be a member of the team associated with this name, and it must have completed creation of the team. The team must not have been destroyed.

retrieves a reference to the team instance associated with this name.

upc++ progress level: none

future<team &> team_id::when_here() const;

precondition: This name must be a valid ID. The calling process must be a member of the team associated with this name. The calling thread must have the master persona. The team must not have been destroyed.

retrieves a future which is readied after the calling process constructs the team corresponding to this name.

upc++ progress level: none

11.3.3 Fundamental Teams

team& world();

returns a reference to the team representing all the processes in the upc++ program. the result is undefined if a move is performed on the returned team. calling destroy() on the returned team results in undefined behavior.

upc++ progress level: none

intrank_t rank_n();

returns the number of ranks in the world() team.

equivalent to: world().rank_n.

upc++ progress level: none

intrank_t rank_me();

returns the rank of the calling process in the world() team.

equivalent to: world().rank_me.

upc++ progress level: none
team& local_team();

Returns a reference to the local team containing this process. The local team represents an ordered set of processes where memory allocated from the shared segment of any member is local to all team members (§11.2). The result is undefined if a move is performed on the returned team. Calling destroy() on the returned team results in undefined behavior.

**UPC++ progress level: none**

bool local_team_contains(intrank_t world_index);

**Precondition:** world_index >= 0 and world_index < world().rank_n().

Determines if the process whose rank is world_index in world() is a member of the local team containing the calling process (§11.2).

Equivalent to: local_team().from_world(world_index,-1) >= 0

**UPC++ progress level: none**
Chapter 12

Collectives

1 A collective operation is a UPC++ operation that must be matched across all participating processes. Informally, any two processes that both participate in a pair of collective operations must agree on their ordering. Furthermore, if a parameter or other property of a collective operation is specified as single-valued, all participating processes must provide the same value for the parameter or property.

2 A collective operation need not provide any actual synchronization between processes, unless otherwise noted. The collective requirement simply states a relative ordering property of calls to collective operations that must be maintained in the parallel execution trace for all executions of any valid program. Some implementations may include unspecified synchronization between processes within collective operations, but programs must not rely upon the presence or absence of such unspecified synchronization for correctness.

3 A noteworthy exception to the previous paragraph is that collective calls specified with progress level: none are additionally prohibited from synchronizing between processes. However, such calls still require the proper collective ordering of matching calls across all participating processes.

4 UPC++ provides several collective communication operations over teams, described below.
12.1 Common Requirements

1 For an execution of a UPC++ program to be valid, the collective operations invoked by the program must obey the following ordering constraints:

2 • For a collective operation \( C \) over a team \( T \), let \( \text{Participants}(C) \) denote the set of processes that are members of \( T \).

3 • For a process \( P \in \text{Participants}(C_1) \cap \text{Participants}(C_2) \), let \( \text{Precedes}_P(C_1, C_2) \) be true if and only if \( C_1 \neq C_2 \) and \( C_1 \) is initiated before \( C_2 \) on \( P \).

4 • Let \( \text{Collectives} \) be the set of collective operations invoked during execution of the program. The collectives must satisfy the following property:

\[
\forall C_1, C_2 \in \text{Collectives}. \forall P, Q \in \text{Participants}(C_1) \cap \text{Participants}(C_2). \quad \text{Precedes}_P(C_1, C_2) = \text{Precedes}_Q(C_1, C_2) \tag{12.1}
\]

5 The constraints above formalize the notion that any two processes that both participate in a pair of collectives must agree on their ordering.

6 For any collective operation \( C \), it is an error if the completion of the operation (return from synchronous collectives, operation-completion notifications for asynchronous collectives) on at least one participant has a happens-before relationship with the initiation of operation \( C \) on another participant.

7 A collective operation must be invoked by the thread that has the master persona (§10.5.1) of a process.

12.2 API Reference

1 \begin{verbatim}
enum class entry_barrier {
  none,
  internal,
  user
};
\end{verbatim}

2 Constants used with some UPC++ operations to specify the entry barrier to be used by the operation:

3 • \texttt{none}: the operation has no entry barrier
• **internal**: the operation should perform a barrier at entry that makes only internal-level progress

• **user**: the operation should perform a barrier at entry that makes user-level progress

```
void barrier(const team &team = world());
```

This function is collective (§12.1) over the given team, and it must be called by the thread that has the master persona (§10.5.1).

Performs a barrier operation over the given team. The call will not return until all processes in the team have entered the call. There is no implied relationship between this call and other in-flight operations. This call will invoke user-level progress, so the caller may expect incoming RPCs to fire before it returns.

*C++ memory ordering:* With respect to all threads participating in this collective, all evaluations which are sequenced-before their respective thread’s invocation of this call will have a happens-before relationship with all evaluations sequenced after the call.

*UPC++ progress level: user*

```
template<typename Cx=/*unspecified*/>
RType barrier_async(const team &team = world(),
                     Cx &completions=operation_cx::as_future());
```

This function is collective (§12.1) over the given team, and it must be called by the thread that has the master persona (§10.5.1).

Initiates an asynchronous barrier operation over the given team. The call will return without waiting for other processes to make the call. Operation completion will be signaled after all other processes in the team have entered the call.

**Completions:**

• **Operation**: Indicates completion of the collective from the viewpoint of the caller, implying that all processes in the given team have entered the collective.
C++ memory ordering: With respect to all threads participating in this collective, all evaluations which are sequenced-before their respective thread’s invocation of this call will have a happens-before relationship with all evaluations sequenced after the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment).

UPC++ progress level: internal

```cpp
cconstexpr /* unspecified */ op_fast_add;
cconstexpr /* unspecified */ op_fast_mul;
cconstexpr /* unspecified */ op_fast_min;
cconstexpr /* unspecified */ op_fast_max;
cconstexpr /* unspecified */ op_fast_bit_and;
cconstexpr /* unspecified */ op_fast_bit_or;
cconstexpr /* unspecified */ op_fast_bit_xor;
```

Instances of unspecified function-object types that have the following overloaded function-call operator:

```
T operator() (T a, T b) const;
```

The unspecified function-object types meet the requirements for the `BinaryOp` template parameter to `reduce_one` and `reduce_all` (e.g. they are referentially transparent and concurrently invokable).

For `op_fast_add`, `op_fast_mul`, `op_fast_min`, and `op_fast_max`, the allowed types for `T` are those for which `std::is_arithmetic<T>::value` is true. For `op_fast_bit_and`, `op_fast_bit_or`, and `op_fast_bit_xor`, the allowed types for `T` are those for which `std::is_integral<T>::value` is true.

The operation performed by the function-call operator is, respectively: binary +, binary *, `std::min`, `std::max`, binary &, |, and ^. If `T` is `bool`, then `op_fast_add` and `op_fast_max` perform the same operation as `op_fast_bit_or`, and `op_fast_mul` and `op_fast_min` perform the same operation as `op_fast_bit_and`. 

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23 \texttt{template<typename T, typename BinaryOp, typename Cx=/*unspecified*/>}
\texttt{RType reduce\_one(T \texttt{value}, BinaryOp \&\&\texttt{op}, intrank_t \texttt{root},}
\texttt{const team &\texttt{team} = world(),}
\texttt{Cx \&\&\texttt{completions=operation\_cx::as\_future());}

24 \texttt{template<typename T, typename BinaryOp, typename Cx=/*unspecified*/>}
\texttt{RType reduce\_all(T \texttt{value}, BinaryOp \&\&\texttt{op},}
\texttt{const team &\texttt{team} = world(),}
\texttt{Cx \&\&\texttt{completions=operation\_cx::as\_future());}

25 \texttt{template<typename T, typename BinaryOp, typename Cx=/*unspecified*/>}
\texttt{RType reduce\_one(const T *\texttt{src}, T *\texttt{dst}, size_t \texttt{count},}
\texttt{BinaryOp \&\&\texttt{op}, intrank_t \texttt{root},}
\texttt{const team &\texttt{team} = world(),}
\texttt{Cx \&\&\texttt{completions=operation\_cx::as\_future());}

26 \texttt{template<typename T, typename BinaryOp, typename Cx=/*unspecified*/>}
\texttt{RType reduce\_all(const T *\texttt{src}, T *\texttt{dst}, size_t \texttt{count},}
\texttt{BinaryOp \&\&\texttt{op},}
\texttt{const team &\texttt{team} = world(),}
\texttt{Cx \&\&\texttt{completions=operation\_cx::as\_future());}

27 \texttt{This function is collective (§12.1) over the given team, and it must be called by}
\texttt{the thread that has the master persona (§10.5.1).}

28 \texttt{Precondition: T must be TriviallySerializable. BinaryOp must be a function-}
\texttt{object type representing an associative and commutative mathematical}
\texttt{operation taking two values of type T and returning a value implicitly convertible}
\texttt{to T. BinaryOp must be referentially transparent and concurrently invokable.}
\texttt{BinaryOp may not invoke any UPC++ routine with a progress level other than}
\texttt{none. In the first and third variants, root must be single-valued and a valid}
\texttt{rank in team. In the third variant, src and dst on the process whose rank}
\texttt{is root in the team may be equal but must not otherwise overlap, and count}
\texttt{must be single-valued across all participants. In the fourth variant, src and}
\texttt{dst may be equal but must not otherwise overlap, and src == dst and count}
\texttt{must both be single-valued.}

29 \texttt{Performs a reduction operation over the processes in the given team.}

30 \texttt{If the team contains only a single process, then the resulting operation com-}
\texttt{pletion will produce value in the first two variants. In the latter two variants,}
\texttt{the contents of src will be copied to dst if src != dst.}

31 \texttt{If the team contains more than one process, initiates an asynchronous reduction}
\texttt{over the values provided by each process. The reduction is performed in some}
\texttt{non-deterministic order by applying op to combine values and intermediate}
results. In the second and fourth variants, the order in which \texttt{op} is applied may differ between processes, so the results may differ if \texttt{op} is not fully associative and commutative (as with floating-point arithmetic on some operands). In the third and fourth variants, the contents of \texttt{src} are combined element-wise across the processes in the team, with the results placed in \texttt{dst}.

In the first variant, the process whose rank is \texttt{root} in \texttt{team} receives the result of the reduction as part of operation completion, while the remaining processes receive an undefined value.

In the second variant, each process receives the result of the reduction as part of operation completion.

In the third variant, operation completion signifies that the results have been stored in \texttt{dst} on the process whose rank is \texttt{root} in \texttt{team} and that \texttt{src} is no longer in use by the reduction. On the remaining processes, the argument \texttt{dst} is ignored, and operation completion signifies that \texttt{src} is no longer in use by the reduction.

In the fourth variant, operation completion on each process signifies that the results have been stored in \texttt{dst} on that process and that \texttt{src} is no longer in use by the reduction.

\textit{Advice to users:} If \texttt{op} is one of \texttt{op\_fast\_*} and \texttt{T} is one of the allowed types for \texttt{op}, implementations may offload the reduction operations to NIC hardware.

\textbf{Completions:}

- \textit{Operation:} Indicates completion of the collective from the viewpoint of the caller, implying that the results of the reduction are available to this process as described above. In the third and fourth variants, also signifies that the \texttt{src} buffer may be modified. In the first two variants, this completion produces a value of type \texttt{T}. In the latter two variants, this completion does not produce a value.

\textit{C++ memory ordering:} With respect to all threads participating in this collective, all evaluations which are \texttt{sequenced-before} any thread’s invocation of this call will have a \texttt{happens-before} relationship with all evaluations sequenced after the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment) on the threads that receive the results of the collective (on the root process in the first and third variants; on all participating processes in the second and fourth variants).

\textit{UPC++ progress level:} \texttt{internal}
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37 template<typename T, typename Cx=/*unspecified*/>
   RType broadcast(T value, intrank_t root,
                   const team &team = world(),
                   Cx &&completions=operation_cx::as_future());

38 template<typename T, typename Cx=/*unspecified*/>
   RType broadcast(T *buffer, std::size_t count, intrank_t root,
                   const team &team = world(),
                   Cx &&completions=operation_cx::as_future());

39 This function is collective (§12.1) over the given team, and it must be called by
   the thread that has the master persona (§10.5.1).

39 Precondition: root must be single-valued and a valid rank in team. In the
   second variant, count must be single-valued. The type T must be TriviallySer-
   ializable.

40 Initiates an asynchronous broadcast (one-to-all) operation, with rank root in
   team acting as the producer of the broadcast. In the first variant, value will
   be asynchronously sent to all processes in the team, encapsulated in operation
   completion, which will be signaled upon receipt of the value. In the second
   variant, the objects in [buffer,buffer+count) of rank root in team are sent
   to the addresses [buffer,buffer+count) provided by the receiving processes.
   Operation completion signals completion of the operation with respect to the
   calling process. For the root, this indicates its buffer is available for reuse, and
   for a receiver, it indicates that the data have been received in its buffer.

41 Completions:
   • Operation: In the first variant, indicates that the value provided by the
     root is available at the caller, and this completion produces a value of type
     T. In the second variant, indicates completion of the collective from the
     viewpoint of the caller as described above, and this completion does not
     produce a value.

42 C++ memory ordering: With respect to all threads participating in this col-
   lective, all evaluations which are sequenced-before the producing thread’s invo-
   cation of this call will have a happens-before relationship with all evaluations
   sequenced after the operation-completion notification actions (future readying,
   promise fulfillment, or persona LPC enlistment).

43 UPC++ progress level: internal
Chapter 13

Atomics

13.1 Overview

1 UPC++ supports atomic operations on shared memory locations. Atomicity entails that a read-modify-write sequence on a memory location will happen without interference or interleaving with other concurrently executing atomic operations. Atomicity is not guaranteed if a memory location is concurrently targeted by both atomic and non-atomic operations. The order in which concurrent atomics update the same memory is not guaranteed, not even for successively issued operations by a single process. Ordering of atomics with respect to other asynchronous operations is also not guaranteed. The only means to ensure such ordering is by waiting for one operation to complete before initiating its successor. Note that UPC++ atomics do not interoperate with std::atomic.

2 At this time, it is unclear how UPC++ will support mixing of atomic and non-atomic accesses to the same memory location. Until this is resolved, users must assume that for the duration of the program, once a memory location is accessed via a UPC++ atomic, only further atomic operations to that location will have meaningful results (note that even global barrier synchronization does not grant an exception to this rule). This unfortunately implies that deallocation of such memory is unsafe, as that would allow the memory to be reallocated to a context unaware of its constrained condition.

3 All atomic operations are associated with an atomic domain. An atomic domain is defined for an integer or floating-point type and a set of operations. Currently, the allowed types are float, double, and any signed or unsigned integral type with a 32-bit or 64-bit representation. The list of operations is detailed in the API section below. A process’s
representative of an atomic domain is an instance of an atomic_domain class, and the operations are defined as methods on that class.

4 An atomic domain is created collectively over a team. The result is a semantic binding of atomic_domain objects as a collective object. We use the phrase atomic domain to refer to this semantic binding. An atomic domain must be destroyed by the processes in the team collectively calling the destroy() member function, which releases the resources associated with the domain.

5 The use of atomic domains permits selection (at construction) of the most efficient available implementation which can provide correct results for the given set of operations on the given data type. This is important because the best possible implementation of a operation 'X' may not be compatible with operation 'Y'. So, this best 'X' can only be used when it is known that 'Y' will not be used. This issue arises because a NIC may offload "X" (but not "Y") and use of a CPU-based implementation of "Y" would not be coherent with the NIC performing a concurrent 'X' operation.

6 Similar to a mutex, an atomic domain exists independent of the data it applies to. User code is responsible for ensuring that data accessed via a given atomic domain is only accessed via that domain, never via a different domain or without use of a domain.

7 Users may create as many domains as needed to describe their uses of atomic operations, so long as there is at most one domain per atomic datum. If distinct data of the same type are accessed using differing sets of operations, then creation of distinct domains for each operation set is recommended to achieve the best performance on each set.

8 For example, to use atomic fetch-and-add, load and store operations on an int64_t, a user must first define a domain as follows:

9    atomic_domain<int64_t> ad_i64({atomic_op::load,
                                      atomic_op::store,
                                      atomic_op::fetch_add});

10 Each atomic operation works on a global pointer to the type given when the domain was constructed. The target memory must have affinity to a member of the domain’s team.

11 All atomic operations are non-blocking and provide an operation-completion event to indicate completion of the atomic. By default, all operations return futures. So, for example, this is the way to call an atomic operation for the previous example’s domain:

1 global_ptr<int64_t> x = new_<int64_t>(0);
2 future<int64_t> f = ad_i64.fetch_add(x, 2,
                                      std::memory_order_relaxed);
3 int64_t res = f.wait();
Atomic domains enable a user to select a subset of operations that are supported in hardware on a given platform, and hence more performant.

13.2 Deviations from IEEE 754

UPC++ atomics on float and double are permitted to deviate from the IEEE 754 standard [1], even where float and double otherwise conform to the standard in the underlying C++ implementation. For example, a UPC++ atomic may perform a compare_exchange operation on floating-point values as if they were integers of the same width, and it may compare floating-point values as if they were sign-and-magnitude-representation integers of the same width. This can lead to non-conforming behavior with respect to NaNs and negative zero.

13.3 API Reference

```cpp
enum class atomic_op : /* implementation-defined integral type */ { /* Syntax below is only for clarity of presentation: All enum values are implementation-defined */
    load = ..., 
    store, 
    compare_exchange, 
    add, fetch_add, 
    sub, fetch_sub, 
    mul, fetch_mul, 
    min, fetch_min, 
    max, fetch_max, 
    bit_and, fetch_bit_and, 
    bit_or, fetch_bit_or, 
    bit_xor, fetch_bit_xor, 
    inc, fetch_inc, 
    dec, fetch_dec
};
```

```cpp
template<typename T>
class atomic_domain;
```

C++ Concepts: MoveConstructible, Destructible
\texttt{template<typename T>}
\begin{verbatim}
atomic_domain<T>::atomic_domain(std::vector<atomic_op> const &ops, 
    const team &team = world());
\end{verbatim}

This function is collective (§12.1) over the given team, and it must be called by the thread that has the master persona (§10.5.1).

\textit{Precondition:} T must be one of the approved atomic types: \texttt{float}, \texttt{double}, or any signed or unsigned integral type with a 32-bit or 64-bit representation. T must be a permitted type for each of the operations in \texttt{ops}.

Constructs an atomic domain for type \texttt{T}, with supported operations \texttt{ops}. This instance acts as the calling process's representative in the resulting atomic domain.

\textit{UPC++ progress level: user}

\texttt{template<typename T>}
\begin{verbatim}
atomic_domain<T>::atomic_domain(atomic_domain &&other);
\end{verbatim}

\textit{Precondition:} Calling thread must have the master persona.

Makes this instance the calling process's representative of the atomic domain associated with \texttt{other}, transferring all state from \texttt{other}. Invalidates \texttt{other}, and any subsequent operations on \texttt{other}, except for move construction or destruction, produce undefined behavior.

\textit{UPC++ progress level: none}

\texttt{template<typename T>}
\begin{verbatim}
void atomic_domain<T>::destroy(entry_barrier lev = 
    entry_barrier::user);
\end{verbatim}

This function is collective (§12.1) over the team associated with this atomic domain, and it must be called by the thread that has the master persona (§10.5.1).

\textit{Precondition:} This instance must be the process's representative of the atomic domain. \texttt{lev} must be single-valued (Ch. 12). After the entry barrier specified by \texttt{lev} completes, or upon entry if \texttt{lev == entry_barrier::none}, all operations on this atomic domain must have signaled operation completion.

Destroys the calling process's state associated with the atomic domain. Subsequent operations on this \texttt{atomic_domain}, other than move construction or destruction, produce undefined behavior.
C++ memory ordering: If \( \text{lev} \neq \text{entry}\_\text{barrier}::\text{none} \), with respect to all threads participating in this collective, all evaluations which are sequenced-before their respective thread’s invocation of this call will have a happens-before relationship with all evaluations sequenced after the call.

UPC++ progress level: user if \( \text{lev} = \text{entry}\_\text{barrier}::\text{user} \),
internal otherwise

```
template<typename T>
atomic_domain<T>::~atomic_domain();
```

Precondition: Either UPC++ must have been uninitialized since this domain’s creation, or the \text{atomic\_domain} must either have had \text{destroy}() called on it or been invalidated by being passed to the move constructor.

Destructs this \text{atomic\_domain} object.

This function may be called when UPC++ is in the uninitialized state.

```
template<typename T>
template<typename Cx=/*unspecified*/>
RType atomic_domain<T>::load(
    global_ptr<const T> p, std::memory_order order,
    Cx &&completions=operation_cx::as_future()) const;
```

Precondition: T must be the only type used by any atomic referencing any part of p’s target memory for the entire lifetime of UPC++. order must be std::memory_order_relaxed or std::memory_order_acquire. The \text{atomic\_op::load} operation must have been included in the \text{ops} used to construct this \text{atomic\_domain}. The target of p must have affinity to a member of the team associated with this domain, and that team must not have been destroyed.

Initiates an atomic read of the object at location p and produces its value as part of operation completion.
CHAPTER 13. ATOMICS

Completions:

- Operation: Indicates completion of all aspects of the operation: the remote atomic read and transfer of the result are complete. This completion produces a value of type \( T \).

\( C++ \) memory ordering: If \( \text{order} \) is \( \text{std::memory_order_acquire} \) then the read performed will have a \textit{happens-before} relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment).

\( UPC++ \) progress level: \textit{internal}

\begin{verbatim}
#include <type_traits>

template<typename T>
template<typename Cx=std::as_future>
RType atomic_domain<T>::store(
    global_ptr<T> p, T val, std::memory_order order,
    Cx &&completions)
    const;

Precondition: \( T \) must be the only type used by any atomic referencing any part of \( p \)'s target memory for the entire lifetime of \( UPC++ \). \( \text{order} \) must be \( \text{std::memory_order_relaxed} \) or \( \text{std::memory_order_release} \). The \texttt{atomic_op::store} operation must have been included in the \texttt{ops} used to construct this \texttt{atomic_domain}. The target of \( p \) must have affinity to a member of the team associated with this domain, and that team must not have been destroyed.

Initiates an atomic write of \( \text{val} \) to the location \( p \). Completion of the write is indicated by operation completion.

Completions:

- Operation: Indicates completion of all aspects of the operation: the transfer of the value and remote atomic write are complete.

\( C++ \) memory ordering: If \( \text{order} \) is \( \text{std::memory_order_release} \) then all evaluations \textit{sequenced-before} this call will have a \textit{happens-before} relationship with the write performed. The write performed will have a \textit{happens-before} relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment).

\( UPC++ \) progress level: \textit{internal}
\end{verbatim}
template<typename T>

RType atomic_domain<T>::compare_exchange(
    global_ptr<T> p, T val1, T val2, std::memory_order order,
    Cx &&completions=operationCx::as_future()) const;

Precondition: T must be the only type used by any atomic referencing any part of p's target memory for the entire lifetime of UPC++. order must be std::memory_order_relaxed, std::memory_order_acquire, or std::memory_order_acq_rel. The ops used to construct this atomic_domain must have included the atomic_op::compare_exchange operation. The target of p must have affinity to a member of the team associated with this domain, and that team must not have been destroyed.

Initiates the atomic read-modify-write operation consisting of: reading the value of the object located at p, and if it is equal to val1, writing val2 back. The value produced by operation completion is the one initially read.

Completions:

- Operation: Indicates completion of all aspects of the operation: the transfer of the given value to the recipient, remote atomic update, and transfer of the old value to the initiator are complete. This completion produces a value of type T.

C++ memory ordering: If order is either std::memory_order_release or std::memory_order_acq_rel then all evaluations sequenced-before this call will have a happens-before relationship with the atomic action. If order is std::memory_order_acquire or std::memory_order_acq_rel then the atomic action will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or LPC enlistment).

UPC++ progress level: internal
template<typename T>
    template<typename Cx=/*unspecified*/>
    RType atomic_domain<T>::binary_key(
        global_ptr<T> p, T val, std::memory_order order,
        Cx &&completions=operation_cx::as_future()) const;

template<typename T>
    template<typename Cx=/*unspecified*/>
    RType atomic_domain<T>::fetch_binary_key(
        global_ptr<T> p, T val, std::memory_order order,
        Cx &&completions=operation_cx::as_future()) const;

template<typename T>
    template<typename Cx=/*unspecified*/>
    RType atomic_domain<T>::unary_key(
        global_ptr<T> p, std::memory_order order,
        Cx &&completions=operation_cx::as_future()) const;

template<typename T>
    template<typename Cx=/*unspecified*/>
    RType atomic_domain<T>::fetch_unary_key(
        global_ptr<T> p, std::memory_order order,
        Cx &&completions=operation_cx::as_future()) const;

Precondition: T must be the only type used by any atomic referencing any part of p’s target memory for the entire lifetime of UPC++, and it must be one of the permitted types for the operation. order must be std::memory_order_relaxed, std::memory_order_acquire, std::memory_order_release, or std::memory_order_acq_rel. The atomic_op::op operation must have been included in the ops used to construct this atomic_domain, where op is the following for each variant, respectively: binary_key, fetch_binary_key, unary_key, fetch_unary_key. The target of p must have affinity to a member of the team associated with this domain, and that team must not have been destroyed.

Initiates the atomic read-modify-write operation consisting of: reading the value of the object located at p, performing the operation corresponding to binary_key or unary_key, and writing the new value back. For binary operations, the operation is performed on the value initially read and the val argument. For unary operations, the operation is performed on the value initially read. In the fetch variants, the value initially read is produced by operation completion.
The correspondence between `binary_key`, its respective arithmetic operation, and the permitted types is as in Table 13.1. All operations support the integral types.

<table>
<thead>
<tr>
<th><code>binary_key</code></th>
<th>Computation</th>
<th>Supports float and double</th>
</tr>
</thead>
<tbody>
<tr>
<td>add</td>
<td>+</td>
<td>yes</td>
</tr>
<tr>
<td>sub</td>
<td>-</td>
<td>yes</td>
</tr>
<tr>
<td>mul</td>
<td>*</td>
<td>yes</td>
</tr>
<tr>
<td>min</td>
<td>std::min</td>
<td>yes</td>
</tr>
<tr>
<td>max</td>
<td>std::max</td>
<td>yes</td>
</tr>
<tr>
<td>bit_and</td>
<td>&amp;</td>
<td>no</td>
</tr>
<tr>
<td>bit_or</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bit_xor</td>
<td>^</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 13.1: Binary atomic arithmetic computations

The correspondence between `unary_key`, its respective arithmetic operation, and the permitted types is as in Table 13.2. All operations support the integral types.

<table>
<thead>
<tr>
<th><code>unary_key</code></th>
<th>Computation</th>
<th>Supports float and double</th>
</tr>
</thead>
<tbody>
<tr>
<td>inc</td>
<td>++</td>
<td>yes</td>
</tr>
<tr>
<td>dec</td>
<td>--</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 13.2: Unary atomic arithmetic computations

**Completions:**

- **Operation**: Indicates completion of all aspects of the operation: the transfer of the given value to the recipient and remote atomic update, and transfer of the old value to the initiator in the fetch variants, are complete. This completion does not produce a value in the non-fetch variants and produces a value of type T in the fetch variants.

**C++ memory ordering**: If `order` is either `std::memory_order_release` or `std::memory_order_acq_rel` then all evaluations sequenced-before this call will have a happens-before relationship with the atomic action. If `order` is `std::memory_order_acquire` or `std::memory_order_acq_rel` then the atomic action will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment).

**UPC++ progress level**: `internal`
Chapter 14

Distributed Objects

14.1 Overview

In distributed-memory parallel programming, the concept of a single logical object partitioned over several processes is a useful capability in many contexts: for example, geometric meshes, vectors, matrices, tensors, and associative maps. Since UPC++ is a communication library, it strives to focus on the mechanisms of communication as opposed to the various programming idioms for managing distribution. However, a basic framework for users to implement their own distributed objects is useful and also enables UPC++ to provide the user with the following valuable features:

1. Universal distributed object naming: per-object names that can be transmitted to other processes while retaining their meaning.

2. Name-to-this mapping: Mapping between the universal name and the calling process’s memory address holding that distributed object’s state for the process (the calling process’s this pointer).

The need for universal distributed object naming stems primarily from RPC-based communication. If one process needs to remotely invoke code on a peer’s partition of a distributed object, there needs to be some mutually agreeable identifier for referring to that distributed object. For simplicity, this identifier value should be: identical across all processes so that it may be freely communicated while maintaining its meaning. Moreover, the name should be TriviallyCopyable so that it may be serialized into RPCs efficiently (including with the auto-capture [=] lambda syntax), hashable, and comparable so that it works well with standard C++ containers. UPC++ provides distributed object names meeting these criteria.
as well as the registry for mapping names to and from the calling process’s partition of the distributed object.

14.2 Building Distributed Objects

Distributed objects are built with the \texttt{upcxx::dist\_object<T>} constructor over a specific \texttt{team} (defaulting to team \texttt{world()}). For all processes in the given team, each process constructs an instance of \texttt{dist\_object<T>}, supplying a value of type \texttt{T} representing this process’s instance value. All processes in the team must call this constructor collectively. Once construction completes, the distributed object has a universal name which can be used by any rank in the team to locate the resident instance. When the \texttt{dist\_object<T>} is destructed the \texttt{T} value is also destructed. At this point the name will cease to carry meaning on this process. Thus, the programmer should ensure that no process destructs a distributed object until all name lookups destined for it complete and all hanging references of the form \texttt{T\&} or \texttt{T*} to the value have expired.

The names of \texttt{dist\_object<T>}’s are encoded by the \texttt{dist\_id<T>} type. This type is TriviallyCopyable, EqualityComparable, LessThanComparable, hashable, and Trivially-Serializable. It has the members \texttt{.here()} and \texttt{.when\_here()} for retrieving the resident \texttt{dist\_object<T>} instance registered with the name.

14.3 Ensuring Distributed Existence

The \texttt{dist\_object<T>} constructor requires it be called in a collective context, but it does not guarantee that, after the call, all other ranks in the team have exited or even reached the constructor. Thus users are required to guard against the possibility that when an RPC carrying an distributed object’s name executes, the recipient process may not yet have an entry for that name in its registry. Possible ways to deal with this include:

1. Barrier: Before issuing communication containing a \texttt{dist\_id<T>} for a newly created distributed object, the relevant team completes a \texttt{barrier} to ensure global existence of the \texttt{dist\_object<T>}.

2. Point to point: Before communicating a \texttt{dist\_id<T>} with a given process, the initiating process uses some two-party protocol to ensure that the peer has constructed the \texttt{dist\_object<T>}.
3. Asynchronous point-to-point: The user performs no synchronization to ensure remote existence. Instead, an RPC is sent which, upon arrival, must wait asynchronously via a continuation for the peer to construct the distributed object.

2 UPC++ enables the asynchronous point-to-point approach implicitly when arguments of type \texttt{cq dist_object<T>&} are given to any of the RPC family of functions (see Ch. 9).

### 14.4 API Reference

#### 14.4.1 dist_object

1 \texttt{template<typename T>}
\texttt{class dist_object;}

2 \textit{C++ Concepts:} MoveConstructible (when \(T\) is MoveConstructible), Destructible

3 \texttt{template<typename T>}
\texttt{dist_object<T>::dist_object(T value, const team &team = world());}

4 \textit{This function is collective (§12.1) over the given team, and it must be called by the thread that has the master persona (§10.5.1).}

5 \textit{Precondition:} \(T\) must be MoveConstructible.

6 Constructs this process's member of the distributed object identified by the collective calling context across \texttt{team}. The initial value for this process is given in \texttt{value}. The future returned from \texttt{dist_id<T>::when_here} for the corresponding \texttt{dist_id<T>} will be readied during this constructor. This implies that continuations waiting for that future will execute before the constructor returns.

7 \textit{UPC++ progress level:} none
template<typename T>
    template<typename ...Arg>
    dist_object<T>::dist_object(const team &team, Arg &&...arg);

This function is collective (§12.1) over the given team, and it must be called by
the thread that has the master persona (§10.5.1).

Constructs this process’s member of the distributed object identified by the
collective calling context across team. The initial value for this process is con-
structed with T(std::forward<Arg>(arg)....). The result is undefined if this
call throws an exception. The future returned from dist_id<T>::when_here
for the corresponding dist_id<T> will be readied during this constructor. This
implies that continuations waiting for that future will execute before the con-
structor returns.

UPC++ progress level: none

template<typename T>
    dist_object<T>::dist_object(dist_object<T> &&other);

Precondition: Calling thread must have the master persona. T must be Move-
Constructible.

Makes this instance the calling process’s representative of the distributed object
associated with other, transferring all state from other. Invalidates other, and
any subsequent operations on other, except for destruction, produce undefined
behavior.

UPC++ progress level: none

template<typename T>
    dist_object<T>::~dist_object();

Precondition: Calling thread must have the master persona, or UPC++ must
have been uninitialized since the dist_object<T> construction.

~T() is invoked to destroy the resident value instance.

If this instance has not been invalidated by being passed to the move con-
structor, then this will destroy the calling process’s member of the distributed
object, and further lookups on this process using the dist_id<T> corresponding
to this distributed object will have undefined behavior. If this instance has
been invalidated by a move, then this call will not affect the distributed object.

This function may be called when UPC++ is in the uninitialized state.
CHAPTER 14. DISTRIBUTED OBJECTS

21 \textit{UPC++ progress level: none}

22 \texttt{template<\texttt{typename} \texttt{T}>}
\texttt{dist\textunderscore id\textless \texttt{T}\textgreater \ dist\textunderscore object\textless \texttt{T}\textgreater ::id() \ const;}

23 Returns the \texttt{dist\textunderscore id\textless \texttt{T}\textgreater} representing the universal name of this distributed object.

24 \textit{UPC++ progress level: none}

25 \texttt{template\texttt{<typename \texttt{T}>}
\texttt{team\& dist\textunderscore object\textless \texttt{T}\textgreater ::team();
\texttt{template\texttt{<typename \texttt{T}>}
\texttt{const team\& dist\textunderscore object\textless \texttt{T}\textgreater ::team() \ const;}

26 \texttt{Precondition:} The \texttt{team} associated with this distributed object must not have been destroyed.

27 Retrieves a reference to the \texttt{team} instance associated with this distributed object.

28 \textit{UPC++ progress level: none}

29 \texttt{template\texttt{<typename \texttt{T}>}
\texttt{T\* dist\textunderscore object\textless \texttt{T}\textgreater ::operator\texttt{\textasciitilde}() \ const;}

30 Access to the calling process’s value instance for this distributed object.

31 \textit{UPC++ progress level: none}

32 \texttt{template\texttt{<typename \texttt{T}>}
\texttt{T\& dist\textunderscore object\textless \texttt{T}\textgreater ::operator\texttt{*}() \ const;}

33 Access to the calling process’s value instance for this distributed object.

34 \textit{UPC++ progress level: none}
template<typename T>
future<deserialized_type_t<T>>
dist_object<T>::fetch(intrank_t rank) const;

Preconditions:

- rank must be a valid rank in the team associated with this distributed object.
- T must be MoveConstructible.
- T must be Serializable, but not `view<U, IterType>`.
- rank’s instance of this distributed object must not have been destroyed by the owning process.
- The team associated with this distributed object must not have been destroyed.

Asynchronously retrieves a copy of the instance of this distributed object associated with the peer index rank in this distributed object’s team. The result is encapsulated in the returned future. This call is equivalent to:

```cpp
call rpc(team(), rank, [
    dist_object<T> &obj) -> const T& {
        return *obj;
    }, *this)
```

UPC++ progress level: internal

### 14.4.2 dist_id

```
template<typename T>
struct dist_id<T>;
```

C++ Concepts: DefaultConstructible, TriviallyCopyable, StandardLayoutType, EqualityComparable, LessThanComparable, hashable

UPC++ Concepts: TriviallySerializable
template< typename T >
    dist_id<T>::dist_id();

Initializes this name to be an invalid ID.

UPC++ progress level: none

template< typename T >
    future< dist_object<T>& > dist_id<T>::when_here() const;

Precondition: This name must be a valid ID for the calling process. The
dist_object<T> instance owned by the calling process that is associated with
this name must not have been destroyed. The calling thread must have the
master persona.

Retrieves a future representing when the calling process constructs the
dist_object<T> corresponding to this name.

UPC++ progress level: none

template< typename T >
    dist_object<T>& dist_id<T>::here() const;

Precondition: This name must be a valid ID for the calling process. The
dist_object<T> instance owned by the calling process that is associated with
this name must have been previously constructed but not yet destroyed. The
calling thread must have the master persona.

Retrieves a reference to the calling process’s dist_object<T> instance associ-
ated with this name.

UPC++ progress level: none

template< typename T >
    std::ostream & operator<<(std::ostream &os, dist_id<T> id);

Inserts an unspecified character representation of id into the output stream
os. The textual representation of two objects of type dist_id<T> is identical
if and only if the two objects compare equal.

UPC++ progress level: none
Chapter 15

Non-Contiguous One-Sided Communication

15.1 Overview

1 UPC++ provides functions to perform one-sided communications similar to `rget` and `rput` which are dedicated to handle data stored in non-contiguous locations. These functions are denoted with a suffix added to the type of operation, in increasing order of specialization:

2 `{rput,rget}_{irregular,regular,strided}`

3 The most general variant of the API, `{rput,rget}_irregular`, accept iterators over an array or collection of `std::pair` (or `std::tuple`) that contain a local or global pointer to a memory location in the first member while the second member contains the size of the contiguous chunk of memory to be transferred. This variant is capable of expressing non-contiguous RMA of arbitrary shape, but pays the highest overhead in metadata to payload ratio.

4 The next set of functions, `{rput,rget}_regular`, operates over contiguous elements of identical size on each side of the transfer, and only requires the caller to provide an array or collection of base pointers to each element.

5 Finally, the most specialized set of functions, `{rput,rget}_strided`, provide an interface for expressing translational and transposing copies between arbitrary rectangular sections of densely stored N-dimensional arrays. This specialized pattern requires the least metadata, which is constant in size for a given dimensionality. An example of such a transfer is depicted in Figure 15.1.
15.2 API Reference

15.2.1 Requirements on Iterators

1 An iterator used with a UPC++ operation in this section must adhere to the following requirements:

2 - It must satisfy the Iterator and EqualityComparable C++ concepts.

3 - Calling std::distance on the iterator must not invalidate it.
15.2.2 Irregular Put

```cpp
template<typename SrcIter, typename DestIter,
typeName Cx=/*unspecified*/>
RType rput_irregular(
    SrcIter src_runs_begin, SrcIter src_runs_end,
    DestIter dest_runs_begin, DestIter dest_runs_end,
    Cx &&completions=operation_cx::as_future());
```

**Preconditions:**

1. `SrcIter` and `DestIter` both satisfy the iterator requirements above.
2. `std::get<0>(*std::declval<SrcIter>())` has a return type convertible to `T const*`, for some TriviallySerializable type `T`.
3. `std::get<1>(*std::declval<SrcIter>())` has a return type convertible to `std::size_t`.
4. `std::get<0>(*std::declval<DestIter>())` has the return type `global_ptr<T>`, for the same type `T` as with `SrcIter`.
5. `std::get<1>(*std::declval<DestIter>())` has a return type convertible to `std::size_t`.
6. All destination addresses must be `global_ptr<T>`’s referencing memory with affinity to the same process.
7. The length of the expanded address sequence (the sum over the run lengths) must be the same for the source and destination sequences.
8. The source and destination addresses must not be null pointers, even if the length of a run is zero.

For some type `T`, takes a sequence of source addresses of `T const*` and a sequence of destination addresses of `global_ptr<T>` and does the corresponding puts from each source address to the destination address of the same sequence position.

Address sequences are encoded in run-length form as sequences of runs, where each run is a pair consisting of a starting address plus the number of consecutive elements of type `T` beginning at that address.

As an example of valid types for individual runs, `SrcIter` could be an iterator over elements of type `std::pair<T const*, std::size_t>`, and `DestIter` an...
iterator over `std::pair<global_ptr<T>, std::size_t>`. Variations replacing `std::pair` with `std::tuple` or `size_t` with other primitive integral types are also valid.

The source sequence iterators must remain valid, and the underlying addresses and source memory contents must not be modified until source completion is signaled. Only after source completion is signaled can the source address sequences and memory be reclaimed by the application.

The destination sequence iterators must remain valid until source completion is signaled.

The destination memory regions must be completely disjoint and must not overlap with any source memory regions, otherwise behavior is undefined. Source regions are permitted to overlap with each other.

Remote-completion operations execute on the master persona of the process associated with the destination (i.e. `dest_runs_begin->where()`), unless the destination sequence is empty (i.e. `dest_runs_begin == dest_runs_end`), in which case they run on the master persona of the initiating process.

**Completions:**

- **Source:** Indicates that the source sequence iterators and underlying memory, as well as the destination sequence iterators, are no longer in use by UPC++ and may be reclaimed by the user.

- **Remote:** Indicates completion of the transfer of all values.

- **Operation:** Indicates completion of all aspects of the operation: the transfer and remote stores are complete.

**C++ memory ordering:** The reads of the sources will have a happens-before relationship with the source-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). The writes to the destinations will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment) and remote-completion actions (RPC enlistment). For LPC and RPC completions, all evaluations sequenced-before this call will have a happens-before relationship with the execution of the completion function.

**UPC++ progress level:** internal
15.2.3 Irregular Get

```cpp
1 template<typename SrcIter, typename DestIter,
    typename Cx=/*unspecified*/>
2 RType rget_irregular(
3    SrcIter src_runs_begin, SrcIter src_runs_end,
4    DestIter dest_runs_begin, DestIter dest_runs_end,
5    Cx &&completions=operation_cx::as_future());
```

**Preconditions:**

1. `SrcIter` and `DestIter` both satisfy the iterator requirements above.
2. `std::get<0>(*std::declval<SrcIter>())` has a type that is convertible to `global_ptr<const T>` for some TriviallySerializable type `T`.
3. `std::get<1>(*std::declval<SrcIter>())` has a type that is convertible to `std::size_t`.
4. `std::get<0>(*std::declval<DestIter>())` has the type `T*`, for the same type `T` as with `SrcIter`.
5. `std::get<1>(*std::declval<DestIter>())` has a type that is convertible to `std::size_t`.
6. All source addresses must be `global_ptr<const T>`’s referencing memory with affinity to the same process.
7. The length of the expanded address sequence (the sum over the run lengths) must be the same for the source and destination sequences.
8. The source and destination addresses must not be null pointers, even if the length of a run is zero.

For some type `T`, takes a sequence of source addresses of `global_ptr<const T>` and a sequence of destination addresses of `T*` and does the corresponding gets from each source address to the destination address of the same sequence position.

Address sequences are encoded in run-length form as sequences of runs, where each run is a pair consisting of a starting address plus the number of consecutive elements of type `T` beginning at that address.

As an example of valid types for individual runs, `DestIter` could be an iterator over elements of type `std::pair<T*, std::size_t>`, and `SrcIter` an
CHAPTER 15. NON-CONTIGUOUS ONE-SIDED COMMUNICATION

iterator over std::pair<global_ptr<T>, std::size_t>. Variations replacing std::pair with std::tuple or std::size_t with other primitive integral types are also valid.

The source sequence iterators must remain valid, and the underlying addresses and memory contents must not be modified until operation completion is signaled. Only after operation completion is signaled can the address sequences and source memory be reclaimed by the application.

The destination sequence iterators must remain valid until operation completion is signaled.

The destination memory regions must be completely disjoint and must not overlap with any source memory regions, otherwise behavior is undefined. Source regions are permitted to overlap with each other.

Completions:

• Operation: Indicates completion of all aspects of the operation: the transfer and local stores are complete.

C++ memory ordering: The reads of the sources and writes to the destinations will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). For LPC completions, all evaluations sequenced-before this call will have a happens-before relationship with the execution of the completion function.

UPC++ progress level: internal

15.2.4 Regular Put

template<typename SrcIter, typename DestIter, 
         typename Cx=/*unspecified*/>
RType rput_regular(
    SrcIter src_runs_begin, SrcIter src_runs_end, 
    std::size_t src_run_length, 
    DestIter dest_runs_begin, DestIter dest_runs_end, 
    std::size_t dest_run_length, 
    Cx &&completions=operation_cx::as_future());

Preconditions:

• SrcIter and DestIter both satisfy the iterator requirements above.
• *std::declval<SrcIter>() has a type convertible to T const*, for some TriviallySerializable type T.

• *std::declval<DestIter>()) has the type global_ptr<T>, for the same type T as with SrcIter.

• All destination addresses must be global_ptr<T>`s referencing memory with affinity to the same process.

• The length of the two sequences delimited by (src_runs_begin, src_runs_end) and (dest_runs_begin, dest_runs_end) multiplied by src_run_length and dest_run_length, respectively, must be the same.

• The source and destination addresses must not be null pointers, even if src_run_length and dest_run_length are zero.

This call has the same semantics as rput_irregular with the exception that, for each sequence, all run lengths are the same and are factored out of the sequences into two extra parameters src_run_length and dest_run_length, which express the number of consecutive elements of type T in units of element count. Thus the iterated elements are no longer pairs, but just pointers.

The source sequence iterators must remain valid, and the underlying addresses and source memory contents must not be modified until source completion is signaled. Only after source completion is signaled can the source address sequences and memory be reclaimed by the application.

The destination sequence iterators must remain valid until source completion is signaled.

Remote-completion operations execute on the master persona of the process associated with the destination (i.e. dest_runs_begin->where()), unless the destination sequence is empty (i.e. dest_runs_begin == dest_runs_end), in which case they run on the master persona of the initiating process.

**Completions:**

• **Source:** Indicates that the source sequence iterators and underlying memory, as well as the destination sequence iterators, are no longer in use by UPC++ and may be reclaimed by the user.

• **Remote:** Indicates completion of the transfer of all values.

• **Operation:** Indicates completion of all aspects of the operation: the transfer and remote stores are complete.
C++ memory ordering: The reads of the sources will have a happens-before relationship with the source-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). The writes to the destinations will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment) and remote-completion actions (RPC enlistment). For LPC and RPC completions, all evaluations sequenced-before this call will have a happens-before relationship with the execution of the completion function.

UPC++ progress level: internal

### 15.2.5 Regular Get

```cpp
template<typename SrcIter, typename DestIter, 
          typename Cx=/*unspecified*/> 
RType rget_regular( 
     SrcIter src_runs_begin, SrcIter src_runs_end, 
     std::size_t src_run_length, 
     DestIter dest_runs_begin, DestIter dest_runs_end, 
     std::size_t dest_run_length, 
     Cx &&completions=operation_cx::as_future());
```

**Preconditions:**

- **SrcIter** and **DestIter** both satisfy the iterator requirements above.
- `*std::declval<DestIter>()` has a type convertible to `T*`, for some TriviallySerializable type `T`.
- `*std::declval<SrcIter>()` has a type that is convertible to `global_ptr<const T>`, for the same type `T` as with **DestIter**.
- All source addresses must be `global_ptr<const T>`’s referencing memory with affinity to the same process.
- The length of the two sequences delimited by (``src_runs_begin, src_runs_end``) and (``dest_runs_begin, dest_runs_end``) multiplied by `src_run_length` and `dest_run_length`, respectively, must be the same.
- The source and destination addresses must not be null pointers, even if `src_run_length` and `dest_run_length` are zero.
This call has the same semantics as `rget_irregular` with the exception that, for each sequence, all run lengths are the same and are factored out of the sequences into two extra parameters `src_run_length` and `dest_run_length`, which express the number of consecutive elements of type `T` in units of element count. Thus, the iterated elements are no longer pairs, but just pointers.

The source sequence iterators must remain valid, and the underlying addresses and memory contents must not be modified until operation completion is signaled. Only after operation completion is signaled can the address sequences and source memory be reclaimed by the application.

The destination sequence iterators must remain valid until operation completion is signaled.

**Completions:**

- **Operation:** Indicates completion of all aspects of the operation: the transfer and local stores are complete.

**C++ memory ordering:** The reads of the sources and writes to the destinations will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). For LPC completions, all evaluations sequenced-before this call will have a happens-before relationship with the execution of the completion function.

**UPC++ progress level:** internal

### 15.2.6 Strided Put

```cpp
template<std::size_t Dim, typename T, typename Cx=/*unspecified*/>
RType rput_strided(
    T const *src_base,
    std::ptrdiff_t const *src_strides,
    global_ptr<T> dest_base,
    std::ptrdiff_t const *dest_strides,
    std::size_t const *extents,
    Cx &&completions=operation_cx::as_future());
```
template <std::size_t Dim, typename T, typename Cx=/*unspecified*/>
RType rput_strided(
    T const * src_base,
    std::array<std::ptrdiff_t,Dim> const & src_strides,
    global_ptr<T> dest_base,
    std::array<std::ptrdiff_t,Dim> const & dest_strides,
    std::array<std::size_t,Dim> const & extents,
    Cx &&completions=operation_cx::as_future());

Precondition: T must be a TriviallySerializable type. src_base and dest_base
must not be null pointers, even if the number of bytes to be transferred is zero.

If Dim == 0, src_strides, dest_strides, and extents are ignored, and the
data movement performed is equivalent to rput(src_base, dest_base, 1).

Otherwise, performs the semantic equivalent of many put’s of type T. Let the
index space be the set of integer vectors of dimension Dim contained in the
bounding box with the inclusive lower bound at the all-zero origin, and the
exclusive upper bound equal to extents. For each index vector index in this
index space, a put will be executed with addresses computed according to the
following pseudo-code, where dotprod is the vector dot product and pointer
arithmetic is done in units of bytes (not elements of T):
Completions:

- **Source**: Indicates that the source memory is no longer in use by UPC++ and may be reclaimed by the user.
- **Remote**: Indicates completion of the transfer of all values.
- **Operation**: Indicates completion of all aspects of the operation: the transfer and remote stores are complete.

C++ memory ordering: The reads of the sources will have a happens-before relationship with the source-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). The writes to the destinations will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment) and remote-completion actions (RPC enlistment). For LPC and RPC completions, all evaluations sequenced-before this call will have a happens-before relationship with the execution of the completion function.

UPC++ progress level: **internal**

### 15.2.7 Strided Get

```c++
1 template< std::size_t Dim, typename T, typename Cx=/*unspecified*/>
2 RType rget_strided(
3     global_ptr<const T> src_base,
4     std::ptrdiff_t const *src_strides,
5     T *dest_base,
6     std::ptrdiff_t const *dest_strides,
7     std::size_t const *extents,
8     Cx &&completions=operation_cx::as_future());

template< std::size_t Dim, typename T, typename Cx=/*unspecified*/>
RType rget_strided(
    global_ptr<const T> src_base,
    std::array< std::ptrdiff_t ,Dim> const &src_strides,
    T *dest_base,
    std::array< std::ptrdiff_t ,Dim> const &dest_strides,
    std::array< std::size_t ,Dim> const &extents,
    Cx &&completions=operation_cx::as_future());
```
Precondition: T must be a TriviallySerializable type. src_base and dest_base must not be null pointers, even if the number of bytes to be transferred is zero.

If Dim == 0, src_strides, dest_strides, and extents are ignored, and the data movement performed is equivalent to rget(src_base, dest_base, 1).

Otherwise, performs the reverse direction of rput_strided where now the source memory is remote and the destination is local.

The destination memory regions must be completely disjoint and must not overlap with any source memory regions, otherwise behavior is undefined. Source regions are permitted to overlap with each other.

The elements of type T residing in the source addresses must remain valid and unmodified until operation completion is signaled.

The contents of the src_strides, dest_strides, and extents arrays are consumed synchronously before the call returns.

Completions:

- Operation: Indicates completion of all aspects of the operation: the transfer and local stores are complete.

C++ memory ordering: The reads of the sources and writes to the destinations will have a happens-before relationship with the operation-completion notification actions (future readying, promise fulfillment, or persona LPC enlistment). For LPC completions, all evaluations sequenced-before this call will have a happens-before relationship with the execution of the completion function.

UPC++ progress level: internal
Chapter 16

Memory Kinds

16.1 Overview

1 The memory kinds interface enables the programmer to identify regions of memory requiring different access methods or having different performance properties, and subsequently rely on the UPC++ communication services to perform transfers among such regions (both local and remote) in a manner transparent to the programmer. With GPU devices, HBM, scratch-pad memories, NVRAM and various types of storage-class and fabric-attached memory technologies featured in vendors’ public road maps, UPC++ must be prepared to deal efficiently with data transfers among all the memory technologies in any given system.

2 UPC++ uses device objects to represent storage that is distinct from main memory, regardless of whether the storage is directly addressable from the host process. Each kind of memory has its own device type; for example, a CUDA-enabled GPU device is represented by a cuda_device object. The device type has a member type-alias template pointer that refers to the device’s pointer type, as well as a null_pointer member-function template that returns a null-pointer value of that type. Each device type is associated with a memory_kind constant, and global pointers are parameterized by a memory_kind (Ch. 3).

3 Creating active device objects is a collective operation over the world() team so that UPC++ can allocate the resources required to support remote access to device memory. The result is a semantic binding of device objects as a collective object, which we refer to as a collective device. A device type also provides a mechanism for constructing inactive device objects, so that processes without a device resource can still participate in the collective device-creation operation. A collective device must be destroyed by collectively calling the
CHAPTER 16. MEMORY KINDS

destroy() member function, which releases the resources associated with the collective device.

```
cuda_device::id_type device_id =
  rank_me() % 2 == 0 ? cuda_device::invalid_device_id;
cuda_device gpu_device(device_id); // device 0 on even processes
...  
gpu_device.destroy(); // collective destroy
```

A device object can be associated with a `device_allocator` that manages memory on the device. Only one `device_allocator` may be associated with a particular device object. The region of memory that a `device_allocator` manages is called a `device segment`. Users can either create their own segments and pass them to the `device_allocator` constructor, or they can request that the `device_allocator` allocate its own segment. In the latter case, the segment is automatically freed when the `device_allocator` is destroyed.

```
std::size_t seg_size = 4*1024*1024; // 4MB
device_allocator<cuda_device> gpu_alloc(gpu_device, seg_size);
global_ptr<double, memory_kind::cuda_device> gpu_array =
  gpu_alloc.allocate<double>(1024);
...  
gpu Alloc.deallocate(gpu_array);
```

We define the affinity (Ch. 3) of memory allocated by a `device_allocator` to be the host process that owns the allocator and its associated device.

The device types defined in this section are available to `UPC++` programs even in `UPC++` installations that are not aware of a particular kind of device. For example, a program may create `cuda_device` objects. However, there are no valid CUDA device IDs in a non-CUDA-aware installation, so any `cuda_device` object created by the program will be inactive.

The `copy` functions transfer data between memory locations of any kind. The source and destination locations may either be local or remote, and they may refer to either host or device memory.

```
  global_ptr<double> host_array = new_array<double>(1024);
  global_ptr<double, memory_kind::cuda_device> array0 =
    broadcast(gpu_array, 0).wait();
  // copy from gpu array on process 0 to host array on this process
  copy(array0, host_array, 1024).wait();
```
16.2 API Reference

```cpp
class bad_segment_alloc : public std::bad_alloc;
```

1. An exception type derived from `std::bad_alloc` that is thrown by some shared segment constructors to indicate failure to allocate resources needed to create the memory segment.

16.2.1 `cuda_device`

```cpp
struct cuda_device;
```


```cpp
struct cuda_device {
    using id_type = int;
    // ...
};
```

1. Member alias for the type of a CUDA device ID.

```cpp
struct cuda_device {
    template<typename T>
    using pointer = T*;
    // ...
};
```

1. Member template alias for raw pointer types on a CUDA device.

```cpp
template<typename T>
[static] constexpr cuda_device::pointer<T>
cuda_device::null_pointer();
```

1. Returns a representation of a null CUDA pointer.

```cpp
template<typename T>
[static] constexpr std::size_t cuda_device::default_alignment();
```

1. Returns the default alignment of an object of type `T` on a CUDA device.


11 [static] const memory_kind cuda_device::kind =
    memory_kind::cuda_device;

12 Constant that has the same value as memory_kind::cuda_device.

13 [static] constexpr cuda_device::id_type
    cuda_device::invalid_device_id = /* implementation-defined */;

14 A constant representing an invalid device ID.

15 cuda_device::cuda_device();

16 Constructs an inactive cuda_device object.

17 cuda_device::cuda_device(cuda_device::id_type device_id);

18 This function is collective (§12.1) over the world() team, and it must be called
    by the thread that has the master persona (§10.5.1).

19 Precondition: device_id must be cuda_device::invalid_device_id or a
    valid CUDA device ID on the calling process

20 If the device ID is valid, constructs a cuda_device with the given device ID,
    which acts as the calling process’s representative of the resulting collective
    device. If the device ID is cuda_device::invalid_device_id, constructs an
    inactive cuda_device object.

21 UPC++ progress level: user

22 cuda_device::cuda_device(cuda_device &&other);

23 Transfers the state represented by other to this cuda_device. Deactivates
    other.

24 UPC++ progress level: none
void cuda_device::destroy(entry_barrier lev = entry_barrier::user);

This function is collective (§12.1) over the world() team, and it must be called by the thread that has the master persona (§10.5.1).

Precondition: If this process’s representative of the collective device being destroyed is inactive, then this cuda_device must be inactive. Otherwise, this instance must be the process’s representative of the collective device. lev must be single-valued (Ch. 12). After the entry barrier specified by lev completes, or upon entry if lev == entry_barrier::none, all asynchronous UPC++ operations on memory associated with this device must have signaled operation completion.

Destroys the calling process’s state associated with this cuda_device, deactivating this device object. Also deactivates any device_allocator associated with this device.

C++ memory ordering: If lev != entry_barrier::none, with respect to all threads participating in this collective, all evaluations which are sequenced-before their respective thread’s invocation of this call will have a happens-before relationship with all evaluations sequenced after the call.

UPC++ progress level: user if lev == entry_barrier::user, internal otherwise

cuda_device::~cuda_device();

Precondition: Either UPC++ must have been uninitialized since the cuda_device creation, or the cuda_device must either have had destroy() called on it, been deactivated by being passed to the move constructor, or be an inactive cuda_device.

Destructs this cuda_device object.

This function may be called when UPC++ is in the uninitialized state.

UPC++ progress level: none

cuda_device::id_type cuda_device::device_id() const;

Returns the device ID of this cuda_device. If this is an inactive device, returns cuda_device::invalid_device_id.

UPC++ progress level: none
39 bool cuda_device::is_active() const;

Returns whether or not this cuda_device is active. A cuda_device is active if it was created with a valid device ID, has not been passed to the move constructor, and has not had its state destroyed by a call to destroy.

UPC++ progress level: none

16.2.2 device_allocator

1 template< typename Device >
class device_allocator;

C++ Concepts: DefaultConstructible, MoveConstructible, Destructible

3 template< typename Device >
class device_allocator {
    using device_type = Device;
    // ...
};

Member type that is an alias for the template parameter Device.

5 template< typename Device >
device_allocator<Device>::device_allocator();

Constructs an inactive device_allocator object.
template<typename Device>
device_allocator<Device>::device_allocator(Device &device, size_t sz_in_bytes);

This function is collective (§12.1) over the world() team, and it must be called by the thread that has the master persona (§10.5.1).

Precondition: Either device is inactive, or device must not have been previously used to create a device_allocator.

Although this operation is collective, the arguments need not be single-valued. If device is inactive, then the other argument is ignored and that caller constructs an inactive device_allocator object. Otherwise, allocates a segment of size sz_in_bytes (which much be non-zero) on the device and constructs an active device_allocator to manage that device segment.

If the allocation fails for any active device participating in this collective, then all callers will throw upcxx::bad_segment_alloc.

The segment is allocated from the associated device in a device-specific manner. Any device-specific properties of the resulting allocation are implementation-defined. If special properties are required, users may allocate their own segment instead and use the second constructor to initialize an allocator from that segment.

Exceptions: May throw upcxx::bad_segment_alloc.

UPC++ progress level: user

template<typename Device>
device_allocator<Device>::device_allocator(Device &device, typename Device::pointer<void> device_memory, size_t sz_in_bytes);

This function is collective (§12.1) over the world() team, and it must be called by the thread that has the master persona (§10.5.1).

Precondition: Either device is inactive, or device must not have been previously used to create a device_allocator. If device is inactive, the other arguments provided by that caller are ignored. Otherwise device_memory must be a pointer to memory associated with the given device, and it must not be managed by another allocator. The memory referenced by device_memory must be at least sz_in_bytes bytes in size. sz_in_bytes must be non-zero.
Although this operation is collective, the arguments need not be single-valued. If `device` is inactive, then that caller constructs an inactive `device_allocator` object. Otherwise, constructs an active `device_allocator` associated with the given device to manage the given `device_memory` as its device segment.

**UPC++ progress level:** user

```cpp
template<typename Device>
device_allocator<Device>::device_allocator(
    device_allocator &&other);
```

Transfers the state represented by `other` to this `device_allocator`. Deactivates `other`.

**UPC++ progress level:** none

```cpp
template<typename Device>
bool device_allocator<Device>::is_active() const;
```

Returns whether or not this `device_allocator` is active. A `device_allocator` is active if it was created with an active device that remains active, and this object has not been passed to the move constructor.

**UPC++ progress level:** none

```cpp
template<typename Device>
device_allocator<Device>::~device_allocator();
```

Destructs this `device_allocator` object. If `is_active()` then any global pointers referencing memory in the associated segment are invalidated. If this `device_allocator` allocated a segment on construction, additionally frees the associated segment, without invoking any destructors for objects in the segment.

This function may be called when UPC++ is in the uninitialized state.

**UPC++ progress level:** none
template<typename Device>
template<typename T>
global_ptr<T, Device::kind>
  device_allocator<Device>::allocate(size_t n = 1,
                                      std::size_t alignment = Device::default_alignment<T>());

Precondition: this->is_active(). alignment is a valid alignment.

Allocates enough space for n objects of type T from the segment managed by this
curator, with the memory aligned as specified by alignment. If the allocation
succeeds, returns a global pointer to the start of the allocated memory, and the
allocated memory is uninitialized. If the allocation fails, returns a null pointer.

UPC++ progress level: none

template<typename Device>
template<typename T>
void device_allocator<Device>::deallocate(
  global_ptr<T, Device::kind> g);

Precondition: g.is_null() || (this->is_active() && g.where == rank_me()).
g must be either a null pointer or a non-deallocated pointer that resulted
from a call to allocate<T, alignment> on this allocator, for some value of
alignment.

Deallocationes the storage previously allocated by a call to allocate. Does nothing
if g is a null pointer. Does not invoke the destructor for T.

UPC++ progress level: none

template<typename Device>
template<typename T>
global_ptr<T, Device::kind>
  device_allocator<Device>::to_global_ptr(
    typename Device::pointer<T> ptr) const;

Precondition: ptr is a null pointer, or this->is_active() and ptr is a valid
pointer such that the expression *ptr on this allocator’s device yields a (possibly
uninitialized) object of type T that resides within the segment managed by
this allocator

Converts a raw device pointer to a global pointer.

UPC++ progress level: none
template<typename Device>

template<typename Device::pointer T>

[static] typename Device::pointer<T>
device_allocator<Device>::local(global_ptr<T, Device::kind> g);

Precondition: g.is_null() || g.where() == rank_me(). g must be either a null pointer or a non-deallocated pointer that resulted from a call to allocate<T, alignment> on a device_allocator<Device> on the caller’s process, for some value of alignment.

Returns the raw device pointer associated with g. If g is a null pointer, returns Device::null_pointer<T>().

UPC++ progress level: none

template<typename Device>

template<typename Device::id_type T>

[static] typename Device::id_type
device_allocator<Device>::device_id(global_ptr<T, Device::kind> ptr);

Precondition: g.is_null() || g.where() == rank_me(). g must be either a null pointer or a non-deallocated pointer that resulted from a call to allocate<T, alignment> on a device_allocator<Device> on the caller’s process, for some value of alignment.

If the pointer is not null, returns the ID of the device where the referenced object resides. If the pointer is null, returns Device::invalid_device_id.

UPC++ progress level: none

16.2.3 Data Movement

template<typename T, memory_kind Kind1, memory_kind Kind2, typename Cx=/*unspecified*/>

RType copy(
    global_ptr<const T, Kind1> src, global_ptr<T, Kind2> dest,
    size_t count, Cx &&completions=operation_cx::as_future());
template<typename T, memory_kind Kind, typename Cx=/*unspecified*/>
RType copy(
    T const *src, global_ptr<T, Kind> dest, size_t count,
    Cx &&completions=operation_cx::as_future());

template<typename T, memory_kind Kind, typename Cx=/*unspecified*/>
RType copy(
    global_ptr<const T, Kind> src, T *dest, size_t count,
    Cx &&completions=operation_cx::as_future());

Precondition: T must be TriviallySerializable. The source and destination memory regions must not overlap. src and dest must not be null pointers, even if count is zero. src in the second variant and dest in the third variant must reference host memory.

Initiates an operation to transfer and store the count items of type T beginning at src to the memory beginning at dest. The values referenced in the [src,src+count) interval must not be modified until either source or operation completion is indicated.

Source- and operation-completion operations execute on the current (initiating) persona of the calling process. In the first and second variant, remote-completion operations execute on the master persona of the host process associated with the destination (i.e. dest.where()). In the third variant, remote-completion operations execute on the master persona of the calling process.

Completions:

- **Source**: Indicates completion of injection or internal buffering of the source values, signifying that the src buffer may be modified.
- **Remote**: Indicates completion of the transfer of the values, implying readiness of the target buffer [dest,dest+count).
- **Operation**: Indicates completion of all aspects of the operation: the transfer and stores are complete.

C++ memory ordering: For LPC and RPC completions, all evaluations sequenced-before this call will have a happens-before relationship with the execution of the completion function.

UPC++ progress level: internal
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