CSE 613: Parallel Programming

Lecture 12
(The Message Passing Interface)

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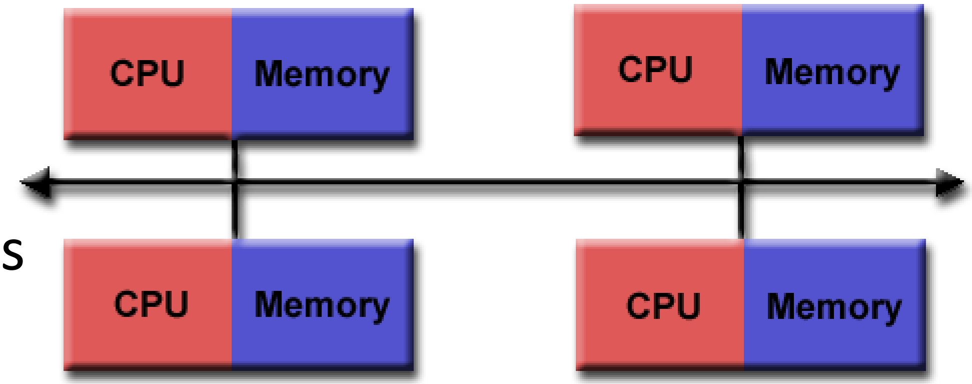
Principles of Message-Passing Programming



Source: Blaise Barney, LLNL

- One of the oldest and most widely used approaches for programming parallel computers
- Two key attributes
  - Assumes a partitioned address space
  - Supports only explicit parallelism
- Two immediate implications of partitioned address space
  - Data must be explicitly partitioned and placed to appropriate partitions
  - Each interaction (read-only and read/write) requires cooperation between two processes: process that has the data, and the one that wants to access the data

Structure of Message-Passing Programs

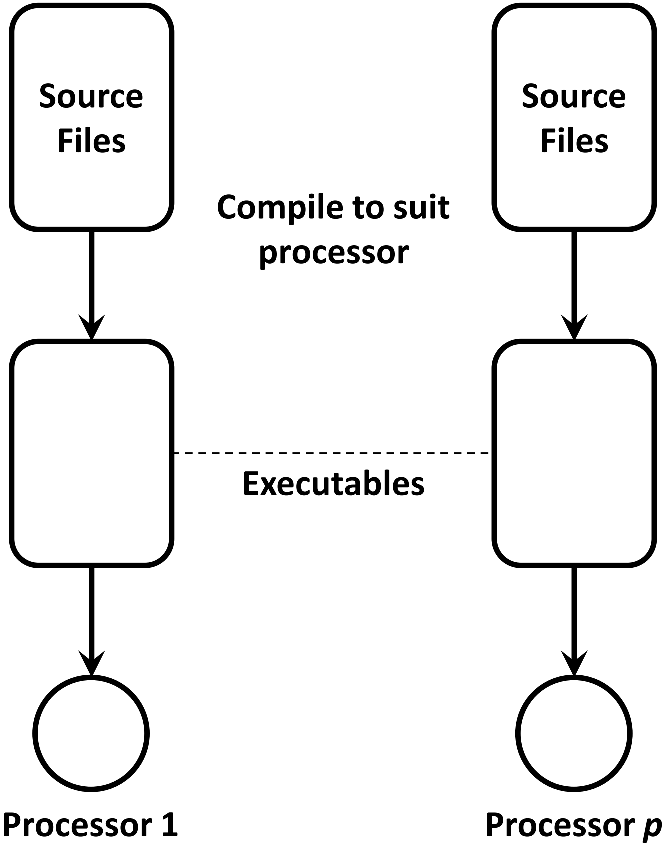
Asynchronous

- All concurrent tasks execute asynchronously
- Most general (can implement any parallel algorithm)
- Can be difficult to reason about
- Can have non-deterministic behavior due to races

Loosely Synchronous

- A good compromise between synchronous and asynchronous
- Tasks or subset of tasks synchronize to interact
- Between the interactions tasks execute asynchronously
- Easy to reason about these programs

Structure of Message-Passing Programs



Source Files

Source Files

Compile to suit processor

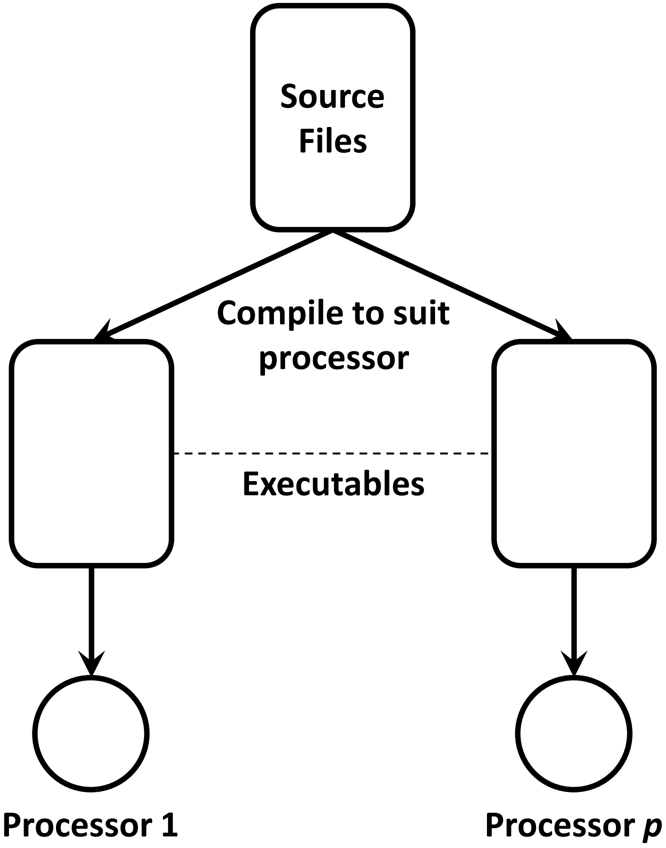
Executables

Processor 1

Processor *p*

Multiple Program Multiple Data (MPMD)

- Ultimate flexibility in parallel programming
- Unscalable



Source Files

Compile to suit processor

Executables

Processor 1

Processor *p*

Single Program Multiple Data (SPMD)

- Most message-passing programs
- Loosely synchronous or completely asynchronous

The Building Blocks: Send & Receive Operations

send(&*data*, *n*, *dest* **):**

Send *n* items pointed to by &*data* to a processor with id *dest*

receive(&*data*, *n*, *src* **):**

Receive *n* items from a processor with id *src* to location pointed to by &*data*

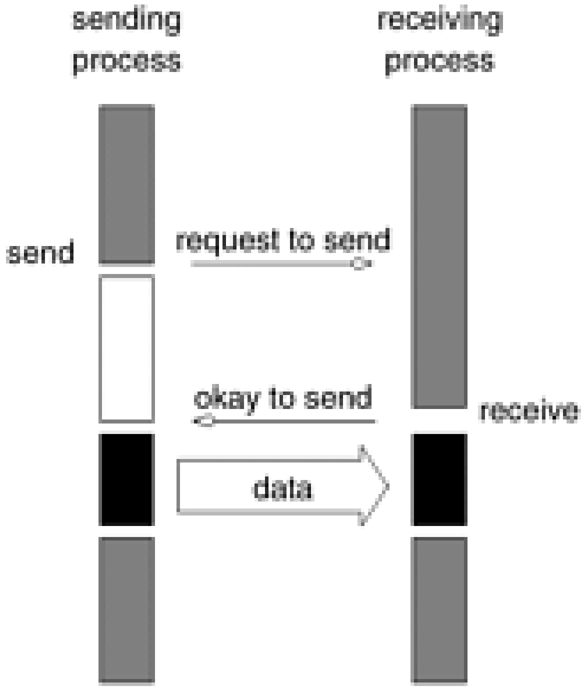
But wait! What P1 prints when P0 and P1 execute the following code?

```
P0                                P1

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

Source: Grama et al., “Introduction to Parallel Computing”, 2nd Edition

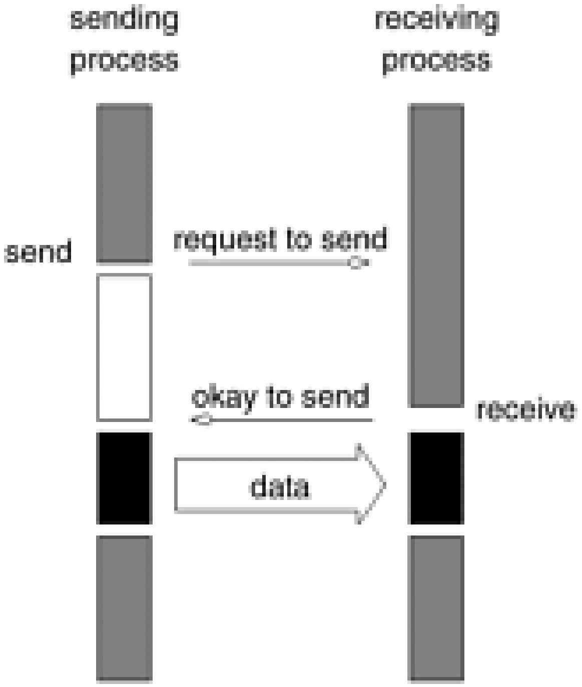
Blocking Non-Buffered Send / Receive

Sending operation waits until the matching receive operation is encountered at the receiving process, and data transfer is complete.



Blocking Non-Buffered Send / Receive

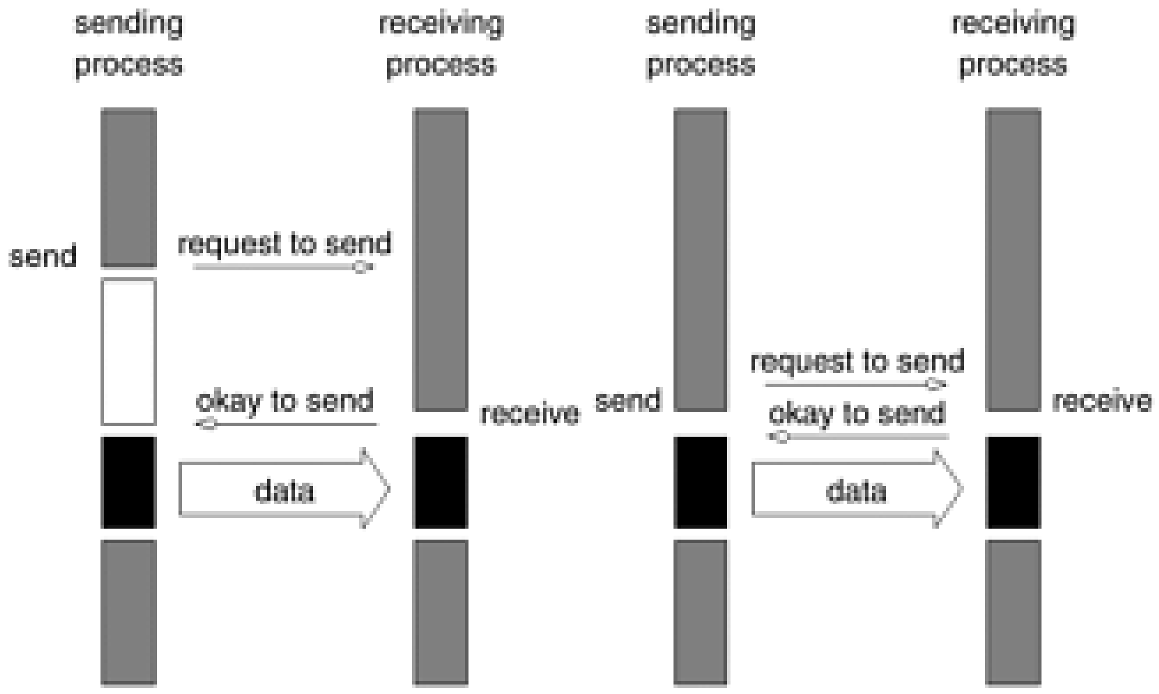
May lead to idling:



(a) Sender comes first; idling at sender

Blocking Non-Buffered Send / Receive

May lead to idling:

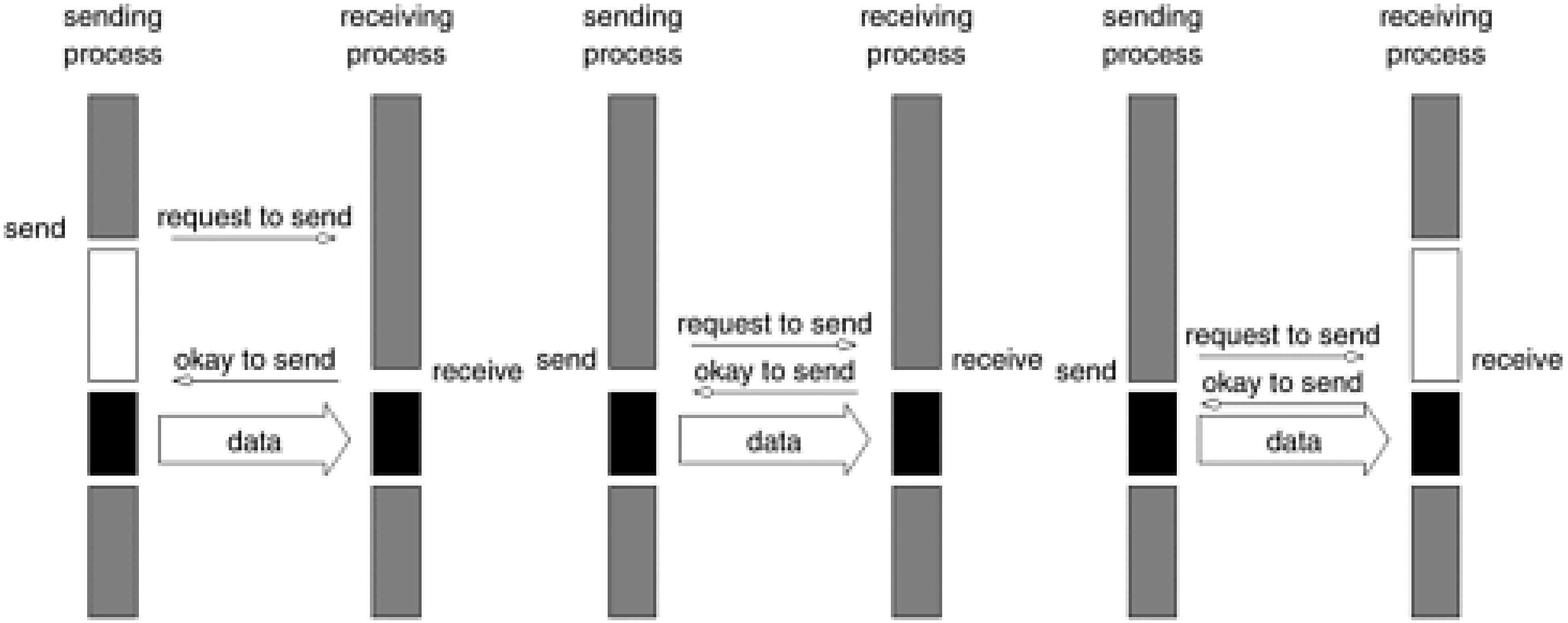


(a) Sender comes first; idling at sender

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

Blocking Non-Buffered Send / Receive

May lead to idling:



(a) Sender comes first; idling at sender

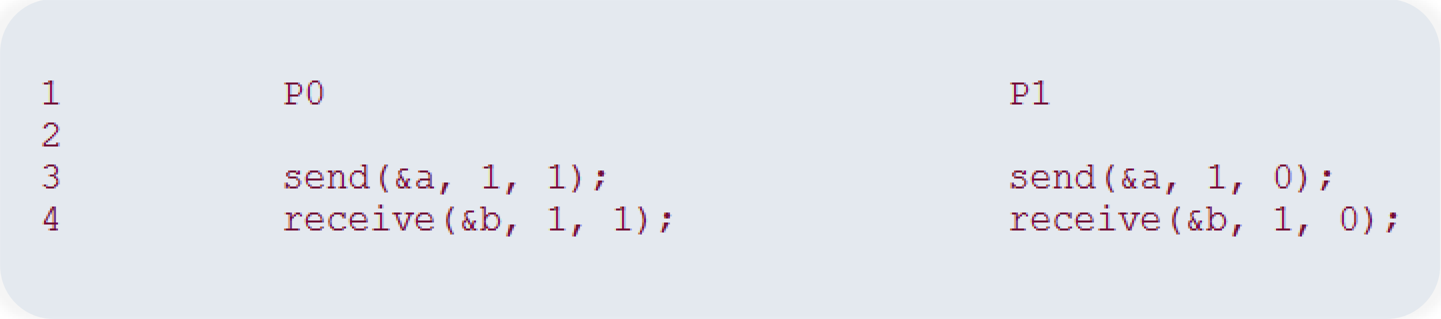
(b) Sender and receiver come at about the same time; idling minimized

(c) Receiver comes first; idling at receiver

Source: Grama et al., "Introduction to Parallel Computing", 2nd Edition

Blocking Non-Buffered Send / Receive

May lead to deadlocks:



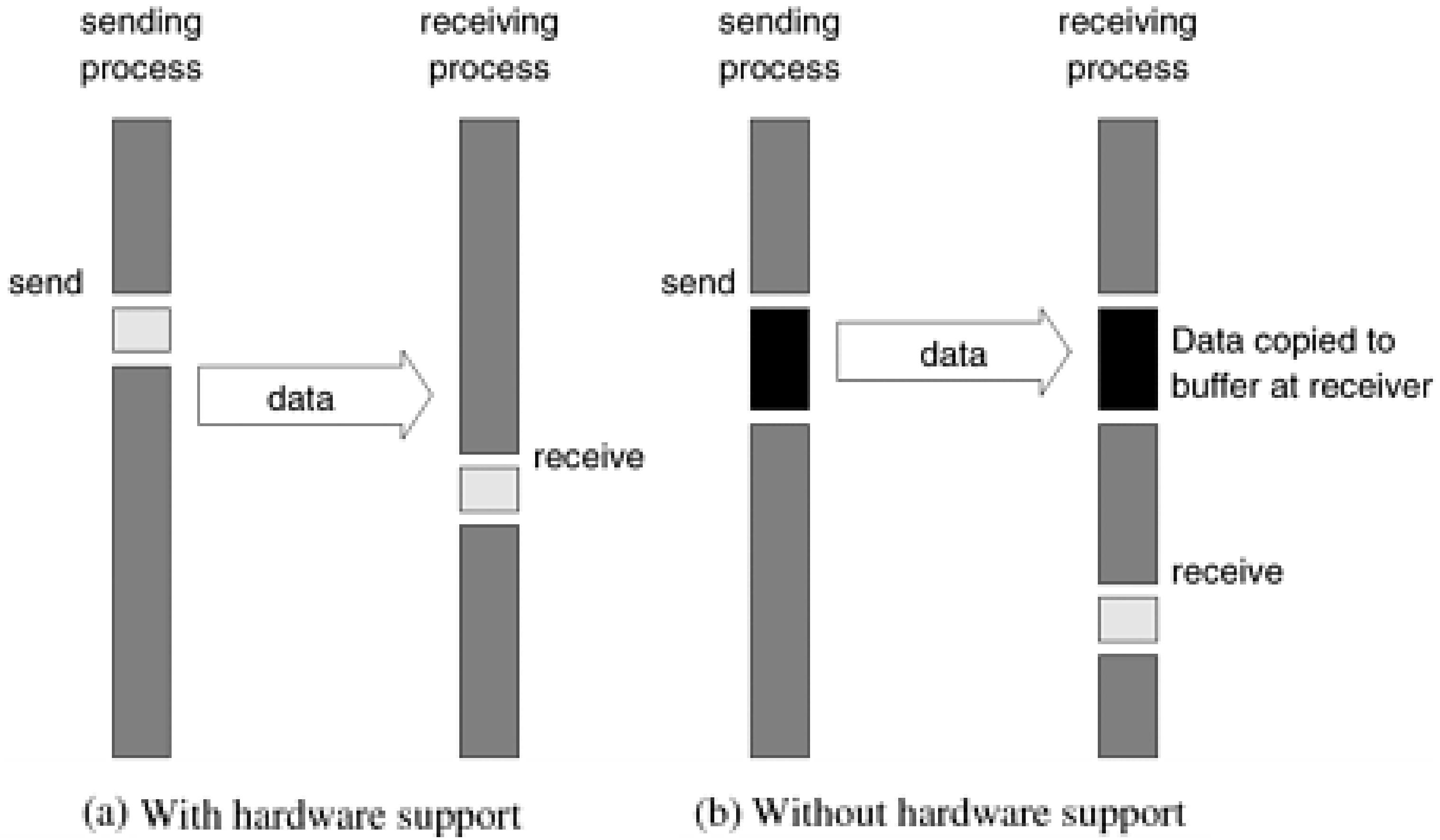
```
        P0                              P1

        send(&a, 1, 1);                 send(&a, 1, 0);
        receive(&b, 1, 1);              receive(&b, 1, 0);
```

Source: Grama et al., "Introduction to Parallel Computing", 2nd Edition

- The send at P0 waits for the matching receive at P1
- The send at P1 waits for the matching receive at P0

Blocking Buffered Send / Receive

- Sending operation waits until data is copied into a pre-allocated communication buffer at the sending process
- Data is first copied into a buffer at the receiving process as well, from where data is copied to the target location by the receiver

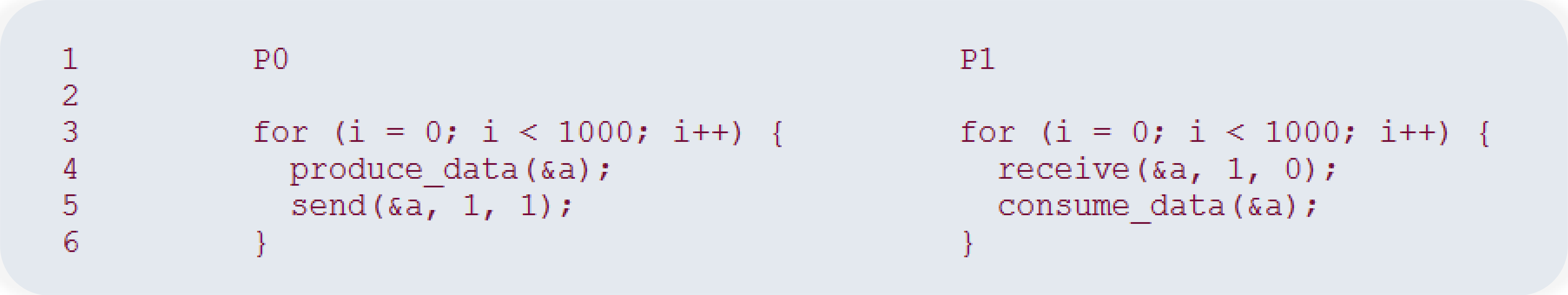


(a) With hardware support (b) Without hardware support

Source: Grama et al., "Introduction to Parallel Computing", 2^{nd} Edition

Blocking Buffered Send / Receive

Finite buffers lead to delays:



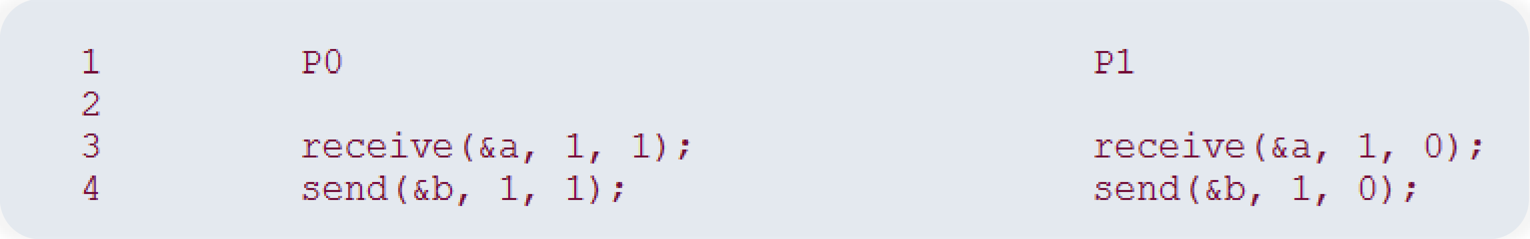
```
P0                                     P1

for (i = 0; i < 1000; i++) {           for (i = 0; i < 1000; i++) {
  produce_data(&a);                      receive(&a, 1, 0);
  send(&a, 1, 1);                        consume_data(&a);
}                                      }
```

Source: Grama et al., “Introduction to Parallel Computing”, 2nd Edition

- What happens if the receiver’s buffer can only hold 10 items?

Blocking Buffered Send / Receive

May still lead to deadlocks:



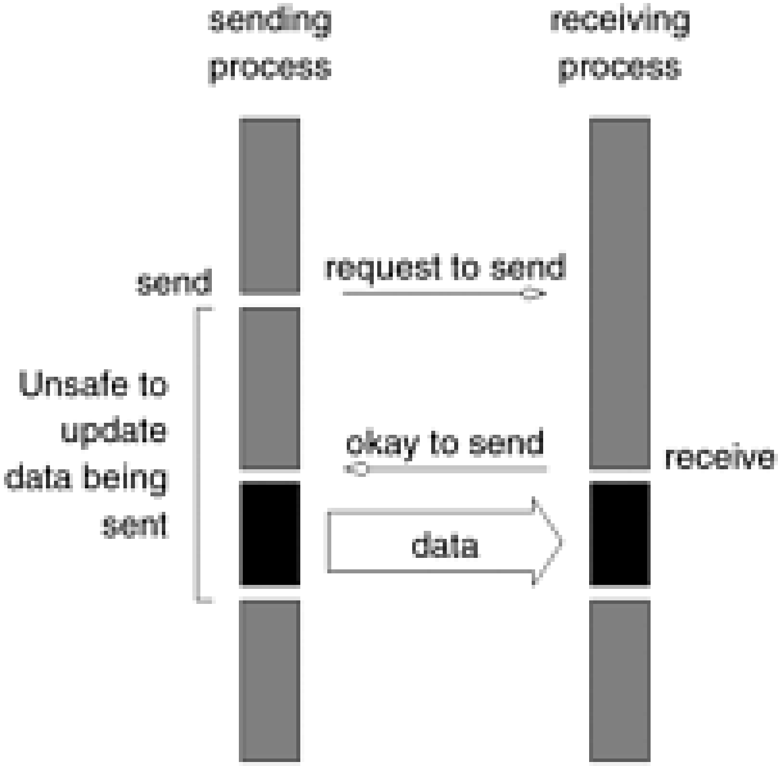
```
P0                                  P1

receive(&a, 1, 1);                  receive(&a, 1, 0);
send(&b, 1, 1);                     send(&b, 1, 0);
```

Source: Grama et al., “Introduction to Parallel Computing”, 2nd Edition

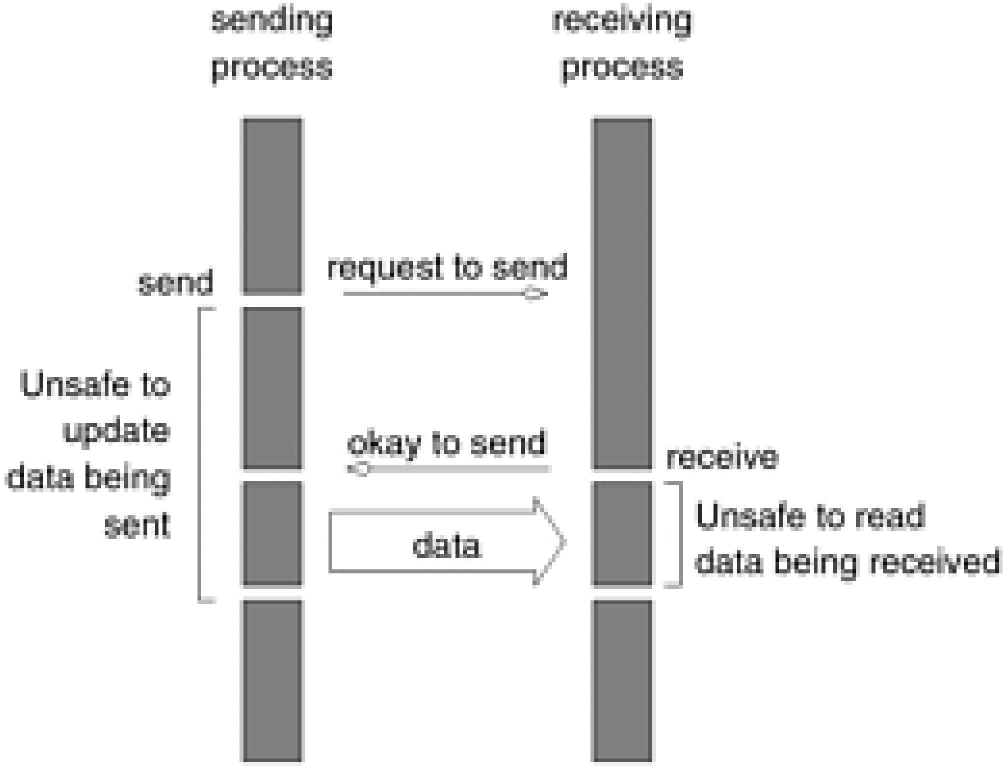
- Blocks because the receive calls are always blocking in order to ensure consistency

Non-Blocking Non-Buffered Send / Receive

- Sending operation posts a pending message and returns
- When the corresponding receive is posted data transfer starts
- When data transfer is complete the *check-status* operation indicates that it is safe to touch the data



(a) Without hardware support



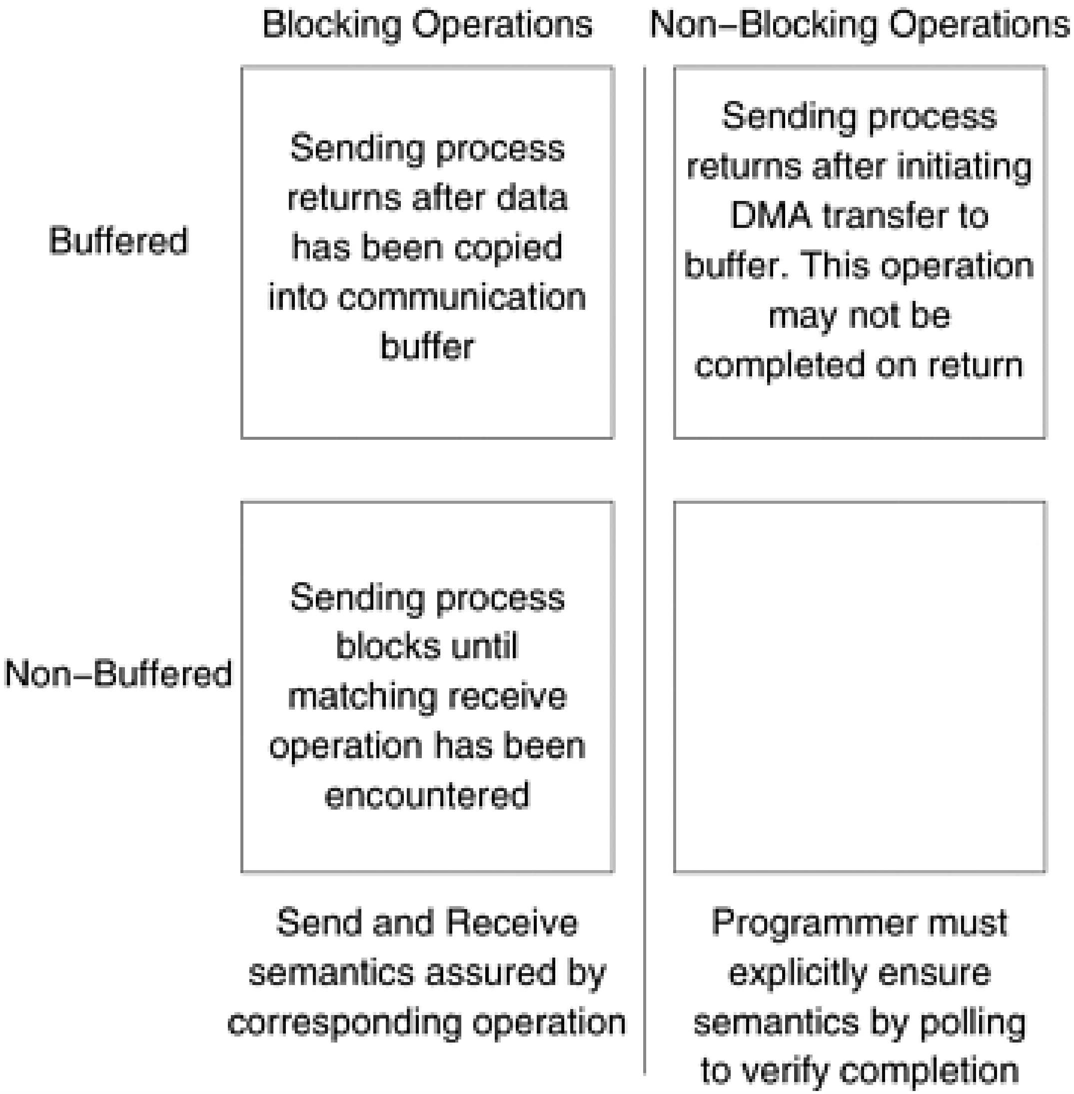
(b) With hardware support

Source: Grama et al., "Introduction to Parallel Computing", 2nd Edition

Non-Blocking Buffered Send / Receive

- Sending operation initiates a DMA (Direct Memory Access) operation and returns immediately
- Data becomes safe as soon as the DMA operation completes
- The receiver initiates a transfer from sender’s buffer to receiver’s target location
- Reduces the time during which the data is unsafe to touch

Possible Protocols for Send & Receive Operations

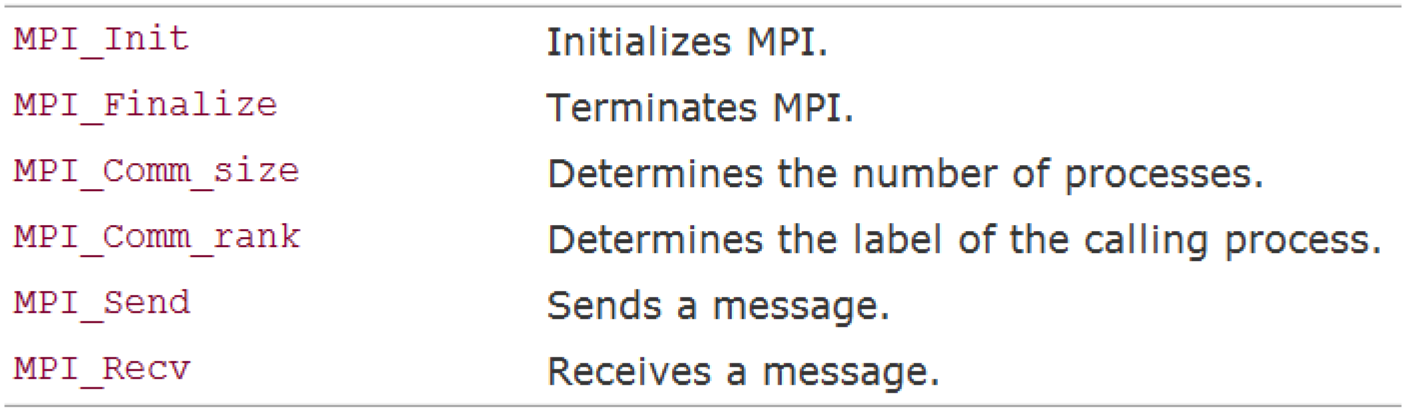


	Blocking Operations	Non–Blocking Operations
Buffered	Sending process returns after data has been copied into communication buffer	Sending process returns after initiating DMA transfer to buffer. This operation may not be completed on return
Non–Buffered	Sending process blocks until matching receive operation has been encountered	
	Send and Receive semantics assured by corresponding operation	Programmer must explicitly ensure semantics by polling to verify completion

Source: Grama et al.,
“Introduction to Parallel Computing”,
2nd Edition

The Minimal Set of MPI Routines

- The MPI library contains over 125 routines
- But fully functional message-passing programs can be written using only the following 6 MPI routines



`MPI_Init`	Initializes MPI.
`MPI_Finalize`	Terminates MPI.
`MPI_Comm_size`	Determines the number of processes.
`MPI_Comm_rank`	Determines the label of the calling process.
`MPI_Send`	Sends a message.
`MPI_Recv`	Receives a message.

- All 6 functions return *MPI_SUCCESS* upon successful completion, otherwise return an implementation-defined error code
- All MPI routines, data-types and constants are prefixed by *MPI_*
- All of them are defined in *mpi.h* (for C/C++)

Starting and Terminating the MPI Library

```
#include < mpi.h >

main( int argc, char *argv[ ] )
{
    MPI_Init( &argc, &argv );
    … … …                          // do some work
    MPI_Finalize( );
}
```

- Both *MPI_Init* and *MPI_Finalize* must be called by all processes
- Command line should be processed only after *MPI_Init*
- No MPI function may be called after *MPI_Finalize*

Communicators

- A *communicator* defines the scope of a communication operation
- Each process included in the communicator has a rank associated with the communicator
- By default, all processes are included in a communicator called *MPI_COMM_WORLD*, and each process is given a unique rank between 0 and *p* – 1, where *p* is the number of processes
- Additional communicator can be created for groups of processes
- To get the size of a communicator:

```
int MPI_Comm_size( MPI_Comm comm, int *size )
```

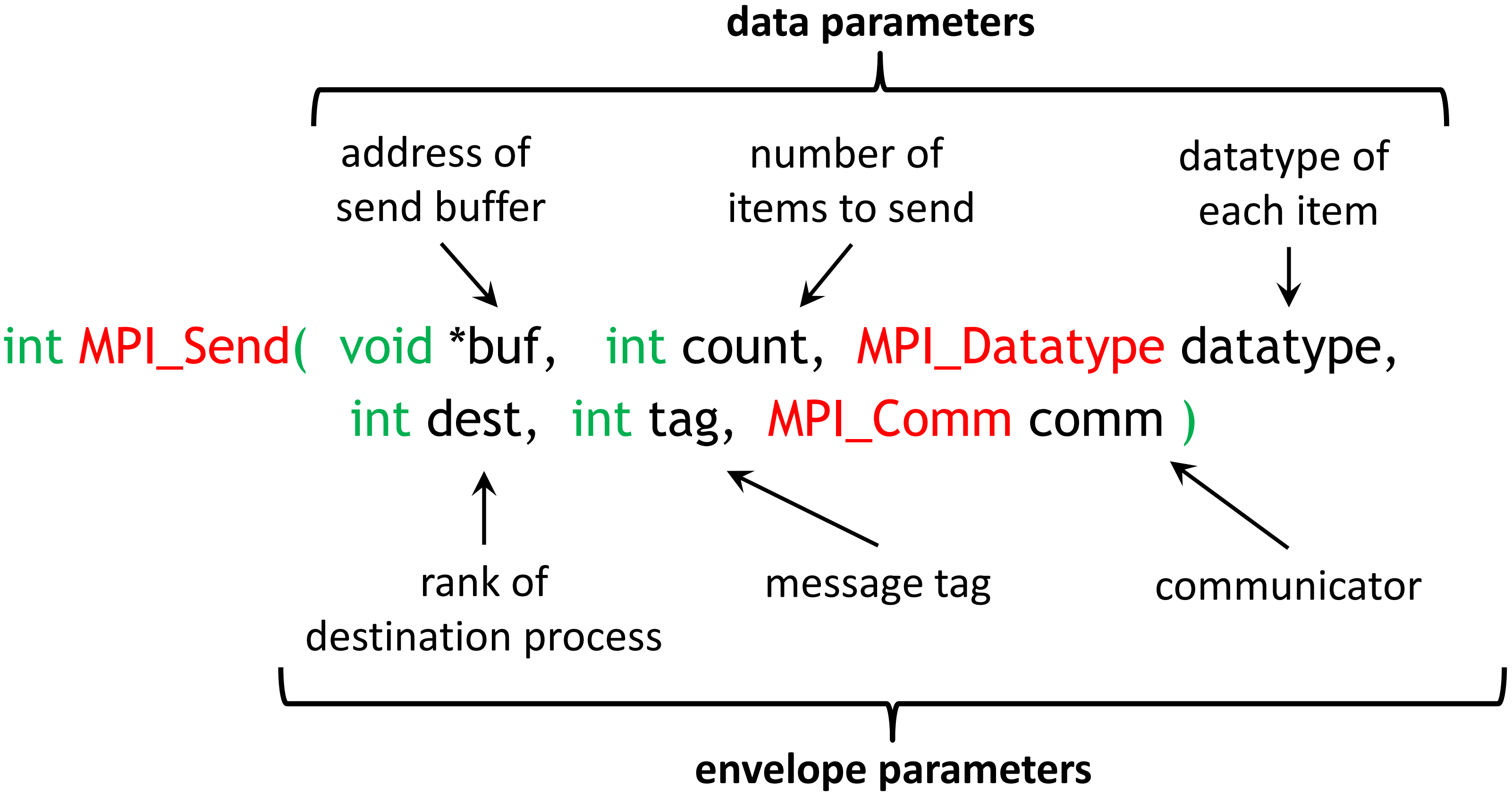
- To get the rank of a process associated with a communicator:

```
int MPI_Comm_rank( MPI_Comm comm, int *rank )
```

Communicators

```
#include < mpi.h >

main( int argc, char *argv[ ] )
{
    int p, myrank;
    MPI_Init( &argc, &argv );
    MPI_Comm_size( MPI_COMM_WORLD, &p );
    MPI_Comm_rank( MPI_COMM_WORLD, &myrank );
    printf( “This is process %d out of %d!\n”, p, myrank );
    MPI_Finalize( );
}
```

MPI Standard Blocking Send Format



data parameters

address of send buffer

number of items to send

datatype of each item

```
int MPI_Send(  void *buf,   int count,   MPI_Datatype datatype,
               int dest,   int tag,   MPI_Comm comm )
```

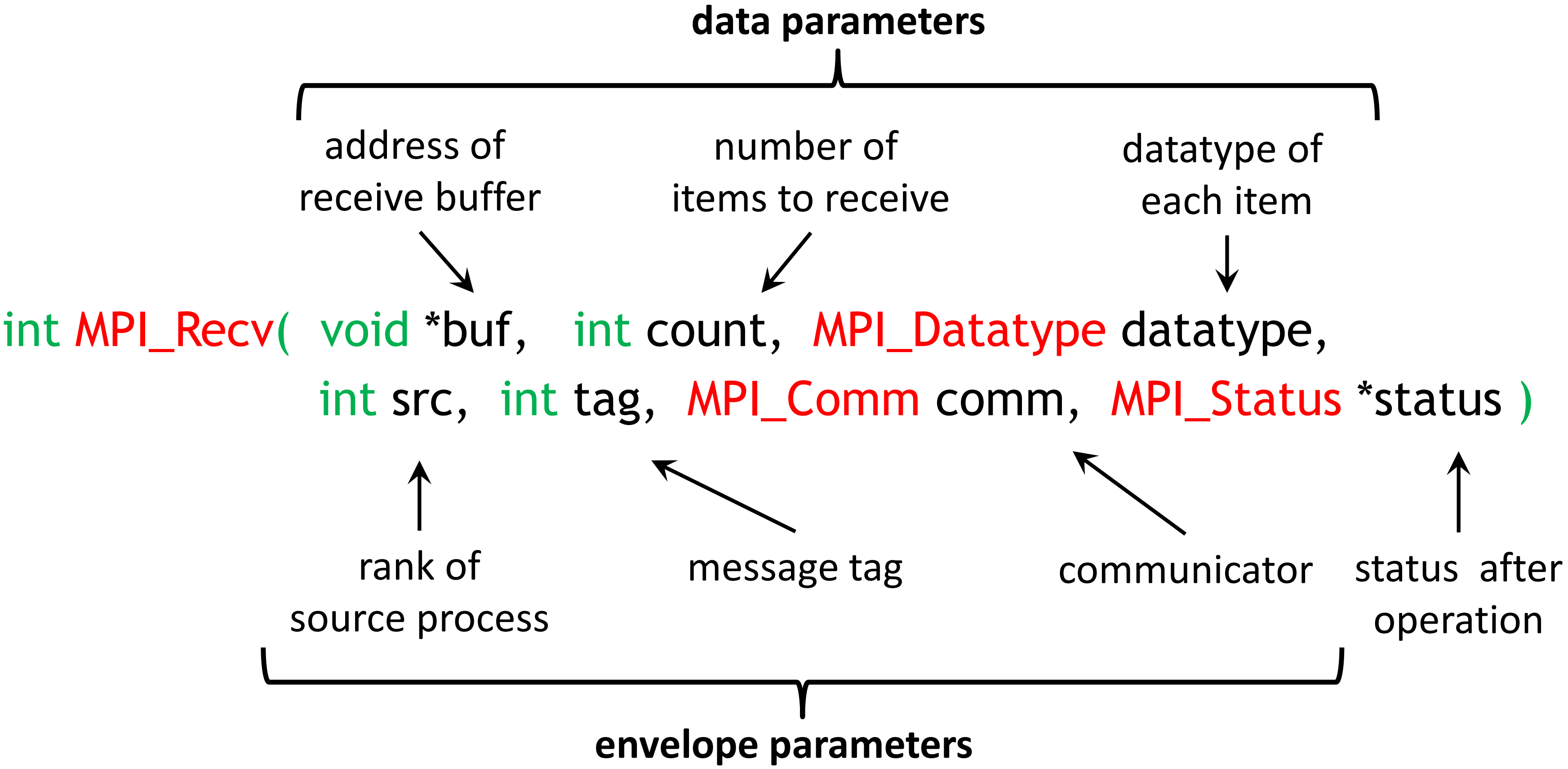
rank of destination process

message tag

communicator

envelope parameters

MPI Standard Blocking Receive Format



data parameters

address of receive buffer

number of items to receive

datatype of each item

```
int MPI_Recv(  void *buf,   int count,  MPI_Datatype datatype,
               int src,  int tag,  MPI_Comm comm,  MPI_Status *status )
```

rank of source process

message tag

communicator

status after operation

envelope parameters

MPI Datatypes

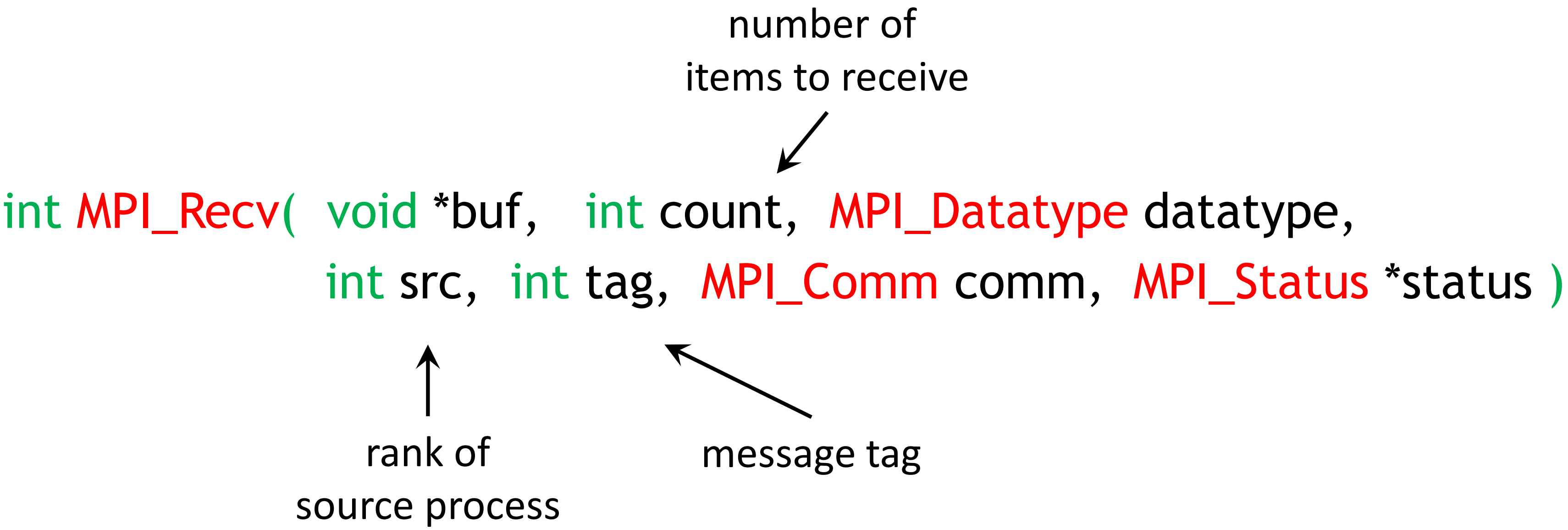
MPI Datatype	C Datatype
MPI_CHAR	signed char
MPI_SHORT	signed short int
MPI_INT	signed int
MPI_LONG	signed long int
MPI_UNSIGNED_CHAR	unsigned char
MPI_UNSIGNED_SHORT	unsigned short int
MPI_UNSIGNED	unsigned int
MPI_UNSIGNED_LONG	unsigned long int
MPI_FLOAT	float
MPI_DOUBLE	double
MPI_LONG_DOUBLE	long double
MPI_BYTE	
MPI_PACKED	

Blocking Send/Receive between Two Processes

```
#include < mpi.h >

main( int argc, char *argv[ ] )
{
    int myrank, v = 121;
    MPI_Status status;
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &myrank );
    if ( myrank == 0 ) {
        MPI_Send( &v, 1, MPI_INT,  1, MPI_ANY_TAG, MPI_COMM_WORLD );
        printf( “Process %d sent %d!\n”, p, myrank, v );
    }  else if ( myrank == 1 ) {
        MPI_Recv( &v, 1, MPI_INT,  0, MPI_ANY_TAG, MPI_COMM_WORLD , &status );
        printf( “Process %d received %d!\n”, p, myrank, v );
    }
    MPI_Finalize( );
}
```

MPI Status

MPI_Status holds few primary pieces of information: MPI_SOURCE, MPI_TAG, count, cancelled and MPI_ERROR. If we look at the the **MPI_Recv**, it has source, tag and count as parameters.



number of items to receive

```
int MPI_Recv(  void *buf,   int count,  MPI_Datatype datatype,
               int src,  int tag,  MPI_Comm comm,  MPI_Status *status )
```

rank of source process

message tag

MPI_STATUS_IGNORE can be used as status parameter. But, why do we need these information inside MPI_Status?

Dynamic Receiving and MPI Status

It turns out that **MPI_Recv** can have MPI_ANY_SOURCE and MPI_ANY_TAG for receiving data for any *tag* and from any *source*. Later, *source* and *tag* can be extracted from *status* parameter by directly accessing status.MPI_SOURCE and status.MPI_TAG.

What if the receiver doesn't know the size of the received data?

Dynamic Receiving and MPI Status

It turns out that **MPI_Recv** can have MPI_ANY_SOURCE and MPI_ANY_TAG for receiving data for any *tag* and from any *source*. Later, *source* and *tag* can be extracted from *status* parameter by directly accessing status.MPI_SOURCE and status.MPI_TAG.

What if the receiver doesn't know the size of the received data?

In that case, it one can use a buffer of maximum possible size and extract the received data size from *status* using **MPI_Get_count**.

```
int MPI_Get_count( MPI_Status *status, MPI_Datatype datatype,
                   int *count )
```

But isn't it a waste to allocate that unused receive buffer?

Dynamic Receiving and MPI_Probe

Instead of using a large buffer to handle all the cases, we can use **MPI_Probe** to query the message size before receiving it.

```
int MPI_Probe( int source, int tag, MPI_Comm comm, MPI_Status *status )
```

MPI_Probe does everything **MPI_Recv** does but receiving the actual message. Element count can be extracted from *status* using **MPI_Get_count**.

Dynamic Receive and MPI_Probe

```
#include < mpi.h >
main( int argc, char *argv[ ] )
{
    int myrank, v = 121, count;
    MPI_Status status;
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &myrank );
    if ( myrank == 0 ) {
        MPI_Send( &v, 1, MPI_INT,  1, MPI_ANY_TAG, MPI_COMM_WORLD, &status );
    }  else if ( myrank == 1 ) {
        MPI_Probe( 0, MPI_ANY_TAG, MPI_COMM_WORLD, &status );
        MPI_Get_count( &status, MPI_INT,  &count );
        int recv_buf = (int *) malloc(sizeof(int) * count);
        MPI_Recv( &recv_buff, count, MPI_INT,  0, MPI_ANY_TAG,
                              MPI_COMM_WORLD, MPI_STATUS_IGNORE );
    }
    MPI_Finalize( );
}
```

Non-Blocking Send / Receive

```
int MPI_Isend(  void *buf,   int count,  MPI_Datatype datatype,
                int dest,  int tag,  MPI_Comm comm,  MPI_Request *req )
```

```
int MPI_Irecv(  void *buf,   int count,  MPI_Datatype datatype,
                int src,  int tag,  MPI_Comm comm,  MPI_Request *req )
```

The MPI_Request object is used as an argument to the following two functions to identify the operation whose status we want to query or to wait for its completion.

```
int MPI_Test( MPI_Request *req,  int *flag,  MPI_Status *status )
```

- Returns *flag = 1, if the operation associated with *req has completed, otherwise returns *flag = 0

```
int MPI_Wait( MPI_Request *req,  MPI_Status *status )
```

- Waits until the operation associated with *req completes

Non-Blocking Send and Blocking Receive

```
#include < mpi.h >

main( int argc, char *argv[ ] )
{
    int myrank, v = 121;
    MPI_Status status;
    MPI_Request req;
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &myrank );
    if ( myrank == 0 ) {
          MPI_Isend( &v, 1, MPI_INT,  1, MPI_ANY_TAG, MPI_COMM_WORLD, &req );
          compute( );              /* but do not modify v */
          MPI_Wait( &req, &status );
    }  else if ( myrank == 1 ) MPI_Recv( &v, 1, MPI_INT,  0, MPI_ANY_TAG, MPI_COMM_WORLD , &status );
    MPI_Finalize( );
}
```

Non-Blocking Send/Receive

```
#include < mpi.h >
main( int argc, char *argv[ ] )
{
    int myrank, v = 121;
    MPI_Status status;
    MPI_Request req;
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &myrank );
    if ( myrank == 0 ) {
        MPI_Isend( &v, 1, MPI_INT,  1, MPI_ANY_TAG, MPI_COMM_WORLD, &req );
        compute( );              /* but do not modify v */
        MPI_Wait( &req, &status );
    }  else if ( myrank == 1 ) {
        MPI_Irecv( &v, 1, MPI_INT,  0, MPI_ANY_TAG, MPI_COMM_WORLD, &req );
        compute( );              /* but do not read or modify v */
        MPI_Wait( &req, &status );
    }
    MPI_Finalize( );
}
```

MPI Collective Communication & Computation Operations

Synchronization

- Barrier

Data Movement

- Broadcast
- Scatter
- Gather
- All-to-all

Global Computation

- Reduce
- Scan

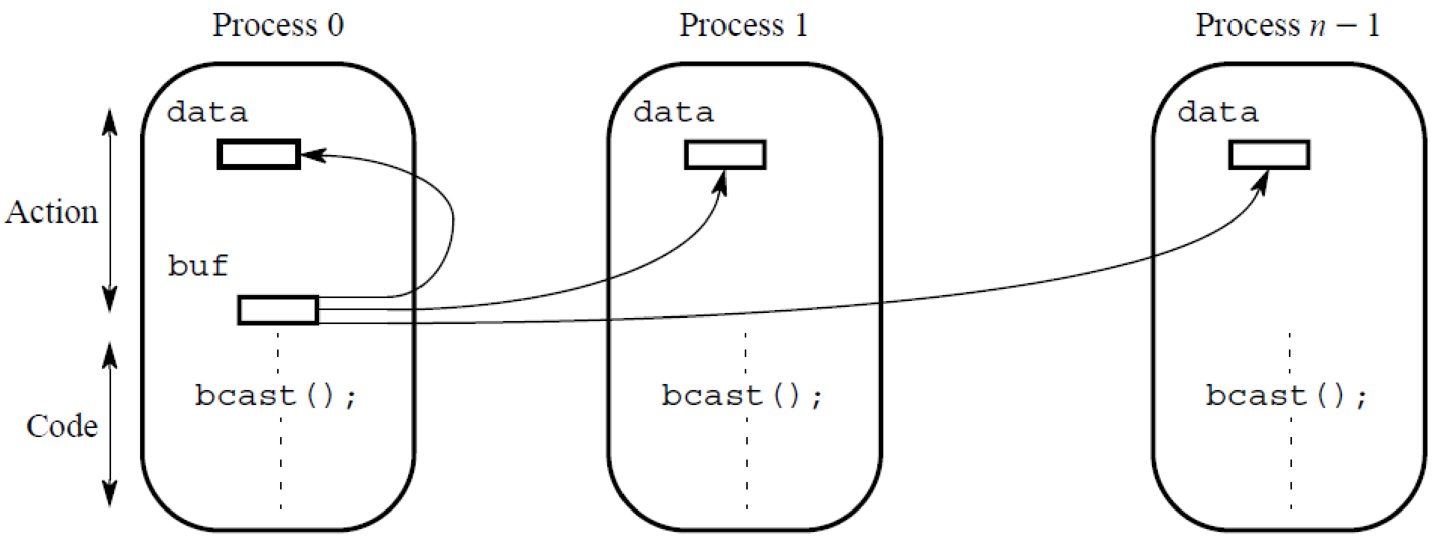
These routines must be called by all processes in the communication group

Barrier Synchronization

`int MPI_Barrier( MPI_Comm comm )`

Returns only after all processes in the communication group have called this function

Broadcast

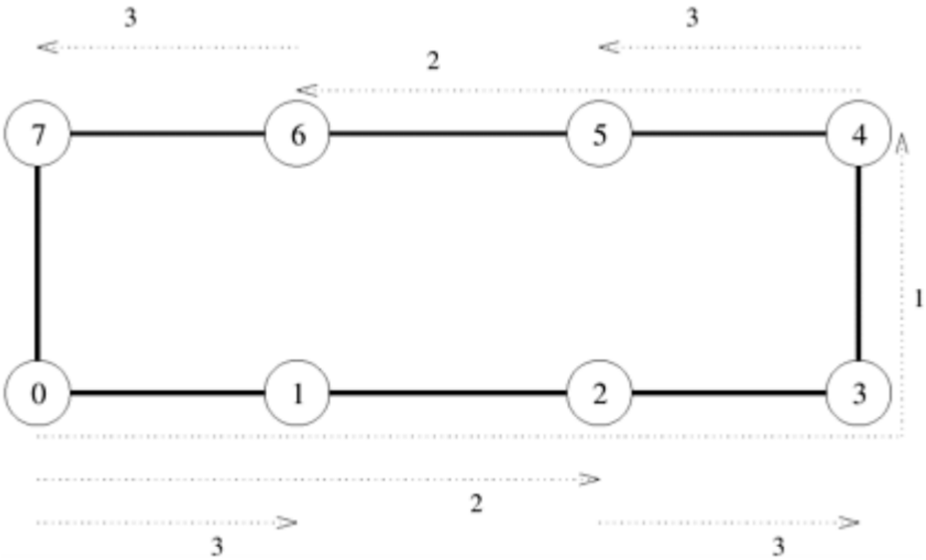


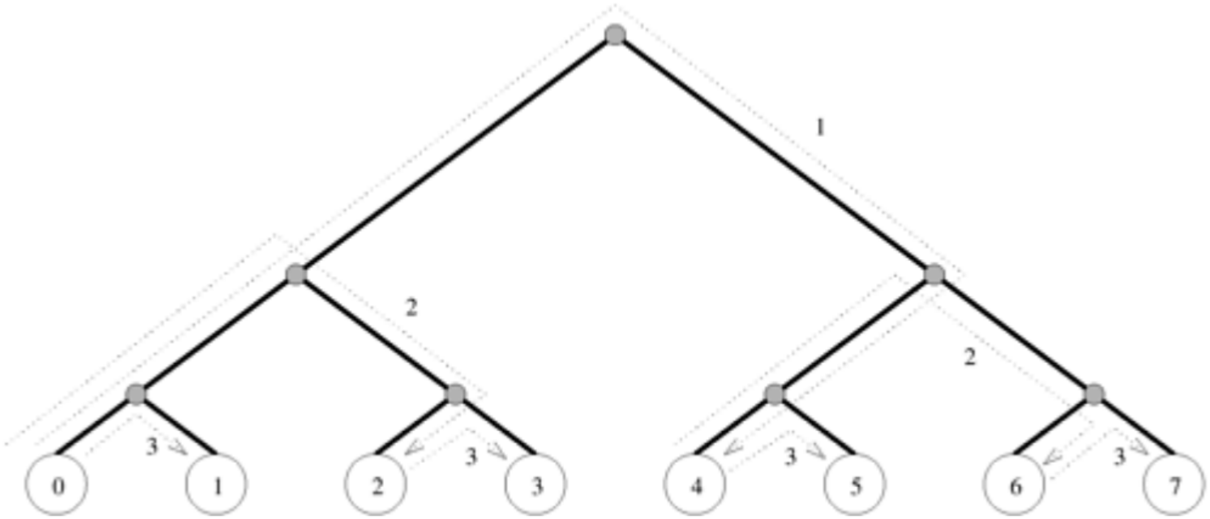
Source: Wilkinson & Allen., "Parallel Programming", 2nd Edition

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

Sends the data stored in the buffer *buf* of process *src* to all the other processes in the group

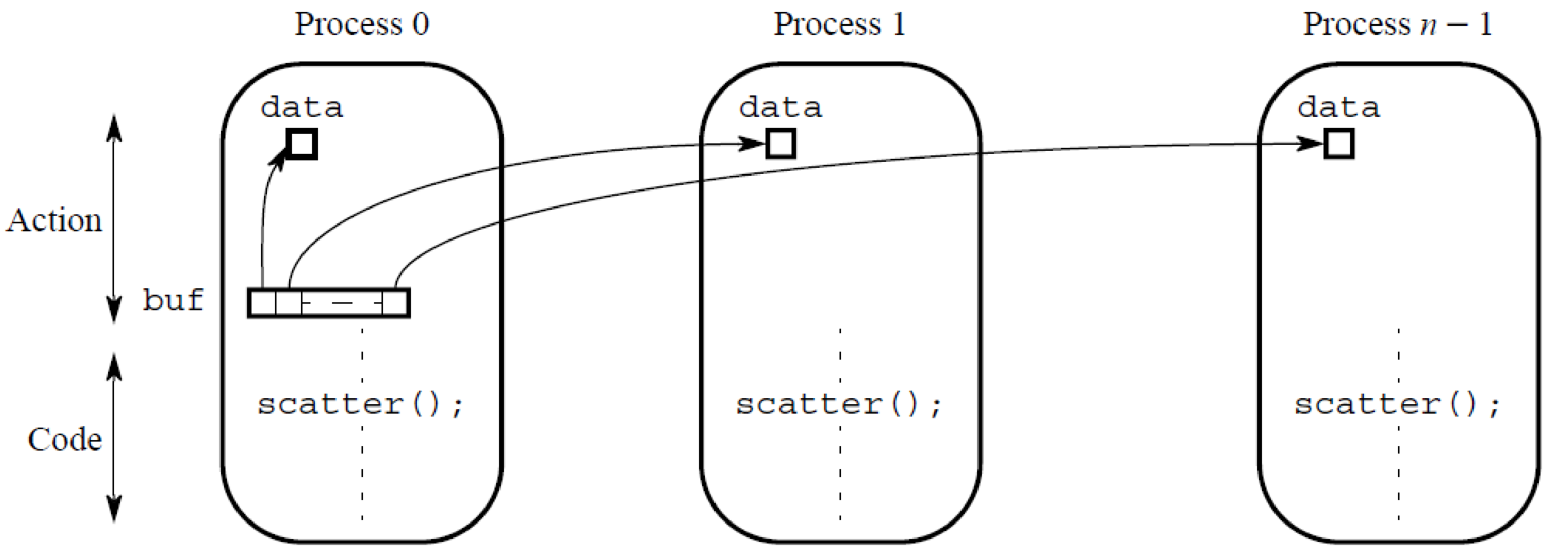
Broadcast





Source: Wilkinson & Allen., "Parallel Programming", 2nd Edition

Scatter



Source: Wilkinson & Allen., "Parallel Programming", 2^{nd} Edition

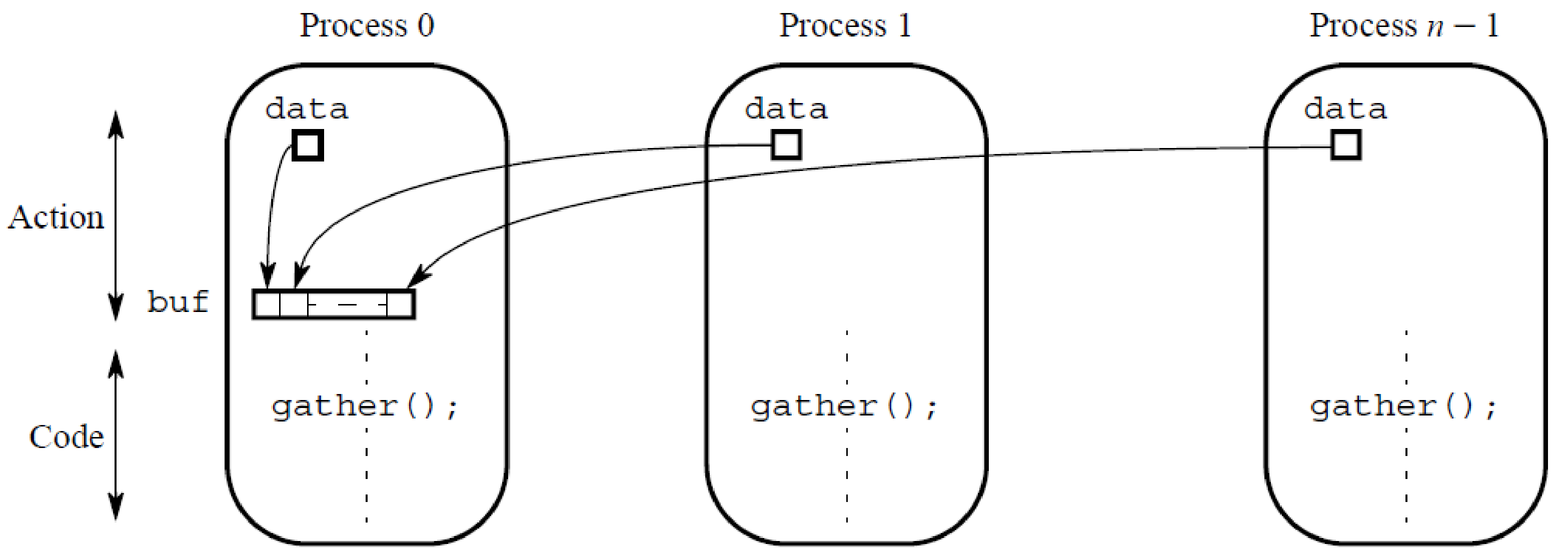
```
int MPI_Scatter(  void *sendbuf,
                  int sendcount,
                  MPI_Datatype sendtype,
                  void *recvbuf,
                  int recvcount,
                  MPI_Datatype recvtype,
                  int src,
                  MPI_Comm comm )
```

The *src* process sends a different part of *sendbuf* to each process, including itself.

Process *i* receives *sendcount* contiguous elements starting from *i* × *sendcount.*

The received data are stored in *recvbuf*.

Gather



Source: Wilkinson & Allen., "Parallel Programming", 2nd Edition

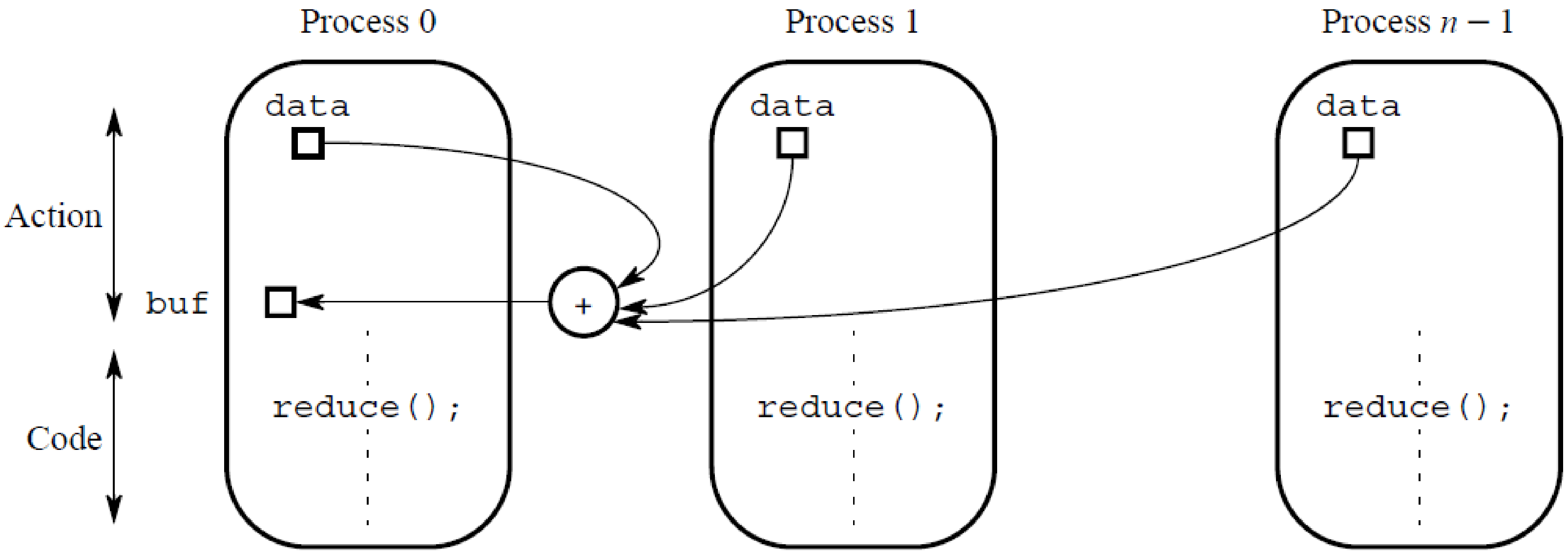
```
int MPI_Gather(  void *sendbuf,
                 int sendcount,
                 MPI_Datatype sendtype,
                 void *recvbuf,
                 int recvcount,
                 MPI_Datatype recvtype,
                 int dest,
                 MPI_Comm comm )
```

The opposite of scatter.

Every process, including *dest* sends data stored in *sendbuf* to *dest*.

Data from process *i* occupy *sendcount* contiguous locations of *recvbuf* starting from *i* × *sendcount.*

Reduce

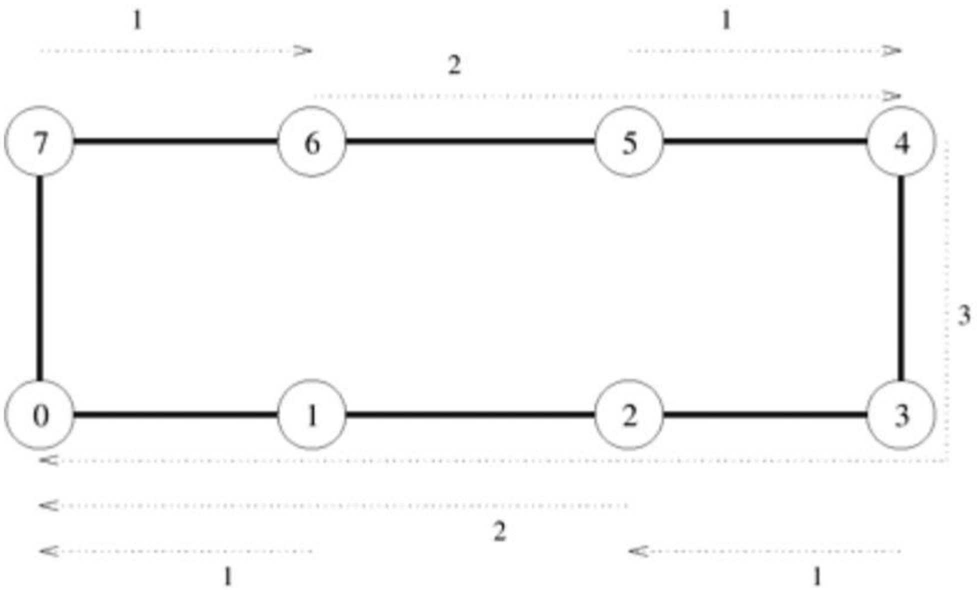


Source: Wilkinson & Allen., "Parallel Programming", 2nd Edition

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

Combines the elements stored in *sendbuf* of each process using the operation *op*, and stores the combined values in *recvbuf* of the process with rank *dest*.

Reduce



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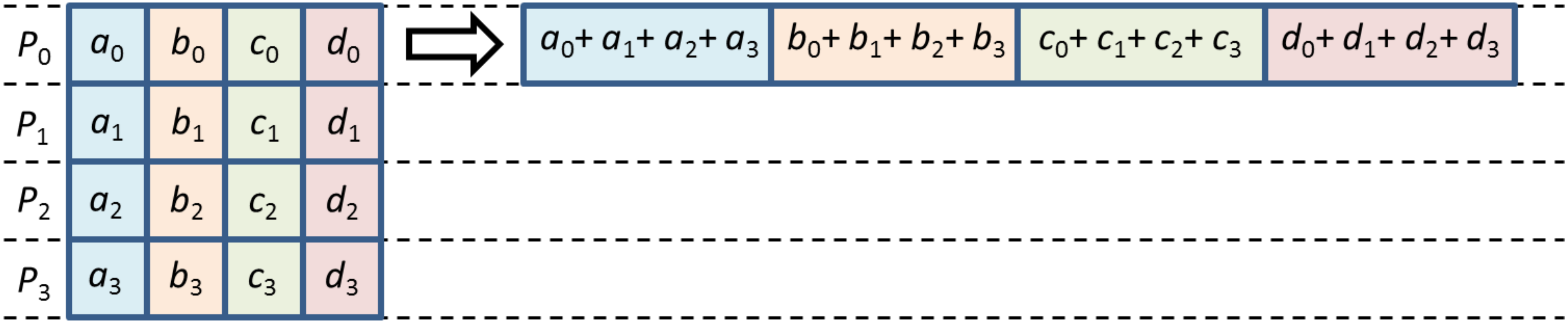
```
int MPI_Reduce(  void *sendbuf,
                 void *recvbuf,
                 int count,
                 MPI_Datatype datatype,
                 MPI_Op op,
                 int dest,
                 MPI_Comm comm )
```

Combines the elements stored in *sendbuf* of each process using the operation *op*, and stores the combined values in *recvbuf* of the process with rank *dest*.

Reduce

```
MPI_Reduce(  vals,  sums,  4,  MPI_INT,  MPI_SUM,  0,  MPI_COMM_WORLD )
```

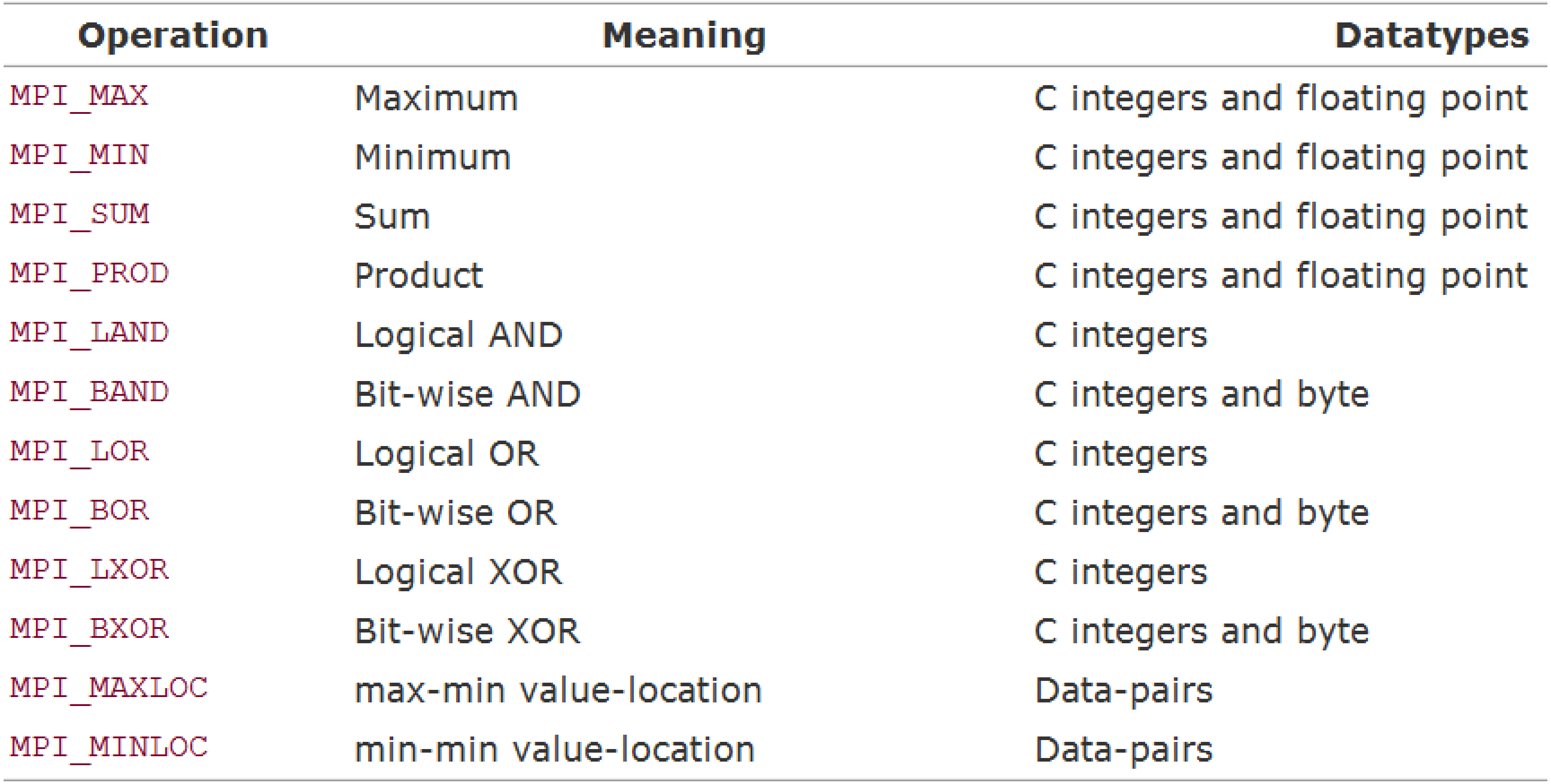


P_0	a_0	b_0	c_0	d_0
P_1	a_1	b_1	c_1	d_1
P_2	a_2	b_2	c_2	d_2
P_3	a_3	b_3	c_3	d_3

⇨

$a_0+a_1+a_2+a_3$	$b_0+b_1+b_2+b_3$	$c_0+c_1+c_2+c_3$	$d_0+d_1+d_2+d_3$

Predefined Reduction Operations

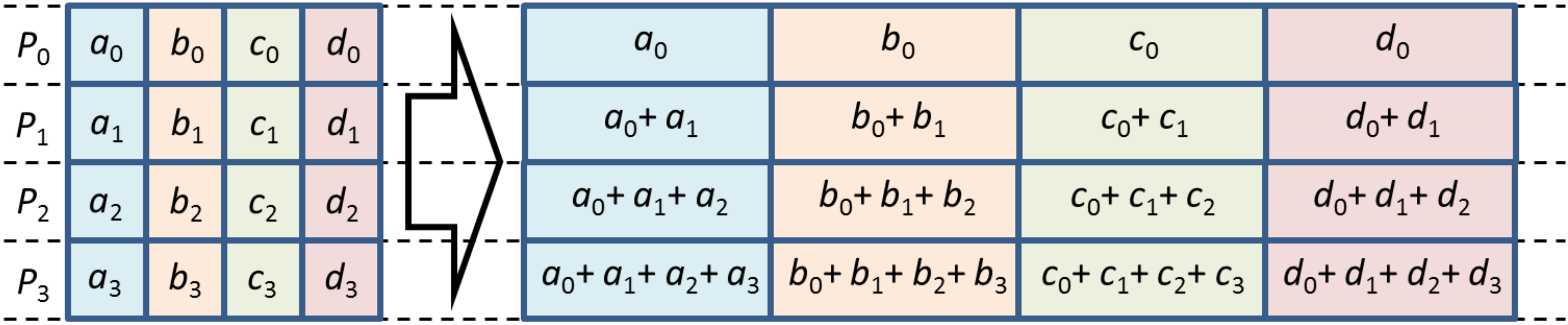


Operation	Meaning	Datatypes
`MPI_MAX`	Maximum	C integers and floating point
`MPI_MIN`	Minimum	C integers and floating point
`MPI_SUM`	Sum	C integers and floating point
`MPI_PROD`	Product	C integers and floating point
`MPI_LAND`	Logical AND	C integers
`MPI_BAND`	Bit-wise AND	C integers and byte
`MPI_LOR`	Logical OR	C integers
`MPI_BOR`	Bit-wise OR	C integers and byte
`MPI_LXOR`	Logical XOR	C integers
`MPI_BXOR`	Bit-wise XOR	C integers and byte
`MPI_MAXLOC`	max-min value-location	Data-pairs
`MPI_MINLOC`	min-min value-location	Data-pairs

Scan / Prefix

```
int MPI_Scan(  void *sendbuf,
               void *recvbuf,
               int count,
               MPI_Datatype datatype,
               MPI_Op op,
               MPI_Comm comm )
```

Performs a prefix reduction of the data stored in *sendbuf* at each process and returns the results in *recvbuf* of the process with rank *dest*.



P_0	a_0	b_0	c_0	d_0
P_1	a_1	b_1	c_1	d_1
P_2	a_2	b_2	c_2	d_2
P_3	a_3	b_3	c_3	d_3

a_0	b_0	c_0	d_0
a_0+a_1	b_0+b_1	c_0+c_1	d_0+d_1
$a_0+a_1+a_2$	$b_0+b_1+b_2$	$c_0+c_1+c_2$	$d_0+d_1+d_2$
$a_0+a_1+a_2+a_3$	$b_0+b_1+b_2+b_3$	$c_0+c_1+c_2+c_3$	$d_0+d_1+d_2+d_3$

```
MPI_Scan(  vals,  sums,  4,  MPI_INT,  MPI_SUM,  MPI_COMM_WORLD )
```