SPMD Model

Robert Keller

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SPMD vs. SIMD

- SPMD means “Single Program, Multiple Data”.
- The same program is run locally on each processor, but there is no master control as in SIMD.
- The program can do different things on different processors by conditional branching.

Why SPMD?

- SPMD allows us to take advantage of commodity processors and compilers.
- Special hardware for parallel computing is not necessary.
- Special language constructs are also not necessary, as library calls can be used.

Application Granularity Considerations

- Two kinds of granularity:
  - **Load-balancing** granularity: ratio of size of parallel work units to overall work
  - **Communication granularity**: ratio of communication intervals to computation intervals

Load-Balancing Granularity

- Finer granularity is better, since it provides more ways to distribute the work.
- Imagine that the computation work load is a 10 kg. of material:
  - Sand = fine-grain
  - Cinder blocks = coarse grain
- Which is easier to **distribute** evenly?

Communication Granularity

- Parallelism with fine-grain concurrency may require relatively **frequent communication** compared to the length of the computation interval.

- If the communication is not so fast, the process' waiting time will **dilute** the speedup from parallel execution.

Communication Granularity

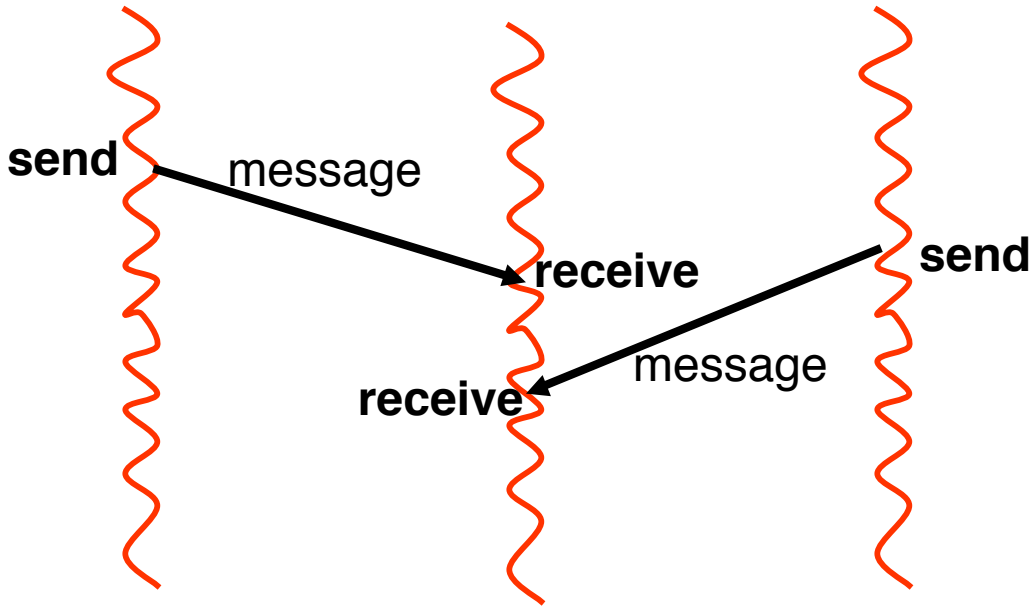
- Consequently, fine-grain is more suited to shared memory than to distributed memory.
- Conversely, distributed memory requires relatively coarse grain to be effective.
- Because SIMD has less synchronization overhead, very-fine grain is more suited to SIMD than to MIMD.

Message-Passing Paradigm

- Message-passing is the programming paradigm most closely associated with distributed memory.
- However, it can also be used in a shared memory system if the problem permits.
- It is more effective for **coarser granularity**, due to the **overhead** in passing messages.

Message-Passing (2)

threads/processes on different processors

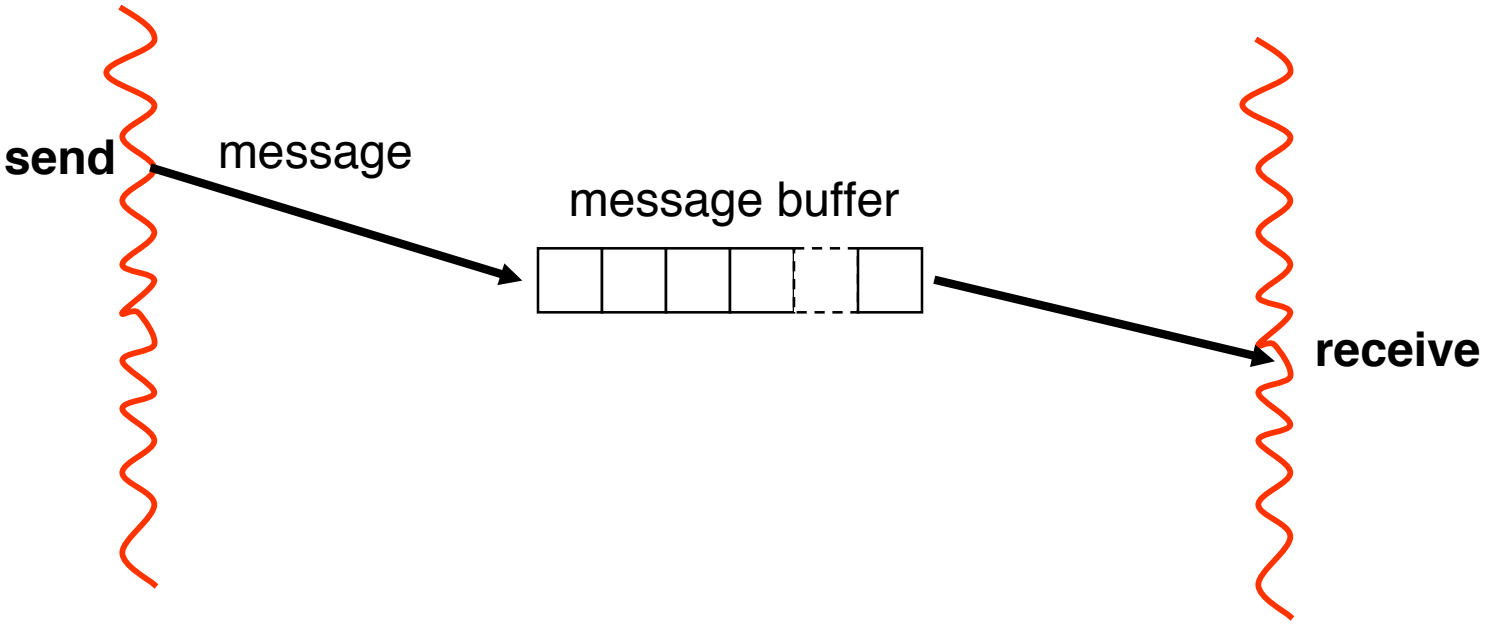


Message-Passing (3)

- Two varieties of **send**:
  - **Blocking send**: The sending process waits for the message to be received before proceeding.
  - **Non-blocking send**: The sending process can proceed immediately.
    (The message may be buffered pending receipt.)

Message Buffering

can be used to avoid blocking the sender



Message-Passing (4)

- Two varieties of **receive**:
  - **Blocking receive** (most common): The receiving process **waits until** there is a message.
  - **Non-blocking receive**: The receiving process can **check whether** there is a message to be received, and continue if not.

Multi-cast, Scatter, Gather

- **Multi-cast** is the equivalent of a *send* of a **single message** to **each of a *set*** of processes

  (**Broadcast** means to *all* processes.)

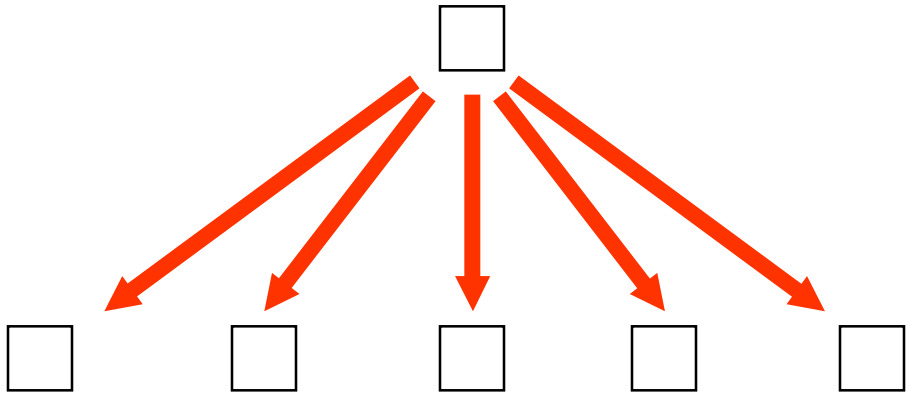
- **Scatter** means to send **different** elements of an aggregate to different processes.

- **Gather** means to **collect elements** from different processes into a single aggregate.

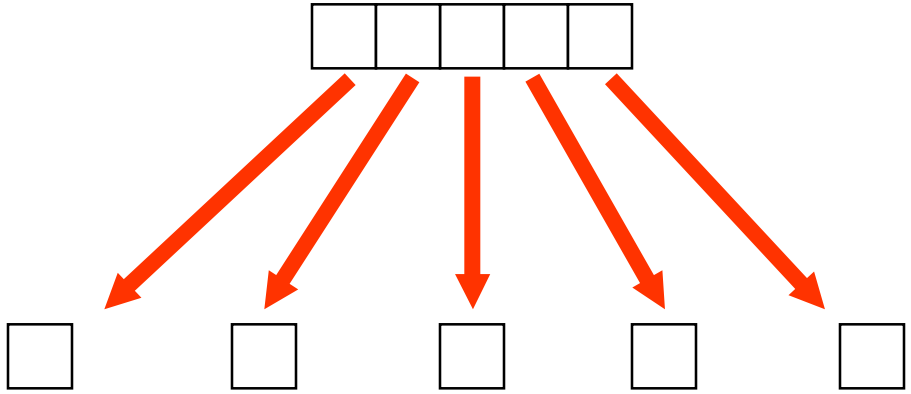
Reduce, Map

- **Reduce** means to form a single element from an aggregate using a specified **binary** operation.
- **Map** means to apply a single **unary** operation to all elements of an aggregate.

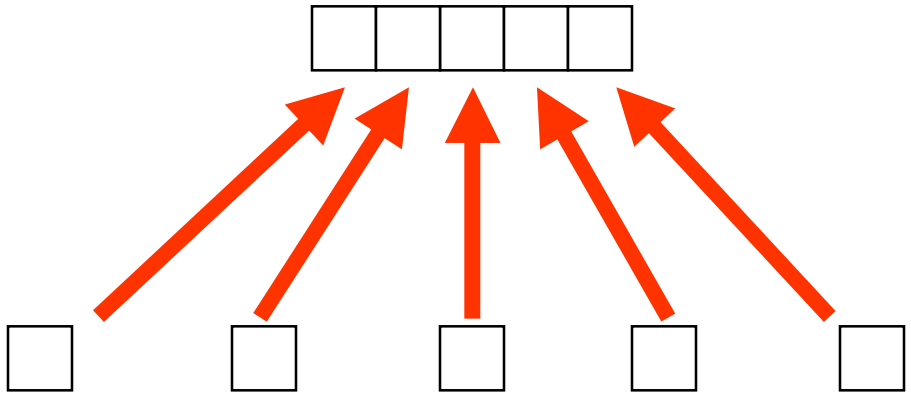
Multi-cast



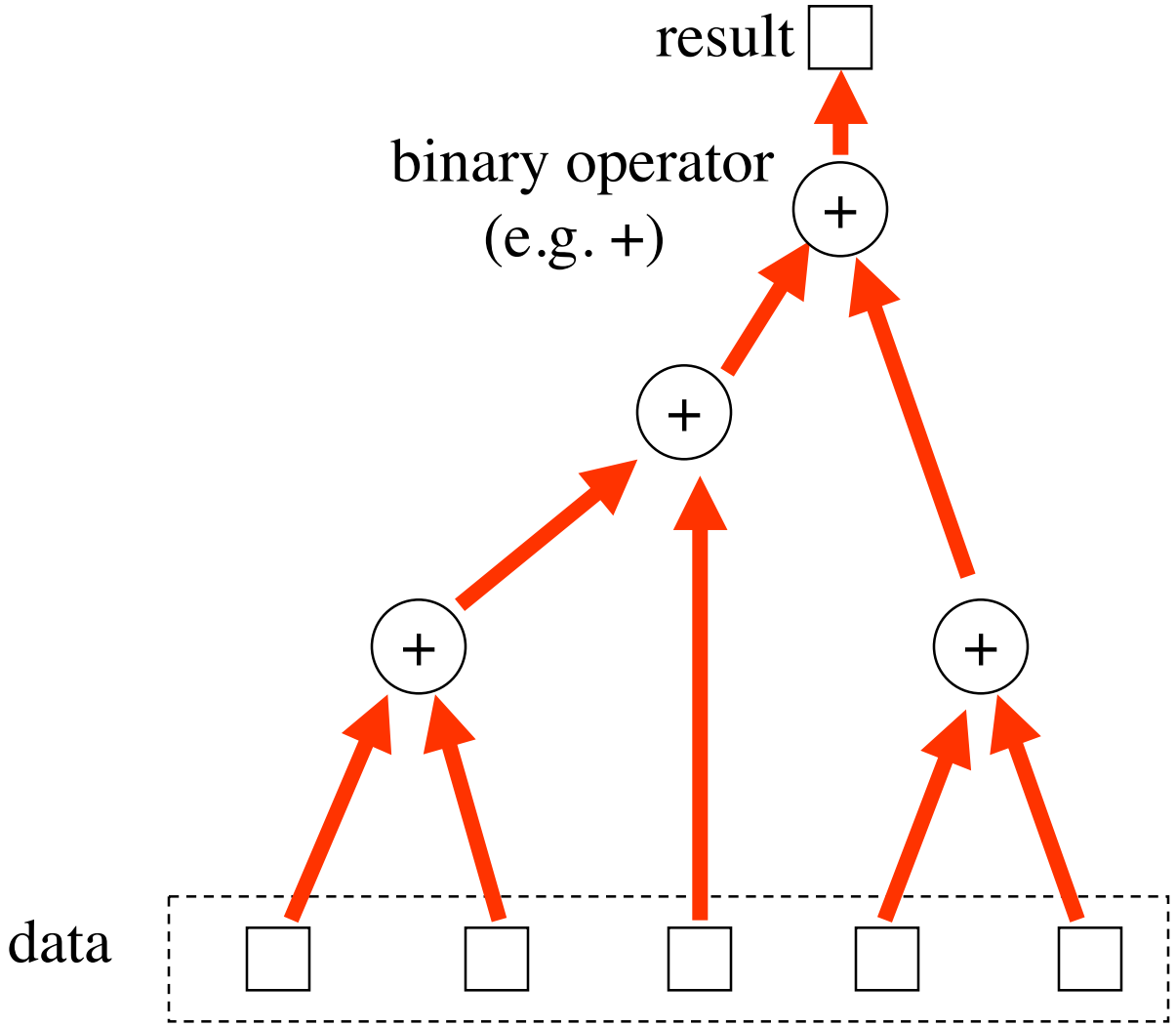
Scatter



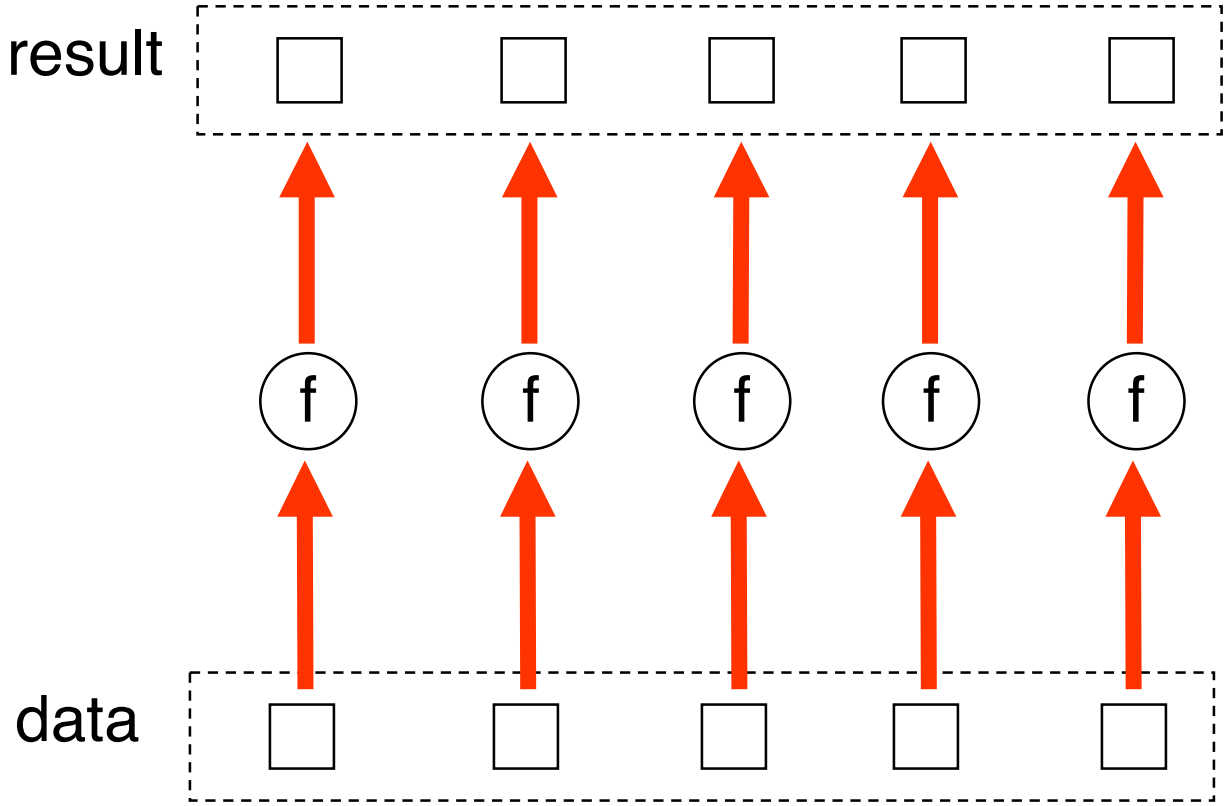
Gather



Reduce



Map



MPI Library
(Message-Passing Interface, Lusk et al.)

- Based on the SPMD (Single Program, Multiple Data Stream) idea.

Ewing (Rusty) Lusk

- All processes run the same program, but
- processes can **differentiate** themselves using assigned ID's (called the ***rank*** of the process).

Rank Usage

- The code executed can be **different** in different processes by discriminating based on rank.

- Processes can also be divided into ***groups***, the rank (0,1, 2, …) applying within the group.

MPI

- Based on processes, rather than processors.
- There can be one process per processor, or more than one.
- It is up to the programmer to decide how many.

MPI

- MPI standard library is defined for:
  - Fortran
  - C
  - C++
  - Java
  - Python
  - Perl
  - Ocaml
  - Matlab
  - . . .

MPI Communicators

- Communication between or within a group is defined by an abstraction called a ***Communicator***
  (type is MPI_Comm).

- A common pre-defined communicator is

  MPI_COMM_WORLD

MPI Invocation

- The number of processes is defined on the command line of the master process:

  mpirun -np *Number-of-processes Executable Args*

  Executable is the single program binary.

- The program initializes using (in C syntax):

  ```
  MPI_Init(&argc, &argv);
  ```

  where argc and argv are from *Args* on the command line.

MPI Finalization

- Always terminate execution with:

```
MPI_Finalize();
```

MPI

- The program can find out the **number of processes**:

(C syntax)

MPI_Comm_size(*Communicator*, &nprocs);

sets the int variable **nprocs**

e.g.

MPI_Comm_ size(MPI_COMM_WORLD, &nprocs);

MPI Process Identification

- A process can find out its own **rank**:

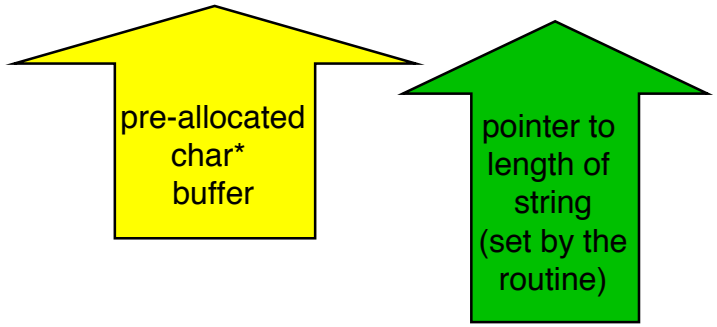
  MPI_Comm_rank(*Communicator*, &id);

- int variable **id** is set.

MPI Processor Identification

- A process can find out the name of the processor on which it is running:

```
MPI_Get_processor_name(name, &namelen);
```



MPI Barrier

- A process can **join** a **barrier** within its group:

  MPI_Barrier(*Communicator*);

- This means that each process waits until each has reached the barrier statement.

Master and Slaves

- It is common to view one process (usually the one with id 0) as the **master** and others as slaves.
- A process can then can execute code **conditioned** upon whether it is master or slave (by checking its own id).
- The **slaves** do the main work in parallel.
- The **master** is in charge of initial setup and later direction, although it could also do work.

Sending Messages

```
int MPI_Send(
        void* buf,                  // address of buffer
        int count,                  // number of items
        MPI_Datatype datatype,      // type of each item
        int dest,                   // rank of destination
        int tag,                    // tag value of message
        MPI_Comm comm)              // communicator
```

The return value indicates a success code, which will be MPI_SUCCESS if the send operation is successful.

Receiving Messages

```
int MPI_Recv(
        void* buf,                  // address of buffer
        int count,                  // maximum number of items
        MPI_Datatype datatype,      // type of each item
        int source,                 // rank of source
        int tag,                    // tag value of message
        MPI_Comm comm,              // communicator
        MPI_Status *status)         // status indicator
```

The status indicator gives information about what was received.

Send-Receive Matching

- The purpose of the **tag** argument is to allow a single receive operation to **discriminate** among different tags of messages that might be sent.

- For a message to be received from a sender, both the tag **and** the **source** must match the sender values in the receive statement.

Wild Cards

- Wild cards can also be used to designate receiving from *any* source:

  MPI_ANY_SOURCE

- The tag value can also be a wild-card:

  MPI_ANY_TAG

MPI Datatypes

(most correspond to C datatypes of a similar name)

- MPI_CHAR
- MPI_SHORT
- MPI_INT
- MPI_LONG
- MPI_FLOAT
- MPI_DOUBLE
- MPI_LONG_DOUBLE

- MPI_UNSIGNED
- MPI_UNSIGNED_SHORT
- MPI_UNSIGNED_LONG
- MPI_UNSIGNED_CHAR

These do not correspond to any C dataype:

- MPI_PACKED
- MPI_BYTE

The Status indicator

- Variable of type MPI_Status is a struct containing three fields:
  - MPI_SOURCE
  - MPI_TAG
  - MPI_ERROR

  indicating the corresponding information about the message received.

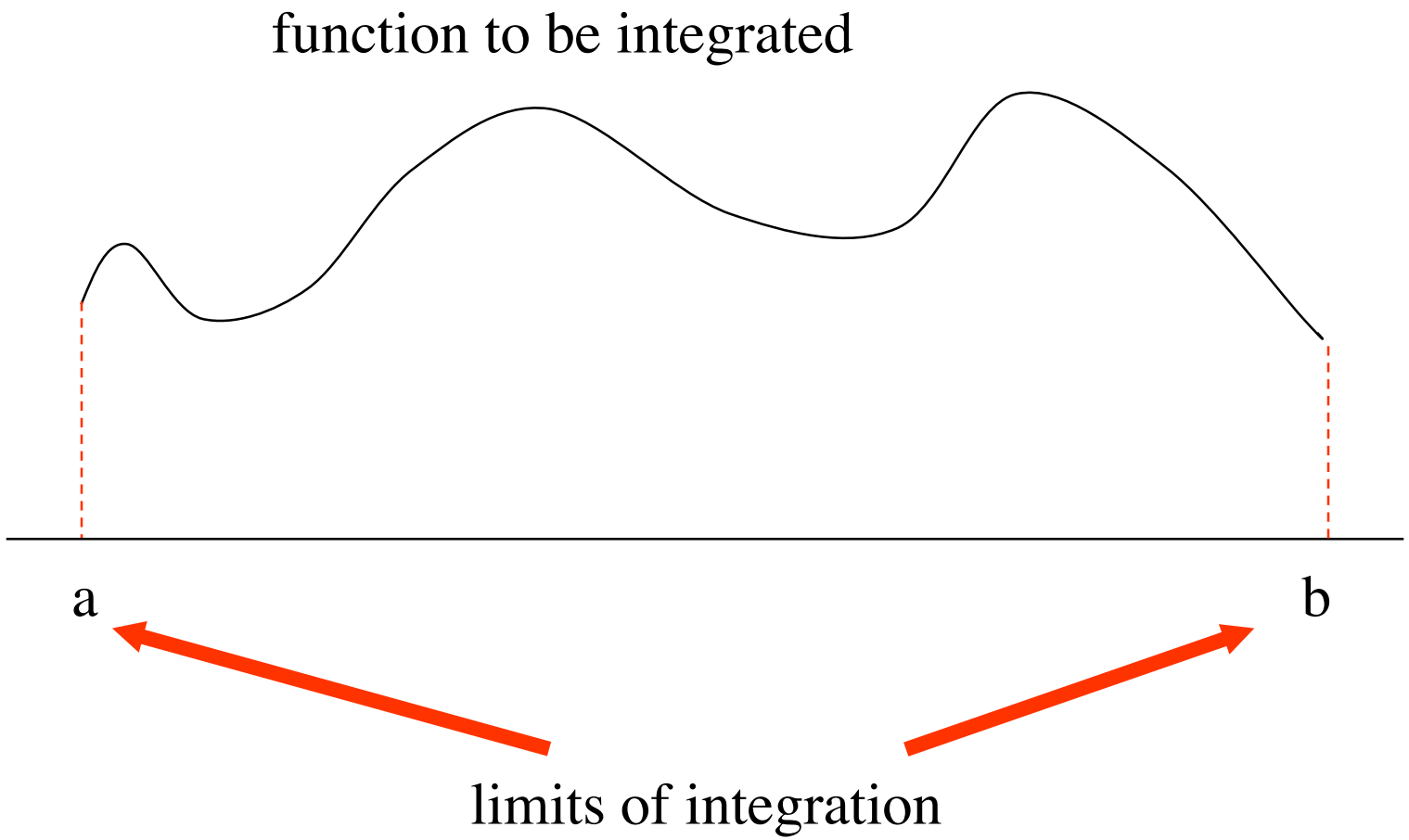
- It also contains the length of the message received, using a call of the form:

  MPI_Get_count(MPI_ Status, MPI_Datatype, int *count)

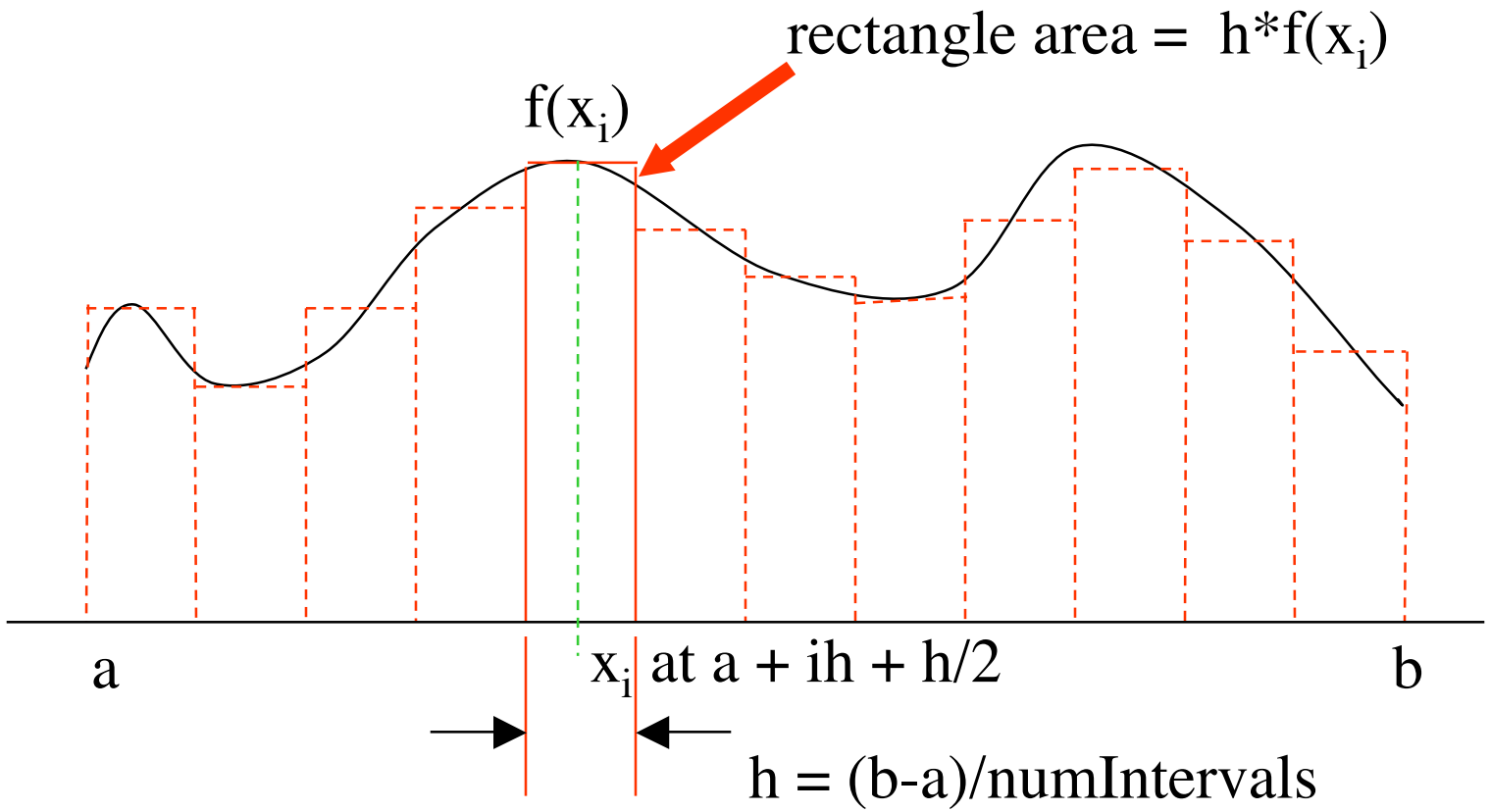
An Example

- **Integrate** a function of one real variable numerically.
- The function will be passed as an argument to the *integrate* function.
- Other arguments to the integrate function include:
  - The limits of integration
  - The number of sub-divisions
  - The MPI communicator to be used

Integration Example



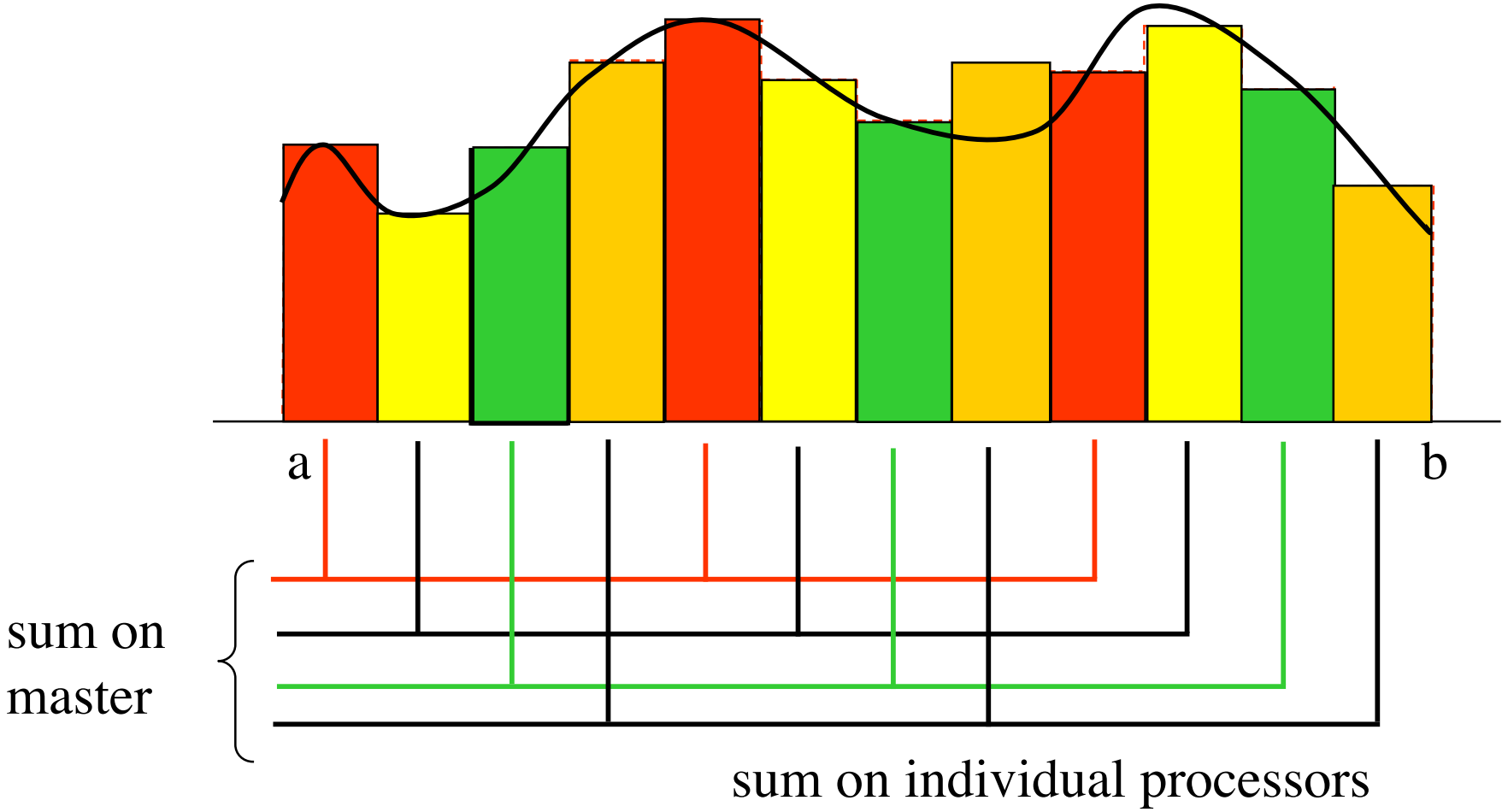
Rectangles approximate area under curve



Point-to-Point Version

- The number of processes is given on the command line.
- Process 0 will be the master.
- Each process j, *including the master*, computes the sum the rectangles (implicitly) numbered i such that i%numProcs == j .
- All of the slave processes send their sum to the master, which adds them together with its own sum.

Example with 4 processes



Reading/Writing MPI Code

- Must keep in mind that MPI is an ***SPMD*** (single-program, multiple-data stream) model.
- All processes execute the **same** program.
- Some processes execute one branch or another based on value of the processes' id.

MPI Code for Integration Problem (C syntax)

```
double integrate(
            double f(double),          /* function to integrate                */
            double low,                /* lower limit of integration           */
            double high,               /* upper limit of integration           */
            int numIntervals,          /* number of intervals to be used       */
            MPI_Comm comm)             /* MPI communicator to use              */
 {
 MPI_Status stat;                      /* status indicator                     */
 int numProcs;                         /* number of processes in comm          */
 int buffsize = 1;                     /* buffer size for messages             */
 int tag = 1;                          /* tag for messages                     */
 int id;                               /* id of this process                   */
 int master = 0;                       /* id of master process                 */
 double h;                             /* width of rectangle                   */
 double area;                          /* area of this process' rectangles     */
 double integral;                      /* approximation to integral            */
 int i;

 MPI_Comm_size(comm, &numProcs);       /* get number of processes              */
 MPI_Comm_rank(comm, &id);             /* get this process' id                 */
```

```
h  = (high - low) / numIntervals;                    /* compute rectangle width          */

area = 0;                                            /* compute area of rectangles       */
for( i = id ; i < numIntervals; i += numProcs )
  {
  area += f( h * ((double)i + 0.5) );
  }

if (id == master)
  {                                                  /* master adds up all sums          */
  integral = area;
  for( i = 1; i < numProcs; i++ )
    {
    MPI_Recv(&area, buffsize, MPI_DOUBLE, MPI_ANY_SOURCE, tag, comm, &stat);
    integral += area;
    }
  }
else
  {                                                  /* slave sends area to master       */
  MPI_Send(&area, buffsize, MPI_DOUBLE, master, tag, comm);
  }

return h * integral;
}
```

MPI Reduce Version

- The same basic idea as the point-to-point version, except
- No explicit sending and receiving messages
- Use the **reduce** operation of MPI instead.

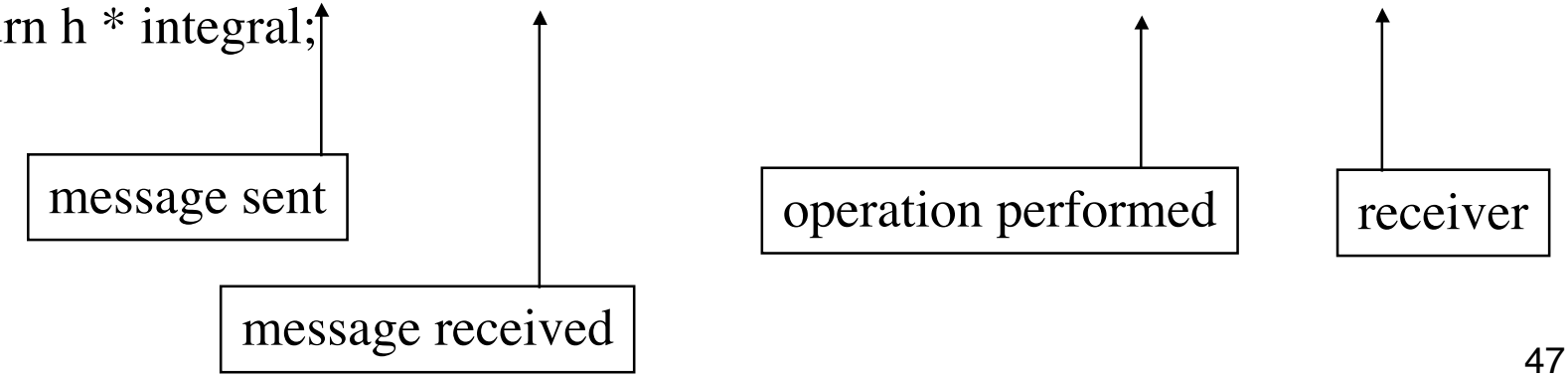
MPI Code for reduce version

```
h  = (high - low) / numIntervals;          /* compute rectangle width        */

area = 0;                                  /* compute area of rectangles     */
for( i = id ; i < numIntervals; i += numProcs )
  {
  area += f(h * ((double)i + 0.5));
  }
```

Note that the receiver sends also.
There is an implicit **barrier**.

```
MPI_Reduce(&area, &integral, tag, MPI_DOUBLE, MPI_SUM, master, comm);
return h * integral;
```



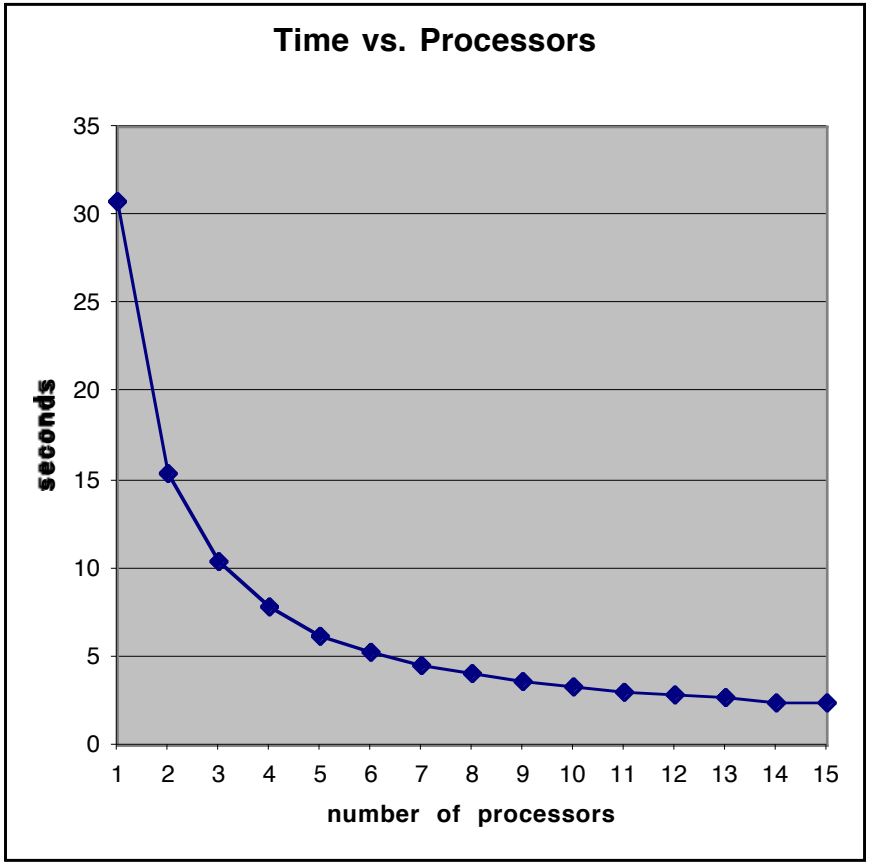
MPI Reduce Functions

- The operator applied in reduce is limited to the repertoire provided by MPI:
  - [MPI_MAX] maximum
  - [MPI_MIN] minimum
  - [MPI_SUM] sum
  - [MPI_PROD] product
  - [MPI_LAND] logical and
  - [MPI_BAND] bit-wise and
  - [MPI_LOR] logical or
  - [MPI_BOR] bit-wise or
  - [MPI_LXOR] logical xor
  - [MPI_BXOR] bit-wise xor
  - [MPI_MAXLOC] max value **and location**
  - [MPI_MINLOC] min value **and location**

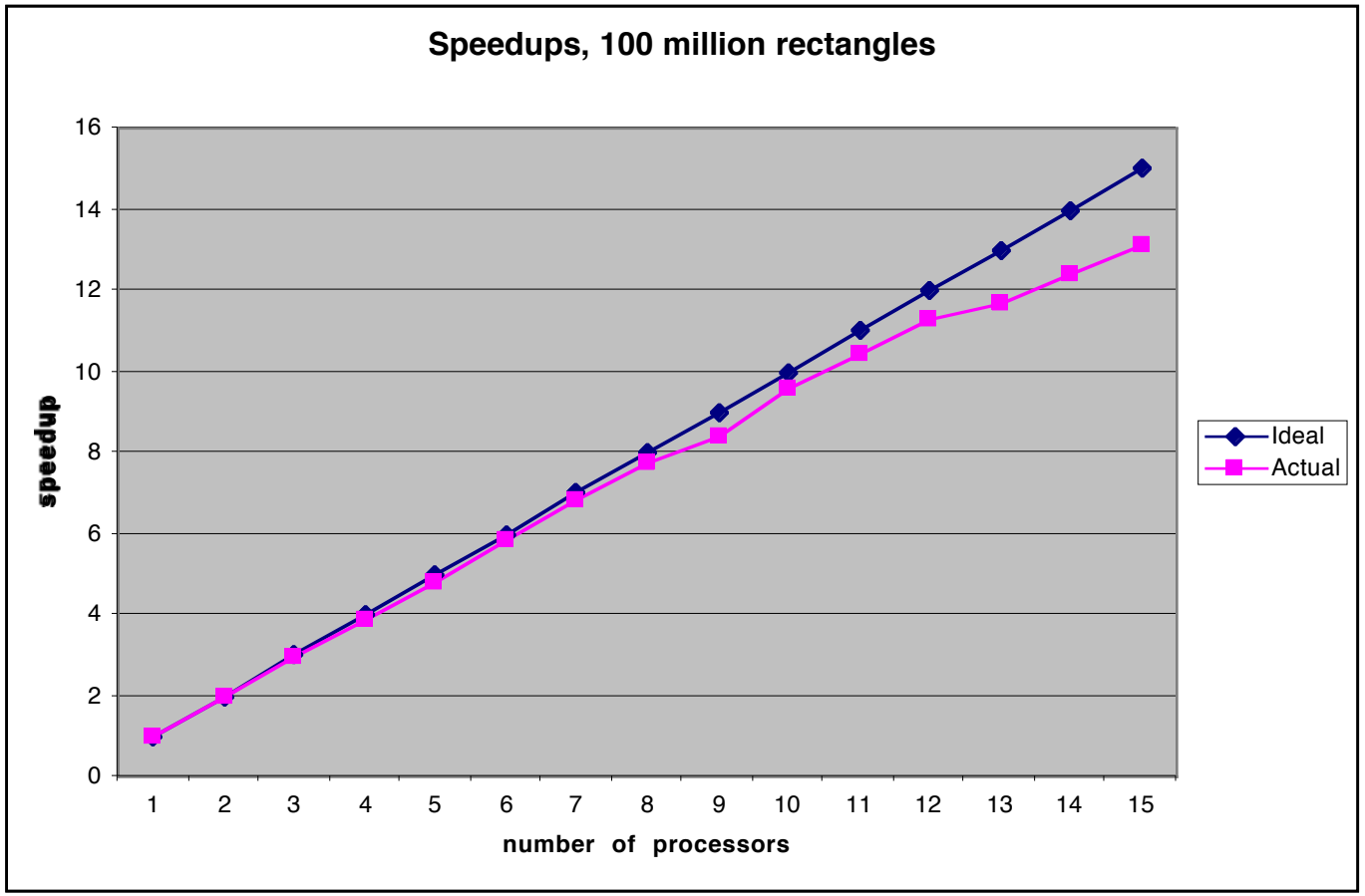
Results on early HMC Math Beowulf 100 million rectangles

processors	result	error	time (sec)	effort	speedup
1	3.14159265359023	4.41E-13	30.73	30.73	1.00
2	3.14159265358999	2.07E-13	15.48	30.96	1.99
3	3.14159265359014	3.49E-13	10.46	31.38	2.94
4	3.14159265359019	4.01E-13	7.90	31.60	3.89
5	3.14159265358964	-1.50E-13	6.38	31.89	4.82
6	3.14159265358965	-1.37E-13	5.24	31.43	5.86
7	3.14159265358964	-1.53E-13	4.51	31.60	6.81
8	3.14159265358960	-1.85E-13	3.97	31.77	7.74
9	3.14159265358974	-4.53E-14	3.67	33.01	8.37
10	3.14159265358974	-4.84E-14	3.22	32.16	9.54
11	3.14159265358973	-5.46E-14	2.95	32.41	10.42
12	3.14159265358973	-5.51E-14	2.72	32.64	11.30
13	3.14159265358973	-5.37E-14	2.64	34.32	11.64
14	3.14159265358974	-4.71E-14	2.48	34.67	12.39
15	3.14159265358974	-4.62E-14	2.34	35.05	13.13

Time vs. Processors



Speedup vs. Processors



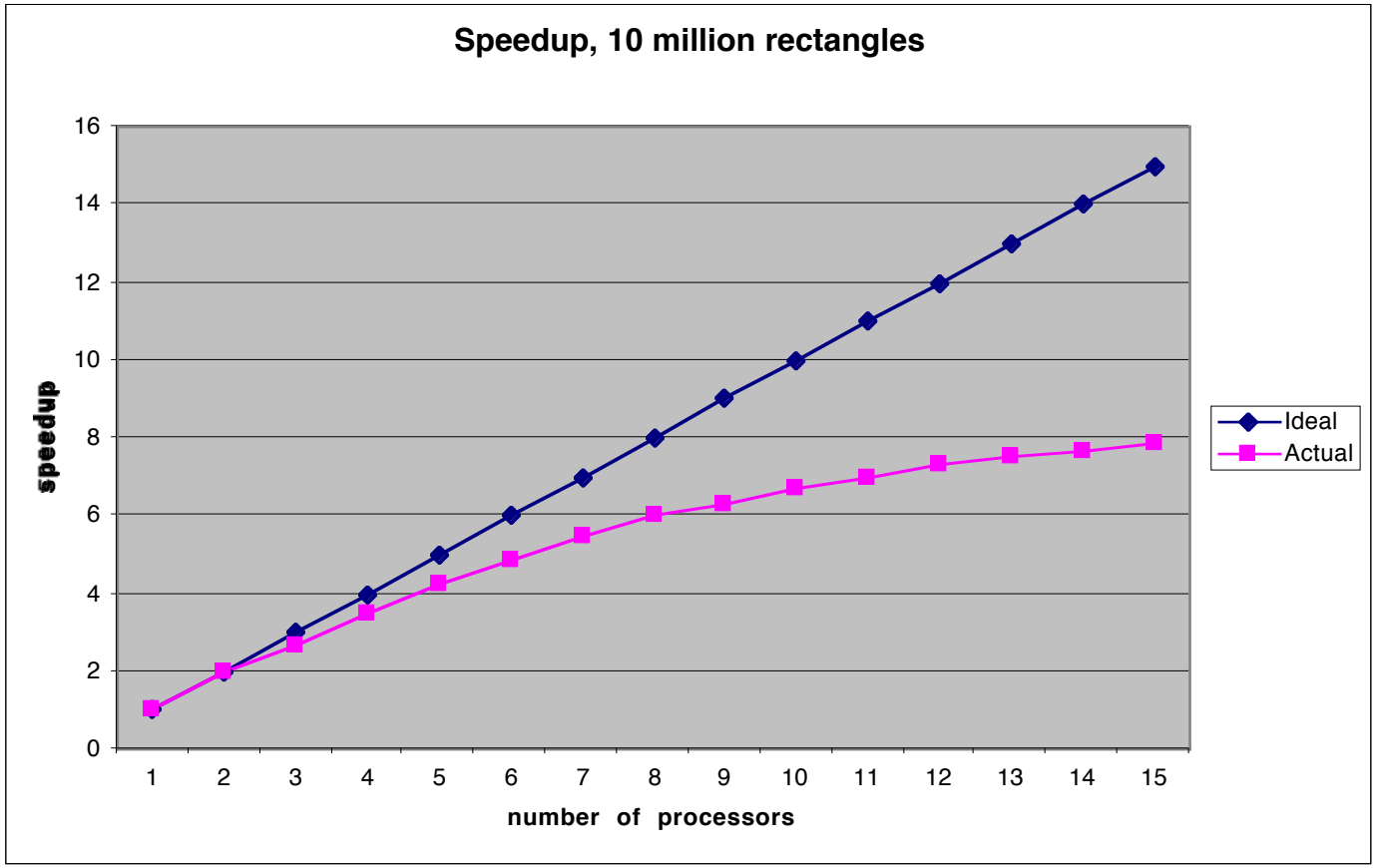
Perspective

- The application seems to have good speedup.
- However, we can get the same or better accuracy with only 10 million points.
- In the latter case, the speedup is not so dramatic:

Results on HMC Beowulf
10 million rectangles

processors	result	error	time (sec)	effort	speedup
1	3.14159265358972	-6.44E-14	3.07	3.07	1.00
2	3.14159265358998	1.89E-13	1.54	3.08	1.99
3	3.14159265358990	1.12E-13	1.14	3.42	2.69
4	3.14159265358968	-1.10E-13	0.88	3.53	3.49
5	3.14159265358970	-8.44E-14	0.73	3.65	4.21
6	3.14159265358976	-2.71E-14	0.63	3.77	4.87
7	3.14159265358979	-4.44E-16	0.56	3.92	5.48
8	3.14159265358980	1.11E-14	0.51	4.04	6.02
9	3.14159265358979	1.33E-15	0.49	4.42	6.27
10	3.14159265358979	-8.88E-16	0.46	4.60	6.67
11	3.14159265358977	-1.47E-14	0.44	4.87	6.98
12	3.14159265358976	-2.62E-14	0.42	5.02	7.31
13	3.14159265358977	-2.22E-14	0.41	5.31	7.49
14	3.14159265358978	-6.66E-15	0.40	5.55	7.68
15	3.14159265358978	-7.55E-15	0.39	5.80	7.87

Speedup vs. Processors

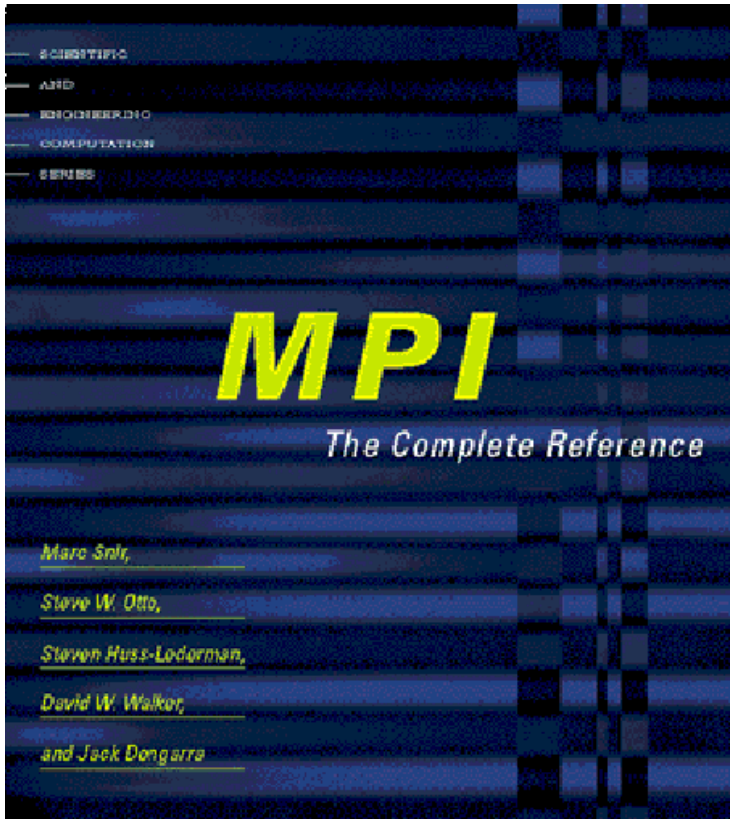


Results on early HMC Beowulf
1 million rectangles

processors	result	error	time (sec)	effort	speedup
1	3.14159265358976	-2.98E-14	0.31	0.31	1.00
2	3.14159265358994	1.47E-13	0.16	0.33	1.94
3	3.14159265358990	1.16E-13	0.22	0.66	1.41
4	3.14159265358990	1.10E-13	0.19	0.78	1.63
5	3.14159265358992	1.28E-13	0.18	0.90	1.72
6	3.14159265358989	1.04E-13	0.17	1.03	1.82
7	3.14159265358990	1.12E-13	0.16	1.13	1.94
8	3.14159265358989	9.77E-14	0.16	1.27	1.94
9	3.14159265358987	8.62E-14	0.15	1.39	2.07
10	3.14159265358987	7.73E-14	0.19	1.87	1.63
11	3.14159265358986	7.37E-14	0.19	2.07	1.63
12	3.14159265358987	8.26E-14	0.08	0.90	3.88
13	3.14159265358987	8.22E-14	0.08	1.02	3.88
14	3.14159265358987	8.44E-14	0.08	1.14	3.88
15	3.14159265358987	8.53E-14	0.09	1.34	3.44

Free book on-line at

http://netlib2.cs.utk.edu/utk/papers/mpi-book/mpi-book.html



Other Links of Importance

http://www.mcs.anl.gov/research/projects/mpich2/

http://en.wikipedia.org/wiki/MPICH

MPI Scatter/Gather

Gather:

Used to collect “rows” of an array in a “root” process

```
MPI_Gather(void* sendbuf,
           int sendcount,
           MPI_Datatype sendtype,
           void* recvbuf,
           int recvcount,
           MPI_Datatype recvtype,
           int root,
           MPI_Comm comm)
```

rank of the root

The outcome is ***as if*** each of the n processes in the group (including the root process) had executed a call to

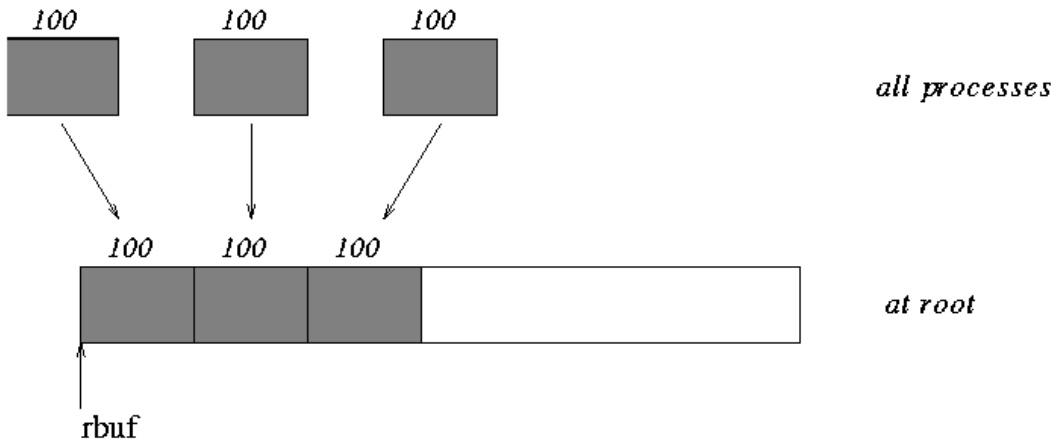
MPI_Send(sendbuf, sendcount, sendtype, root, ...),

and the root process had executed n calls to

MPI_Recv(recvbuf+i-recvcount-extent(recvtype), recvcount, recvtype, i ,...),

where extent(recvtype) is the type extent obtained from a call to MPI_Type_extent().

Gather Example




```
MPI_Comm comm;
   int gsize,sendarray[100];
   int root, myrank, *rbuf;
   ...
   MPI_Comm_rank( comm, myrank);
   if ( myrank == root) {
     MPI_Comm_size( comm, &gsize);
     rbuf = (int *)malloc(gsize*100*sizeof(int));
     }
   MPI_Gather( sendarray, 100, MPI_INT, rbuf, 100, MPI_INT, root, comm);
```

Scatter:

Used to distribute “rows” of an array

```
MPI_Scatter(void* sendbuf,
            int sendcount,
            MPI_Datatype sendtype,
            void* recvbuf,
            int recvcount,
            MPI_Datatype recvtype,
            int root,
            MPI_Comm comm)
```

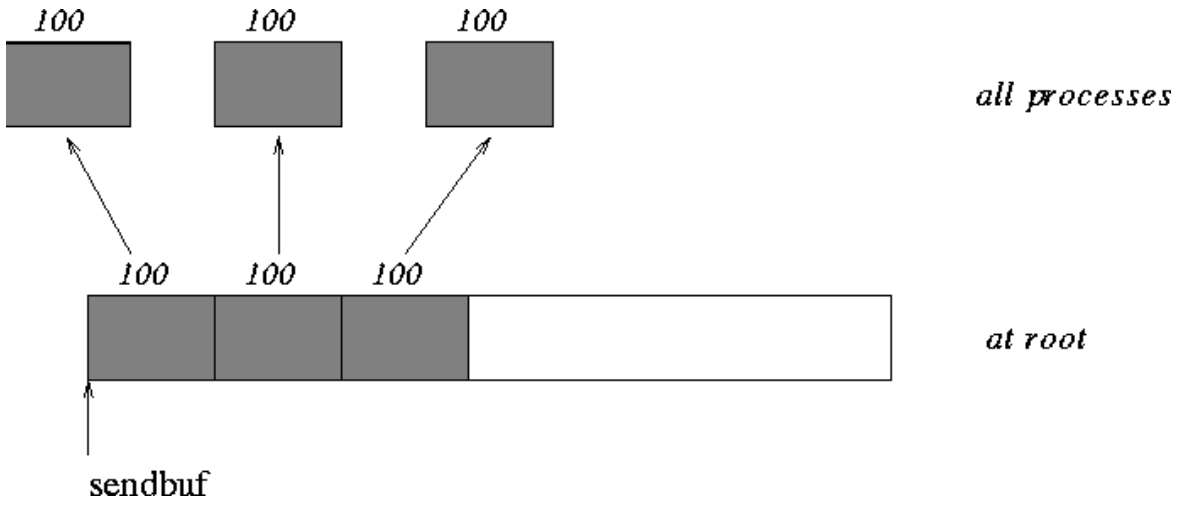
The outcome is *as if* the root executed n send operations,

MPI_Send(sendbuf+i-sendcount-extent(sendtype), sendcount, sendtype, i,...),

i = 0 to n - 1. and each process executed a receive,

MPI_Recv(recvbuf, recvcount, recvtype, root,...).

Scatter Example

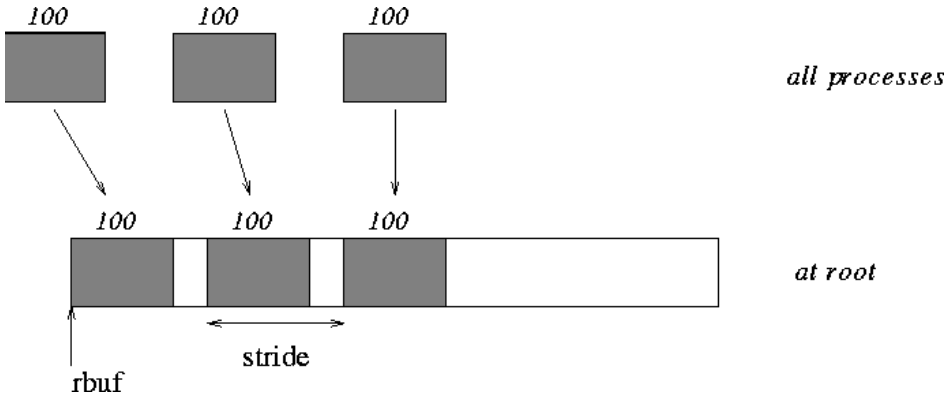



```
MPI_Comm comm;
   int gsize,*sendbuf;
   int root, rbuf[100];
   ...
   MPI_Comm_size( comm, &gsize);
   sendbuf = (int *)malloc(gsize*100*sizeof(int));
   ...
   MPI_Scatter( sendbuf, 100, MPI_INT, rbuf, 100, MPI_INT, root, comm);
```

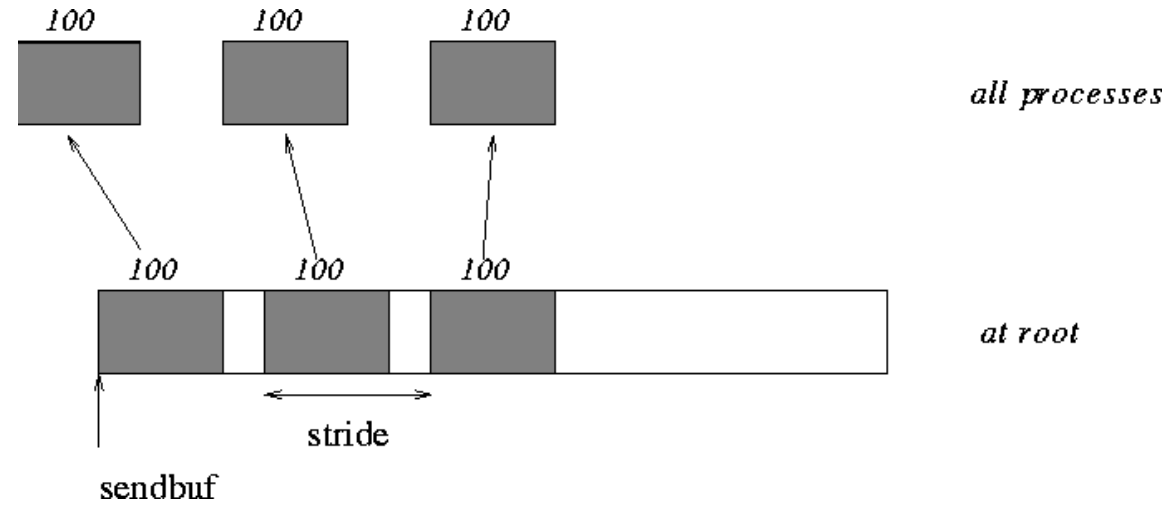
Vector Variants append “v”

- The **Vector Variants** allow the gathered/scattered sub-arrays to be of **different sizes**, by specifying an **array of lengths** of the sizes. They also allow there to be “gaps” (or “stride”) by making the displacements explicit.

MPI_Gatherv(void* sendbuf, int sendcount, MPI_Datatype sendtype, void* recvbuf,
int *recvcounts, int *displs, arrays
MPI_Datatype recvtype, int root, MPI_Comm comm)



Vector Variants of Scatter



MPI_Scatter**v**(void* sendbuf,
int *sendcounts, int *displs, arrays
MPI_Datatype sendtype, void* recvbuf, int recvcount,
MPI_Datatype recvtype, int root, MPI_Comm comm)

“All” Variants

- The **all variants** distribute the results of a gather to all processors in the communicator, rather than just one. There is a vector version analogous to gather.

MPI_**All**gather(void* sendbuf, int sendcount, MPI_Datatype sendtype, void* recvbuf, int recvcount, MPI_Datatype recvtype, MPI_Comm comm)

MPI_**All**gather**v**(void* sendbuf, int sendcount, MPI_Datatype sendtype, void* recvbuf, int *recvcounts, int *displs, MPI_Datatype recvtype, MPI_Comm comm)

arrays

extremely useful

“All-to-All” Variants

Alltoall allows everything to be scattered and gathered in one call.

Contents of distinct send buffers are sent to all receive buffers

```
MPI_Alltoall(void* sendbuf, int sendcount, MPI_Datatype sendtype,
             void* recvbuf, int recvcount, MPI_Datatype recvtype,
             MPI_Comm comm)
```

```
MPI_Alltoallv(void* sendbuf, int *sendcounts,
              int *sdispls, MPI_Datatype sendtype,
              void* recvbuf, int *recvcounts, int *rdispls,
              MPI_Datatype recvtype, MPI_Comm comm)
```

PVM vs. MPI

Jack Dongarra

Started PVM, contributed to MPI
Distinguished Professor, University of Tennessee
Distinguished Scientist, Oak Ridge National Laboratory
Also known for netlib, lapack, etc. Tutorial presentation:
http://www.netlib.org/utk/people/jd-tutorial/Presentation.html

PVM vs. MPI

- MPI = Message-Passing Interface
  - SPMD (Single program, multiple data)
  - Each node runs the same program
  - The program “just exists”, it is not spawned explicitly
- PVM = Parallel Virtual Machine
  - “MPMD” (Multiple program, multiple data)
  - Processes are explicitly spawned
  - Processes are assigned to nodes in separate layer, possibly multiple per node

PVM

- PVM came before MPI.
- Lower level, but more flexible
- Can be used for heterogeneous network
- Arbitrary topology
- Messages can cross outside of host boundaries.
- Explicit packing and unpacking of messages required in code
- Fault tolerance features

PVM

- In PVM *daemon* processes must be resident on nodes prior to spawning PVM processes there.
- Upon command, the daemon launches the process.
- The PVM **host file** identifies participating nodes, or they can be added manually from the command line.
- Root process is started from pvm console command-line on one host.

PVM

- Processes explicitly spawn child processes.
- Child can determine its parent.
- Processes have their own “task id”.
- Point-to-point send/receive similar to MPI.
- Tags, wildcards similar to MPI.

Code Fragment for simple PVM process (1)
(I have left out the error checking, etc.)

```
int main(int argc, char* argv[]) {
/* find out my task id number */
mytid = pvm_mytid();

/* find my parent's task id number */
myparent = pvm_parent();

/* if I don't have a parent then I am the parent */
if (myparent == PvmNoParent) {

/* spawn the child tasks */
info = pvm_spawn(argv[0], (char**)0, PvmTaskDefault, (char*)0,
```

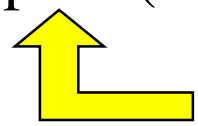
Code Fragment (2)

```
/* I'm still the parent */

    for (i = 0; i < ntask; i++) {
        /* receive a message from any (-1) child process */
        buf = pvm_recv(-1, JOINTAG);

        info = pvm_bufinfo(buf, &len, &tag, &tid);

        info = pvm_upkint(&mydata, 1, 1);
        }
    pvm_exit();
    }
```

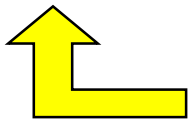


"unpack int data"

Code Fragment (3)

```
    /* I'm a child */

    info = pvm_initsend(PvmDataDefault);
    info = pvm_pkint(&mytid, 1, 1);
```



"pack int data"

```
    info = pvm_send(myparent, JOINTAG);
    pvm_exit();
}
```

See http://www.netlib.org/pvm3/ for more details.

PVM groups

- Processes explicitly join and leave groups, named symbolically.
- Multicast, gather, barriers, etc. are done relative to group, to explicit receives.
- Multicast can be into group from outside.
- Reduce operator for +, *, max, min, or *user-defined*.
- A process can be in multiple groups.

Timing Analysis for Parallel Applications with Message Passing

Time Decompositon

- Parallel execution time can be divided into:
  - Computation time

    + Communication time

    $$t_{parallel} = t_{comp} + t_{comm}$$

  - If there are m non-parallel message steps overall, then

    $$t_{comm} = m * t_{message}$$

Message Time Decomposition

- Message time can be divided into:
  - **Latency** (or start-up time) +
  - (number of data communicated)*(delay per datum)

$$t_{message} = t_{startup} + n * t_{datum}$$

$1/ t_{datum}$ is often called "**bandwidth**", the amount of data that can be sent per unit time.

Latency Hiding

- In order to prevent $t_{message}$ from destroying any speedup due to parallelism, we can try the following:
  - While a processing element is awaiting a message, perform some other computation that doesn't require the message.
- Note that we are really trying to hide the entire communication cost, not just the "latency" component of it.

Latency Hiding (2)

- One technique for hiding latency is "multiprogramming":
  - On a single processor, run more than one process.
  - While one process is awaiting a message, another could be doing useful computational work.
  - This requires that process-switching be relatively efficient (e.g. using threads rather than processes).
- The ratio of processes to processors is sometimes called the "parallel slackness".