Distributed Systems
CS 15-440/640

Programming Models

Borrowed and adapted from our good friends at
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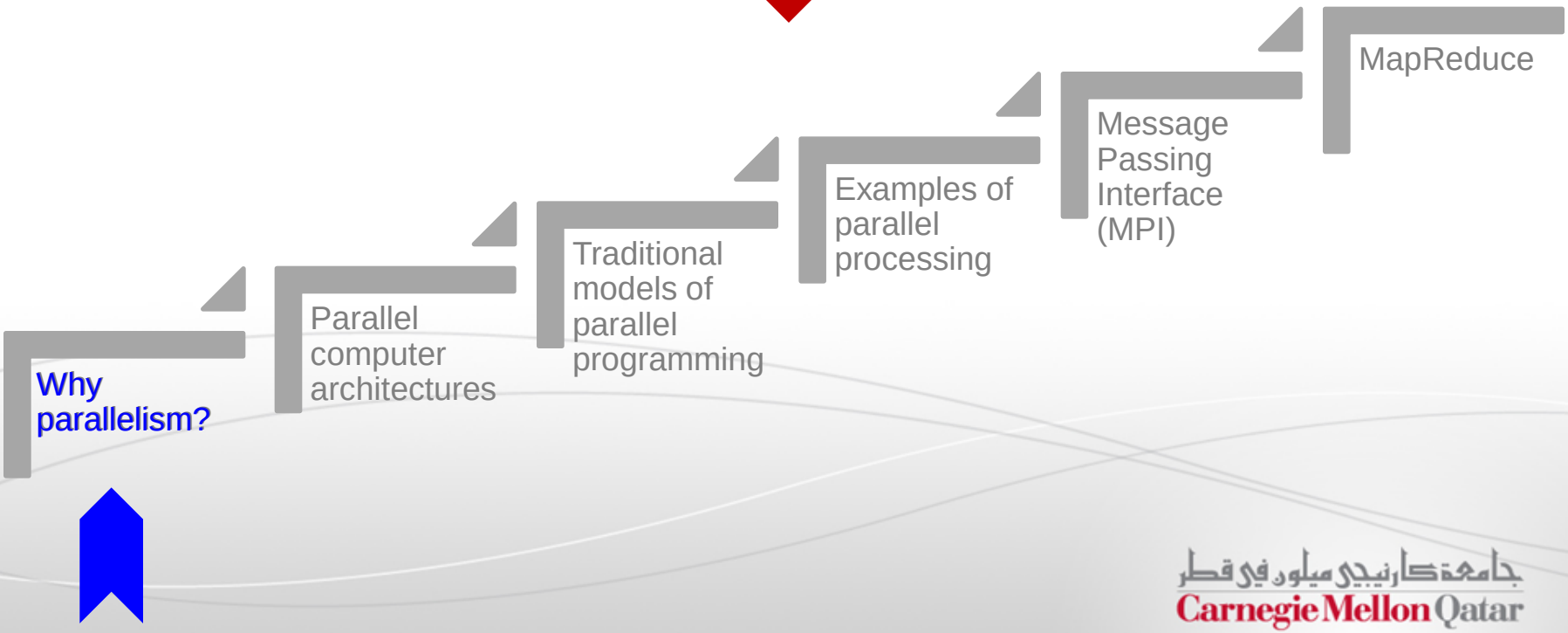
Objectives

Discussion on Programming Models



Amdahl's Law

- We parallelize our programs in order to run them faster
- How much faster will a parallel program run?
  - Suppose that the sequential execution of a program takes T_1 time units and the parallel execution on p processors takes T_p time units
  - Suppose that out of the entire execution of the program, s fraction of it is not parallelizable while $1-s$ fraction is parallelizable
  - Then the speedup (***Amdahl's formula***):

$$\frac{T_1}{T_p} = \frac{T_1}{(T_1 \times s + T_1 \times \frac{1-s}{p})} = \frac{1}{s + \frac{1-s}{p}}$$

Amdahl's Law: An Example

- Suppose that 80% of you program can be parallelized and that you use 4 processors to run your parallel version of the program

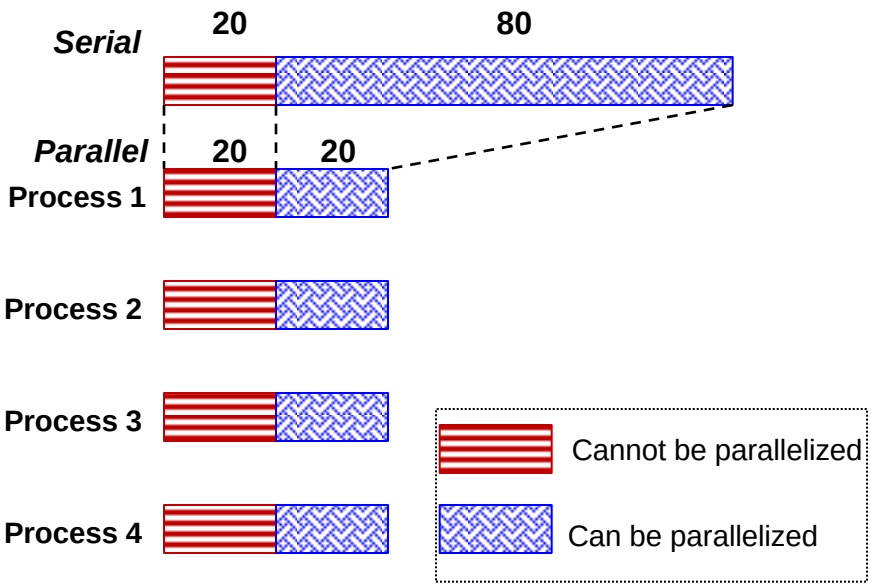
- The speedup you can get according to Amdahl is:

$$\frac{1}{s+\frac{1-s}{p}} = \frac{1}{0.2+\frac{0.8}{4}} = 2.5 \text{ times}$$

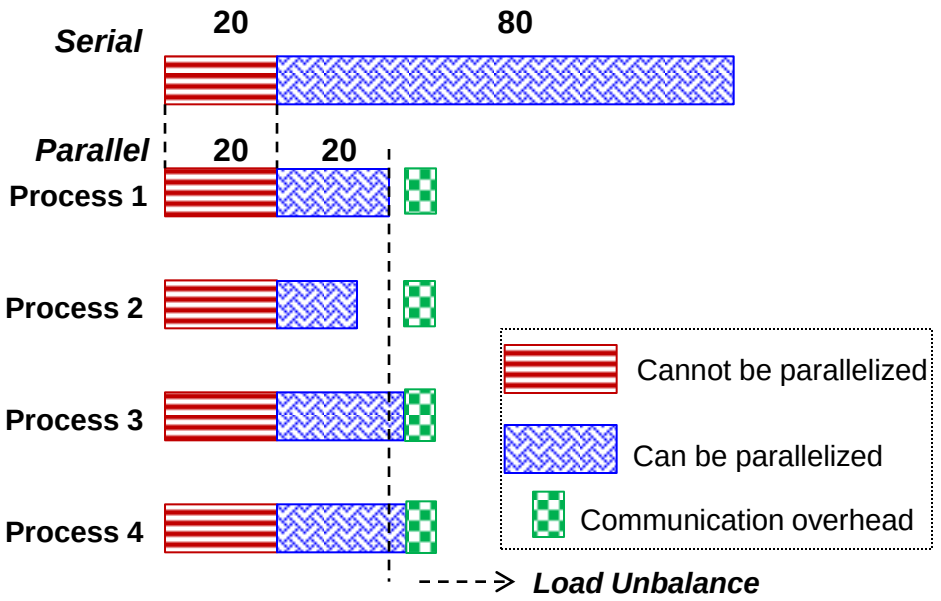
- Although you use 4 processors you cannot get a speedup more than 2.5 times (or 40% of the serial running time)

Real Vs. Actual Cases

- Amdahl's argument is too simplified to be applied to real cases
- When we run a parallel program, there are a communication overhead and a workload imbalance among processes in general



1. Parallel Speed-up: An Ideal Case



2. Parallel Speed-up: An Actual Case

Guidelines

- In order to efficiently benefit from parallelization, we ought to follow these guidelines:

1. Maximize the fraction of our program that can be parallelized
2. Balance the workload of parallel processes
3. Minimize the time spent for communication

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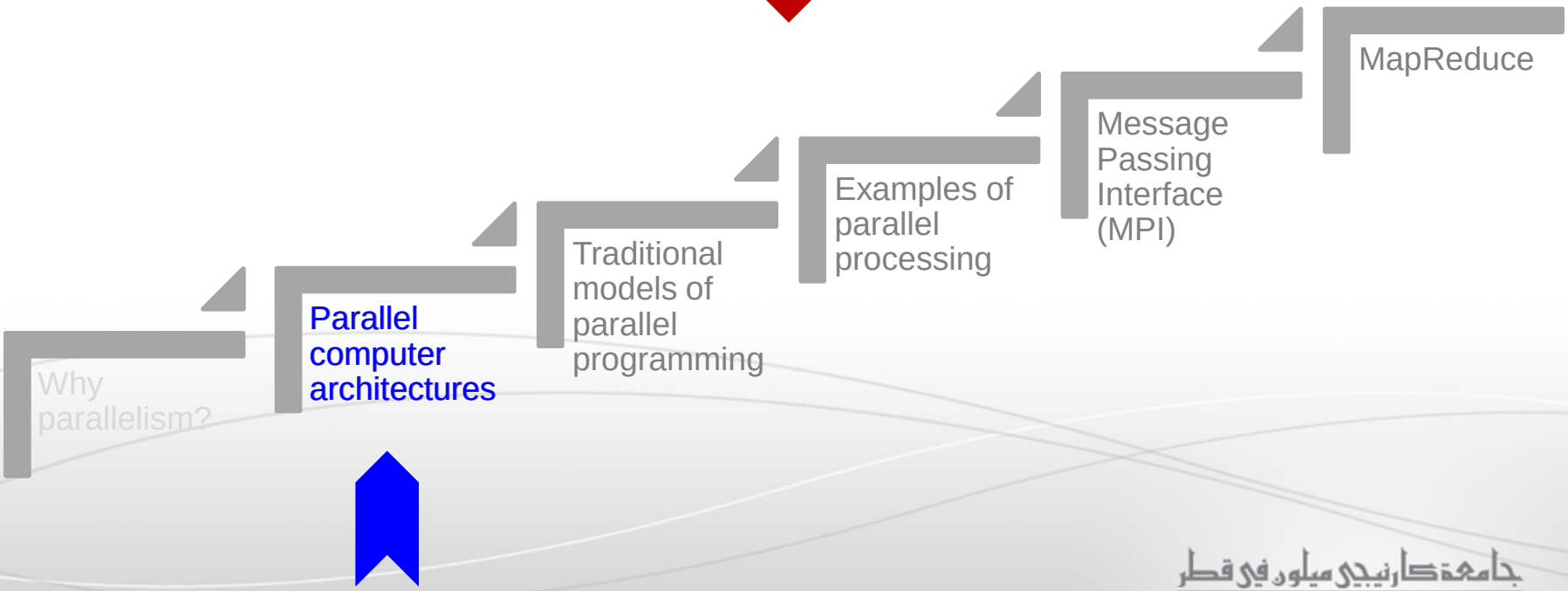


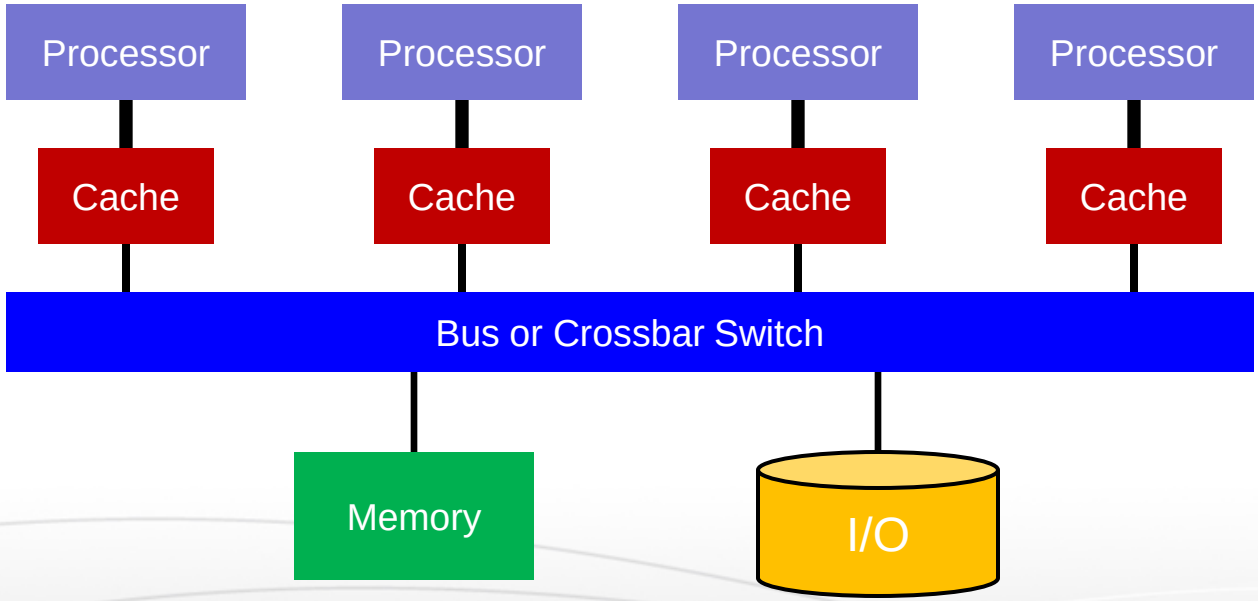
Parallel Computer Architectures

- We can categorize the architecture of parallel computers in terms of two aspects:
  - Whether the memory is physically centralized or distributed
  - Whether or not the address space is shared

Memory		Address Space	
		Shared	**Individual**
	Centralized	UMA – SMP (Symmetric Multiprocessor)	N/A
	Distributed	NUMA (Non-Uniform Memory Access)	MPP (Massively Parallel Processors)

Symmetric Multiprocessor

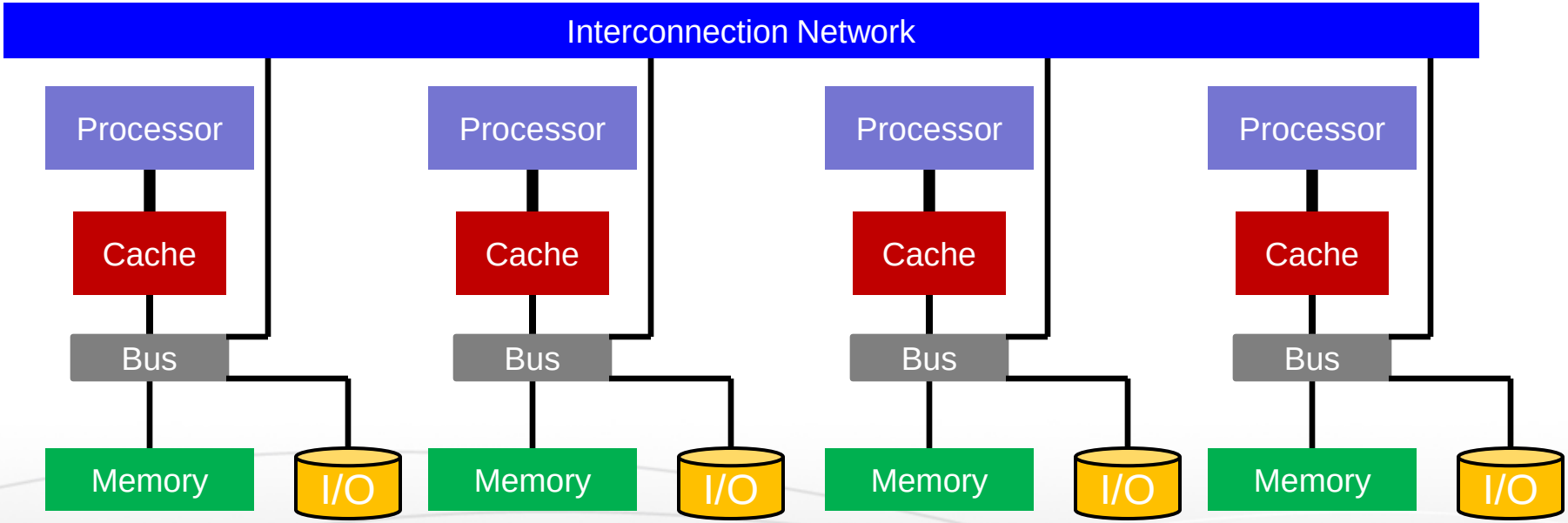
- Symmetric Multiprocessor (SMP) architecture uses shared system resources that can be accessed equally from all processors



- A single OS controls the SMP machine and it schedules processes and threads on processors so that the load is balanced

Massively Parallel Processors

- Massively Parallel Processors (MPP) architecture consists of nodes with each having its own processor, memory and I/O subsystem



- An independent OS runs at each node

Non-Uniform Memory Access

- Non-Uniform Memory Access (NUMA) architecture machines are built on a similar hardware model as MPP
- NUMA typically provides a shared address space to applications using a hardware/software directory-based coherence protocol
- The memory latency varies according to whether you access memory directly (local) or through the interconnect (remote). Thus the name non-uniform memory access
- As in an SMP machine, a single OS controls the whole system

Objectives

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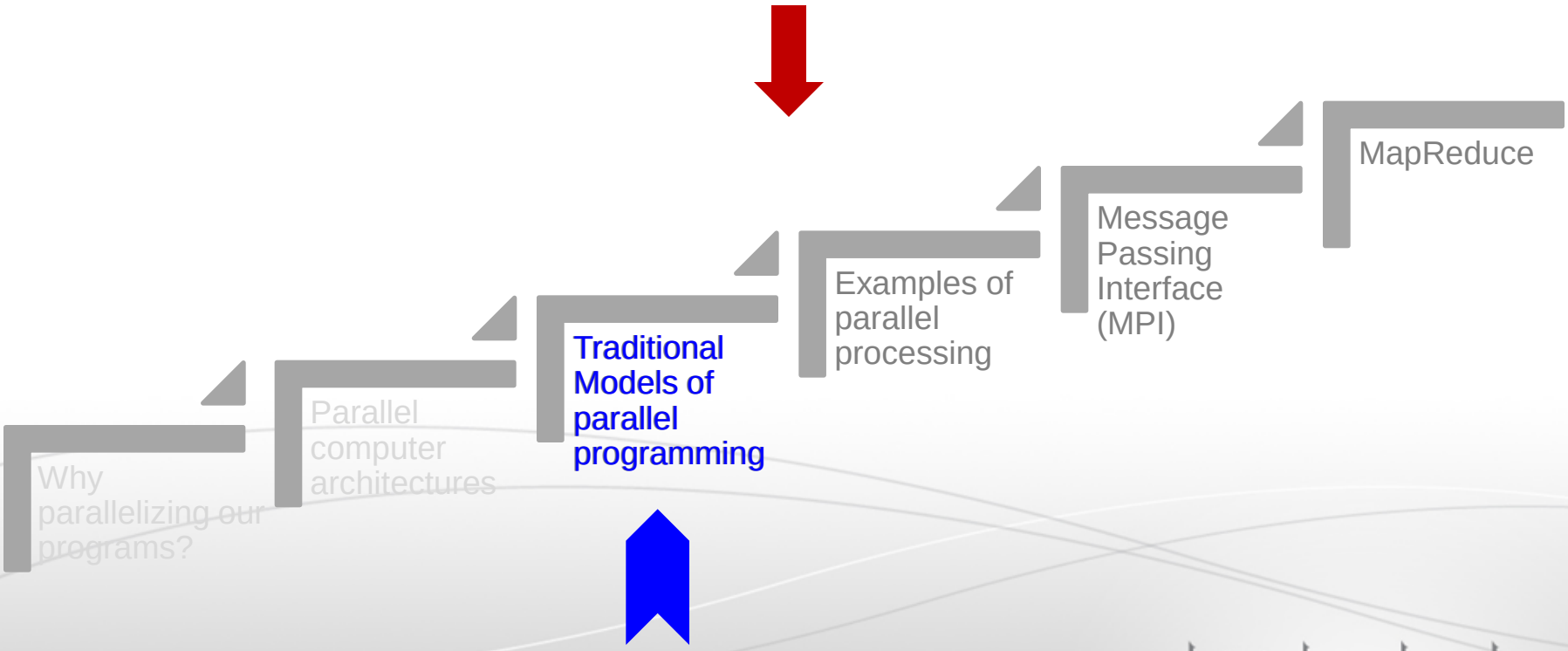
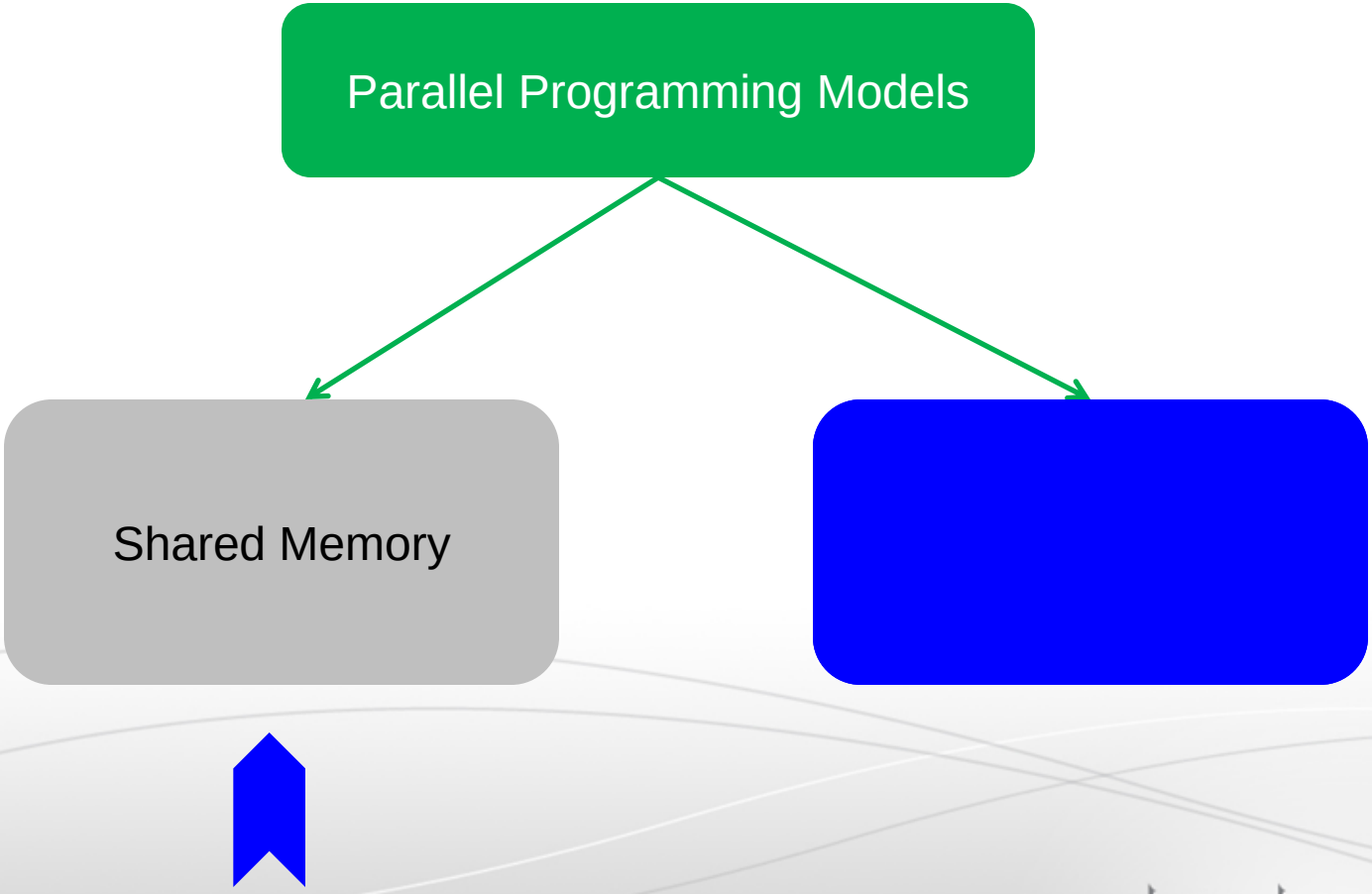


Models of Parallel Programming

- What is a parallel programming model?
  - A programming model is an abstraction provided by the hardware to programmers
  - It determines how easily programmers can specify their algorithms into parallel unit of computations (i.e., tasks) that the hardware understands
  - It determines how efficiently parallel tasks can be executed on the hardware
- Main Goal: utilize all the processors of the underlying architecture (e.g., SMP, MPP, NUMA) and minimize the elapsed time of your program

Traditional Parallel Programming Models

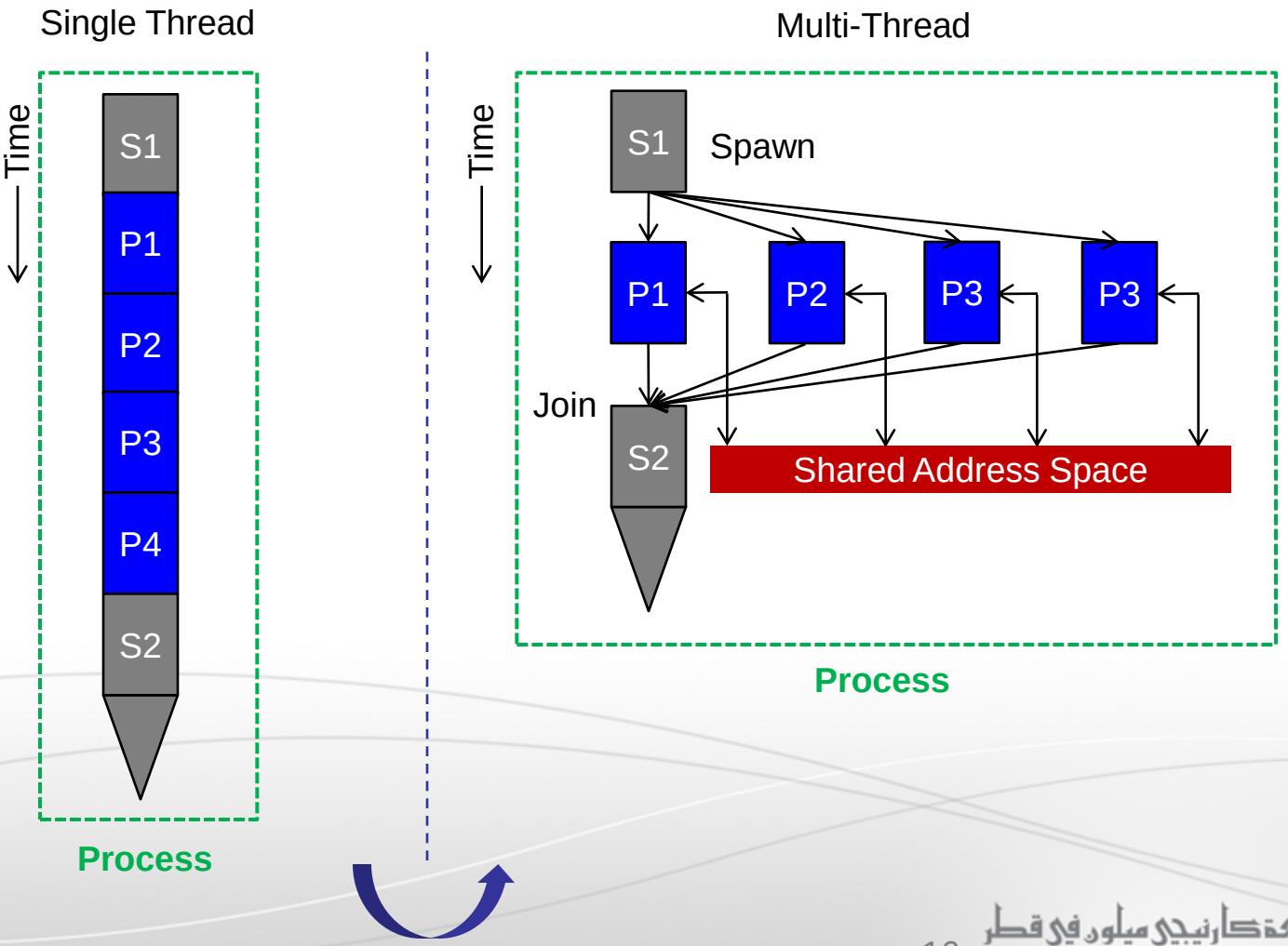


Shared Memory Model

- In the shared memory programming model, the abstraction is that parallel tasks can access any location of the memory
- Parallel tasks can communicate through reading and writing common memory locations
- This is similar to threads from a single process which share a single address space
- Multi-threaded programs (e.g., OpenMP programs) are the best fit with shared memory programming model

Shared Memory Model

S_i = *Serial*
P_j = *Parallel*



Shared Memory Example

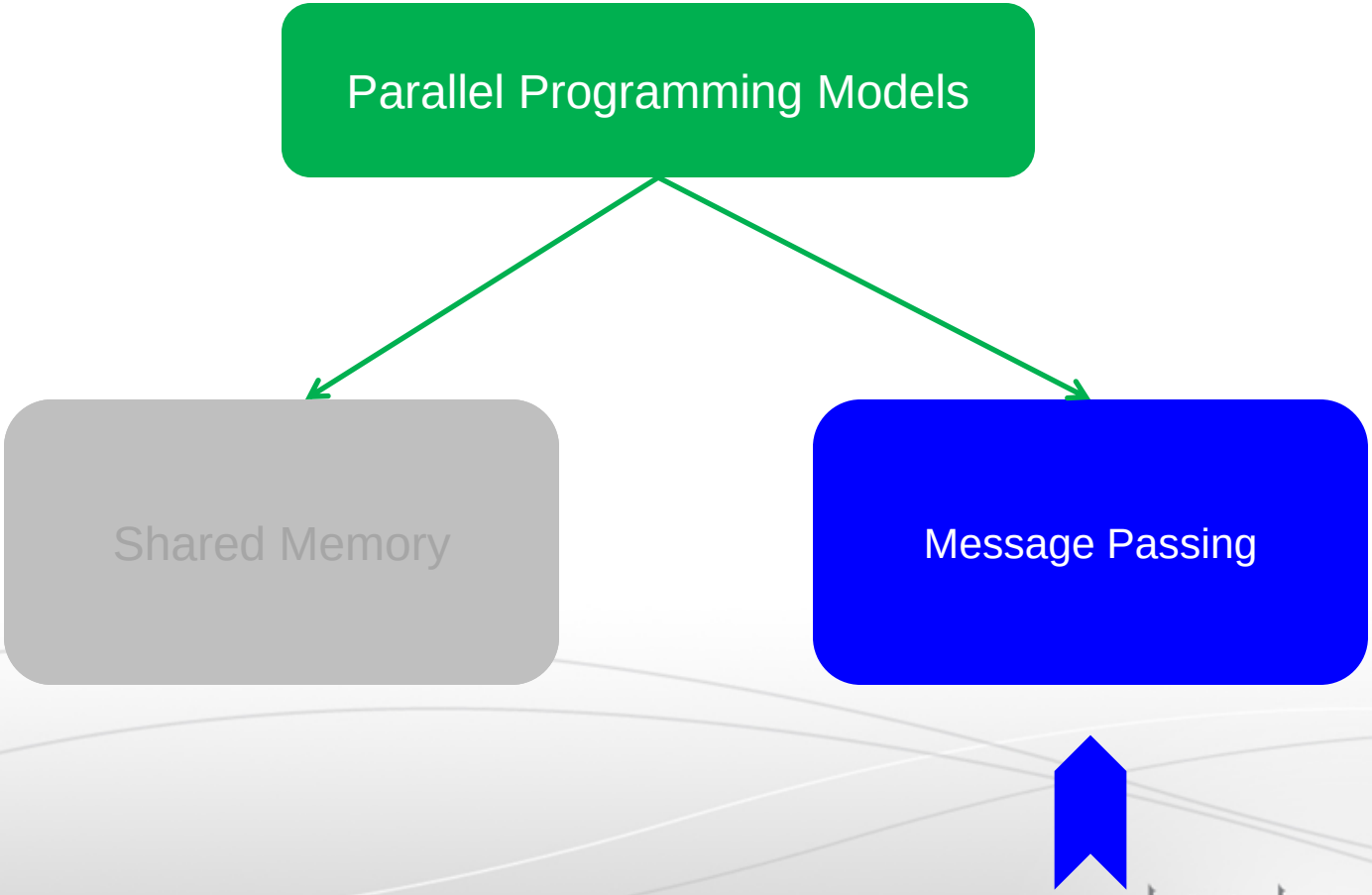
```
for (i=0; i<8; i++)
  a[i] = b[i] + c[i];
sum = 0;
for (i=0; i<8; i++)
  if (a[i] > 0)
    sum = sum + a[i];
Print sum;
```

Sequential

```
begin parallel // spawn a child thread
private int start_iter, end_iter, i;
shared int local_iter=4, sum=0;
shared double sum=0.0, a[], b[], c[];
shared lock_type mylock;

start_iter = getid() * local_iter;
end_iter = start_iter + local_iter;
for (i=start_iter; i<end_iter; i++)
  a[i] = b[i] + c[i];
barrier;

for (i=start_iter; i<end_iter; i++)
  if (a[i] > 0) {
    lock(mylock);
      sum = sum + a[i];
    unlock(mylock);
  }
barrier;     // necessary

end parallel // kill the child thread
Print sum;
```

Parallel

Traditional Parallel Programming Models

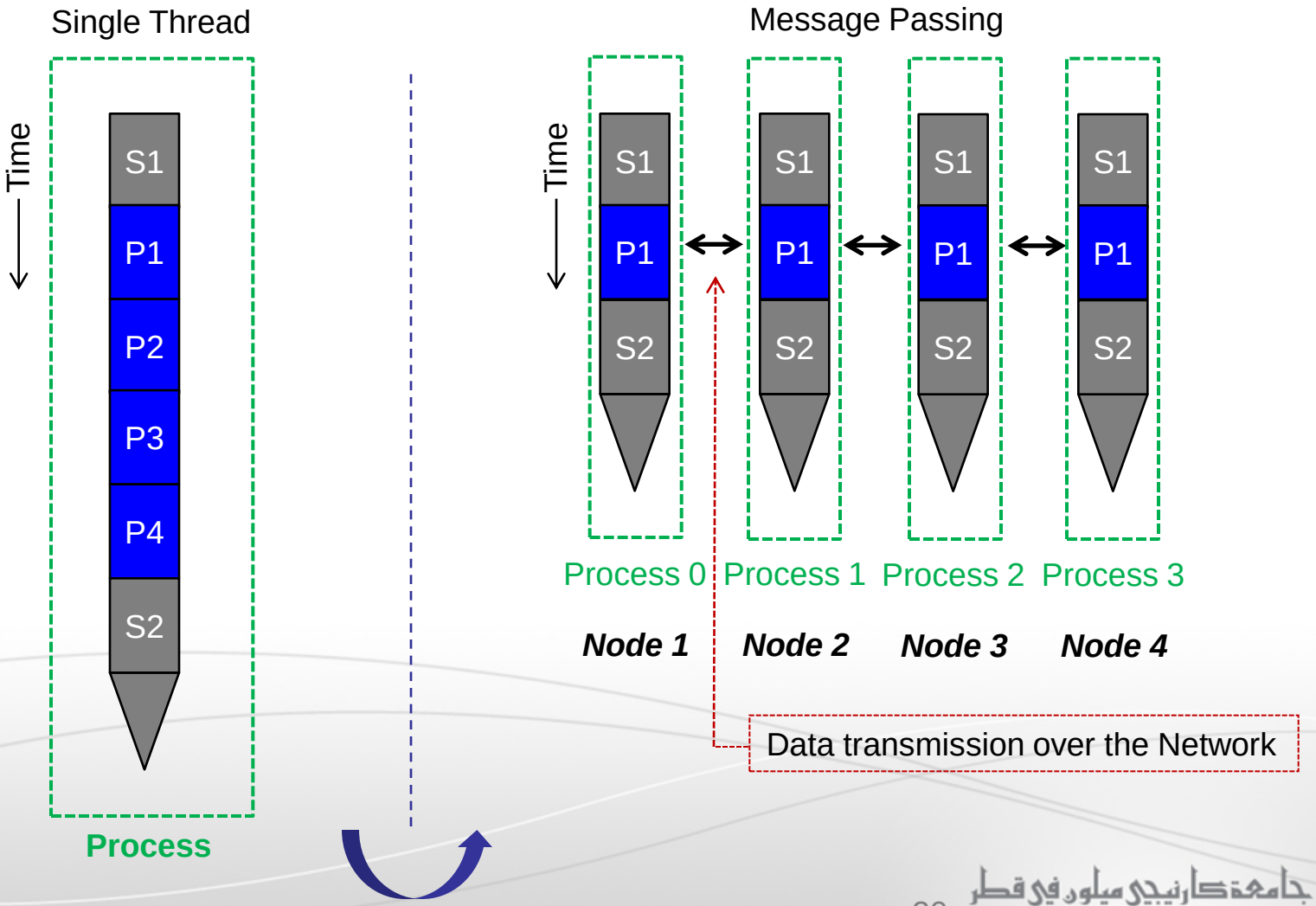


Message Passing Model

- In message passing, parallel tasks have their own local memories
- One task cannot access another task's memory
- Hence, to communicate data they have to rely on explicit messages sent to each other
- This is similar to the abstraction of processes which do not share an address space
- MPI programs are the best fit with message passing programming model

Message Passing Model

S = Serial
P = Parallel



Message Passing Example

```
for (i=0; i<8; i++)
  a[i] = b[i] + c[i];
sum = 0;
for (i=0; i<8; i++)
  if (a[i] > 0)
    sum = sum + a[i];
Print sum;
```

Sequential

```
id = getpid();
local_iter = 4;
start_iter = id * local_iter;
end_iter = start_iter + local_iter;

if (id == 0)
  send_msg (P1, b[4..7], c[4..7]);
else
  recv_msg (P0, b[4..7], c[4..7]);

for (i=start_iter; i<end_iter; i++)
  a[i] = b[i] + c[i];

local_sum = 0;
for (i=start_iter; i<end_iter; i++)
  if (a[i] > 0)
    local_sum = local_sum + a[i];
if (id == 0) {
  recv_msg (P1, &local_sum1);
  sum = local_sum + local_sum1;
  Print sum;
}
else
  send_msg (P0, local_sum);
```

Parallel

Shared Memory Vs. Message Passing

- Comparison between shared memory and message passing programming models:

Aspect	Shared Memory	Message Passing
Communication	Implicit (via loads/stores)	Explicit Messages
Synchronization	Explicit	Implicit (Via Messages)
Hardware Support	Typically Required	None
Development Effort	Lower	Higher
Tuning Effort	Higher	Lower

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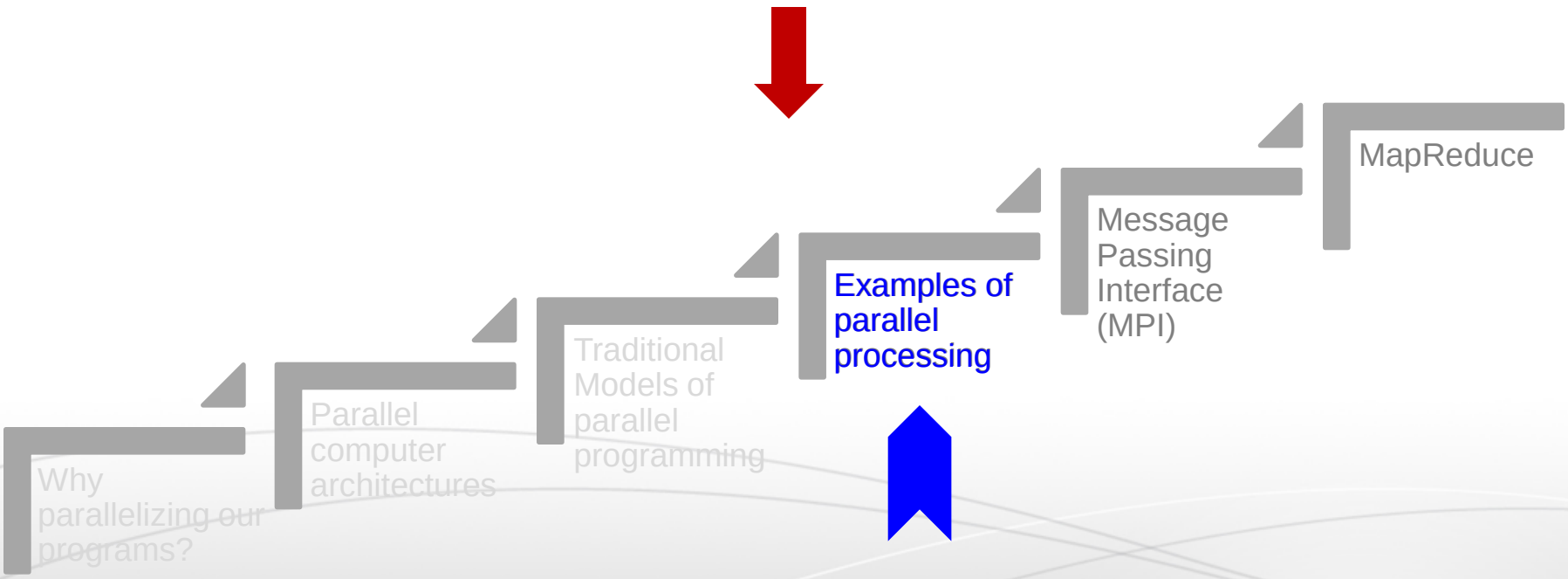


SPMD and MPMD

- When we run multiple processes with message-passing, there are further categorizations regarding how many *different* programs are cooperating in parallel execution

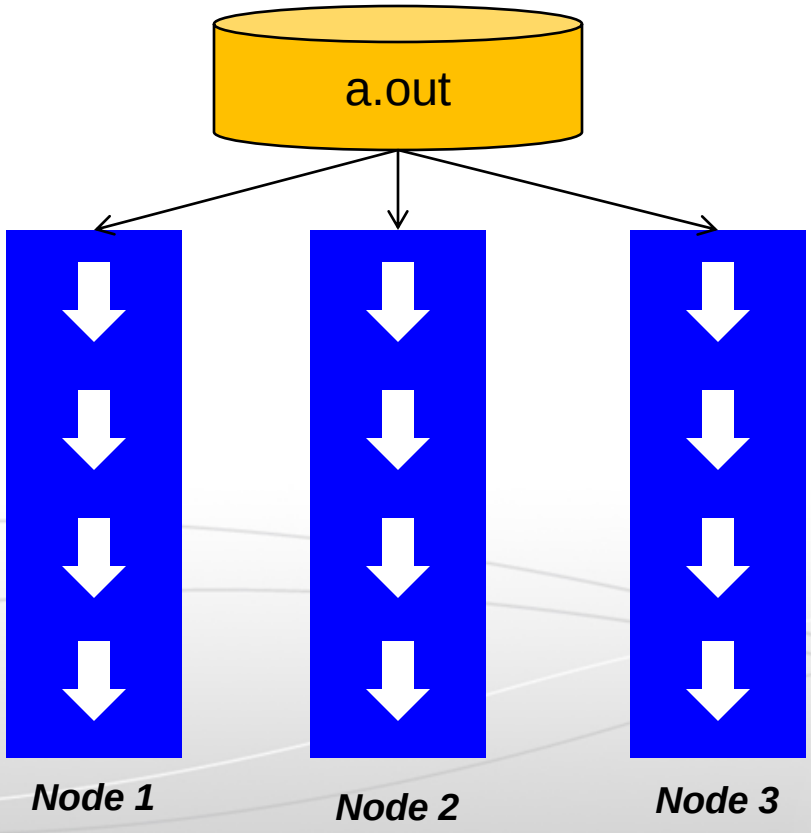
- We distinguish between two models:

  1. Single Program Multiple Data (**SPMD**) model

  2. Multiple Programs Multiple Data (**MPMP**) model

SPMD

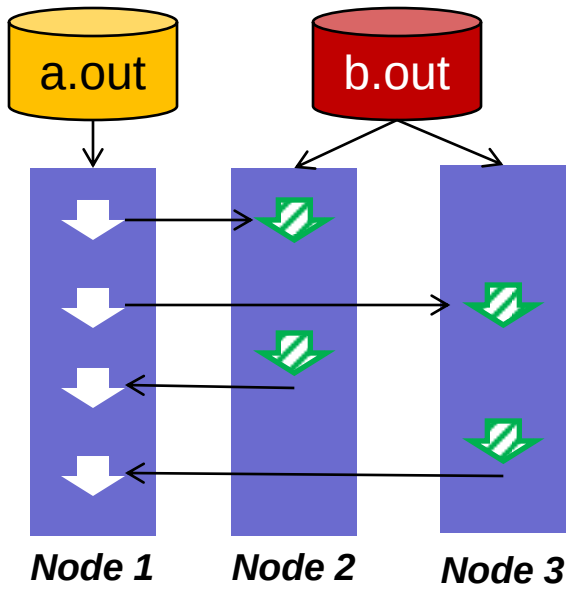
- In the SPMD model, there is only one program and each process uses the same executable working on different sets of data

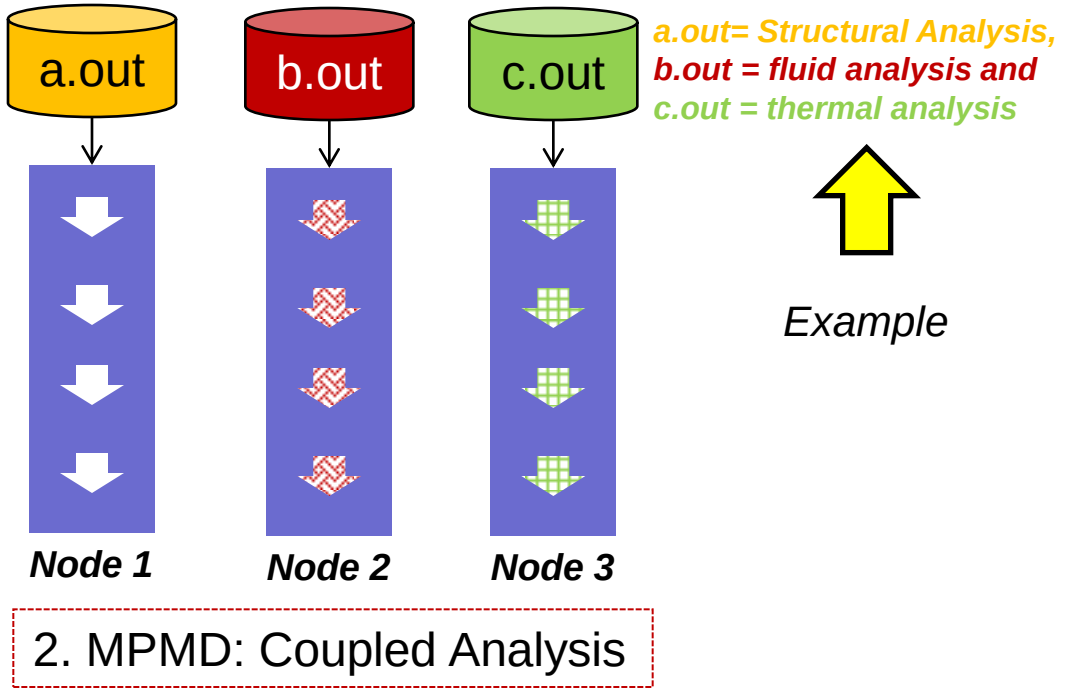


MPMD

- The MPMD model uses different programs for different processes, but the processes collaborate to solve the same problem

- MPMD has two styles, the *master/worker* and the *coupled analysis*





3 Key Points

- To summarize, keep the following 3 points in mind:
  - The purpose of parallelization is to reduce the time spent for computation
  - Ideally, the parallel program is *p* times faster than the sequential program, where *p* is the number of processes involved in the parallel execution, *but this is not always achievable*
  - Message-passing is the tool to consolidate what parallelization has separated. It should not be regarded as the parallelization itself

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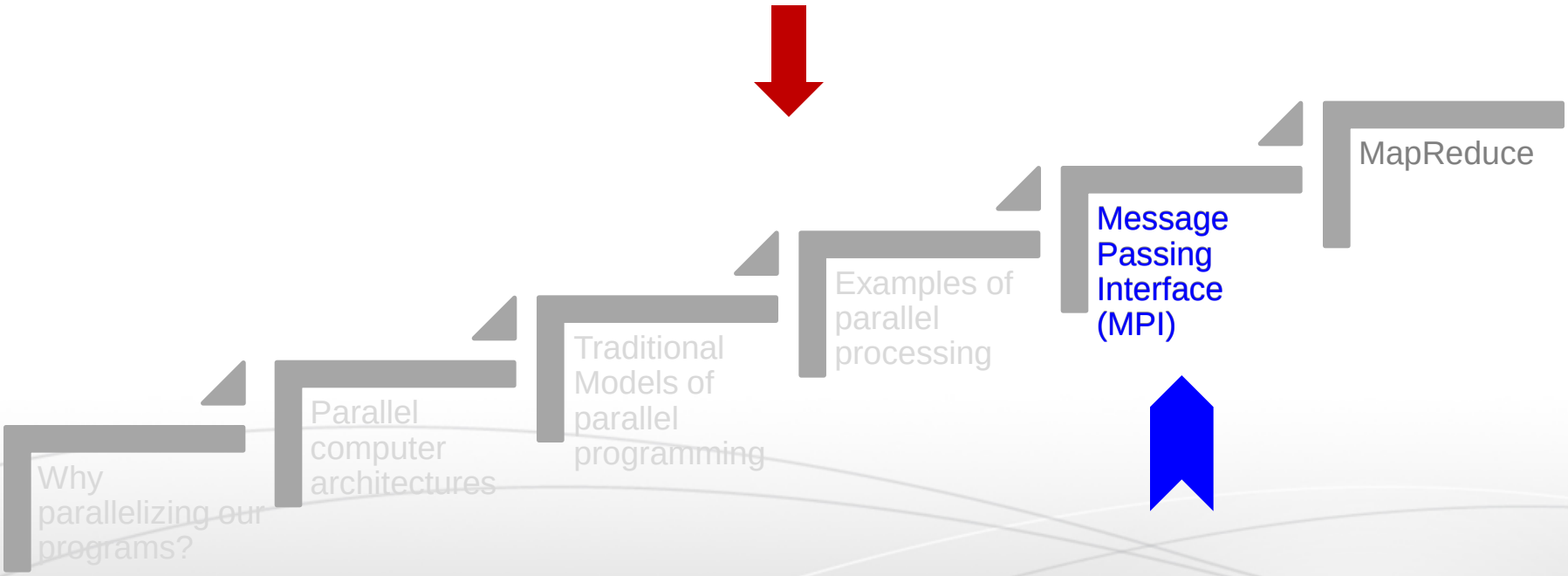


Message Passing Interface

- In this part, the following concepts of MPI will be described:
  - Basics
  - Point-to-point communication
  - Collective communication

What is MPI?

- The Message Passing Interface (MPI) is a message passing library standard for writing message passing programs
- The goal of MPI is to establish a *portable*, *efficient*, and *flexible* standard for message passing
- By itself, MPI is NOT a library - but rather the specification of what such a library should be
- MPI is not an IEEE or ISO standard, but has in fact, become the *industry standard* for writing message passing programs on HPC platforms

Reasons for using MPI

Reason	Description
Standardization	MPI is the only message passing library which can be considered a standard. It is supported on virtually all HPC platforms
Portability	There is no need to modify your source code when you port your application to a different platform that supports the MPI standard
Performance Opportunities	Vendor implementations should be able to exploit native hardware features to optimize performance
Functionality	Over 115 routines are defined
Availability	A variety of implementations are available, both vendor and public domain

Programming Model

- MPI is an example of a message passing programming model
- MPI is now used on just about any common parallel architecture including MPP, SMP clusters, workstation clusters and heterogeneous networks
- With MPI the programmer is responsible for correctly identifying parallelism and implementing parallel algorithms using MPI constructs

Communicators and Groups

- MPI uses objects called *communicators and groups* to define which collection of processes may communicate with each other to solve a certain problem

- Most MPI routines require you to specify a communicator as an argument

- The communicator **MPI_COMM_WORLD** is often used in calling communication subroutines

- MPI_COMM_WORLD is the predefined communicator that includes *all* of your MPI processes

Ranks

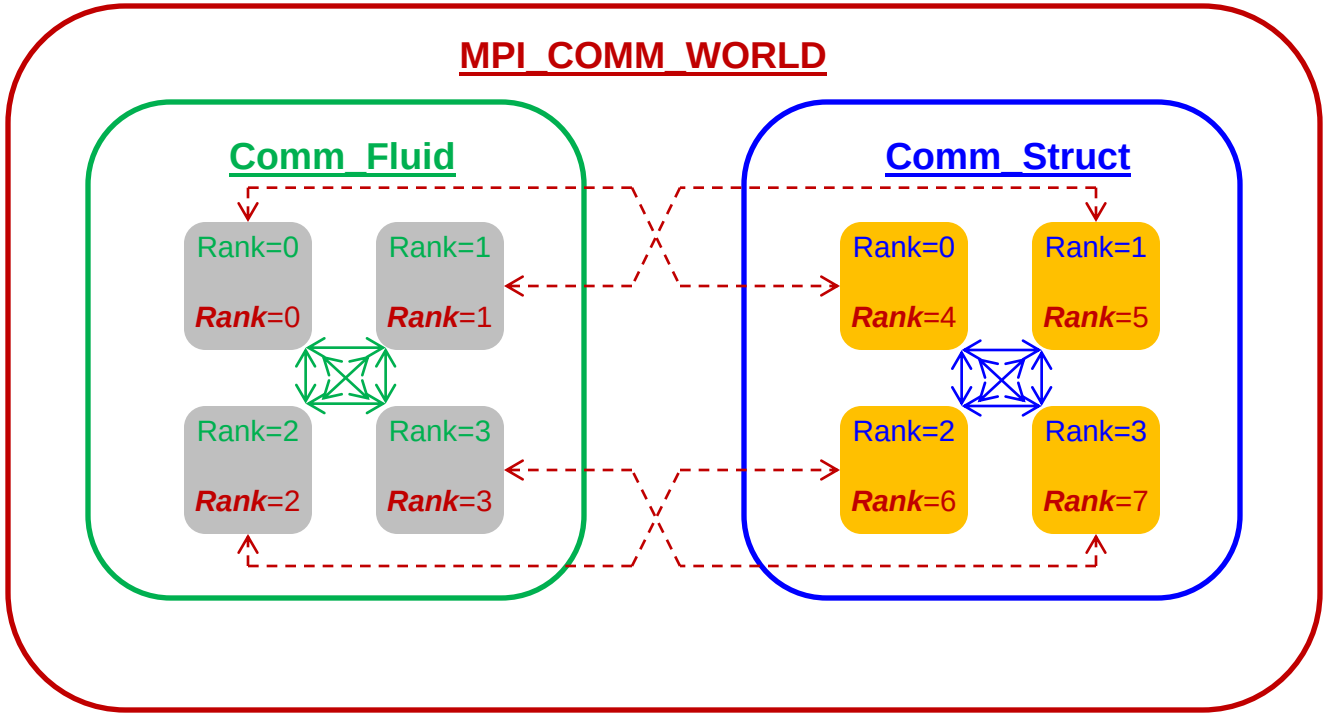
- Within a communicator, every process has its own unique, integer identifier referred to as *rank*, assigned by the system when the process initializes
- A rank is sometimes called a *task ID*. Ranks are contiguous and begin at *zero*
- Ranks are used by the programmer to specify the source and destination of messages
- Ranks are often also used conditionally by the application to control program execution (e.g., *if rank=0 do this / if rank=1 do that*)

Multiple Communicators

- It is possible that a problem consists of several sub-problems where each can be solved concurrently
- This type of application is typically found in the category of MPMD coupled analysis
- We can create a new communicator for each sub-problem as a subset of an existing communicator
- MPI allows you to achieve that by using **MPI_COMM_SPLIT**

Example of Multiple Communicators

- Consider a problem with a fluid dynamics part and a structural analysis part, where each part can be computed in parallel



- ✓ Ranks within MPI_COMM_WORLD are printed in red
- ✓ Ranks within Comm_Fluid are printed with green
- ✓ Ranks within Comm_Struct are printed with blue