CIS 631
Parallel Processing

Lecture 8: MPI Programming and Applications

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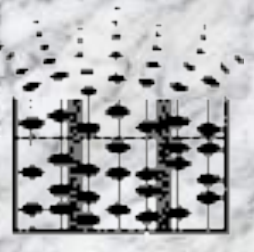
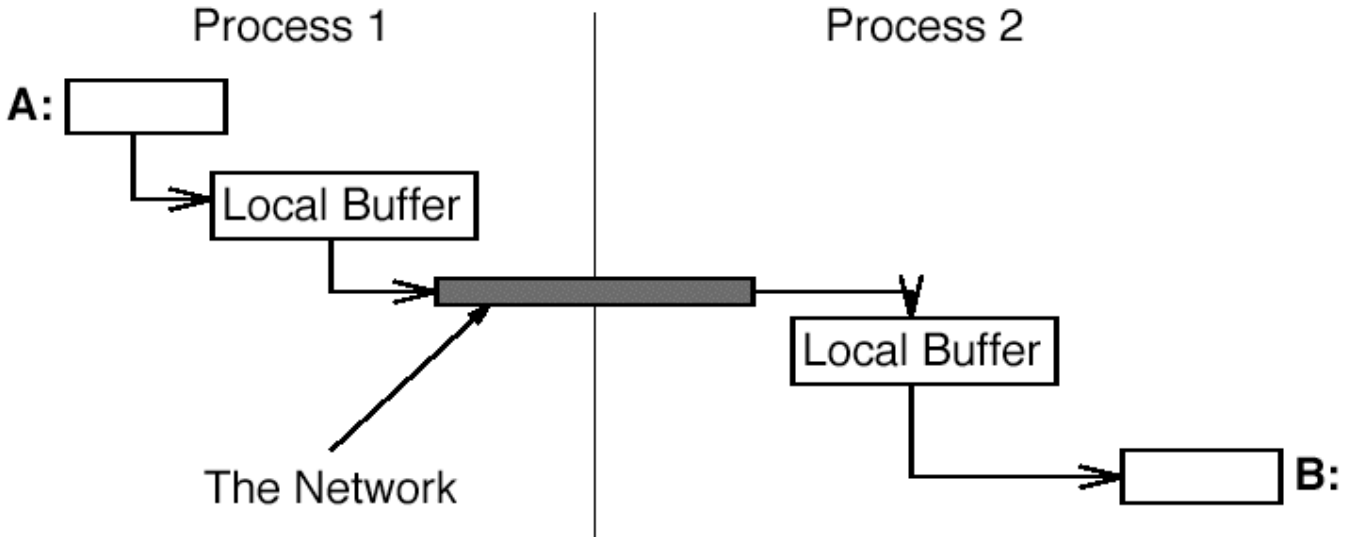


Owner Computes Rule

- The process that owns the data is the process that will compute new data values
- Ownership is determined by data distribution
  - Domain decomposition
- Ownership may be implicitly determined
  - Could depend on other aspects of the program
- Why is the owner computes rule useful in distributed memory parallel programming?

Buffering Issues

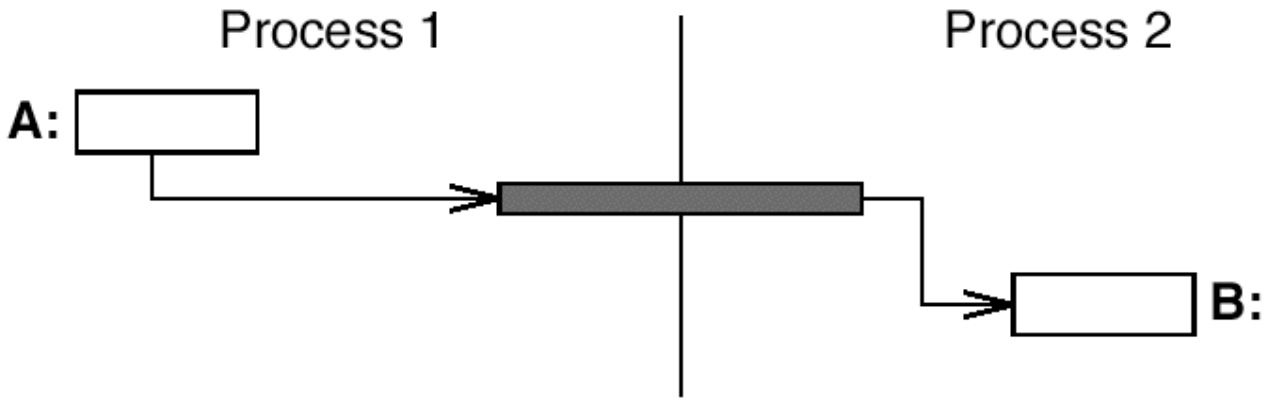
- Where does data go when you send it?
- One possibility is:



- This is not very efficient
  - Three copies in addition to the exchange of data
  - Copies are "bad"

Better Buffering

- Prefer:



- Requires either
  - `MPI_SEND` does not return until data delivered
  - Or allow a send to return before completing transfer
- In the latter case, we need to test for completion later

Blocking vs. Non-Blocking Send and Receive

- The semantics of blocking/non-blocking has nothing to do with when messages are sent or received
- The difference is when the buffer is free to be re-used
- Is this a good way to think about it? Why?
- Blocking
  - A blocking send routine will only "return" if it is safe to modify the application buffer (your send data)
  - A blocking send is *synchronous* when the receiver confirms a safe send (again, we are talking semantics)
  - A blocking send is *asynchronous* if a system buffer is used to hold the data for eventual delivery to the receiver
  - A blocking receive only "returns" after the data has arrived and is ready for use by the program

Non-Blocking

- Non-blocking
  - Send and receive routines do not wait for any communication events to complete, either
    - message copying from user memory to system buffer space
    - actual arrival of message
  - Simply "request" the MPI library to perform the operation when it is able, but cannot predict when
  - It is unsafe to modify the application buffer until you know the non-blocking operation was actually performed
    - use "wait" routines to do this
  - Non-blocking communications are primarily used to overlap computation with communication and exploit possible performance gain (How?)

Send-Receive

- Send-receive operation combine in one function call the sending of a message to one process and receiving of a message from another:

```
MPI_Sendrecv(sendbuf, sendcount, sendtype,
dest, sendtag, recvbuf, recvcount, recvtype,
source, recvtag, comm, status)
```

- Use same buffer for sending and receiving:

```
MPI_Sendrecv_replace(buf, count, datatype,
dest, sendtag, source, recvtag, comm, status)
```

- Exchange data with neighbors

```
MPI_Sendrecv(&a,n,MPI_DOUBLE,right,TAG,&b,n,
MPI_DOUBLE,left,TAG,MPI_COMM_WORLD,&Status);
```

Non-Blocking MPI Send and Receive Operations

- Saw how non-blocking operations help to avoid deadlock
- Important for overlapping communication / computation
- Non-blocking send and receive routines

```
MPI_Isend(buf, count, datatype, dest,
          tag, comm, request)
MPI_Irecv(buf, count, datatype, source,
          tag, comm, request)
```

- `Request` represents the particular `Isend` or `Irecv`
  - Used as an argument in test and wait routines

MPI Test and Wait

- Routines to test status of non-blocking send and receive
  - **`MPI_Test(request, flag, status)`**
  - **`MPI_Wait(request, status)`**
- `MPI_Test` tests whether or not the non-blocking operation identified by `request` has finished
  - Returns true or false in `flag`
  - If true, `request` object deallocated
- `MPI_Wait` blocks until the non-blocking operation identified by `request` completes
  - `request` object deallocated on return

Waiting on Several Completions

- It is often desirable to wait on multiple requests
  - **`MPI_Waitall(count, request_array, status_array)`**
  - **`MPI_Waitany(count, requests_array, index, status)`**
  - **`MPI_Waitsome(incount, requests_array, outcount, indices_array, status_array)`**
- There are corresponding versions of test for each of these
- Why is this useful?

Exchanging Data with Neighbors

	Blocking Recv	Non-blocking Recv

Blocking Send	`MPI_Send(A,…,left,…);`
	`MPI_Recv(B,…,right,…);`
		`MPI_Send(A,…,left,…);`
		`MPI_Irecv(B,…,right,…,`
		`&req);`
		`MPI_Wait(&req,&status);`

Non-blocking Send	`MPI_Isend(A,…,left,…,`
	`&req);`
	`MPI_Recv(B,…,right…);`
	`MPI_Wait(&req,&status);`
		`MPI_Isend(A,…,left,…,`
		`&req1);`
		`MPI_Irecv(B,…,right…,`
		`&reg2);`
		`MPI_Wait(&req1,&status);`
		`MPI_Wait(&req2,&status);`

Probe and Cancel

- `MPI_Probe()` and `MPI_Iprobe()` allow incoming messages to be checked for, without receiving them
  - **`MPI_Probe(source, tag, comm, status)`**
  - **`MPI_Iprobe(source, tag, comm, flag, status)`**
- `MPI_Cancel()` cancels pending communication
  - **`MPI_Cancel(request)`**

MPI Global Operations

- Often, it is useful to have one-to-many or many-to-one message communication.
- This is what MPI's global operations do
  - `MPI_Barrier`
  - `MPI_Bcast`
  - `MPI_Gather`
  - `MPI_Scatter`
  - `MPI_Reduce`
  - `MPI_Allreduce`
- MPI does not specify how any of these are implemented
- Global operations should be as efficient as possible

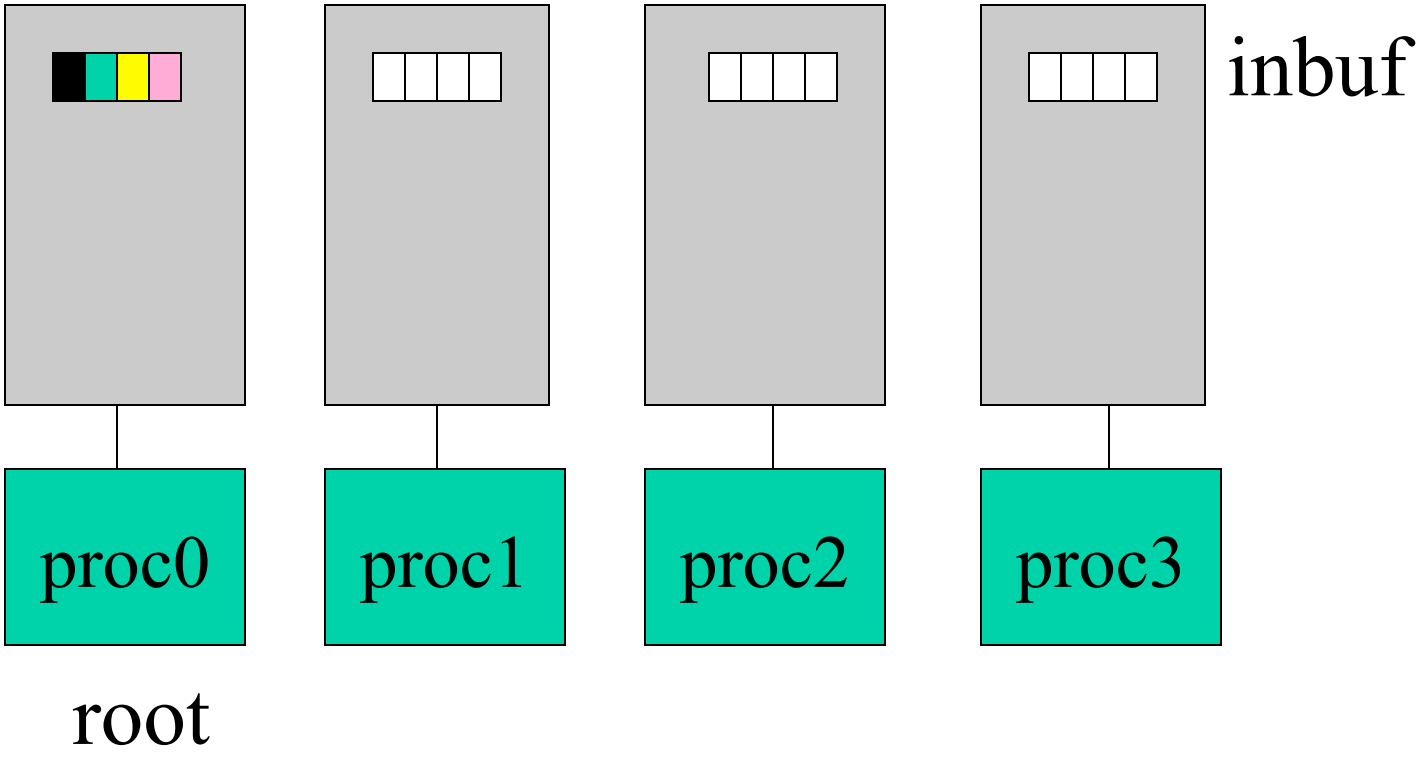
Barrier

- **`MPI_Barrier(comm)`**
  - Global barrier synchronization
  - All processes in communicator wait at barrier
  - Released when all have arrived

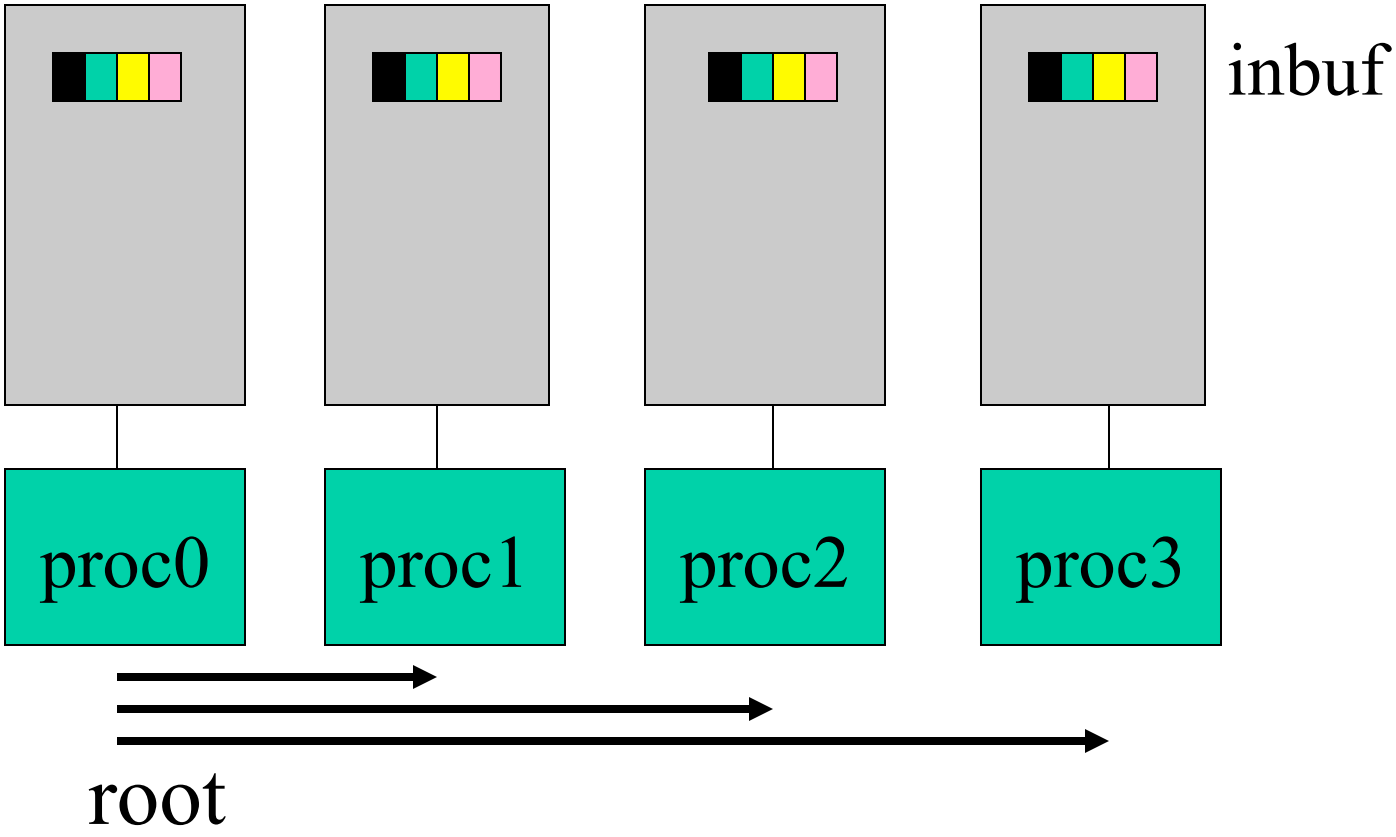
Broadcast

- **`MPI_Bcast(inbuf, incnt, intype, root, comm)`**
  - `inbuf`: address of input buffer on root
  - `inbuf`: address of output buffer elsewhere
  - `incnt`: number of elements
  - `intype`: type of elements
  - `root`: process id of root process

Before Broadcast



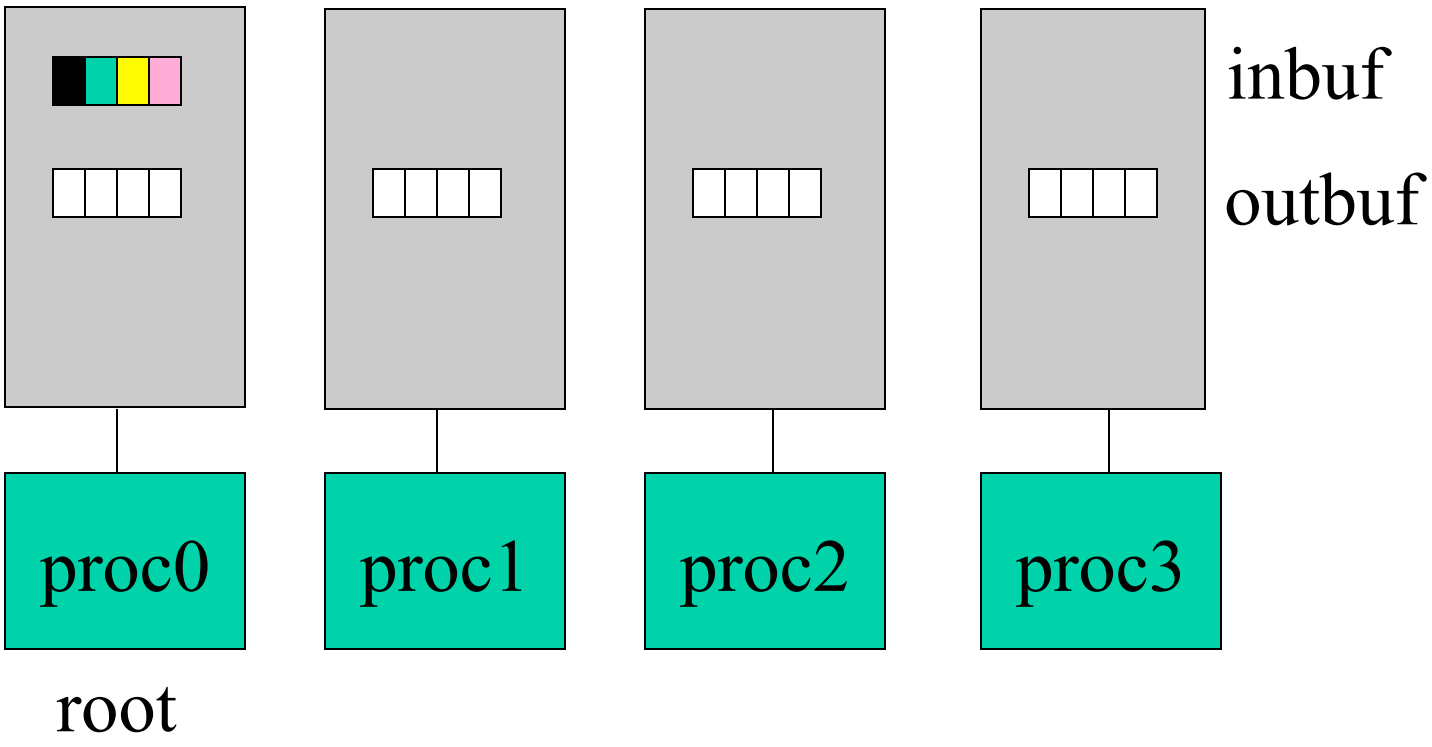
After Broadcast



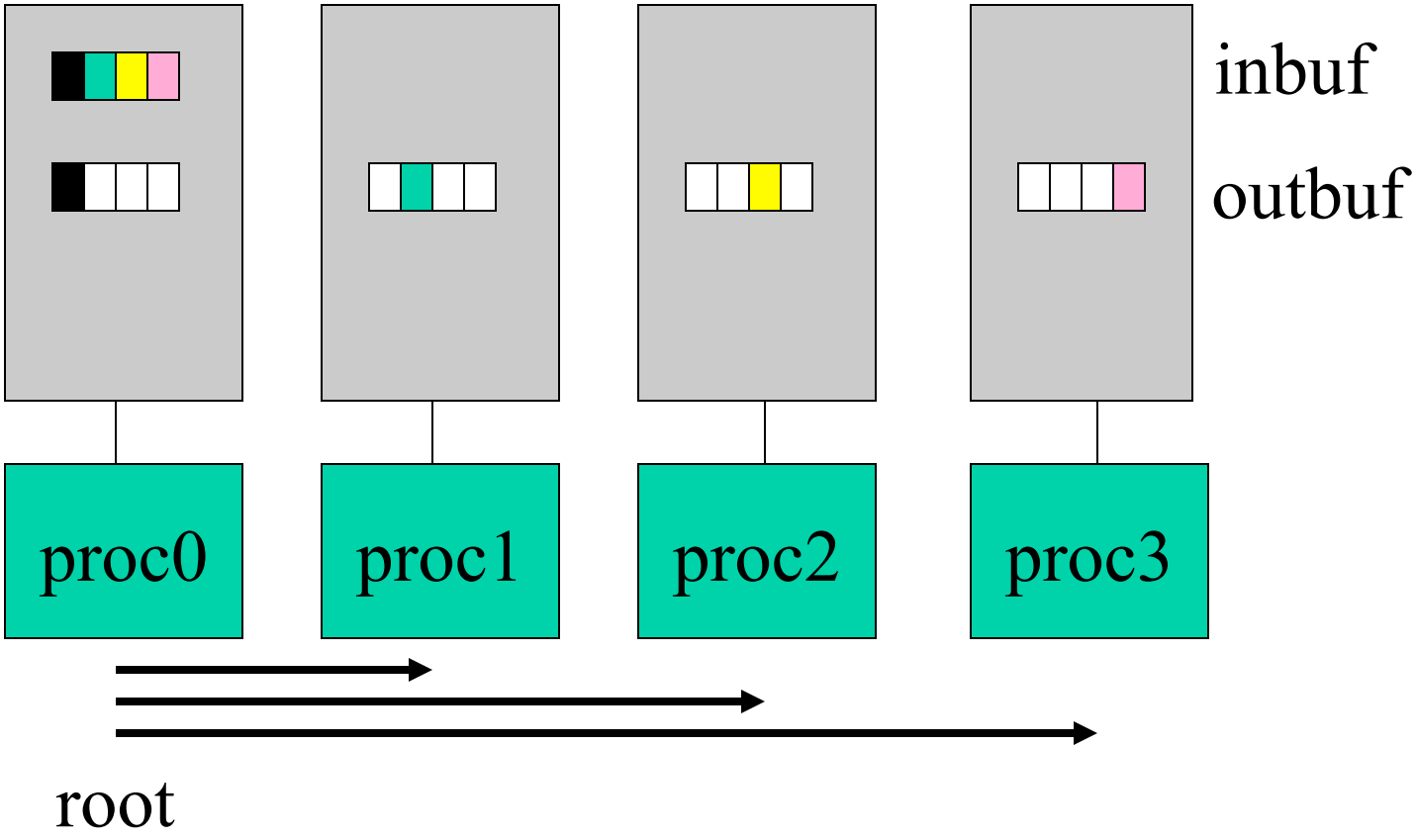
MPI Scatter

- **`MPI_Scatter(inbuf, incnt, intype, outbuf, outcnt, outtype, root, comm)`**
  - `inbuf`: address of input buffer
  - `incnt`: number of input elements
  - `intype`: type of input elements
  - `outbuf`: address of output buffer
  - `outcnt`: number of output elements
  - `outtype`: type of output elements
  - `root`: process id of root process

Before Scatter



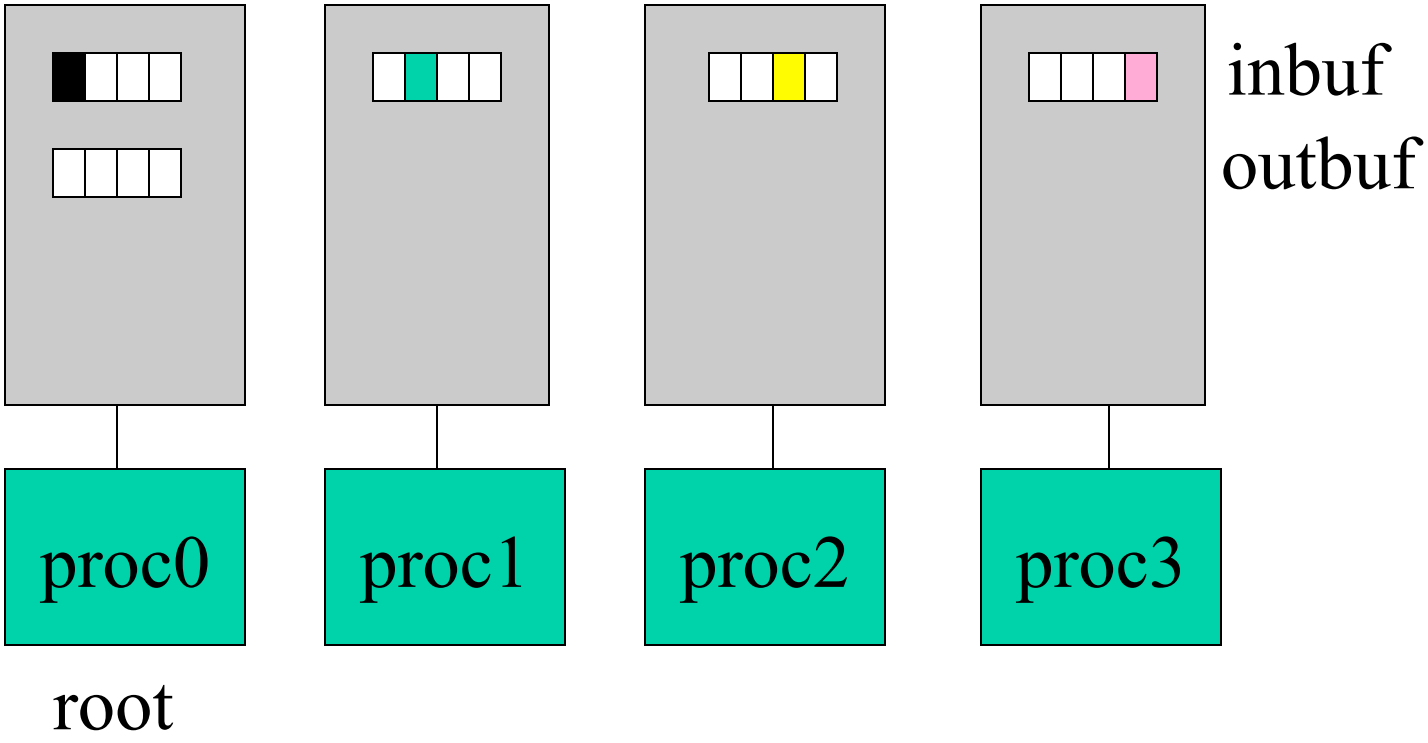
After Scatter



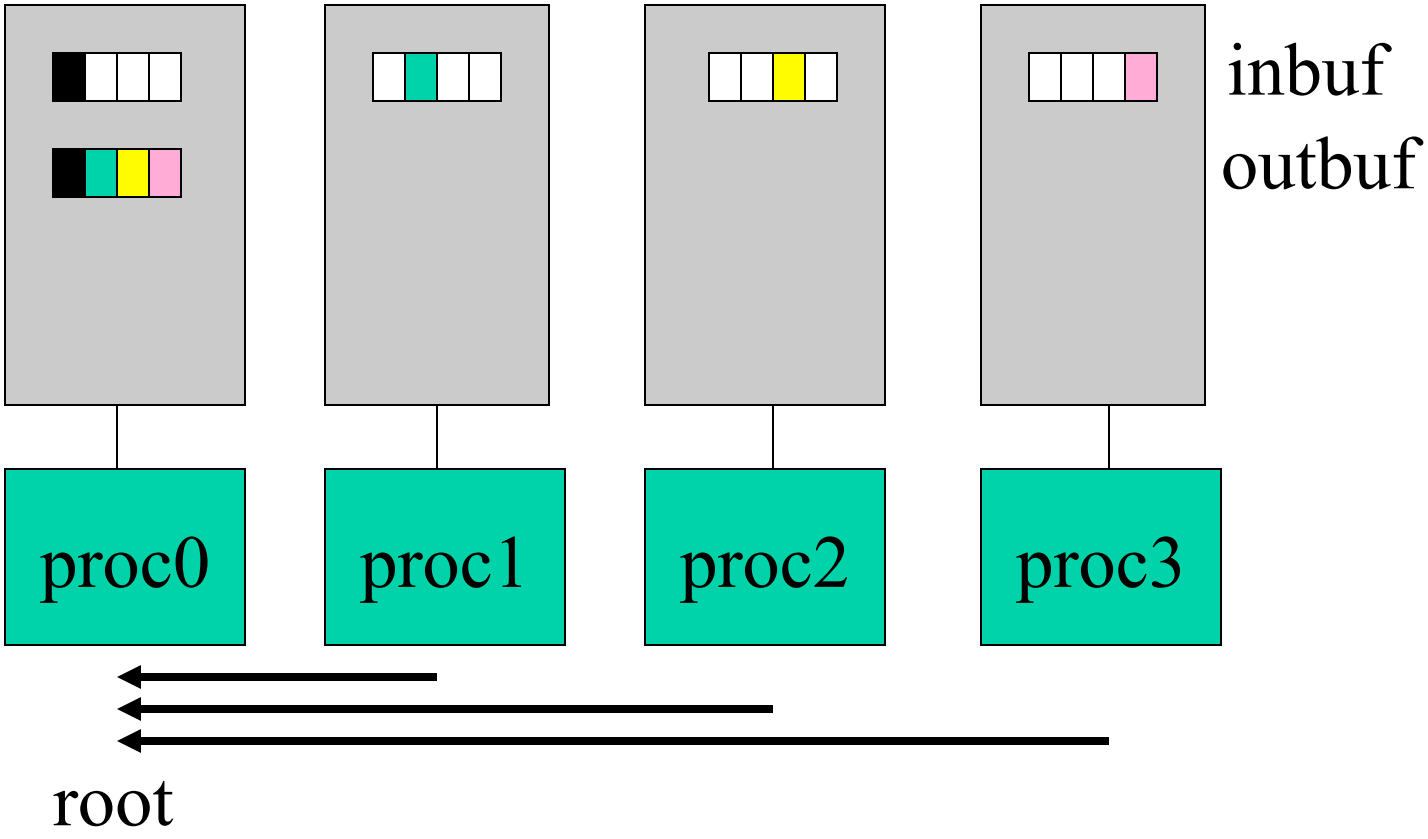
MPI Gather

- **`MPI_Gather(inbuf, incnt, intype, outbuf, outcnt, outtype, root, comm)`**
  - `inbuf`: address of input buffer
  - `incnt`: number of input elements
  - `intype`: type of input elements
  - `outbuf`: address of output buffer
  - `outcnt`: number of output elements
  - `outtype`: type of output elements
  - `root`: process id of root process

Before Gather



After Gather



Broadcast / Gather / Scatter

- These three primitives combine sends and receives
  - May be confusing
  - Collective operations
- Perhaps un-intended consequence
  - Requires global agreement on layout of array

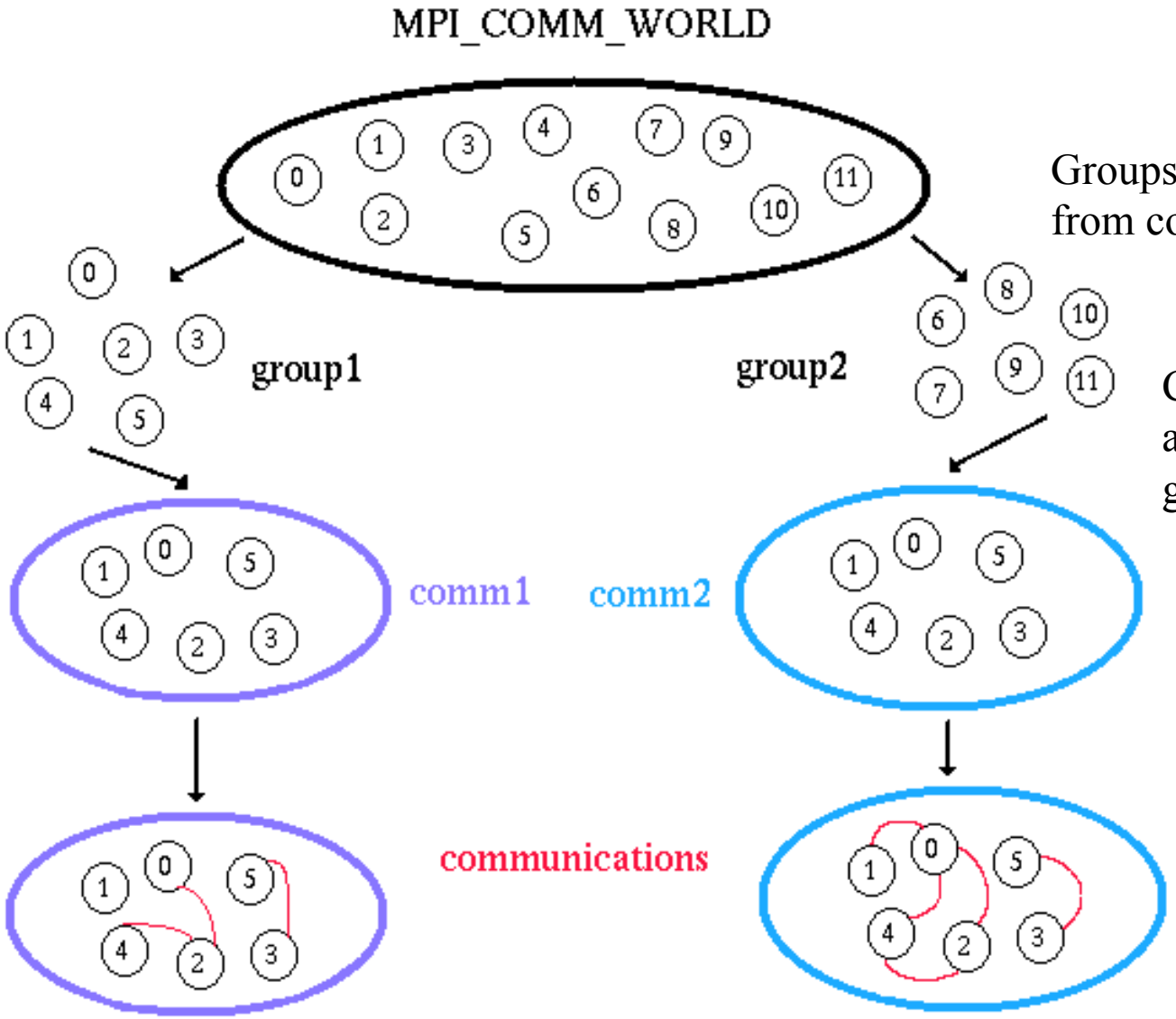
Groups, Communicators, and Contexts

- A *group* is an ordered set of processes
  - Each process in a group has a unique integer rank
  - Rank values are from 0 to N-1, where N is the group size
  - A group is accessible to the programmer by a "handle"
- A *communicator* is a group of processes that are allowed to communicate between themselves
  - All MPI messages must specify a communicator
  - Communicators accessible to programmer by "handles"
- A *context* is a system-defined object that uniquely identifies a communicator

More Groups and Communicators

- Groups/communicators are dynamic
- Processes may be in more than one group/communicator
  - They will have a unique rank within group/communicator
- Typical usage:
  1. Extract handle using `MPI_Comm_group`
  2. Form new group using `MPI_Group_incl`
  3. Create new communicator using `MPI_Comm_create`
  4. Determine new rank in communicator using `MPI_Comm_rank`
  5. Conduct communications using any MPI routine
  6. Free up communicator and group

Logical View



Groups are derived from communicators

Communicators are created from groups

Predefined Communicator

- `MPI_COMM_WORLD`
  - Contains all processes available at start of the program
- `MPI_COMM_NULL`
  - An invalid communicator
- `MPI_COMM_SELF`
  - Contains only the local process
- `MPI_COMM_EMPTY`
  - There is no such thing as `MPI_COMM_EMPTY`
  - Why not?

MPI Parallelization Process

- Divide program in parallel parts
- Create and destroy processes to do above
- Partition and distribute the data
- Communicate data at the right time
- (Sometimes) perform index translation
- Still need to do synchronization?
  - Sometimes, but many times goes hand in hand with data communication

Parallel Libraries and MPI

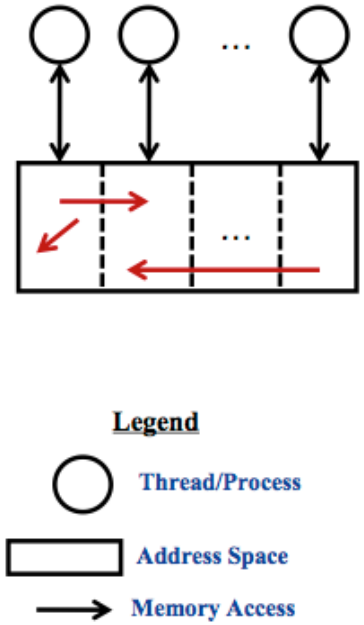
- Many libraries developed using MPI
  - Powerful parallelization and programming model
  - Gain portability advantages
- Scientific linear algebra, numerical, … libraries
  - ScaLAPACK, SuperLU, PETSc, Trilinos, PMTL(Parallel Matrix Template Library), …
- Graph, mesh, data, … libraries
  - PBGL (Parallel Boost Graph Library), ParMetis, PPM (Parallel Particle Mesh), HDF5, …
- Data, communication, computational, … libraries
  - GA (Global Arrays), ADLB (Asynchronous Dynamic Load Balancing), ARMCI (Aggregate Remote Memory Copy Interface), AP (Active Pebbles), LibNBC(Non-Blocking Collectives), AM++ (Active Message), …
- "Writing Parallel Libraries with MPI -- The Good, the Bad, and the Ugly," Torsten Hoefler, Keynote at EuroMPI 2011, Sept. 21, 2011.

The GAS / PGAS Model

- A parallel program consists of a set of *threads* and at least one *address space*
- A program is said to have a *global view* if all threads share a single address space
  - *GAS – Global Address Space*
- A program is said to have a *local view* if the threads have distinct address spaces
  - *PGAS – Partitioned Global Address Space*
- How are global and local views supported in reality
  - Shared memory provides by default
  - Distributed memory requires something more

GAS / PGAS Motivation and Implementation

- Need to support GAS and PGAS model in distributed memory systems
  - Threads with partitioned shared space
  - Datum may reference data in other partitions
  - Global array fragments in multiple partitions
- Advantages
  - Shared memory programming … why?
  - Performance … why?
- Disadvantages
  - Shared memory programming … why?
  - Performance … why?
- Library approach: GA, …
- Language approach: UPC, CAF, X10, Chapel

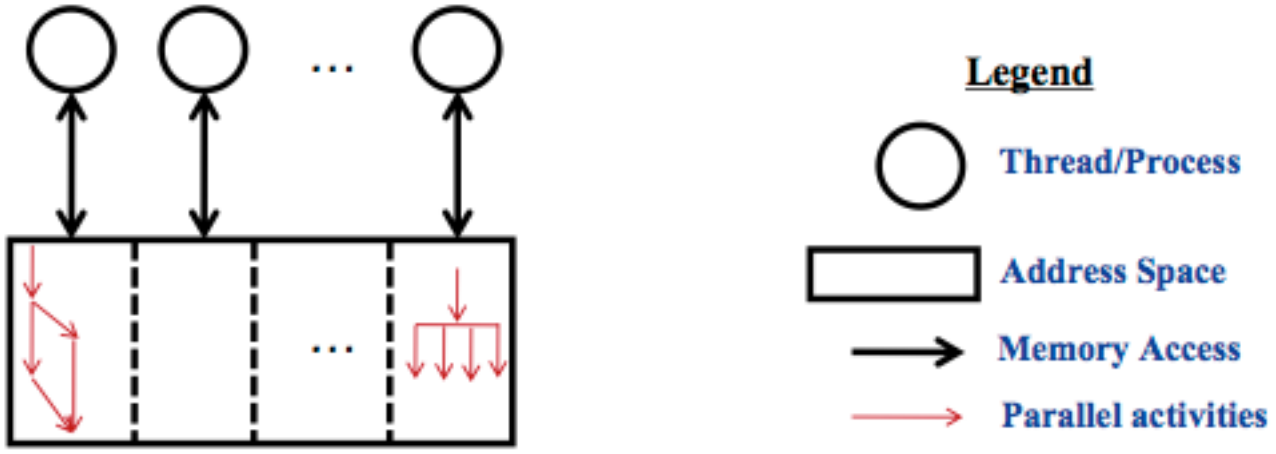


Realizing Dynamic Parallelism in PGAS

- Dynamic PGAS library ...
  - C, Fortran, Java, …
  - Co-habiting with MPI
- … implementing …
  - Remote references
  - Global data structures
  - Inter-place messaging
  - Global and/or collective operations
  - Intra-place concurrency
  - Atomic operations
- … through languages …
  - Asynchronous CAF
  - Asynchronous UPC
  - X10
  - Chapel
- … leveraging runtimes
  - GASNet, ARMCI, LAPI
  - UPC runtime
  - Chapel runtime
- Libraries reduce cost of adoption, languages offer enhanced productivity

PGAS vs. Others

	UPC, X10, Chapel, CAF, Titanium	MPI	OpenMP
Memory model	PGAS (Partitioned Global Address Space)	Distributed Memory	Shared Memory
Notation	Language	Library	Annotations
Global arrays?	Yes	No	No
Global pointers/references?	Yes	No	No
Locality Exploitation	Yes	Yes, necessarily	No



Dynamic parallelism

Next Class

- Shared memory parallel programming
- Threads