Distributed Memory Machines and Programming

Lecture 7

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Slides from Kathy Yelick

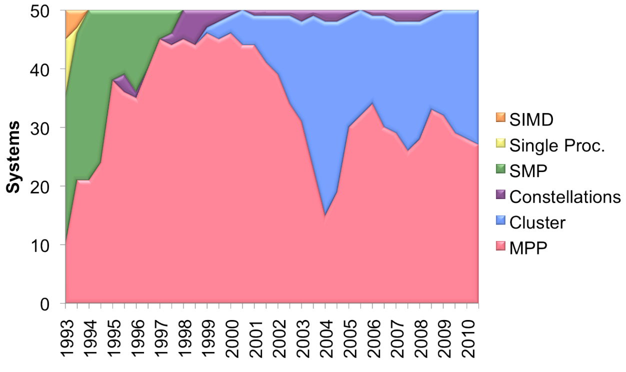
Recap of Lecture 6

- Shared memory multiprocessors
  - Caches may be either shared or distributed.
    - Multicore chips are likely to have shared caches
    - Cache hit performance is better if they are distributed (each cache is smaller/closer) but they must be kept coherent -- multiple cached copies of same location must be kept equal.
  - Requires clever hardware (see CS258, CS252).
  - Distant memory much more expensive to access.
  - Machines scale to 10s or 100s of processors.
- Shared memory programming
  - Starting, stopping threads.
  - Communication by reading/writing shared variables.
  - Synchronization with locks, barriers.

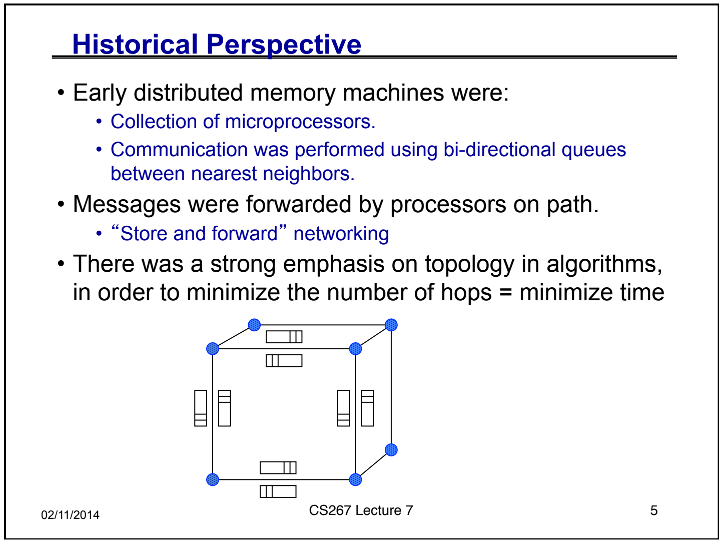
Outline

- Distributed Memory Architectures
  - Properties of communication networks
  - Topologies
  - Performance models
- Programming Distributed Memory Machines using Message Passing
  - Overview of MPI
  - Basic send/receive use
  - Non-blocking communication
  - Collectives

Architectures (TOP50)

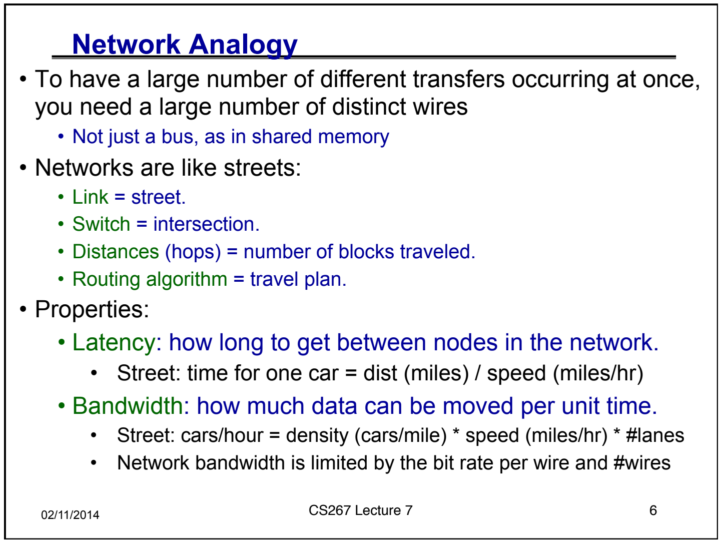


Top500 similar: 100% Cluster + MPP since 2009



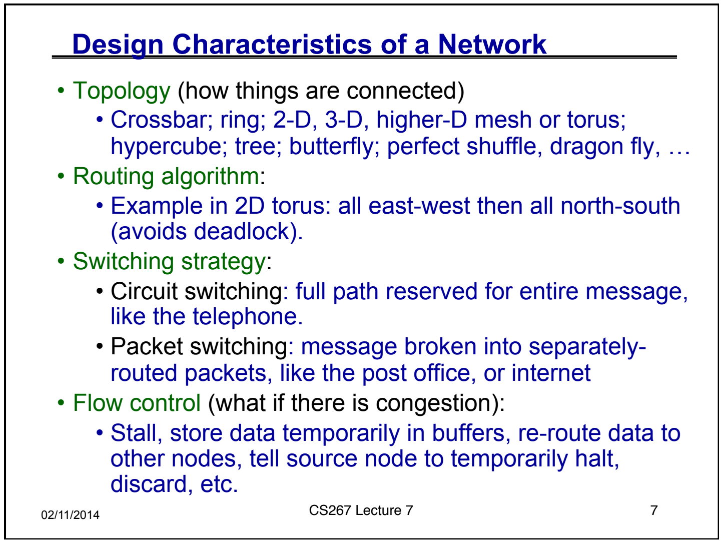
Historical Perspective

- Early distributed memory machines were:
  - Collection of microprocessors.
  - Communication was performed using bi-directional queues between nearest neighbors.
- Messages were forwarded by processors on path.
  - “Store and forward” networking
- There was a strong emphasis on topology in algorithms, in order to minimize the number of hops = minimize time



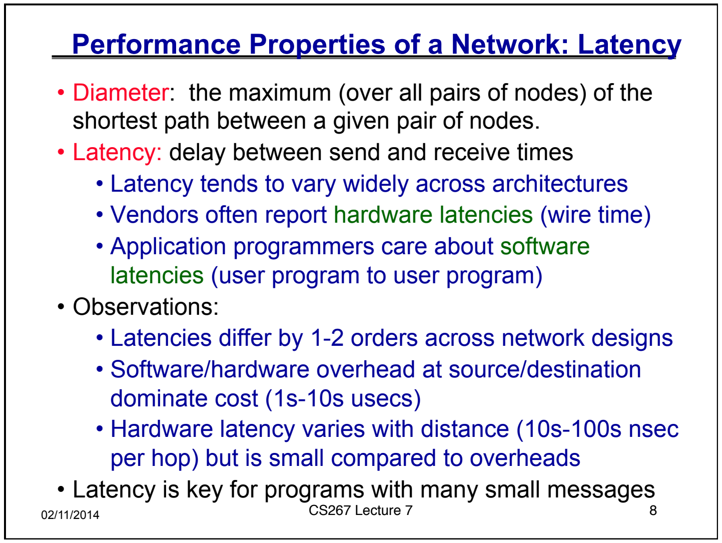
Network Analogy

- To have a large number of different transfers occurring at once, you need a large number of distinct wires
  - Not just a bus, as in shared memory
- Networks are like streets:
  - Link = street.
  - Switch = intersection.
  - Distances (hops) = number of blocks traveled.
  - Routing algorithm = travel plan.
- Properties:
  - Latency: how long to get between nodes in the network.
    - Street: time for one car = dist (miles) / speed (miles/hr)
  - Bandwidth: how much data can be moved per unit time.
    - Street: cars/hour = density (cars/mile) * speed (miles/hr) * #lanes
    - Network bandwidth is limited by the bit rate per wire and #wires



Design Characteristics of a Network

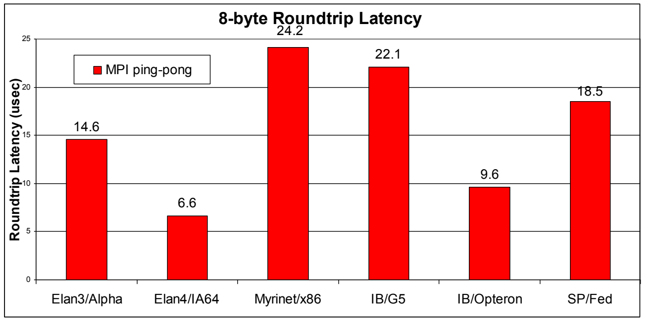
- Topology (how things are connected)
  - Crossbar; ring; 2-D, 3-D, higher-D mesh or torus; hypercube; tree; butterfly; perfect shuffle, dragon fly, …
- Routing algorithm:
  - Example in 2D torus: all east-west then all north-south (avoids deadlock).
- Switching strategy:
  - Circuit switching: full path reserved for entire message, like the telephone.
  - Packet switching: message broken into separately-routed packets, like the post office, or internet
- Flow control (what if there is congestion):
  - Stall, store data temporarily in buffers, re-route data to other nodes, tell source node to temporarily halt, discard, etc.



Performance Properties of a Network: Latency

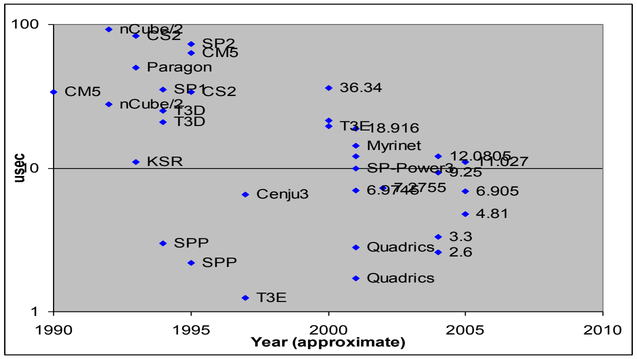
- Diameter: the maximum (over all pairs of nodes) of the shortest path between a given pair of nodes.
- Latency: delay between send and receive times
  - Latency tends to vary widely across architectures
  - Vendors often report hardware latencies (wire time)
  - Application programmers care about software latencies (user program to user program)
- Observations:
  - Latencies differ by 1-2 orders across network designs
  - Software/hardware overhead at source/destination dominate cost (1s-10s usecs)
  - Hardware latency varies with distance (10s-100s nsec per hop) but is small compared to overheads
- Latency is key for programs with many small messages

Latency on Some Machines/Networks



- Latencies shown are from a ping-pong test using MPI
- These are roundtrip numbers: many people use ½ of roundtrip time to approximate 1-way latency (which can't easily be measured)

End to End Latency (1/2 roundtrip) Over Time

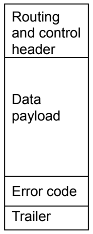


- Latency has not improved significantly, unlike Moore's Law
  - T3E (shmem) was lowest point – in 1997

Data from Kathy Yelick, UCB and NERSC

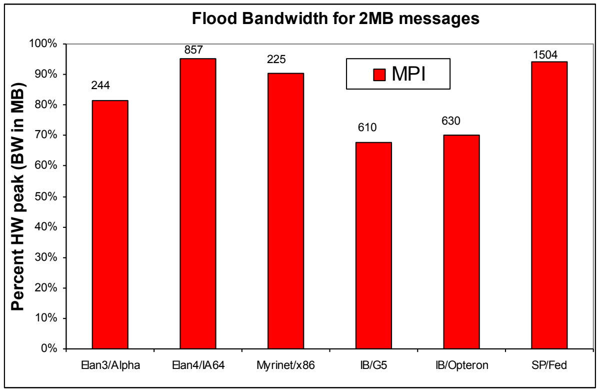
Performance Properties of a Network: Bandwidth

- The bandwidth of a link = # wires / time-per-bit
- Bandwidth typically in Gigabytes/sec (GB/s), i.e., 8* 2^{20} bits per second
- Effective bandwidth is usually lower than physical link bandwidth due to packet overhead.



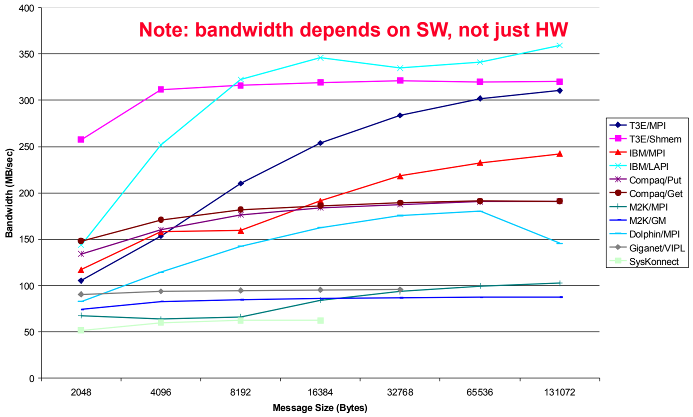
- Bandwidth is important for applications with mostly large messages

Bandwidth on Existing Networks



- Flood bandwidth (throughput of back-to-back 2MB messages)

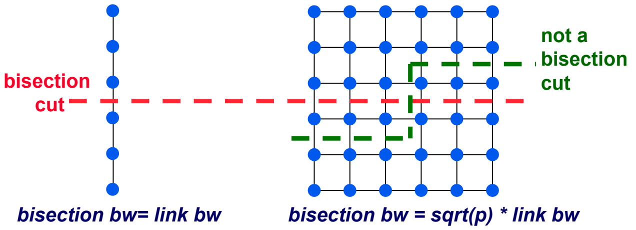
Bandwidth Chart



Data from Mike Welcome, NERSC

Performance Properties of a Network: Bisection Bandwidth

- Bisection bandwidth: bandwidth across smallest cut that divides network into two equal halves
- Bandwidth across "narrowest" part of the network



bisection cut

not a bisection cut

bisection bw= link bw

*bisection bw = sqrt(p) * link bw*

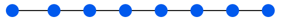
- Bisection bandwidth is important for algorithms in which all processors need to communicate with all others

Network Topology

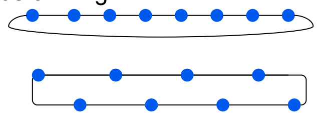
- In the past, there was considerable research in network topology and in mapping algorithms to topology.
  - Key cost to be minimized: number of "hops" between nodes (e.g. "store and forward")
  - Modern networks hide hop cost (i.e., "wormhole routing"), so topology less of a factor in performance of many algorithms
- Example: On IBM SP system, hardware latency varies from 0.5 usec to 1.5 usec, but user-level message passing latency is roughly 36 usec.
- Need some background in network topology
  - Algorithms may have a communication topology
  - Example later of big performance impact

Linear and Ring Topologies

- Linear array



  - Diameter = n-1; average distance ~n/3.
  - Bisection bandwidth = 1 (in units of link bandwidth).
- Torus or Ring

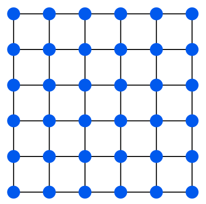


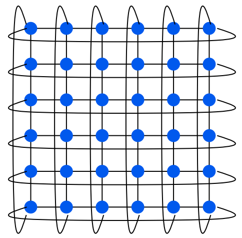
  - Diameter = n/2; average distance ~ n/4.
  - Bisection bandwidth = 2.
  - Natural for algorithms that work with 1D arrays.

Meshes and Tori – used in Hopper

Two dimensional mesh
- **Diameter = 2 * (sqrt(n) – 1)**
- **Bisection bandwidth = sqrt(n)**

Two dimensional torus
- **Diameter = sqrt(n)**
- **Bisection bandwidth = 2* sqrt(n)**

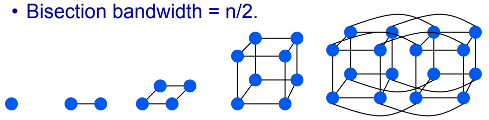




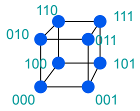
- **Generalizes to higher dimensions**
  - **Cray XT (eg Hopper@NERSC) uses 3D Torus**
- **Natural for algorithms that work with 2D and/or 3D arrays (matmul)**

Hypercubes

- Number of nodes n = 2^d for dimension d.
  - Diameter = d.
  - Bisection bandwidth = n/2.

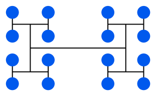


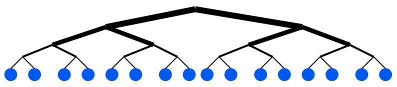
- 0d 1d 2d 3d 4d
- Popular in early machines (Intel iPSC, NCUBE).
  - Lots of clever algorithms.
  - See 1996 online CS267 notes.
- Greycode addressing:
  - Each node connected to d others with 1 bit different.

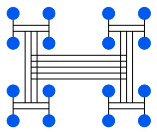


Trees

- Diameter = log n.
- Bisection bandwidth = 1.
- Easy layout as planar graph.
- Many tree algorithms (e.g., summation).
- Fat trees avoid bisection bandwidth problem:
  - More (or wider) links near top.
  - Example: Thinking Machines CM-5.



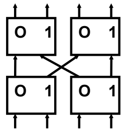




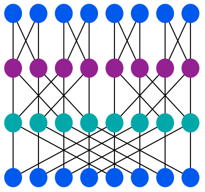
Butterflies

- Diameter = log n.
- Bisection bandwidth = n.
- Cost: lots of wires.
- Used in BBN Butterfly.
- Natural for FFT.

Ex: to get from proc 101 to 110, Compare bit-by-bit and Switch if they disagree, else not



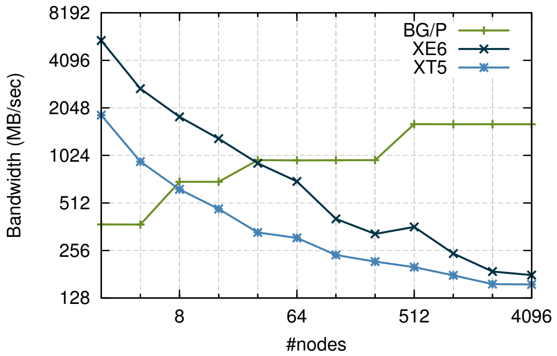
butterfly switch



multistage butterfly network

Does Topology Matter?

1 MB multicast on BG/P, Cray XT5, and Cray XE6



See EECS Tech Report *UCB/EECS-2011-92*, August 2011

Dragonflies – used in Edison

- Motivation: Exploit gap in cost and performance between optical interconnects (which go between cabinets in a machine room) and electrical networks (inside cabinet)
  - Optical more expensive but higher bandwidth when long
  - Electrical networks cheaper, faster when short
- Combine in hierarchy
  - One-to-many via electrical networks inside cabinet
  - Just a few long optical interconnects between cabinets
- Clever routing algorithm to avoid bottlenecks:
  - Route from source to randomly chosen intermediate cabinet
  - Route from intermediate cabinet to destination
- Outcome: programmer can (usually) ignore topology, get good performance
  - Important in virtualized, dynamic environment
  - Programmer can still create serial bottlenecks
- Details in "Technology-Drive, Highly-Scalable Dragonfly Topology," J. Kim. W. Dally, S. Scott, D. Abts, ISCA 2008

Evolution of Distributed Memory Machines

- Special queue connections are being replaced by direct memory access (DMA):
  - Network Interface (NI) processor packs or copies messages.
  - CPU initiates transfer, goes on computing.
- Wormhole routing in hardware:
  - NIs do not interrupt CPUs along path.
  - Long message sends are pipelined.
  - NIs don't wait for complete message before forwarding
- Message passing libraries provide store-and-forward abstraction:
  - Can send/receive between any pair of nodes, not just along one wire.
  - Time depends on distance since each NI along path must participate.

Performance Models

Shared Memory Performance Models

- Parallel Random Access Memory (PRAM)
- All memory access operations complete in one clock period -- no concept of memory hierarchy ("too good to be true").
  - OK for understanding whether an algorithm has enough parallelism at all (see CS273).
  - Parallel algorithm design strategy: first do a PRAM algorithm, then worry about memory/communication time (sometimes works)
- Slightly more realistic versions exist
  - E.g., Concurrent Read Exclusive Write (CREW) PRAM.
  - Still missing the memory hierarchy

Latency and Bandwidth Model

- Time to send message of length n is roughly

Time = latency + n*cost_per_word
= latency + n/bandwidth

- Topology is assumed irrelevant.
- Often called "α−β model" and written

Time = α + n*β

- Usually α >> β >> time per flop.
  - One long message is cheaper than many short ones.

$$\alpha + n*\beta \;<<\; n*(\alpha + 1*\beta)$$

  - Can do hundreds or thousands of flops for cost of one message.
- Lesson: Need large computation-to-communication ratio to be efficient.
- LogP – more detailed model (**L**atency/**o**verhead/**g**ap/**P**roc.)

Alpha-Beta Parameters on Current Machines

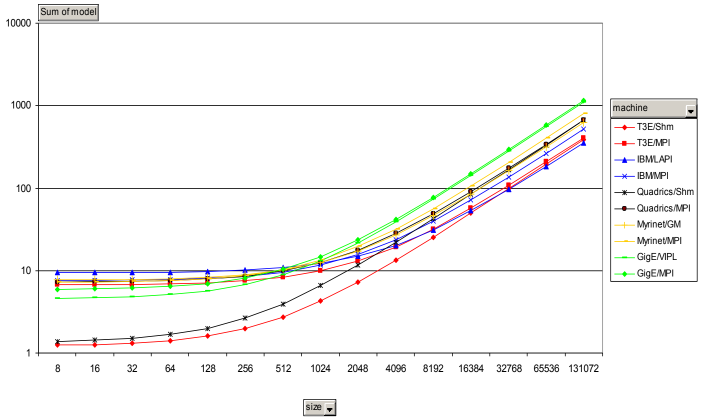
- These numbers were obtained empirically

machine	α	β
T3E/Shm	1.2	0.003
T3E/MPI	6.7	0.003
IBM/LAPI	9.4	0.003
IBM/MPI	7.6	0.004
Quadrics/Get	3.267	0.00498
Quadrics/Shm	1.3	0.005
Quadrics/MPI	7.3	0.005
Myrinet/GM	7.7	0.005
Myrinet/MPI	7.2	0.006
Dolphin/MPI	7.767	0.00529
Giganet/VIPL	3.0	0.010
GigE/VIPL	4.6	0.008
GigE/MPI	5.854	0.00872

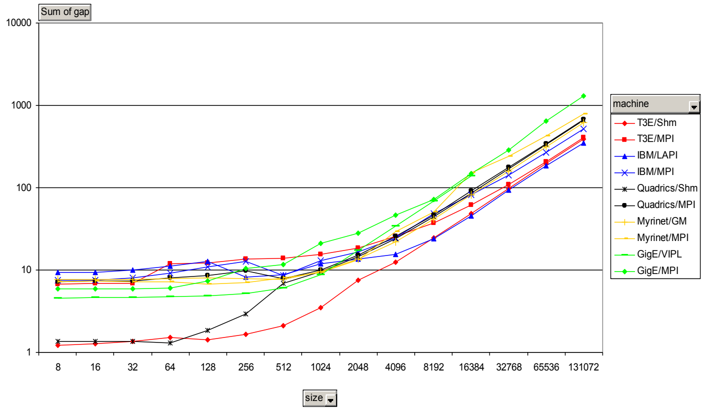
α is latency in usecs
β is BW in usecs per Byte

How well does the model
Time = α + n*β
predict actual performance?

Model Time Varying Message Size & Machines



Measured Message Time



Programming Distributed Memory Machines with Message Passing

Slides from
Jonathan Carter (jtcarter@lbl.gov),
Katherine Yelick (yelick@cs.berkeley.edu),
Bill Gropp (wgropp@illinois.edu)

Message Passing Libraries (1)

- Many “message passing libraries” were once available
  - Chameleon, from ANL.
  - CMMD, from Thinking Machines.
  - Express, commercial.
  - MPL, native library on IBM SP-2.
  - NX, native library on Intel Paragon.
  - Zipcode, from LLL.
  - PVM, Parallel Virtual Machine, public, from ORNL/UTK.
  - Others...
  - MPI, Message Passing Interface, now the industry standard.
- Need standards to write portable code.

Message Passing Libraries (2)

- All communication, synchronization require subroutine calls
  - No shared variables
  - Program run on a single processor just like any uniprocessor program, except for calls to message passing library
- Subroutines for
  - Communication
    - Pairwise or point-to-point: Send and Receive
    - Collectives all processor get together to
      - Move data: Broadcast, Scatter/gather
      - Compute and move: sum, product, max, prefix sum, … of data on many processors
  - Synchronization
    - Barrier
    - No locks because there are no shared variables to protect
  - Enquiries
    - How many processes? Which one am I? Any messages waiting?

Novel Features of MPI

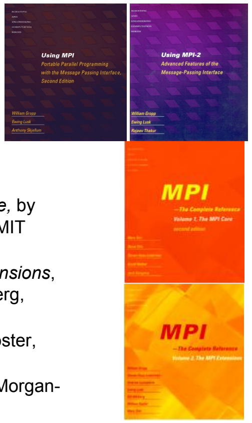
- Communicators encapsulate communication spaces for library safety
- Datatypes reduce copying costs and permit heterogeneity
- Multiple communication modes allow precise buffer management
- Extensive collective operations for scalable global communication
- Process topologies permit efficient process placement, user views of process layout
- Profiling interface encourages portable tools

MPI References

- The Standard itself:
  - at http://www.mpi-forum.org
  - All MPI official releases, in both postscript and HTML
  - Latest version MPI 3.0, released Sept 2012
- Other information on Web:
  - at http://www.mcs.anl.gov/mpi
  - pointers to lots of stuff, including other talks and tutorials, a FAQ, other MPI pages

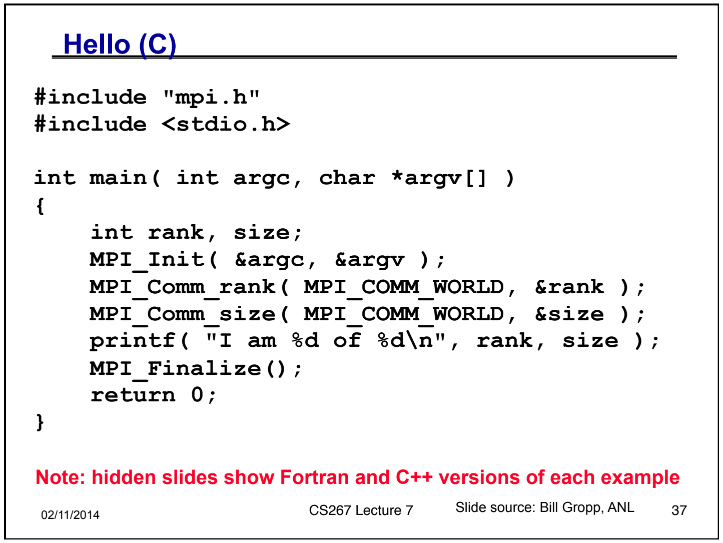
Books on MPI

- *Using MPI: Portable Parallel Programming with the Message-Passing Interface (2nd edition)*, by Gropp, Lusk, and Skjellum, MIT Press, 1999.
- *Using MPI-2: Portable Parallel Programming with the Message-Passing Interface*, by Gropp, Lusk, and Thakur, MIT Press, 1999.
- *MPI: The Complete Reference - Vol 1 The MPI Core*, by Snir, Otto, Huss-Lederman, Walker, and Dongarra, MIT Press, 1998.
- *MPI: The Complete Reference - Vol 2 The MPI Extensions*, by Gropp, Huss-Lederman, Lumsdaine, Lusk, Nitzberg, Saphir, and Snir, MIT Press, 1998.
- *Designing and Building Parallel Programs*, by Ian Foster, Addison-Wesley, 1995.
- *Parallel Programming with MPI*, by Peter Pacheco, Morgan-Kaufmann, 1997.



Finding Out About the Environment

- Two important questions that arise early in a parallel program are:
  - How many processes are participating in this computation?
  - Which one am I?
- MPI provides functions to answer these questions:
  - `MPI_Comm_size` reports the number of processes.
  - `MPI_Comm_rank` reports the *rank*, a number between 0 and size-1, identifying the calling process



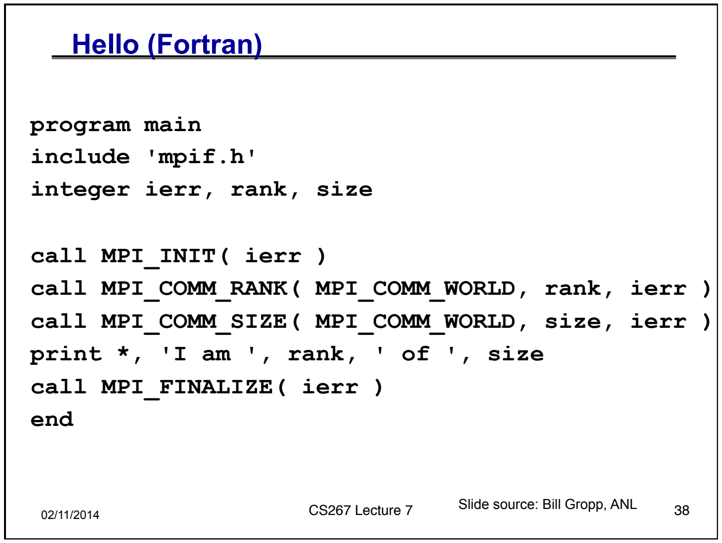
Hello (C)

```
#include "mpi.h"
#include <stdio.h>

int main( int argc, char *argv[] )
{
    int rank, size;
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &rank );
    MPI_Comm_size( MPI_COMM_WORLD, &size );
    printf( "I am %d of %d\n", rank, size );
    MPI_Finalize();
    return 0;
}
```

Note: hidden slides show Fortran and C++ versions of each example

02/11/2014 CS267 Lecture 7 Slide source: Bill Gropp, ANL 37



Hello (Fortran)

```
program main
include 'mpif.h'
integer ierr, rank, size

call MPI_INIT( ierr )
call MPI_COMM_RANK( MPI_COMM_WORLD, rank, ierr )
call MPI_COMM_SIZE( MPI_COMM_WORLD, size, ierr )
print *, 'I am ', rank, ' of ', size
call MPI_FINALIZE( ierr )
end
```

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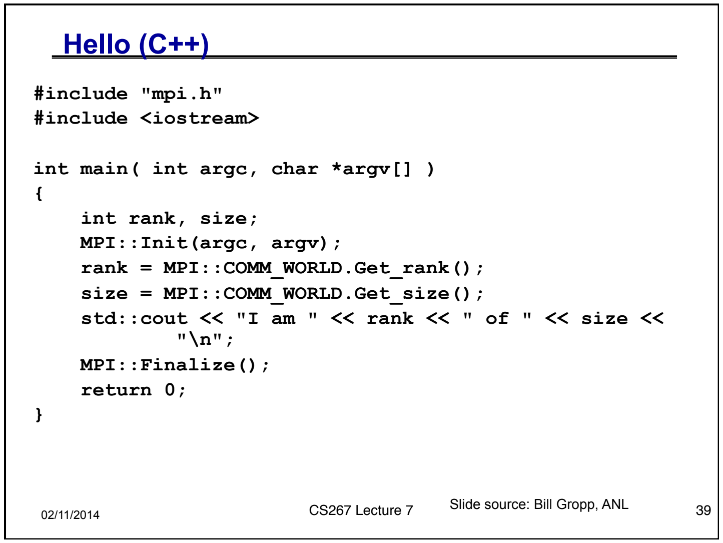

Hello (C++)

```
#include "mpi.h"
#include <iostream>

int main( int argc, char *argv[] )
{
    int rank, size;
    MPI::Init(argc, argv);
    rank = MPI::COMM_WORLD.Get_rank();
    size = MPI::COMM_WORLD.Get_size();
    std::cout << "I am " << rank << " of " << size <<
            "\n";
    MPI::Finalize();
    return 0;
}
```

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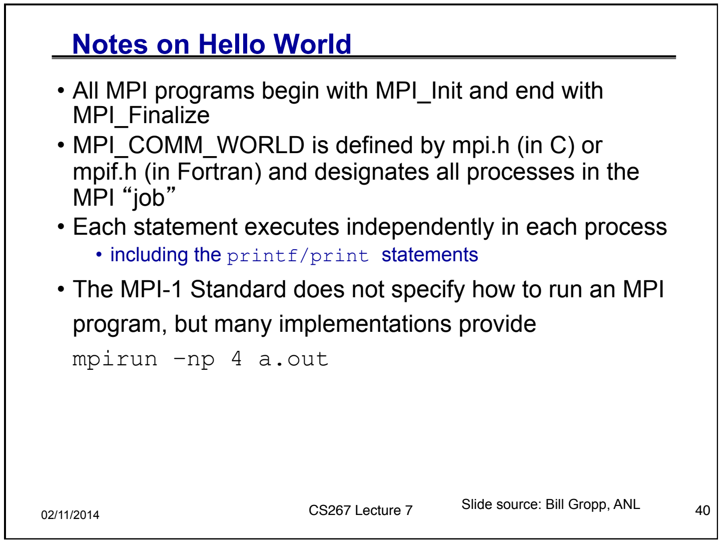

Notes on Hello World

- All MPI programs begin with MPI_Init and end with MPI_Finalize
- MPI_COMM_WORLD is defined by mpi.h (in C) or mpif.h (in Fortran) and designates all processes in the MPI "job"
- Each statement executes independently in each process
  - including the `printf/print` statements
- The MPI-1 Standard does not specify how to run an MPI program, but many implementations provide

```
mpirun -np 4 a.out
```

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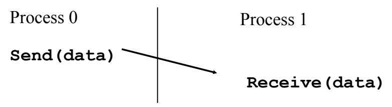
MPI Basic Send/Receive

- We need to fill in the details in



- Things that need specifying:
  - How will “data” be described?
  - How will processes be identified?
  - How will the receiver recognize/screen messages?
  - What will it mean for these operations to complete?

Slide source: Bill Gropp, ANL

Some Basic Concepts

- Processes can be collected into groups
- Each message is sent in a context, and must be received in the same context
  - Provides necessary support for libraries
- A group and context together form a communicator
- A process is identified by its rank in the group associated with a communicator
- There is a default communicator whose group contains all initial processes, called **`MPI_COMM_WORLD`**

Slide source: Bill Gropp, ANL

MPI Datatypes

- The data in a message to send or receive is described by a triple (address, count, datatype), where
- An MPI datatype is recursively defined as:
  - predefined, corresponding to a data type from the language (e.g., MPI_INT, MPI_DOUBLE)
  - a contiguous array of MPI datatypes
  - a strided block of datatypes
  - an indexed array of blocks of datatypes
  - an arbitrary structure of datatypes
- There are MPI functions to construct custom datatypes, in particular ones for subarrays
- May hurt performance if datatypes are complex

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MPI Tags

- Messages are sent with an accompanying user-defined integer tag, to assist the receiving process in identifying the message
- Messages can be screened at the receiving end by specifying a specific tag, or not screened by specifying MPI_ANY_TAG as the tag in a receive
- Some non-MPI message-passing systems have called tags “message types”. MPI calls them tags to avoid confusion with datatypes

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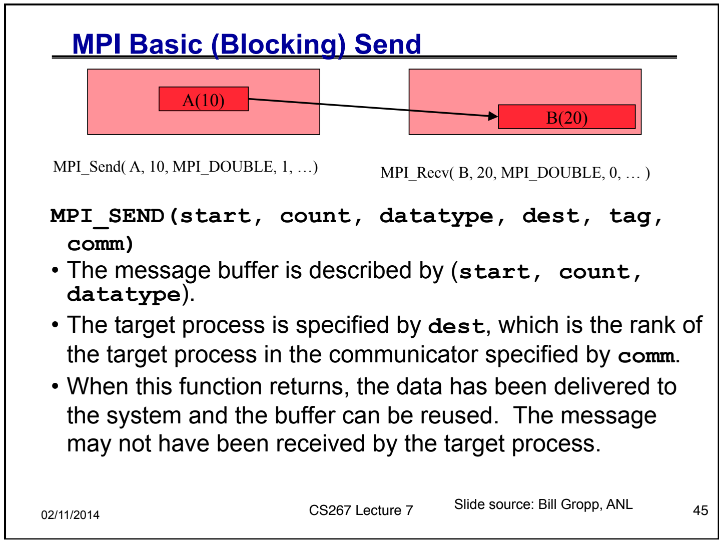

MPI Basic (Blocking) Send

MPI_Send(A, 10, MPI_DOUBLE, 1, …)

MPI_Recv(B, 20, MPI_DOUBLE, 0, …)

`MPI_SEND(start, count, datatype, dest, tag, comm)`

- The message buffer is described by (**`start, count, datatype`**).
- The target process is specified by **`dest`**, which is the rank of the target process in the communicator specified by **`comm`**.
- When this function returns, the data has been delivered to the system and the buffer can be reused. The message may not have been received by the target process.

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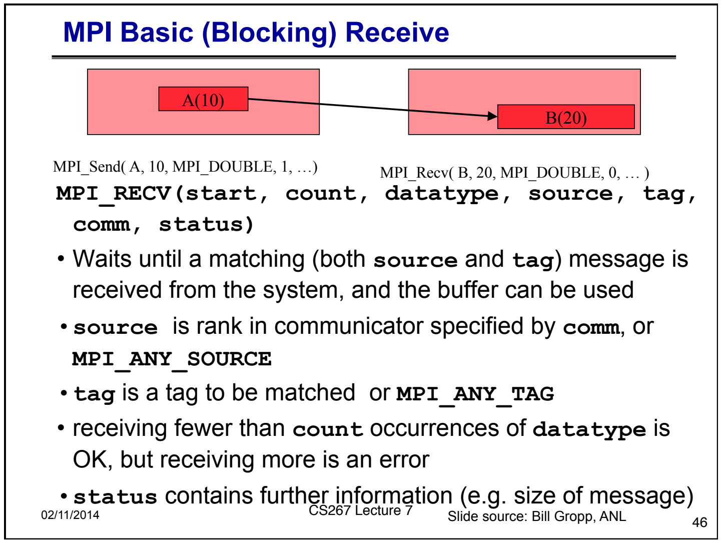

MPI Basic (Blocking) Receive

MPI_Send(A, 10, MPI_DOUBLE, 1, …)

MPI_Recv(B, 20, MPI_DOUBLE, 0, …)

`MPI_RECV(start, count, datatype, source, tag, comm, status)`

- Waits until a matching (both **`source`** and **`tag`**) message is received from the system, and the buffer can be used
- **`source`** is rank in communicator specified by **`comm`**, or **`MPI_ANY_SOURCE`**
- **`tag`** is a tag to be matched or **`MPI_ANY_TAG`**
- receiving fewer than **`count`** occurrences of **`datatype`** is OK, but receiving more is an error
- **`status`** contains further information (e.g. size of message)

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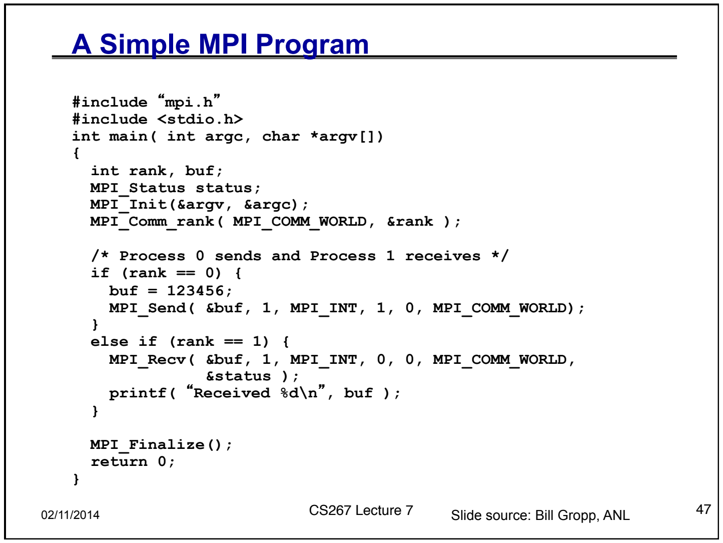

A Simple MPI Program

```
#include “mpi.h”
#include <stdio.h>
int main( int argc, char *argv[])
{
  int rank, buf;
  MPI_Status status;
  MPI_Init(&argv, &argc);
  MPI_Comm_rank( MPI_COMM_WORLD, &rank );

  /* Process 0 sends and Process 1 receives */
  if (rank == 0) {
    buf = 123456;
    MPI_Send( &buf, 1, MPI_INT, 1, 0, MPI_COMM_WORLD);
  }
  else if (rank == 1) {
    MPI_Recv( &buf, 1, MPI_INT, 0, 0, MPI_COMM_WORLD,
              &status );
    printf( “Received %d\n”, buf );
  }

  MPI_Finalize();
  return 0;
}
```

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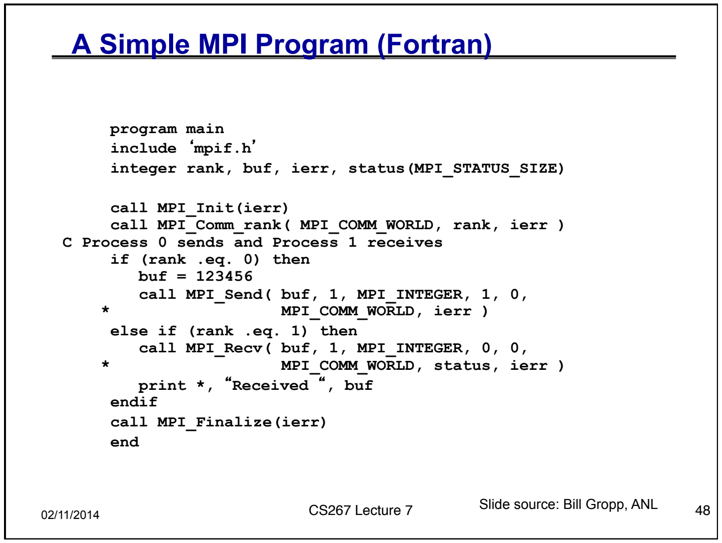

A Simple MPI Program (Fortran)

```
      program main
      include ‘mpif.h’
      integer rank, buf, ierr, status(MPI_STATUS_SIZE)

      call MPI_Init(ierr)
      call MPI_Comm_rank( MPI_COMM_WORLD, rank, ierr )
C Process 0 sends and Process 1 receives
      if (rank .eq. 0) then
         buf = 123456
         call MPI_Send( buf, 1, MPI_INTEGER, 1, 0,
     *                  MPI_COMM_WORLD, ierr )
      else if (rank .eq. 1) then
         call MPI_Recv( buf, 1, MPI_INTEGER, 0, 0,
     *                  MPI_COMM_WORLD, status, ierr )
         print *, “Received “, buf
      endif
      call MPI_Finalize(ierr)
      end
```

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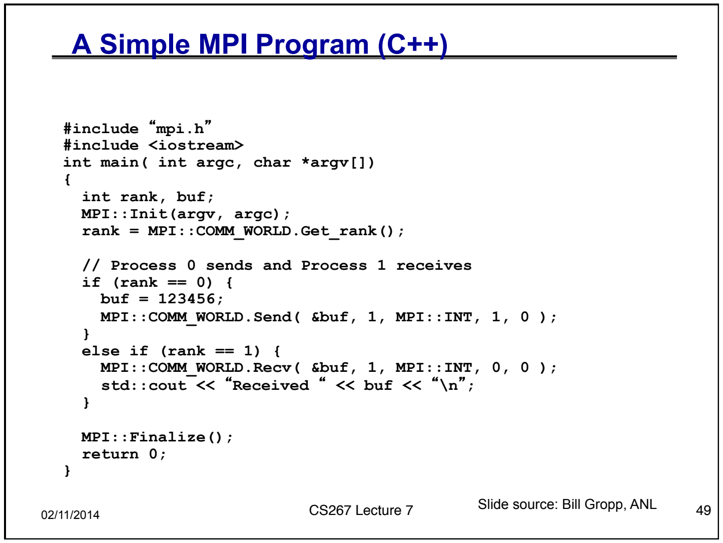

A Simple MPI Program (C++)

```
#include "mpi.h"
#include <iostream>
int main( int argc, char *argv[])
{
  int rank, buf;
  MPI::Init(argv, argc);
  rank = MPI::COMM_WORLD.Get_rank();

  // Process 0 sends and Process 1 receives
  if (rank == 0) {
    buf = 123456;
    MPI::COMM_WORLD.Send( &buf, 1, MPI::INT, 1, 0 );
  }
  else if (rank == 1) {
    MPI::COMM_WORLD.Recv( &buf, 1, MPI::INT, 0, 0 );
    std::cout << "Received " << buf << "\n";
  }

  MPI::Finalize();
  return 0;
}
```

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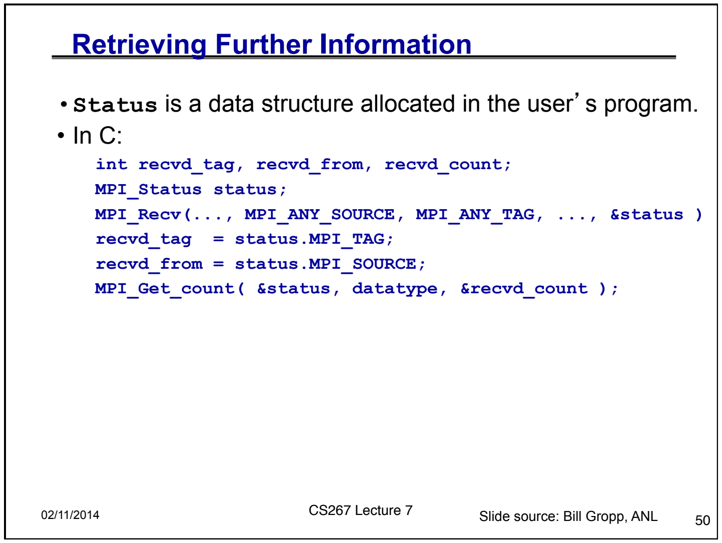

Retrieving Further Information

- `Status` is a data structure allocated in the user's program.
- In C:

```
int recvd_tag, recvd_from, recvd_count;
MPI_Status status;
MPI_Recv(..., MPI_ANY_SOURCE, MPI_ANY_TAG, ..., &status )
recvd_tag  = status.MPI_TAG;
recvd_from = status.MPI_SOURCE;
MPI_Get_count( &status, datatype, &recvd_count );
```

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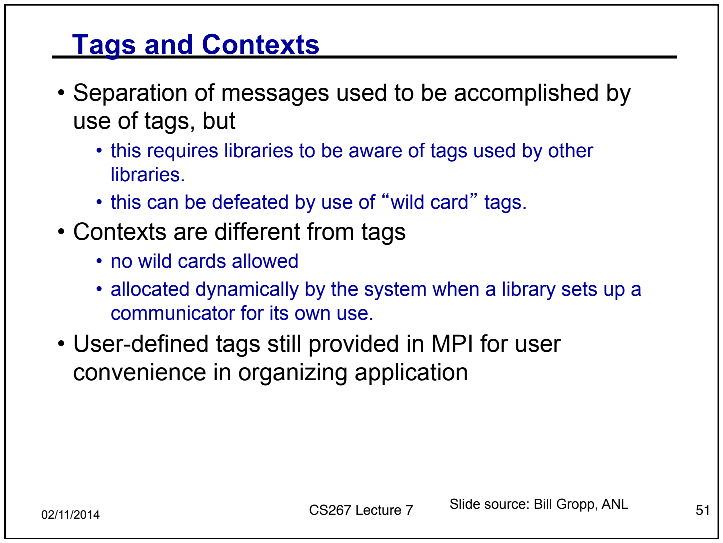

Tags and Contexts

- Separation of messages used to be accomplished by use of tags, but
  - this requires libraries to be aware of tags used by other libraries.
  - this can be defeated by use of "wild card" tags.
- Contexts are different from tags
  - no wild cards allowed
  - allocated dynamically by the system when a library sets up a communicator for its own use.
- User-defined tags still provided in MPI for user convenience in organizing application

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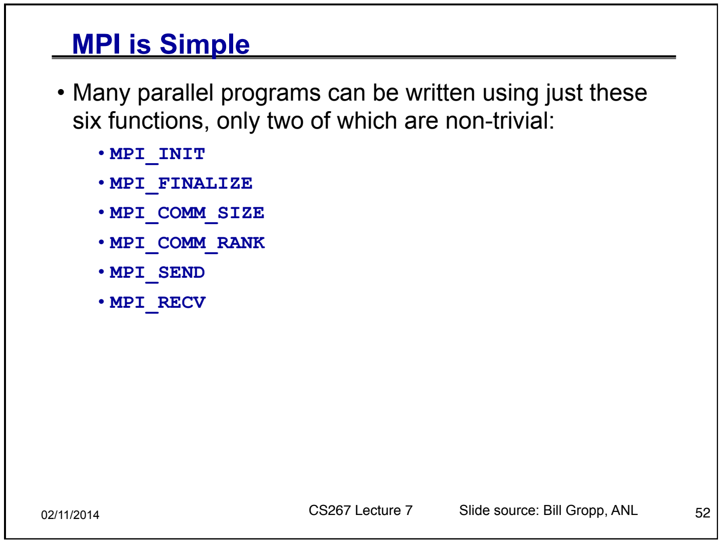

MPI is Simple

- Many parallel programs can be written using just these six functions, only two of which are non-trivial:
  - **MPI_INIT**
  - **MPI_FINALIZE**
  - **MPI_COMM_SIZE**
  - **MPI_COMM_RANK**
  - **MPI_SEND**
  - **MPI_RECV**

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Another Approach to Parallelism

- *Collective* routines provide a higher-level way to organize a parallel program
- Each process executes the same communication operations
- MPI provides a rich set of collective operations…

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Collective Operations in MPI

- Collective operations are called by all processes in a communicator
- **`MPI_BCAST`** distributes data from one process (the root) to all others in a communicator
- **`MPI_REDUCE`** combines data from all processes in communicator and returns it to one process
- In many numerical algorithms, **`SEND/RECEIVE`** can be replaced by **`BCAST/REDUCE`**, improving both simplicity and efficiency

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Alternative Set of 6 Functions

- Claim: most MPI applications can be written with only 6 functions (although which 6 may differ)

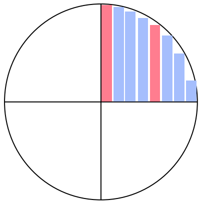
- Using point-to-point:
  - **`MPI_INIT`**
  - **`MPI_FINALIZE`**
  - **`MPI_COMM_SIZE`**
  - **`MPI_COMM_RANK`**
  - **`MPI_SEND`**
  - **`MPI_RECEIVE`**

- Using collectives:
  - **`MPI_INIT`**
  - **`MPI_FINALIZE`**
  - **`MPI_COMM_SIZE`**
  - **`MPI_COMM_RANK`**
  - **`MPI_BCAST`**
  - **`MPI_REDUCE`**

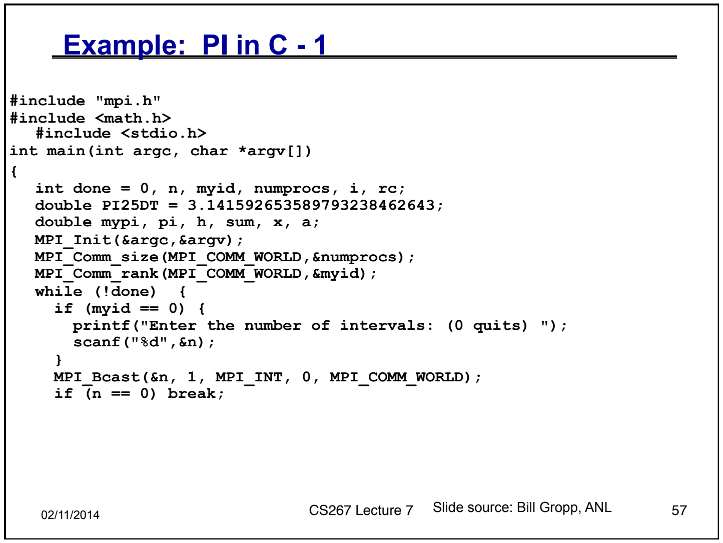
- You may use more for convenience or performance

Example: Calculating Pi

E.g., in a 4-process run, each process gets every 4th interval. Process 0 slices are in red.



- Simple program written in a data parallel style in MPI
  - E.g., for a reduction (recall “tricks with trees” lecture), each process will first reduce (sum) its own values, then call a collective to combine them
- Estimates pi by approximating the area of the quadrant of a unit circle
- Each process gets 1/p of the intervals (mapped round robin, i.e., a cyclic mapping)



Example: PI in C - 1

```
#include "mpi.h"
#include <math.h>
   #include <stdio.h>
int main(int argc, char *argv[])
{
   int done = 0, n, myid, numprocs, i, rc;
   double PI25DT = 3.141592653589793238462643;
   double mypi, pi, h, sum, x, a;
   MPI_Init(&argc,&argv);
   MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
   MPI_Comm_rank(MPI_COMM_WORLD,&myid);
   while (!done)  {
     if (myid == 0) {
       printf("Enter the number of intervals: (0 quits) ");
       scanf("%d",&n);
     }
     MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
     if (n == 0) break;
```

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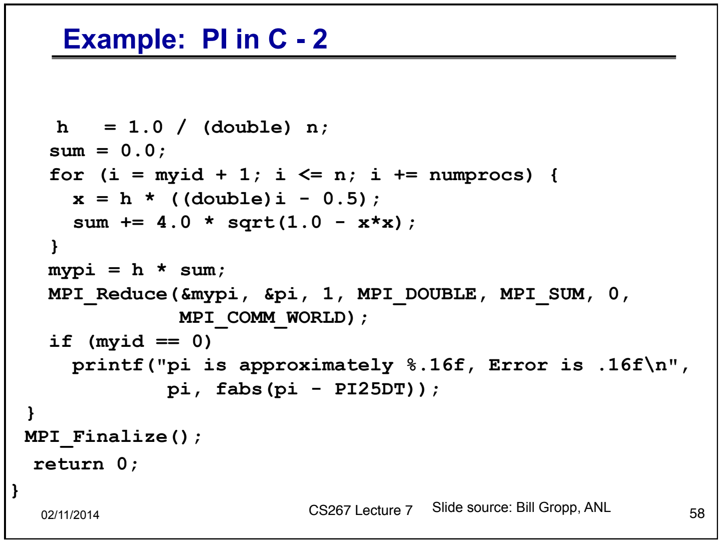

Example: PI in C - 2

```
    h   = 1.0 / (double) n;
   sum = 0.0;
   for (i = myid + 1; i <= n; i += numprocs) {
     x = h * ((double)i - 0.5);
     sum += 4.0 * sqrt(1.0 - x*x);
   }
   mypi = h * sum;
   MPI_Reduce(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0,
              MPI_COMM_WORLD);
   if (myid == 0)
     printf("pi is approximately %.16f, Error is .16f\n",
            pi, fabs(pi - PI25DT));
 }
 MPI_Finalize();
  return 0;
}
```

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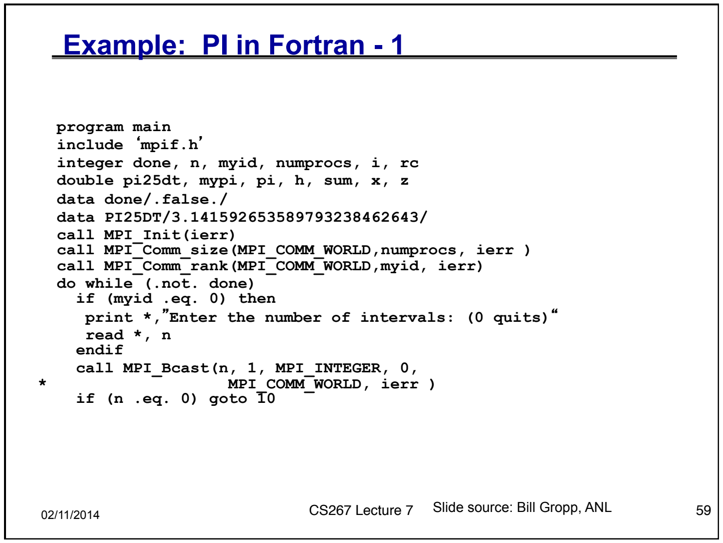

Example: PI in Fortran - 1

```
   program main
   include ‘mpif.h’
   integer done, n, myid, numprocs, i, rc
   double pi25dt, mypi, pi, h, sum, x, z
   data done/.false./
   data PI25DT/3.141592653589793238462643/
   call MPI_Init(ierr)
   call MPI_Comm_size(MPI_COMM_WORLD,numprocs, ierr )
   call MPI_Comm_rank(MPI_COMM_WORLD,myid, ierr)
   do while (.not. done)
     if (myid .eq. 0) then
      print *,”Enter the number of intervals: (0 quits)“
      read *, n
     endif
     call MPI_Bcast(n, 1, MPI_INTEGER, 0,
*                   MPI_COMM_WORLD, ierr )
     if (n .eq. 0) goto 10
```

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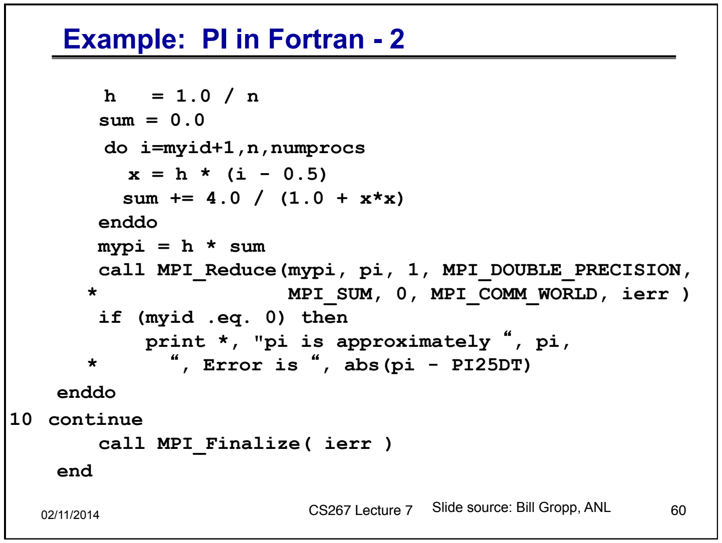

Example: PI in Fortran - 2

```
        h   = 1.0 / n
       sum = 0.0
        do i=myid+1,n,numprocs
          x = h * (i - 0.5)
         sum += 4.0 / (1.0 + x*x)
       enddo
       mypi = h * sum
       call MPI_Reduce(mypi, pi, 1, MPI_DOUBLE_PRECISION,
      *                MPI_SUM, 0, MPI_COMM_WORLD, ierr )
       if (myid .eq. 0) then
           print *, "pi is approximately “, pi,
      *       “, Error is “, abs(pi - PI25DT)
    enddo
10  continue
       call MPI_Finalize( ierr )
    end
```

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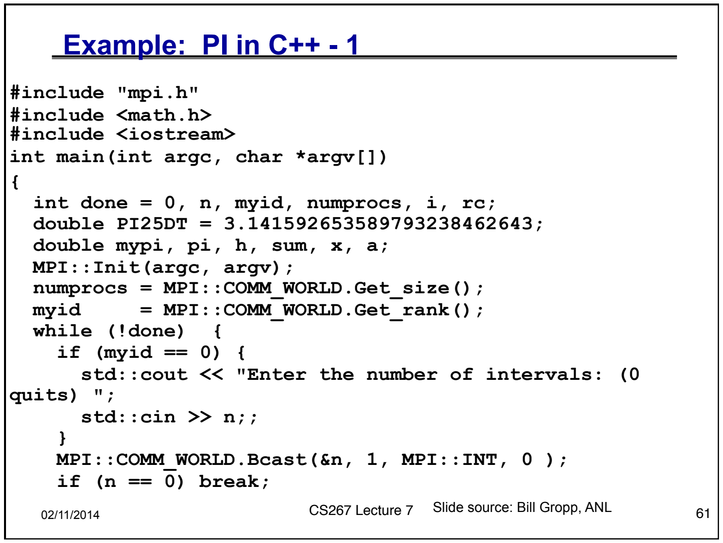

Example: PI in C++ - 1

```
#include "mpi.h"
#include <math.h>
#include <iostream>
int main(int argc, char *argv[])
{
  int done = 0, n, myid, numprocs, i, rc;
  double PI25DT = 3.141592653589793238462643;
  double mypi, pi, h, sum, x, a;
  MPI::Init(argc, argv);
  numprocs = MPI::COMM_WORLD.Get_size();
  myid     = MPI::COMM_WORLD.Get_rank();
  while (!done)  {
    if (myid == 0) {
      std::cout << "Enter the number of intervals: (0
quits) ";
      std::cin >> n;;
    }
    MPI::COMM_WORLD.Bcast(&n, 1, MPI::INT, 0 );
    if (n == 0) break;
```

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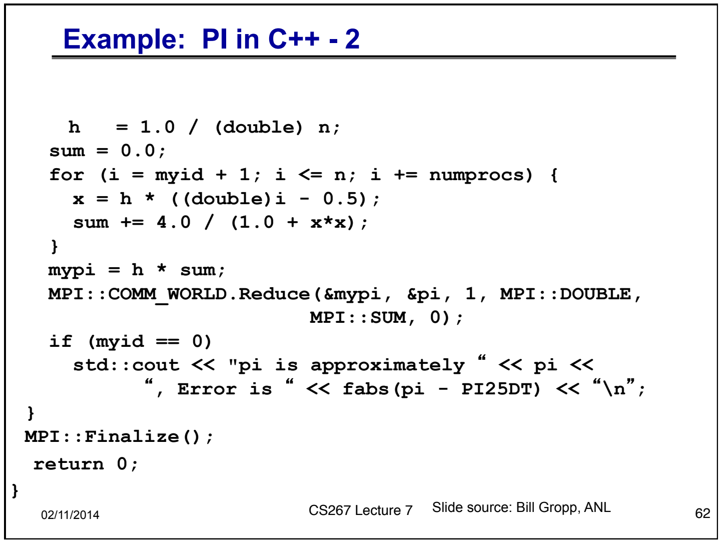
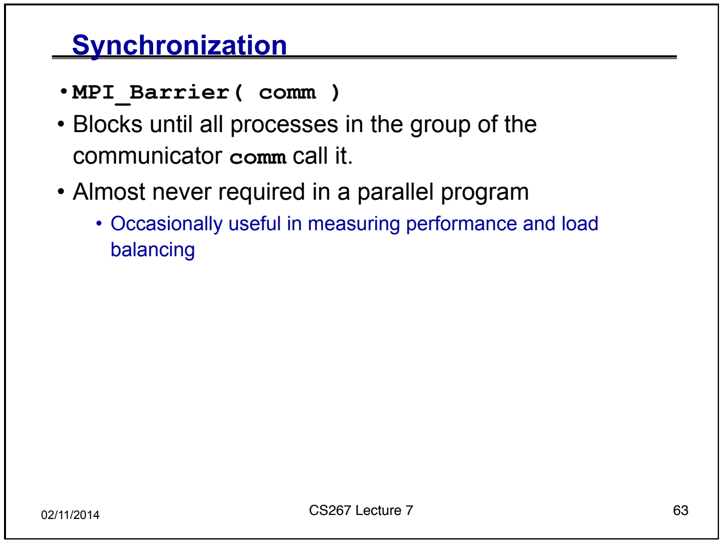


Example: PI in C++ - 2

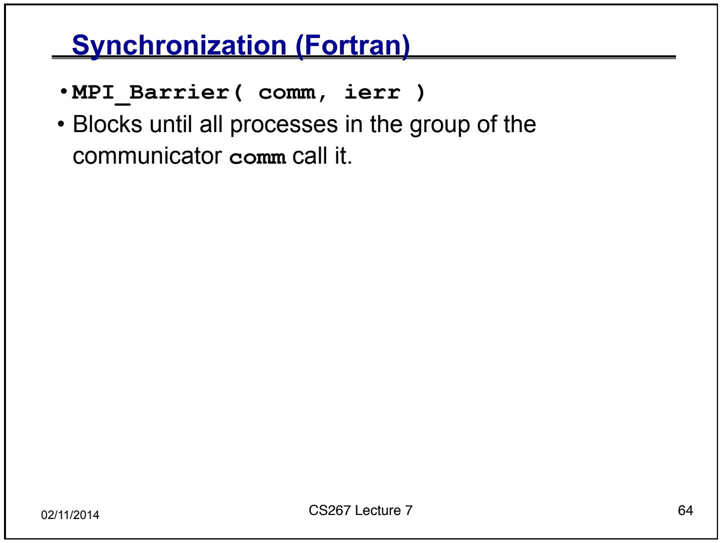
```
    h   = 1.0 / (double) n;
   sum = 0.0;
   for (i = myid + 1; i <= n; i += numprocs) {
     x = h * ((double)i - 0.5);
     sum += 4.0 / (1.0 + x*x);
   }
   mypi = h * sum;
   MPI::COMM_WORLD.Reduce(&mypi, &pi, 1, MPI::DOUBLE,
                          MPI::SUM, 0);
   if (myid == 0)
     std::cout << "pi is approximately “ << pi <<
           “, Error is “ << fabs(pi - PI25DT) << “\n”;
 }
 MPI::Finalize();
  return 0;
}
```

Slide source: Bill Gropp, ANL



Synchronization

- **MPI_Barrier(comm)**
- Blocks until all processes in the group of the communicator **comm** call it.
- Almost never required in a parallel program
  - Occasionally useful in measuring performance and load balancing



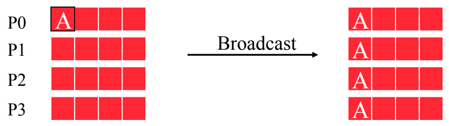
Synchronization (Fortran)

- **MPI_Barrier(comm, ierr)**
- Blocks until all processes in the group of the communicator **comm** call it.

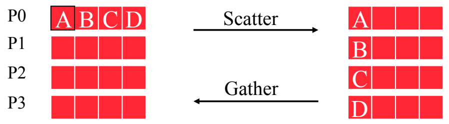
Synchronization (C++)

- `comm.Barrier();`
- Blocks until all processes in the group of the communicator `comm` call it.

Collective Data Movement



P0	A					A			
P1					Broadcast →	A			
P2						A			
P3						A			

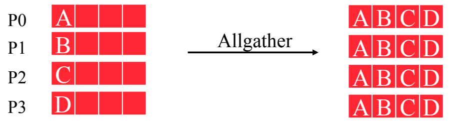


P0	A	B	C	D	Scatter →	A			
P1						B			
P2					← Gather	C			
P3						D			

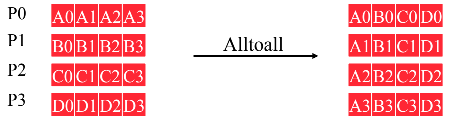
Comments on Broadcast

- All collective operations must be called by *all* processes in the communicator
- MPI_Bcast is called by both the sender (called the root process) and the processes that are to receive the broadcast
  - "root" argument is the rank of the sender; this tells MPI which process originates the broadcast and which receive

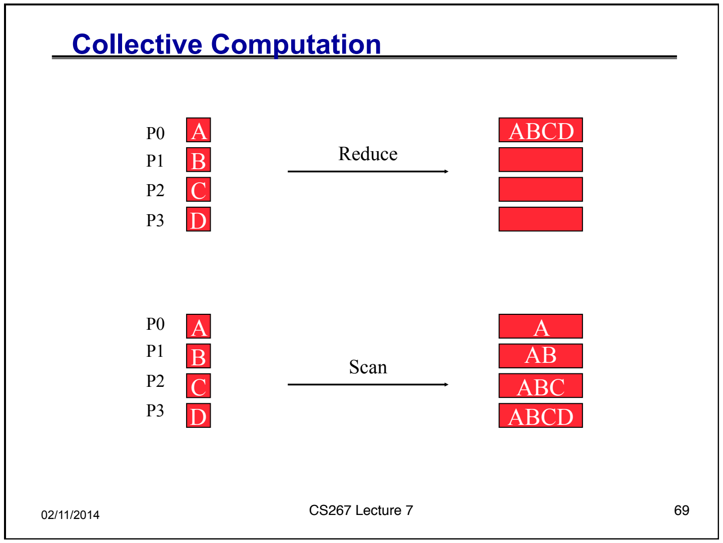
More Collective Data Movement



P0	A					A	B	C	D
P1	B				Allgather →	A	B	C	D
P2	C					A	B	C	D
P3	D					A	B	C	D



P0	A0	A1	A2	A3		A0	B0	C0	D0
P1	B0	B1	B2	B3	Alltoall →	A1	B1	C1	D1
P2	C0	C1	C2	C3		A2	B2	C2	D2
P3	D0	D1	D2	D3		A3	B3	C3	D3



Collective Computation

P0 A
P1 B
P2 C
P3 D

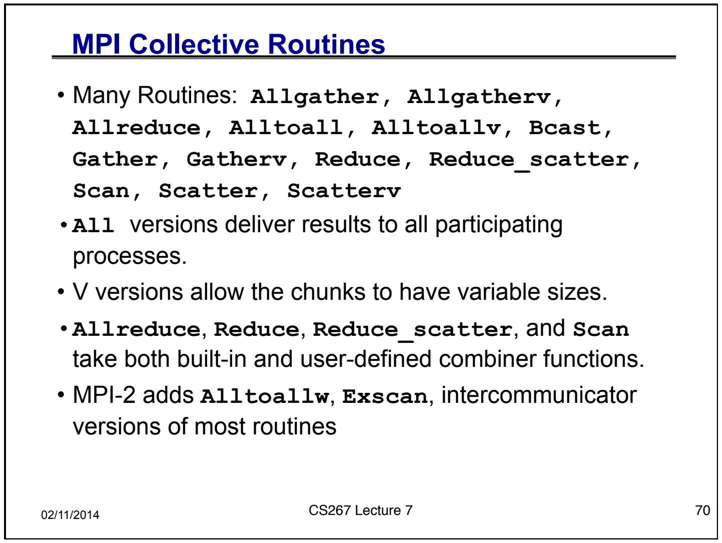
Reduce

ABCD

P0 A
P1 B
P2 C
P3 D

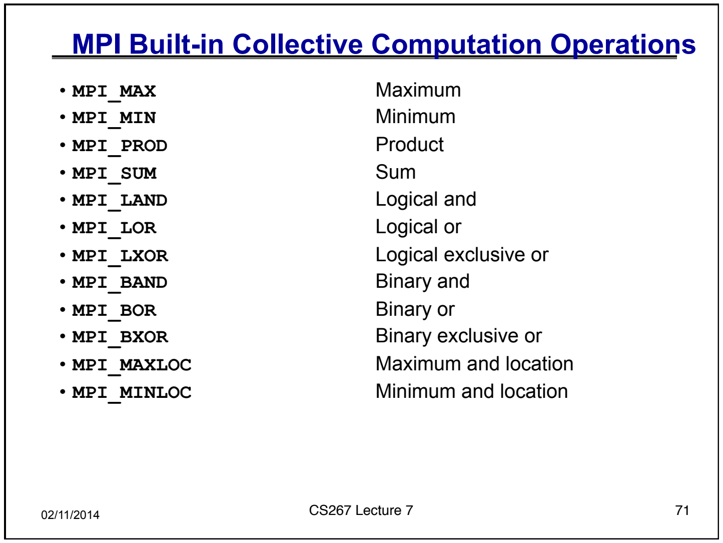
Scan

A
AB
ABC
ABCD



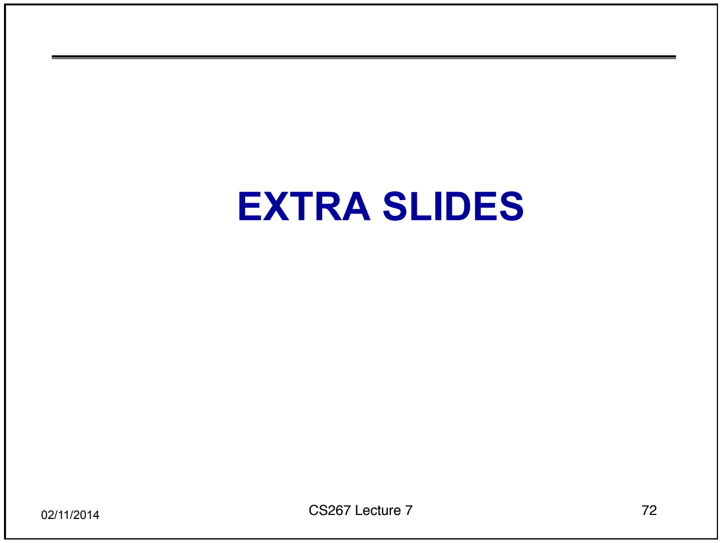
MPI Collective Routines

- Many Routines: **`Allgather, Allgatherv, Allreduce, Alltoall, Alltoallv, Bcast, Gather, Gatherv, Reduce, Reduce_scatter, Scan, Scatter, Scatterv`**
- **`All`** versions deliver results to all participating processes.
- V versions allow the chunks to have variable sizes.
- **`Allreduce`**, **`Reduce`**, **`Reduce_scatter`**, and **`Scan`** take both built-in and user-defined combiner functions.
- MPI-2 adds **`Alltoallw`**, **`Exscan`**, intercommunicator versions of most routines



MPI Built-in Collective Computation Operations

• **`MPI_MAX`**	Maximum
• **`MPI_MIN`**	Minimum
• **`MPI_PROD`**	Product
• **`MPI_SUM`**	Sum
• **`MPI_LAND`**	Logical and
• **`MPI_LOR`**	Logical or
• **`MPI_LXOR`**	Logical exclusive or
• **`MPI_BAND`**	Binary and
• **`MPI_BOR`**	Binary or
• **`MPI_BXOR`**	Binary exclusive or
• **`MPI_MAXLOC`**	Maximum and location
• **`MPI_MINLOC`**	Minimum and location



EXTRA SLIDES