Programming Using the Message-Passing Paradigm

Distributed memory Architecture

- Distributed-memory
  - Collection of core-memory pairs connected by a network.
  - The memory associated with a core is directly
    - accessible only to that core
- Shared-memory systems
  - collection of cores connected to a globally
  - accessible memory, in which each core can have access to any memory location.

Distributed memory Architecture

- Each processor has its own private memory.
- Computational tasks can only operate on local data, if remote data is required, the computational task must communicate with one or more remote processors. Communication through the **message passing**

- **Communication between Process:**
  - a program running on one core-memory pair is usually called a process
  - Two processes can communicate by calling functions:
  - one process calls a send function and the other calls a receive function
  - **MPI- Message-Passing Interface**
    - It defines a library of functions

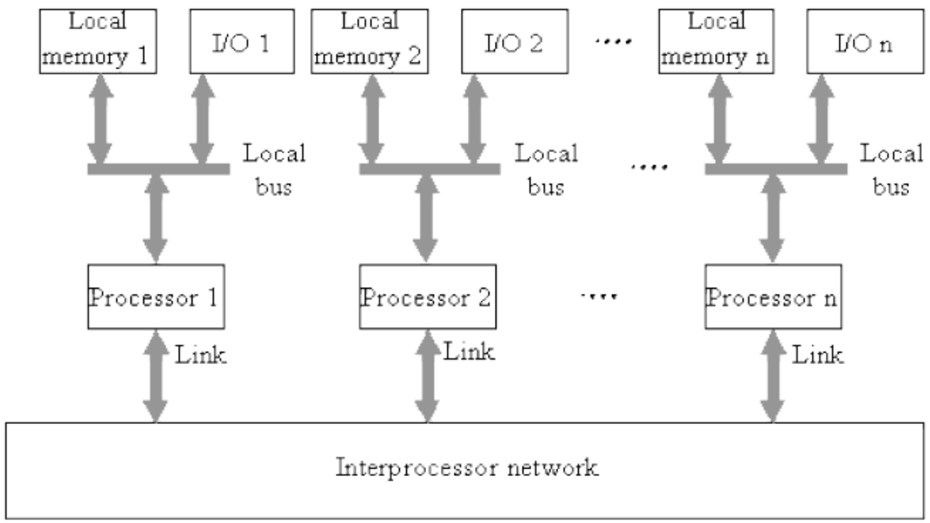


Fig: A multiprocessor system with a distributed memory (loosely coupled system)[1]

Programming using the Message-Passing Paradigm

- **Principles of Message-Passing Programming**
  - Message-passing paradigm consists of p processes, each with its own exclusive address space.
  - All interactions (read-only or read/write) require cooperation of two processes
  - The programmer is fully aware of all the costs of non-local interactions by Two way interactions.

Structure of Message-Passing Programs

Message-passing programs are often written using the asynchronous or loosely synchronous paradigms.

- **In the asynchronous paradigm :**
  - all concurrent tasks execute asynchronously

loosely synchronous :

- Tasks or subsets of tasks synchronize to perform interactions.
- Between these interactions, tasks execute completely asynchronously

What is MPI?

- A message-passing library specification
- extended message-passing model
- For parallel computers, clusters, and heterogeneous networks
- MPI provides a powerful, efficient, and portable way to express parallel programs

Two important questions that arise early in a parallel program are:

- How many processes are participating in this computation?
- Which one am I?

- **`MPI_Comm_size`** reports the number of processes.
- **`MPI_Comm_rank`** reports the *rank*, a number between 0 and size-1, identifying the calling process

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

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

Example

The provided code snippet is a MPI (Message Passing Interface) program written in C that demonstrates the

- **Basic structure of a parallel program.**
- The program initializes MPI, retrieves the rank of each process,
- prints a "Hello from process" message, and then finalizes MPI.
- Each process prints its rank along with the message.

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

int main(int argc, char** argv) {
    MPI_Init(&argc, &argv);
    int rank;
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    printf("Hello from process %d\n", rank);
    MPI_Finalize();
    return 0;
}
```

Build, Compile, Run, and analyze performance.

```
configure
  make
  mpicc -mpitrace myprog.c
  mpirun -np 10 myprog
  upshot myprog.log
```

- There is a default communicator whose group contains all initial processes, called **`MPI_COMM_WORLD`**.
- Processes can be collected into *groups*.
- Each message is sent in a *context*, and must be received in the same context.
- A group and context together form a *communicator*.

The Building Blocks: Send and Receive operations

- ❑Basic operations in the message-passing programming paradigm are send and receive

- ❑ In their simplest form, the prototypes of these operations are defined as follows:

```
send(void *sendbuf, int nelems, int dest)
```

- *sendbuf: points to a buffer that stores the data to be sent,
- nelems: the number of data units to be sent and received,
- dest: the identifier of the process that receives the data,

```
receive(void *recvbuf, int nelems, int source)
```

- *recvbuf: points to a buffer that stores the data to be received
- nelems: the number of data units to be sent and received,
- source: is the identifier of the process that sends the data

MPI Datatypes

The data in a message to sent or received : triple (address, count, datatype)

MPI *datatype* is Defined as:

- Predefined data type (e.g., MPI_INT, MPI_DOUBLE_PRECISION)
- a contiguous array of MPI datatypes
- a strided block of datatypes
- an indexed array of blocks of datatypes
- an arbitrary structure of datatypes

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`

```
P0                              P1

a = 100;                        receive(&a, 1, 0)
send(&a, 1, 1);                 printf("%d\n", a);
a=0;
```

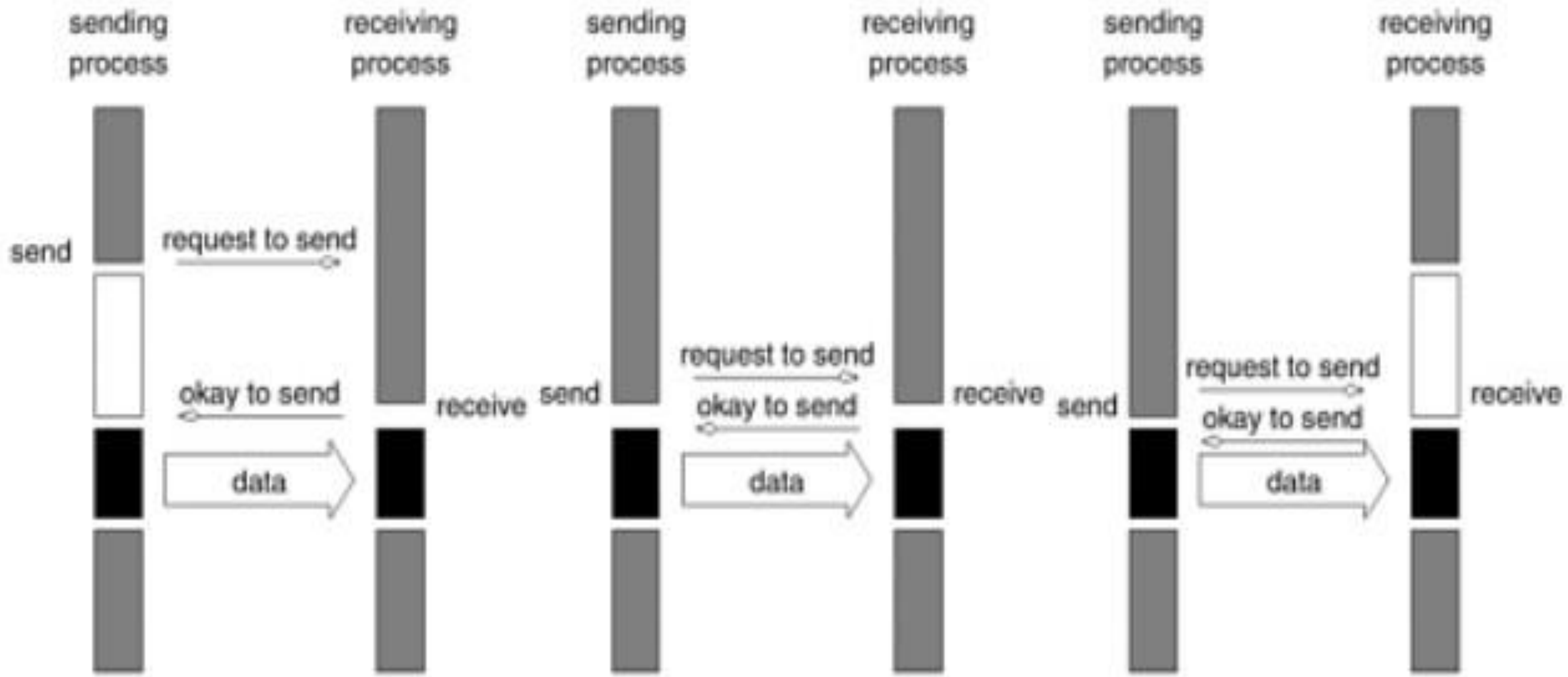
Send and Receive Operations

- Blocking Message Passing Operations
  - •Blocking Non-Buffered Send/Receive
  - •Blocking Buffered Send/Receive.

- Non-Blocking Message Passing Operations

Bl

Figure 6.1. Handshake for a blocking non-buffered send/ receive operation. It is easy to see that in cases where sender and receiver do not reach communication point at similar times, there can be considerable idling overheads.



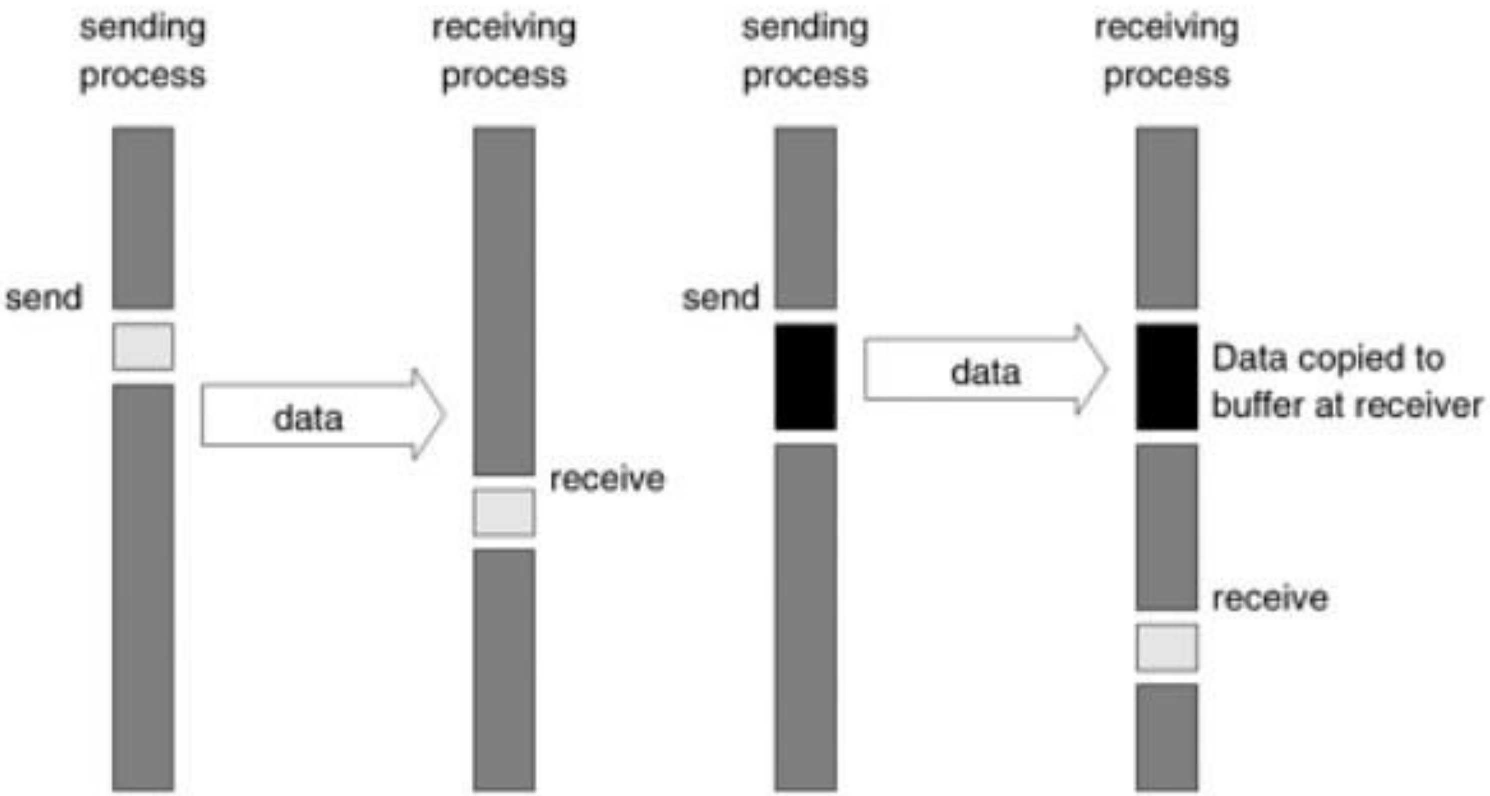
(a) Sender comes first; idling at sender

(b) Sender and receiver come at about the same time; idling minimized

(c) Receiver comes first; idling at receiver

Blocking Buffered Send/Receive

Figure 6.2. Blocking buffered transfer protocols: (a) in the presence of communication hardware with buffers at send and receive ends; and (b) in the absence of communication hardware, sender interrupts receiver and deposits data in buffer at receiver end.



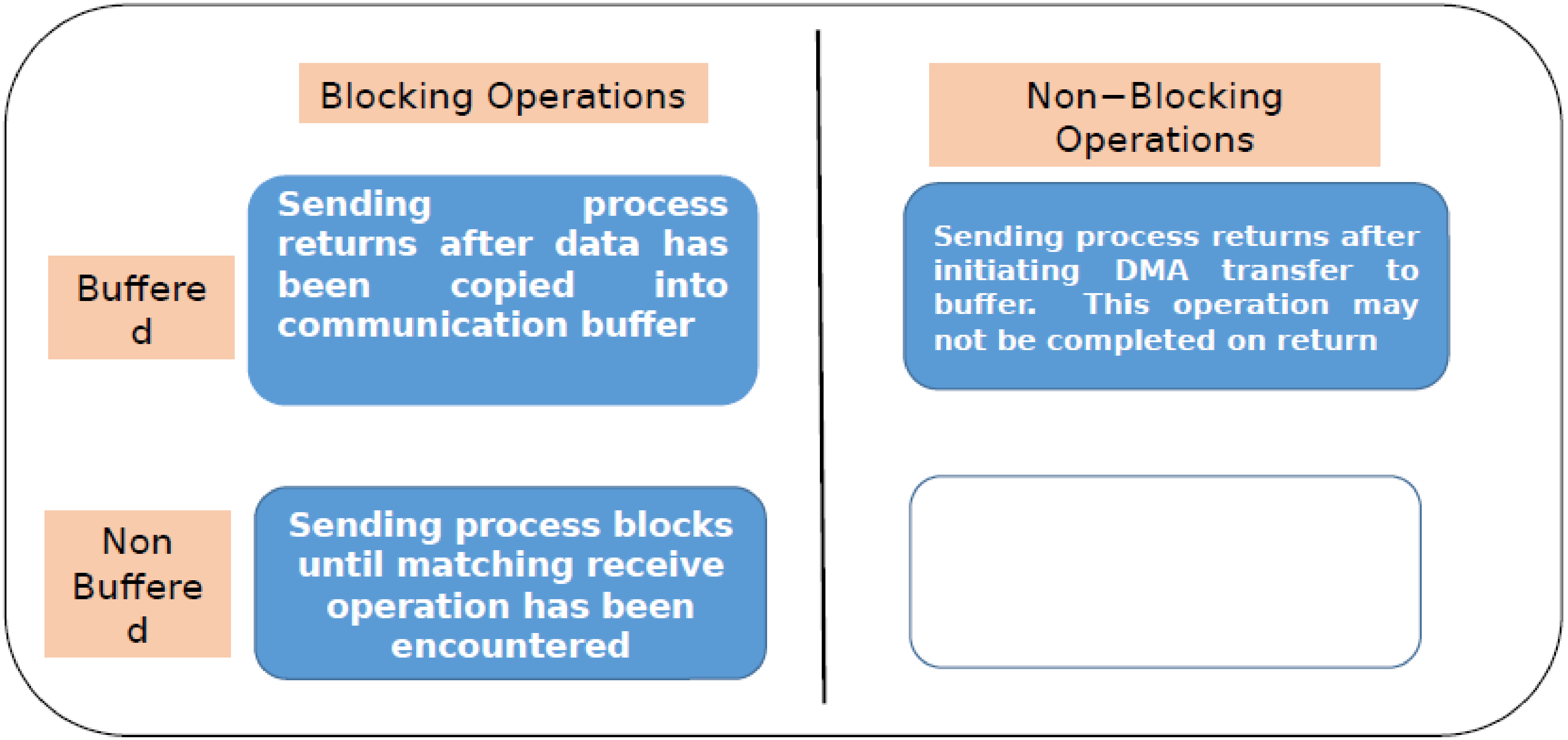
blocking protocols

- overhead of guaranteeing semantic correctness was paid in the form of idling (non-buffered) or buffer management (buffered).

- **non-blocking protocols**
  - – Returns from the send or receive operation before it is semantically safe to
  - do so.
  - – User must be careful not to alter data that may be potentially participating in a communication operation.
  - – process can check, If non-blocking **operation has not completed, and then wait for its completion**.
  - – Non-blocking operations are **generally accompanied by a check-status operation**

Blocking Send and Receive Protocols

Possible protocols for send and receive operations.



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.

MPI Isend (): Nonblocking send. asynchronous

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

Process 0	Process 1

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

MPI Basic (Blocking) Receive

- MPI_RECV(start, count, datatype, source, tag, comm, status)
- Waits until a matching (on **`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`**.
- **`status`** contains further information
- Receiving fewer than **`count`** occurrences of **`datatype`** is OK, but receiving more is an error.

```c
int
main (int argc, char **argv)
{
  int num_procs;
  int rank;

  MPI_Init(&argc, &argv);
  MPI_Comm_size(MPI_COMM_WORLD, &num_procs);
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);

  printf("%d: hello (p=%d)\n", rank, num_procs);
  round_robin(rank, num_procs);
  printf("%d: goodbye\n", rank);

  MPI_Finalize();
}
```

```c
void
round_robin(int rank, int procs)
{
  long int rand_mine, rand_prev;
  int rank_next = (rank + 1) % procs;
  int rank_prev = rank == 0 ? procs - 1 : rank - 1;
  MPI_Status status;

  srandom(time(NULL) + rank);
  rand_mine = random() / (RAND_MAX / 100);
  printf("%d: random is %ld\n", rank, rand_mine);
```

Introduction to Collective Operations in MPI

- **Collective Communication and Computation Operations**
  - MPI provides an extensive set of functions for performing common collective communication operations.
  - Each of these operations is defined over a group corresponding to the communicator.
  - All processors in a communicator must call these operations

Data Distribution

Example :

- Data distributions
  - Suppose we want to write a function that computes a vector sum serial.

$$
\begin{aligned}
\mathbf{x}+\mathbf{y} &= (x_0, x_1, \ldots, x_{n-1}) + (y_0, y_1, \ldots, y_{n-1}) \\
&= (x_0 + y_0, x_1 + y_1, \ldots, x_{n-1} + y_{n-1}) \\
&= (z_0, z_1, \ldots, z_{n-1}) \\
&= \mathbf{z}
\end{aligned}
$$

How could we implement this using MPI?

```
void Vector_sum(double x[], double y[], double z[], int n) {
   int i;

   for (i = 0; i < n; i++)
      z[i] = x[i] + y[i];
}  /* Vector_sum */
```

Step 1:

- Aggregating the tasks and assigning them to the cores
  - If the number of components is **n** and we have **comm_sz** cores or processes
    - define local Task
      - n = n/ comm_sz   i.e block partition

Step 2: Data distributions

- process 0 can prompt the user, read in the value, and broadcast the value to the other processes.
- Better Approach :
  - Entire vector that is on process 0 but only sends the needed components to each of the other processes.

Table 3.4 Different Partitions of a 12-Component Vector among Three Processes

	Components											
Process	Block				Cyclic				Block-Cyclic Blocksize = 2			
0	0	1	2	3	0	3	6	9	0	1	6	7
1	4	5	6	7	1	4	7	10	+6'	3	8	9
2	8	9	10	11	2	5	8	11	4	5	10	11

Basic Communication Operations

- Processes need to exchange data with other processes.
- This exchange of data can significantly impact the efficiency of parallel programs by introducing interaction delays during their execution.
  - One-to-All Broadcast and All-to-One Reduction
    - Parallel algorithms often require a single process to send identical data to all other processes or to a subset of them.
  - Scatter and Gather
    - In the scatter operation, a single node sends a unique message of size m to every other node.
    - gather operation, or concatenation, in which a single node collects a unique message from each node.

Collective Communication and Computation Operations

- MPI provides an extensive set of functions for performing many commonly used collective communication operations.
- All the processes that belong to this communicator participate in the operation, and all of them must call the collective communication function.
- Barrier :
  - The barrier synchronization operation is performed in MPI using the MPI_Barrier function.

```
int MPI_Barrier(MPI_Comm comm)
```

  - The call to MPI_Barrier returns only after all the processes in the group have called this function.
- Broadcast :
  - one-to-all broadcast operation is performed in MPI using the MPI_Bcast function.
  - MPI_Bcast sends the data stored in the buffer buf of process source to all the other processes in the group.

```
int MPI_Bcast(void *buf, int count, MPI_Datatype datatype, int source, MPI_Comm comm)
```

Collective Communication and Computation Operations

Reduction

- The all-to-one reduction operation is performed in MPI using the MPI_Reduce function.

int MPI_Reduce(void *sendbuf, void *recvbuf, int count, MPI_Datatype datatype, MPI_Op op, int target, MPI_Comm comm)

- **Predefined reduction operations.**

Value	15	17	11	12	17	11
Process	0	1	2	3	4	5

```
MinLoc(Value, Process) = (11, 2)
MaxLoc(Value, Process) = (17, 1)
```

Operation	
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-min value-location
MPI_MINLOC	min-min value-location

Collective Communication and Computation Operations

Gather

- The all-to-one reduction operation is performed in MPI using the MPI_Reduce function.

int MPI_Gather(void *sendbuf, int sendcount, MPI_Datatype senddatatype, void *recvbuf, int recvcount, MPI_Datatype recvdatatype, int target, MPI_Comm comm)

- Each process, including the target process, sends the data stored in the array sendbuf to the target process.
- As a result, if *p* is the number of processors in the communication comm, the target process receives a total of *p* buffers.
- The data is stored in the array recvbuf of the target process, in a rank order.

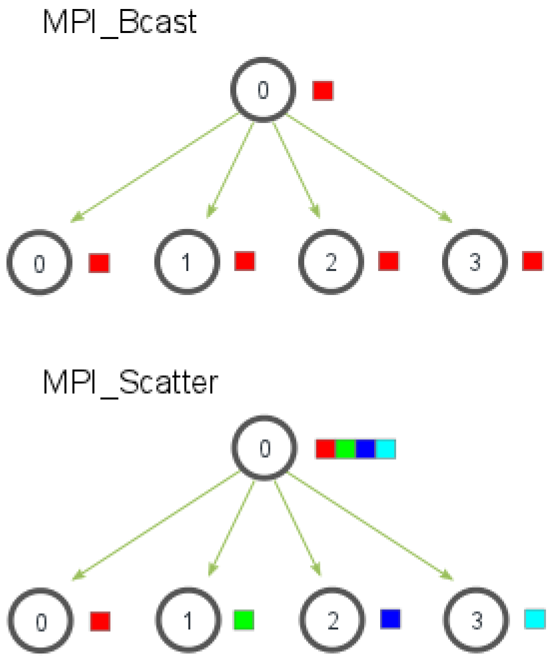
- The data is stored in the array recvbuf of the target process, in a rank order.

Collective Communication and Computation Operations

Scatter

- The scatter operation is performed in MPI using the MPI_Scatter function.

```
int MPI_Scatter(void *sendbuf, int sendcount,
        MPI_Datatype senddatatype, void *recvbuf, int recvcount,
        MPI_Datatype recvdatatype, int source, MPI_Comm comm)
```



Example :**Computing average of numbers with MPI_Scatter and MPI_Gather**

Tutorial 3

- **Write MPI program to print hello from each process in the comm world**
- **Write MPI program to do point-to-point communication:**
  - Master process: send msg with tag 1134
  - Master process: wait for msg with tag 4114
  - Slave process: receive msg with tag 1134
  - Slave process: send back msg with tag 4114
- **Write MPI program for sending and receiving**
  - Process 1 sends 4 characters to process 0
  - Process 0 receives an integer (4 bytes)

Topologies and Embedding Topologies and Embedding

- A virtual topology represents the way that MPI processes communicate.
- A physical topology represents that connections between the cores, chips, and nodes in the hardware.
  - Does it really matter what mapping is used?
  - How does one get a good mapping?

MPI's Topology Routines

MPI provides routines to create new communicators that order the process ranks in a way that may be a better match for the physical topology

Cartesian (regular mesh)	Graph (several ways to define in MPI)

Topologies and Embedding Topologies and Embedding

- MPI's function for describing Cartesian topologies is called MPI_Cart_create.
- A group of processes that belong to the communicator comm_old and creates a virtual process topology.

It Takes the coordinates of the process as argument in the coords array and returns its rank in rank.

```
int MPI_Cart_rank(MPI_Comm comm_cart, int *coords, int *rank)

int MPI_Cart_coord(MPI_Comm comm_cart, int rank, int maxdims, int *coords)
```

The MPI_Cart_coords takes the rank of the process rank and returns its Cartesian coordinates in the array coords

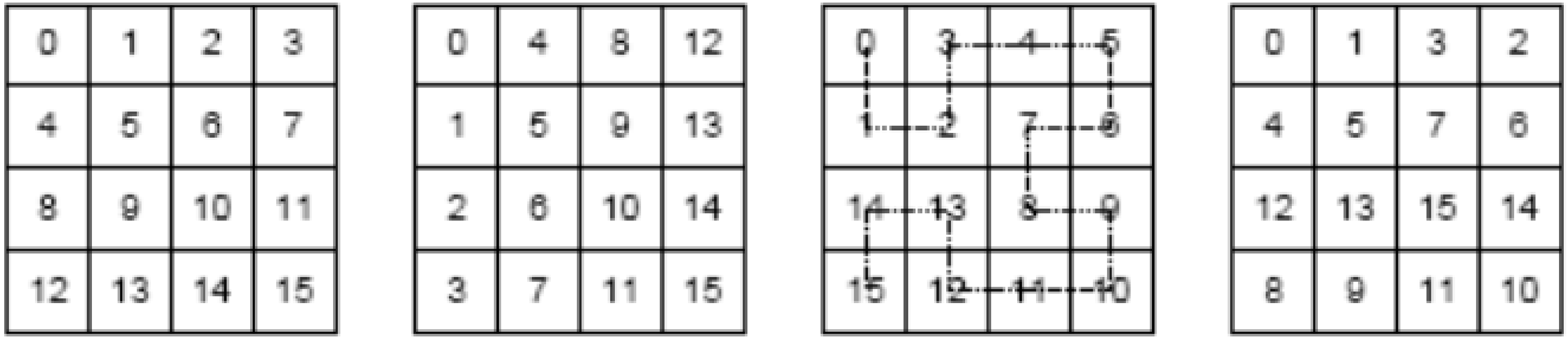
Topologies and Embedding Topologies and Embedding

```
MPI_Cart_create(MPI_Comm oldcomm, int ndim, int dims[], int qperiodic[], int qreorder,
MPI_Comm *newcomm)
```

Many Large Scale Systems use a mesh as the physical topology

- IBM Blue Gene series; Cray through XE6/XK7

Topologies and Embeddings



(a) Row–major mapping

(b) Column–major mapping

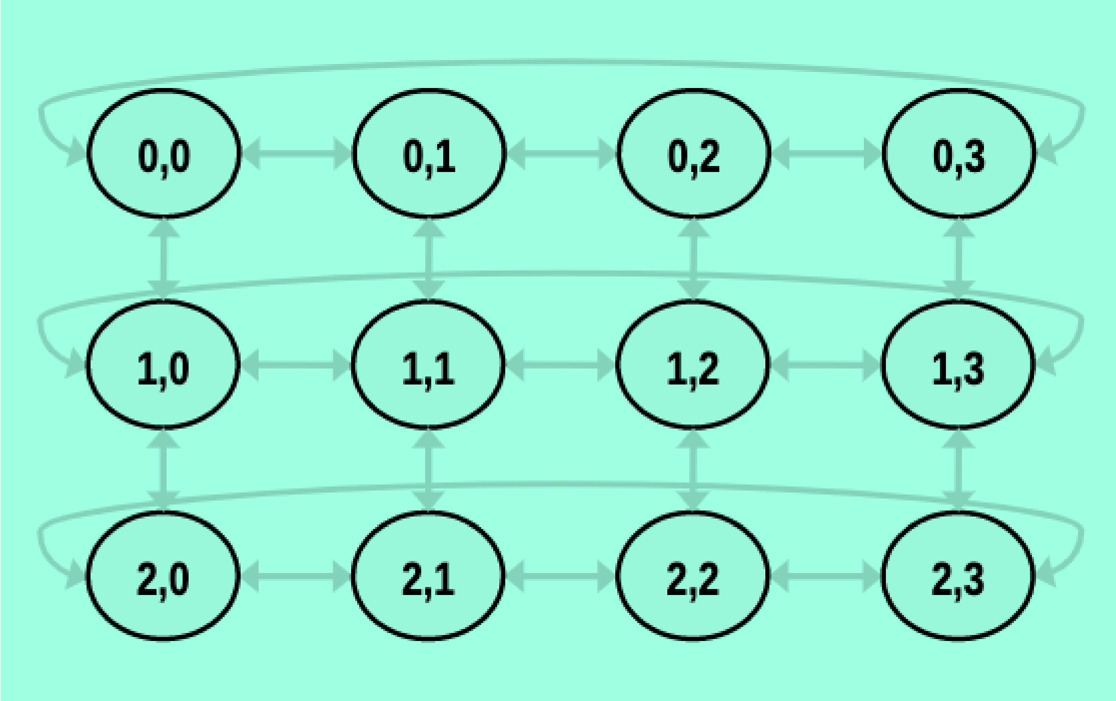
(c) Space–filling curve mapping

(d) Hypercube mapping

Example Cartesian Topology

- Process coordinates in a Cartesian structure begin their numbering at 0.
- Row-major numbering is always used for the processes in a Cartesian structure.

- Group rank and coordinates for four processes in a (2×2) grid is as follows.
  - coord (0,0): rank 0
  - coord (0,1): rank 1
  - coord (1,0): rank 2
  - coord (1,1): rank 3


0,0
0,1
0,2
0,3
1,0
1,1
1,2
1,3
2,0
2,1
2,2
2,3