

What is MPI?

- A *message-passing library specification*
 - extended message-passing model
 - not a language or compiler specification
 - not a specific implementation or product
- For parallel computers, clusters, and heterogeneous networks
- Full-featured
- Designed to provide access to advanced parallel hardware for end users, library writers, and tool developers

- Credits for Slides: Rusty Lusk, Mathematics and Computer Science Division, Argonne National Laboratory

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Where Did MPI Come From?

- Early vendor systems (Intel's NX, IBM's EUI, TMC's CMMD) were not portable (or very capable)
- Early portable systems (PVM, p4, TCGMSG, Chameleon) were mainly research efforts
 - Did not address the full spectrum of issues
 - Lacked vendor support
 - Were not implemented at the most efficient level
- The MPI Forum organized in 1992 with broad participation by:
 - vendors: IBM, Intel, TMC, SGI, Convex, Meiko
 - portability library writers: PVM, p4
 - users: application scientists and library writers
 - finished in 18 months

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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

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MPI References

- The Standard itself:
 - at <http://www.mpi-forum.org>
 - All MPI official releases, in both postscript and HTML
- Books:
 - *Using MPI: Portable Parallel Programming with the Message-Passing Interface*, 2nd Edition, by Gropp, Lusk, and Skjellum, MIT Press, 1999. Also *Using MPI-2*, w. R. Thakur
 - *MPI: The Complete Reference*, 2 vols, MIT Press, 1999.
 - *Designing and Building Parallel Programs*, by Ian Foster, Addison-Wesley, 1995.
 - *Parallel Programming with MPI*, by Peter Pacheco, Morgan-Kaufmann, 1997.
- 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

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Compiling and Running MPI Programs

- To compile and run MPI programs one uses special commands
 - mpicc compiles and includes the MPI libraries
 - mpirun sets up environment variables for running
 - mpirun -np # prog
- One can also configure the set of nodes to be used
- For details on this and on user level configuration of the 2 MPI versions MPICH and LAM see the references in <http://discover.cs.kent.edu/resources/doc/mpiref.htm>
- For examples from Pachero see <http://nexus.cs.usfca.edu/mipi/>

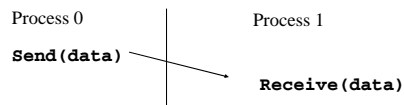
Hello (C)

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

int main( argc, argv )
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;
}
```

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?

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`

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

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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(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_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 on 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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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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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_Bcast (buffer, count, datatype, root, comm);`
- `MPI_REDUCE` combines data from all processes in communicator and returns it to one process
 - `MPI_Reduce(sendbuf, recvbuf, count, datatype, operation, root, comm);`
- In many numerical algorithms, `SEND/RECEIVE` can be replaced by `BCAST/REDUCE`, improving both simplicity and efficiency

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Example: PI in C - 1

```
#include "mpi.h"
#include <math.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 / (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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Alternative Set of 6 Functions

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

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Exercises

- Modify hello program so that each process sends the name of the machine it is running on to process 0, which prints it.
 - See source of `cpi` or `fpi` in `mpich/examples/basic` for how to use `MPI_Get_processor_name`
- Do this in such a way that the hosts are printed in rank order

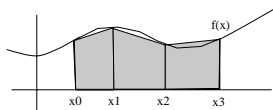
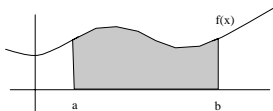
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Trapezoid Rule

- Numerical Integration (Quadrature)
 - approximate the area under the curve by calculating the area of rectangles (the Rectangle Rule) or trapezoids (the Trapezoidal Rule) that fit close to the curve.

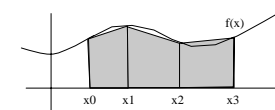


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Trapezoid Rule



- The base of each trapezoid is $h = x_1 - x_0 = x_2 - x_1$ etc.
- The area formed by one trapezoid is
 - area of one trapezoid = $\frac{1}{2} * h * (f(\text{left}) + f(\text{right}))$
- The area under the curve is:

$$\text{Area} = \frac{1}{2} * h * (f(x_0) + f(x_1)) + \frac{1}{2} * h * (f(x_1) + f(x_2)) + \frac{1}{2} * h * (f(x_2) + f(x_3))$$
- which simplifies to

$$\text{Area} = h * \{ \frac{1}{2}f(x_0) + f(x_1) + f(x_2) + \frac{1}{2}f(x_3) \}$$

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Parallelizing Trapezoid Rule

- Divide interval [a,b] into np parts, one for each processor.
- Each processor performs the trapezoidal rule on its part.

Serial and Parallel Versions

- Serial
- Parallel

Adaptive Quadrature

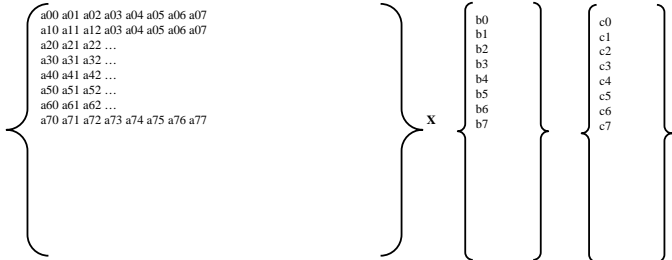
- Adaptive quadrature allows the program to calculate the new value for the integral with a different number of trapezoids each time.
- The program terminates when the final result is "close enough".
- Pseudocode for a sequential program:
 - new = 1;
 - diff = 100000;
 - numtraps = 1;
 - limit = 0.001;
 - while ((diff > limit) && (numtraps < 2048)) {
 - old = new;
 - numtraps = numtraps*2;
 - calculate (new) ;
 - diff = abs((new-old)) / new;
 - }
 - print(new);

Dot products – Block Decomposition

$$\begin{Bmatrix} a_0 & a_1 & a_2 & a_3 & a_4 & a_5 & a_6 & a_7 \end{Bmatrix} \times \begin{Bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \end{Bmatrix} = a_0*b_0 + a_1*b_1 + \dots + a_6*b_6 + a_7*b_7$$

- Serial
- Parallel
- Parallel with Allreduce

Matrix- Vector Multiplication – version 1



- Block-row distribution of the matrix
- Copy of vector on every process
- Each process calculates its corresponding portion of the result vector

How to get the data to where needed

- If the matrix is located in a single process at the start, can use MPI_Scatter to send the rows to all processes.
- (Watch out for how the matrix is stored – in C it is row-major!)
 - MPI_Scatter(
 - void* send_data,
 - int send_count,
 - MPI_Datatype send_type,
 - void* rcv_data,
 - int rcv_count,
 - MPI_Datatype rcv_type,
 - int root,
 - MPI_Comm comm);

Vector Example:

```
/* data starts at process 0 */
float vector[8], local_vector[2];
```

```
...
MPI_Scatter( vector, 2, MPI_FLOAT,
            local_vector, 2, MPI_FLOAT,
            0, MPI_COMM_WORLD);
```

would send 2 elements to each process and store them into local_vector;

- If the vector is initially distributed in block fashion among all processes, can use MPI_Gather to get a copy of the whole vector into the root process.

```
- MPI_Gather(
- void* send_data,
- int send_count,
- MPI_Datatype send_type,
- void* rcv_data,
- int rcv_count,
- MPI_Datatype rcv_type,
- int root,
- MPI_Comm comm);
```

- If the vector is initially distributed in block fashion among all processes, can use MPI_Allgather to get a copy of the whole vector into the **every** process.

```
- MPI_Allgather(
- void* send_data,
- int send_count,
- MPI_Datatype send_type,
- void* rcv_data,
- int rcv_count,
- MPI_Datatype rcv_type,
- MPI_Comm comm);
```

C Versions of Matrix-Vector Multiply

- Serial
- Parallel

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Buffers

- When you send data, where does it go? One possibility is:

```

    graph LR
      subgraph Process_0 [Process 0]
        U0[User data] --> LB0[Local buffer]
      end
      LB0 --> N[the network]
      subgraph Process_1 [Process 1]
        N --> LB1[Local buffer]
        LB1 --> U1[User data]
      end
  
```

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Avoiding Buffering

- It is better to avoid copies:

```

    graph LR
      subgraph Process_0 [Process 0]
        U0[User data]
      end
      U0 --> N[the network]
      subgraph Process_1 [Process 1]
        U1[User data]
      end
      N --> U1
  
```

This requires that **MPI_send** wait on delivery, or that **MPI_send** return before transfer is complete, and we wait later.

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Blocking and Non-blocking Communication

- So far we have been using *blocking* communication:
 - MPI_Recv does not complete until the buffer is full (available for use).
 - MPI_Send does not complete until the buffer is empty (available for use).
- Completion depends on size of message and amount of system buffering.

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Sources of Deadlocks

- Send a large message from process 0 to process 1
 - If there is insufficient storage at the destination, the send must wait for the user to provide the memory space (through a receive)
- What happens with this code?

```

Process 0      Process 1
-----
Send(1)      Send(0)
Recv(1)      Recv(0)
    
```

- This is called “unsafe” because it depends on the availability of system buffers

Some Solutions to the “unsafe” Problem

- Order the operations more carefully:

```

Process 0      Process 1
-----
Send(1)      Recv(0)
Recv(1)      Send(0)
    
```

Supply receive buffer at same time as send:

```

Process 0      Process 1
-----
Sendrecv(1) Sendrecv(0)
    
```

More Solutions to the “unsafe” Problem

- Supply own space as buffer for send

```

Process 0      Process 1
-----
Bsend(1)      Bsend(0)
Recv(1)      Recv(0)
    
```

Use non-blocking operations:

```

Process 0      Process 1
-----
Isend(1)      Isend(0)
Irecv(1)      Irecv(0)
Waitall        Waitall
    
```

MPI’s Non-blocking Operations

- Non-blocking operations return (immediately) “request handles” that can be tested and waited on.

```
MPI_Isend(start, count, datatype,
           dest, tag, comm, request)
```

```
MPI_Irecv(start, count, datatype,
           dest, tag, comm, request)
```

```
MPI_Wait(&request, &status)
```

- One can also test without waiting:

```
MPI_Test(&request, &flag, status)
```

Multiple Completions

- It is sometimes desirable to wait on multiple requests:


```
MPI_Waitall(count, array_of_requests,
             array_of_statuses)
MPI_Waitany(count, array_of_requests,
            &index, &status)
MPI_Waitsome(count, array_of_requests,
             array_of_indices, array_of_statuses)
```
- There are corresponding versions of `test` for each of these.

Communication Modes

- MPI provides multiple *modes* for sending messages:
 - Synchronous mode (**MPI_Ssend**): the send does not complete until a matching receive has begun. (Unsafe programs deadlock.)
 - Buffered mode (**MPI_Bsend**): the user supplies a buffer to the system for its use. (User allocates enough memory to make an unsafe program safe.)
 - Ready mode (**MPI_Rsend**): user guarantees that a matching receive has been posted.
 - Allows access to fast protocols
 - undefined behavior if matching receive not posted
- Non-blocking versions (**MPI_Issend**, etc.)
- **MPI_Recv** receives messages sent in any mode.

Other Point-to Point Features

- **MPI_Sendrecv**
- **MPI_Sendrecv_replace**
- **MPI_Cancel**
 - Useful for multibuffering
- Persistent requests
 - Useful for repeated communication patterns
 - Some systems can exploit to reduce latency and increase performance

MPI_Sendrecv

- Allows simultaneous send and receive
- Everything else is general.
 - Send and receive datatypes (even type signatures) may be different
 - Can use `Sendrecv` with plain `Send` or `Recv` (or `Irecv` or `Ssend_init`, ...)
 - More general than “send left”

Process 0

Process 1

SendRecv(1)

SendRecv(0)



Collective Operations in MPI

- Collective operations must be 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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MPI Collective Communication

- Communication and computation is coordinated among a group of processes in a communicator.
- Groups and communicators can be constructed “by hand” or using topology routines.
- Tags are not used; different communicators deliver similar functionality.
- No non-blocking collective operations.
- Three classes of operations: synchronization, data movement, collective computation.

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Synchronization

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

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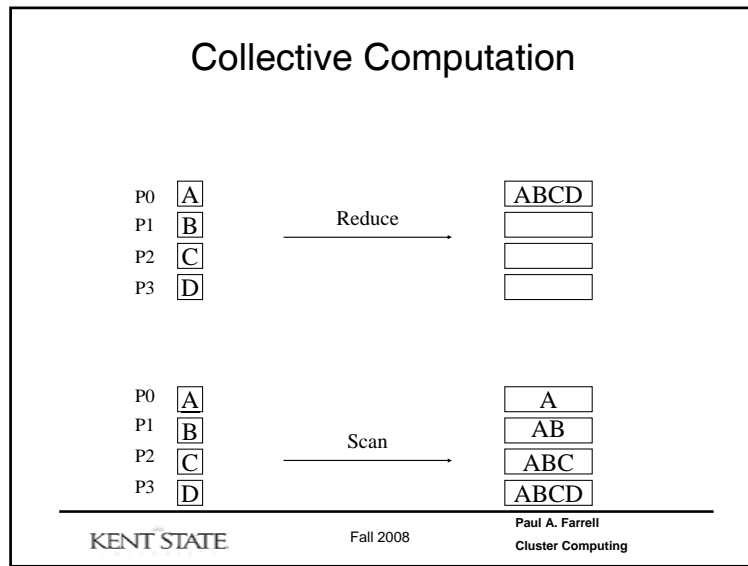
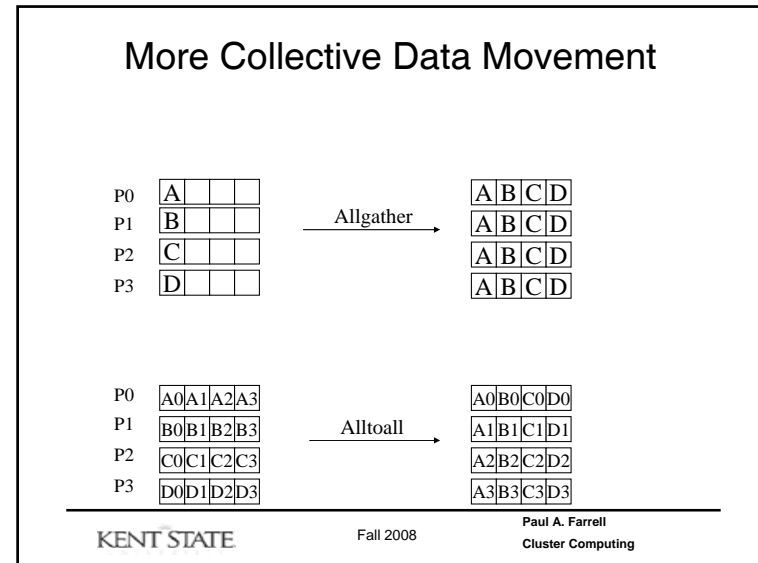
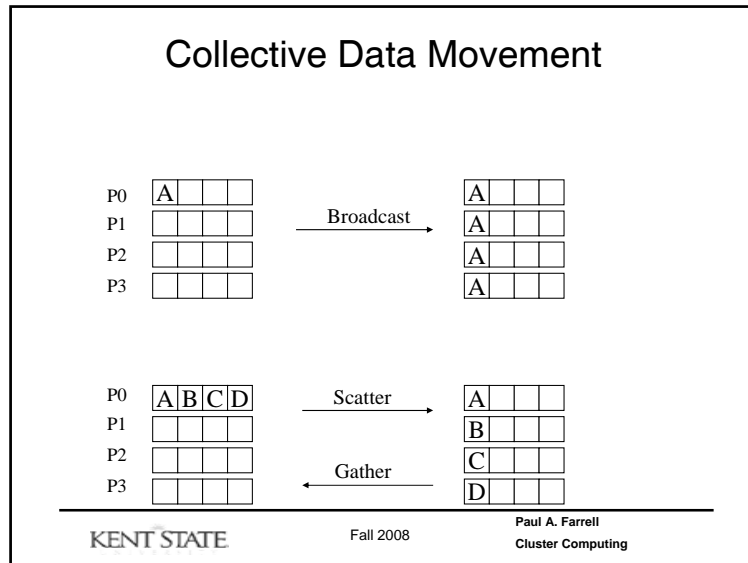
Synchronization

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

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- ### 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 hunks to have different sizes.
 - **Allreduce**, **Reduce**, **Reduce_scatter**, and **Scan** take both built-in and user-defined combiner functions.
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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

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How Deterministic are Collective Computations?

- In exact arithmetic, you always get the same results
 - but roundoff error, truncation can happen
- MPI does *not* require that the same input give the same output
 - Implementations are encouraged but not required to provide *exactly* the same output given the same input
 - Round-off error may cause slight differences
- Allreduce does guarantee that the *same* value is received by all processes for each call
- Why didn't MPI mandate determinism?
 - Not all applications need it
 - Implementations can use "deferred synchronization" ideas to provide better performance

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Defining your own Collective Operations

- Create your own collective computations with:


```
MPI_Op_create( user_fcn, commutes, &op );
MPI_Op_free( &op );
```

```
user_fcn( invec, inoutvec, len, datatype );
```
- The user function should perform:


```
inoutvec[i] = invec[i] op inoutvec[i];
```

for *i* from 0 to *len*-1.
- The user function can be non-commutative.

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Blocking and Non-blocking

- Blocking
 - `MPI_Recv` does not complete until the buffer is full (available for use).
 - `MPI_Send` does not complete until the buffer is empty (available for use).
- Non-blocking operations return (immediately) "request handles" that can be tested and waited on.


```
MPI_Isend(start, count, datatype, dest, tag, comm, request)
MPI_Irecv(start, count, datatype, dest, tag, comm, request)
MPI_Wait(&request, &status)
```

 - One can also test without waiting:


```
MPI_Test(&request, &flag, status)
```

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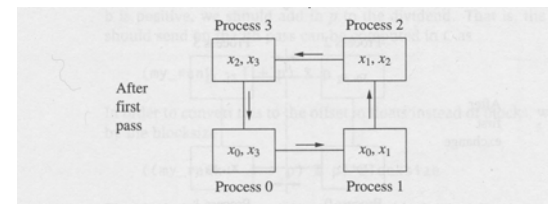
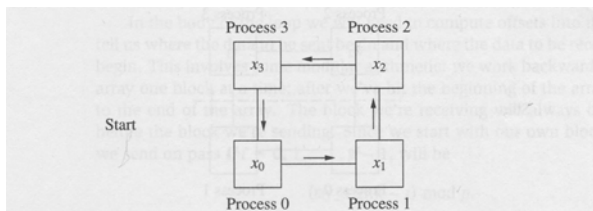
Persistent Requests

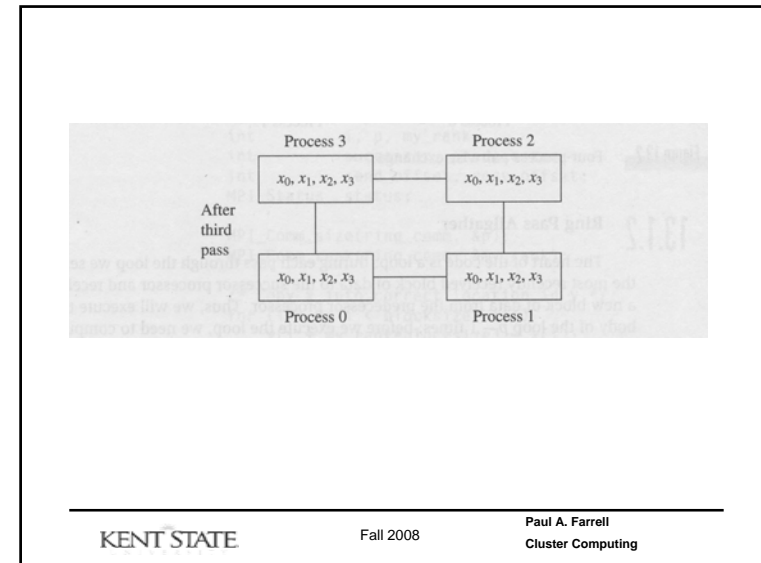
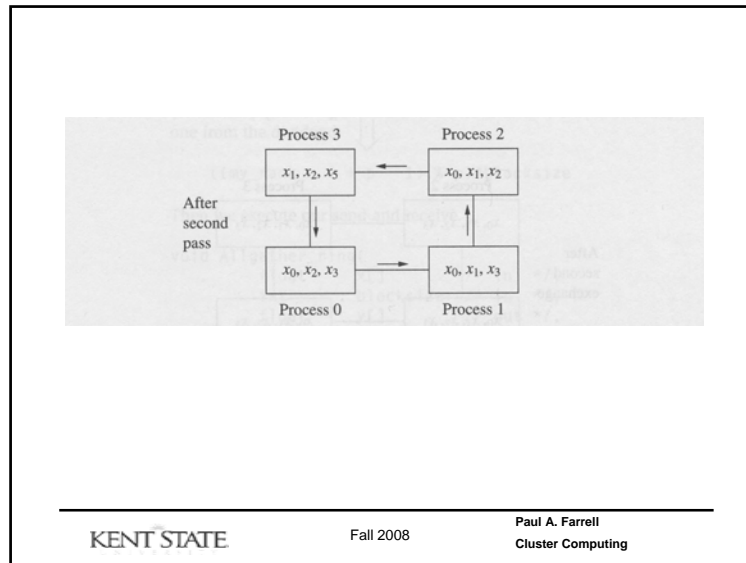
- Persistent requests
 - Useful for repeated communication patterns
 - Some systems can exploit to reduce latency and increase performance

Communication Modes

- MPI provides multiple *modes* for sending messages:
 - Synchronous mode (**MPI_Ssend**): the send does not complete until a matching receive has begun. (Unsafe programs deadlock.)
 - Buffered mode (**MPI_Bsend**): the user supplies a buffer to the system for its use. (User allocates enough memory to make an unsafe program safe.)
 - Ready mode (**MPI_Rsend**): user guarantees that a matching receive has been posted.
 - Allows access to fast protocols
 - undefined behavior if matching receive not posted
- Non-blocking versions (**MPI_Isend**, etc.)
- **MPI_Recv** receives messages sent in any mode.

Ring Based Allgather





Advanced Communication Examples

- All_gather Ring
 - Blocking
 - Nonblocking
 - Persistent
 - Synchronous
 - Ready
 - Buffered
- Examples

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Allgather_ring_blk All (Part 1)

```

void Allgather_ring(
    float x[] /* in */,
    int blocksize /* in */,
    float y[] /* out */,
    MPI_Comm ring_comm /* in */) {

    int i, p, my_rank;
    int successor, predecessor;
    int send_offset, recv_offset;
    MPI_Status status;

    MPI_Comm_size(ring_comm, &p);
    MPI_Comm_rank(ring_comm, &my_rank);

    /* Copy x into correct location in y */
    for (i = 0; i < blocksize; i++)
        y[i + my_rank*blocksize] = x[i];

    successor = (my_rank + 1) % p;
    predecessor = (my_rank - 1 + p) % p;
  }
  
```

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Allgather_ring_blk Blocking

```

for (i = 0; i < p - 1; i++) {
    send_offset = ((my_rank - i + p) % p)*blocksize;
    recv_offset =
        ((my_rank - i - 1 + p) % p)*blocksize;
    MPI_Send(y + send_offset, blocksize, MPI_FLOAT,
            successor, 0, ring_comm);
    MPI_Recv(y + recv_offset, blocksize, MPI_FLOAT,
            predecessor, 0, ring_comm, &status);
}
} /* Allgather_ring */

```

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Allgather_ring_nblk Non Blocking

```

send_offset = my_rank*blocksize;
recv_offset = ((my_rank - 1 + p) % p)*blocksize;
for (i = 0; i < p - 1; i++) {
    MPI_Isend(y + send_offset, blocksize, MPI_FLOAT,
            successor, 0, ring_comm, &send_request);
    MPI_Irecv(y + recv_offset, blocksize, MPI_FLOAT,
            predecessor, 0, ring_comm, &recv_request);

    send_offset = ((my_rank - i - 1 + p) % p)*blocksize;
    recv_offset = ((my_rank - i - 2 + p) % p)*blocksize;

    MPI_Wait(&send_request, &status);
    MPI_Wait(&recv_request, &status);
}
} /* Allgather_ring */

```

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Persistent

- Persistent requests
 - Useful for repeated communication patterns
 - Some systems can exploit to reduce latency and increase performance
 - In this case only send_offset and recv_offset change
 - Can pack contents into a buffer and send buffer
 - Then all calls to send and receive are identical
 - Persistent mode lets you create the envelope etc. (information required to send message) only once
 - Normal requests are set to MPI_REQUEST_NULL after a Wait, however persistent ones only become inactive and may be reactivated by MPI_Start

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Allgather_ring_pers Persistent

```

MPI_Send_init(send_buf, blocksize*sizeof(float),
    MPI_PACKED, successor, 0, ring_comm,
    &send_request);
MPI_Recv_init(recv_buf, blocksize*sizeof(float),
    MPI_PACKED, predecessor, 0, ring_comm,
    &recv_request);

send_offset = my_rank*blocksize;
for (i = 0; i < p - 1; i++) {
    position = 0;
    MPI_Pack(y+send_offset, blocksize, MPI_FLOAT,
            send_buf, MAX_BYTES, &position, ring_comm);
    MPI_Start(&send_request);
    MPI_Start(&recv_request);
}

```

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Allgather_ring_pers Persistent

```

recv_offset = send_offset =
    ((my_rank - i - 1 + p) % p)*blocksize;
position = 0;
MPI_Wait(&send_request, &status);
MPI_Wait(&recv_request, &status);
MPI_Unpack(recv_buf, MAX_BYTES, &position,
    y+recv_offset, blocksize, MPI_FLOAT,
    ring_comm);
}
MPI_Request_free(&send_request);
MPI_Request_free(&recv_request);
} /* Allgather_ring */

```

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Synchronous mode

- Synchronous mode (**MPI_ssend**): the send does not complete until a matching receive has begun. (Unsafe programs deadlock.)
- The standard version of Allgather_ring would hang
- Must alternate order of send and receive on successive nodes

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Allgather_ring_syn Synchronous

```

for (i = 0; i < p - 1; i++) {
    send_offset = ((my_rank - i + p) % p)*blocksize;
    recv_offset =
        ((my_rank - i - 1 + p) % p)*blocksize;
    if ((my_rank % 2) == 0) { /* Even ranks send first */
        MPI_Ssend(y + send_offset, blocksize, MPI_FLOAT,
            successor, 0, ring_comm);
        MPI_Recv(y + recv_offset, blocksize, MPI_FLOAT,
            predecessor, 0, ring_comm, &status);
    } else { /* Odd ranks receive first */
        MPI_Recv(y + recv_offset, blocksize, MPI_FLOAT,
            predecessor, 0, ring_comm, &status);
        MPI_Ssend(y + send_offset, blocksize, MPI_FLOAT,
            successor, 0, ring_comm);
    }
}

```

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Ready Mode

- Ready mode (**MPI_Rsend**):
- user guarantees that a matching receive has been posted.
 - Allows access to fast protocols
 - undefined behavior if matching receive not posted
- User must post receive before matching send

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Allgather_ring_rdy Ready

```

MPI_Comm_size(ring_comm, &p);
MPI_Comm_rank(ring_comm, &my_rank);

request = (MPI_Request*) malloc(p*sizeof(MPI_Request));

/* Copy x into correct location in y */
for (i = 0; i < blocksize; i++)
    y[i + my_rank*blocksize] = x[i];

successor = (my_rank + 1) % p;
predecessor = (my_rank - 1 + p) % p;

```

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Allgather_ring_rdy Ready

```

for (i = 0; i < p - 1; i++) {
    recv_offset =
        ((my_rank - i - 1 + p) % p)*blocksize;
    MPI_Irecv(y + recv_offset, blocksize, MPI_FLOAT,
predecessor, i, ring_comm, &(request[i]));
}

MPI_Barrier(ring_comm);

for (i = 0; i < p - 1; i++) {
    send_offset = ((my_rank - i + p) % p)*blocksize;
    MPI_Rsend(y + send_offset, blocksize, MPI_FLOAT,
successor, i, ring_comm);
    MPI_Wait(&(request[i]), &status);
}

```

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Buffered Mode

- Buffered mode (**MPI_Bsend**):
- the user supplies a buffer to the system for its use.
- User allocates enough memory to make an unsafe program safe
- All send operations are local into this user supplied buffer
- Send can then return and user program can continue
- As long as the buffer does not fill, a program which would be unsafe in the absence of buffering will run correctly

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Allgather_ring_buf Buffered

```

char    buffer[MAX_BUF];
int     buffer_size = MAX_BUF;

/* Copy x into correct location in y */
for (i = 0; i < blocksize; i++)
    y[i + my_rank*blocksize] = x[i];

successor = (my_rank + 1) % p;
predecessor = (my_rank - 1 + p) % p;

MPI_Buffer_attach(buffer, buffer_size);

for (i = 0; i < p - 1; i++) {
    send_offset = ((my_rank - i + p) % p)*blocksize;
    recv_offset =
        ((my_rank - i - 1 + p) % p)*blocksize;
    MPI_Bsend(y + send_offset, blocksize, MPI_FLOAT,
successor, 0, ring_comm);
    MPI_Recv(y + recv_offset, blocksize, MPI_FLOAT,
predecessor, 0, ring_comm, &status);
}

MPI_Buffer_detach(&buffer, &buffer_size);

```

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MPICH Goals

- Complete MPI implementation
- Portable to all platforms supporting the message-passing model
- High performance on high-performance hardware
- As a research project:
 - exploring tradeoff between portability and performance
 - removal of performance gap between user level (MPI) and hardware capabilities
- As a software project:
 - a useful free implementation for most machines
 - a starting point for vendor proprietary implementations

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MPICH Architecture

- Most code is completely portable
- An “Abstract Device” defines the communication layer
- The abstract device can have widely varying instantiations, using:
 - sockets
 - shared memory
 - other special interfaces
 - e.g. Myrinet, Quadrics, InfiniBand, Grid protocols

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Getting MPICH for your cluster

- <http://www.mcs.anl.gov/mpi/mpich>
- Either MPICH-1 or
- MPICH-2

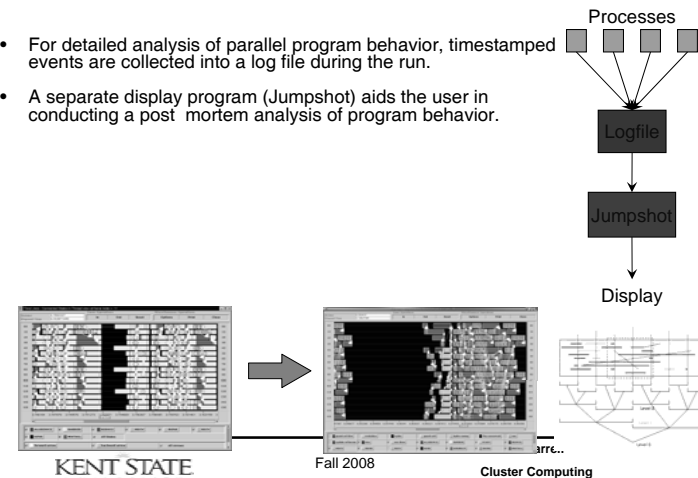
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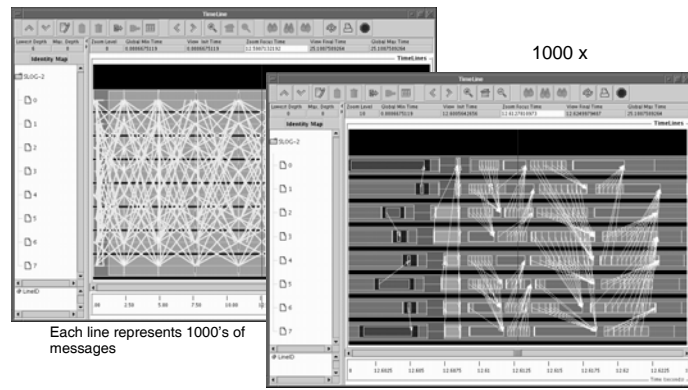
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Performance Visualization with Jumpshot

- For detailed analysis of parallel program behavior, timestamped events are collected into a log file during the run.
- A separate display program (Jumpshot) aids the user in conducting a post-mortem analysis of program behavior.



Using Jumpshot to look at FLASH at multiple Scales



Detailed view shows opportunities for optimization

What's in MPI-2

- Extensions to the message-passing model
 - Dynamic process management
 - One-sided operations (remote memory access)
 - Parallel I/O
 - Thread support
- Making MPI more robust and convenient
 - C++ and Fortran 90 bindings
 - External interfaces, handlers
 - Extended collective operations
 - Language interoperability
- Many vendors have partial implementations, especially I/O

MPI as a Setting for Parallel I/O

- Writing is like sending and reading is like receiving
- Any parallel I/O system will need:
 - collective operations
 - user-defined datatypes to describe both memory and file layout
 - communicators to separate application-level message passing from I/O-related message passing
 - non-blocking operations
- I.e., lots of MPI-like machinery

MPI-2 Status of MPICH

MPICH2 designed

- To support research into high-performance implementations of MPI-1 and MPI-2 functionality
- to provide an MPI implementation for important platforms, including clusters, SMPs, and massively parallel processors
- a vehicle for MPI implementation research
- was at release 1.0.3 as of November 23, 2005
- High Performance versions
 - MVAPICH2 (OSU) - for InfiniBand
 - MPICH2-CH3 Device for InfiniBand (Chemnitz) - based on the Verbs interface, currently using the Mellanox Verbs implementation VAPI
 - ATOLL is a high-performance interconnect based on MPICH2

Some Research Areas

- MPI-2 RMA interface
 - Can we get high performance?
- Fault Tolerance and MPI
 - Are intercommunicators enough?
- MPI on 64K processors
 - Umm...how do we make this work :)?
 - Reinterpreting the MPI “process”
- MPI as system software infrastructure
 - With dynamic processes and fault tolerance, can we build services on MPI?

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High-Level Programming With MPI

- MPI was designed from the beginning to support libraries
- Many libraries exist, both open source and commercial
- Sophisticated numerical programs can be built using libraries
 - Solve a PDE (e.g., PETSc)
 - Scalable I/O of data to a community standard file format

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Higher Level I/O Libraries

- Scientific applications work with structured data and desire more self-describing file formats
- netCDF and HDF5 are two popular “higher level” I/O libraries
 - Abstract away details of file layout
 - Provide standard, portable file formats
 - Include metadata describing contents
- For parallel machines, these should be built on top of MPI-IO

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Exercise

- Jacobi problem in 2 dimensions with 1-D decomposition
 - Explained in class
 - Simple version – fixed number of iterations
 - Fancy version – test for convergence

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The PETSc Library

- PETSc provides routines for the parallel solution of systems of equations that arise from the discretization of PDEs
 - Linear systems
 - Nonlinear systems
 - Time evolution
- PETSc also provides routines for
 - Sparse matrix assembly
 - Distributed arrays
 - General scatter/gather (e.g., for unstructured grids)

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Structure of PETSc

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PETSc Numerical Components

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Flow of Control for PDE Solution

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Poisson Solver in PETSc

- The following 7 slides show a complete 2-d Poisson solver in PETSc. Features of this solver:
 - Fully parallel
 - 2-d decomposition of the 2-d mesh
 - Linear system described as a sparse matrix; user can select many different sparse data structures
 - Linear system solved with any user-selected Krylov iterative method and preconditioner provided by PETSc, including GMRES with ILU, BiCGstab with Additive Schwarz, etc.
 - Complete performance analysis built-in
- Only 7 slides of code!