COMP 322: Fundamentals of Parallel Programming

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Lecture 37: Introduction to MPI (contd)

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Acknowledgments for Today's Lecture

- "Principles of Parallel Programming", Calvin Lin & Lawrence Snyder
  - Includes resources available at http://www.pearsonhighered.com/educator/academic/product/0,3110,0321487907,00.html
- "Parallel Architectures", Calvin Lin
  - Lectures 5 & 6, CS380P, Spring 2009, UT Austin
  - http://www.cs.utexas.edu/users/lin/cs380p/schedule.html
- mpiJava home page: http://www.hpjava.org/mpiJava.html
- "MPI-based Approaches for Java" presentation by Bryan Carpenter
  - http://www.hpjava.org/courses/arl
- MPI lectures given at Rice HPC Summer Institute 2009, Tim Warburton, May 2009

Announcements

- Homework 7 due by 5pm on Friday, April 22nd
  - Send email to comp322-staff if you're running into issues with accessing SUG@R nodes, or anything else
- Take-home final exam will be given on Friday, April 22nd
  - Content will cover second half of semester
    - Come to Friday's lecture for review of final exam material!
  - Due by 5pm on Friday, April 29th

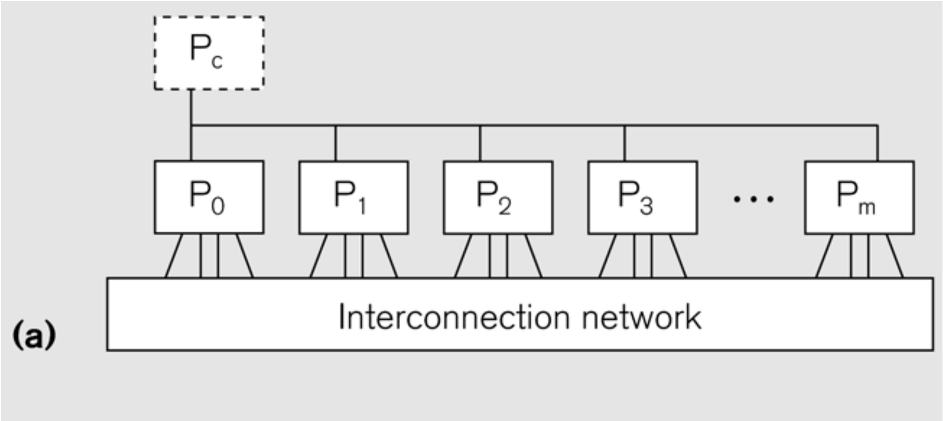
Organization of a Distributed-Memory Multiprocessor

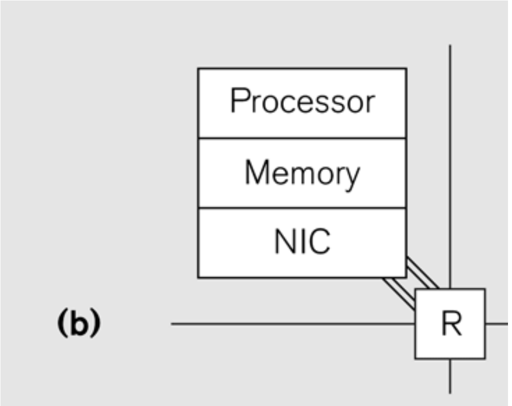
Figure (a)

- Host node (Pc) connected to a *cluster* of processor *nodes* (P_0 … P_m)
- Processors P_0 … P_m communicate via an *interconnection network*
  - Supports much lower latencies and higher bandwidth than standard TCP/IP networks

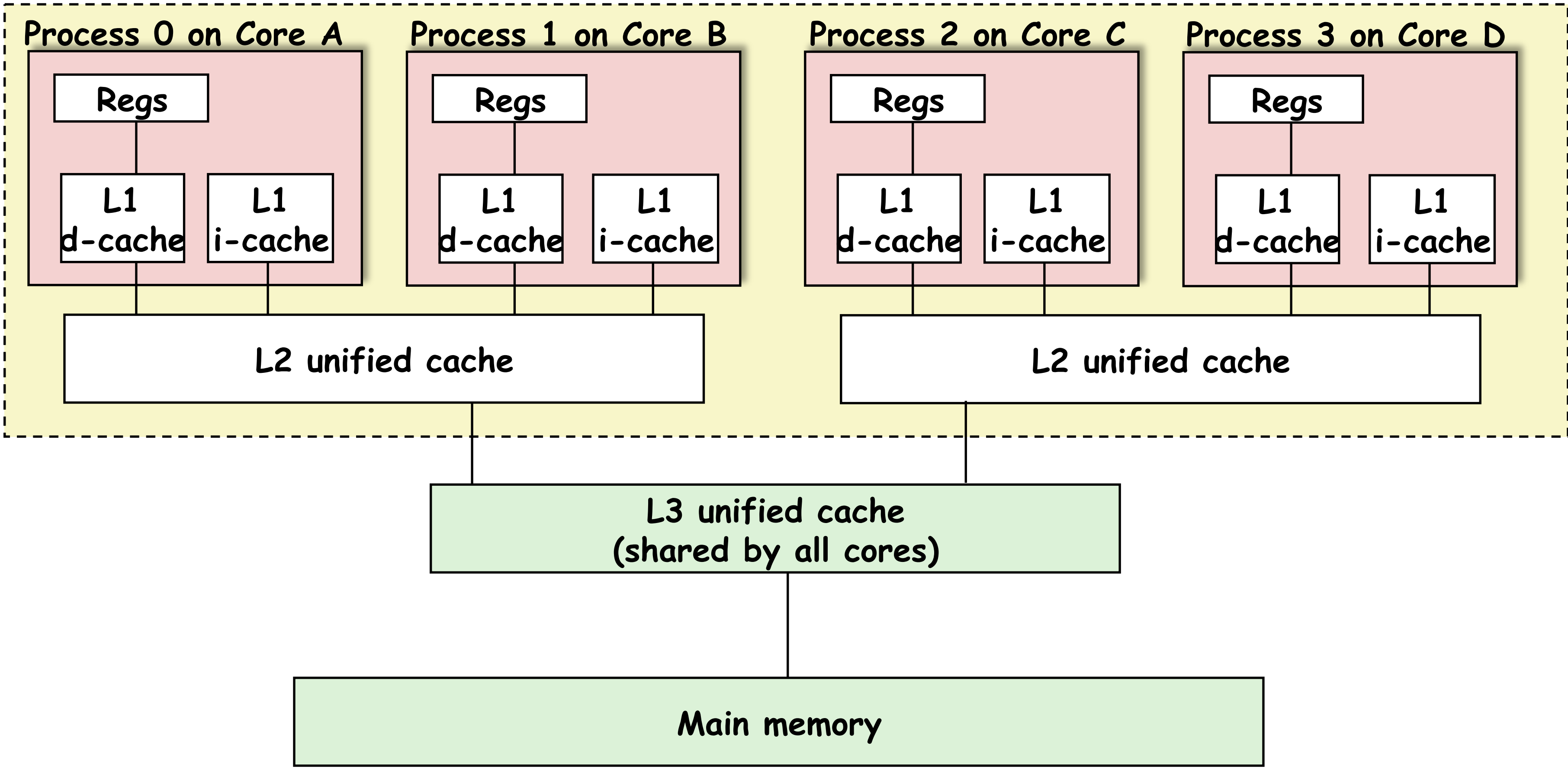
Figure (b)

- Each processor node consists of a processor, memory, and a Network Interface Card (NIC) connected to a router node (R) in the interconnect





Use of MPI on an SMP



- Memory hierarchy for a single Intel Xeon Quad-core E5440 HarperTown processor chip
  - A SUG@R node contains two such chips

Recap of mpiJava Send() and Recv()

- Send and receive members of Comm:

```
void Send(Object buf, int offset, int count, Datatype type,
          int dst, int tag) ;

Status Recv(Object buf, int offset, int count, Datatype type,
            int src, int tag) ;
```

- The arguments buf, offset, count, type describe the data buffer—the storage of the data that is sent or received. They will be discussed on the next slide.
- dst is the rank of the destination process relative to this communicator. Similarly in Recv(), src is the rank of the source process.
- An arbitrarily chosen tag value can be used in Recv() to select between several incoming messages: the call will wait until a message sent with a matching tag value arrives.
- The Recv() method returns a Status value, discussed later.
- Both Send() and Recv() are *blocking* operations by default
  - Analogous to a phaser next operation

Deadlock Scenario #1 (C version)

Consider:

```
int a[10], b[10], myrank;
MPI_Status status;
...
MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
if (myrank == 0) {
    MPI_Send(a, 10, MPI_INT, 1, 1, MPI_COMM_WORLD);
    MPI_Send(b, 10, MPI_INT, 1, 2, MPI_COMM_WORLD);
}
else if (myrank == 1) {
    MPI_Recv(b, 10, MPI_INT, 0, 2, MPI_COMM_WORLD);
    MPI_Recv(a, 10, MPI_INT, 0, 1, MPI_COMM_WORLD);
}
...
```

If MPI_Send is blocking, there is a deadlock.

Deadlock Scenario #2 (C version)

Consider the following piece of code, in which process i sends a message to process *i* + 1 (modulo the number of processes) and receives a message from process *i* - 1 (module the number of processes).

```
int a[10], b[10], npes, myrank;
MPI_Status status;
...
MPI_Comm_size(MPI_COMM_WORLD, &npes);
MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
MPI_Send(a, 10, MPI_INT, (myrank+1)%npes, 1,
        MPI_COMM_WORLD);
MPI_Recv(b, 10, MPI_INT, (myrank-1+npes)%npes, 1,
        MPI_COMM_WORLD);
...
```

Once again, we have a deadlock if MPI_Send is blocking.

Approach #1 to Deadlock Avoidance --- Reorder Send and Recv calls

We can break the circular wait to avoid deadlocks as follows:

```
int a[10], b[10], npes, myrank;
MPI_Status status;
...
MPI_Comm_size(MPI_COMM_WORLD, &npes);
MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
if (myrank%2 == 1) {
        MPI_Send(a, 10, MPI_INT, (myrank+1)%npes, 1,
                MPI_COMM_WORLD);
        MPI_Recv(b, 10, MPI_INT, (myrank-1+npes)%npes, 1,
                MPI_COMM_WORLD);
}
else {
        MPI_Recv(b, 10, MPI_INT, (myrank-1+npes)%npes, 1,
                MPI_COMM_WORLD);
        MPI_Send(a, 10, MPI_INT, (myrank+1)%npes, 1,
                MPI_COMM_WORLD);
}
...
```

Approach #2 to Deadlock Avoidance --- a combined Sendrecv() call

- Since it is fairly common to want to simultaneously send one message while receiving another (as illustrated on the previous) slide, MPI provides a more specialized operation for this.
- In mpiJava the corresponding method of Comm has the complicated signature:

```
Status Sendrecv(Object sendBuf, int sendOffset, int sendCount,
                Datatype sendType, int dst, int sendTag,
                Object recvBuf, int recvOffset, int recvCount,
                Datatype recvType, int src, int recvTag) ;
```

  - This can be more efficient that doing separate sends and receives, and it can be used to avoid deadlock conditions in certain situations
    - Analogous to phaser "next" operation, where programmer does not have access to individual signal/wait operations
  - There is also a variant called Sendrecv_replace() which only specifies a single buffer: the original data is sent from this buffer, then overwritten with incoming data.

Using Sendrecv for Deadlock Avoidance in Scenario #2 (C version)

Consider the following piece of code, in which process i sends a message to process *i* + 1 (modulo the number of processes) and receives a message from process *i* - 1 (module the number of processes).

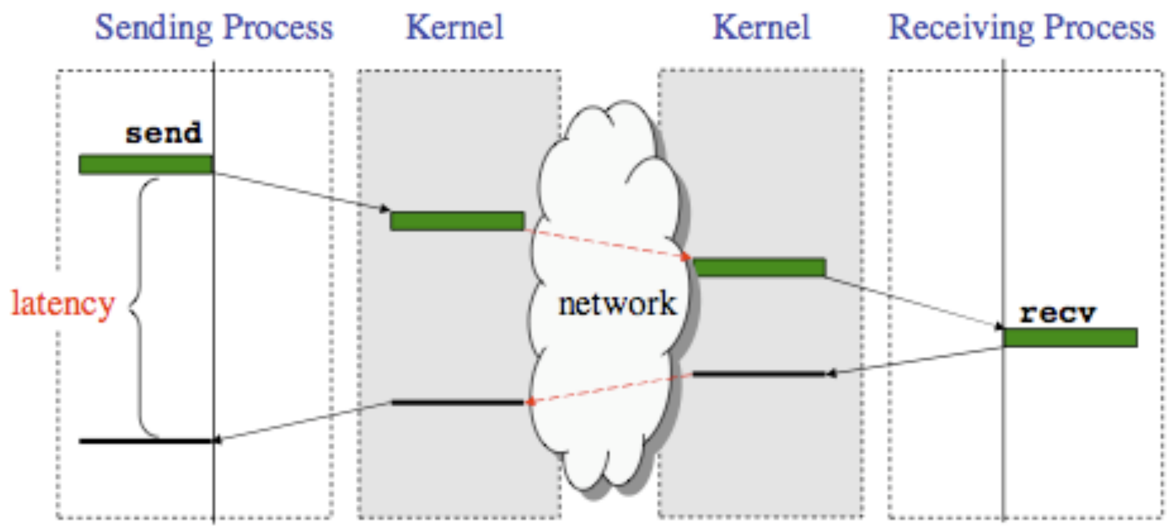
```
int a[10], b[10], npes, myrank;
MPI_Status status;
...
MPI_Comm_size(MPI_COMM_WORLD, &npes);
MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
MPI_Sendrecv(a, 10, MPI_INT, (myrank+1)%npes, 1,
             b, 10, MPI_INT, (myrank-1+npes)%npes, 1,
             MPI_COMM_WORLD);
...
```

A combined Sendrecv() call avoids deadlock in this case

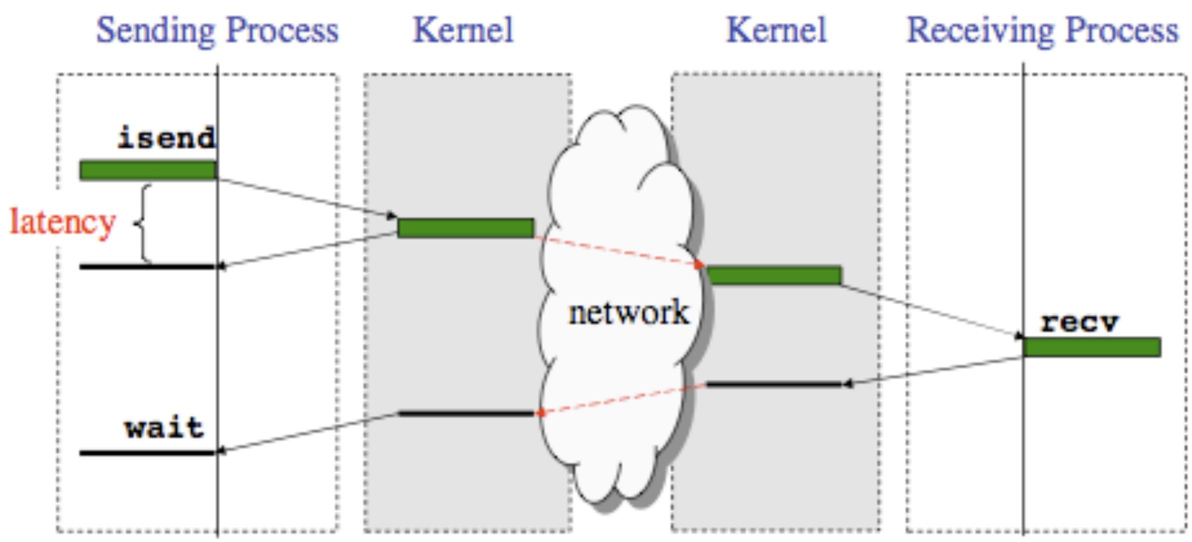
MPI Nonblocking Point-to-point Communication

Latency in Blocking vs. Nonblocking Communication

Blocking communication



Nonblocking communication



Non-Blocking Send and Receive operations

- In order to overlap communication with computation, MPI provides a pair of functions for performing non-blocking send and receive operations ("I" stands for "Immediate"):

```
int MPI_Isend(void *buf, int count, MPI_Datatype datatype,
              int dest, int tag, MPI_Comm comm,
              MPI_Request *request)

int MPI_Irecv(void *buf, int count, MPI_Datatype datatype,
              int source, int tag, MPI_Comm comm,
              MPI_Request *request)
```

- These operations return before the operations have been completed. Function `MPI_Test` tests whether or not the non-blocking send or receive operation identified by its request has finished.

```
int MPI_Test(MPI_Request *request, int *flag, MPI_Status *status)
```

- `MPI_Wait` waits for the operation to complete.

```
int MPI_Wait(MPI_Request *request, MPI_Status *status)
```

Non-blocking Example

Example pseudo-code on process 0:

```
if(procid==0){

  MPI_Isend outgoing  to 1
  MPI_Irecv  incoming from 1

  .. compute ..

  MPI_Wait until Irecv  has received
incoming

  .. compute ..

  MPI_Wait until Isend does not need
outgoing

}
```

Example pseudo-code on process 1:

```
if(procid==1){

  MPI_Isend outgoing to 0
  MPI_Irecv  incoming from 0

  .. compute ..

  MPI_Wait until Irecv  has filled incoming

  .. compute ..

  MPI_Wait until Isend does not need outgoing

}
```

Using the "*non-blocked*" send and receives allows us to overlap the latency and buffering overheads with useful computation.

Avoiding Deadlocks (C version)

Using non-blocking operations removes most deadlocks. Consider:

```
int a[10], b[10], myrank;
MPI_Status status;
...
MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
if (myrank == 0) {
   MPI_Send(a, 10, MPI_INT, 1, 1, MPI_COMM_WORLD);
   MPI_Send(b, 10, MPI_INT, 1, 2, MPI_COMM_WORLD);
}
else if (myrank == 1) {
   MPI_Recv(b, 10, MPI_INT, 0, 2, &status, MPI_COMM_WORLD);
   MPI_Recv(a, 10, MPI_INT, 0, 1, &status, MPI_COMM_WORLD);
}
...
```

Replacing either the send or the receive operations with non-blocking counterparts fixes this deadlock.

MPI Collective Communication

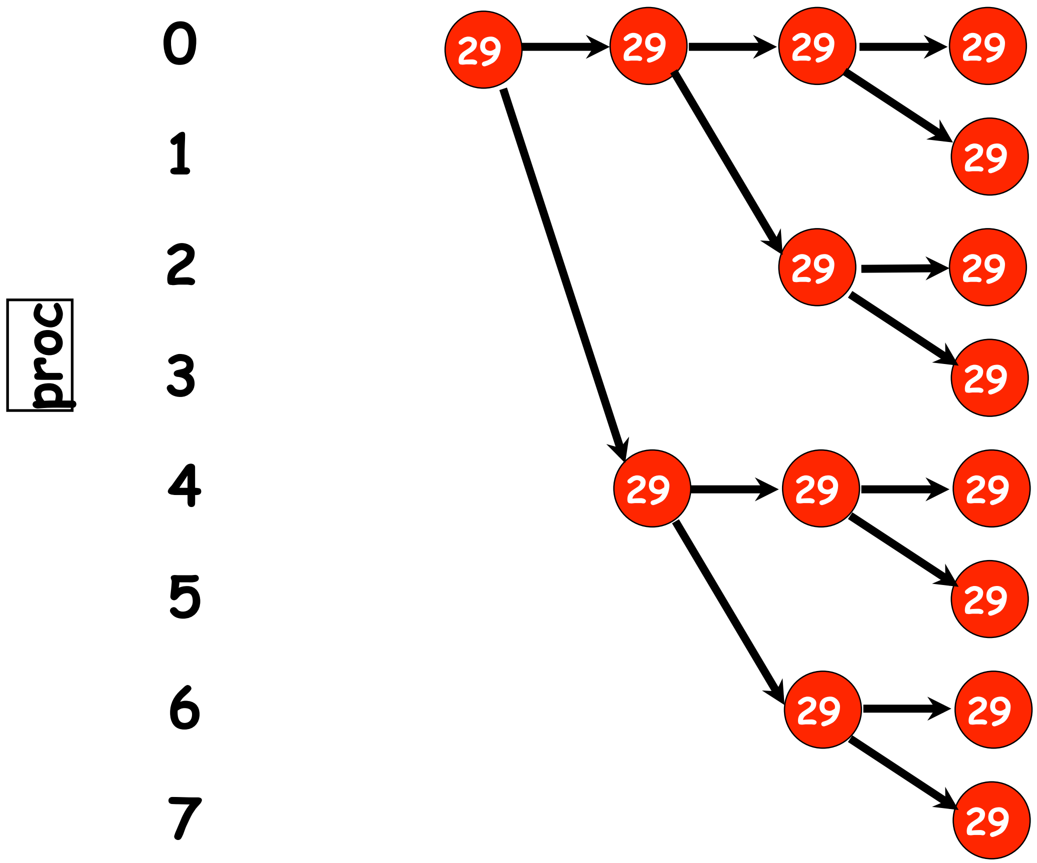
Collective Communications

- A popular feature of MPI is its family of collective communication operations.
- Each of these operations is defined over a communicator.
  - All processes in a communicator must perform the same operation
  - Implicit barrier (next)
- The simplest example is the broadcast operation: all processes invoke the operation, all agreeing on one root process. Data is broadcast from that root.

```
void Bcast(Object buf, int offset, int count, Datatype type,
  int root)
```

  - Broadcast a message from the process with rank root to all processes of the group.

MPI_Bcast



A root process sends same message to all

29 represents an array of values

Simple tree broadcast

More Examples of Collective Operations

- All the following are instance methods of Intracom:

  void Barrier()

  - Blocks the caller until all processes in the group have called it.

  void Gather(Object sendbuf, int sendoffset, int sendcount, Datatype sendtype, Object recvbuf, int recvoffset, int recvcount, Datatype recvtype, int root)

  - Each process sends the contents of its send buffer to the root process.

  void Scatter(Object sendbuf, int sendoffset, int sendcount, Datatype sendtype, Object recvbuf, int recvoffset, int recvcount, Datatype recvtype, int root)

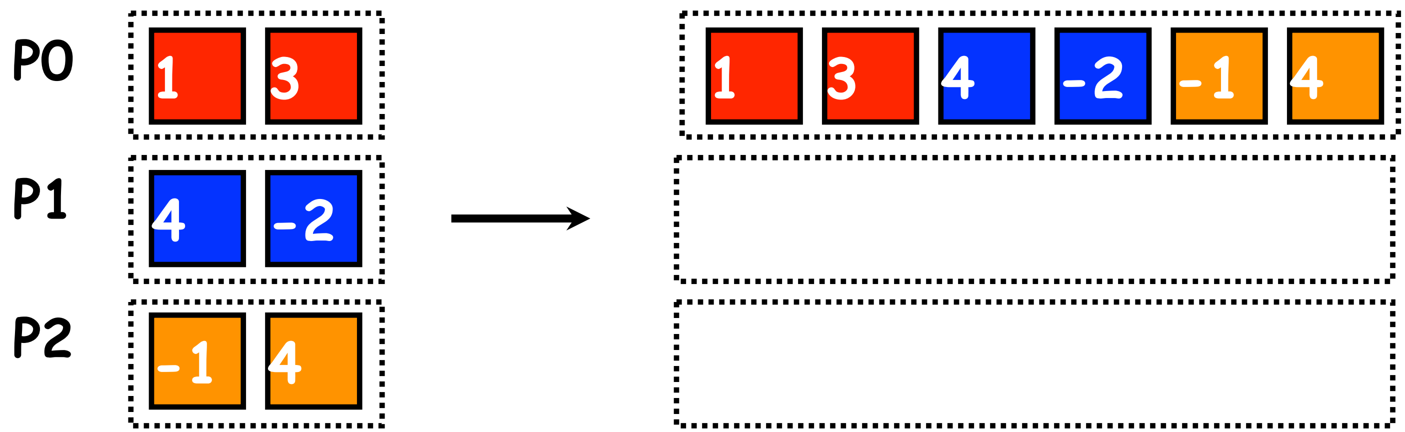
  - Inverse of the operation Gather.

  void Reduce(Object sendbuf, int sendoffset, Object recvbuf, int recvoffset, int count, Datatype datatype, Op op, int root)

  - Combine elements in send buffer of each process using the reduce operation, and return the combined value in the receive buffer of the root process.

MPI_Gather

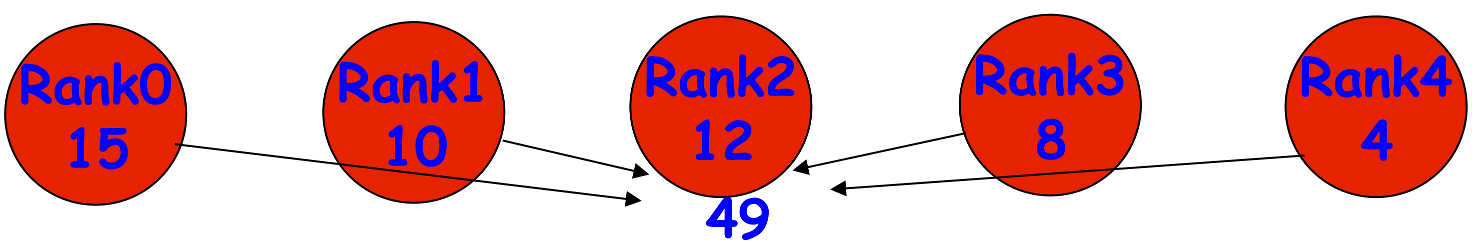
- On occasion it is necessary to copy an array of data from each process into a single array on a single process.
- Graphically:



- Note: only process 0 (P0) needs to supply storage for the output

MPI_Reduce

```
void MPI.COMM_WORLD.Reduce(
                    Object[]      sendbuf     /* in */,
                    int           sendoffset  /* in */,
                    Object[]      recvbuf     /* out */,
                    int           recvoffset  /* in */,
                    int           count       /* in */,
                    MPI.Datatype  datatype    /* in */,
                    MPI.Op        operator    /* in */,
                    int           root        /* in */ )
```




```
MPI.COMM_WORLD.Reduce( msg, 0, result, 0, 1, MPI.INT, MPI.SUM, 2);
```

Predefined Reduction Operations

Operation	Meaning	Datatypes
MPI_MAX	Maximum	C integers and floating point
MPI_MIN	Minimum	C integers and floating point
MPI_SUM	Sum	C integers and floating point
MPI_PROD	Product	C integers and floating point
MPI_LAND	Logical AND	C integers
MPI_BAND	Bit-wise AND	C integers and byte
MPI_LOR	Logical OR	C integers
MPI_BOR	Bit-wise OR	C integers and byte
MPI_LXOR	Logical XOR	C integers
MPI_BXOR	Bit-wise XOR	C integers and byte
MPI_MAXLOC	max-min value-location	Data-pairs
MPI_MINLOC	min-min value-location	Data-pairs

MPI_MAXLOC and MPI_MINLOC

- The operation `MPI_MAXLOC` combines pairs of values (v_i, l_i) and returns the pair (v, l) such that v is the maximum among all v_i 's and l is the corresponding l_i (if there are more than one, it is the smallest among all these l_i 's).
- `MPI_MINLOC` does the same, except for minimum value of v_i.

Value	15	17	11	12	17	11
Process	0	1	2	3	4	5

```
MinLoc(Value, Process) = (11, 2)
MaxLoc(Value, Process) = (17, 1)
```

An example use of the `MPI_MINLOC` and `MPI_MAXLOC` operators.

Datatypes for MPI_MAXLOC and MPI_MINLOC

MPI datatypes for data-pairs used with the `MPI_MAXLOC` and `MPI_MINLOC` reduction operations.

MPI Datatype	C Datatype
`MPI_2INT`	pair of ints
`MPI_SHORT_INT`	short and int
`MPI_LONG_INT`	long and int
`MPI_LONG_DOUBLE_INT`	long double and int
`MPI_FLOAT_INT`	float and int
`MPI_DOUBLE_INT`	double and int

More Collective Communication Operations

- If the result of the reduction operation is needed by all processes, MPI provides:

```
int MPI_Allreduce(void *sendbuf, void *recvbuf,
        int count, MPI_Datatype datatype, MPI_Op op,
  MPI_Comm comm)
```

- MPI also provides the MPI_Allgather function in which the data are gathered at all the processes.

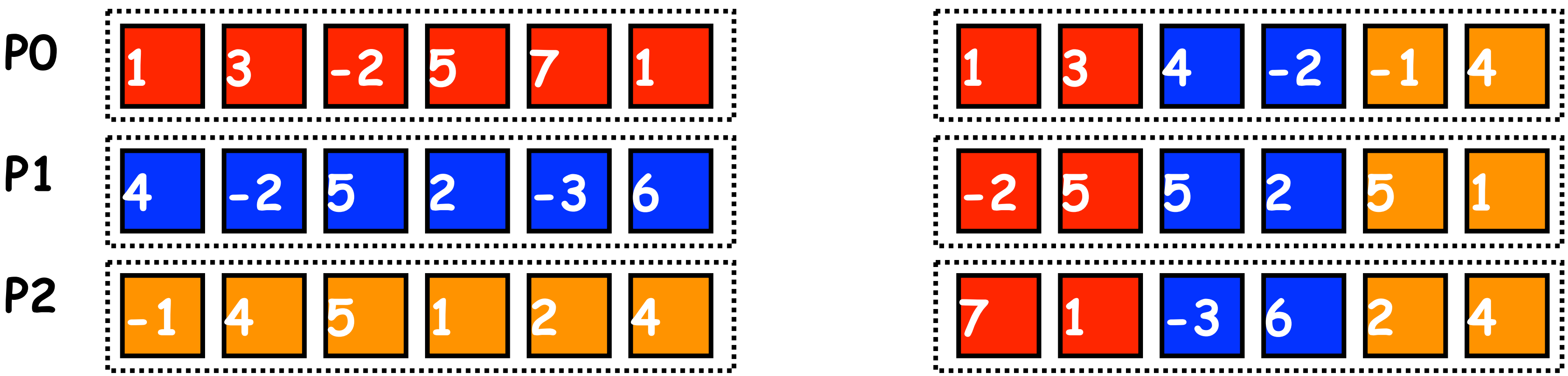
```
int MPI_Allgather(void *sendbuf, int sendcount,
  MPI_Datatype senddatatype, void *recvbuf,
        int recvcount, MPI_Datatype recvdatatype,
        MPI_Comm comm)
```

- To compute prefix-sums, MPI provides:

```
int MPI_Scan(void *sendbuf, void *recvbuf, int count,
  MPI_Datatype datatype, MPI_Op op,
        MPI_Comm comm)
```

MPI_Alltoall

```
int MPI_Alltoall(void *sendbuf, int sendcount,
          MPI_Datatype senddatatype, void *recvbuf,
          int recvcount, MPI_Datatype recvdatatype,
          MPI_Comm comm)
```



- **Each process submits an array to MPI_Alltoall.**
- **The array on each process is split into *nprocs* sub-arrays**
- **Sub-array *n* from process *m* is sent to process *n* placed in the *m*'th block in the result array.**

Groups and Communicators

- In many parallel algorithms, communication operations need to be restricted to certain subsets of processes.
- MPI provides mechanisms for partitioning the group of processes that belong to a communicator into subgroups each corresponding to a different communicator.
- The simplest such mechanism is:

```
int MPI_Comm_split(MPI_Comm comm, int color, int key,
                   MPI_Comm *newcomm)
```

- This operation groups processors by color and sorts resulting groups on the key.

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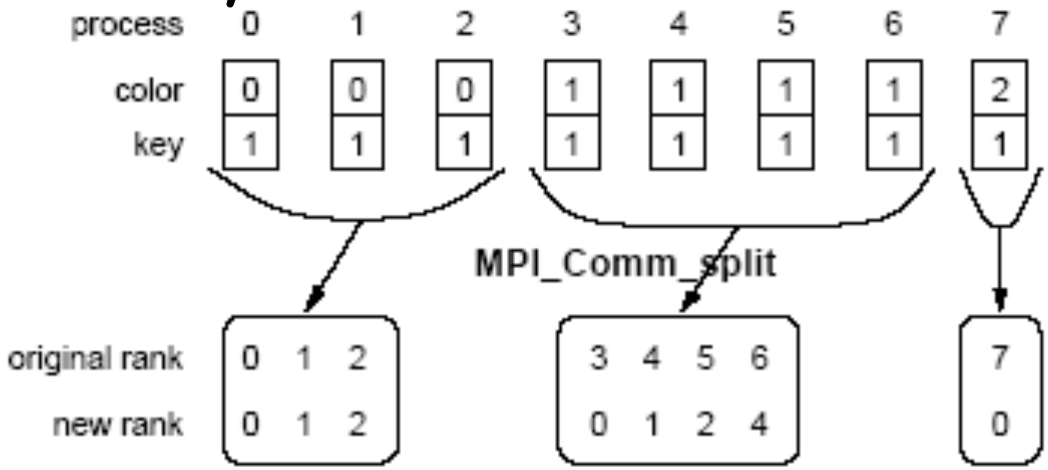

Summary of MPI Collective Communications

- A large number of collective operations are available with MPI
- Too many to mention...
- This table summarizes some of the most useful collective operations

Collective Function	Action
MPI_Gather	gather together arrays from all processes in comm
MPI_Reduce	reduce (elementwise) arrays from all processes in communicator
MPI_Scatter	a “root” process sends consecutive chunks of an array to all processes
MPI_Alltoall	Block transpose
MPI_Bcast	a “root” process sends the same array of data to all processes.