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UPC++: An Asynchronous RMA/RPC Library for Distributed C++ Applications

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UPC++: An Asynchronous RMA/RPC Library for Distributed C++ Applications

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GASNet-EX

ECP

upc++

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What does UPC++ offer?

Asynchronous behavior

- **RMA**:
  - Get/put to a remote location in another address space
  - Low overhead, zero-copy, one-sided communication.
- **RPC: Remote Procedure Call**:
  - Moves computation to the data

Design principles for performance

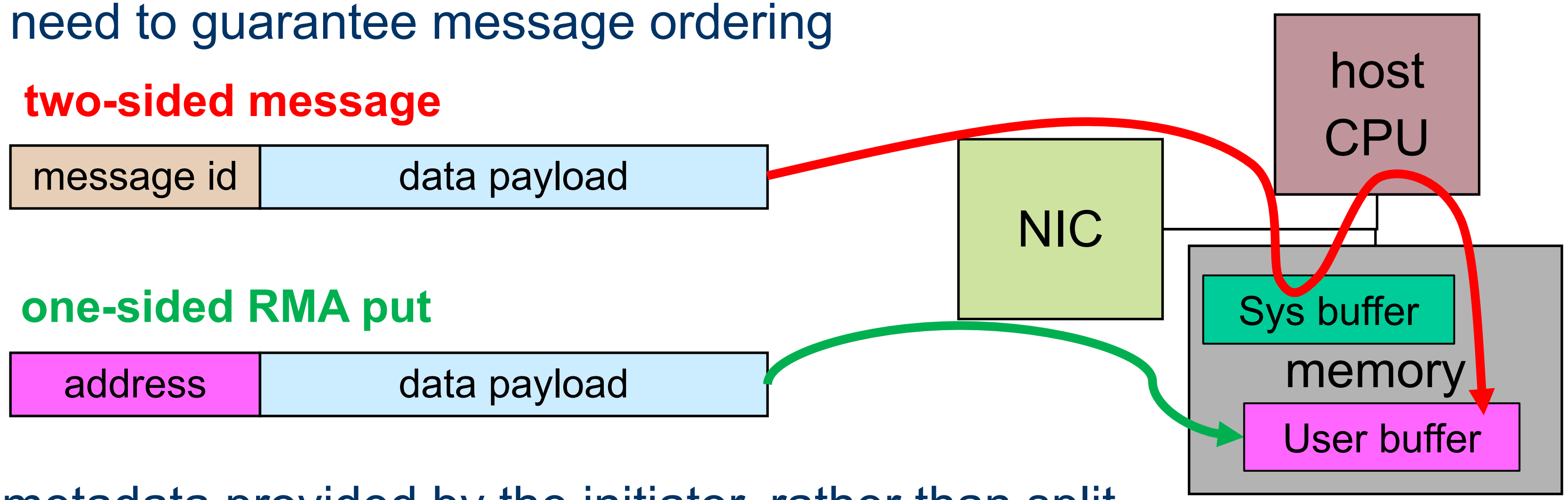
- All communication is syntactically explicit
- All communication is asynchronous: futures and promises
- Scalable data structures that avoid unnecessary replication

Reducing communication overhead

Let each process directly access another's memory via a global pointer

Communication is **one-sided** – there is no "receive" operation

- No need to match sends to receives
- No unexpected messages
- No need to guarantee message ordering



- All metadata provided by the initiator, rather than split between sender and receiver
- Supported in hardware through RDMA (Remote Direct Memory Access)

Looks like shared memory: shared data structures with asynchronous access

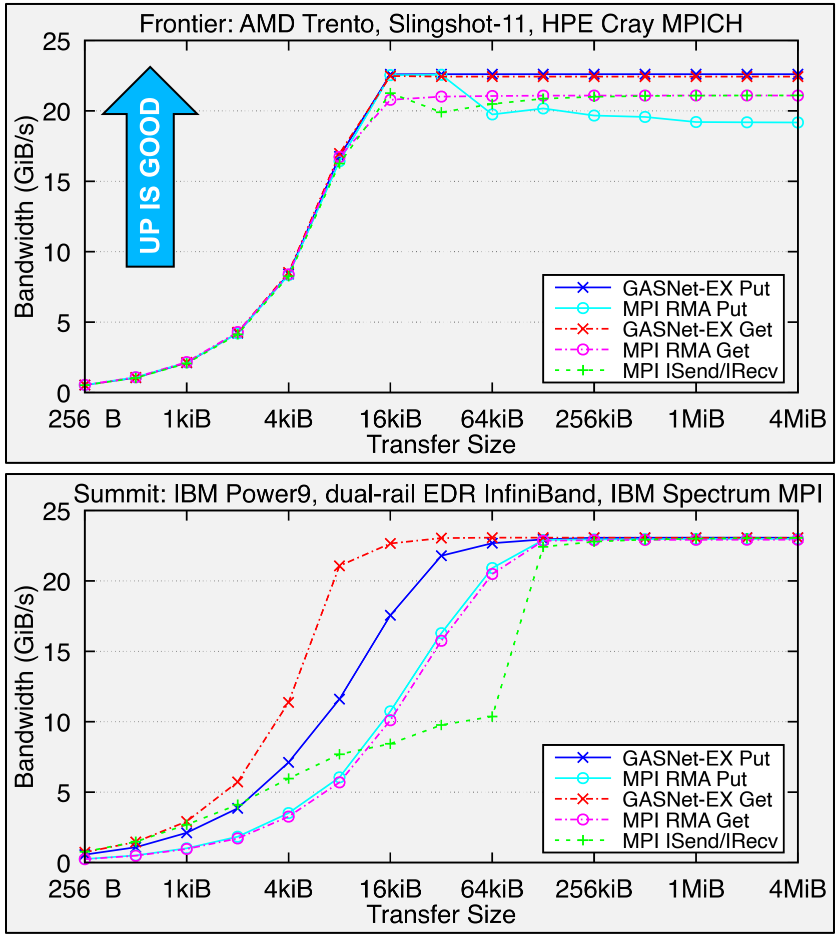
One-sided GASNet-EX vs one- and two-sided MPI

Two distinct network hardware types

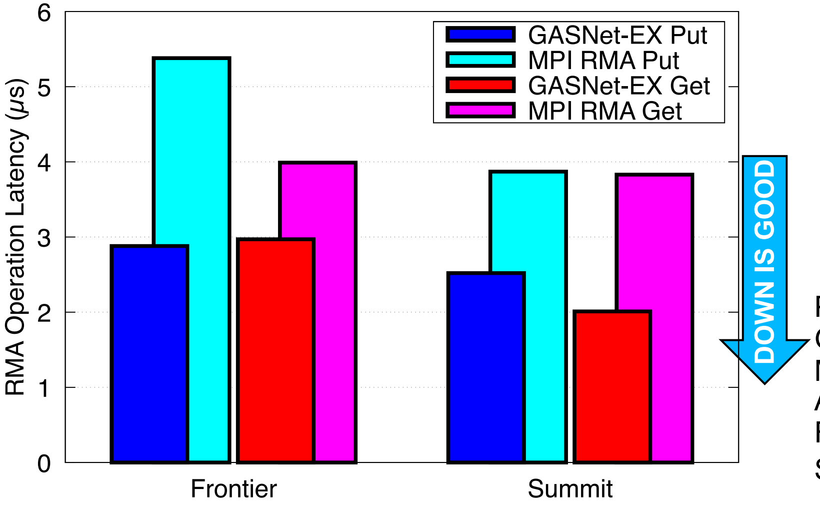
The performance of one-sided GASNet-EX matches or exceeds that of MPI RMA and message-passing:

- 8-byte Put latency 35 - 46% better
- 8-byte Get latency 26 - 47% better
- Better flood bandwidth efficiency: often reaching same or better peak at ½ or ¼ the transfer size

Uni-directional Flood Bandwidth (many-at-a-time)



8-Byte RMA Operation Latency (one-at-a-time)

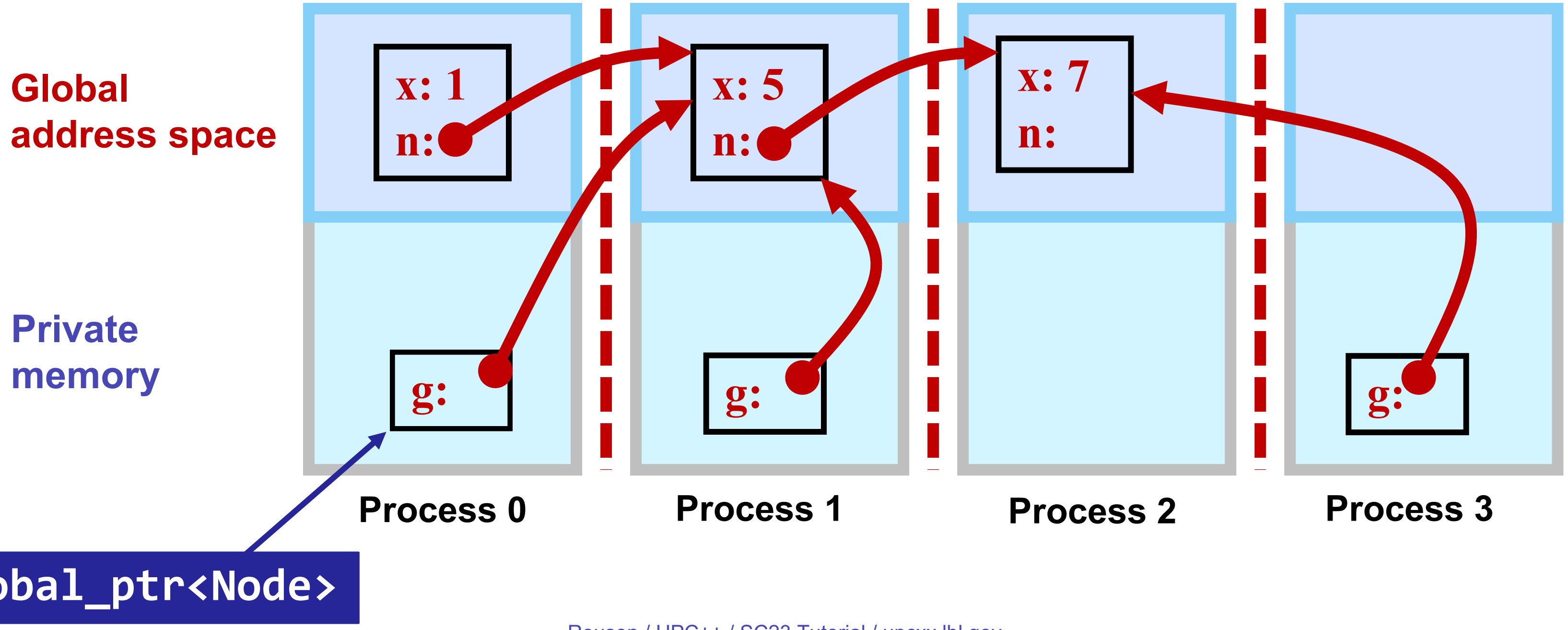


Perlmutter Phase-I results collected July 2022, all others collected April 2023.
GASNet-EX tests were run using then-current GASNet library and its tests.
MPI tests were run using then-current center default MPI version and Intel MPI Benchmarks.
All tests use two nodes and one process per node.
For details see LCPC'18 doi.org/10.25344/S4QP4W and PAW-ATM'22 doi.org/10.25344/S40C7D
See also: gasnet.lbl.gov/performance

Global pointers

Global pointers are used to create logically shared but physically distributed data structures

Parameterized by the type of object it points to, as with a C++ (raw) pointer: e.g. `global_ptr<double>`, `global_ptr<Node>`

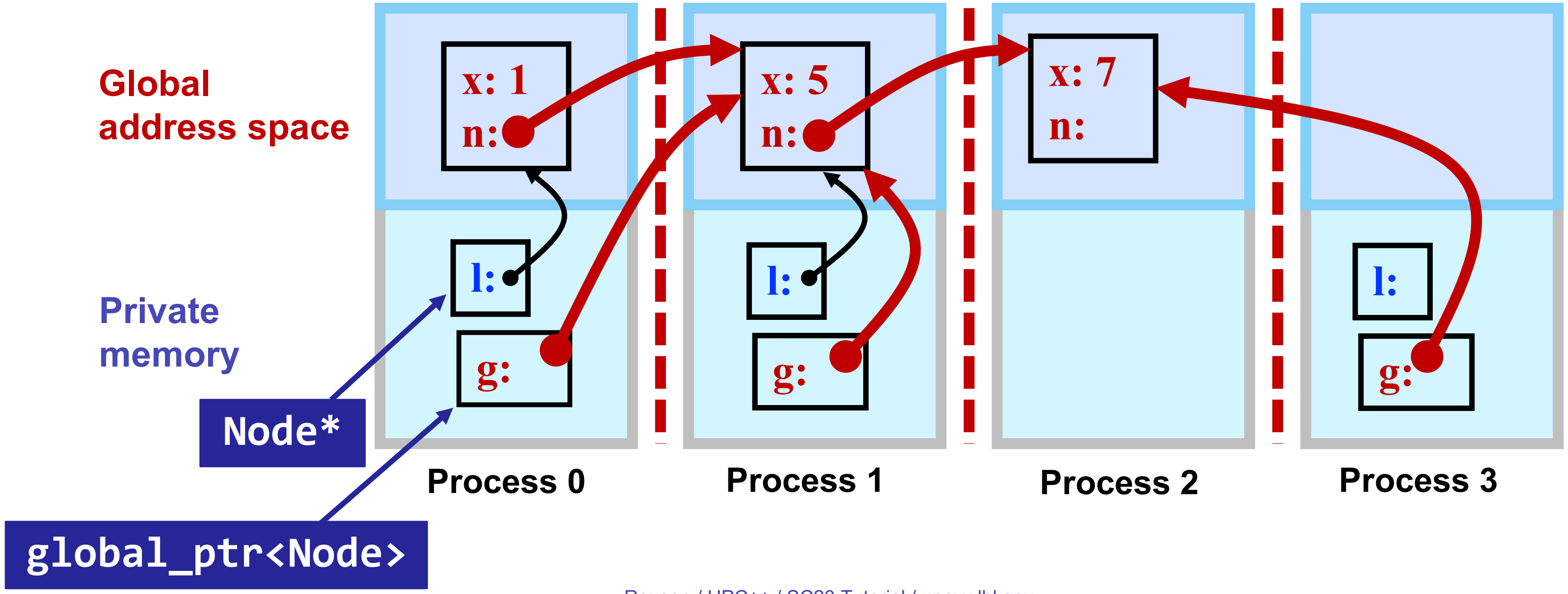


Global vs raw pointers and affinity

The affinity identifies the process that created the object

Global pointer carries both an address and the affinity for the data

Raw C++ pointers (e.g. `Node*`) can be used on a process to refer to objects in the global address space that have affinity to that process



How does UPC++ deliver the PGAS model?

UPC++ uses a “compiler-free,” library approach

- UPC++ leverages C++ standards, needs only a standard C++ compiler

Relies on GASNet-EX for low-overhead communication

- Efficiently utilizes network hardware, including RDMA
- Provides Active Messages on which UPC++ RPCs are built
- Enables portability (laptops to supercomputers)

Designed for interoperability

- Same SPMD process model as MPI, enabling hybrid applications
- On-node compute models (e.g. OpenMP, CUDA, HIP, Kokkos) can be mixed with UPC++ as in MPI+X

Asynchronous communication (RMA)

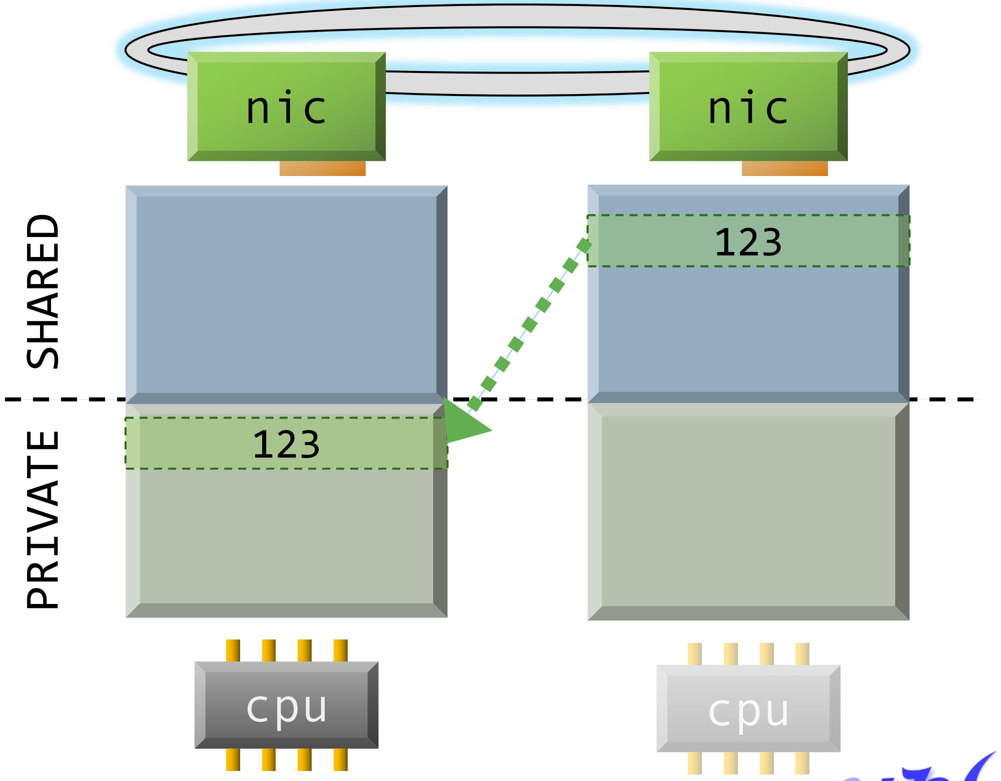
By default, all communication operations are split-phased

- **Initiate** operation
- **Wait** for completion

  A future holds a value and a state: ready/not-ready

```
global_ptr<int> gptr1 = ...;
future<int> f1 = rget(gptr1);
// unrelated work...
int t1 = f1.wait();
```

Wait returns the result when the rget completes

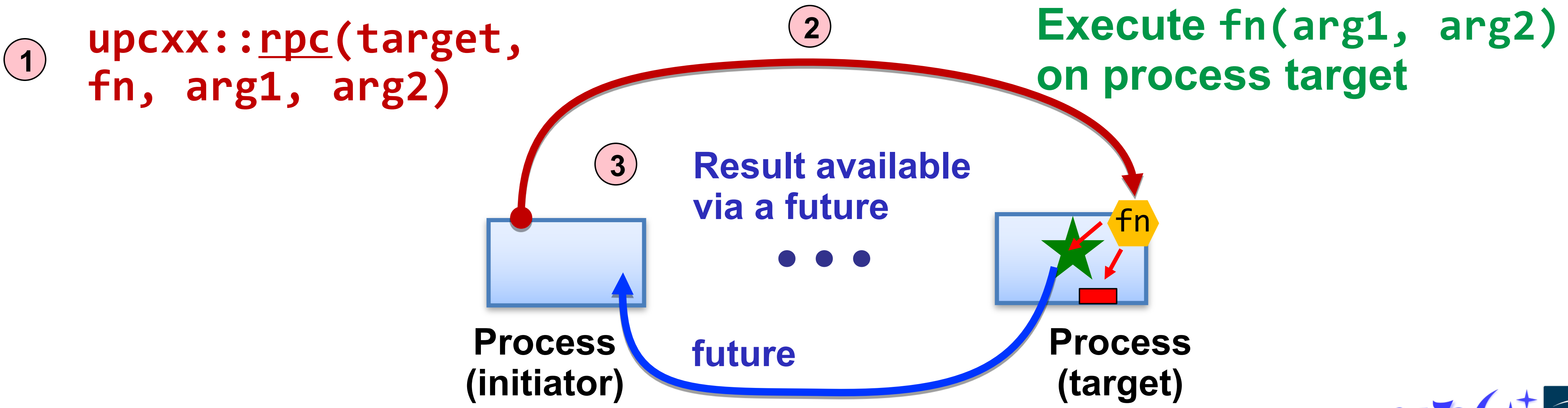


Remote procedure call (RPC)

Execute a function on another process, sending arguments and returning an optional result

1. Initiator injects the RPC to the *target* process
2. Target process executes `fn(arg1, arg2)` at some later time determined at the target
3. Result becomes available to the initiator via the future

Many RPCs can be active simultaneously, hiding latency



1 `upcxx::rpc(target, fn, arg1, arg2)`

2 Execute `fn(arg1, arg2)` on process target

3 Result available via a future

Compiling and running a UPC++ program

UPC++ provides tools for ease-of-use

Compiler wrapper:

```
$ upcxx -g hello-world.cpp -o hello-world.exe
```

- Invokes a normal backend C++ compiler with the appropriate arguments (`-I`/`-L` etc).
- We also provide other mechanisms for compiling
  - `upcxx-meta`
  - CMake package

Launch wrapper:

```
$ upcxx-run -N 1 -n 4 ./hello-world.exe
```

- Arguments similar to other familiar tools
- Also support launch using platform-specific tools, such as **`srun`**, **`jsrun`** and **`aprun`**.

Example: Hello world compile and run

Everything needed for the example codes is at:

https://go.lbl.gov/SC23

Online materials include:

- Module info for NERSC Perlmutter, OLCF Frontier, and other machines
- Download links to install UPC++

Once you have set up your environment, copied the tutorial materials, and changed to the `sc23/upcxx` directory:

Command to run in the terminal

```
$ make run-hello-world
upcxx hello-world.cpp -Wall  -o hello-world
upcxx-run -N 1 -n 4 ./hello-world
Hello world from process 2 out of 4 processes
Hello world from process 0 out of 4 processes
Hello world from process 3 out of 4 processes
Hello world from process 1 out of 4 processes
```

Copy this and change the number after `-n` to use a different number of processes, e.g.:

`upcxx-run -N 1 -n 8 ./hello-world`

```
make run-hello-world
```

Example: Hello world

```
#include <iostream>
#include <upcxx/upcxx.hpp>
using namespace std;

int main() {
  upcxx::init();
  cout << "Hello world from process "
       << upcxx::rank_me()
       << " out of " << upcxx::rank_n()
       << " processes" << endl;
  upcxx::finalize();
}
```

Set up UPC++ runtime

Close down UPC++ runtime

```
Hello world from process 0 out of 4 processes
Hello world from process 2 out of 4 processes
Hello world from process 3 out of 4 processes
Hello world from process 1 out of 4 processes
```

```
make run-hello-world-rpc-to-0
```

Hello world with RPC (synchronous)

We can rewrite hello world by having each process launch an RPC to process 0

```
int main() {
  upcxx::init();
  for (int i = 0; i < upcxx::rank_n(); ++i) {
    if (upcxx::rank_me() == i) {

      upcxx::rpc(0, [](int rank) {
        cout << "Hello from process " << rank << endl;
      }, upcxx::rank_me()).wait();
    }

    upcxx::barrier();
  }
  upcxx::finalize();
}
```

C++ lambda function

Wait for RPC to complete before continuing

Rank number is the argument to the lambda

Barrier prevents any process from proceeding until all have reached it

Futures

RPC returns a *future* object, which represents a computation that may or may not be complete

Calling `wait()` on a future causes the current process to wait until the future is ready

Empty future type that does not hold a value, but still tracks readiness

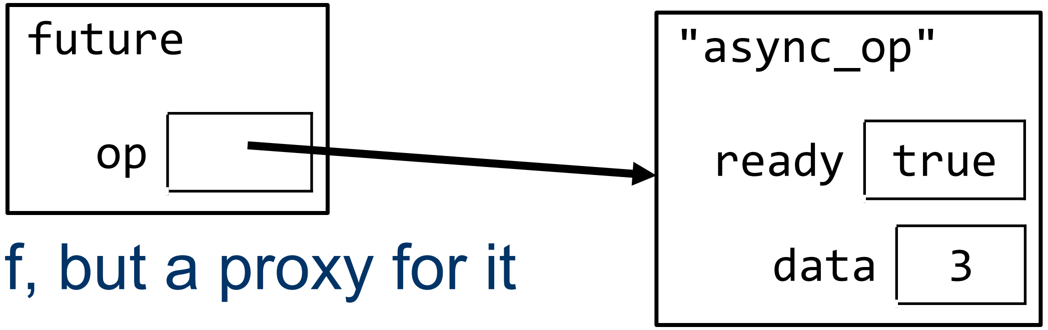
```
upcxx::future<> fut =
  upcxx::rpc(0, [](int rank) {
    cout << "Hello from process " << rank << endl;
  }, upcxx::rank_me());

fut.wait();
```

What is a UPC++ future?

A future is a handle to an asynchronous operation, which holds:

- The status/readiness of the operation
- The results (zero or more values) of the completed operation



The future is not the result itself, but a proxy for it

The wait() method blocks until a future is ready and returns the result

```
upcxx::future<int> fut = /* ... */;
int result = fut.wait();
```

The then() method can be used instead to attach a callback to the future

```
make run-jac1d
```

1D 3-point Jacobi in UPC++

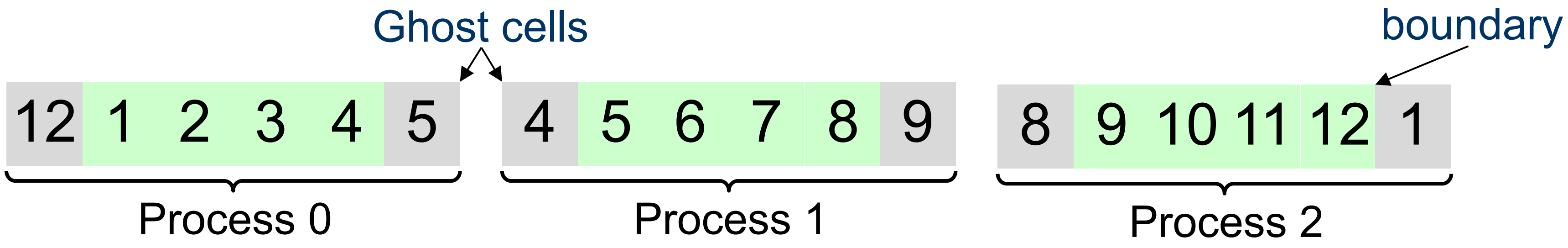
Iterative algorithm that updates each grid cell as a function of its old value and those of its immediate neighbors

Out-of-place computation requires two grids

Local grid size

```
for (long i = 1; i < N - 1; ++i)
  new_grid[i] = 0.25 *
      (old_grid[i - 1] + 2*old_grid[i] + old_grid[i + 1]);
```

Sample data distribution of each grid
(12 domain elements, 3 processes, N=12/3+2=6):



Ghost cells

Periodic boundary

12 1 2 3 4 5
Process 0

4 5 6 7 8 9
Process 1

8 9 10 11 12 1
Process 2

Jacobi boundary exchange (version 1)

RPCs can refer to static variables, so we use them to keep track of the grids

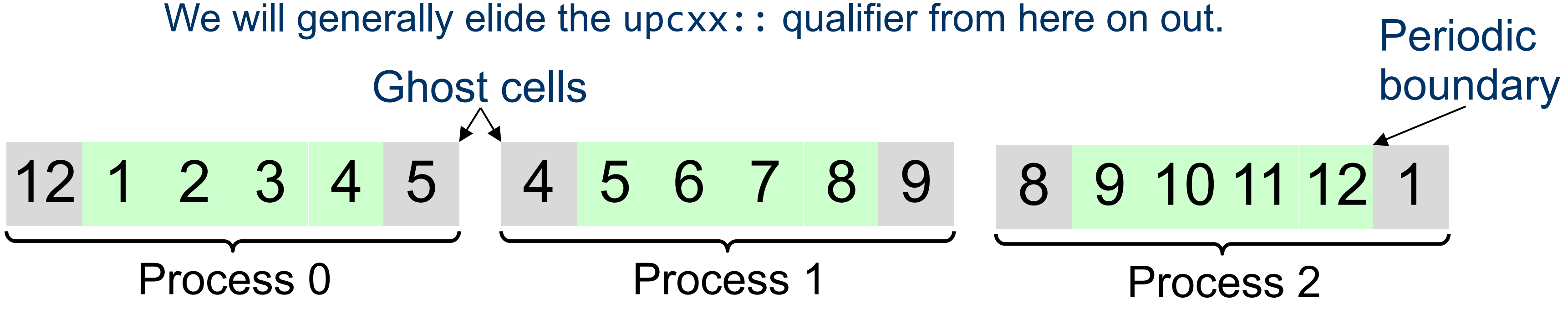
```
double *old_grid, *new_grid;

double get_cell(long i) {
  return old_grid[i];
}

...

double val = rpc(right, get_cell, 1).wait();
```

We will generally elide the `upcxx::` qualifier from here on out.



12 1 2 3 4 5

Process 0

4 5 6 7 8 9

Process 1

8 9 10 11 12 1

Process 2

Jacobi computation (version 1)

We can use RPC to communicate boundary cells

```
future<double> left_ghost = rpc(left, get_cell, N-2);
future<double> right_ghost = rpc(right, get_cell, 1);
```

Initiate communication

```
for (long i = 2; i < N - 2; ++i)
  new_grid[i] = 0.25 *
    (old_grid[i-1] + 2*old_grid[i] + old_grid[i+1]);
```

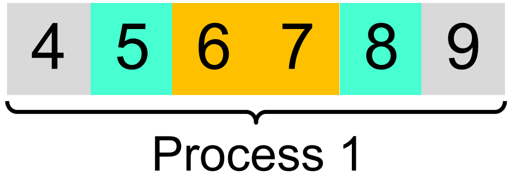
Do interior computation

```
new_grid[1] = 0.25 *
  (left_ghost.wait() + 2*old_grid[1] + old_grid[2]);

new_grid[N-2] = 0.25 *
  (old_grid[N-3] + 2*old_grid[N-2] + right_ghost.wait());
```

Wait for communication to complete and do boundary computation

```
std::swap(old_grid, new_grid);
```



One-sided put and get (RMA)

UPC++ provides APIs for one-sided puts and gets

Implemented using network RDMA if available – most efficient way to move large payloads

- Scalar put and get:

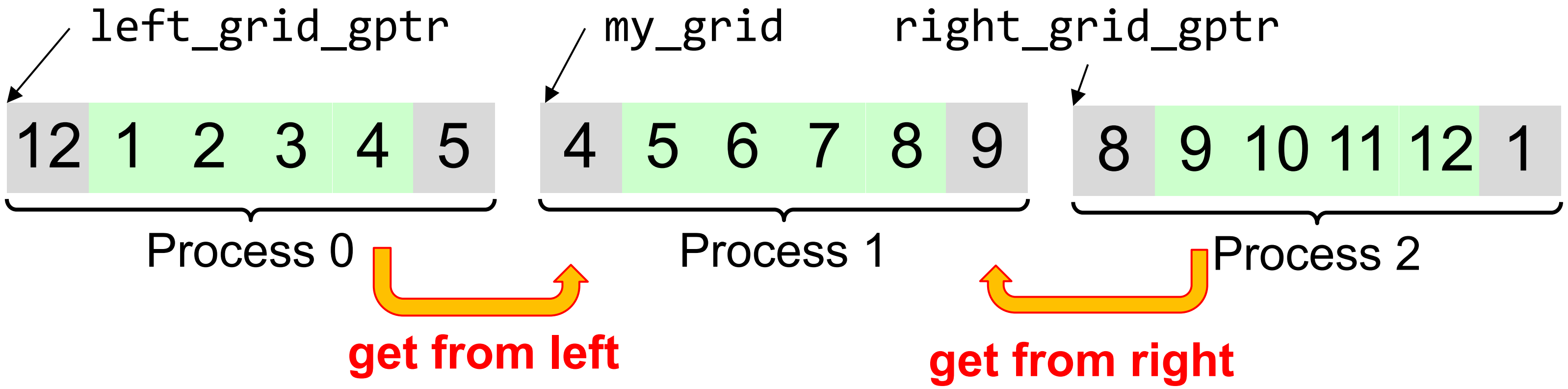
```
global_ptr<int> remote = /* ... */;
future<int> fut1 = rget(remote);
int result = fut1.wait();
future<> fut2 = rput(42, remote);
fut2.wait();
```

- Vector put and get:

```
int *local = /* ... */;
future<> fut3 = rget(remote, local, count);
fut3.wait();
future<> fut4 = rput(local, remote, count);
fut4.wait();
```

Jacobi with ghost cells

Each process maintains *ghost cells* for data from neighboring processes



Assuming we have *global pointers* to our neighbor grids, we can do a one-sided put or get to communicate the ghost data:

```
double *my_grid;
global_ptr<double> left_grid_gptr, right_grid_gptr;
my_grid[0] = rget(left_grid_gptr + N - 2).wait();
my_grid[N-1] = rget(right_grid_gptr + 1).wait();
```

Storage management

Memory must be allocated in the shared segment in order to be accessible through RMA

```
global_ptr<double> old_grid_gptr, new_grid_gptr;
...
old_grid_gptr = new_array<double>(N);
new_grid_gptr = new_array<double>(N);
```

These are not collective calls – each process allocates its own memory, and there is no synchronization

- Explicit synchronization may be required before retrieving another process’s pointers with an RPC
- The pointers must be communicated to other processes before they can access the data

Downcasting global pointers

If a process has direct load/store access to the memory referenced by a global pointer, it can *downcast* the global pointer into a raw pointer with `local()`

```
global_ptr<double> old_grid_gptr, new_grid_gptr;
double *old_grid, *new_grid;

void make_grids(size_t N) {
  old_grid_gptr = new_array<double>(N);
  new_grid_gptr = new_array<double>(N);
  old_grid = old_grid_gptr.local();
  new_grid = new_grid_gptr.local();
}
```

Downcasting can also be used to optimize for co-located processes that share physical memory

Jacobi RMA with gets

Each process obtains boundary data from its neighbors with rget()

Remote source (global_ptr)

Local dest ptr

```
future<> left_get = rget(left_old_grid + N - 2, old_grid, 1);
future<> right_get = rget(right_old_grid + 1, old_grid + N - 1, 1);

for (long i = 2; i < N - 2; ++i)
  /* ... */;



left_get.wait();
new_grid[1] = 0.25*(old_grid[0] + 2*old_grid[1] + old_grid[2]);

right_get.wait();
new_grid[N-2] = 0.25*(old_grid[N-3] + 2*old_grid[N-2] + old_grid[N-1]);
```

Begin asynchronous RMA gets

Overlapped computation on interior cells

Wait for communication, then consume values

Callbacks

The then() method attaches a callback to a future

- The callback will be invoked after the future is ready, with the future's values as its arguments

```
future<> left_update =
  rget(left_old_grid + N - 2, old_grid, 1)
  .then([]() {
    new_grid[1] = 0.25 *
      (old_grid[0] + 2*old_grid[1] + old_grid[2]);
  });
```

Vector get does not produce a value

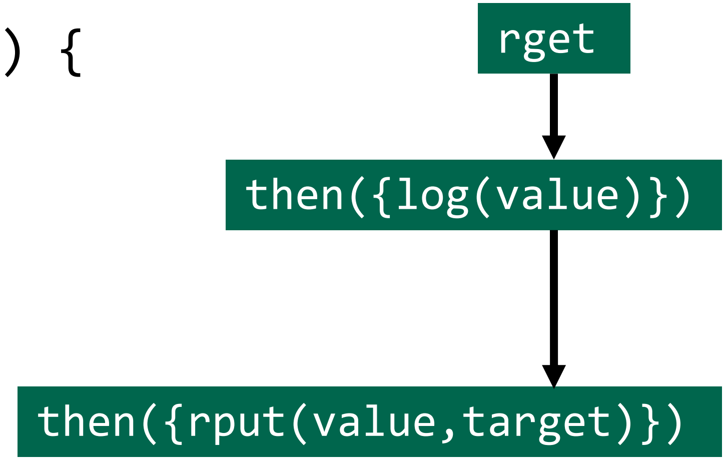
```
future<> right_update =
  rget(right_old_grid + N - 2)
  .then([](double value) {
    new_grid[N-2] = 0.25 *
      (old_grid[N-3] + 2*old_grid[N-2] + value);
  });
```

Scalar get produces a value

Chaining calls using futures

Callbacks can be chained through calls to then()

```
global_ptr<int> source = /* ... */;
global_ptr<double> target = /* ... */;
future<int> fut1 = rget(source);
future<double> fut2 = fut1.then([](int value) {
  return std::log(value);
});
future<> fut3 =
  fut2.then([target](double value) {
    return rput(value, target);
  });
fut3.wait();
```



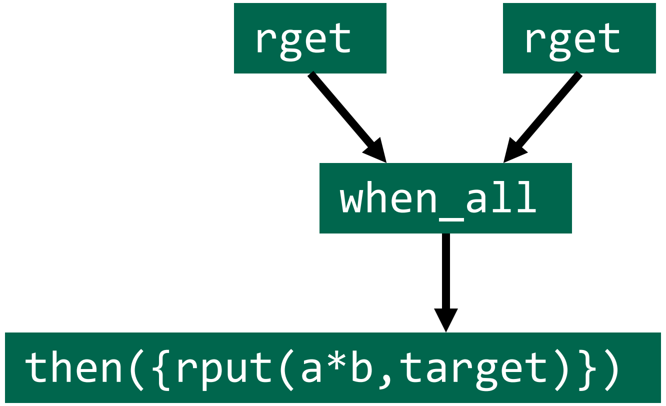
This code retrieves an integer from a remote location, computes its log, and then sends it to a different remote location

Conjoining futures

Multiple futures can be *conjoined* with when_all() into a single future that encompasses all their results

Can be used to specify multiple dependencies for a callback

```
global_ptr<int>    source1 = /* ... */;
global_ptr<double> source2 = /* ... */;
global_ptr<double> target = /* ... */;
future<int>    fut1 = rget(source1);
future<double> fut2 = rget(source2);
future<int, double> both =
    when_all(fut1, fut2);
future<> fut3 =
    both.then([target](int a, double b) {
        return rput(a * b, target);
    });
fut3.wait();
```



rget

rget

when_all

then({rput(a*b,target)})

Example: 2D heat diffusion

$$u_{i,j}^{n+1} = u_{i,j}^{n} + \alpha\left(u_{i+1,j}^{n} + u_{i-1,j}^{n} - 4u_{i,j}^{n} + u_{i,j+1}^{n} + u_{i,j-1}^{n}\right)$$

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Online materials include download links to install UPC++

Once you have set up your environment, copied the tutorial materials, and changed to the `sc23/upcxx` directory:

Command to run in the terminal

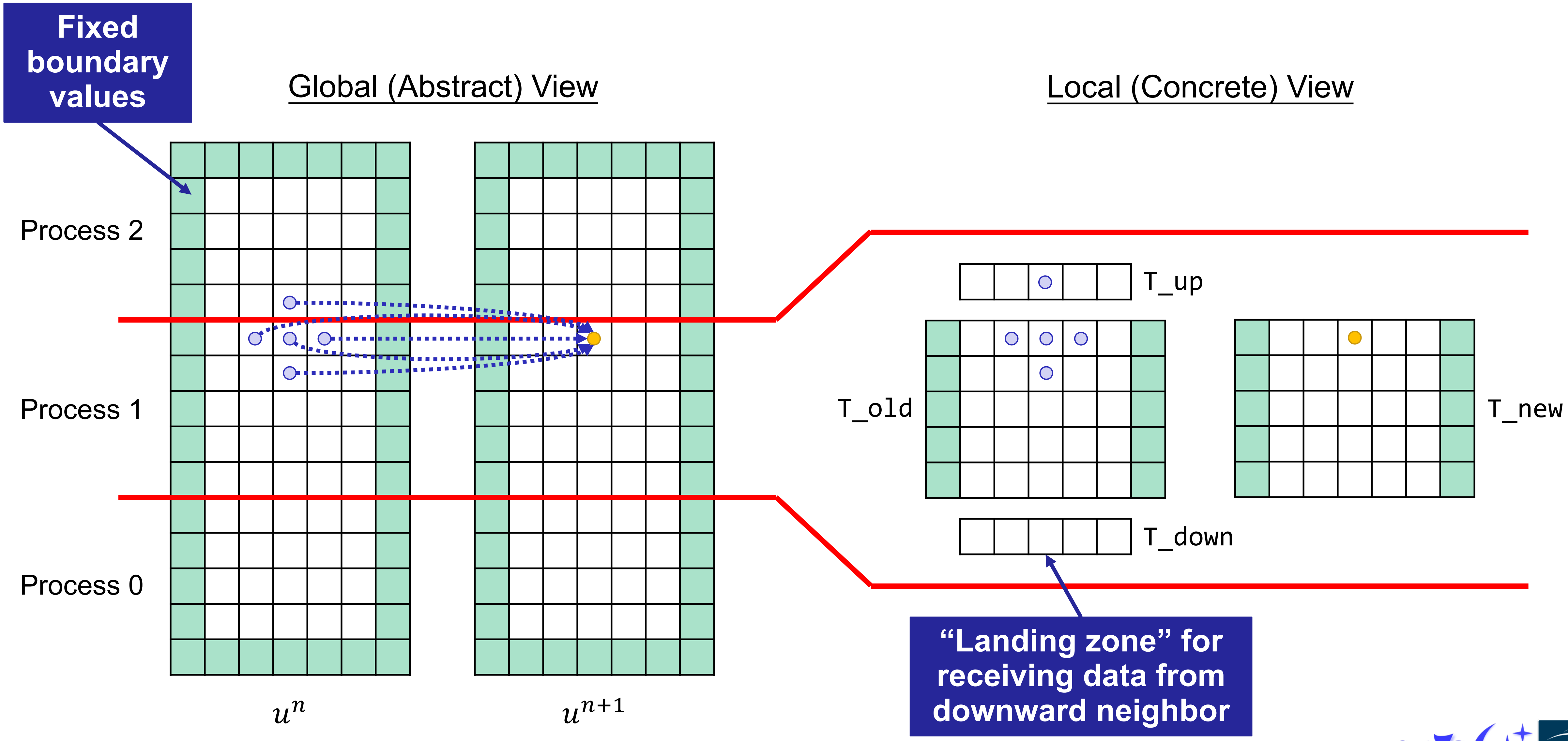
```
$ make run-heat2d
upcxx heat2d.cpp -Wall  -o heat2d
upcxx-run -N 1 -n 4 ./heat2d
[2]   My Neighbors: (1, 3)       My Domain: (2048,3072)
[3]   My Neighbors: (2, -1)      My Domain: (3072,4096)
[0]   My Neighbors: (-1, 1)      My Domain: (0,1024)
[1]   My Neighbors: (0, 2)       My Domain: (1024,2048)
[0] mean temperature=1.06256 | Solve time: 0.734826 seconds
```

Copy this and add arguments to change the problem size, e.g.:
`upcxx-run -N 1 -n 4 ./heat2d 8192 8192`

2D heat diffusion data layout

$$u_{i,j}^{n+1} = u_{i,j}^{n} + \alpha\left(u_{i+1,j}^{n} + u_{i-1,j}^{n} - 4u_{i,j}^{n} + u_{i,j+1}^{n} + u_{i,j-1}^{n}\right)$$

```
make run-heat2d
```



2D heat diffusion computation

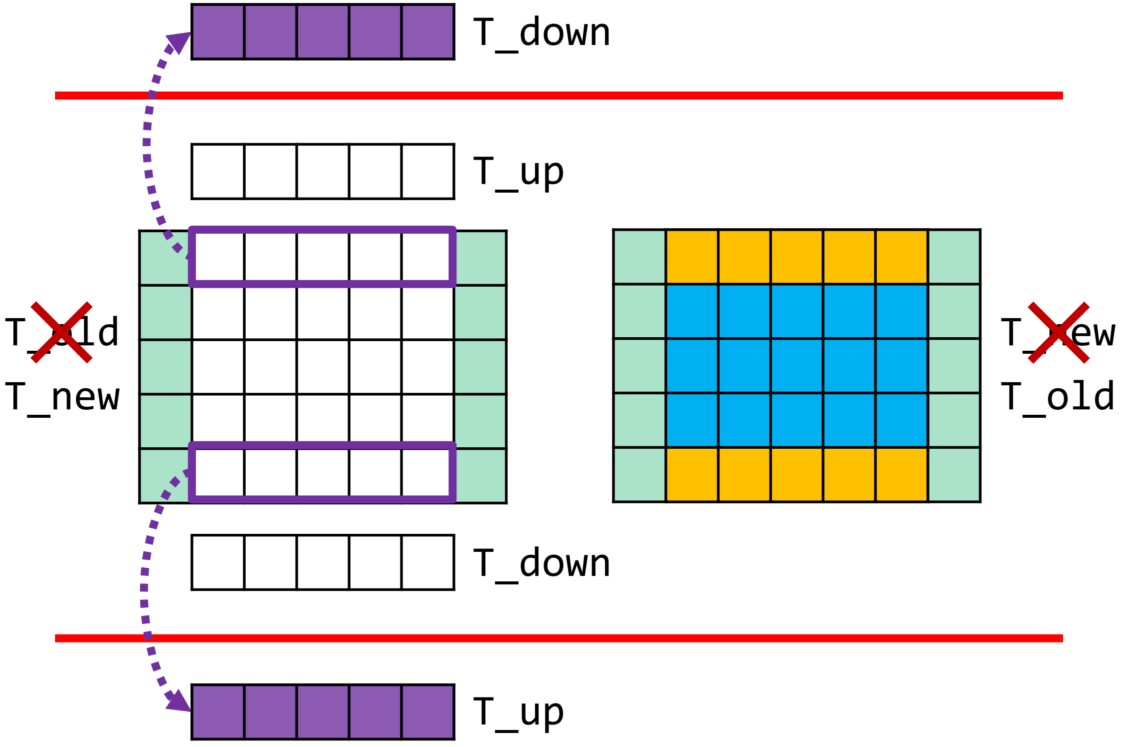
$$u_{i,j}^{n+1} = u_{i,j}^{n} + \alpha\left(u_{i+1,j}^{n} + u_{i-1,j}^{n} - 4u_{i,j}^{n} + u_{i,j+1}^{n} + u_{i,j-1}^{n}\right)$$

```
make run-heat2d
```

Computation loop:

Global pointer to neighbor’s landing zone

```
for (int t = 0; t < num_timesteps; t++) {
  // initiate asynchronous puts to neighbors
  future<> fut =
    when_all(rput(T_old, gptr_down, X),
             rput(T_old+offset, gptr_up, X));
  // overlapped computation of interior
  compute_inner_T_new();
  // wait for my puts to complete
  fut.wait();
  // ensure everyone's puts have completed
  barrier();
  // compute boundaries using data received from neighbors
  compute_surface_T_new();
  // set up next timestep
  std::swap(T_new, T_old);
  barrier();
}
```



Distributed objects

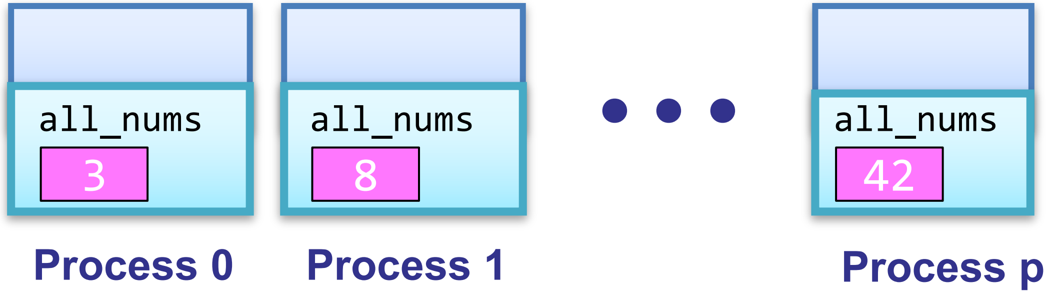
A *distributed object* is an object that is partitioned over a set of processes

```
dist_object<T>(T value, team &team = world());
```

The processes share a universal name for the object, but each has its own local value

Similar in concept to a co-array, but with advantages

- Scalable metadata representation
- Does not require a symmetric heap
- No communication to set up or tear down



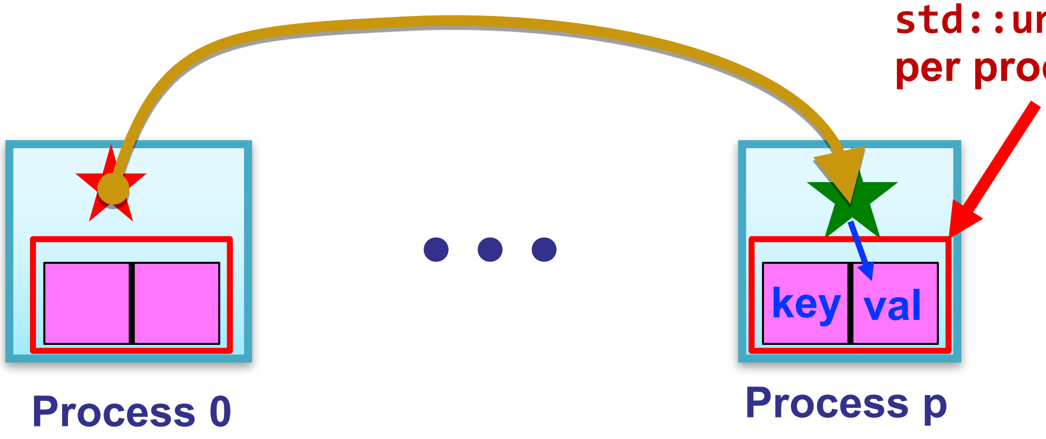
```
dist_object<int>
  all_nums(rand());
```

```
make run-dmap-insert-test
```

Example: Distributed hash table (DHT)

Distributed analog of `std::unordered_map` (similar to Python `dict`, Java `HashMap`)

- Supports insertion and lookup
- We will assume the key and value types are `std::string`
- Represented as a collection of individual unordered maps across processes
- We use RPC to move hash-table operations to the owner



Hash table partition: a `std::unordered_map` per process

DHT data representation

A distributed object represents the directory of unordered maps

```
class DistrMap {
  using dobj_map_t =
    dist_object<std::unordered_map<std::string, std::string>>;

  // Construct empty map
  dobj_map_t local_map{{}};


  int get_target_rank(const std::string &key) {
    return std::hash<string>{}(key) % rank_n();
  }
};
```

Define an abbreviation for a helper type

Computes owner for the given key

DHT insertion

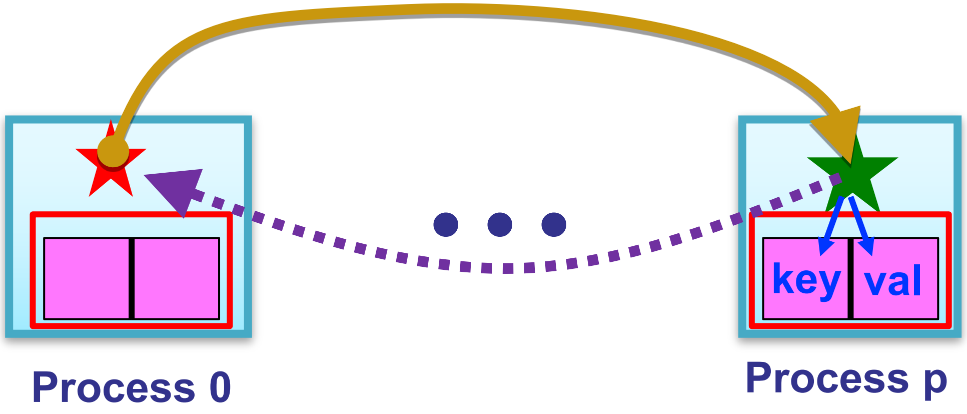
Insertion initiates an RPC to the owner and returns a future that represents completion of the insert

```
future<> insert(const string &key,
                const string &val) {
  return rpc(get_target_rank(key),
    [](dobj_map_t &lmap, const string &key, const string &val) {
      (*lmap)[key] = val;
    }, local_map, key, val);
}
```

Send RPC to the process determined by key hash

Key and value passed as arguments to the remote function

UPC++ uses the distributed object's universal name to look it up on the remote process



DHT find

Find also uses RPC and returns a future

```
future<string> find(const string &key) {
  return rpc(get_target_rank(key),
    [](dobj_map_t &lmap, const string &key) {
      if (lmap->count(key) == 0)
        return string("NOT FOUND");
      else
        return (*lmap)[key];
    }, local_map, key);
}
```

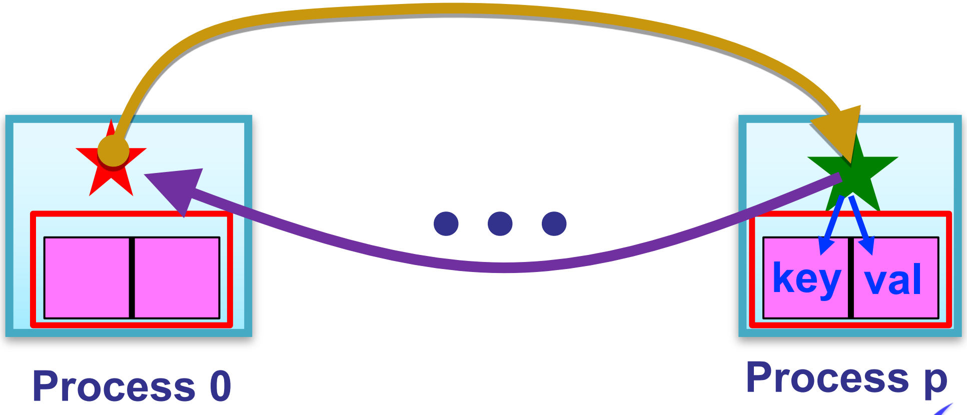
Send RPC to the process determined by key hash

Check whether key exists in local map

Retrieve corresponding value from the local map and return it

UPC++ uses the distributed object's universal name to look it up on the remote process

Key passed as argument to the remote function



Optimized DHT scales well

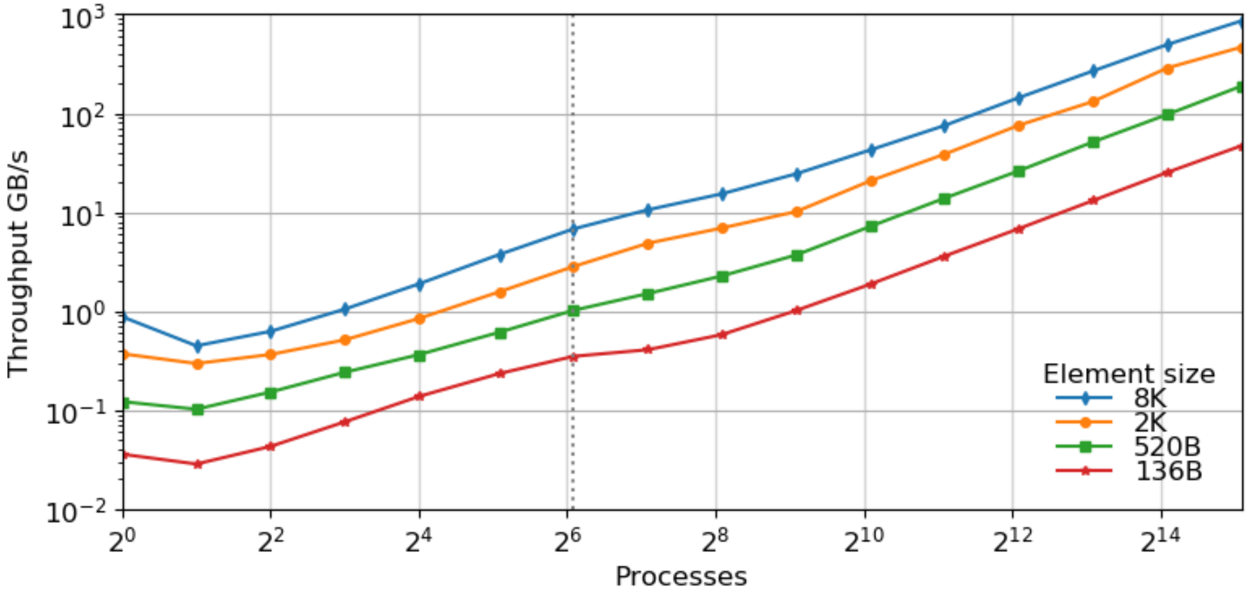
```
make run-drmap-insert-test
```

Excellent weak scaling up to 32K cores [IPDPS19]

- Randomly distributed keys

RPC and RMA lead to simplified and more efficient design

- Key insertion and storage allocation handled at target
- Without RPC, complex updates would require explicit synchronization and two-sided coordination



Cori @ NERSC (KNL)

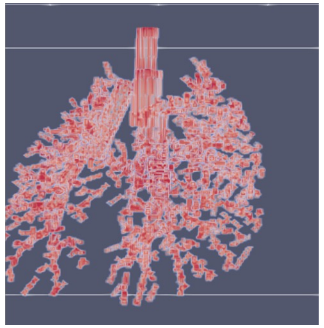
Cray XC40

UPC++ advanced features

UPC++ has many advanced features that enable further optimizations

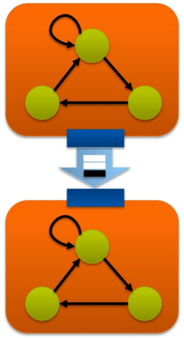
- Team-based barrier, reduction, and broadcast collectives
- Remote atomic operations that utilize hardware offload capabilities of modern networks
- Serialization of complex standard-library and user types in RPC’s
- Shared-memory bypass for co-located processes on many-core nodes
- Additional forms of communication completion notification such as promises and “signaling put”
- Non-contiguous RMA with automated packing and aggregation of strided or sparse data
- Memory kinds for data transfer between remote or local host (CPU) and device (e.g. GPU) memory
- …

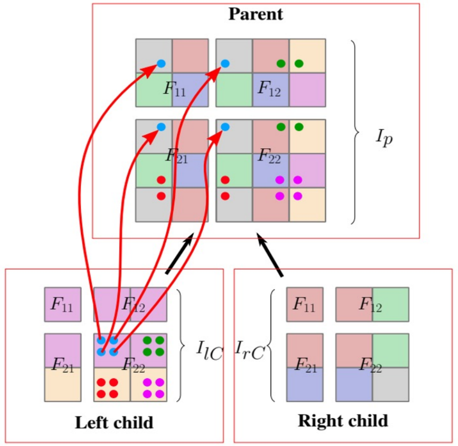
UPC++ applications

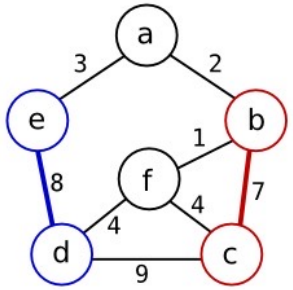


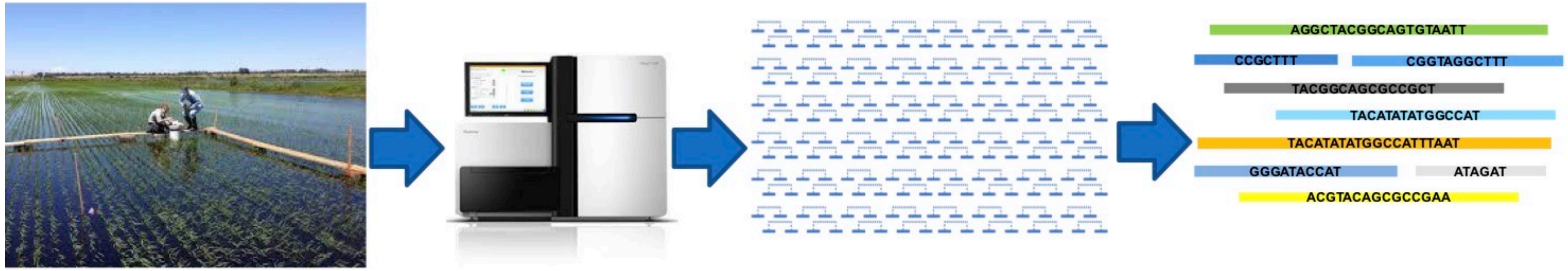
UPC++ has been used successfully in several applications to improve programmer productivity and runtime performance, including:

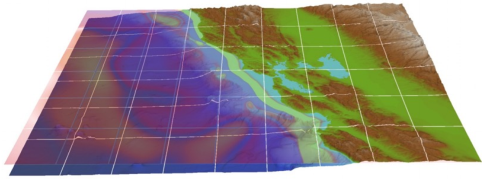
- symPACK, a sparse symmetric matrix solver: PAW-ATM tomorrow
- SIMCoV, agent-based simulation of lungs with COVID
- MetaHipMer, a genome assembler
- Actor-UPCXX, used in the Pond tsunami simulator
- A UPC++ backend for NWChemEx/TAMM
- UPC++ DepSpawn, a library for data-flow computing
- Mel-UPX, half-approximate graph matching solver











SIMCoV: Spatial Model of Immune Response to Viral Lung Infection

Model the entire lung at the cellular level:

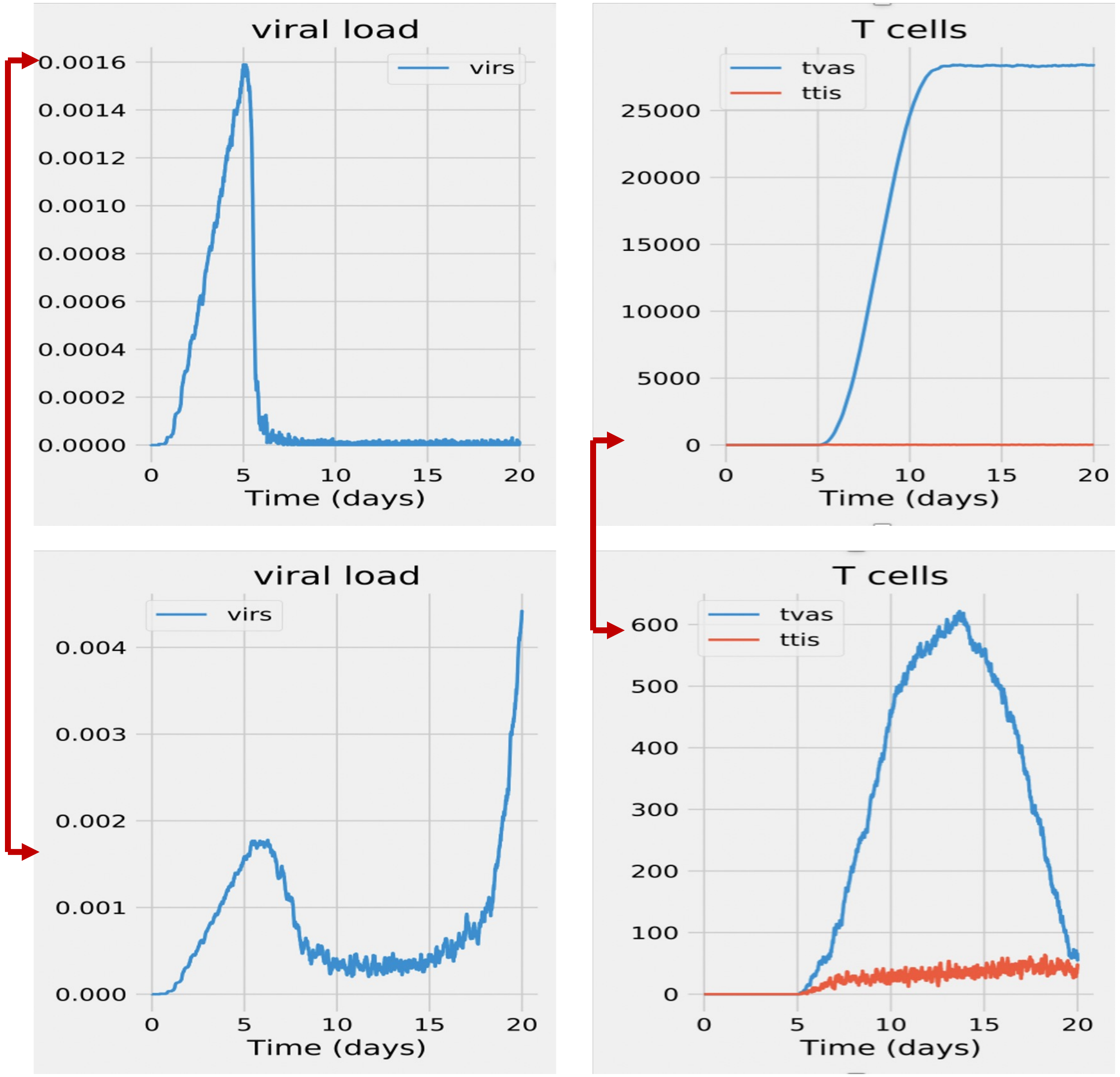
- 100 billion epithelial cells
- 100s of millions of T cells
- Complex branching fractal structure
- Time resolution in seconds for 20 to 30 days

SIMCoV in UPC++

- Distributed 3D spatial grid
- Particles move over time, but computation is localized
- Load balancing is tricky: active near infections

UPC++ benefits:

- Heavily uses RPCs
- Easy to develop first prototype
- Good distributed performance and avoids explicit locking
- Extensive support for asynchrony improves computation/communication overlap

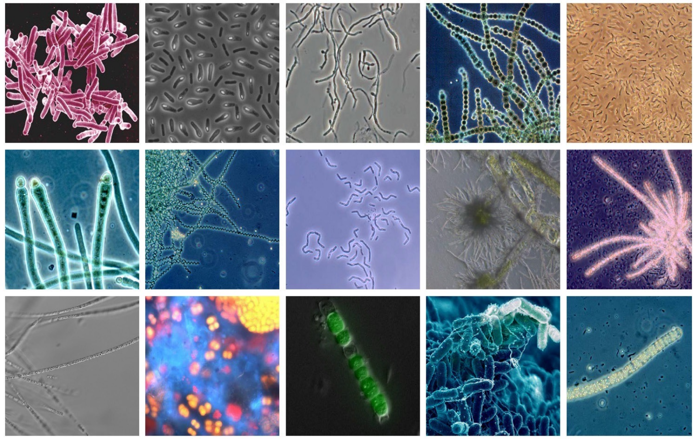


https://github.com/AdaptiveComputationLab/simcov

ExaBiome: Exascale Solutions for Microbiome Analysis

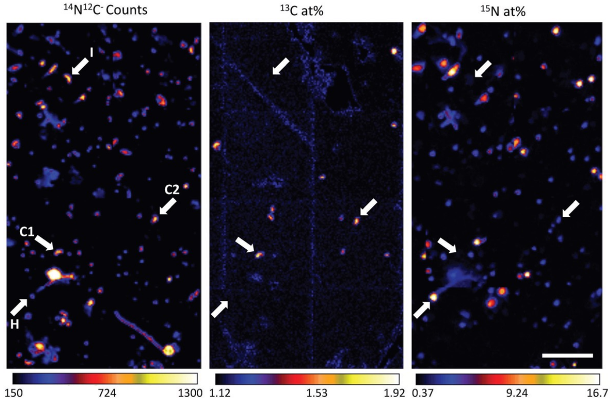
What happens to microbes after a wildfire? (1.5TB)

What at the seasonal fluctuations in a wetland mangrove? (1.6 TB)



What are the microbial dynamics of soil carbon cycling? (3.3 TB)

How do microbes affect disease and growth of switchgrass for biofuels (4TB)



Combine genomics with isotope tracing methods for improved functional understanding (8TB)

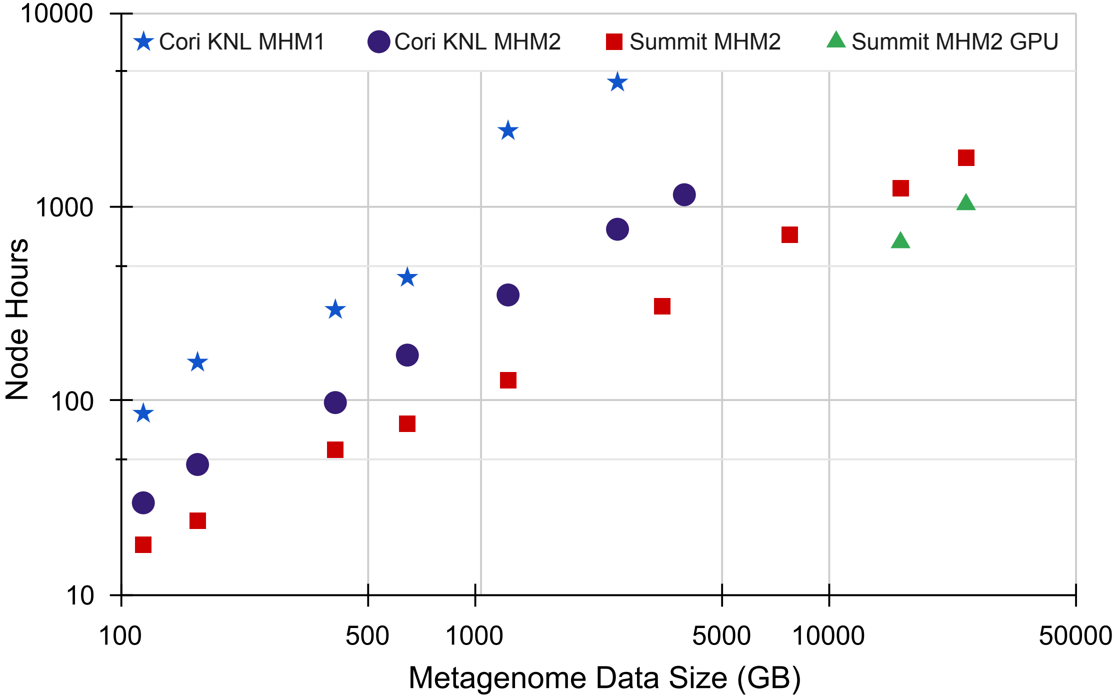
Co-Assembly improves quality and is an HPC problem

Full wetlands data: 2.6 TB of data in 21 lanes (samples)

- Time-series samples from multiple sites of Twitchell Wetlands in the San Francisco Bay-Delta
- Previously assembled 1 lane at a time (multiassembly)
- MetaHipMer coassembled together – higher quality assembly, in **3.5 hours on 16K cores**

Multiassembly
1 lane at a time

Coassembly all assembled together – more new genomes at higher completeness



This was the largest, high-quality de novo metagenome assembly completed at the time
More recently: new record 71TB metagenome assembly on 9000 nodes (288K processes and 72K GPUs) of OLCF Frontier earlier this year.

Evangelos Georganas, Rob Egan, Steven Hofmeyr, Eugene Goltsman, Bill Arndt, Andrew Tritt**,** Aydın Buluc, Leonid Oliker, Katherine Yelick, **SC18 best paper finalist**

UPC++ additional resources

Website: upcxx.lbl.gov includes the following content:

- Open-source/free library implementation
  - Portable from laptops to supercomputers
- Tutorial resources at upcxx.lbl.gov/training
  - UPC++ Programmer’s Guide
  - Videos and exercises from past tutorials
- Formal UPC++ specification
  - All the semantic details about all the features
- Links to various UPC++ publications
- Links to optional extensions and partner projects
- Contact information and support forum

“We found UPC++ to be a very powerful and flexible tool for the development of parallel applications in distributed memory environments that enabled us to reach the high level of performance required by our DepSpawn project, so that we could outperform the state-of-the-art approaches. It is also particularly important in our opinion that, while supporting a really wide range of mechanisms, it is very well documented and supported.”
-- Basilio Bernardo Fraguela Rodríguez,
Universidade da Coruña, Spain

“If your code is already written in a one-sided fashion, moving from MPI RMA or SHMEM to UPC++ RMA is quite straightforward and intuitive; it took me about 30 minutes to convert MPI RMA functions in my application to UPC++ RMA, and I am getting similar performance to MPI RMA at scale.”
-- Sayan Ghosh, PNNL

Backup Slides

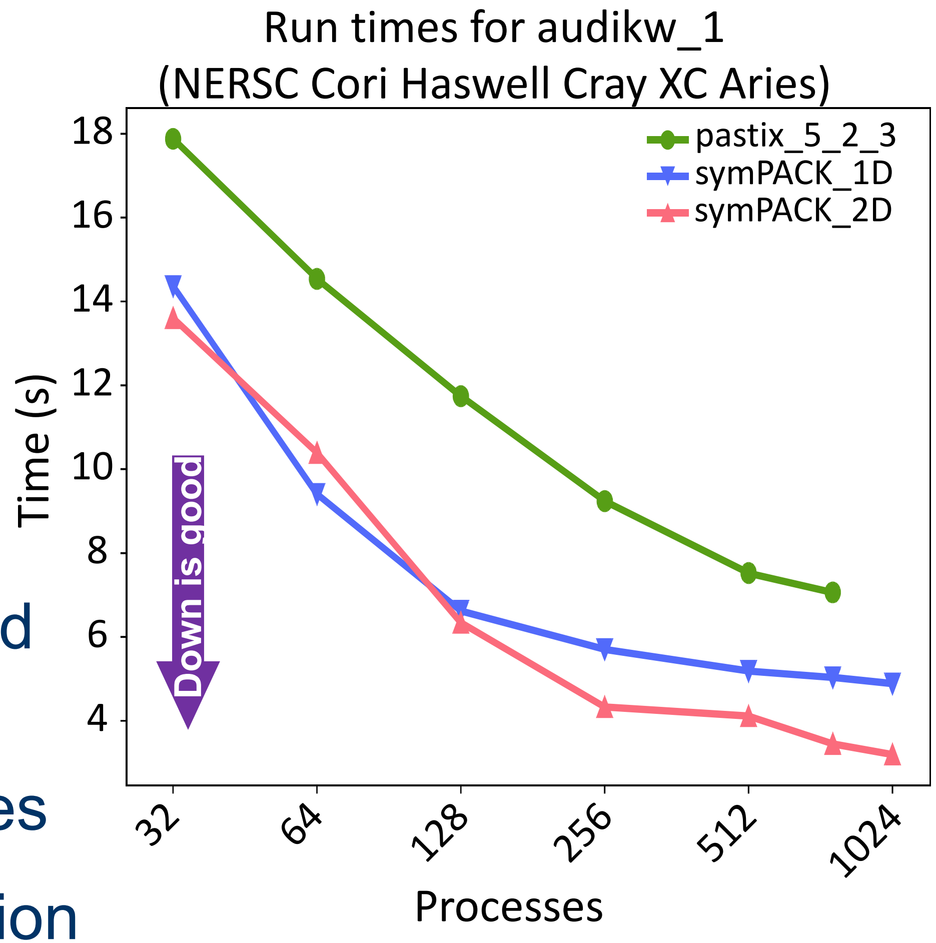
symPACK: UPC++ provides productivity + performance

Productivity

- RPC allowed very simple notify-get system
- Interoperates with MPI
- Non-blocking API

Reduced communication costs

- Low overhead reduces the cost of fine-grained communication
- Overlap communication via asynchrony/futures
- Increased efficiency in the extend-add operation
- Outperform state-of-the-art sparse symmetric solvers



https://upcxx.lbl.gov/sympack

Jacobi RMA with puts and conjoining

Each process sends boundary data to its neighbors with rput(), and the resulting futures are conjoined

```
future<> puts = when_all(
    rput(old_grid[1], left_old_grid + N - 1),
    rput(old_grid[N-2], right_old_grid));

for (long i = 2; i < N - 2; ++i)
  /* ... */;
```

```
puts.wait();
barrier();
```

Ensure outgoing puts have completed

Ensure incoming puts have completed

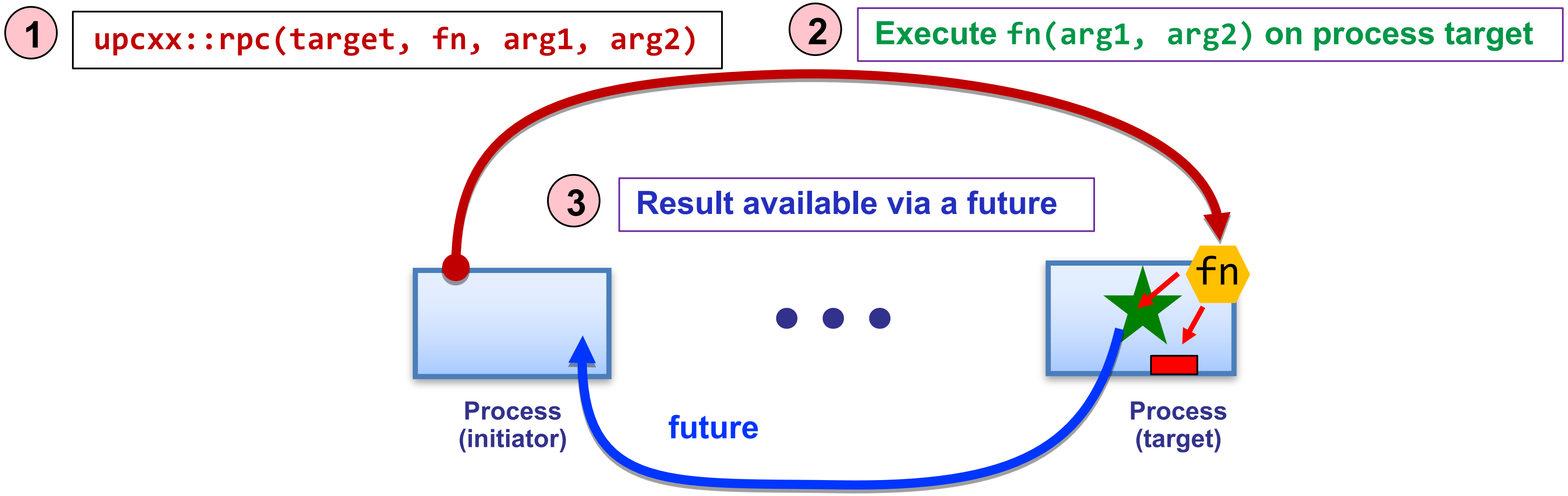
```
new_grid[1] = 0.25 * (old_grid[0] + 2*old_grid[1] + old_grid[2]);
new_grid[N-2] = 0.25 * (old_grid[N-3] + 2*old_grid[N-2] + old_grid[N-1]);
```

RPC and progress

Review: high-level overview of an RPC's execution

1. Initiator injects the RPC to the target process
2. Target process executes `fn(arg1, arg2)` at some later time determined at target
3. Result becomes available to the initiator via the future

Progress is what ensures that the RPC is eventually executed at the target



1 `upcxx::rpc(target, fn, arg1, arg2)`

2 Execute `fn(arg1, arg2)` on process target

3 Result available via a future

Progress

UPC++ does not spawn hidden threads to advance its internal state or track asynchronous communication

This design decision keeps the runtime lightweight and simplifies synchronization

- RPCs are run in series on the main thread at the target process, avoiding the need for explicit synchronization

The runtime relies on the application to invoke a progress function to process incoming RPCs and invoke callbacks

Two levels of progress

- Internal: advances UPC++ internal state but no notification
- User: also notifies the application
    - Readying futures, running callbacks, invoking inbound RPCs

Invoking user-level progress

The `progress()` function invokes user-level progress

- So do blocking calls such as `wait()` and `barrier()`

A program invokes user-level progress when it expects local callbacks and remotely invoked RPCs to execute

- Enables the user to decide how much time to devote to progress, and how much to devote to computation

User-level progress executes some number of outstanding received RPC functions

- “Some number” could be zero, so may need to periodically invoke when expecting callbacks
- Callbacks may not wait on communication, but may chain new callbacks on completion of communication

Remote atomics

Remote atomic operations are supported with an *atomic domain*

Atomic domains enhance performance by utilizing hardware offload capabilities of modern networks

The domain dictates the data type and operation set

```
atomic_domain<int64_t> dom({atomic_op::load, atomic_op::min,
                            atomic_op::fetch_add});
```

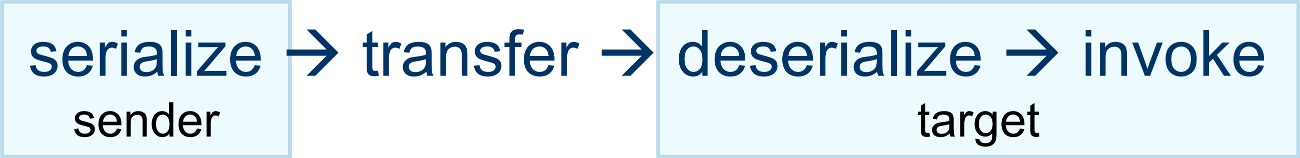
- Supports all {32,64}-bit signed/unsigned integers, `float`, `double`

Operations are performed on global pointers and are asynchronous

```
global_ptr <int64_t> ptr = new_<int64_t>(0);
future<int64_t> f = dom.fetch_add(ptr,2,memory_order_relaxed);
int64_t res = f.wait();
```

Serialization

RPC's transparently *serialize* shipped data

- Conversion between in-memory and byte-stream representations
- 

  serialize → transfer → deserialize → invoke

  sender

  target

Conversion makes byte copies for C-compatible types

- `char, int, double, struct{double;double;}, ...`

Serialization works with most STL container types

- `vector<int>, string, vector<list<pair<int,float>>>, ...`
- Hidden cost: containers deserialized at target (copied) before being passed to RPC function

Views

UPC++ *views* permit optimized handling of collections in RPCs, without making unnecessary copies

- `view<T>`: non-owning sequence of elements

When deserialized by an RPC, the `view` elements can be accessed directly from the internal network buffer, rather than constructing a container at the target

```
vector<float> mine = /* ... */;
rpc_ff(dest_rank, [](view<float> theirs) {
    for (float scalar : theirs)
      /* consume each */
  },
  make_view(mine)
);
```

Process elements directly from the network buffer

Cheap view construction

Shared memory hierarchy and `local_team`

Memory systems on supercomputers are hierarchical

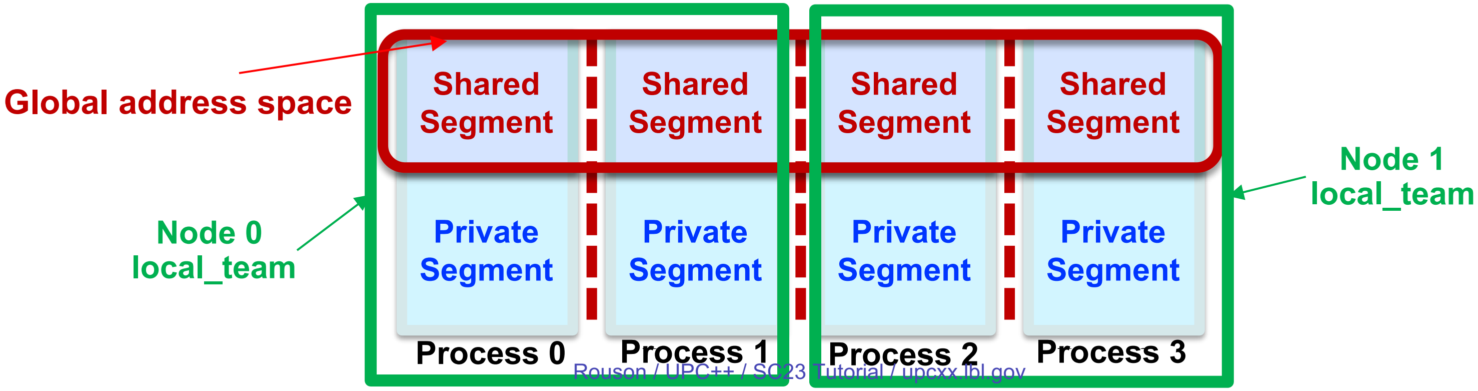
- Some process pairs are “closer” than others
- Ex: cabinet > switch > node > NUMA domain > socket > core

Traditional PGAS model is a “flat” two-level hierarchy

- “same process” vs “everything else”

UPC++ adds an intermediate hierarchy level

- `local_team()` – a team corresponding to a physical node
- These processes share a physical memory domain
    - **Shared** segments are CPU load/store accessible across the same `local_team`



Downcasting and shared-memory bypass

Earlier we covered downcasting global pointers

- Converting `global_ptr<T>` from this process to raw C++ `T*`
- Also works for `global_ptr<T>` from **any** process in `local_team()`

```
int l_id  = local_team().rank_me();

int l_cnt = local_team().rank_n();
```

Rank and count in my local node

```
global_ptr<int> gp_data;

if (l_id == 0) gp_data = new_array<int>(l_cnt);

gp_data = broadcast(gp_data, 0, local_team()).wait();
```

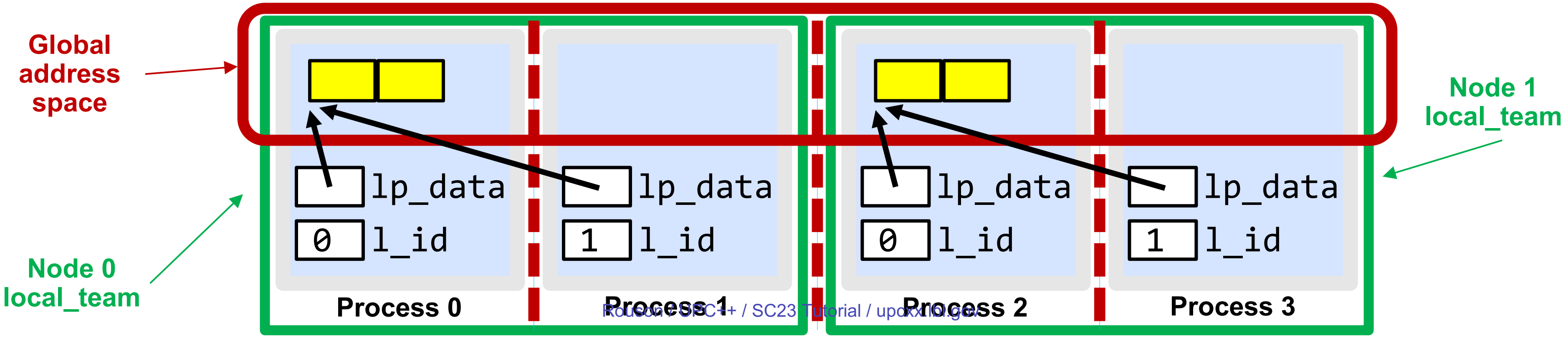
Allocate and share one array **per node**

```
int *lp_data = gp_data.local();
```

Downcast to get raw C++ ptr to shared array

```
lp_data[l_id] = l_id;
```

Direct store to shared array created by node leader



Optimizing for shared memory in many-core

`local_team()` allows optimizing co-located processes for physically shared memory in two major ways:

- Memory scalability
  - Need only one copy per **node** for replicated data
  - E.g. Cori KNL has 272 hardware threads/node
- Load/store bypass – avoid explicit communication overhead for RMA on local shared memory
  - Downcast `global_ptr` to raw C++ pointer
  - Avoid extra data copies and communication overheads

Completion: synchronizing communication

Earlier we synchronized communication using futures:

```
future<int> fut = rget(remote_gptr);
int result = fut.wait();
```

This is just the default form of synchronization

- Most communication ops take a defaulted completion argument
- More explicit: `rget(gptr, operation_cx::as_future());`
  - Requests future-based notification of operation completion

Other completion arguments may be passed to modify behavior

- Can trigger different actions upon completion, e.g.:
  - Signal a promise, inject an RPC, etc.
- Can even combine several completions for the same operation

Can also detect other “intermediate” completion steps

- For example, source completion of an RMA put or RPC

Completion: promises

A *promise* represents the producer side of an asynchronous operation

- A future is the consumer side of the operation

By default, communication operations create an implicit promise and return an associated future

Instead, we can create our own promise and register it with multiple communication operations

```
void do_gets(global_ptr<int> *gps, int *dst, int cnt) {
  promise<> p;
  for (int i = 0; i < cnt; ++i)
    rget(gps[i], dst+i, 1, operation_cx::as_promise(p));
  future<> fut = p.finalize();
  fut.wait();
}
```

Close registration and obtain an associated future

Register an operation on a promise

Completion: “signaling put”

One particularly interesting case of completion:

```
rput(src_lptr, dest_gptr, count,
     remote_cx::as_rpc([=]() {
       // callback runs at target rank after put data arrives
       compute(dest_gptr, count);
     });
```

- Performs an RMA put, informs the target upon arrival
  - RPC callback to inform the target and/or process the data
  - Implementation can transfer both the RMA and RPC with a single network-level operation in many cases
  - Couples data transfer w/sync like message-passing
  - BUT can deliver payload using RDMA *without* rendezvous (because initiator specified destination address)

Memory Kinds

Supercomputers are becoming increasingly heterogeneous in compute, memory, storage

UPC++ memory kinds enable sending data between different kinds of memory/storage media

API is meant to be flexible, but initially supports memory copies between remote or local CUDA GPU devices and remote or local host memory

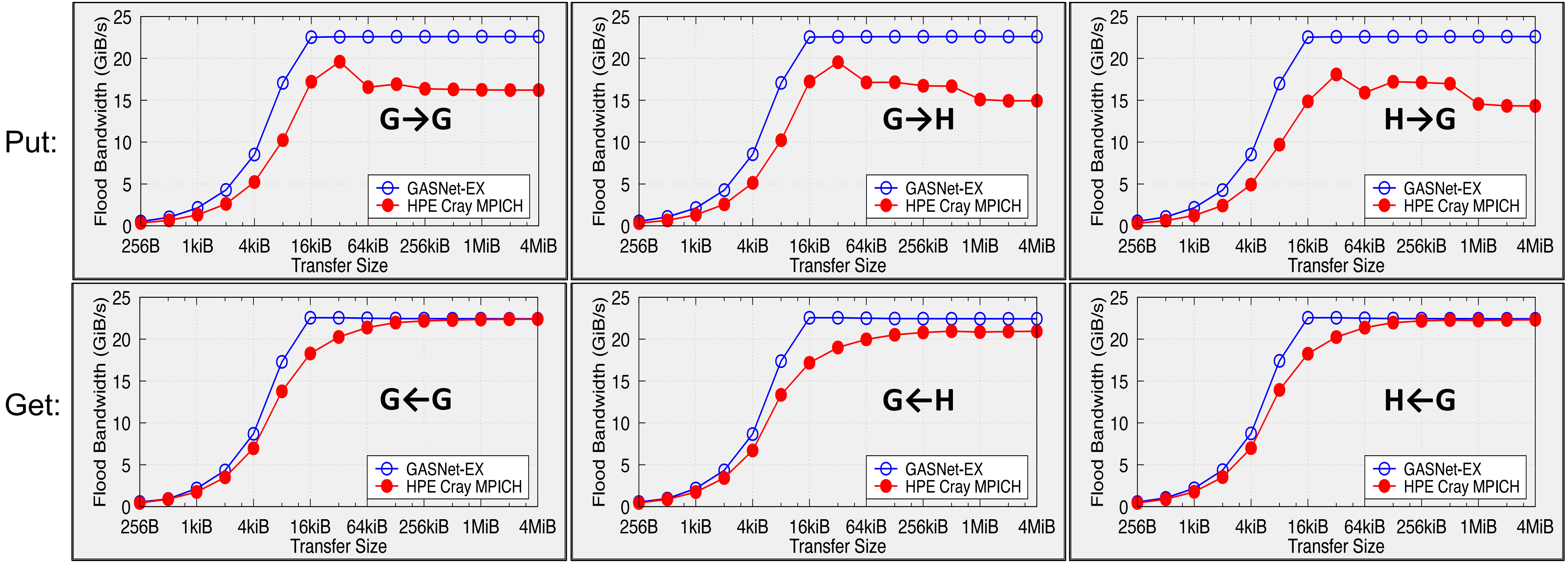
```
global_ptr<int, memory_kind::cuda_device> src = ...;
global_ptr<int, memory_kind::cuda_device> dst = ...;

copy(src, dst, N).wait();
```

Can point to memory on a local or remote GPU

GPU memory RMA on OLCF’s Frontier

Recent comparison of GASNet-EX and Cray MPICH performance on internode flood bandwidth benchmarks for six distinct combinations of (H)ost versus (G)PU memory and direction of transfer (Put or Get)



GASNet results were collecting using the `testlarge` benchmark that appears in the 2023.3.0 release.
MPI results are from `osu_put_bw` and `osu_get_bw` tests in a ROCM-enabled build of OSU Micro-Benchmarks 7.1-1.
All tests were run on OLCF Frontier in April 2023, between two nodes with one process per node, over its Slingshot-11 network.

Distributed objects in 2D heat diffusion

Distributed objects can be used to obtain global pointers to other processes' landing zones

```
global_ptr<double> down_in, up_in;
if (lo != 0) {
  down_in = new_array<double>(X);
  // ...
}
if (hi != Y) {
  up_in = new_array<double>(X);
  // ...
}
dist_object<global_ptr<double>> dist_up{down_in};
dist_object<global_ptr<double>> dist_down{up_in};
if (lo != 0) gptr_down = dist_down.fetch(down).wait();
if (hi != Y) gptr_up = dist_up.fetch(up).wait();
barrier();
```

Construct landing zones for each neighbor (if necessary)

Construct distributed objects containing pointers to each process's landing zones

Fetch landing-zone pointer from the neighbor below

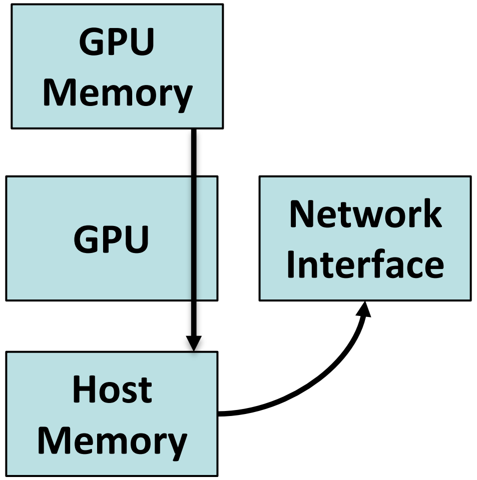
Ensure that all fetches have completed before the distributed objects are destroyed

Memory kinds: Accelerated RMA to/from GPU memory

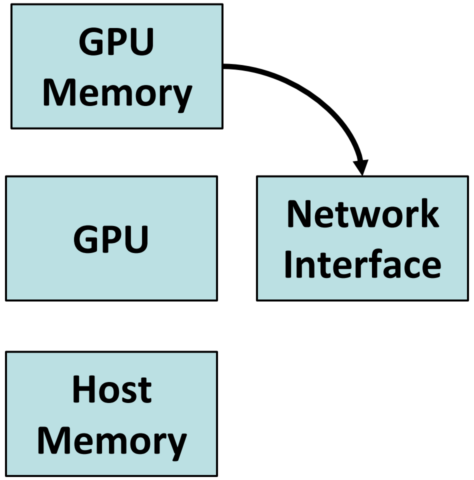
Modern GPUs and NICs can support peer-to-peer data transfers

Example: Put with source on GPU

- In the absence of necessary hardware and OS support:
  1. Data must be copied from GPU memory to host memory
  2. RDMA from host memory's copy
- With support:
  1. RDMA directly from GPU memory (no copies)



Data movement without acceleration



Data movement with acceleration

Memory kinds: Accelerated RMA to/from GPU memory

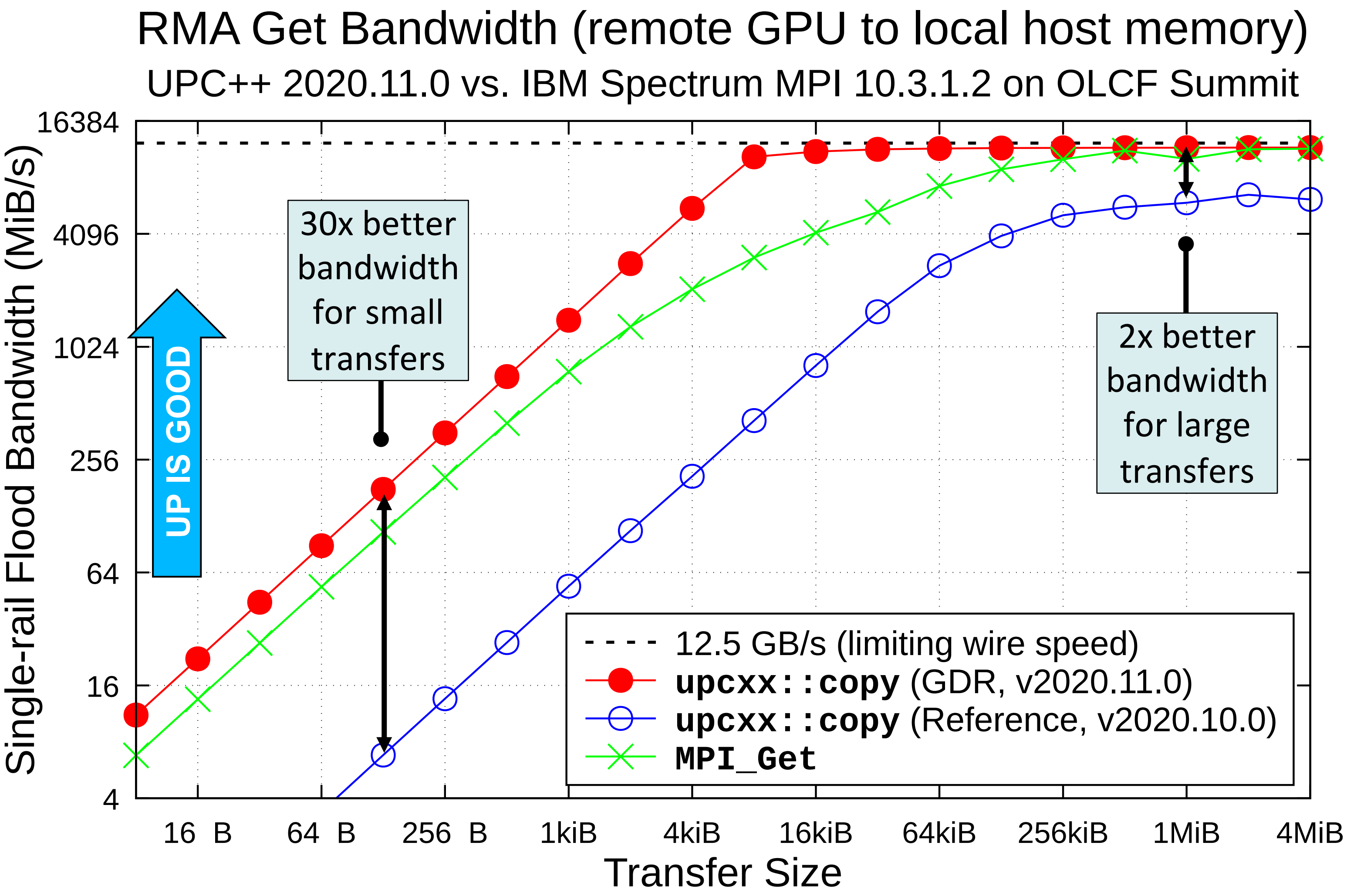
Measurements of flood bandwidth of `upcxx::copy()` on OLCF's Summit

Difference between two consecutive releases shows benefit of GASNet-EX's support for accelerated transfers via Nvidia's "GDR".

- No longer staging through host memory
- Large xfers: 2x better bandwidth
- Small xfers: up to 30x better bandwidth

Get operations to/from GPU memory now perform comparably to host memory

Comparisons to MPI RMA in GDR-enabled IBM MPI show UPC++ saturating more quickly to the peak



UPC++ results were collecting using the version of the **cuda_benchmark** test that appears in the 2020.11.0 release.
MPI results are from **osu_get_bw** test in a CUDA-enabled build of OSU Micro-Benchmarks 5.6.3.
All tests were run on OLCF Summit, between two nodes with one process per node, over its EDR InfiniBand network.

Non-contiguous RMA

We've seen contiguous RMA

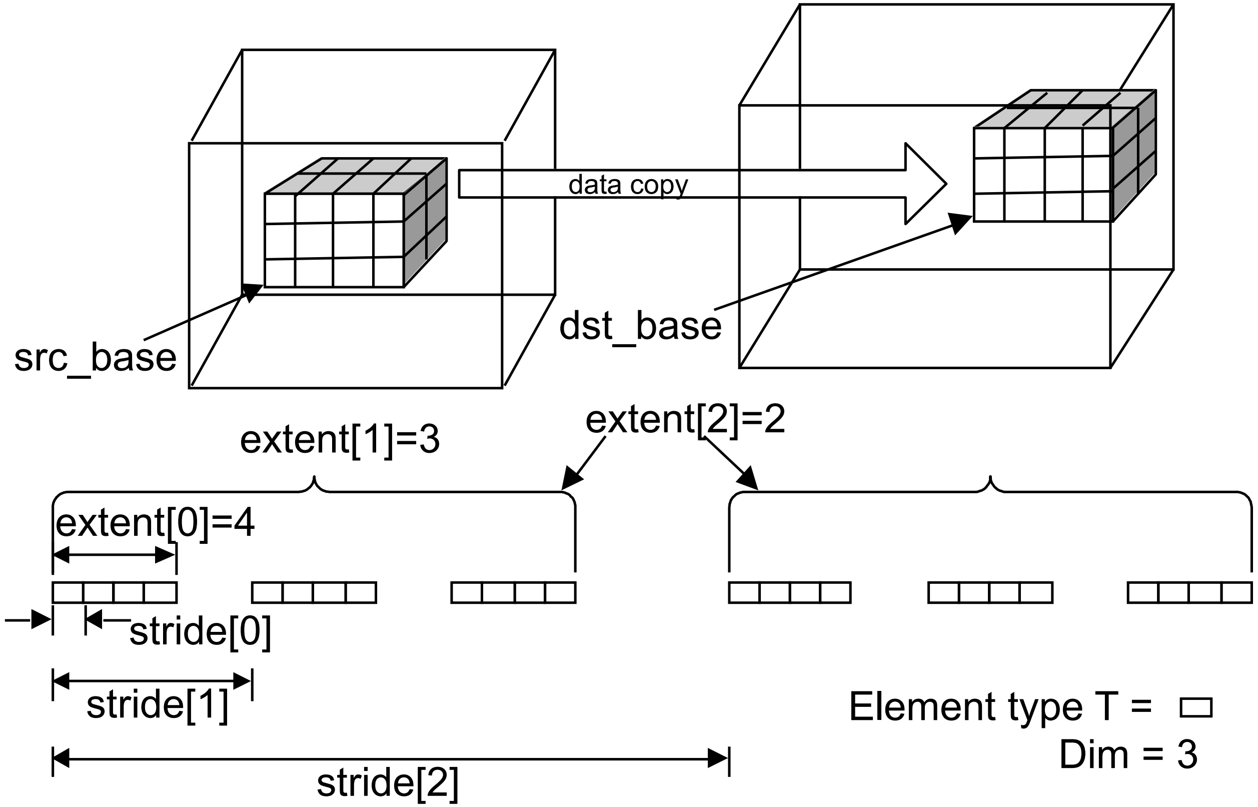
- Single-element
- Dense 1-d array

Some apps need sparse RMA access

- Could do this with loops and fine-grained access
- More efficient to pack data and aggregate communication
- We can automate and streamline the pack/unpack

Three different APIs to balance metadata size vs. generality

- Irregular: *iovec*-style iterators over pointer+length
- Regular: iterators over pointers with a fixed length
- Strided: N-d dense array copies + transposes



data copy
src_base
dst_base
extent[1]=3
extent[2]=2
extent[0]=4
stride[0]
stride[1]
stride[2]
Element type T = ▭
Dim = 3