COMP 633 - Parallel Computing

Lecture 19
November 2-4, 2021

MPI: *Message Passing Interface*

- **Skim**
  - B. Barney (LLNL)
    - MPI tutorial and reference

Topics

- **Optimal BSP matrix multiply**
- **Short overview of basic issues in message passing**
- **MPI: A message-passing interface for distributed-memory parallel programming**
- **Collective communication operations**

Exercise

- **The version of matrix product we developed had BSP cost**

$$T_P^{MM}(n,p) = \frac{2n^3}{p} + \left(\frac{2n^2}{\sqrt{p}}\right)\cdot g + 2\cdot L$$

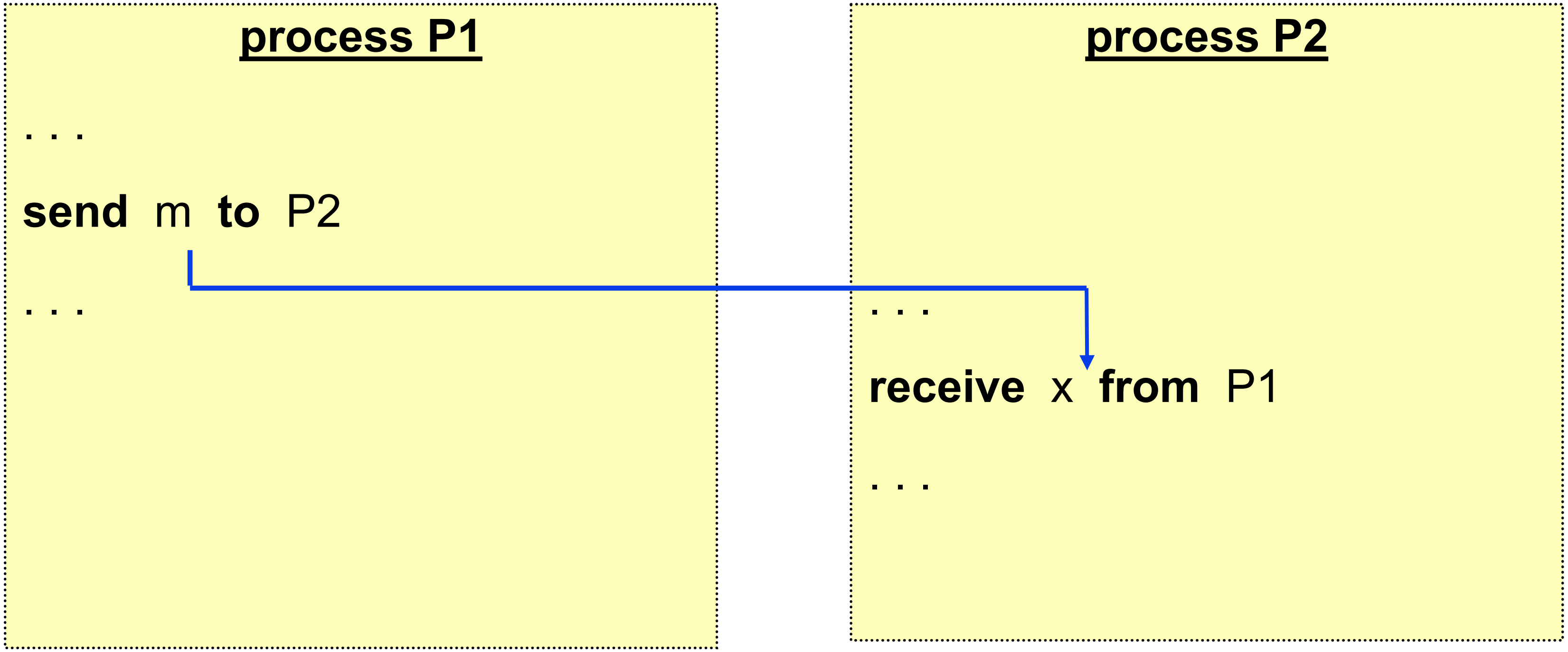
- **The BSP Q & A paper suggests this can be improved to**

$$T_P^{MM}(n,p) = \frac{2n^3}{p} + O\left(\frac{n^2}{p^{2/3}}\right)\cdot g + O(1)\cdot L$$

- **How?**

Basic Interprocess Communication

- **Basic building block**
  - message passing: send and receive operations between processes (address spaces)



process P1

. . .

send m **to** P2

. . .

process P2

. . .

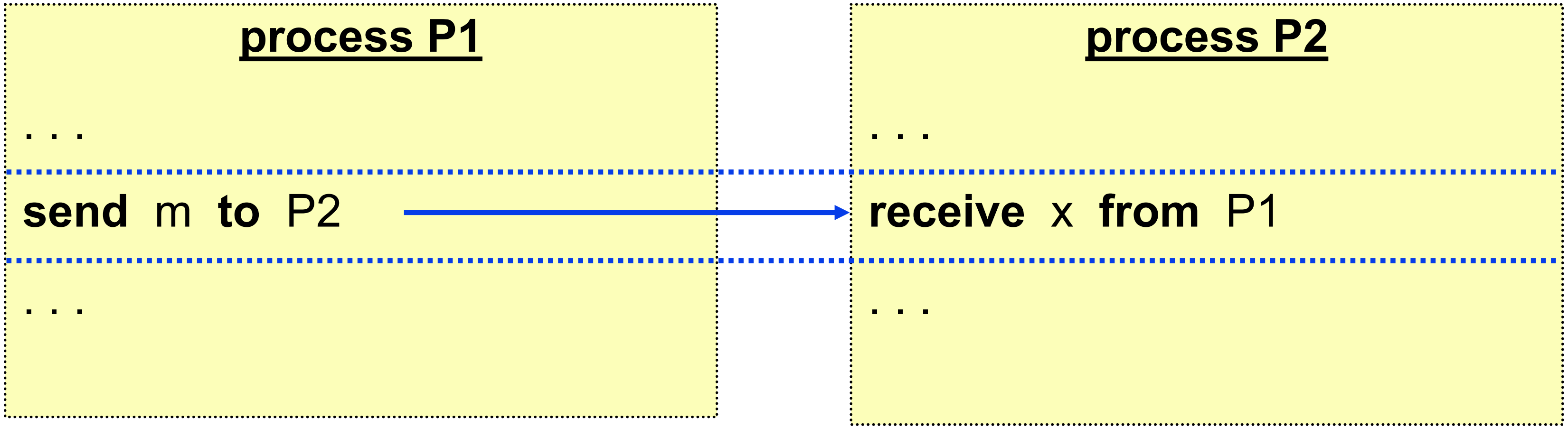
receive x **from** P1

. . .

How will this really be performed?

Synchronous Message Passing

- **Communication upon synchronization**
  - Hoare’s Communicating Sequential Processes (1978)
- **BLOCKING send and receive operations**
  - unbuffered communication
  - several steps in protocol
    - » synchronization, data movement, completion
  - delays participating processes



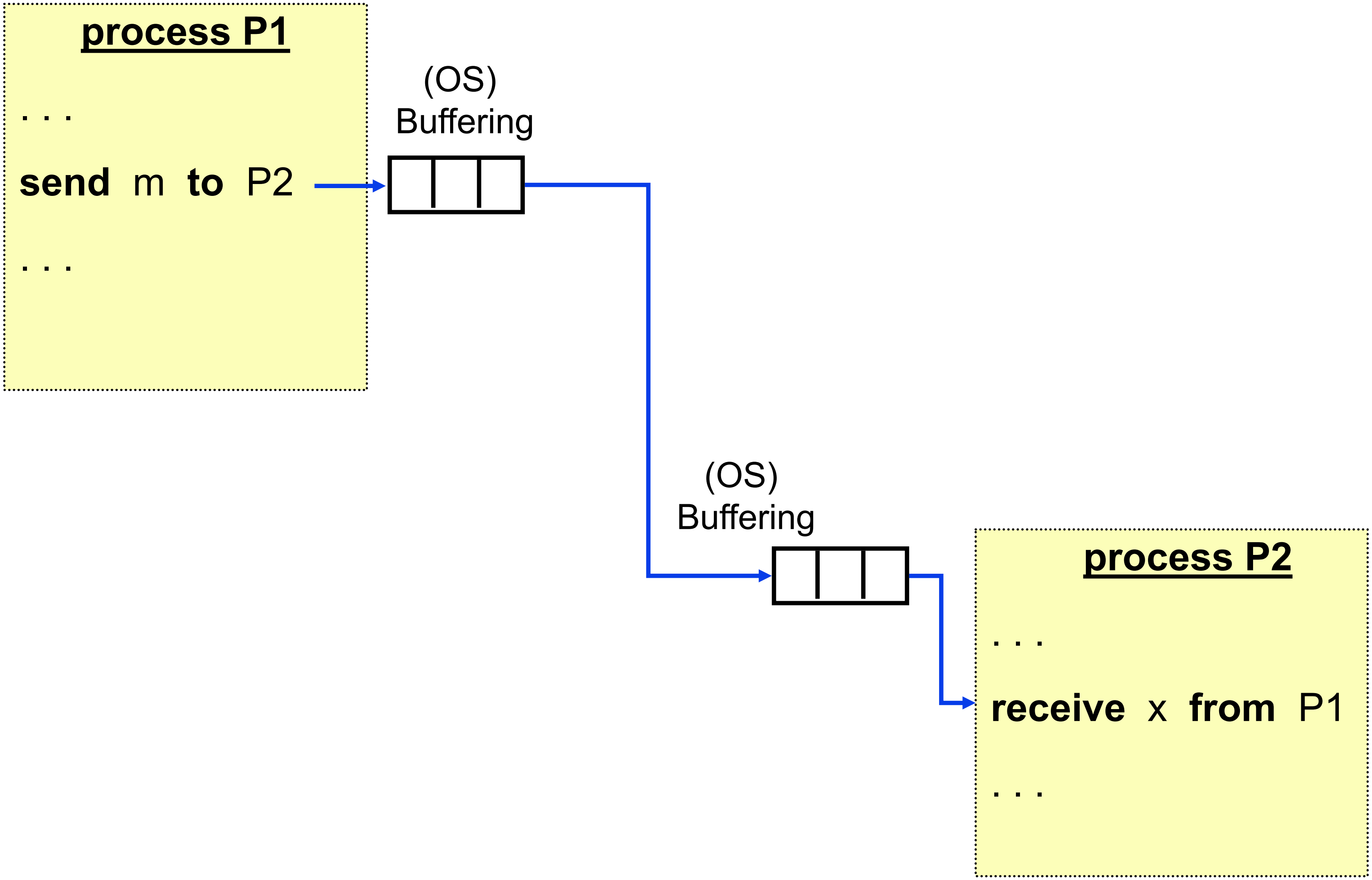
Asynchronous Message Passing

- **Buffered communication**
  - send/receive via OS-maintained buffers
    - e.g. pipes or TCP connections
    - may increase concurrency (e.g. producer/consumer)
    - may increase transit time

  - send operation
    - send operation completes when message is completely copied to buffer
    - generally non-blocking but will block if buffer is full

  - receive operation – two flavors
    - BLOCKING
      - receive operation completes when message has been delivered
    - NON-BLOCKING
      - receive operation provides location for message
      - notified when receive complete (via flag or interrupt)

Asynchronous Message Passing



process P1

. . .

send m **to** P2

. . .

(OS)
Buffering

(OS)
Buffering

process P2

. . .

receive x **from** P1

. . .

Deadlock in message passing

- **Can concurrent execution of P1 and P2 lead to deadlock?**
  - assuming synchronous message passing?
  - assuming asynchronous message passing?

process P1

```
. . .
send m1 to P2
receive y from P2
. . .
```

process P2

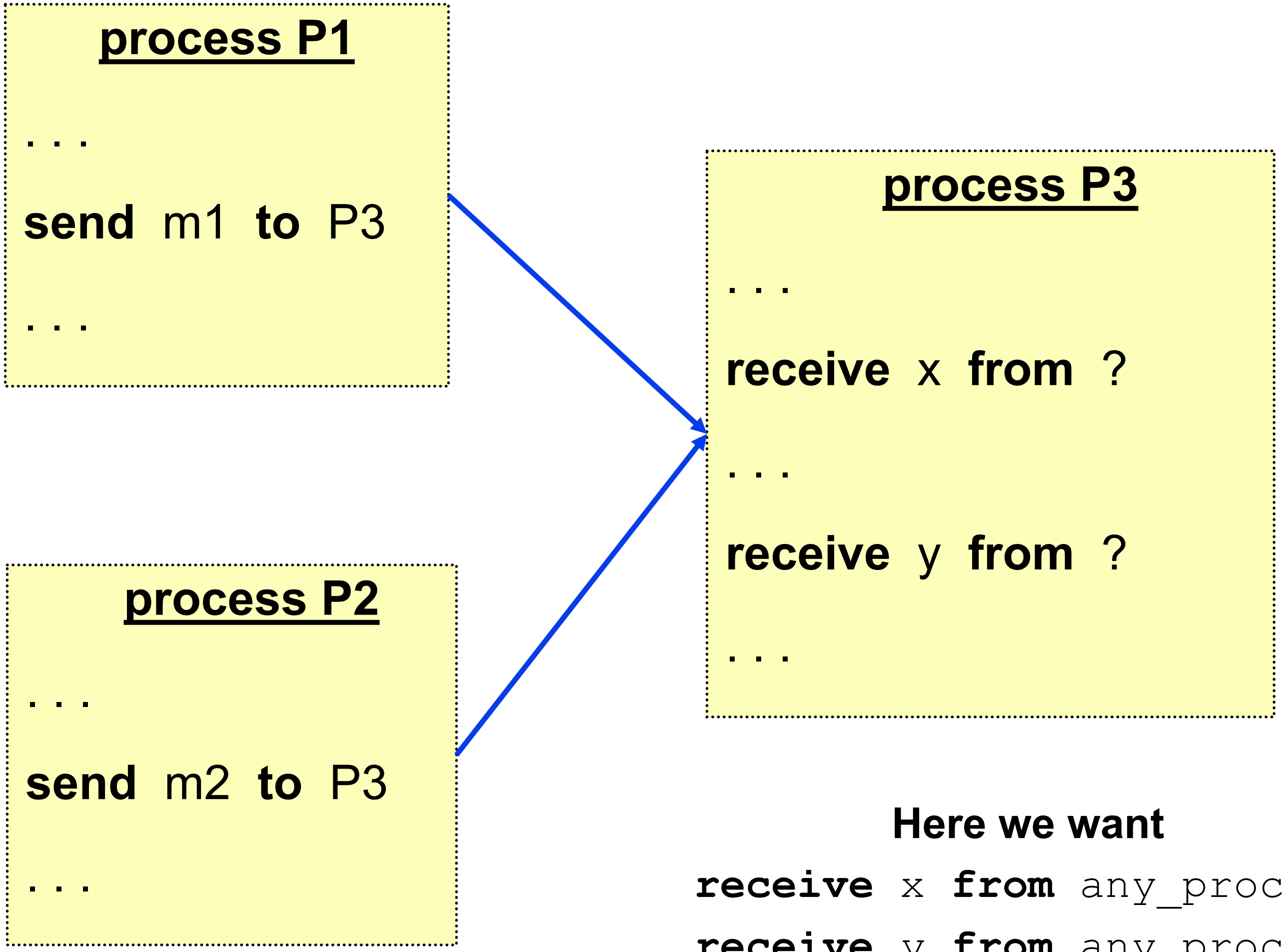
```
. . .
send m2 to P1
receive x from P1
. . .
```

Non-determinism in Message Passing

- In what order should the receive operations be performed?

Two producers

One consumer



process P1

. . .

send m1 **to** P3

. . .

process P2

. . .

send m2 **to** P3

. . .

process P3

. . .

receive x **from** ?

. . .

receive y **from** ?

. . .

Here we want

`receive x from any_process`

`receive y from any_process`

Safe communication

- **MPI has four pairwise message passing modes**
  - Synchronous
    - unbuffered, but all send-receive pairs must synchronize
  - Buffered (asynchronous)
    - Programmer supplies (sufficient) buffer space
  - Ready
    - Receiver guaranteed to be ready to receive at the time of the send
  - “Standard”
    - OS Buffered for small messages, synchronous for large messages

- **Most programs rely on a certain amount of buffering in communication**
  - SPMD programming models: send, then receive
  - Nondeterminacy: receive from left, receive from right

- **Most programs use standard model**
  - Dangerous, as buffer size is system-dependent

Destination naming

- **How are messages addressed to their receiver?**
  - Static process to processor mapping
    - Fixed set of processes at compile time
    - *mapper* statically assigns processes to processors at run time.
    - Ex: Communicating Sequential Processes (CSP)
  - Semi-dynamic process to processor mapping (SPMD)
    - Unknown set of processes at compile time
    - Fixed set of processes at run time
    - fixed mapping over execution lifetime
    - Ex: MPI communicators
  - Dynamic process to processor mapping
    - Unknown set of processes at compile time
    - Processes may be created or moved dynamically at run time
    - Communication requires lookup
    - MPI-2

Data Representation

- **In general, prefer to send an abstract data type (ADT) rather than single elements**
  - ADTs represent abstractions suited to program
  - higher performance can be obtained for large messages
    - e.g. aggregate data types
- **How are components of an ADT combined together?**
  - data marshalling
    - packing components into a send buffer
- **How is a message represented as a sequence of bits?**
  - encoding must be suitable for source and destination
    - XDR (eXternal Data Representation)
- **How is a message disassembled into an ADT?**
  - data unmarshalling
    - extracting components from a receive buffer

Message Selection

- **Receiving process may need to receive message from multiple potential senders**
  - How to specify/distinguish message to be received?
    - » sender selection (socket, MPI, CSP)
    - » message data type selection (MPI, CSP)
    - » condition selection (CSP)
    - » message “tag” (MPI)
  - specification of message to be received can decrease nondeterminacy
    - » Non-deterministic reception order requires care with blocking sends/receives

Message Passing Interface (MPI)

- **A library of communication operations for distributed-memory parallel programming**
  - history
    - TCP/IP, …., PVM (1990), MPI (1994), MPI-2 (1997), MPI-3 (2012)
  - programming model
    - SPMD - single program with library calls
  - MPI functionality
    - send/receive, synchronization, collective communication
    - MPI specifies 129 procedures
      - widely implemented and generally efficient
    - MPI 2 adds one-sided communication, dynamic processes, parallel I/O and more
      - One-sided communication: remote direct memory access – good for BSP.
      - Over 15 years from full specification to correct and (generally) efficient implementations
    - MPI-3
      - Tweaks and shared memory segments between MPI processes
  - portability
    - MPI is the most portable parallel programming paradigm – it runs on
      - shared and distributed memory machines
      - homogeneous and heterogeneous systems
      - variety of interconnection networks
    - BUT functional portability ≠ performance portability !

MPI Example (C + MPI)

```
#include <mpi.h>
main(int argc, char **argv) {
  int nproc, myid;

  MPI_Init (&argc, &argv);
  MPI_Comm_size (MPI_COMM_WORLD, &nproc);
  MPI_Comm_rank (MPI_COMM_WORLD, &myid);

  printf("Hello World! Here is process %d of %d.\n",
            myid, nproc);

  MPI_Finalize ();
}
```

MPI return codes

```
#include <mpi.h>
#include <stdio.h>
#include <err.h>
main(int argc, char **argv) {
  int nproc, myid, ierr;

  ierr = MPI_Init(&argc, &argv);
  if (ierr != MPI_SUCCESS) err(4, "Error %d in MPI_Init\n", ierr);

  ierr =  MPI_Comm_size (MPI_COMM_WORLD, &nproc);
  if (ierr != MPI_SUCCESS) err(4, "Error %d in MPI_Comm_size\n", ierr);

  ierr = MPI_Comm_rank (MPI_COMM_WORLD, &myid);
  if (ierr != MPI_SUCCESS) err(4, "Error %d in MPI_Comm_rank\n", ierr);

  printf("Hello World! Here is process %d of %d.\n", myid, nproc);

  ierr = MPI_Finalize();
  if (ierr != MPI_SUCCESS) err(4, "Error %d in mpi_finalize\n", ierr);
}
```

Point-to-point communication

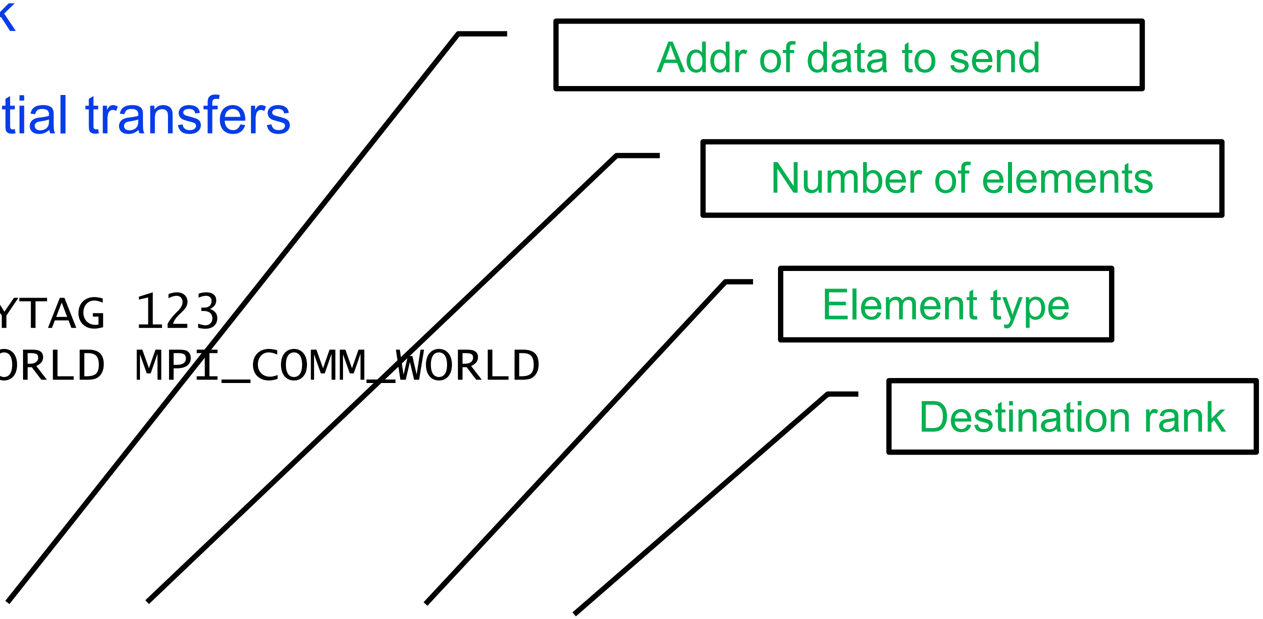
- **Specification of message to receive**
    - communicator – identifies logical set of processors
        - intracommunicator vs. intercommunicator
    - sending process rank (= proc id)
    - tag
  - details of received message via status parameter
    - wildcard specifications may result in non-deterministic programs

- **Type Specification**
  - must provide types of transmitted values
    - predefined types & user-defined types
    - implicit conversions in heterogeneous* systems

- **Protocol specification**
  - send
    - blocking / non-blocking / repeated / …
        - standard / buffered / synchronous / “ready”

Simple message exchange

- no deadlock
- two sequential transfers



Addr of data to send

Number of elements

Element type

Destination rank

```
#define MYTAG 123
#define WORLD MPI_COMM_WORLD
```

Process 0:

```
MPI_Send(A, 100, MPI_DOUBLE, 1, MYTAG, WORLD);
MPI_Recv(B, 100, MPI_DOUBLE, 1, MYTAG, WORLD);
```

Process 1:

```
MPI_Recv(B, 100, MPI_DOUBLE, 0, MYTAG, WORLD);
MPI_Send(A, 100, MPI_DOUBLE, 0, MYTAG, WORLD);
```

Non-blocking message exchange

- no deadlock
- possibility of concurrent transfer

```
#define MYTAG 123
#define WORLD MPI_COMM_WORLD

MPI_Request request;
MPI_Status status;
```

Process 0:

```
MPI_Irecv(B, 100, MPI_DOUBLE, 1, MYTAG, WORLD, &request);
MPI_Send(A, 100, MPI_DOUBLE, 1, MYTAG, WORLD);
MPI_Wait(&request, &status);
```

Process 1:

```
MPI_Irecv(B, 100, MPI_DOUBLE, 0, MYTAG, WORLD, &request);
MPI_Send(A, 100, MPI_DOUBLE, 0, MYTAG, WORLD);
MPI_Wait(&request, &status);
```

Overlapping communication and computation

Process 0 and 1:

```
#define MYTAG 123
#define WORLD MPI_COMM_WORLD

MPI_Request requests[2];
MPI_Status statuses[2];

// p is process id of the partner in a pairwise exchange

MPI_Irecv(B, 100, MPI_DOUBLE, p, 0, WORLD, &request[1]);
MPI_Isend(A, 100, MPI_DOUBLE, p, 0, WORLD, &request[0]);
```

.... do some useful work here ....

```
MPI_Waitall(2, requests, statuses);
```

- no deadlock
- concurrent transfer
- communication and computation may be overlapped on some machines
  - requires hardware communication support

Communicators

- **MPI_COMM_WORLD is a communicator**
  - group of processes numbered 0 ... p-1
  - set of logical communication channels between them

- **Message sent with one communicator cannot be received in another communicator**
  - all communication is intra-communicator
  - enables development of safe libraries
  - restricting communication to subgroups is useful

- **Creating new communicators**
  - duplication
  - splitting

- **Intercommunicators**
  - orchestrate communication between two different communicators

Collective Communication

- **Operations involve all processes in an (intra)communicator**
  - encapsulate important communication patterns (cf. BSP)
    - broadcast
    - total exchange (transpose)
    - reduction + scan
    - barrier
  - operations do not necessarily imply a barrier synchronization
    - however, all processes must issue the same collective communication operations in the same order

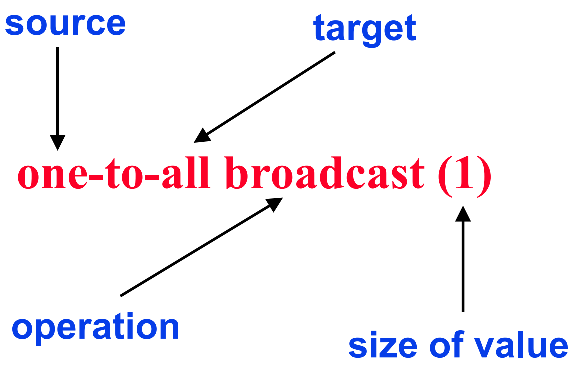
- **Type specification**
  - predefined or user-defined types
  - predefined or user-defined associative operation for reduction & scan

- **Distinguished process**
  - for broadcast or reduction operations

Collective communication operations

- **classified by**
  - source of values
    - » one/all processor(s)
  - target of result
    - » one/all processors(s)
  - operation
    - » broadcast
    - » exchange
    - » accumulate (reduce)
  - size of values
    - » 1 or n

Ex:



source

target

one-to-all broadcast (1)

operation

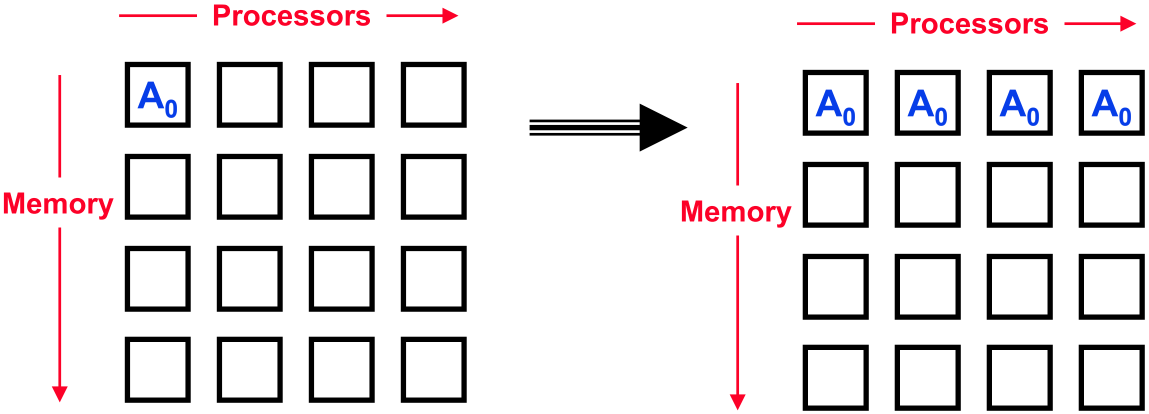
size of value

- **duality of communication operations**
  - communication patterns are related
  - broadcast & reduction are duals
  - exchange is its own dual

Broadcast: single source, single value

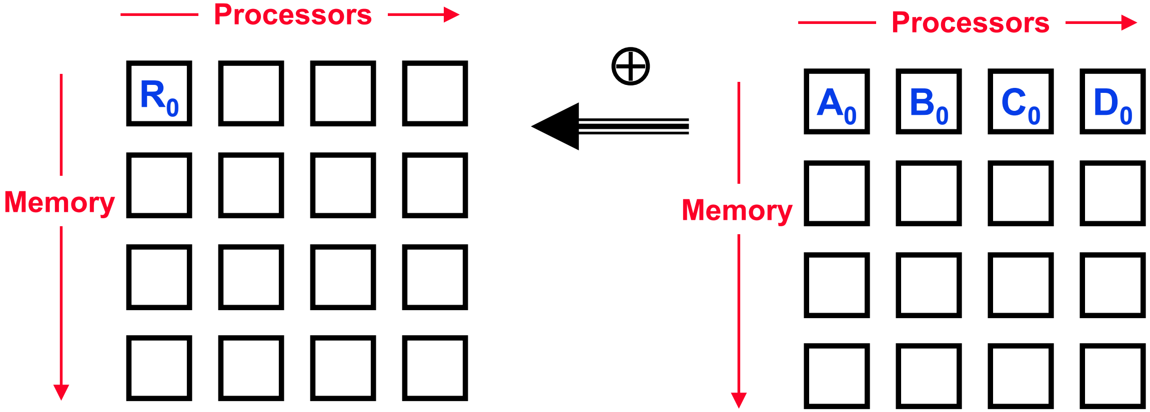
one-to-all broadcast (1)

`MPI_Bcast(…1…)`



all-to-one sum (1)

`MPI_Reduce(…1…)`

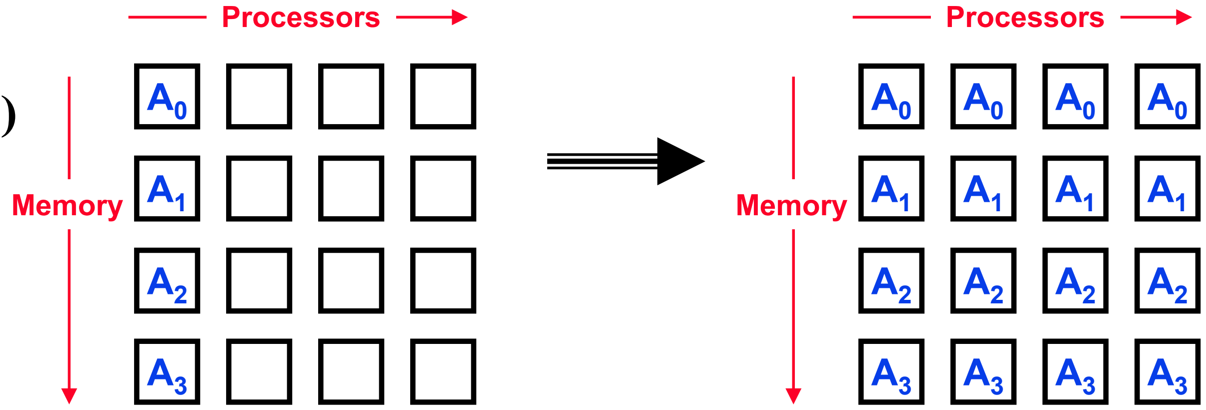


$R_0 = A_0 \oplus B_0 \oplus C_0 \oplus D_0$

Broadcast: single source, multiple values

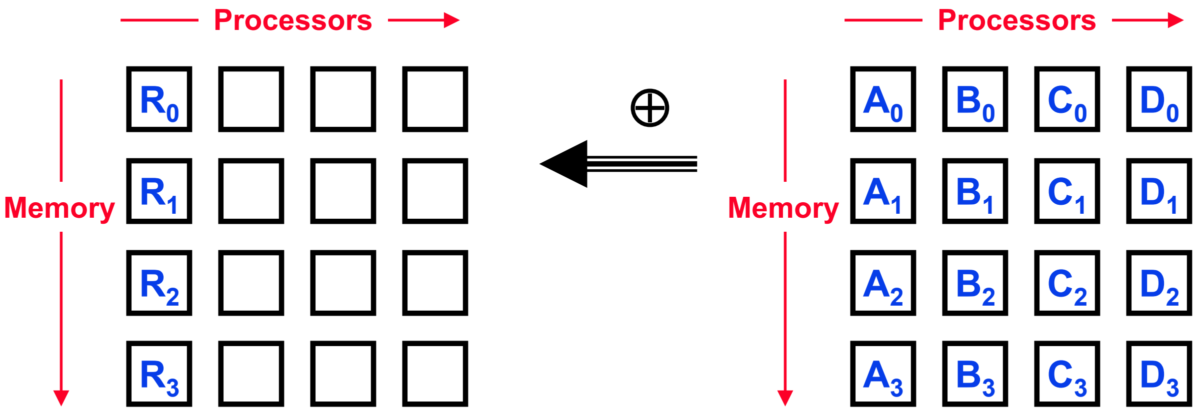
one-to-all broadcast (n)

`MPI_Bcast(…n…)`



all-to-one sum (n)

`MPI_Reduce(…n…)`

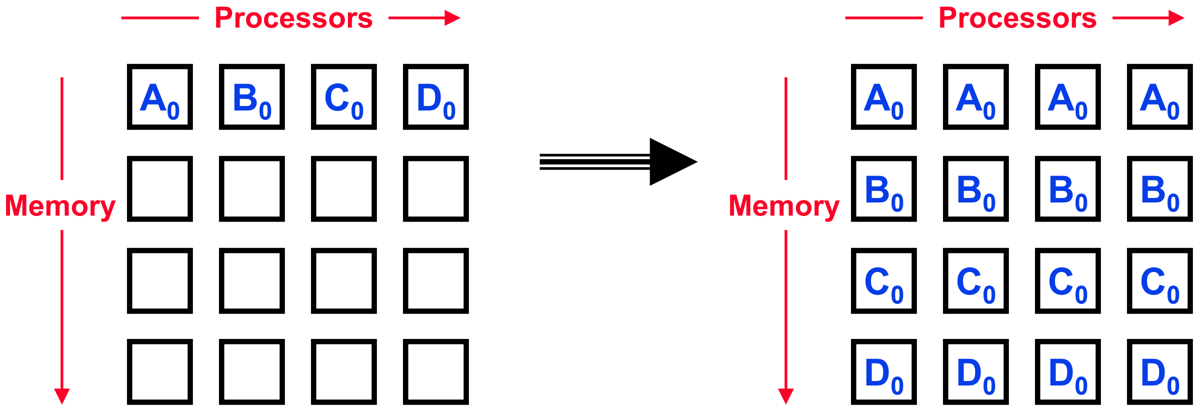


$R_i = A_i \oplus B_i \oplus C_i \oplus D_i$

Broadcast: multiple source, single value

all-to-all broadcast (1)

`MPI_Allgather(…n…)`

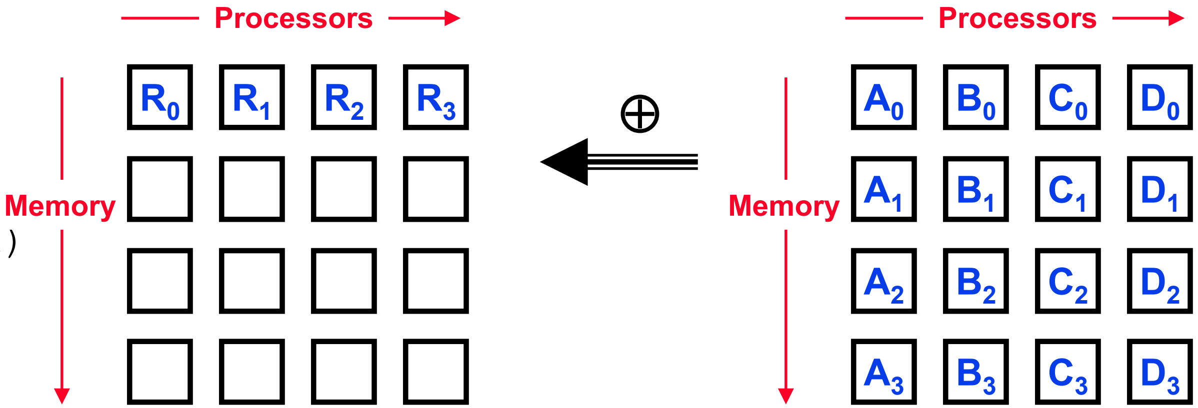


A_0	B_0	C_0	D_0

A_0	A_0	A_0	A_0
B_0	B_0	B_0	B_0
C_0	C_0	C_0	C_0
D_0	D_0	D_0	D_0

all-to-all sum (1)

`MPI_Reduce_scatter(…n…)`



R_0	R_1	R_2	R_3

A_0	B_0	C_0	D_0
A_1	B_1	C_1	D_1
A_2	B_2	C_2	D_2
A_3	B_3	C_3	D_3

$R_i = A_i \oplus B_i \oplus C_i \oplus D_i$

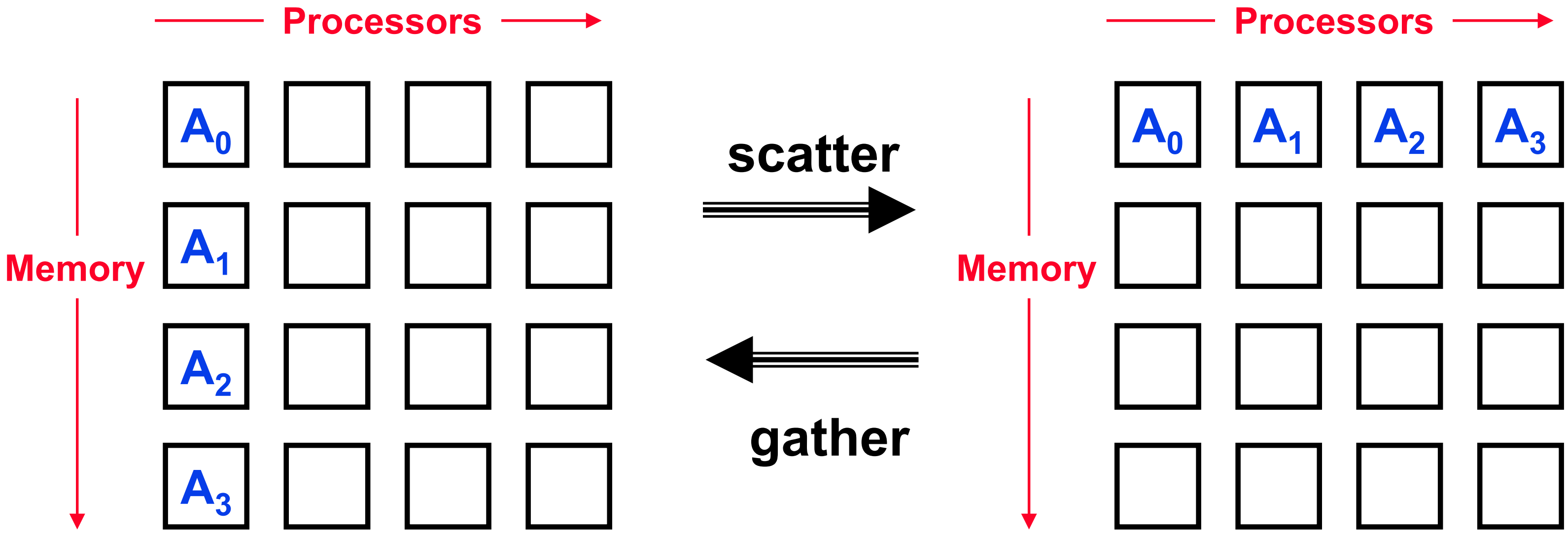
Exchange: single source or single target

- **One-to-all exchange (n)**

  `MPI_Scatter( … )`

- **All-to-one exchange (1)**

  `MPI_Gather( … )`

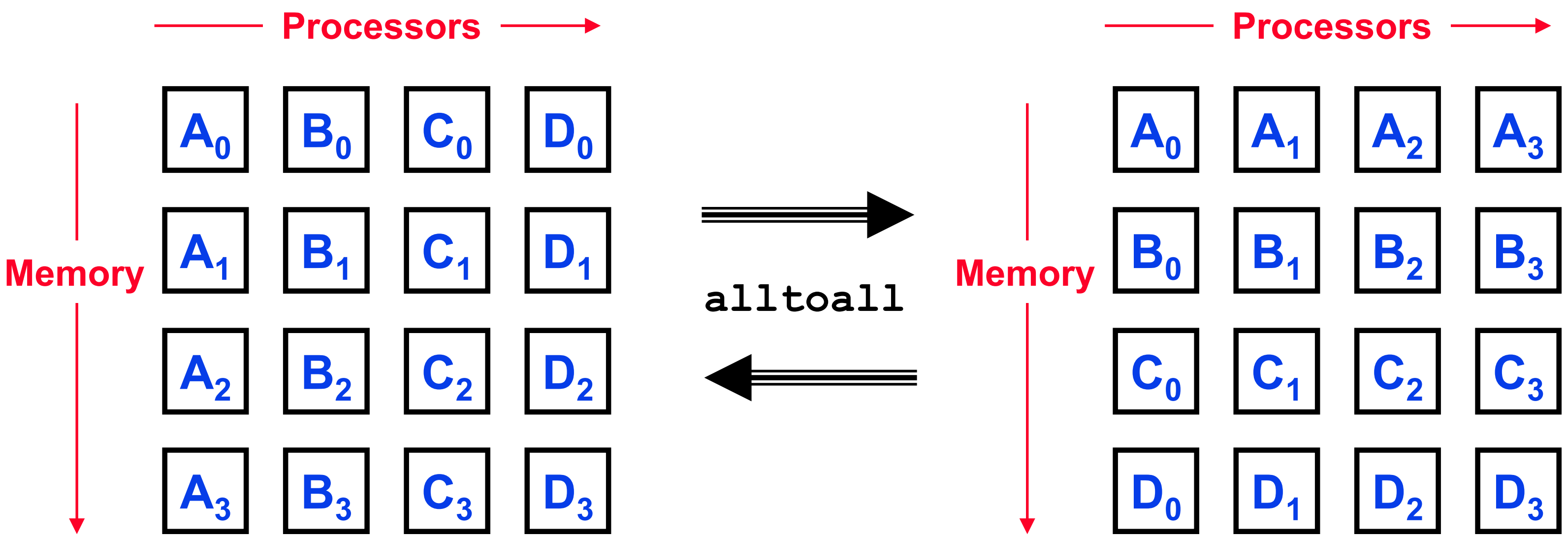


Exchange: multiple source, multiple values

- **all-to-all exchange (n)**

  `MPI_Alltoall(…)`

  – BSP “total exchange” or transpose



Processors →

Memory ↓

A_0	B_0	C_0	D_0
A_1	B_1	C_1	D_1
A_2	B_2	C_2	D_2
A_3	B_3	C_3	D_3

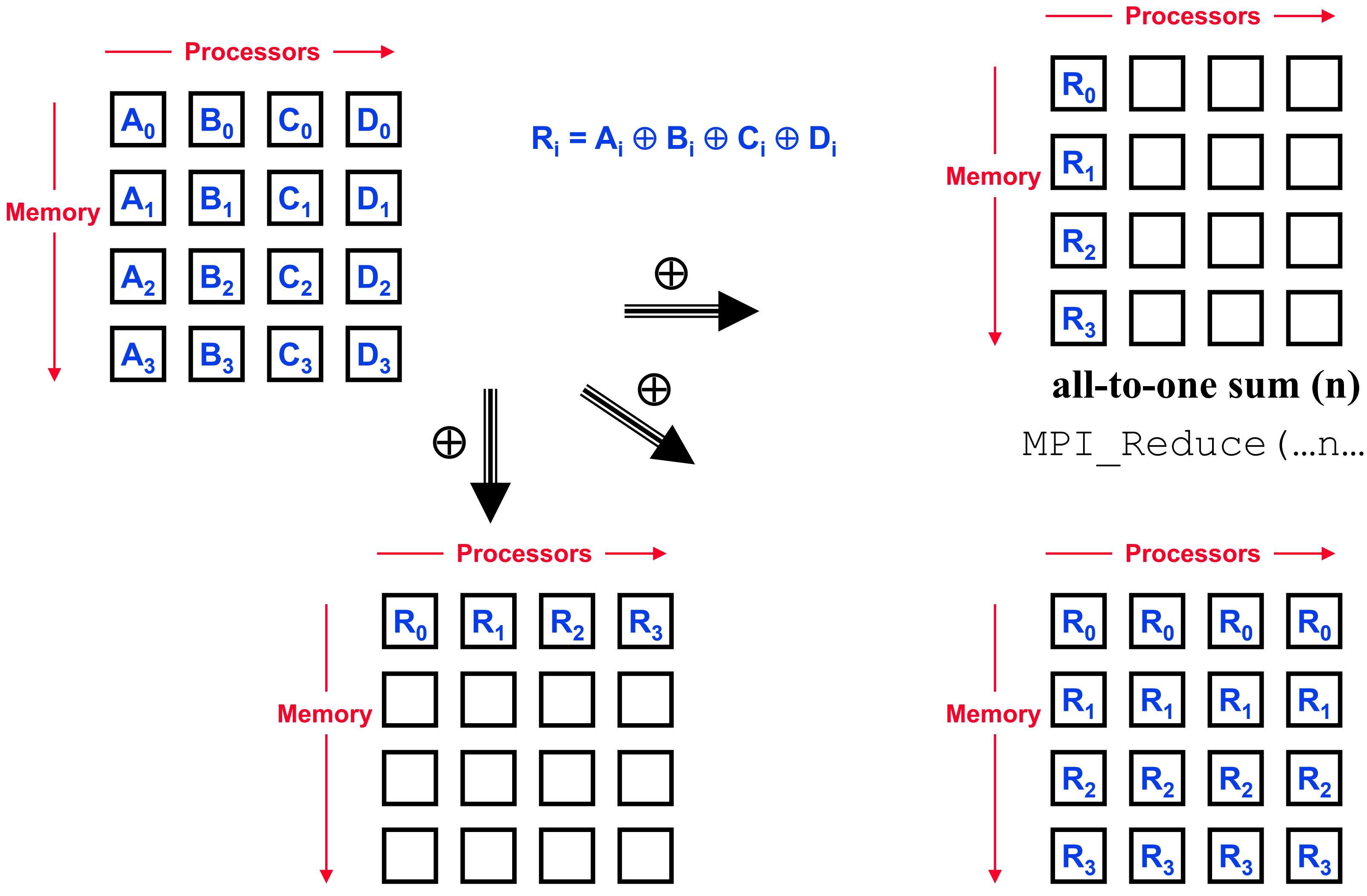
⇄ `alltoall`

Processors →

Memory ↓

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

Reductions: multiple source, multiple values



A_0	B_0	C_0	D_0
A_1	B_1	C_1	D_1
A_2	B_2	C_2	D_2
A_3	B_3	C_3	D_3

$R_i = A_i \oplus B_i \oplus C_i \oplus D_i$

R_0			
R_1			
R_2			
R_3			

all-to-one sum (n)

`MPI_Reduce(…n…)`

R_0	R_1	R_2	R_3

all-to-all sum (1)

`MPI_Reduce_scatter(…n…)`

R_0	R_0	R_0	R_0
R_1	R_1	R_1	R_1
R_2	R_2	R_2	R_2
R_3	R_3	R_3	R_3

all-to-all sum (n)

`MPI_Allreduce(…n…)`