Summer School on PARALLEL COMPUTING

Introduction to Parallel Programming

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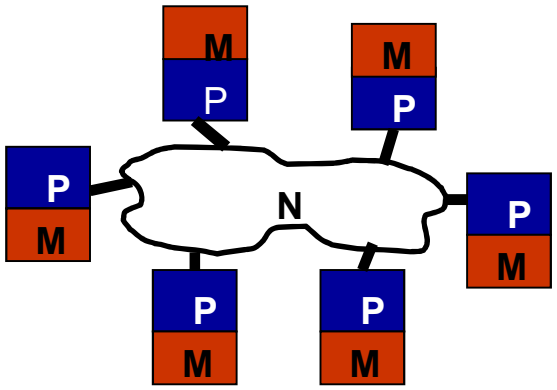
Outline

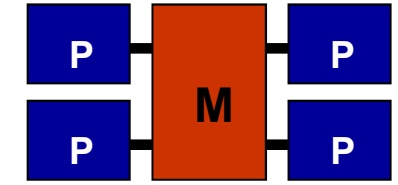
Parallel programming
Shared memory paradigm
Distributed memory paradigm
Processes and Threads
Local or Global Addressing
SPMD Philosophy
Models of parallelism
    Data parallelism
    Control parallelism
Load balancing
Critical sections and Mutual exclusion
Deadlock

Parallel computers

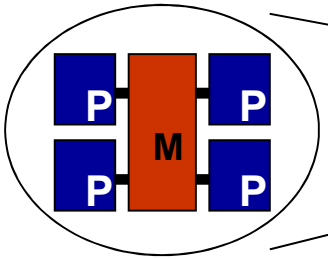
A **parallel computer** is a system consisting of a collection of processors able to communicate and cooperate to solve large computational problems quickly.

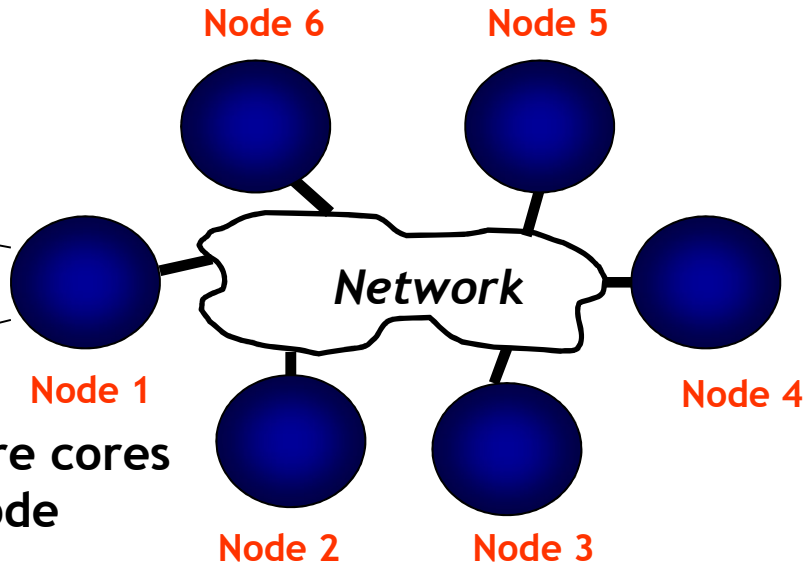


Distribuited Memory System



Shared Memory System





Distributed Memory system with more cores sharing the memory of the single node

Parallel Programming

Parallel programming is a programming technique that involves the use of multiple processors working together on a single problem

The global problem is split in different sub-problems, each of which is performed by a different processor in parallel.

Parallel Program
program composed from different **tasks** that communicate with each other to achieve an overall computational target.

To realize and execute a parallel program is requires:

- A programming language that allows to formally describe non-sequential algorithms
- A non-sequential computer able to perform any number of tasks simultaneously.

Parallel Programming paradigms

A **programming model** is a collection of program abstractions that provides a simplified and transparent vision of the hardware and software system in its entirety.

Communication in a parallel computer is possible according to these patterns:

- **Shared memory**: by accessing shared variables
- **Message-passing**: exchanging messages

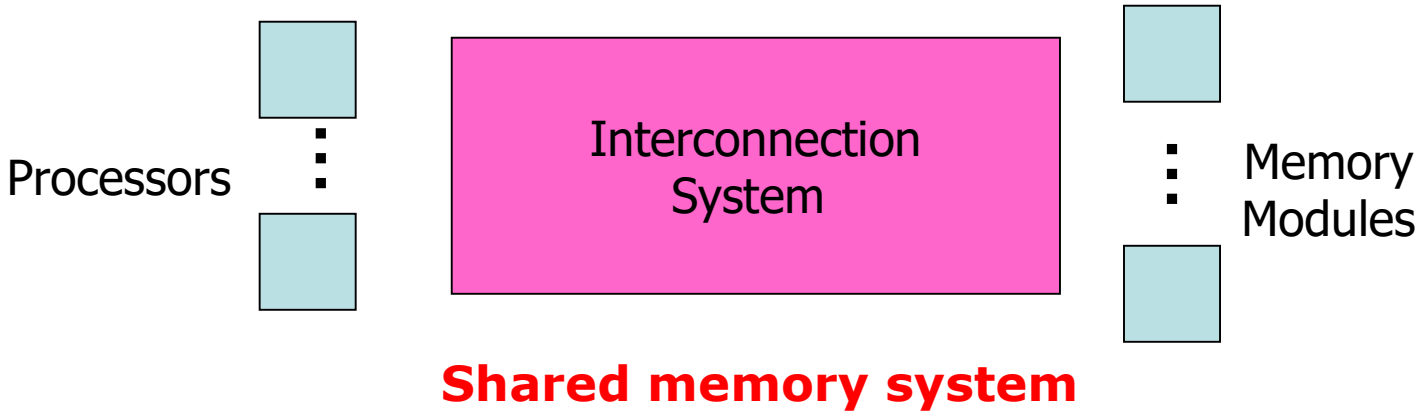
These patterns identify two parallel programming paradigms:

- **Shared memory** or global environment paradigm
  where processes interact exclusively working on common resources

- **Message passing** or local environment paradigm
  where there are no shared resources, processes handle only local information and the only way to interact is by exchange of messages (message passing)

Shared Memory Paradigm

Processes communicate by accessing shared variables and shared data structures.



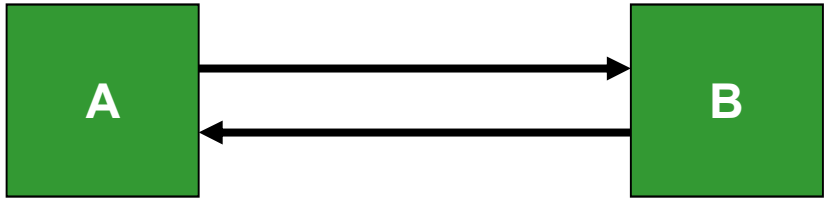
Shared memory system

Basic shared memory primitives:

- Read from a shared variable
- Write on a shared variable

Message Passing Paradigm

Tasks communicate by exchanging messages



Basic message passing Primitives:

- Send (*parameter list*)
- Receive (*parameter list*)

What is a Process

Algorithm

identify the sequence of logical steps that must be followed to solve a given problem.

Program

implementation of the algorithm, by means of a suitable formalism (programming language) so that it can be executed on a specific computer.

Sequential process

sequence of events (execution of operations) which gives place the computer when operates under the control of a particular program.
Abstract entity which identifies the activity of the computer on the program execution.

Process

A process is created by the operating system, and requires a fair amount of "overhead".

Processes contain information about program resources and program execution state, including:

- Process ID, process group ID, user ID, and group ID
- Environment
- Working directory.
- Program instructions
- Registers
- Stack
- Heap
- File descriptors
- Signal actions
- Shared libraries
- Inter-process communication tools
  (such as message queues, pipes, semaphores, or shared memory).

Thread

A thread is defined as an **independent stream of instructions** that can be scheduled to run as such by the operating system.

Threads

- exist within the process and use the process resources
- are able to be scheduled by the operating system
- run as independent entities
- they duplicate only the bare essential resources that enable them to exist as executable code.

This independent flow of control is accomplished because a thread maintains its own:

- Stack pointer
- Registers
- Scheduling properties (such as policy or priority)
- Set of pending and blocked signals
- Thread specific data.

Thread /1

Threads may share the process resources with other threads that act equally Independently

Reading and writing to the same memory locations is possible, and therefore requires explicit synchronization by the programmer.

Thread die if the parent process dies

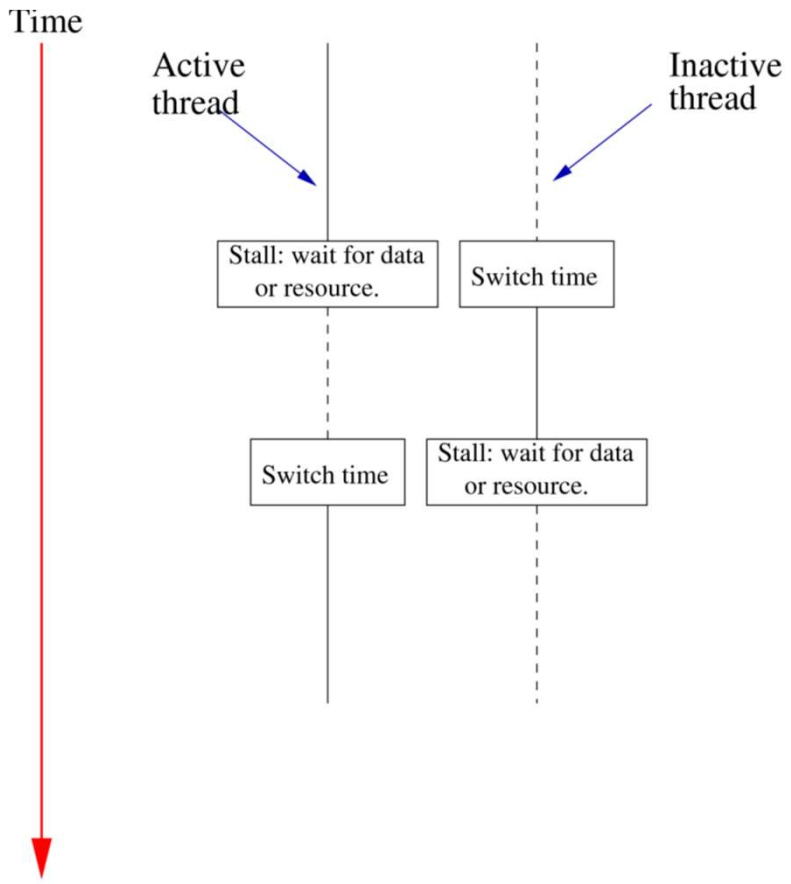
Thread Iis "lightweight" because most of the overhead has already been accomplished through the creation of its process.

Multi-threading

Available in almost all main processor families.

Specific hardware support on some processors

However, care must be taken in using **automatic multi-threading**: can, in some case, slow down applications.



Toward a parallel algorithm

Bubble Sort

Input: a sequence of **n** numbers $\langle a_1, a_2, a_3, \ldots a_n \rangle$

Output: a permutation $\langle a'_1, a'_2, a'_3, \ldots a'_n \rangle$ of the elements such that $a'_1 \leq a'_2, \leq a'_3 \leq \ldots \leq a'_n$

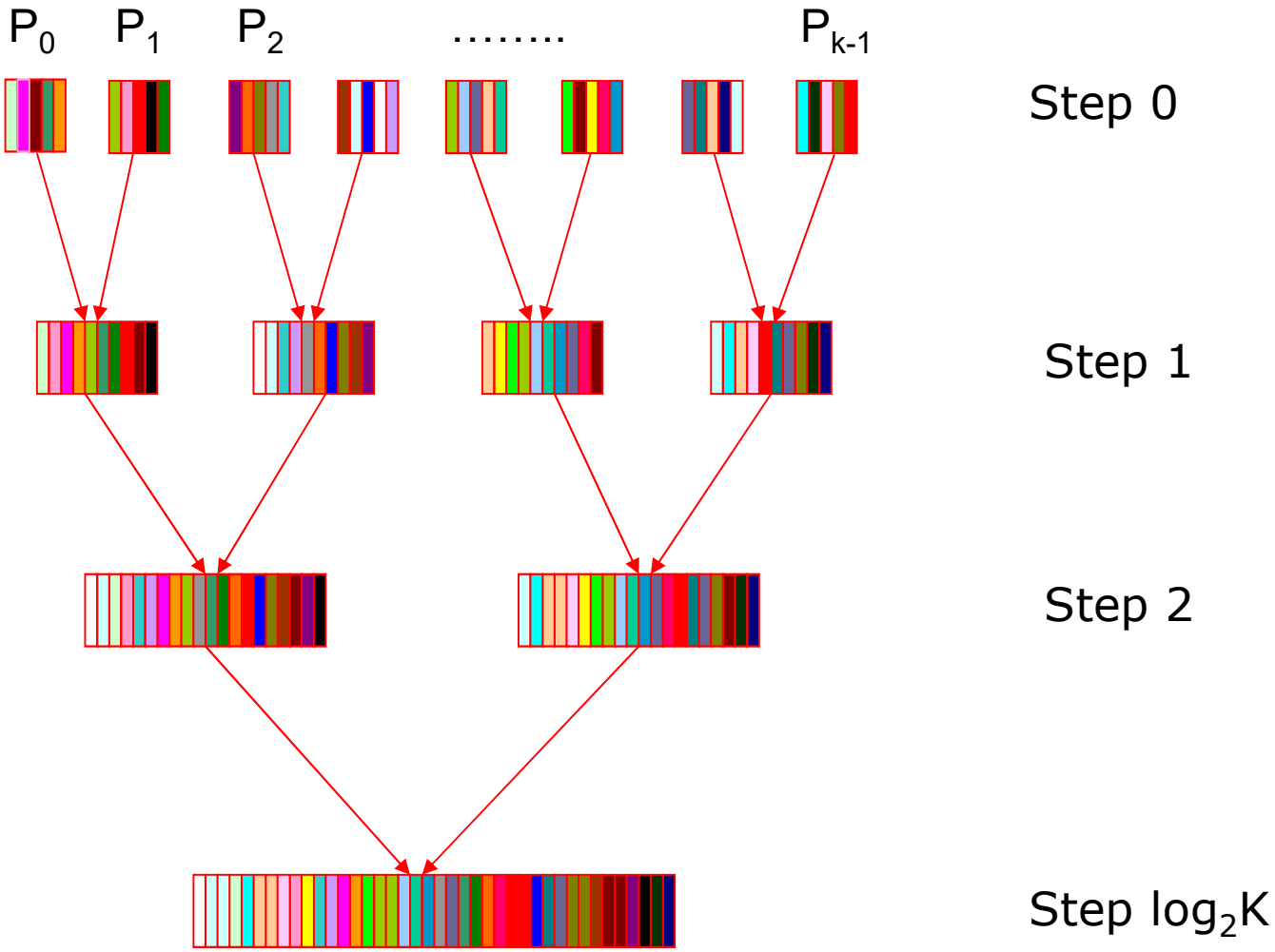
```
/* Bubble sort for integers */
#define SWAP(a,b) { int t; t=a; a=b; b=t; }

void SORT( int a[], int n )
/* Pre-condition: a contains n items to be sorted */
     {
     int i, j;
     /* Make n passes through the array */
     for(i=0;i<n;i++)
          {
          /* From the first element to the end of the unsorted section */
          for(j=1;j<(n-i);j++)
               {
               /* If adjacent items are out of order, swap them */
               if( a[j-1]>a[j] ) SWAP(a[j-1],a[j]);
               }
          }
     }
```

Sort of n numbers

Idea:
- Split the array to sort into two array of n / 2 elements each,
- Order the two array separately
- Merge the two ordered arrays to reconstruct the whole array

```
SORT(a[0 : n/2-1])
SORT(a[n/2 : n-1])
MERGE(a[0 : n/2-1], a[n/2 : n-1])
```

Sort on k Processors



Problem

```
Read the data to sort
   SORT(a[0 : n/2-1])
   SORT(a[n/2 : n-1])
   MERGE(a[0 : n/2-1], a[n/2 : n-1])
Print the ordered array
```

Parallel programming requires to address problems that do not occur with sequential programming.
We need to decide:

- what are the parts of the code which form the parallel sections
- when to start the execution of different parallel sections
- when to end the execution of parallel sections
- when and how to make the communication between the parallel entities
- when make the synchronization between the parallel entities

Then we need the right tools to implement all this

Local or Global addressing

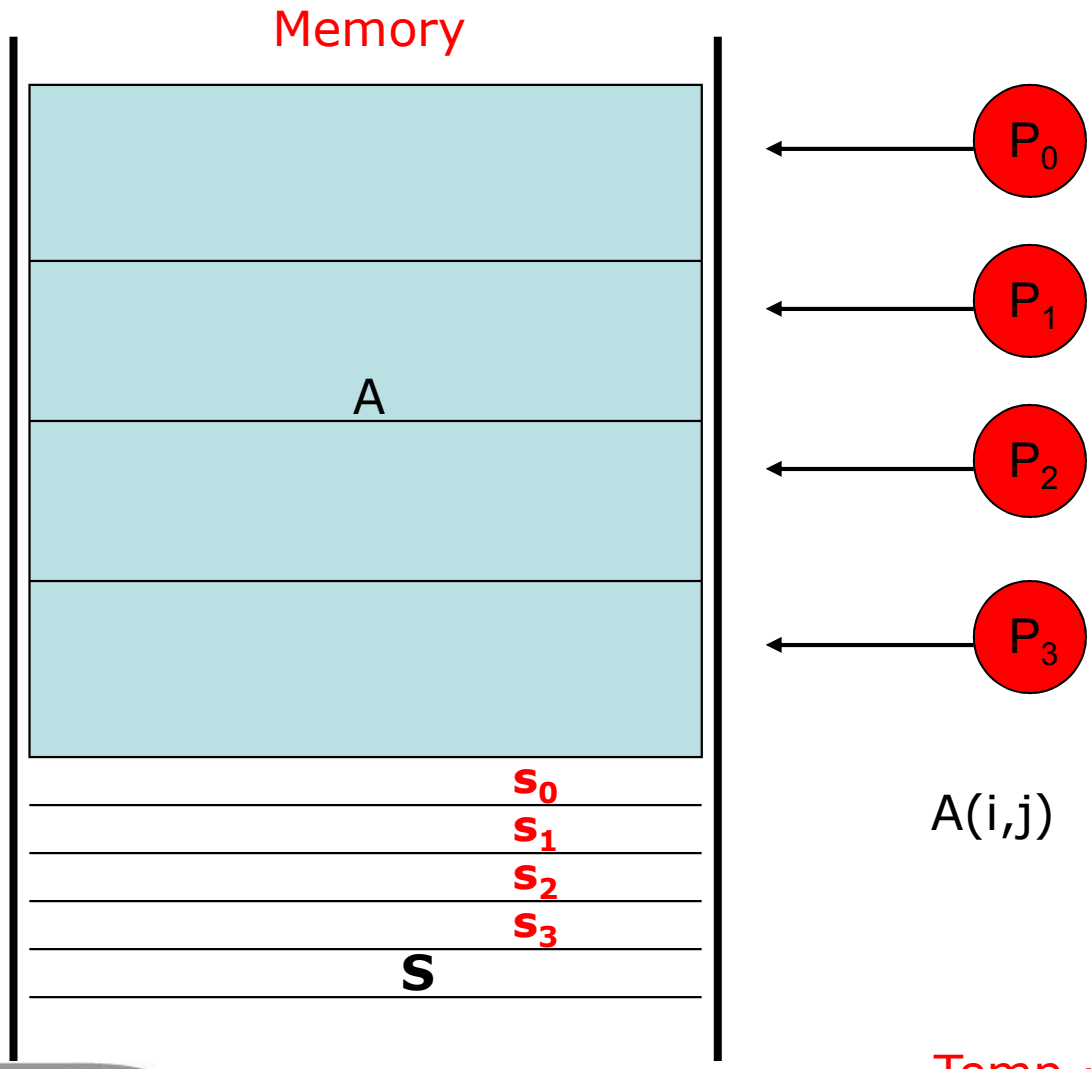
With the shared memory paradigm we rely on the global memory addressing

With the distributed memory paradigm we rely only on local memories and so we can only handle a local address space.

Example: Compute the sum of the elements of array **A[n, n]**

$$S = \sum_i \sum_j a_{ij}$$

Global Addressing



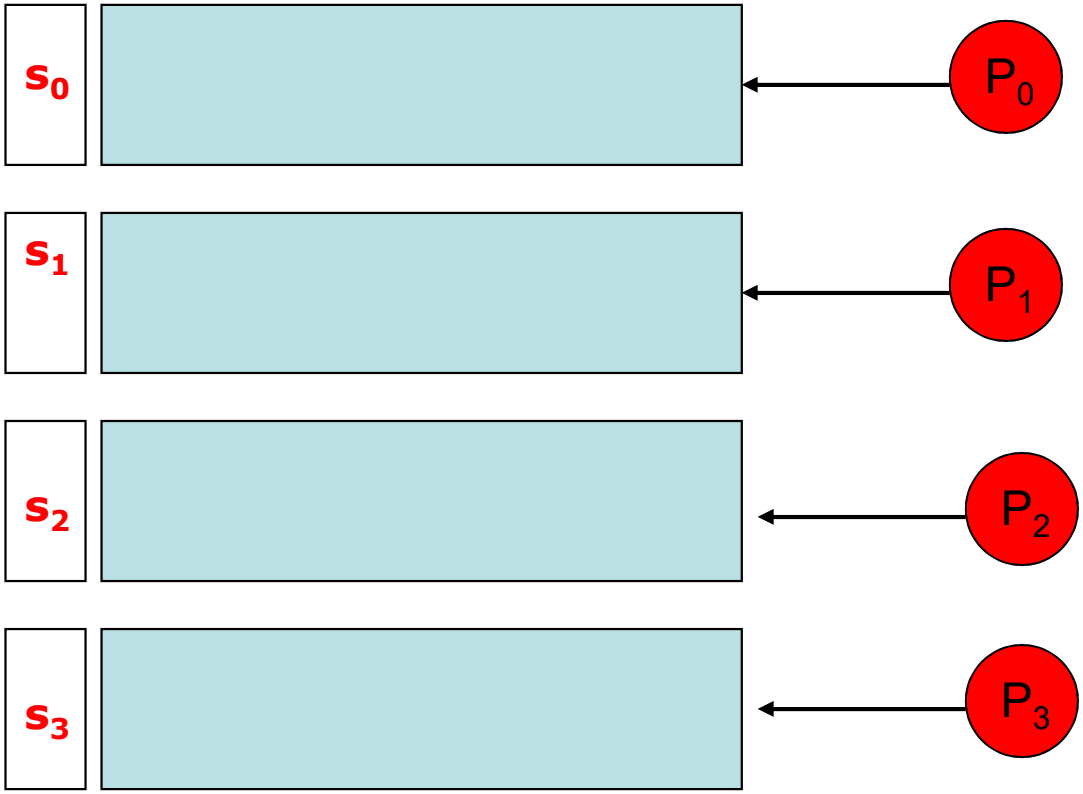
Array **A[n, n]** is allocated in the shared memory.

All the processors involved in the computation can reference any element of **A**.

A(i,j) i = 1, n, j = 1,m

Temp = A(857,760) + A(321, 251)

Local Addressing



Each processor can reference only his own local memory.

A slice of **A[n, n]** is allocate in each local memory

A(i,j) i = 1, n/k, j = 1,m

Temp = A(857,760) + A(321, 251) →

→ Temp = A(107,760)P_3 + A(71, 251) P_1

(N = 1000, 4 proc)

Master Slave and SPMD philosophy

Master / Slave

A single process (the master) controls the work done by other processes (slaves, workers).
These can run the same program or different programs

Single Program Multiple Data

Each process runs the same copy of the program
The execution flow of each process varies as a function of the local environment (data, number of process, etc..)
We can emulate the master / slave philosophy

C

```
main (int argc, char **argv)
{
    if (process is to become a controller process)
    {
        Controller (/* Arguments /*);
    }
    else
    {
        Worker (/* Arguments /*);
    }
}
```

Fortran

```
PROGRAM
IF (process is to become a controller process)
THEN
            CALL Controller (/* Arguments /*)
ELSE
            CALL Worker (/* Arguments /*)
ENDIF
END
```

Implementing Parallel Programming Paradigms

- Shared Memory Paradigm (**OpenMP**)
- Message Passing Paradigm (MPI)

Sequential procedural languages (Fortran 90,C,C++) + API (Compiler Directives)
It tends to favor an **implicit parallelism**

- Parallelism is not visible to the programmer
- Compiler responsible for parallelism
- Easy to do
- Small improvements in performance

Sequential procedural languages (Fortran 90, C, C++) + API (Library routines)
Explicit Parallelism

- Parallelism is visible to the programmer
- Difficult to do (right)
- Large improvements in performance

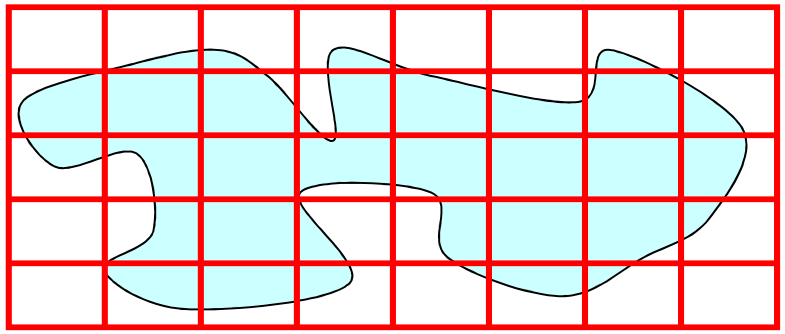
Partitioned Global Address Space (PGAS) models

- PGAS programming models provide a global memory address space allowing ,for example arrays, to be shared across different nodes in a system (like an OpenMP model on a distributed set of nodes).
- Often built with MPI but the APIs are at a higher level, thus programmers do not need to include explicitly commands for message passing, etc. Simplifies parallel programming, particularly for large packages.
- Implementation examples include UPC (Unified Parallel C), Global Arrays and Co-array Fortran.
- Despite "locality awareness" (each node knows which portion of the array is assigned to it) tend to provide lower performances than full MPI implementations. Although a long history, still not widely used.

```
me = ga_nodeid() ! rank of the process
nprocs = ga_nnodes() ! total # of processes

dims = nprocs*nelem
chunk(1) = nelem
ld = nelem

call nga_create(MT_INT, ndim, dims, 'array A', chunk, g_a)
call nga_duplicate(g_a, g_b, 'array B')
```

Models of parallelism

Data Parallelism (domain decomposition)



Data structures partitioned (data parallelism)

- Each process execute the same work on a sub-set of the data structure
- Data placement is critical
- More scalable than functional parallelism

Problem for the boundary management
Load balancing (in some cases)

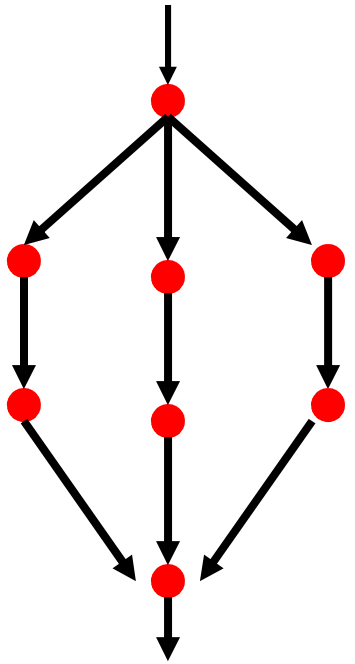
Models of parallelism / 1

Control Parallelism (Functional Parallelism)

- the different functions are distributed

Partitioning by task:

each process executes a different "function": Identify the functions, and then the data requirements



Load balancing

Functional or data Parallelism

Functional or Data Parallelism?

Partition by task (functional parallelism)

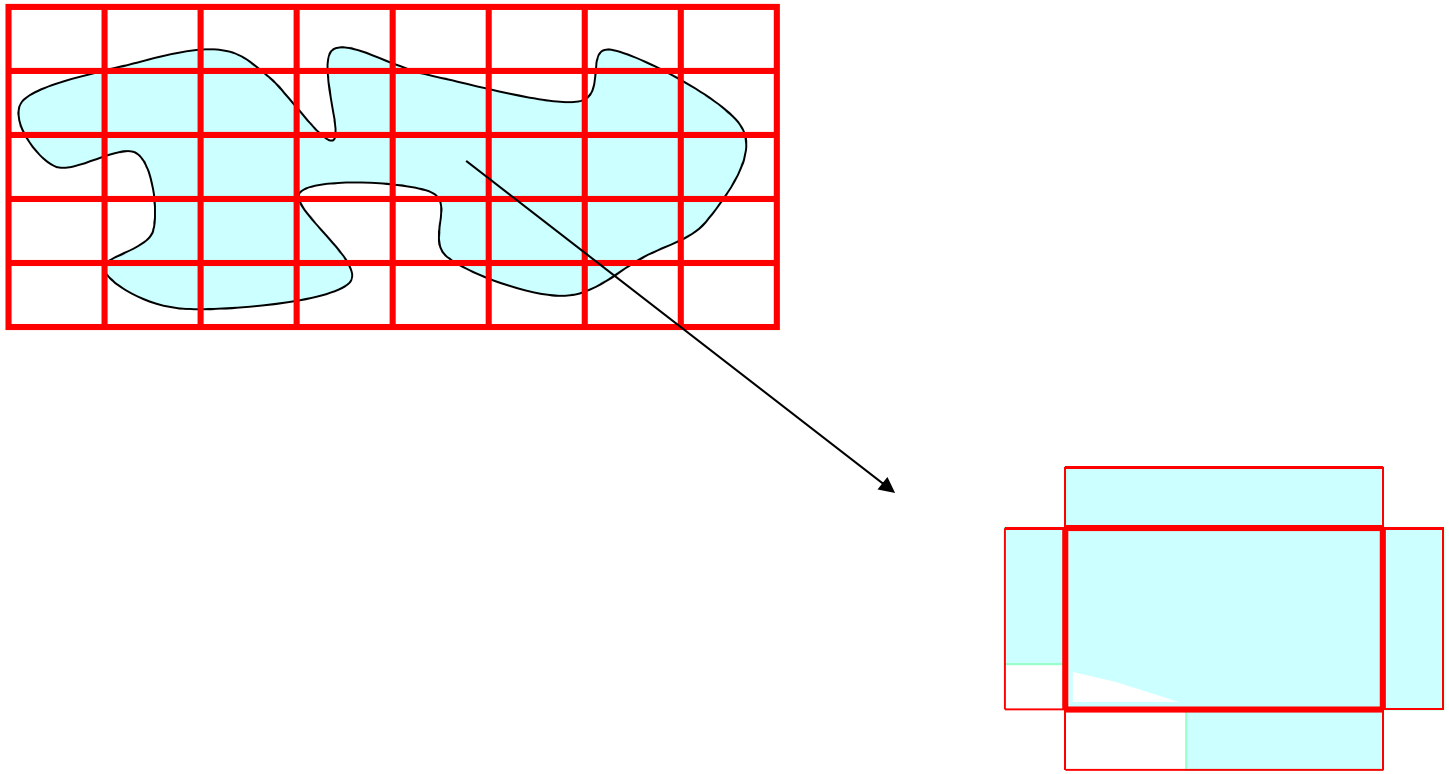
- each process performs a different "function"
- identify functions, then data requirements
- commonly programmed with message-passing

Partition by data (data parallelism)

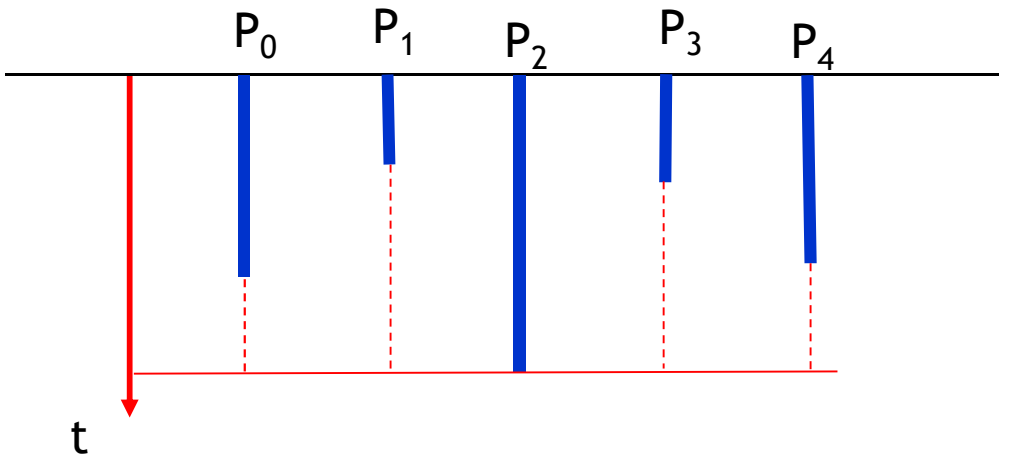
- each process does the same work on a unique piece of data
- data placement is critical
- more scalable than functional parallelism

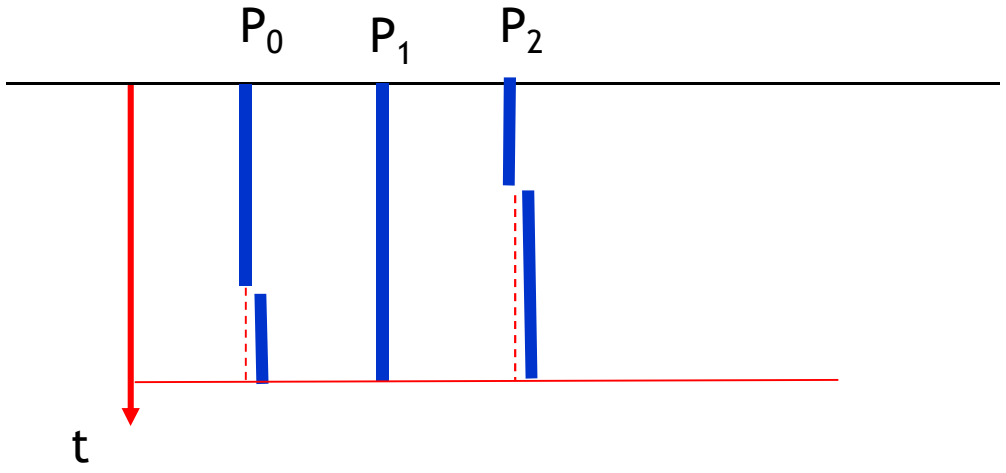
Boundary management

Data Parallelism

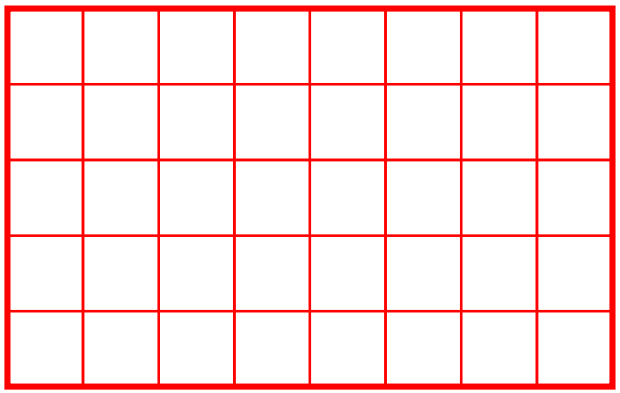


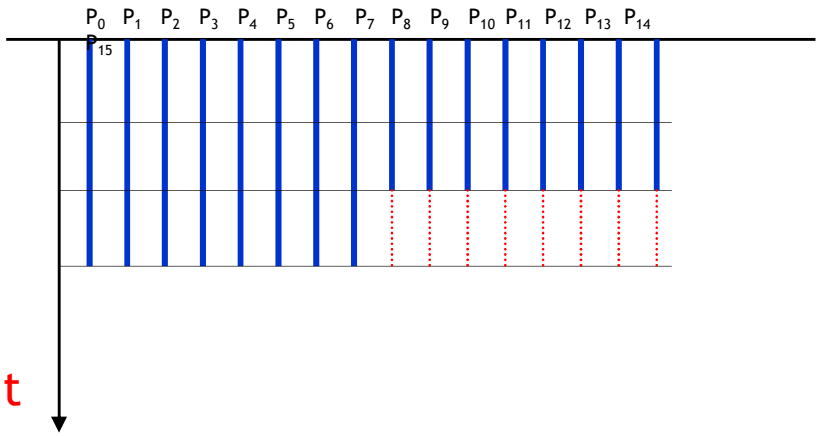
Load Balancing

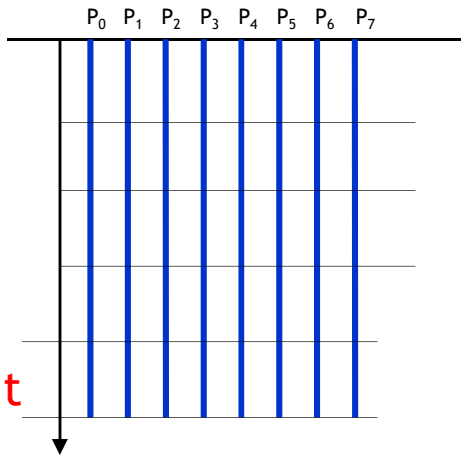




Load balancing /1





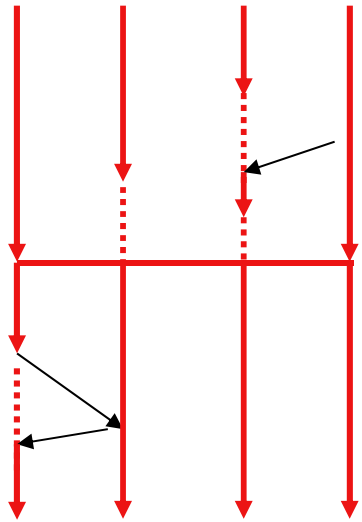


MPI Execution Model

- Single Program Multiple Data

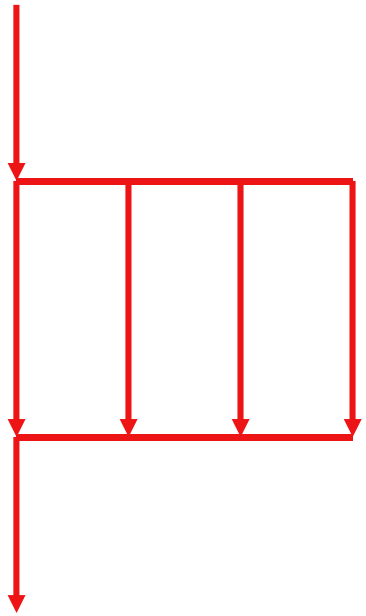
- A copy of the code is executed by each process

- The execution flow is different depending from the context (process id, local data, etc)



OpenMP Execution Model

- A single thread starts execute sequentially
- When a parallel region is reached, several slave threads are forked to run in parallel
- At the end of the parallel region, all the slave threads die
- Only the master thread continues the sequential execution



Notes on Shared Memory model: Access to Shared variables

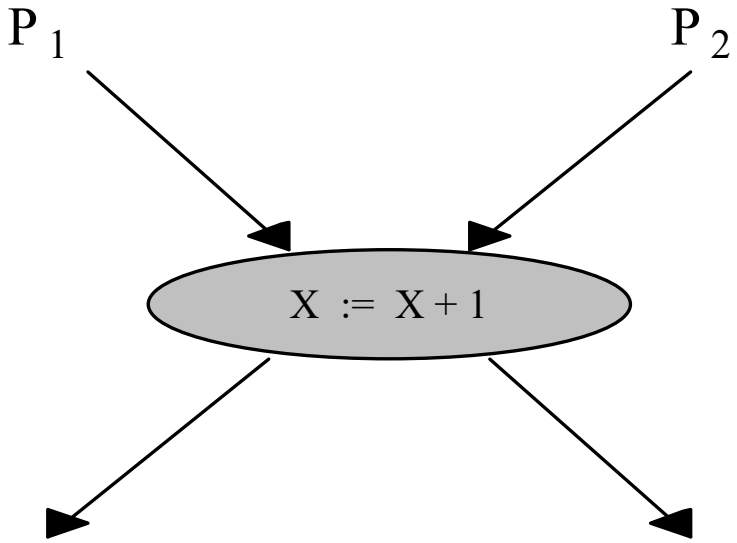
More process can read (load) concurrently the same memory location without any problems.

This operation is well-defined conceptually each process makes a copy of the contents of the memory location and stores it in its own register.

Problems can occur when there is a concurrent access in writing (store) that is when multiple processes simultaneously write to the same memory location.

The programmer, the programming language and the architecture should provide tools to solve the conflicts

Two processes P1 and P2 share a variable x that both must increment



What is the final value of x?

P1 **loads x in a Register(P1)**

P2 **loads x in a Register(P2)**

P1 **increments the value loaded**

P2 **increments the value loaded**

P1 **stores the new value**

P2 **stores the new value**

Notes on Shared Memory model: non determinism

Non-determinism is caused by **race conditions**.
A race condition occurs when two different concurrent tasks access the **same memory location**, at least one of them in writing.

There is not a guaranteed execution order between the accesses.
The access must be **mutually exclusive**
The problem of non-determinism can be solved by synchronizing the use of shared data.

The portions of a parallel program that require synchronization to avoid non-determinism are called **critical sections**. These sections must be executed in a mutual exclusive way

Notes on Shared Memory model: Locks

In shared-memory programming specific constructs are needed to guarantee the execution of critical sections in a mutually exclusive way.

i.e lock (), or higher level constructs, with hardware support

Thread 1:

```
LOCK (X)
        X = X + 1
UNLOCK (X)
```

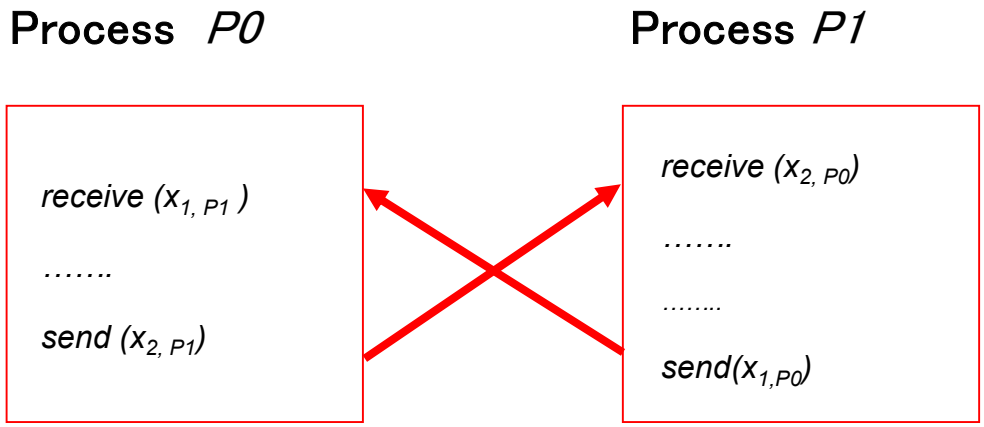
Thread 2:

```
LOCK (X)
        X = X + 2
UNLOCK (X)
```

Notes on message passing model: Deadlock

Situation in which one or more processes remain indefinitely blocked because do not happen the necessary conditions for their continuation

A group of processes are in deadlock when all the processes of the group are waiting for an event (acquisition or release of resources) that can be caused only by one of the waiting processes.



Performance assessment: scalable algorithms

- Generally the choice of algorithm is what has the biggest impact on parallel scalability
- An efficient and scalable algorithm typically has the following characteristics:
  - The work can be separated into numerous tasks that proceed almost totally independently of one another
  - Communication between the tasks is infrequent or unnecessary
  - Lots of computation takes place before messaging or I/O occurs
  - There is little or no need for tasks to communicate globally
  - There are good reasons to initiate as many tasks as possible
  - Tasks retain all the above properties as their numbers grow

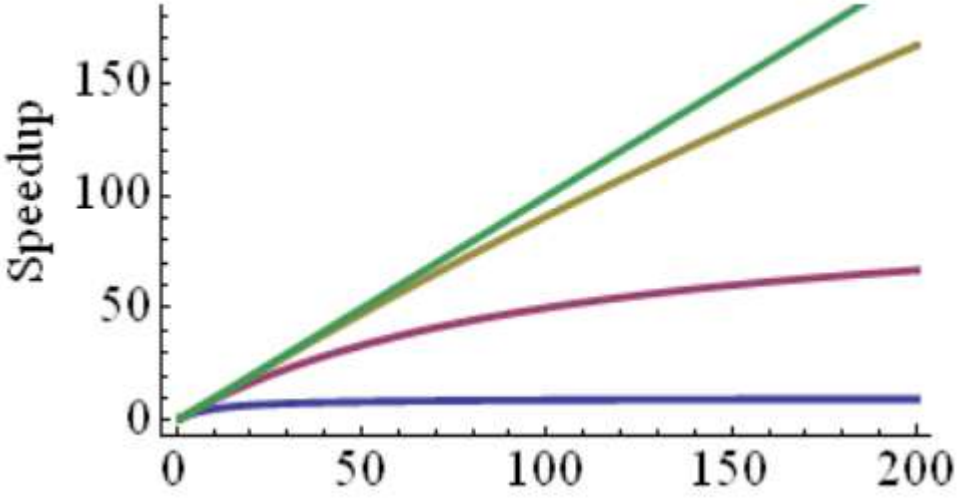
What is scalability?

- Ideal is to get N times more work done on N processors
- Strong scaling: compute a fixed-size problem N times faster
- Speedup S = T1 / TN ;
  - linear speedup occurs when S = N –
  - Can't achieve it due to Amdahl's Law (no speedup for serial parts)
- Weak scaling: compute a problem N times bigger in the same amount of time
  - Speedup depends on the amount of serial work remaining constant or increasing slowly as the size of the problem grows
  - Assumes amount of communication among processors also remains constant or grows slowly

Amdahl's limitations

- For large N, the parallel speedup doesn't asymptote to N, but to a constant 1/a, where a is the serial fraction of the work
- The graph below compares perfect speedup (green) with maximum speedup of code that is 99.9%, 99% and 90% parallelizable

```
T(N) = total time = p/N + s
     p = parallel workload
     s = serial time

S(N) = speedup = T(1)/T(N)
     = (p + s)/(p/N + s)

If a = s/(p + s), then
S(N) = N/[1+(N-1)a]
     -> 1/a for large N
```



Parallelization: Goals and decisions

Goals (ideals): Ensure the speed-up and scalability:

- Assign each process a unique amount of work
- Assign each process the data required for the job to do
- Minimize the replication of data and computation
- Minimize the communication between processes
- Balance the work load

Keep in mind that:

- For a problem there are several parallel solutions
- The best parallel solution not always comes from the best scalar solution