The Message Passing Interface (MPI)

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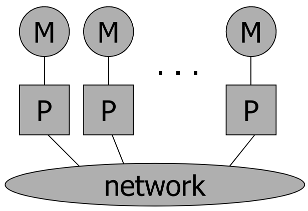
Message Passing



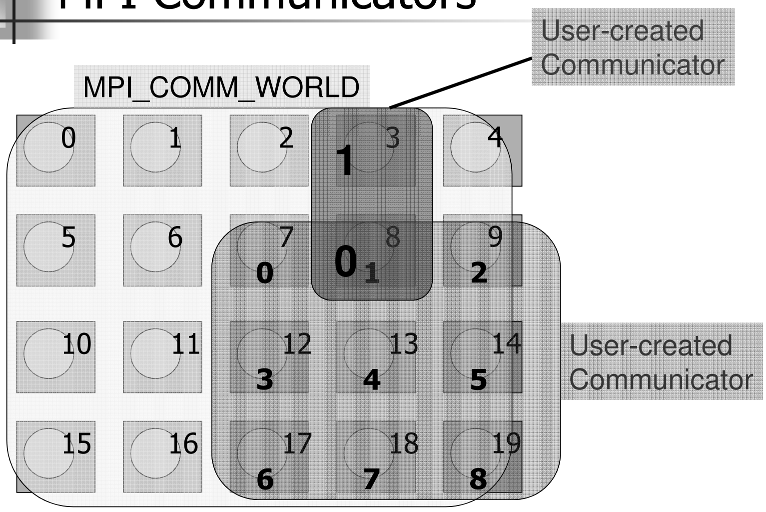
- Each processor runs a process
- Processes communicate by exchanging messages
- They cannot share memory in the sense that they cannot address the same memory cells

- The above is a programming model and things may look different in the actual implementation (e.g., MPI over Shared Memory)
- Message Passing is popular because it is general:
  - Pretty much any distributed system works by exchanging messages, at some level
  - Distributed- or shared-memory multiprocessors, networks of workstations, uniprocessors
- It is not popular because it is easy (it's not)

MPI Concepts

- Fixed number of processors
  - When launching the application one must specify the number of processors to use, which remains unchanged throughout execution
- Communicator
  - Abstraction for a group of processes that can communicate
  - A process can belong to multiple communicators
  - Makes is easy to partition/organize the application in multiple layers of communicating processes
  - Default and global communicator: `MPI_COMM_WORLD`
- Process Rank
  - The index of a process within a communicator
  - Typically user maps his/her own virtual topology on top of just linear ranks
    - ring, grid, etc.

MPI Communicators



A First MPI Program

```
#include <unistd.h>
#include <mpi.h>
int main(int argc, char **argv) {
  int my_rank, n;
  char hostname[128];
  MPI_init(&argc,&argv);
  MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
  MPI_Comm_size(MPI_COMM_WORLD,&n);
  gethostname(hostname,128);
  if (my_rank == 0) { /* master */
    printf("I am the master: %s\n",hostname);
  } else { /* worker */
    printf("I am a worker: %s (rank=%d/%d)\n",
           hostname,my_rank,n-1);
  }
  MPI_Finalize();
  exit(0);
}
```

Has to be called first, and once

Has to be called last, and once

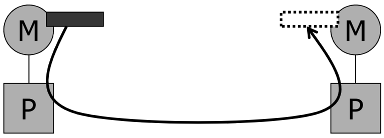
Compiling/Running it

- Link with libmpi.a
- Run with `mpirun`
  - `% mpirun -np 4 my_program <args>`
  - requests 4 processors for running `my_program` with command-line arguments
  - see the `mpirun` man page for more information
  - in particular the `-machinefile` option that is used to run on a network of workstations
- Some systems just run all programs as MPI programs and no explicit call to `mpirun` is actually needed
- Previous example program:

```
% mpirun -np 3 -machinefile hosts my_program
  I am the master: somehost1
  I am a worker: somehost2 (rank=2/2)
  I am a worker: somehost3 (rank=1/2)
```

(stdout/stderr redirected o the process calling mpirun)

Point-to-Point Communication



- Data to be communicated is described by three things:
  - address
  - data type of the message
  - length of the message
- Involved processes are described by two things
  - communicator
  - rank
- Message is identified by a "tag" (integer) that can be chosen by the user

Point-to-Point Communication

- Two modes of communication:
  - Synchronous: Communication does not complete until the message has been received
  - Asynchronous: Completes as soon as the message is "on its way", and hopefully it gets to destination
- MPI provides four versions
  - synchronous, buffered, standard, ready

Synchronous/Buffered sending in MPI

- Synchronous with MPI_Ssend
  - The send completes only once the receive has succeeded
    - copy data to the network, wait for an ack
    - The sender has to wait for a receive to be posted
    - No buffering of data
- Buffered with MPI_Bsend
  - The send completes once the message has been buffered internally by MPI
    - Buffering incurs an extra memory copy
    - Doe not require a matching receive to be posted
    - May cause buffer overflow if many bsends and no matching receives have been posted yet

Standard/Ready Send

- Standard with MPI_Send
  - Up to MPI to decide whether to do synchronous or buffered, for performance reasons
  - The rationale is that a correct MPI program should not rely on buffering to ensure correct semantics
- Ready with MPI_Rsend
  - May be started *only* if the matching receive has been posted
  - Can be done efficiently on some systems as no hand-shaking is required

Example: Sending and Receiving

```
#include <unistd.h>
#include <mpi.h>
int main(int argc, char **argv) {
  int i, my_rank, nprocs, x[4];
  MPI_Init(&argc,&argv);
  MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
  if (my_rank == 0) { /* master */
    x[0]=42; x[1]=43; x[2]=44; x[3]=45;
    MPI_Comm_size(MPI_COMM_WORLD,&nprocs);
    for (i=1;i<nprocs;i++)
      MPI_Send(x,4,MPI_INT,i,0,MPI_COMM_WORLD);
  } else { /* worker */
    MPI_Status status;
    MPI_Recv(x,4,MPI_INT,0,0,MPI_COMM_WORLD,&status);
  }
  MPI_Finalize();
  exit(0);
}
```

destination and source

user-defined tag

Max number of elements to receive

Can be examined via calls like MPI_Get_count(), etc.

Non-blocking Communication

- MPI_Issend, MPI_Ibsend, MPI_Isend, MPI_Irsend, MPI_Irecv

```
MPI_Request request;
MPI_Isend(&x,1,MPI_INT,dest,tag,communicator,&request);
MPI_Irecv(&x,1,MPI_INT,src,tag,communicator,&request);
```

- Functions to check on completion: MPI_Wait, MPI_Test, MPI_Waitany, MPI_Testany, MPI_Waitall, MPI_Testall, MPI_Waitsome, MPI_Testsome.

```
MPI_Status status;
MPI_Wait(&request, &status) /* block */
MPI_Test(&request, &status) /* doesn't block */
```

Collective Communication

- Operations that allow more than 2 processes to communicate simultaneously
  - barrier
  - broadcast
  - reduce
- All these can be built using point-to-point communications, but typical MPI implementations have optimized them, and it's a good idea to use them
- In all of these, all processes place the same call (in good SPMD fashion), although depending on the process, some arguments may not be used

Barrier

- Synchronization of the calling processes
  - the call blocks until all of the processes have placed the call
- No data is exchanged

```
...
MPI_Barrier(MPI_COMM_WORLD)
...
```

Broadcast

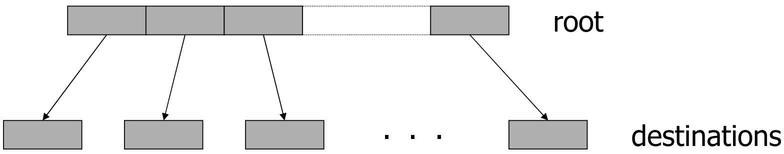
- One-to-many communication
- Note that multicast can be implemented via the use of communicators (i.e., to create processor groups)

```
...
MPI_Bcast(x, 4, MPI_INT, 0,
  MPI_COMM_WORLD)
...
```

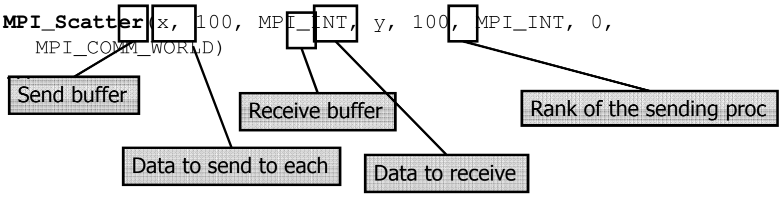
Rank of the root

Scatter

- One-to-many communication
- Not sending the same message to all

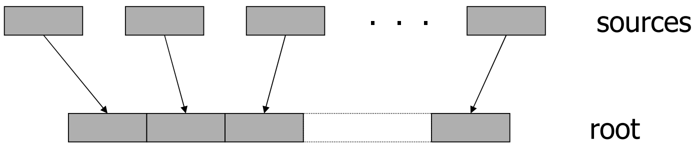



```
...
MPI_Scatter(x, 100, MPI_INT, y, 100, MPI_INT, 0,
   MPI_COMM_WORLD)
```

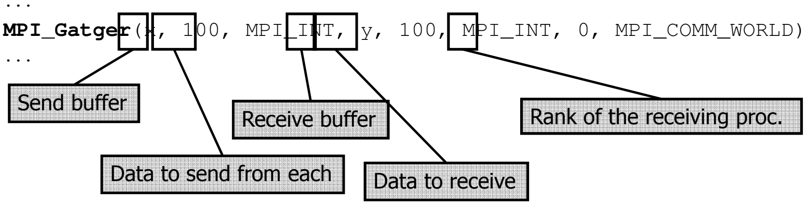


Gather

- Many-to-one communication
- Not sending the same message to the root

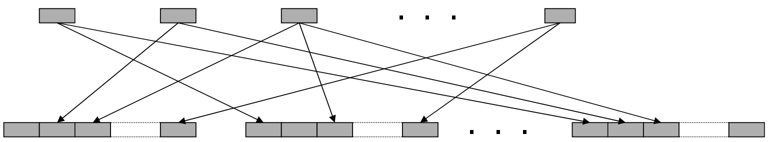



```
...
MPI_Gatger(x, 100, MPI_INT, y, 100, MPI_INT, 0, MPI_COMM_WORLD)
...
```

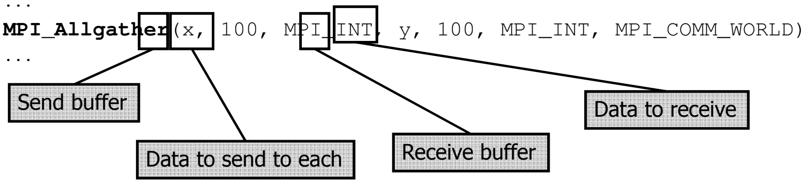


Gather-to-all

- Many-to-many communication
- Each process sends the same message to all
- Different Processes send different messages

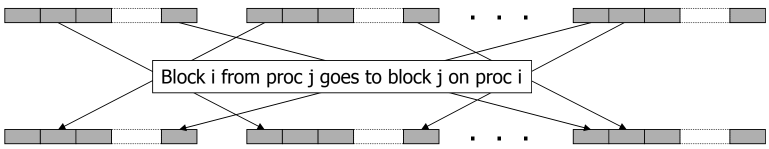


```
...
MPI_Allgather(x, 100, MPI_INT, y, 100, MPI_INT, MPI_COMM_WORLD)
...
```



All-to-all

- Many-to-many communication
- Each process sends a different message to each other process




```
...
MPI_Alltoall(x, 100, MPI_INT, y, 100, MPI_INT, MPI_COMM_WORLD)
...
```

Send buffer

Data to send to each

Receive buffer

Data to receive

Reduction Operations

- Used to compute a result from data that is distributed among processors
  - often what a user wants to do anyway
  - so why not provide the functionality as a single API call rather than having people keep re-implementing the same things
- Predefined operations:
  - MPI_MAX, MPI_MIN, MPI_SUM, etc.
- Possibility to have user-defined operations

MPI_Reduce, MPI_Allreduce

- MPI_Reduce: result is sent out to the root
  - the operation is applied element-wise for each element of the input arrays on each processor
- MPI_Allreduce: result is sent out to everyone

```
...
MPI_Reduce(x, r, 10, MPI_INT, MPI_MAX, 0, MPI_COMM_WORLD)
...
```

input array

output array

array size

root

```
...
MPI_Allreduce(x, r, 10, MPI_INT, MPI_MAX, MPI_COMM_WORLD)
...
```

MPI_Reduce example

```
MPI_Reduce(sbuf,rbuf,6,MPI_INT,MPI_SUM,0,MPI_COMM_WORLD)
```

sbuf

P0	3	4	2	8	12	1
P1	5	2	5	1	7	11
P2	2	4	4	10	4	5
P3	1	6	9	3	1	1

rbuf

P0	11	16	20	22	24	18

MPI_Scan: Prefix reduction

- process i receives data reduced on process 0 to i.

sbuf

P0	3	4	2	8	12	1
P1	5	2	5	1	7	11
P2	2	4	4	10	4	5
P3	1	6	9	3	1	1

rbuf

P0	3	4	2	8	12	1
P1	8	6	7	9	19	12
P2	10	10	11	19	23	17
P3	11	16	12	22	24	18

```
MPI_Scan(sbuf,rbuf,6,MPI_INT,MPI_SUM,MPI_COMM_WORLD)
```

User-defined reduce operations

```
MPI_Op_create(MPI_User_function
  *function,
                int commute, MPI_Op *op)
```

- pointer to a function with a specific prototype
- commute (0 or 1) allows for optimization if true

```
typedef void MPI_User_function(void *a,
  void *b, int *len, MPI_Datatype
  *datatype);
```

- b[i] = a[i] op b[i], for i=0,...,len-1

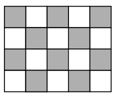
MPI_Op_create example

```
void myfunc(void *a, void *b, int *len, MPI_Datatype
   *dtype) {
    int i;
    for (i = 0; i < *len; ++i)  ((int*)b)[i] =
   ((int*)b)[i] + ((int*)a)[i];
}
int main(int argc, char *argv[]) {
    int myrank, nprocs, sendbuf, recvbuf;
    MPI_Op myop;
    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &nprocs);
    MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
    MPI_Op_create(myfunc, 1, &myop);
    sendbuf = 2*myrank+1;                       // odd
  numbers
    MPI_Reduce(&sendbuf, &recvbuf, 1, MPI_INT, myop, 0,

  MPI_COMM_WORLD);
    if(myrank == 0) printf("%d^2 = %d\n", nprocs,
```

More Advanced Messages

- Regularly strided data



Blocks/Elements of a matrix

- Data structure

```
struct {
    int a;
    double b;
 }
```

- A set of variables

```
int a; double b; int x[12];
```

Derived Data Types

- A data type is defined by a “type map”
  - set of <type, displacement> pairs
- Created at runtime in two phases
  - Construct the data type from existing types
  - Commit the data type before it can be used
- Simplest constructor: contiguous type

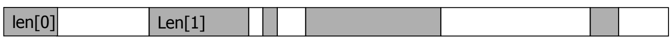
```
int MPI_Type_contiguous(int count,
     MPI_Datatype oldtype,
     MPI_Datatype *newtype)
```

MPI_Type_contiguous example

```
int buffer[100];
MPI_Datatype chvec;
MPI_Type_contiguous(20, MPI_CHAR,
  &chvec);
MPI_Type_commit(&chvec);
...
MPI_Send(buffer,1,chvec,1,44,MPI_COMM_WOR
  LD);
MPI_Type_free(&chvec);
```

MPI_Type_indexed()

```
int MPI_Type_indexed(int count,
    int *array_of_blocklengths,
    int *array_of_displacements,
    MPI_Datatype oldtype,
    MPI_Datatype *newtype)
```

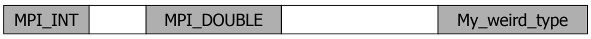


MPI_Type_indexed example

```
 int vector[4][3] = { 11, 12, 13, 21, 22, 23, 31, 32, 33,
41, 42, 43 };
 int wvector[4][3] = { 0 };
 int blocklengths[2] = {2, 2};
 int displacements[2] = {4, 10};  int rank;
 MPI_Datatype mytype;
 MPI_Status mystatus;
 MPI_Init(&argc, &argv);
 MPI_Type_indexed(4, blocklengths, displacements, MPI_INT,
&mytype);
 MPI_Type_commit(&mytype);
 MPI_Comm_rank(MPI_COMM_WORLD, &rank);
 if (rank == 0) MPI_Send(vector, 1, mytype, 1, 0,
MPI_COMM_WORLD);
 else {
      MPI_Recv(wvector, 1, mytype, 0, 0, MPI_COMM_WORLD,
&mystatus);
       for (i = 0; i < 4; i++) { printf("\n");
              for (j=0; j < 3; j++) printf("%02d ",
```

MPI_Type_struct()

```
int MPI_Type_struct(int count,
    int *array_of_blocklengths,
    MPI_Aint *array_of_displacements,
    MPI_Datatype *array_of_types,
    MPI_Datatype *newtype)
```



MPI_Type_vector example

- Sending the 5th column of a 2-D matrix:

```
double results[IMAX][JMAX];
MPI_Datatype newtype;
MPI_Type_vector (IMAX, 1, JMAX, MPI_DOUBLE, &newtype);
MPI_Type_Commit (&newtype);
MPI_Send(&(results[0][5]), 1, newtype, dest, tag, comm);
```