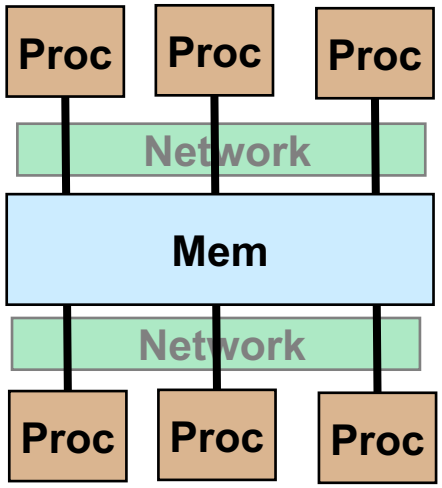
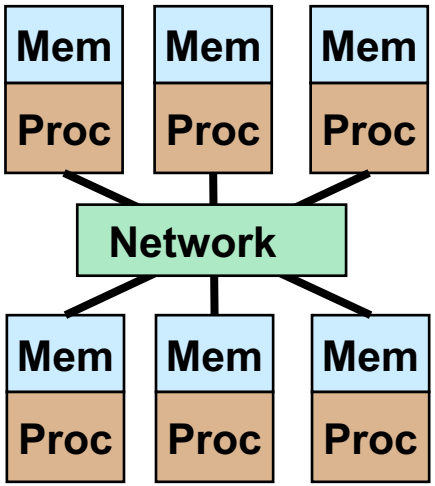
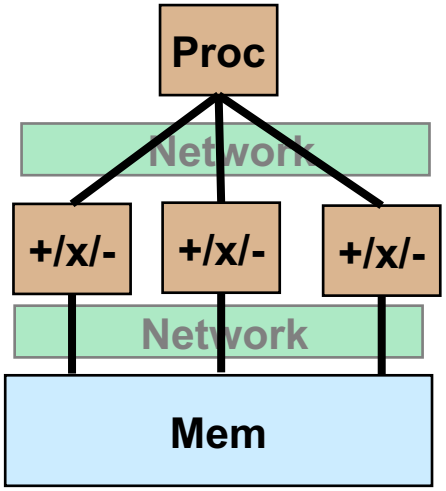
Partitioned Global Address Space Languages
CS267 Lecture 11

Kathy Yelick

Parallel Machines and Programming







Shared Memory	Distributed Memory	Single Instruction Multiple Data (SIMD)
OpenMP, Threads	**MPI (send/receive)**	**Data parallel (collectives)**
Processors execute own instruction stream	Processors execute own instruction stream	One instruction stream (all run same instruction)
Communicate by reading/writing memory	Communicate by sending messages	Communicate through memory
Ideal cost: Cost of a read/write is constant	Memory access time depends on size and whether local vs. remote	Assume unbounded # of arithmetic units

Advantages and disadvantages of each

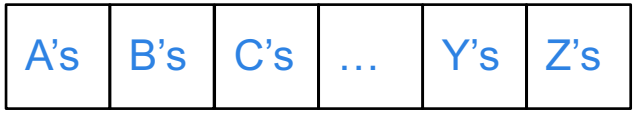
- Shared memory / OpenMP
  - + **Ease:** Easier to parallelize existing serial code
  - – **Correctness:** Race conditions
  - – **Scalability:** No locality control for multi-node scaling
  - – **Performance:** False sharing, lack of parallelism, etc.

- Message Passing / two-sided MPI
  - – **Ease:** More work up front to partition data
  - + **Correctness:** Harder to create races (deadlocks are more of a problem)
  - + **Scalability**: Effectively unlimited
  - + **Performance:** More transparent, but messages are expensive (need to pack/unpack)

Parallel Programming Problem: Histogram

- Consider the problem of computing a histogram:
  - Large number of "words" streaming in from somewhere
  - You want to count the # of words with a given property

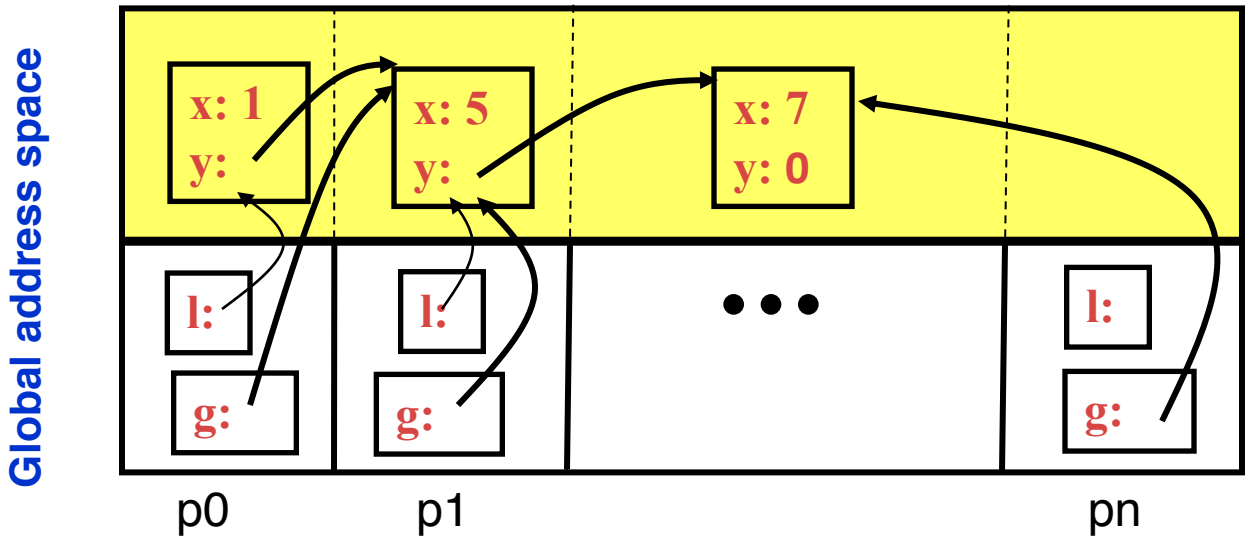
- Shared memory
  - Lock each bucket



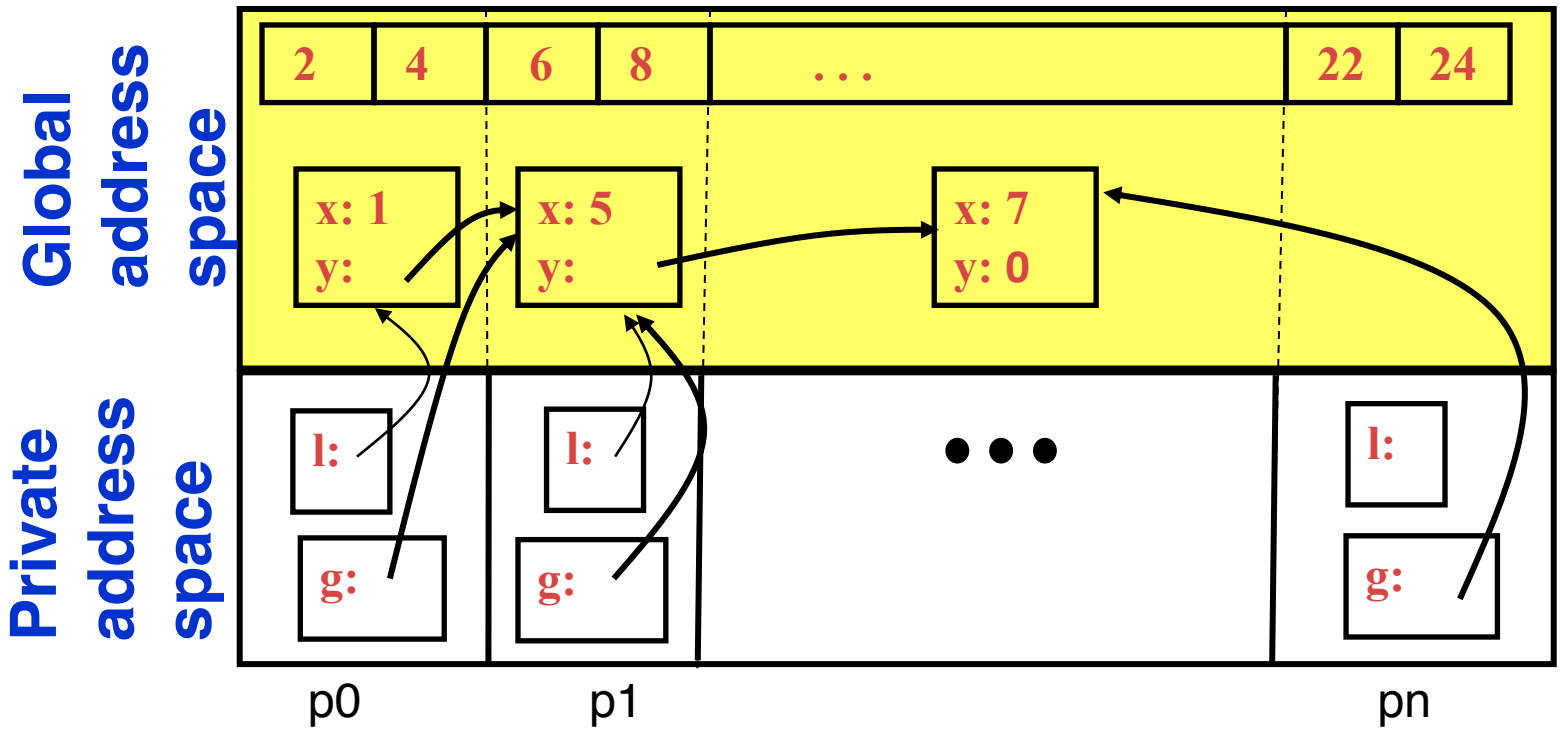
- Message passing: the array is huge and spread out
  - Each processor has a substream and sends +1 to the appropriate processor…
  - When does that processor "receive"?

PGAS = Partitioned Global Address Space

- ***Global address space:*** thread may directly read/write remote data
  - Convenience of shared memory
- ***Partitioned:*** data is designated as local or global
  - Locality and scalability of message passing

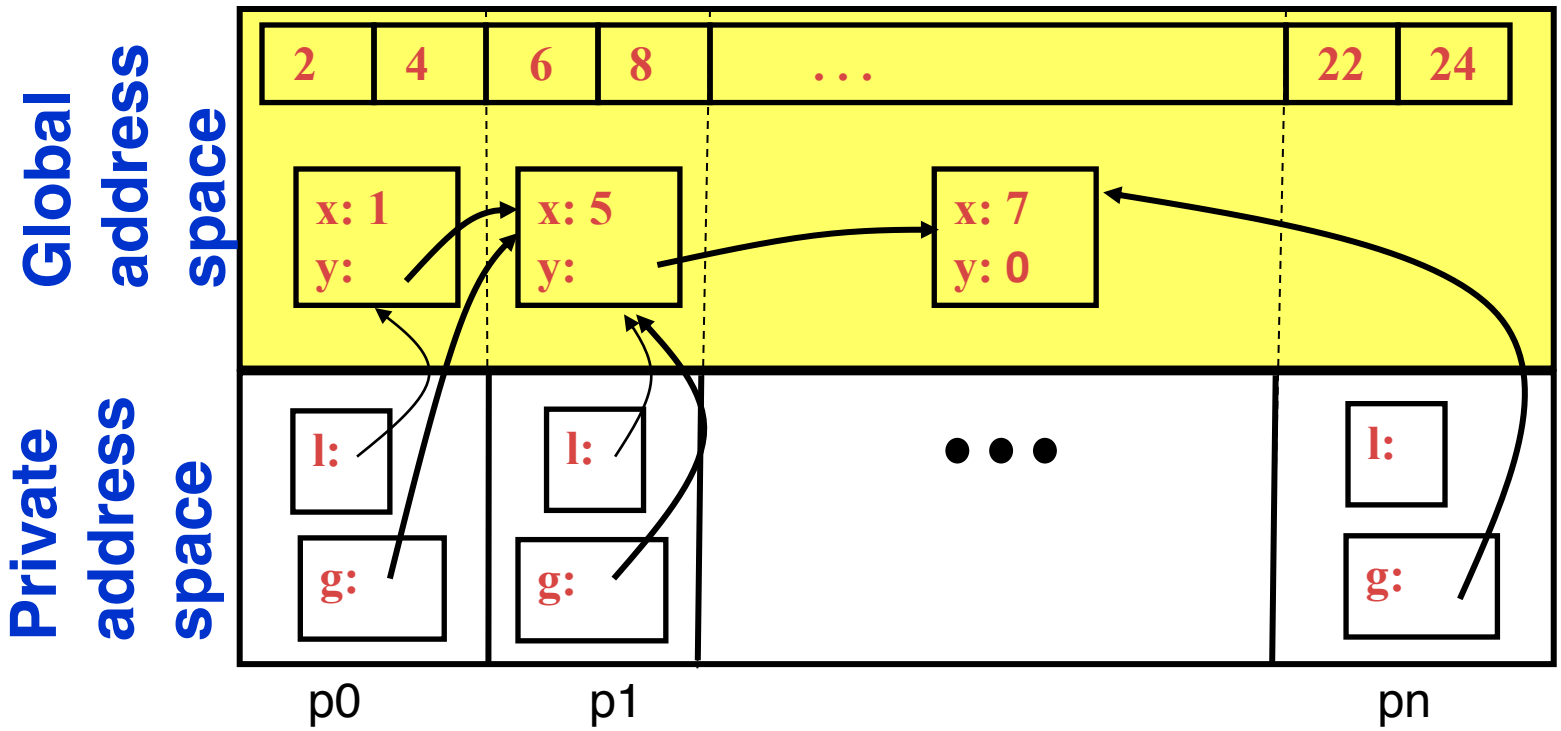


Partitioned Global Address Space (PGAS)



- Need a way to name remote memory (UPC syntax)
  - Global pointers: shared int * p = upc_malloc(4);
  - Distributed arrays: shared int a [12];

One-sided communication in PGAS



- Directly read/write remote memory; partitioned for locality
- One-sided communication underneath (UPC syntax):

  Put: a[i] = … ; *p = ...; upc_mem_put(..)

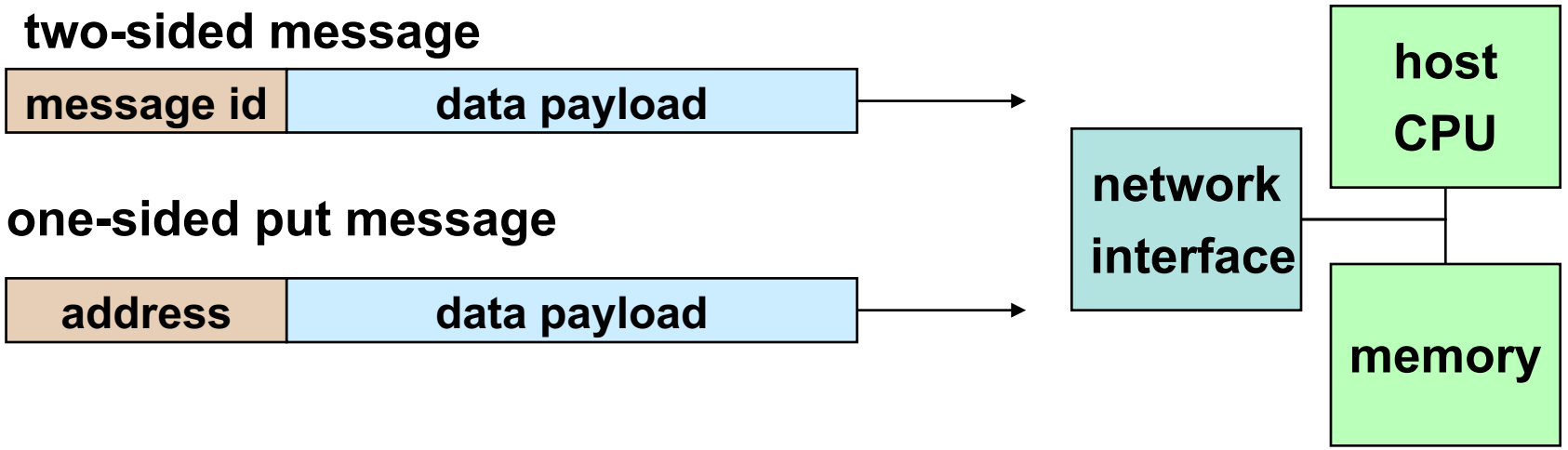
  Get: ... = a[i]...; ... = *p; upc_mem_get(...)

Goals of PGAS Programming

- Applications: convenient programming of irregular codes
  - Graphs
  - Hash tables
  - Sparse matrices
  - Adaptive (hierarchical) meshes

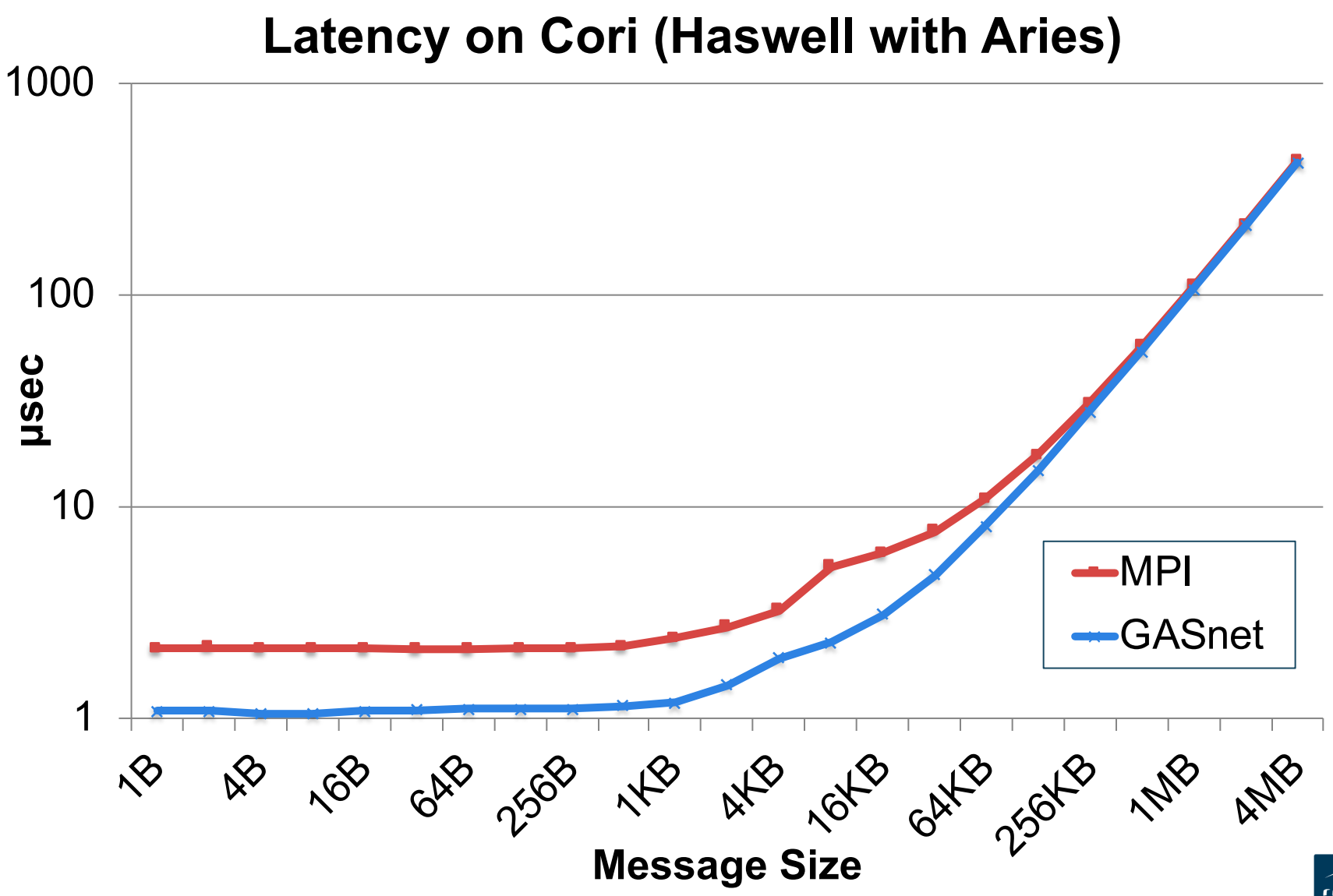
- Machines: expose best available performance on a given machine
  - Low latency for small messages
  - High bandwidth even for medium sized messages
  - High injection rate (number of messages / second)
  - Minimize software overhead and match hardware

One-Sided Communication in PGAS (e.g., GASnet inside)

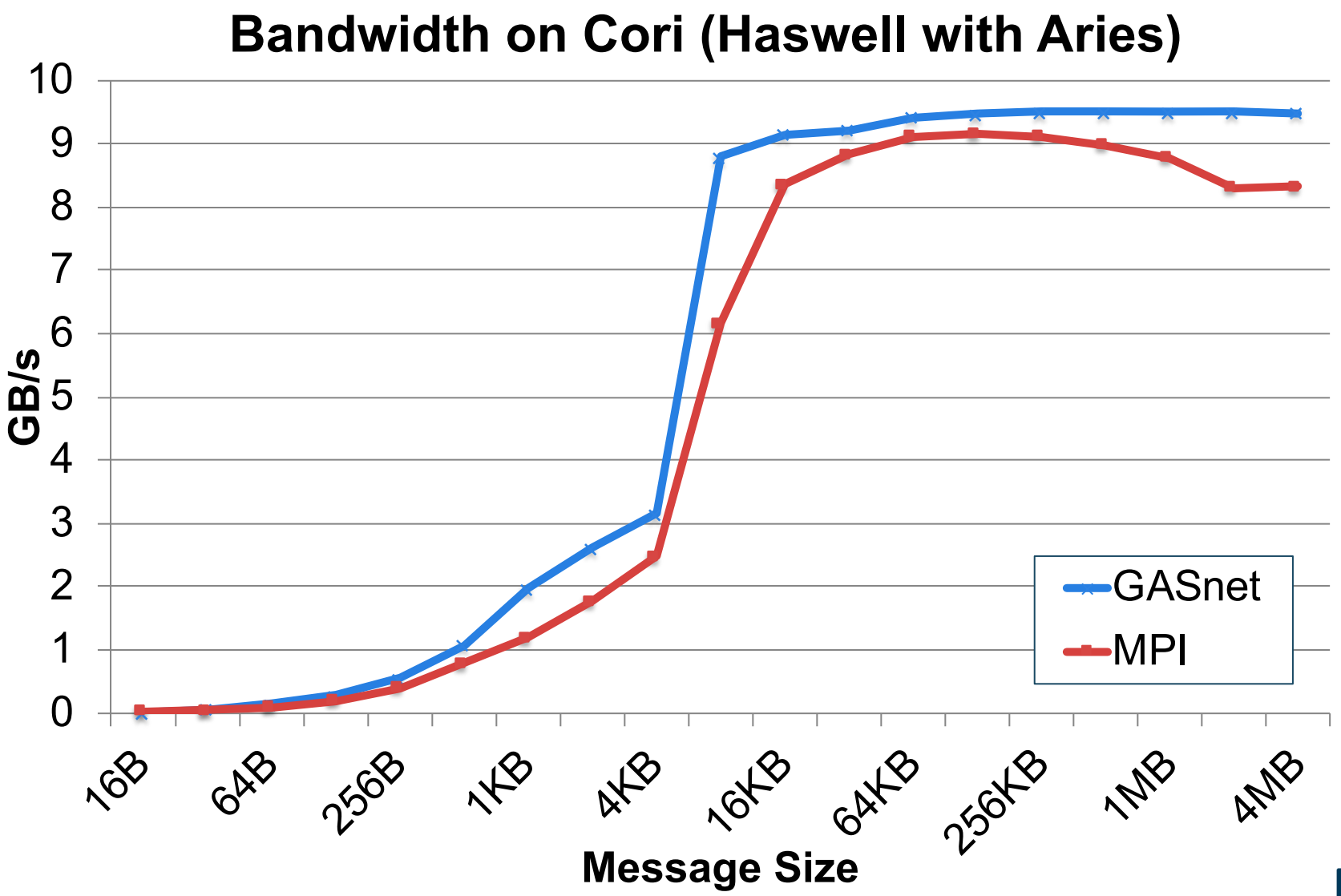


- A two-sided message needs to be matched with a receive
  - Ordering requirements can also hinder bandwidth
- A put/get can be handled by a network interface with RDMA
  - Decouples transfer from synchronization
  - Avoids interrupting the CPU or getting address from CPU
- Will still want to pack data and overlap
  - Pipeline messages, overlap with computation

Latency on a Cray Aries (NERSC Cori-P1)



Bandwidth on a Cray Aries (NERSC Cori-P1)



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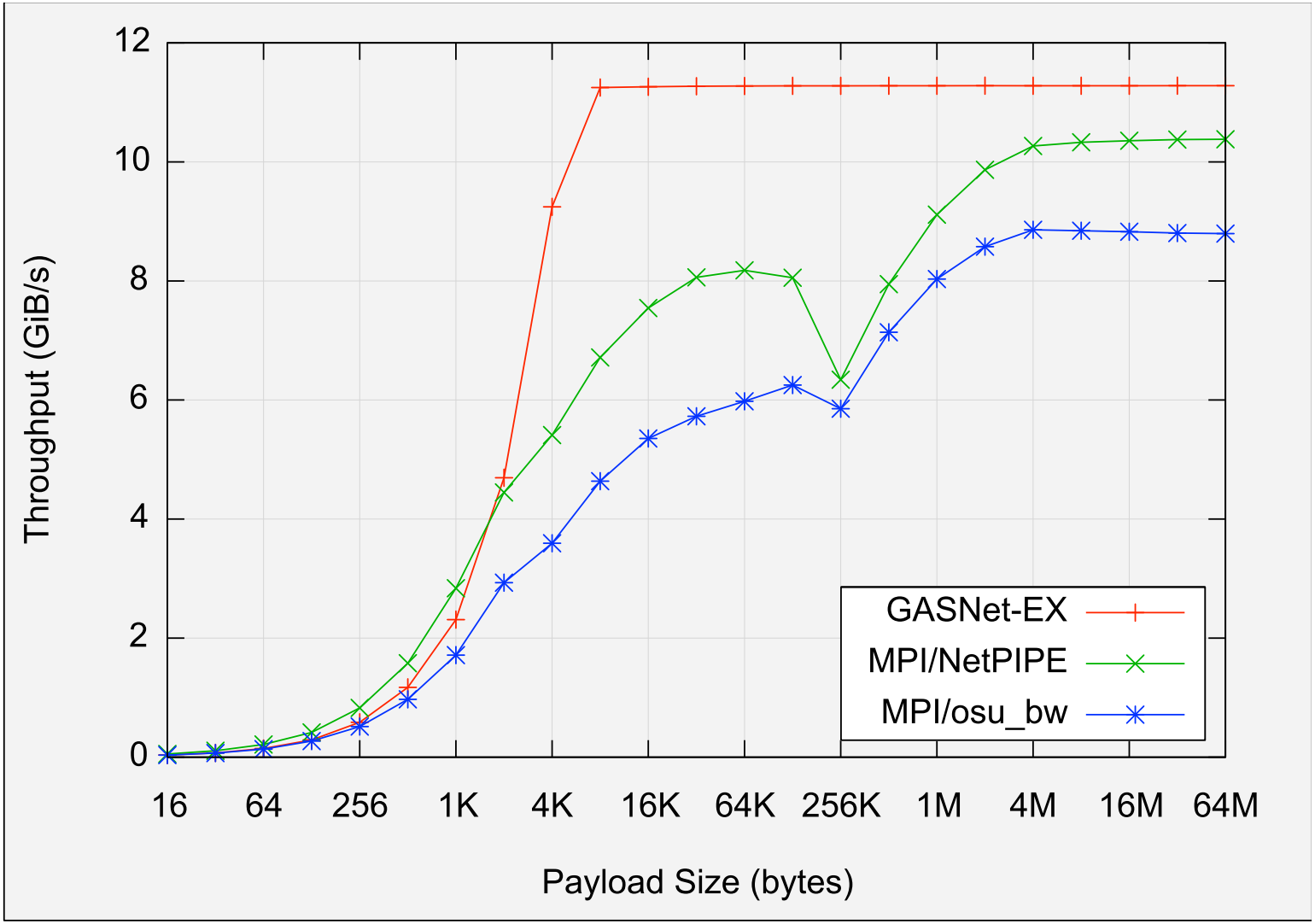
Bandwidth on Infiniband (Summit-Dev at ORNL)



Flood Bandwidth Graphs report tests of achievable one-way bandwidth for point-to-point data transfer between two nodes. All bandwidths have been converted for uniform reporting in units of Gibibytes/sec (GiB/sec), where GiB = 2^{30} bytes.

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Introduction to UPC++

Led by Scott B. Baden and Paul Hargrove (LBNL)
Slides and examples from Amir Kamil

See also the Programmer's Guide at:
https://bitbucket.org/upcxx/upcxx/downloads/upcxx-guide-2018.1.0.pdf

Hello World in UPC++

- UPC++ programs are just C++ programs
- They run as SPMD programs (similar to MPI)
- They use the GASNet library for communication

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

int main(int argc, char *argv[])
{
    upcxx::init(); // setup UPC++ runtime
    cout << "Hello from " << upcxx::rank_me() << endl;
    upcxx::finalize(); // close down UPC++ runtime
    return 0;
}
```

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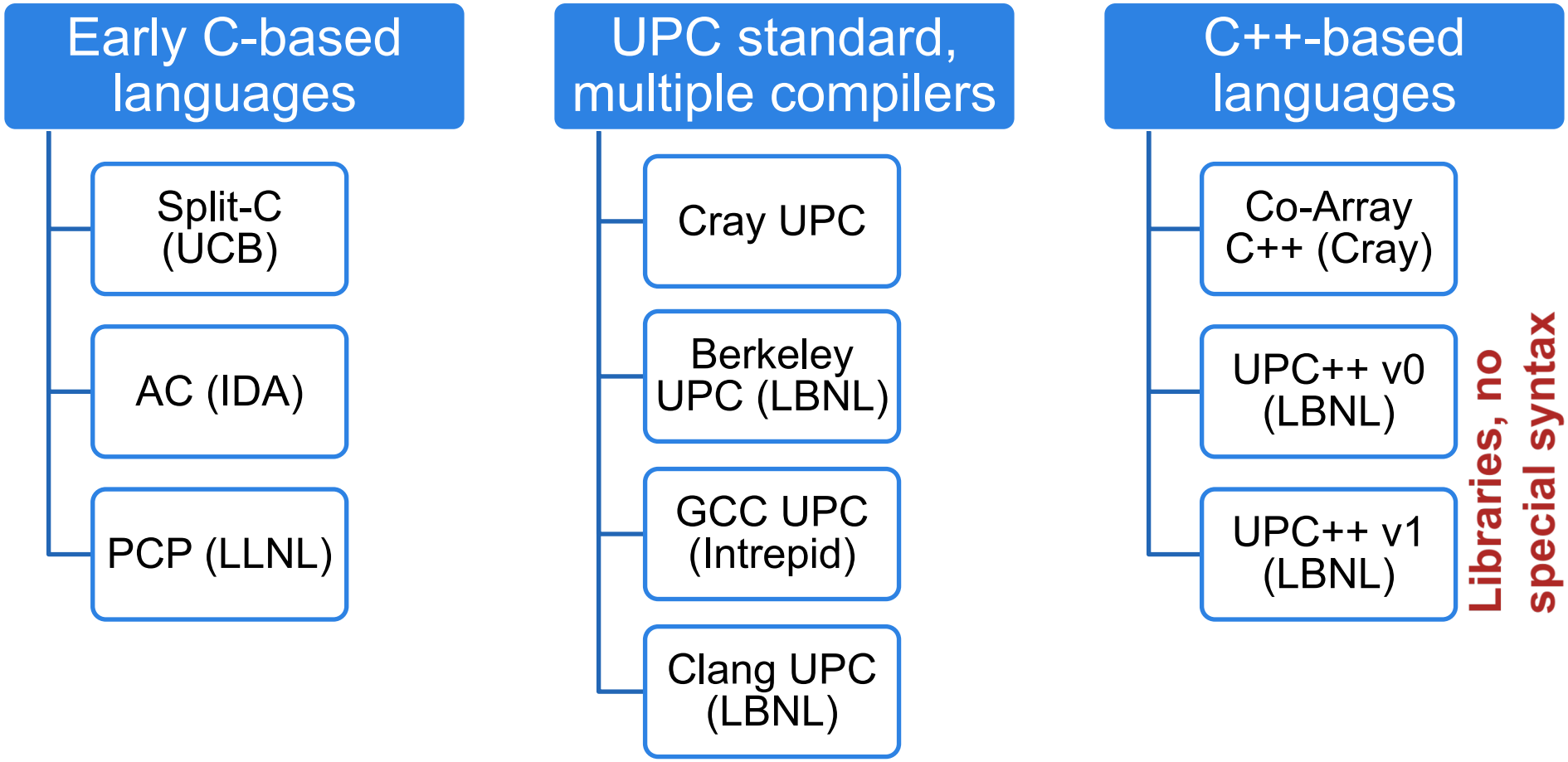
Roadmap of the C/C++ PGAS languages



There are also languages Co-Array Fortran (now in standard Fortran), Chapel, Titanium (Java), Legion and more

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UPC++ V1.0 Overview

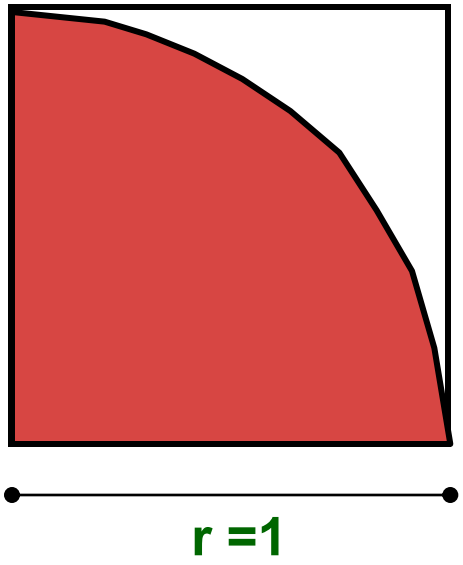
- A complete redesign of UPC++ that leverages GASNet-EX to deliver better performance and scalability
- A “compiler-free” approach for PGAS
  - Leverage C++ standards and compilers
  - Influence future directions of the C++ standard
- Interoperates with existing programming systems
  - 1-to-1 mapping between MPI rank and UPC++ rank
  - OpenMP and CUDA can be easily mixed with UPC++ in the same way as MPI+X
- Design philosophy:
  - All communication is explicit
  - Most operations are non-blocking
  - No non-scalable data structures

The API

- Foundational types
  - Global Pointers
  - Futures (and Promises)
  - Distributed Objects
- Communication
  - 1-sided Communication
    - rput/rget (bulk and single element), non-contiguous transfers, memory kinds
  - RPC (remote procedure call)
- Callbacks
- Remote Atomics
- Teams (mechanism for grouping ranks together)
- Progress and the Memory Model

Example: Monte Carlo Pi Calculation

- Estimate Pi by throwing darts at a unit square
- Calculate percentage that fall in the unit circle
  - Area of square = $r^2 = 1$
  - Area of circle quadrant = $\frac{1}{4} * \pi r^2 = \pi/4$
- Randomly throw darts at x,y positions
- If $x^2 + y^2 < 1$, then point is inside circle
- Compute ratio:
  - # points inside / # points total
  - π = 4*ratio



Pi in UPC++

- Independent estimates of pi:

```
int main(int argc, char **argv) {
  upcxx::init();
  int hits, trials = 0;
  double pi;

  if (argc != 2) trials = 1000000;
  else trials = atoi(argv[1]);

  generator.seed(upcxx::rank_me()*17);

  for (int i=0; i < trials; i++) hits += hit();
  pi = 4.0*hits/trials;
  cout << "PI estimated to " << pi << endl;
  upcxx::finalize();
}
```

Each rank gets its own copy of these variables

Each rank can use input arguments

Initialize random in math library

Each rank calls “hit” separately

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C++ Helper Code for Pi (in C++11)

- Required includes and variables:

```
#include <iostream>
#include <random>
#include <upcxx/upcxx.hpp>
default_random_engine generator;
uniform_real_distribution<> dist(0.0, 1.0);
```

- Function to throw dart and calculate where it hits:

```
int hit() {
  double x = dist(generator);
  double y = dist(generator);
  if (x*x + y*y <= 1.0) {
      return 1;
  } else {
      return 0;
  }
}
```

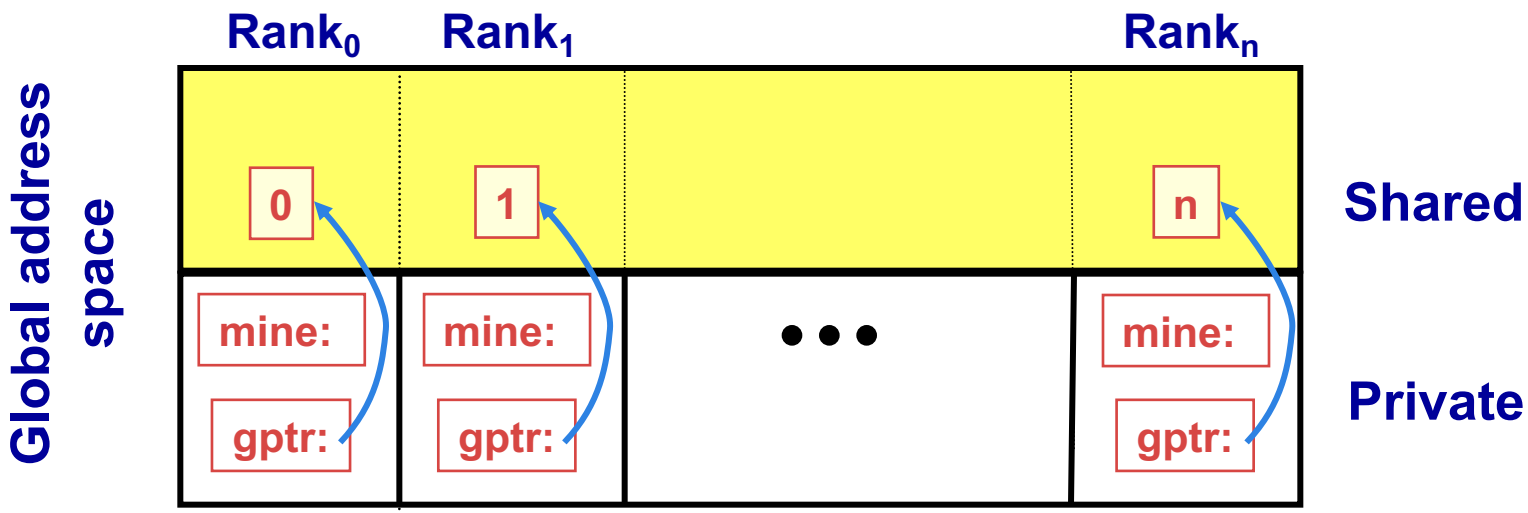
UPC++ allows full use of the C++ Standard Template Library

Private vs. Shared Memory in UPC++

- Normal C++ variables and objects are allocated in the private memory space for each thread
- Allocate in shared space with **new_**
- Free with **delete_**
- There are also array versions

upcxx:: qualifier elided from here on out
UPC++ names in green

```
int mine;
global_ptr<int> gptr = new_<int>(rank_me());
```



Broadcast in UPC++

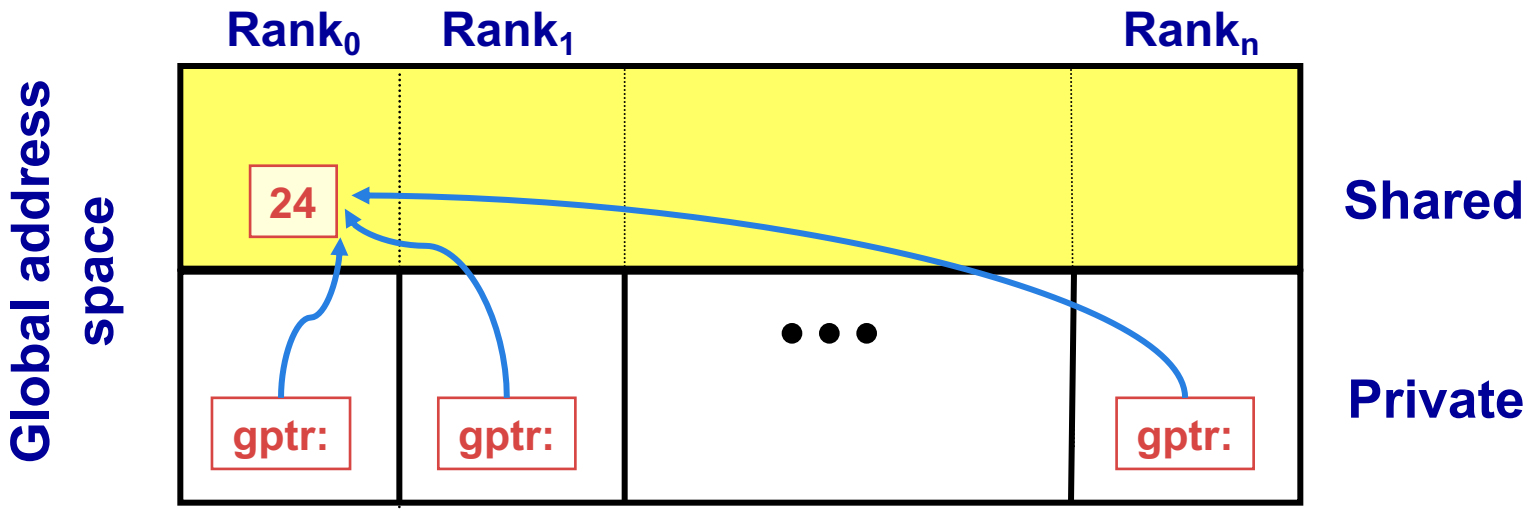
- To write an interesting program, we need to have global pointers refer to remote data
- One approach is to broadcast the pointer

```
global_ptr<int> gptr =
     broadcast(new_<int>(24),0).wait();
```

New int variable in shared space, set to 24

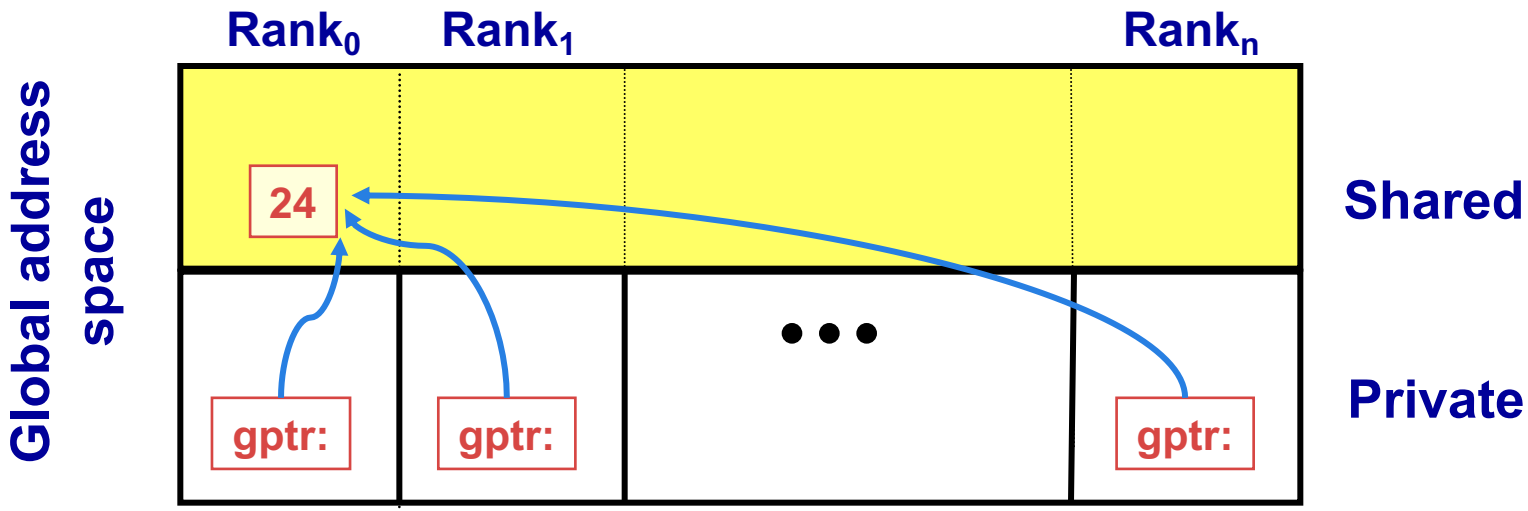
broadcast from rank 0

Will explain wait…



Remote access: Put / Get

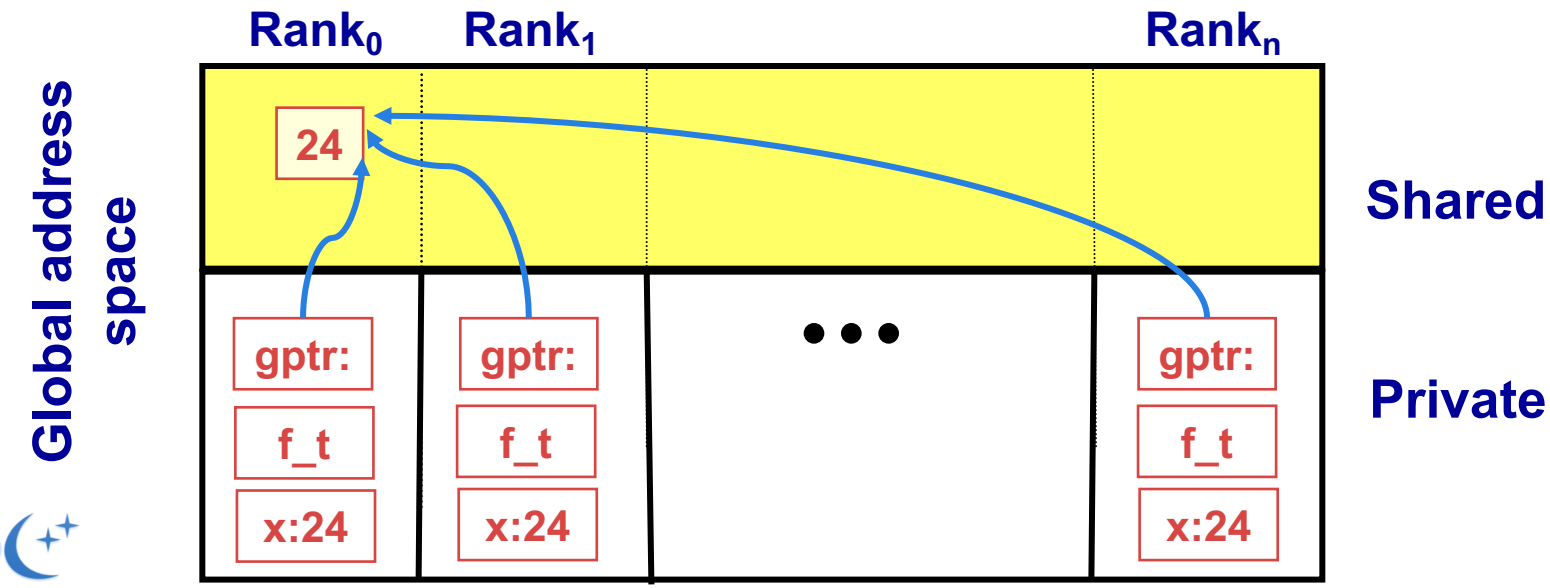
- We access shared memory from a remote rank
  - Remote get – read a variable on a remote rank
  - Remote put – write a variable on a remote rank
- Both done via a global pointer to the remote variable
- But will take microseconds at best!
  - And for most of that time, the processor is just waiting...



Asynchronous remote operations

- Asynchronous execution used to hide remote latency
  - Asynchronous get: start reading, but how to tell if you're done?
  - Put the results into a special "box" called a future

```
future<int> fut_temp = rget(gptr);
// ... Do something expensive
int x = fut_temp.wait();
// all ranks have x = 24
```



Futures in general

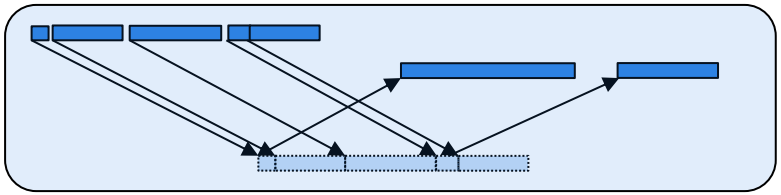
- A *future* holds a sequence of values and a state (ready / not ready)
- Waiting on the returned future lets user tailor degree of asynchrony they desire

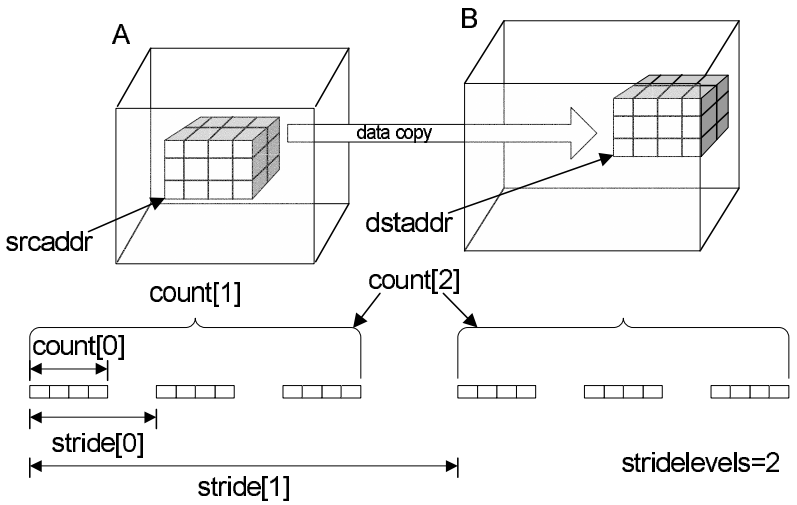
```
future<T> f1 = rget(gptr1);     // asynchronous op
future<T> f2 = rget(gptr2);
// unrelated work...
bool ready = f1.ready();       // non-blocking poll
T t = f1.wait();              // waits if not ready
```

- UPC++ has no *implicit* blocking
  - Except for synchronizing operations like "wait" others are implicitly nonblocking (asynchronous)

One-Sided Communication in General

- In addition to these basic remote put/get operations
  - There is also a version that runs a handler at the destination *after* rput operation is visible at the target
  - And support for non-contiguous transfers





UPC++ Synchronization

- UPC++ has two basic forms of barriers:
  - Barrier: block until all other threads arrive

```
barrier();
```

  - Asynchronous barriers

```
future<> f =
   barrier_async(); // this thread is ready for barrier
// do computation unrelated to barrier
wait(f);      // wait for others to be ready
```

- We will underline all blocking operations in these examples

Pi in UPC++: Shared Memory Style

- Parallel computing of pi, but with a bug

```
int main(int argc, char **argv) {
  init();
  int trials = atoi(argv[1]);
  int my_trials = (trials+rank_me())/rank_n();
  global_ptr<int> hits =
    broadcast(new_<int>(0), 0)).wait();
  generator.seed(rank_me()*17);
  for (int i=0; i < my_trials; i++) {
    int old_hits = rget(hits).wait();
    rput(old_hits+hit(), hits).wait();
  }
  barrier();
  if (rank_me() == 0)
    cout << "PI estimated to "
         << 4.0*(*hits.local())/trials;
  finalize();
}
```

divide work up evenly

broadcast pointer to shared memory from rank 0

accumulate hits

block on communication

Local (C++) pointer to global pointer that points locally

What is the problem with this program?

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Atomics in UPC++

- Atomics are indivisible read-modify-write operations
- As if you put a lock around each operation, but may have hardware support (e.g., within the network interface)

Create "atomic domain" for shared ints that works with fetch-and-add and load operations.

```
atomic_domain<int> ad_int({atomic_op::load,
                           atomic_op::fetch_add});
```

Locally "throw darts"

```
int my_hits = 0;
for (int i=0; i < my_trials; i++) my_hits += hit();
```

Atomically update shared hits variable

```
ad_int.fetch_add(hits, my_hits,
                 memory_order_relaxed).wait();
```

C++ memory order: relaxed says other memory accessed not constrained

```
barrier();
if (rank_me() == 0)
  cout << "PI estimated to " << 4.0*ad_int.load(
                 hits, memory_order_relaxed).wait()
                 /trials;
```

Once a variable is used with atomics, always use atomics

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Remote Procedure Call

```
future<R> rpc(intrank_t r,
              F func, Args&&... args);
```

- Executes `func(args...)` on rank `r` and returns the result
- R is the return type of `func`
  - Empty future if func returns void
- There is also a 'fire and forget' version that returns no result
- Some restrictions apply to what UPC++ operations can be issued in an RPC: the *restricted context*
  - Limits on blocking operations from within an RPC

Pi in UPC++: RPC

- RPC used to synchronize updates

```
int hits = 0;
int main(int argc, char **argv) {
  init();
  int trials = atoi(argv[1]);
  int my_trials = (trials+rank_me())/rank_n();
  generator.seed(rank_me()*17);
  for (int i=0; i < my_trials; i++) {
    rpc(0, [](int hit) { hits += hit; },
            hit()).wait();
  }
  barrier();
  if (rank_me() == 0)
    cout << "PI estimated to " << 4.0*hits/trials;
  finalize();
}
```

RPC can refer to global variable

send update to rank 0
block on the update

Similar to atomics, but always runs on the remote processor (not in network) and can be arbitrary function (not just simple operation)

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UPC++ Collectives

- UPC++ has a small set of collectives (so far)
- They are all asynchronous
  - Broadcast (value, sender): get a value from one rank

```
template <typename T> future <T>
  broadcast (T && value , intrank_t root);
```

  - Broadcast (buffer, count, sender): get a buffer of values from one rank

```
template <typename T> future <T>
  broadcast (T * buffer, std::size_t count,
             intrank_t sender);
```

  - Reduce (value, op): combine values across ranks

```
template <typename T, typename BinaryOp>
future <T> reduce_all (T && value, BinaryOp &&op);
```

- All of these take an optional “team” of ranks and have more general completion semantics (details in UPC++ guide)

Pi in UPC++: Data Parallel Style w/ Collectives

- The previous version of Pi works, but is not scalable:
  - Updates are serialized on rank 0, ranks block on updates
- Use a reduction for better scalability:

```
// int hits;
int main(int argc, char **argv) {
  ...
  for (int i=0; i < my_trials; i++)
     my_hits += hit();
  int hits = reduce_all(my_hits,
                        op_fast_add).wait();
  // barrier();
  if (rank_me() == 0)
    cout << "PI: " << 4.0*hits/trials;
  finalize();
}
```

no global variables or shared memory

barrier implied by reduce +wait

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Distributed Objects

- Any C++ type can be made into a *distributed object*
- One instance on every rank of a team

Mesh is a 3D array

```
dist_object<int> counter(0); // over world team
```

  - Collectively allocate a set of shared counters
- Can access remote instances

```
future<int> f = fetch(counter, someRank);
int x = f.wait();
```

Pi in UPC++: Distributed Object Version

- Alternative fix to the race condition
- Have each rank update a separate counter:
  - Do it in a distributed object, have one rank compute sum

```
int main(int argc, char **argv) {
  … declarations and initialization code omitted
  dist_object<int> all_hits(0);
  for (int i=0; i < my_trials; i++)
    *all_hits += hit();
  barrier();
  if (rank_me() == 0) {
    for (int i=0; i < rank_n(); i++)
      hits += fetch(all_hits, i).wait();
    cout << "PI estimated to " << 4.0*hits/trials;
  }
  finalize();
}
```

all_hits distributed across all ranks

update element with local affinity

collect each rank's contribution

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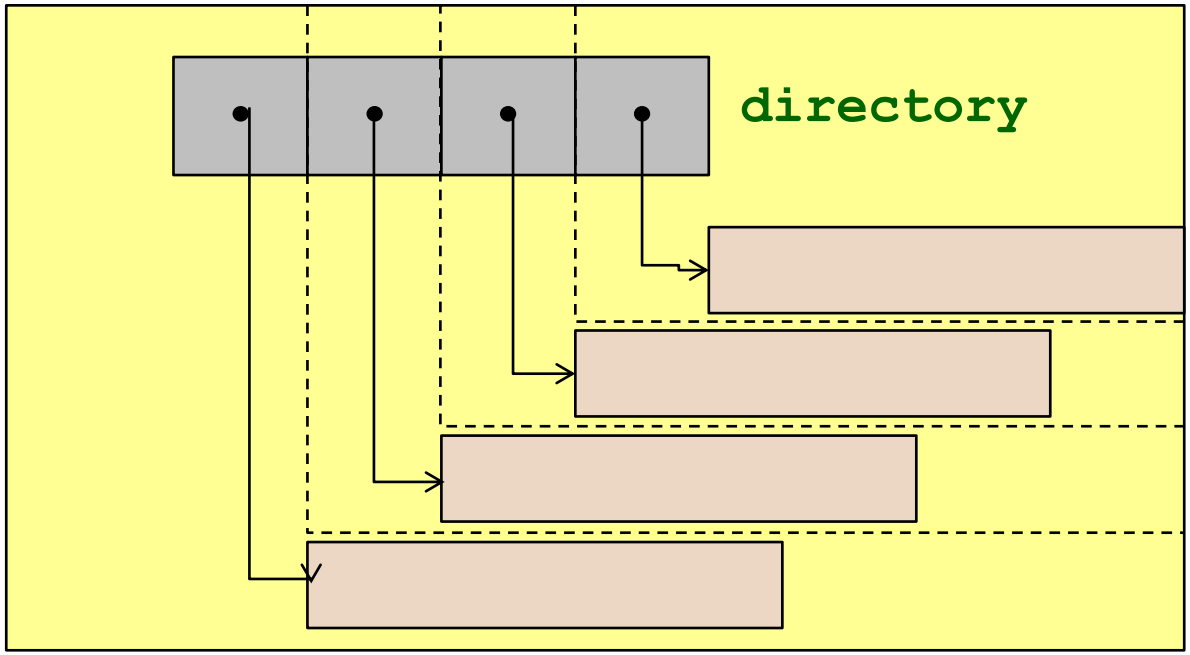
Distributed Arrays Directory Style

- A distributed object can be much more complicated than a set of ints
- Many UPC++ programs use these kinds of “directories” for distributed data structures



Distributed Objects in Stencil Code

- Communication in 1D stencil (nearest-neighbor computation):

```
int main(int argc, char **argv) {
  … declarations and initialization code omitted
  global_ptr<double> my_grid =
    new_array<int>(interior+2);
  dist_object<global_ptr<double>> grids(my_grid);
  global_ptr<double> left =
    fetch(grids, (rank_me()+rank_n()-1)%rank_n()).wait();
  global_ptr<double> right =
    fetch(grids, (rank_me()+1)%rank_n()).wait();
  for (int i=0; i < timesteps; i++) {
    future<double> f1 = rget(left+interior);
    future<double> f2 = rget(right+1);
    … wait on futures and do computation
  }
  …
}
```

construct local grids and distributed object

get pointers to neighbors' grids

get ghost cells

Summary

- UPC++ is a PGAS library that supports lightweight communication over GASNet-EX
- Close to the metal performance, lean interface
  - Trade offs to reduce overheads and increase flexibility
    - Asynchronous and explicit communication
    - Reduced consistency guarantees
- Advanced features not covered in talk:
  - Promises, callbacks, remote atomics, progress, memory model, teams
- V1.0 release targeted for September 30, 2017
  - Will include programmer's guide

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Acknowledgements

- Early work with UPC++ involved Yili Zheng, Amir Kamil, Kathy Yelick, and others [IPDPS ‘14]
- Pagoda Project (GASNet-EX and UPC++): Scott B. Baden (PI), Paul Hargrove (co-PI), John Bachan, Dan Bonachea, Steven Hofmeyer, Khaled Ibrahim, Mathias Jacquelin, Amir Kamil, Brian van Straalen
- This research was supported by the Exascale Computing Project (17-SC-20-SC), funded by the U.S. Department of Energy

- UPC++ V1.0 draft specification available at
  https://bitbucket.org/upcxx/upcxx

PGAS Applications

UPC and old UPC++

Others (not shown) in Co-Array Fortran (Ocean model),Titanium (heart model) and Chapel

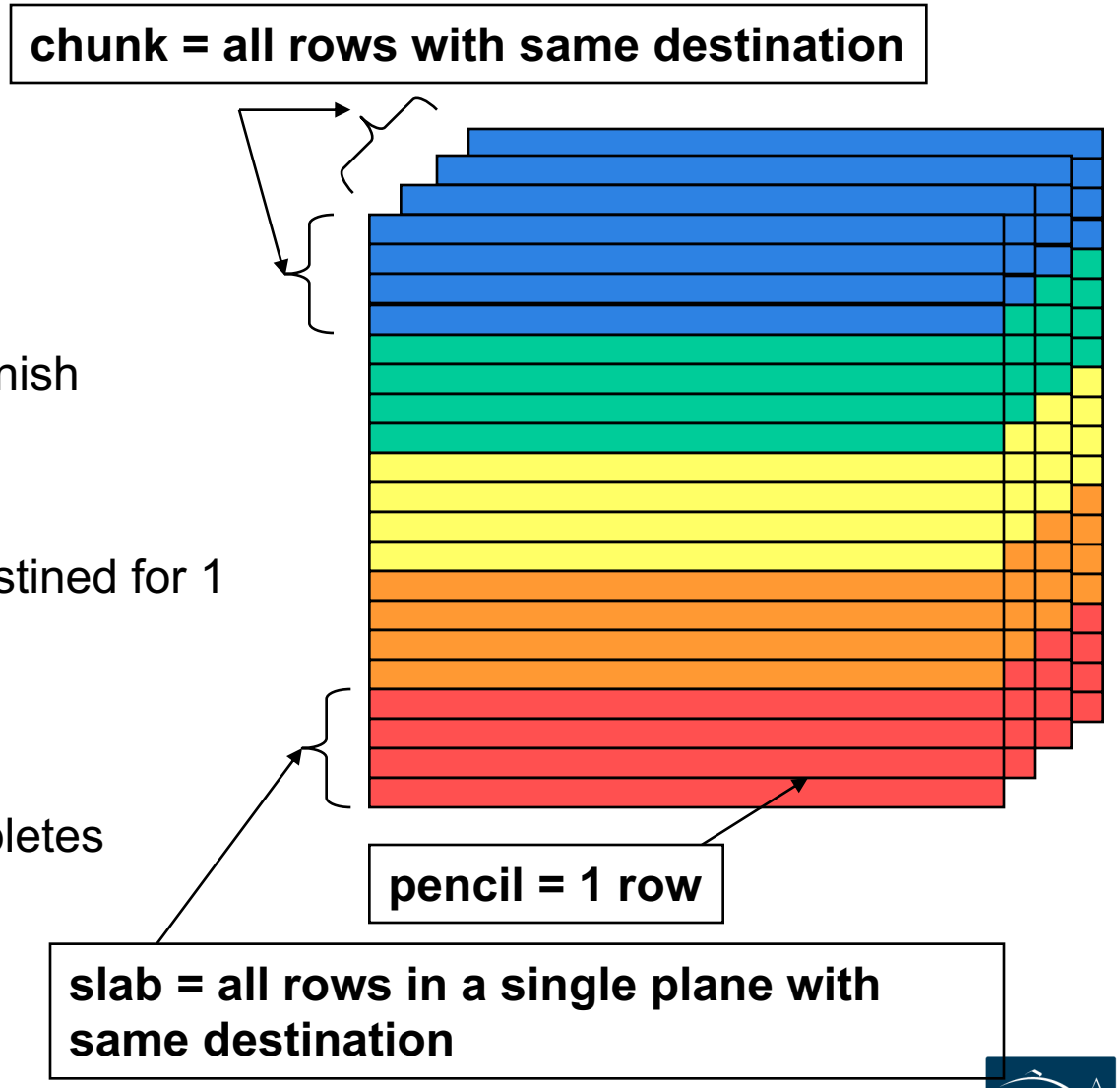
Some of these started as CS267 projects

- Project ideas for this year:
- Contribute to the Berkeley Container Library
  - Data structure library (hash tables, bloom filters, matrices,… -- talk to Ben Brock)
- Compare UPC++ to something else
  - MPI, Ray, …
- Write a more substantial algorithm in UPC++

Application Challenge: Fast All-to-All

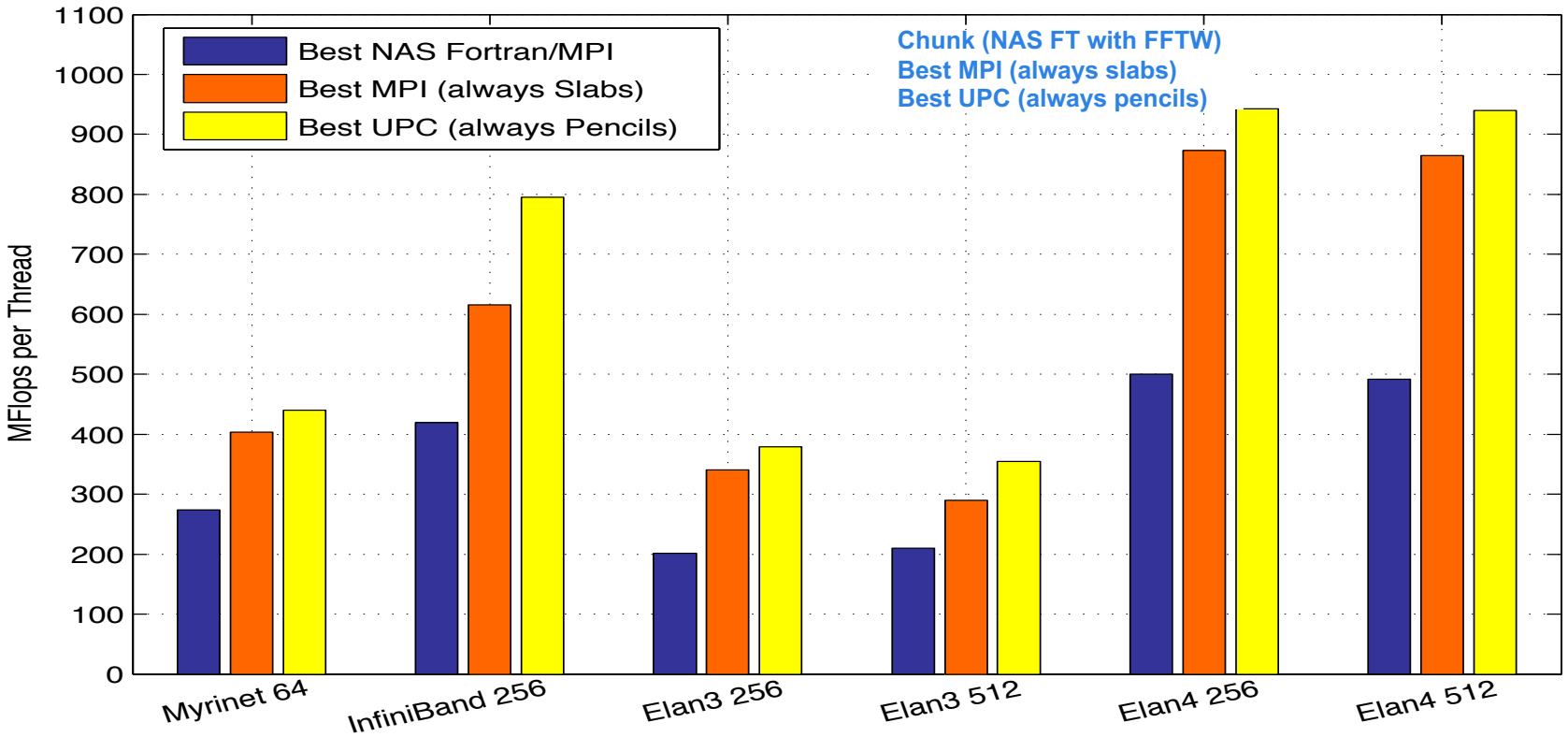
Transpose in 3D FFT

- Three approaches:
  - **Chunk:**
    - Wait for 2nd dim FFTs to finish
    - Minimize # messages
  - **Slab:**
    - Wait for chunk of rows destined for 1 proc to finish
    - Overlap with computation
  - **Pencil:**
    - Send each row as it completes
    - Maximize overlap and
    - Match natural layout



Joint work with Chris Bell, Rajesh Nishtala, Dan Bonachea

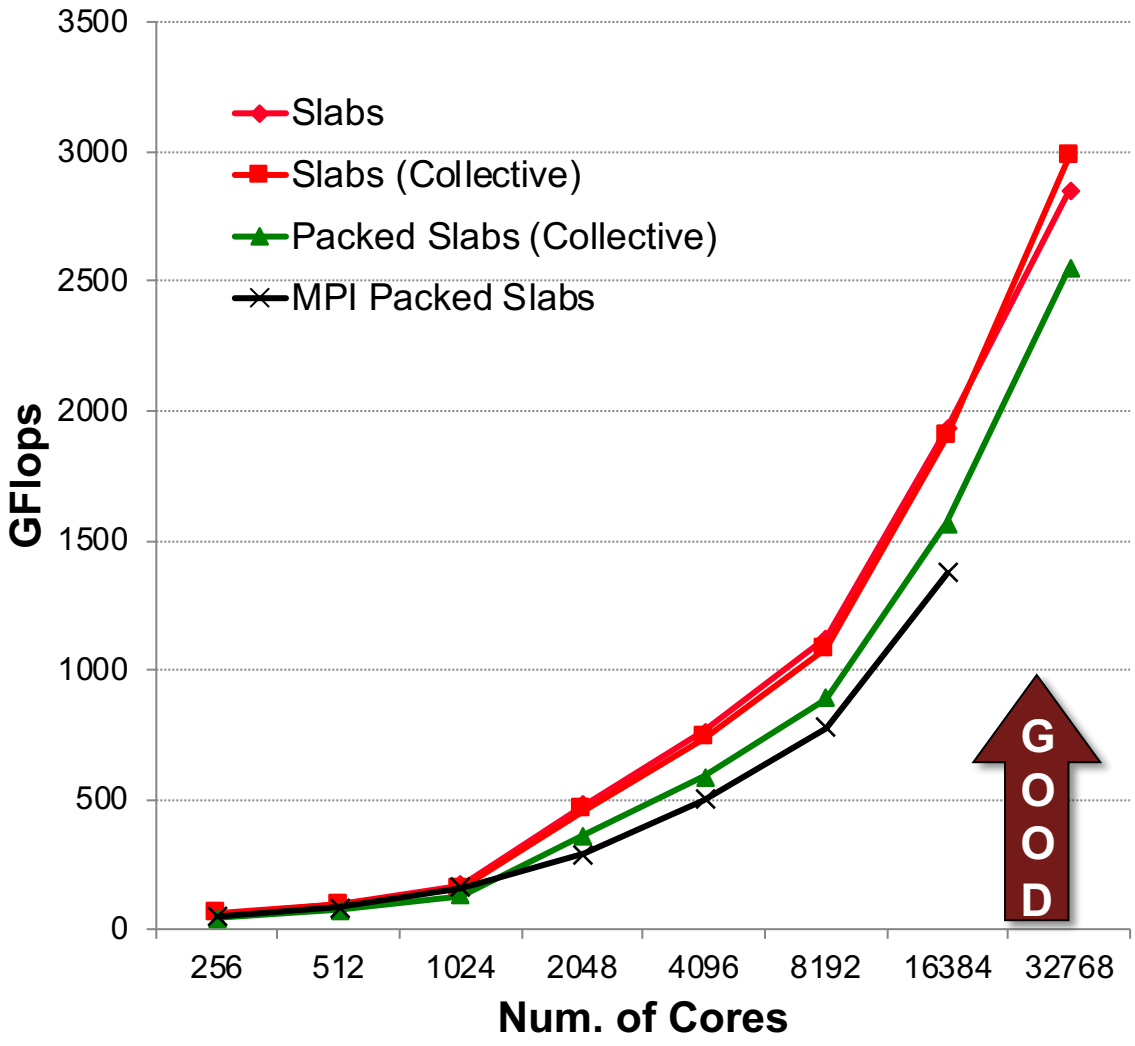
Bisection Bandwidth



- Avoid congestion at node interface: allow all cores to communicate
- Avoid congestion inside global network: spread communication over longer time period (send early and often)

FFT Performance on BlueGene/P (Mira)

- **UPC implementation outperforms MPI**
- **Both use highly optimized FFT library on each node**
- **UPC version avoids send/receive synchronization**
  - Lower overhead
  - Better overlap
  - Better bisection bandwidth



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De novo Genome Assembly

- **DNA sequence consists of 4 bases**: A/C/G/T
- **Read**: short fragment of DNA
- **De novo assembly: Construct a** genome (chromosomes) from a collection of reads

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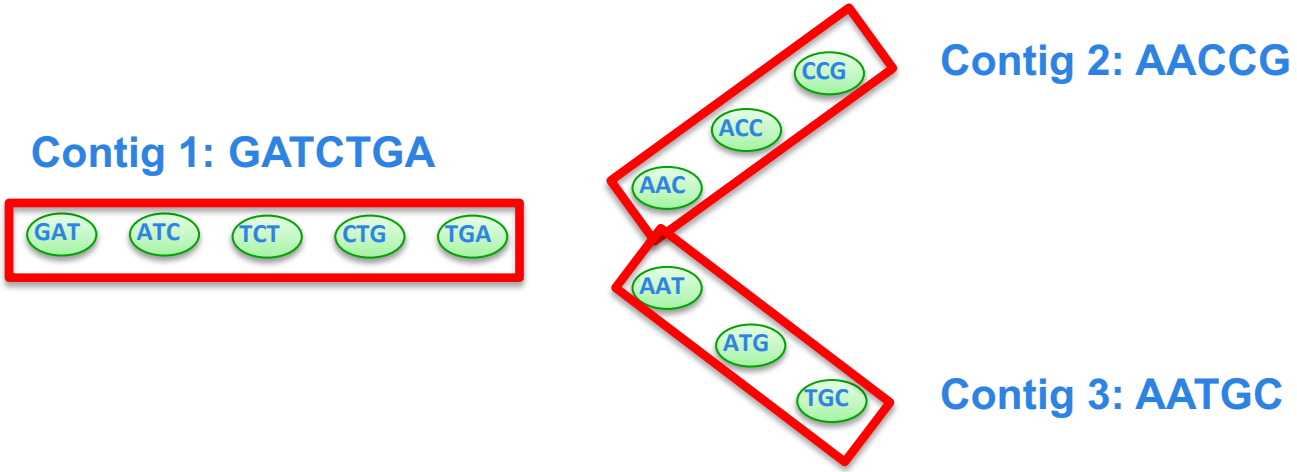
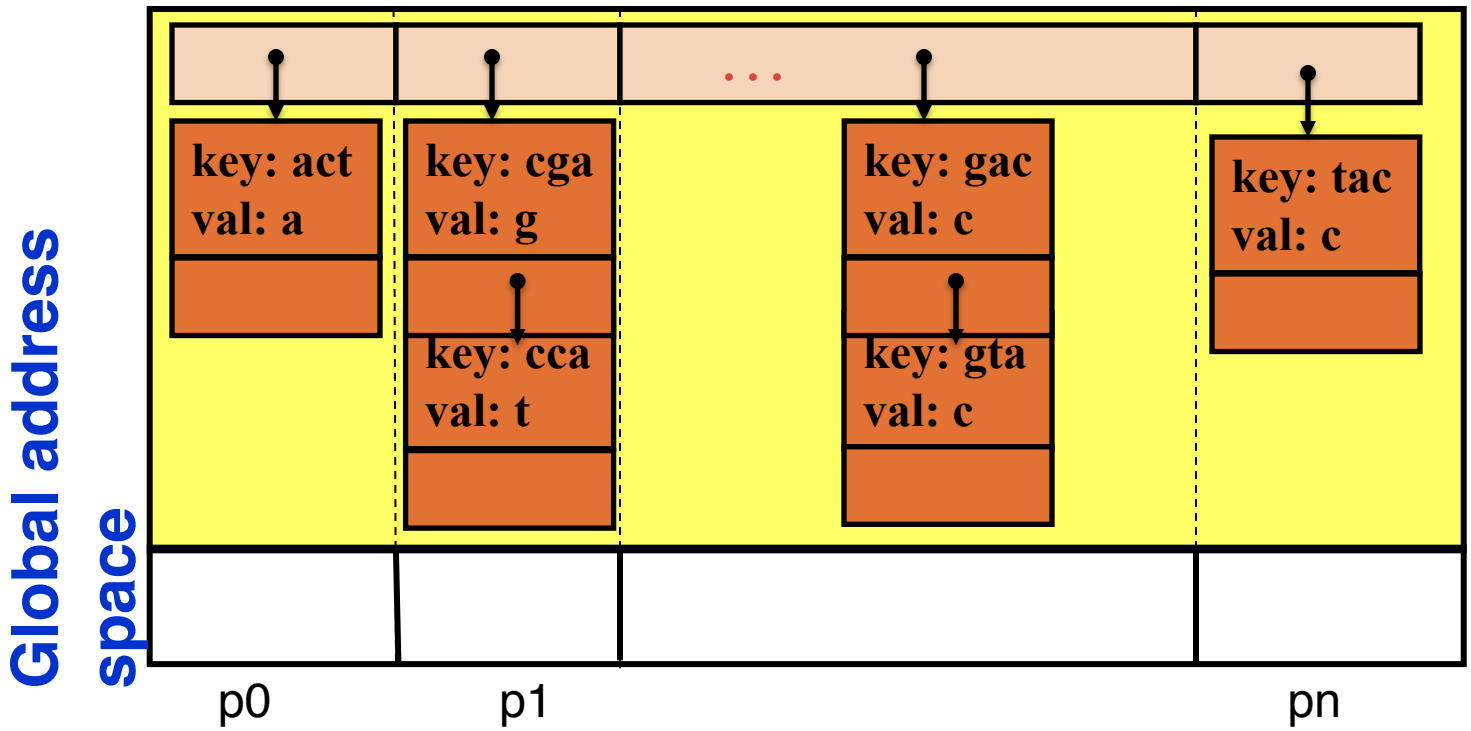
PGAS in Genome Assembly

- Sequencers produce fragments called “reads”
- Chop them into overlap fixed-length fragments, “K-mers”
- Parallel DFS (from randomly selected K-mers) → “contigs”



- Hash tables used here (and in other assembly phases)
  - Different use cases, different implementations
- Some tricky synchronization to deal with conflicts

Partitioned Global Address Space Programming



- Store the connections between read fragments (K-mers) in a hash table
- Allows for TB-PB size data sets

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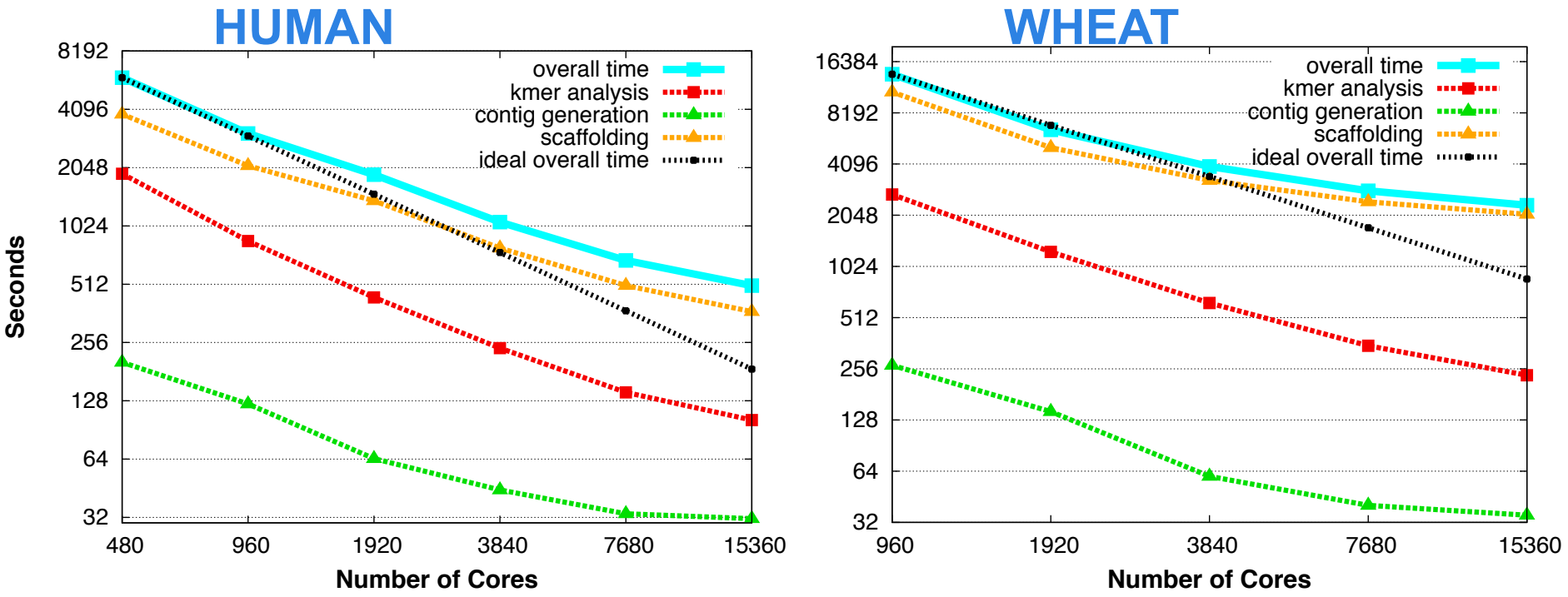
HipMer (High Performance Meraculous) Assembly Pipeline

Distributed Hash Tables in PGAS

- Remote Atomics, Dynamic Aggregation, Software Caching
- 13x Faster than MPI code (Ray) on 960 cores



Evangelos Georganas, Aydın Buluç, Jarrod Chapman, Steven Hofmeyr, Chaitanya Aluru, Rob Egan, Lenny Oliker, Dan Rokhsar, and Kathy Yelick. HipMer: An Extreme-Scale De Novo Genome Assembler, SC'15

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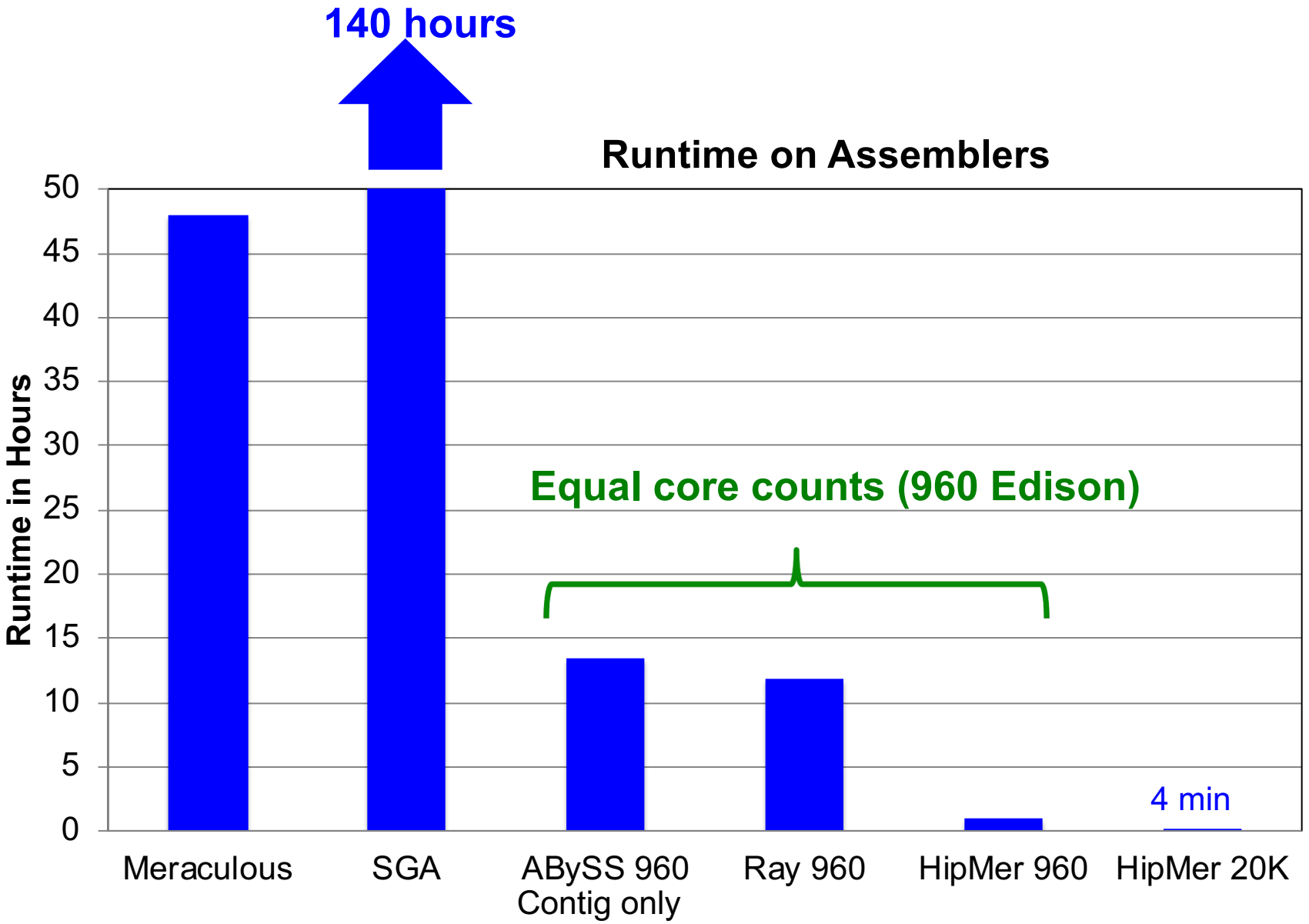
Comparison to other Assemblers



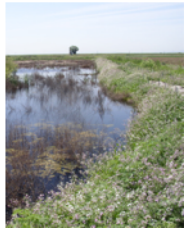
Science Impact: HipMer is transformative

- Human genome (3Gbp) “de novo” assembled :
  - Meraculous: 48 hours
  - HipMer: 4 minutes (720x speedup relative to Meraculous)

Makes unsolvable problems solvable!

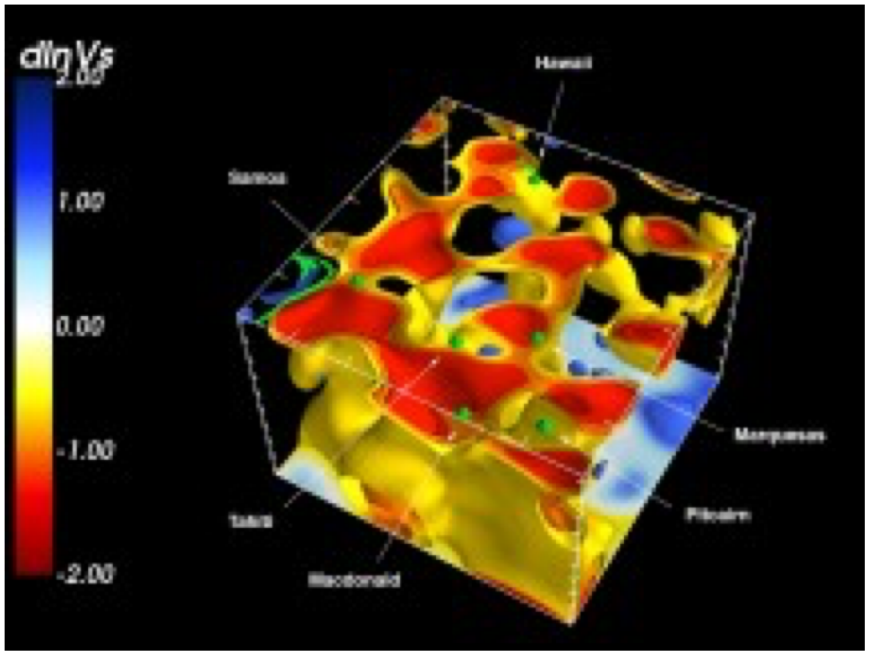
- Wheat genome (17 Gbp) “de novo” assembled (2014):
  - Meraculous (did not run):
  - HipMer: 39 minutes; 15K cores (first all-in-one assembly)

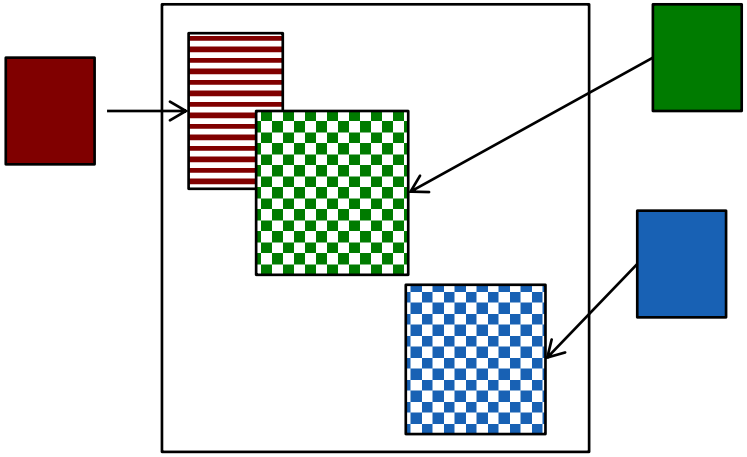
- Pine genome (20 Gbp) “de novo” assembled (2014) :
  - Masurca : 3 months; 1 TB RAM
- Wetland metagenome (1.25 Tbp) analysis (2015):
  - Meraculous (projected): 15 TB of memory
  - HipMER: Strong scaling to over 100K cores (contig gen only)



Application Challenge: Data Fusion in UPC++

- **Seismic modeling for energy applications "fuses" observational data into simulation**
- **With UPC++ "matrix assembly" can solve larger problems**





First ever sharp, three-dimensional scan of Earth's interior that conclusively connects plumes of hot rock rising through the mantle with surface hotspots that generate volcanic island chains like Hawaii, Samoa and Iceland.

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French and Romanowicz use code with UPC++ phase to compute *first ever* whole-mantle global tomographic model using numerical seismic wavefield computations (F & R, 2014, GJI, extending F et al., 2013, Science).

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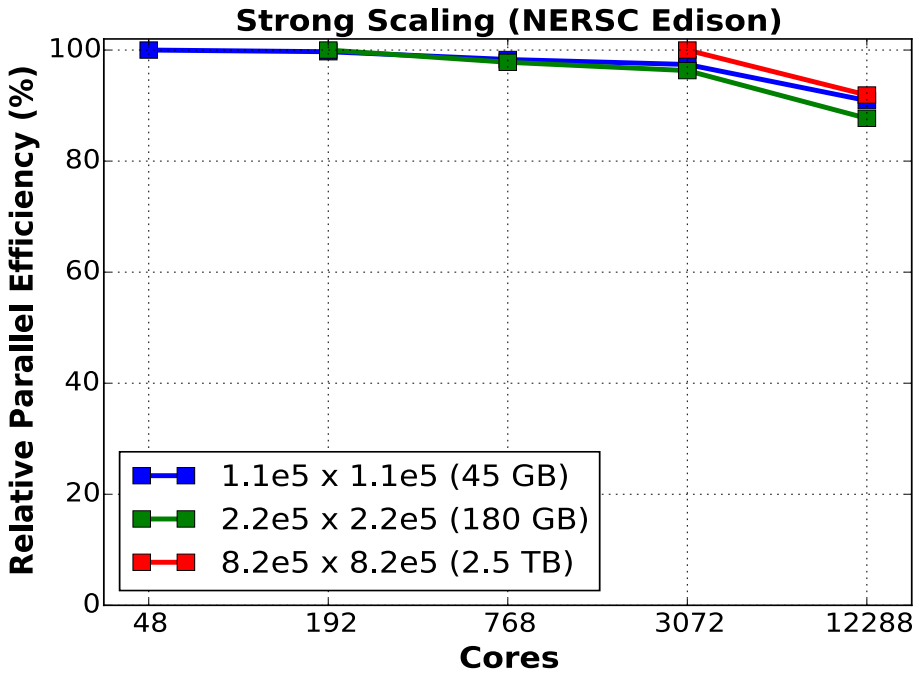
Application Challenge: Data Fusion in UPC++



Distributed Matrix Assembly

- Remote asyncs with user-controlled resource management
- Remote memory allocation
- Team idea to divide threads into injectors / updaters
- 6x faster than MPI 3.0 on 1K nodes

→ Improving UPC++ team support

See French et al, IPDPS 2015 for parallelization overview.

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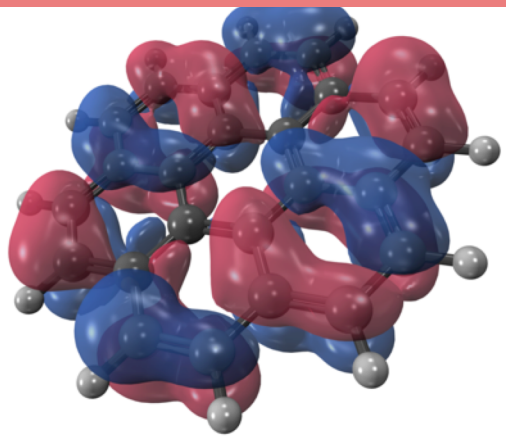
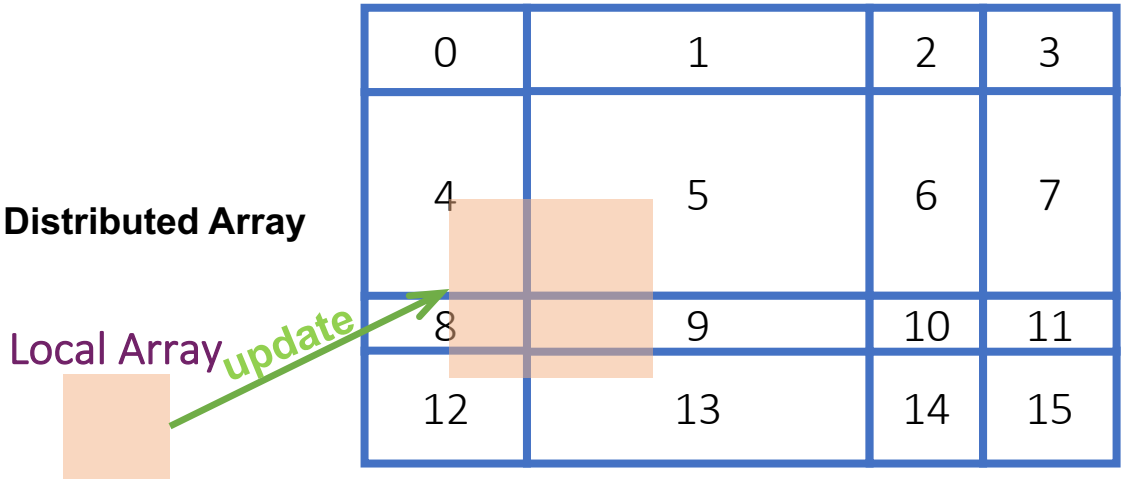
Load Balancing and Irregular Matrix Transpose

- **Hartree Fock example (e.g., in NWChem)**
  - **Inherent load imbalance**
- **UPC++**
  - Work stealing and fast atomics
  - Distributed array: easy and fast transpose
- **Impact**
  - *20% faster than the best existing solution (GTFock with Global Arrays)*

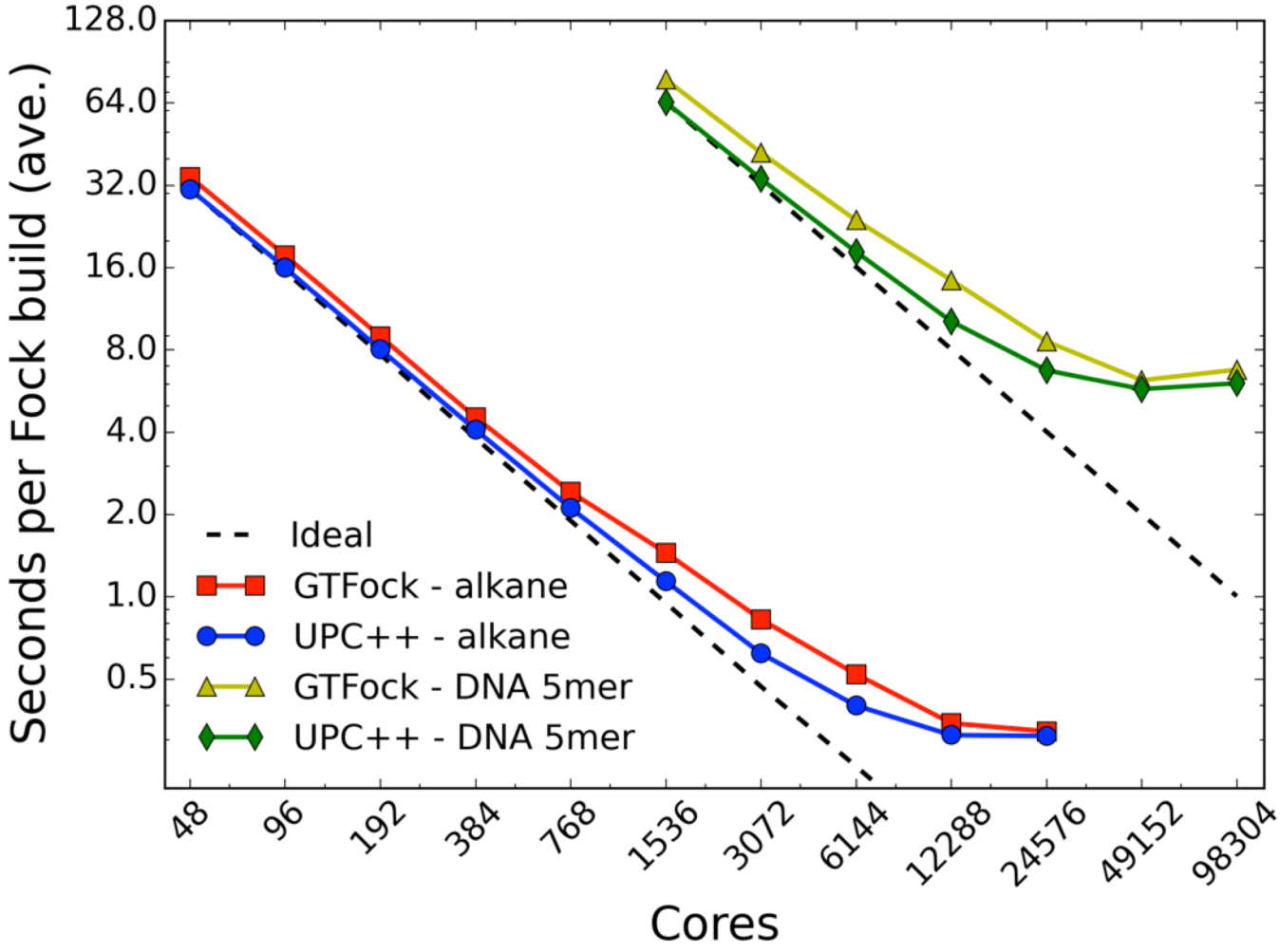
Increase scalability!





David Ozog , Amir Kamil , Yili Zheng, Paul Hargrove , Jeff R. Hammond, Allen Malony, Wibe de Jong, Katherine Yelick

Hartree Fock Code in UPC++

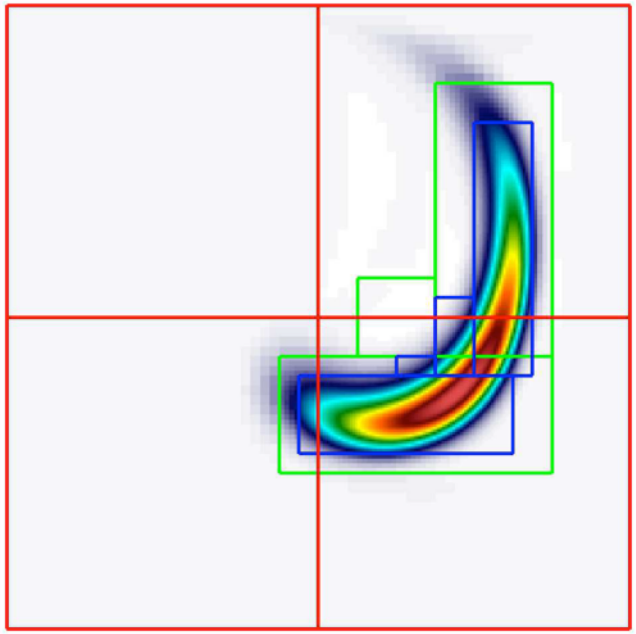


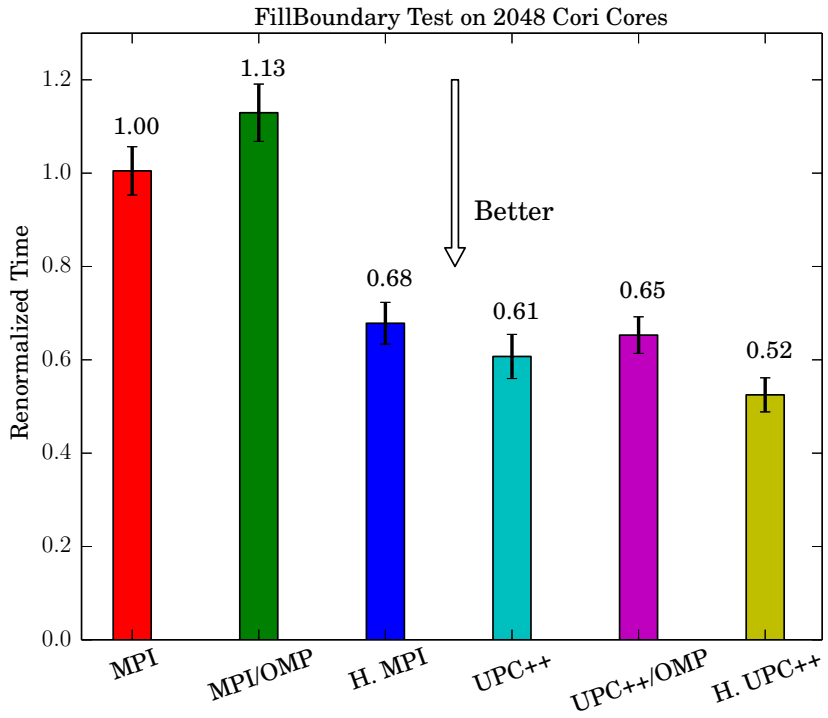
Strong Scaling of UPC++ HF Compared to GTFock with Global Arrays on NERSC Edison (Cray XC30)

David Ozog , Amir Kamil , Yili Zheng, Paul Hargrove , Jeff R. Hammond, Allen Malony, Wibe de Jong, Katherine Yelick

UPC++ Communication Speeds up AMR

- Adaptive Mesh Refinement on Block-Structured Meshes
  - Used in ice sheet modeling, climate, subsurface (fracking),





Hierarchical UPC++ (distributed / shared style)

- UPC++ plus UPC++ is 2x faster than MPI plus OpenMP
- MPI + MPI also does well

upc++

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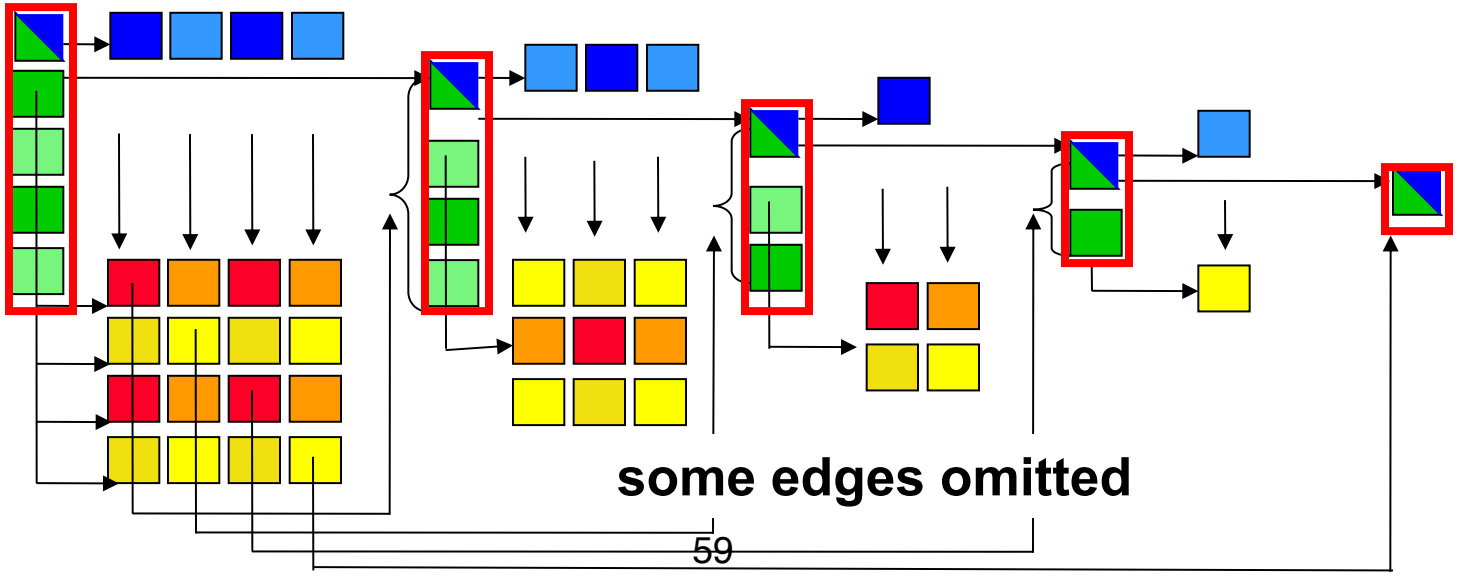
Beyond Put/Get: Event-Driven Execution

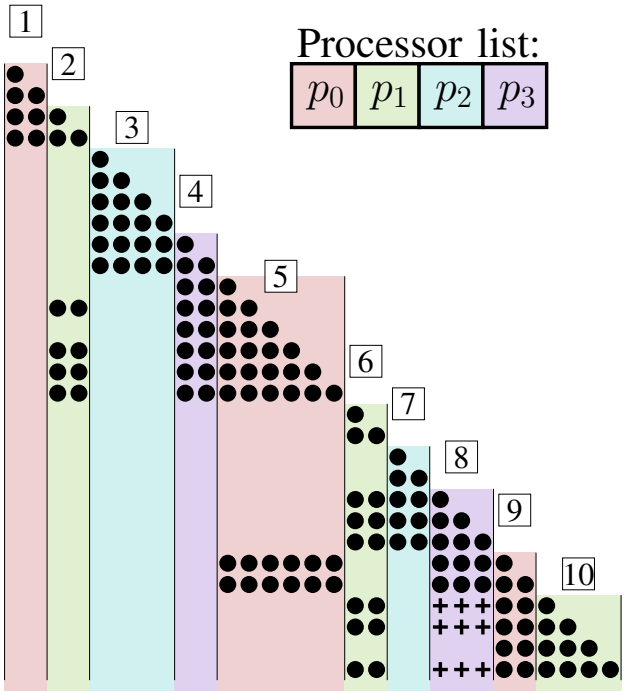
- DAG Scheduling in a distributed (partitioned) memory context
- Assignment of work is static; schedule is dynamic
- Ordering needs to be imposed on the schedule
  - Critical path operation: Panel Factorization
- General issue: dynamic scheduling in partitioned memory
  - Can deadlock in memory allocation
  - "memory constrained" lookahead

Uses a Berkeley extension to UPC to remotely synchronize

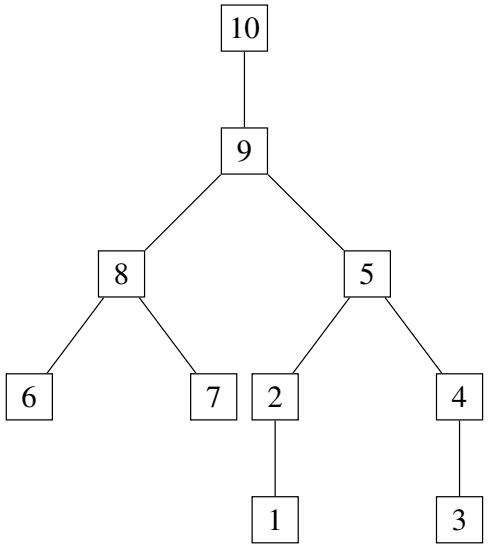


Parry Husbands, Katherine Yelick

symPACK: Sparse Cholesky



(a) Structure of Cholesky factor **L** (



ɔ) Supernodal elimination tree of
ıatrix **A**

- Sparse Cholesky using fan-both algorithm in UPC++
  - Uses asynchronous tasks with dependencies

Matthias Jacquelin, Yili Zheng, Esmond Ng, Katherine Yelick

symPACK: Sparse Cholesky

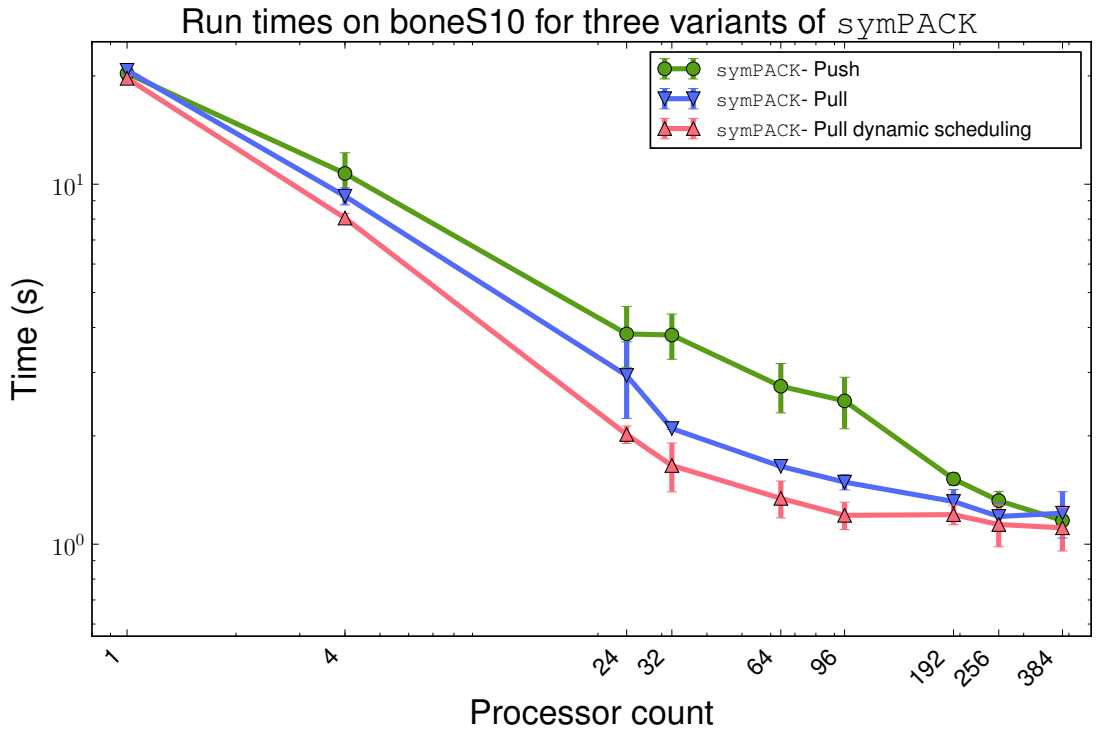


Figure 7: Impact of communication strategy and scheduling on symPACK performance

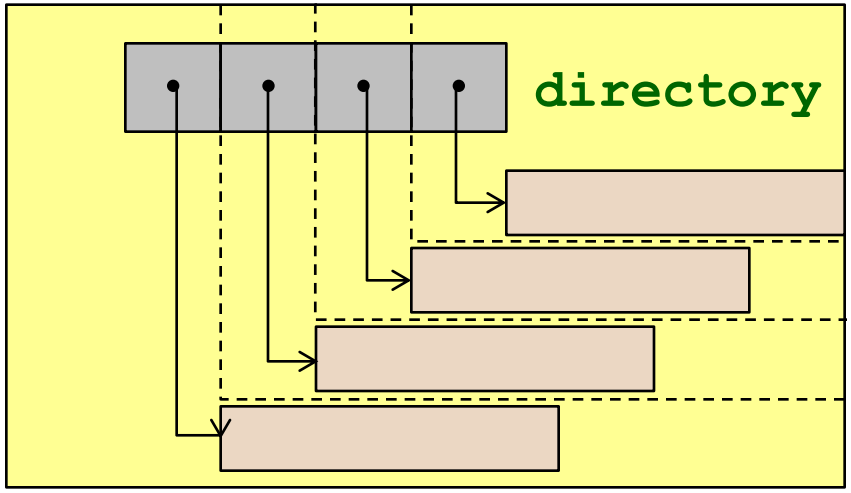
- Scalability of symPACK on Cray XC30 (Edison)
  - Comparable or better than best solvers (evaluation in progress)
  - Notoriously hard parallelism problem

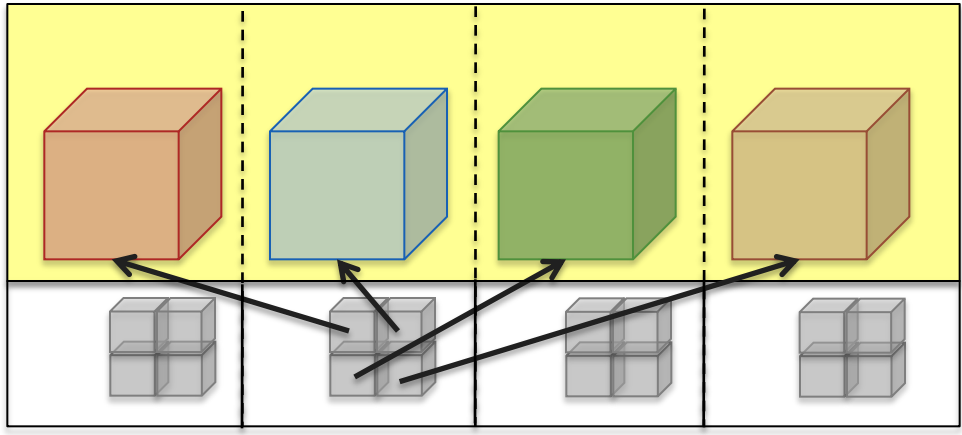
Matthias Jacquelin, Yili Zheng, Esmond Ng, Katherine Yelick

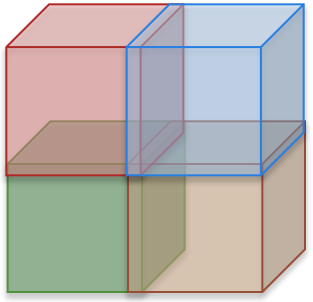
Common Pattern for Distributed Data Structures

- Many UPC programs avoid the UPC style arrays in factor of directories of objects

```
typedef shared [] double *sdblptr;
shared sdblptr directory[THREADS];
directory[i]=upc_alloc(local_size*sizeof(double));
```







physical and conceptual 3D array layout

- These are also more general:
  - Multidimensional, unevenly distributed
  - Ghost regions around blocks

Summary: PGAS for Irregular Applications

- Lower overhead of communication makes PGAS useful for latency-sensitive problems or bisection bandwidth problems
- Specific application characteristics that benefit:
  - Fine-grained updates (Genomics HashTable construction)
  - Latency-sensitive algorithms (Genomics DFS)
  - Distributed task graph (Cholesky)
  - Work stealing (Hartree Fock)
  - Irregular matrix assembly / transpose (Seismic, HF)
  - Medium-grained messages (AMR)
  - All-to-all communication (FFT)
- There are also benefits of thinking algorithmically in this model: parallelize things that are otherwise hard to imagine

Summary: PGAS for Modern HPC Systems

- The lower overhead of communication is also important given current machine trends
  - **Many lightweight cores** per node (do not want a hefty serial communication software stack to run on them)
  - **RDMA mechanisms** between nodes (decouple synchronization from data transfer)
  - **GAS on chip:** direct load/store on chip without full cache coherence across chip
  - **Hierarchical machines:** fits both shared and distributed memory, but supports hierarchical algorithms
  - **New models of memory:** High Bandwidth Memory on chip or NVRAM above disk

Using UPC++ at NERSC

Switch to the gnu C++ compiler

```
module switch PrgEnv-intel PrgEnv-gnu
```

Load the UPC++ module via

```
module load upcxx
```

Compile code with the upcc

```
upcxx="<upcxx-install-path>/bin/upcxx-meta"
g++ --std=c++11 hello-world.cpp $($upcxx PPFLAGS) \
            $($upcxx  LDFLAGS) $($upcxx  LIBFLAGS)
```

Or see the Makefile example…

Installing Berkeley UPC++, UPC, and GASNet

Available on Mac OSX, Linux, Infiniband clusters, Ethernet clusters, and most HPC systems

- UPC++ Open source with BSD license
  https://bitbucket.org/berkeleylab/upcxx/

  Has specification, user guide, codes, and instructions
- GASNet communication
  https://gasnet.lbl.gov

Not used in this course (this year)

- Cray UPC (installed at NERSC)
  http://docs.cray.com/books/S-2179-50/
- Berkeley UPC
  http://upc.lbl.gov