# 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?



# Communication Granularity

- Parallelism with fine-grain requires relatively-frequent communication compared to the computation interval.
- If a process needs to communicate frequently with other processes, then the communication must be very fast or the process' waiting time will absorb the speedup from parallel execution.
- 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.



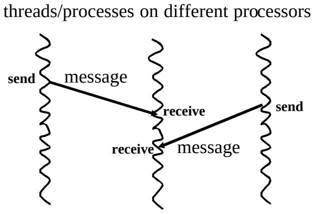
# Message-Passing Paradigm

- 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, since there is overhead in passing messages.



# Message-Passing (2)

threads/processes on different processors

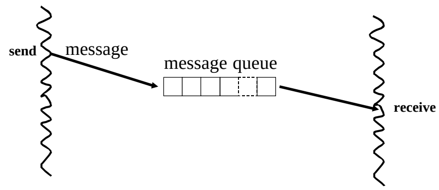





# Message-Passing (3)

- 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






## 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.

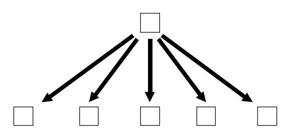


## Multi-cast, Scatter, Gather, Reduce

- **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 array to different processes.
- **Gather** means to collect elements from different processes into a single array.
- **Reduce** means to form a single element using a specified binary operation.

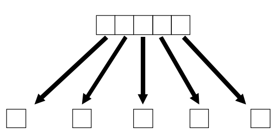


## Multi-cast



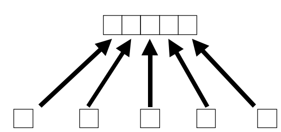


## Scatter

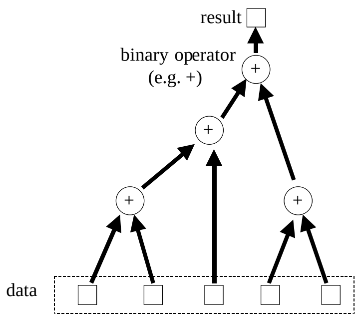




## Gather



# Reduce






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


Ewing Lusk

- Based on the SPMD (Single Program, Multiple Data Stream) idea.
- All processes run the same program, but
- Processes can differentiate themselves using assigned ID's (called the ***rank*** of the process), so the code actually executed can be different in different processes.
- Processes are divided into ***groups*** and the rank (0,1, 2, …) applies within the group.



# MPI (2)

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

  MPI_COMM_WORLD



# MPI (3)

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

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

- The program initializes using (C syntax):

  MPI_Init(&argc, &argv);

where argc and argv are from the command line.



# MPI (4)

- Always terminate execution with:

  MPI_Finalize();



# MPI (5)

- The program can find out the number of processes:

  MPI_Comm_size(*Communicator*, &nprocs);

e.g.

  MPI_Comm_size(MPI_COMM_WORLD, &nprocs);

## MPI (6)

- A process can determine its own **rank**:

MPI_Comm_size(*Communicator*, &id);

- and the name of its processor:

MPI_Get_processor_name(name, &namelen);

pre-allocated buffer

pointer to length of string (set by the routine)



## MPI (7)

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

MPI_Barrier(*Communicator*);



## Master/Slaves

- It is common to declare 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 master is in charge of initial setup and later direction.
- The slaves do the main work in parallel.



## 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 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

03-25

# 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 datatype:

- MPI_PACKED
- MPI_BYTE

03-26

# Status indicator

- 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)

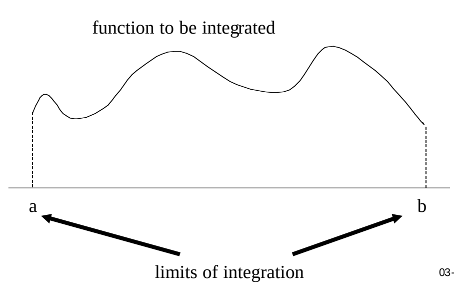
03-27

# 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

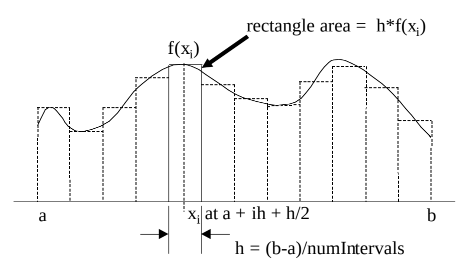
03-28

# Integration Example




03-29

# Rectangles approximate area under curve



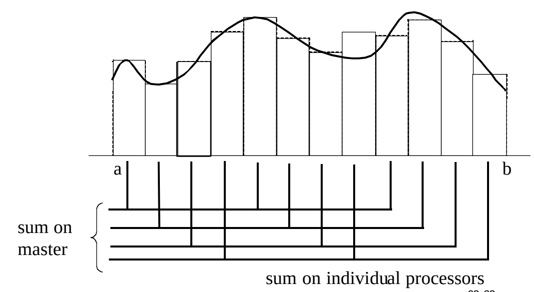

03-30

# 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 sums them together with its own.



# Example with 4 processes






# Reading/Writing MPI Code

- can be a little tricky.
- 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

```
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 buffsiz = 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 areas    */
  integral = area;
  for( i = 1; i < numProcs; i++ )
    {
    MPI_Recv(&area, buffsiz, MPI_DOUBLE, MPI_ANY_SOURCE, tag, comm, &stat);
    integral += area;
    }
  }
else
  {                                         /* slave sends area to master    */
  MPI_Send(&area, buffsiz, MPI_DOUBLE, master, tag, comm);
  }

return h * integral;
}
```

# Reduce Version

- The same basic idea as the point-to-point version, except that rather than explicitly sending and receiving messages, the **reduce** operation of MPI is used.

# 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));
  }

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

message sent

message received

operation performed

receiver

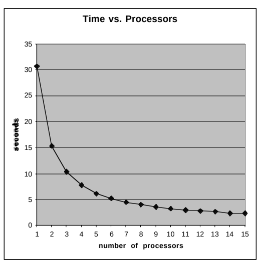
Note that the receiver sends also.

# Results on 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 |

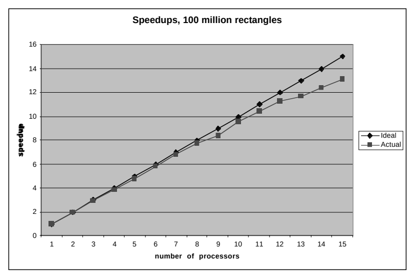


# Time vs. Processors






# Speedup vs. Processors






# Perspective

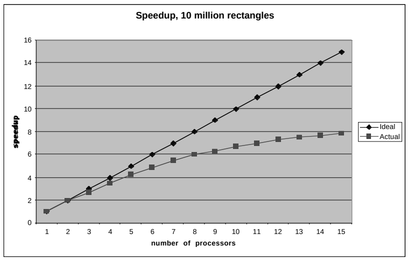
- The application seems to have good speedup.
- However, we can get the same or better accuracy with only 10 million points.
- In the latter case, the speedup is not so dramatic:



# 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






# What about 1 million rectangles?

- Describe what is going on using the vocabulary presented thus far.
- What do you predict for 1 million?



# Results on 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 |