Introduction to Parallel Programming

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What is Parallel Programming?

- Theoretically a very simple concept
  - Use more than one processor to complete a task

- Operationally much more difficult to achieve
  - Tasks must be independent
    - Order of execution can't matter

  - How to define the tasks
    - Each processor works on their section of the problem (functional parallelism)
    - Each processor works on their section of the data (data parallelism)

  - How and when can the processors exchange information

Why Do Parallel Programming?

- Limits of single CPU computing
  – performance
  – available memory

- Parallel computing allows one to:
  – solve problems that don't fit on a single CPU
  – solve problems that can't be solved in a reasonable time

- We can solve…
  – larger problems
  – faster
  – more cases

Terminology

- **node:** a discrete unit of a computer system that typically runs its own instance of the operating system
  - Stampede has 6400 nodes
- **processor:** chip that shares a common memory and local disk
  - Stampede has two Sandy Bridge processors per node
- **core:** a processing unit on a computer chip able to support a thread of execution
  - Stampede has 8 cores per processor or 16 cores per node
- **coprocessor:** a lightweight processor
  - Stampede has a one Phi coprocessor per node with 61 cores per coprocessor
- **cluster:** a collection of nodes that function as a single resource

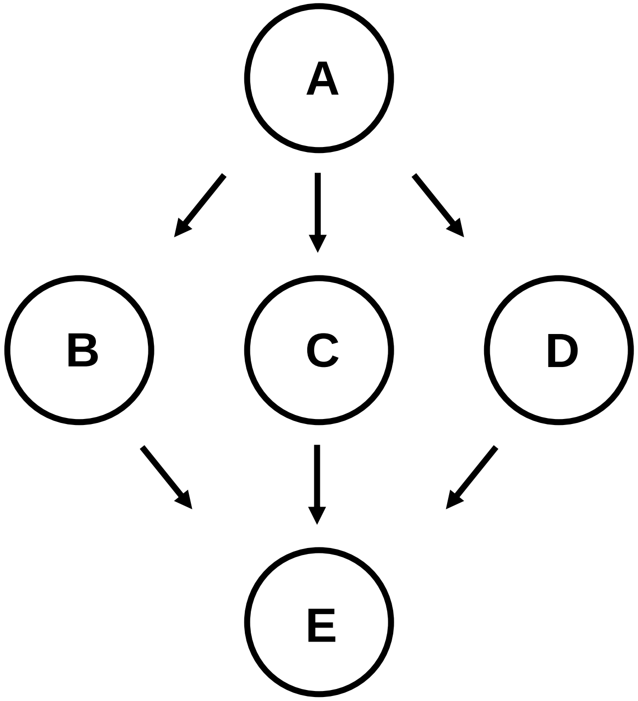
Functional Parallelism

Definition: each process performs a different "function" or executes different code sections that are independent.

Examples:

2 brothers do yard work (1 edges & 1 mows)

8 farmers build a barn



- Commonly programmed with message-passing libraries

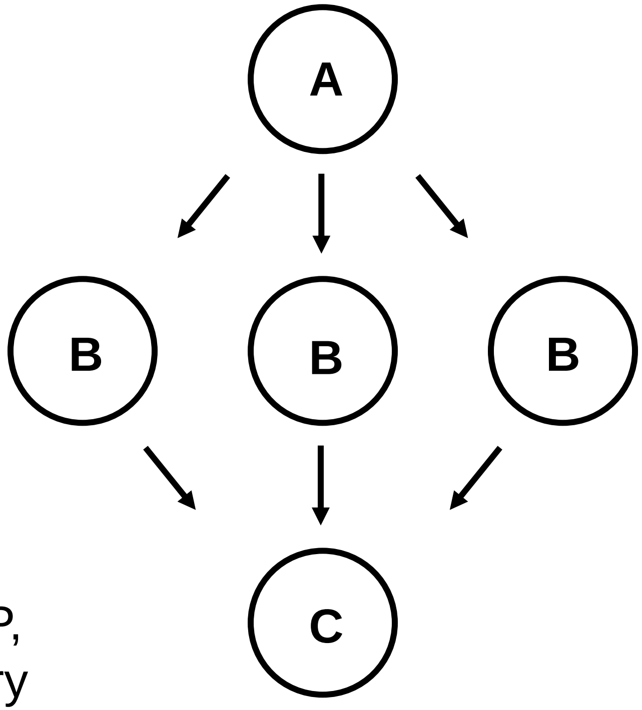
Data Parallelism

Definition: each process does the same work on unique and independent pieces of data

Examples:

2 brothers mow the lawn

8 farmers paint a barn



- Usually more scalable than functional parallelism
- Can be programmed at a high level with OpenMP, or at a lower level using a message-passing library like MPI or with hybrid programming.

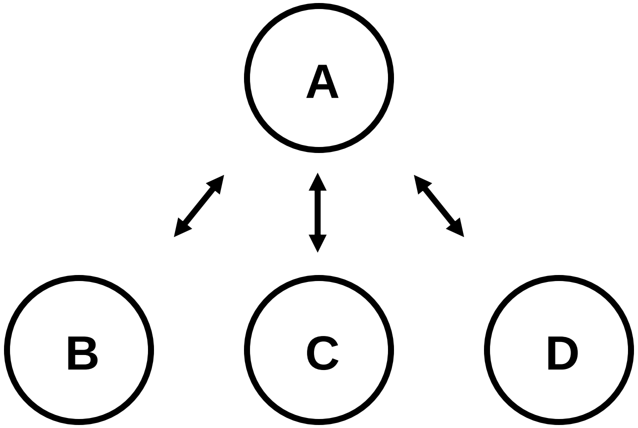
Task Parallelism
a special case of Data Parallelism

Definition: each process performs the same functions but do not communicate with each other, only with a “Master” Process. These are often called “Embarrassingly Parallel” codes.

Examples:

Independent Monte Carlo Simulations

ATM Transactions



Stampede has a special wrapper for submitting this type of job; see https://www.xsede.org/news/-/news/item/5778

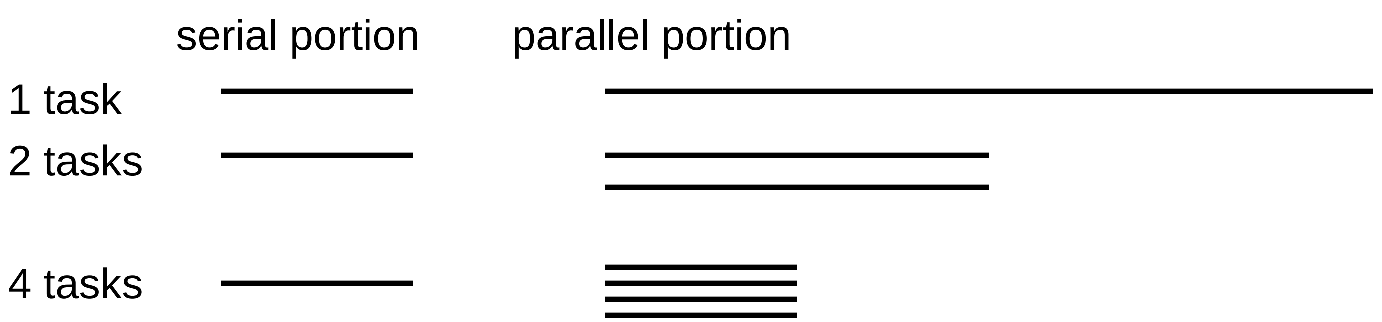
Is it worth it to go Parallel?

- Writing effective parallel applications is difficult!!
  - Load balancing is critical
  - Communication can limit parallel efficiency
  - Serial time can dominate
- Is it worth your time to rewrite your application?
  - Do the CPU requirements justify parallelization? Is your problem really “large”?
  - Is there a library that does what you need (parallel FFT, linear system solving)
  - Will the code be used more than once?

Theoretical Upper Limits to Performance

- All parallel programs contain:
  - parallel sections (we hope!)
  - serial sections (unfortunately)

- Serial sections limit the parallel effectiveness



- Amdahl’s Law states this formally

Amdahl's Law

- Amdahl's Law places a limit on the speedup gained by using multiple processors.
  - Effect of multiple processors on run time

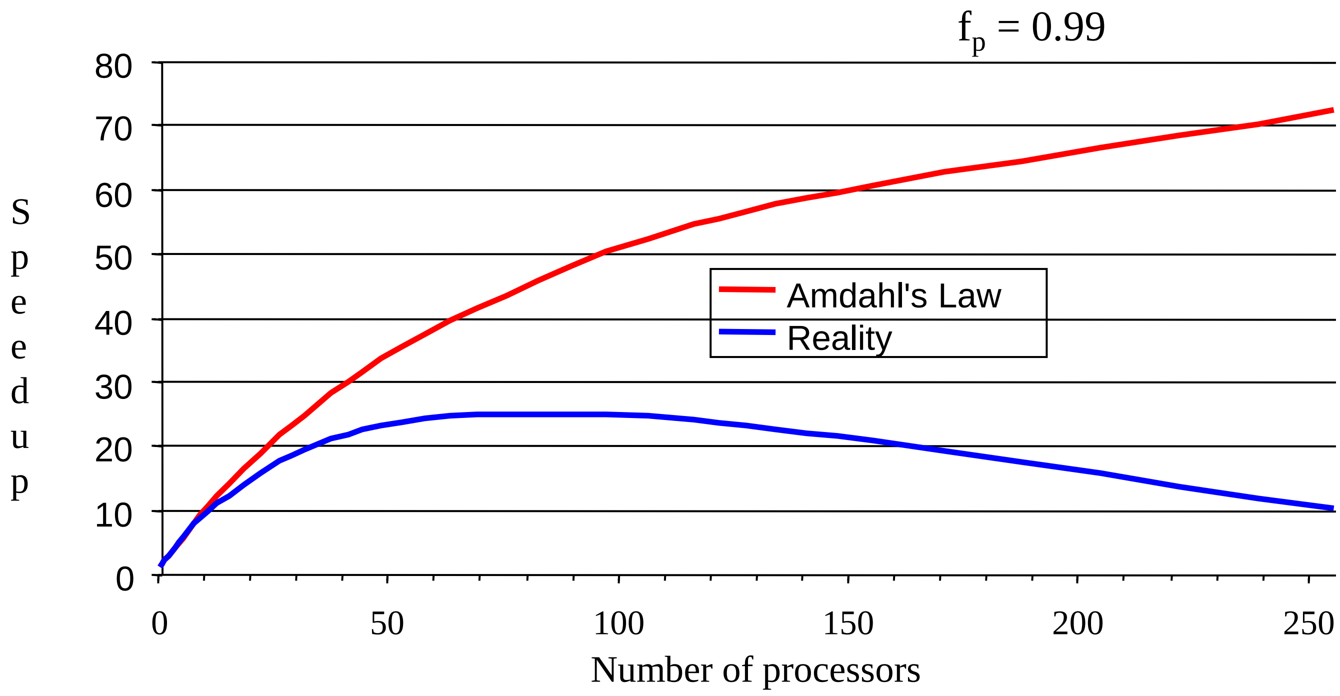
$$t_n = (f_p / N + f_s)t_1$$

  - where
    - f_s = serial fraction of the code
    - f_p = parallel fraction of the code
    - N = number of processors
    - t_1 = time to run on one processor

- Speed up formula: $S = 1 / (f_s + f_p / N)$
  - if $f_s = 0$ & $f_p = 1$, then $S = N$
  - If $N \rightarrow$ infinity: $S = 1/f_s$; if 10% of the code is sequential, you will never speed up by more than 10, no matter the number of processors.

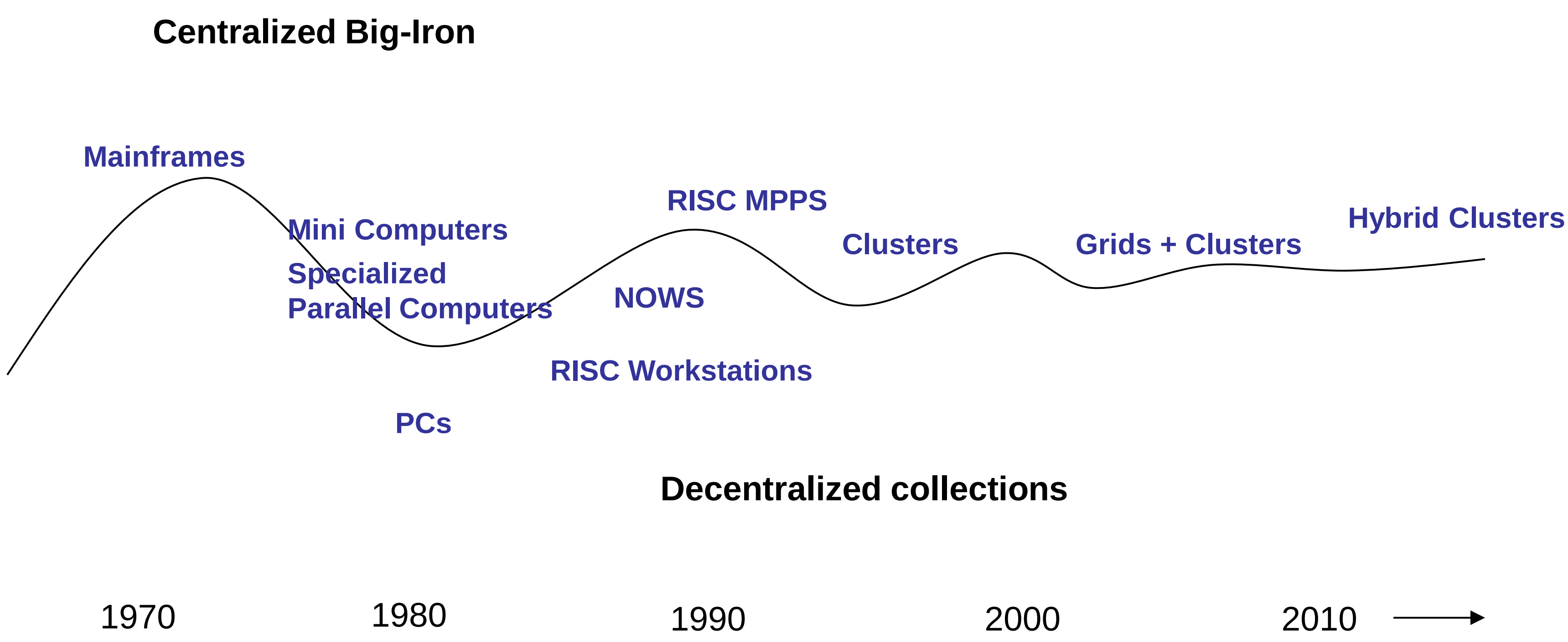
Practical Limits: Amdahl's Law vs. Reality

- Amdahl's Law shows a theoretical upper limit for speedup
- In reality, the situation is even worse than predicted by Amdahl's Law due to:
  - – Load balancing (waiting)
  - – Scheduling (shared processors or memory)
  - – Communications
  - – I/O



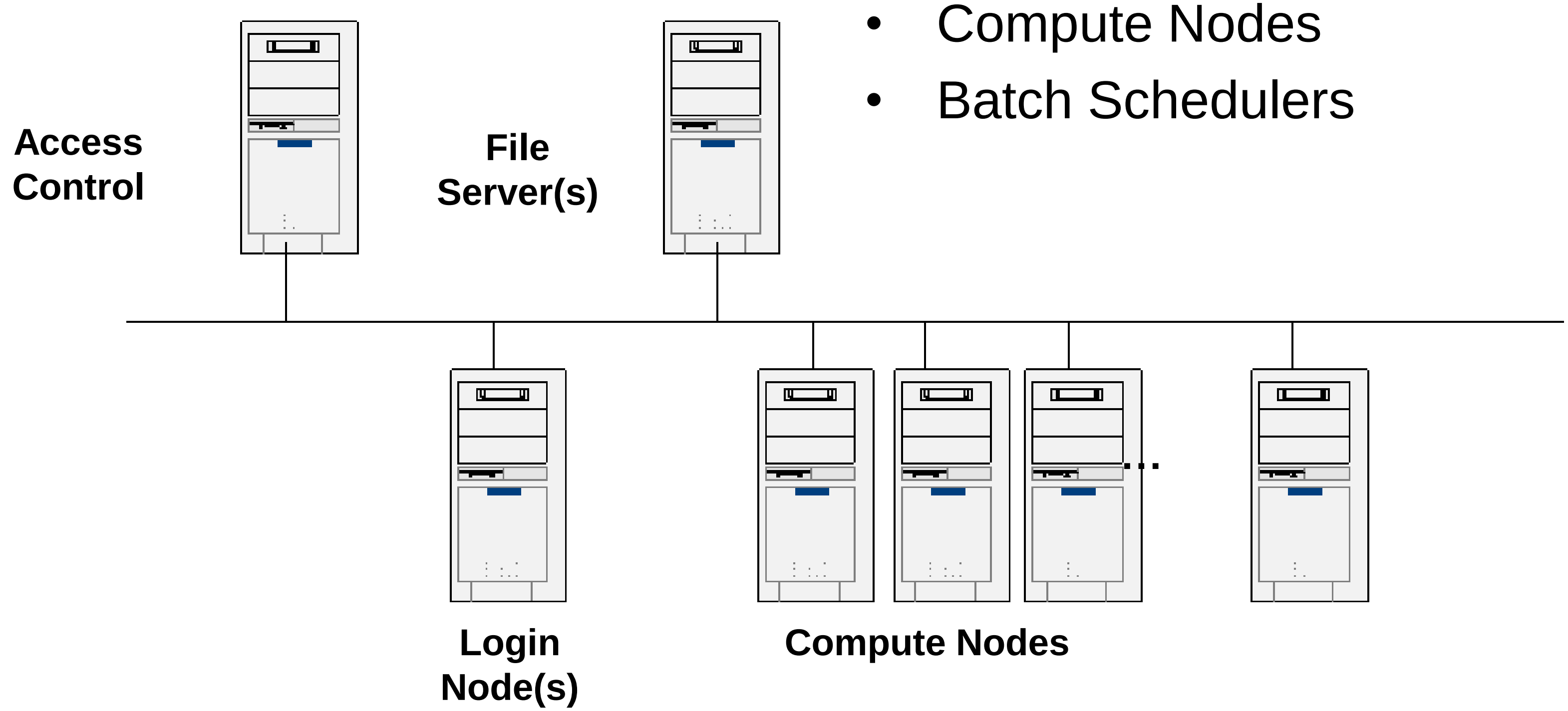
High Performance Computing Architectures

HPC Systems Continue to Evolve Over Time…



Cluster Computing Environment

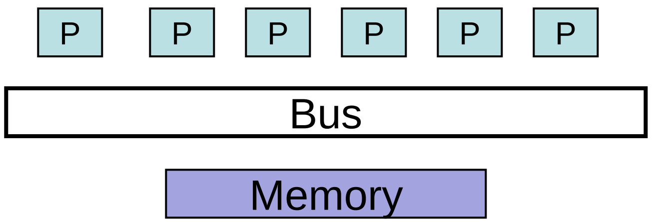
- Login Nodes
- File servers & Scratch Space
- Compute Nodes
- Batch Schedulers

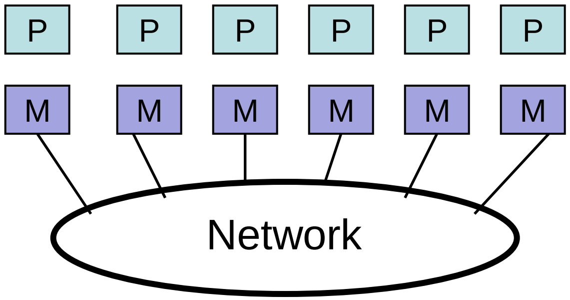


Types of Parallel Computers (Memory Model)

- Useful to classify modern parallel computers by their memory model
  - shared memory
    multiple cores with access to the same physical memory
  - distributed memory
    each task has its own virtual address space
  - hybrid
    mixture of shared and distributed memory; shared memory on cores in a single node and distributed memory between nodes
- Most parallel machines today are multiple instruction, multiple data (MIMD)

Shared and Distributed Memory Models





Shared memory: single address space. All processors have access to a pool of shared memory; easy to build and program, good price-performance for small numbers of processors; predictable performance due to uniform memory access (UMA).

Methods of memory access :
- Bus
- Crossbar

Distributed memory: each processor has its own local memory. Must do message passing to exchange data between processors. cc-NUMA enables larger number of processors and shared memory address space than SMPs; still easy to program, but harder and more expensive to build. (example: Clusters)

Methods of memory access :
- various topological interconnects

Programming Parallel Computers

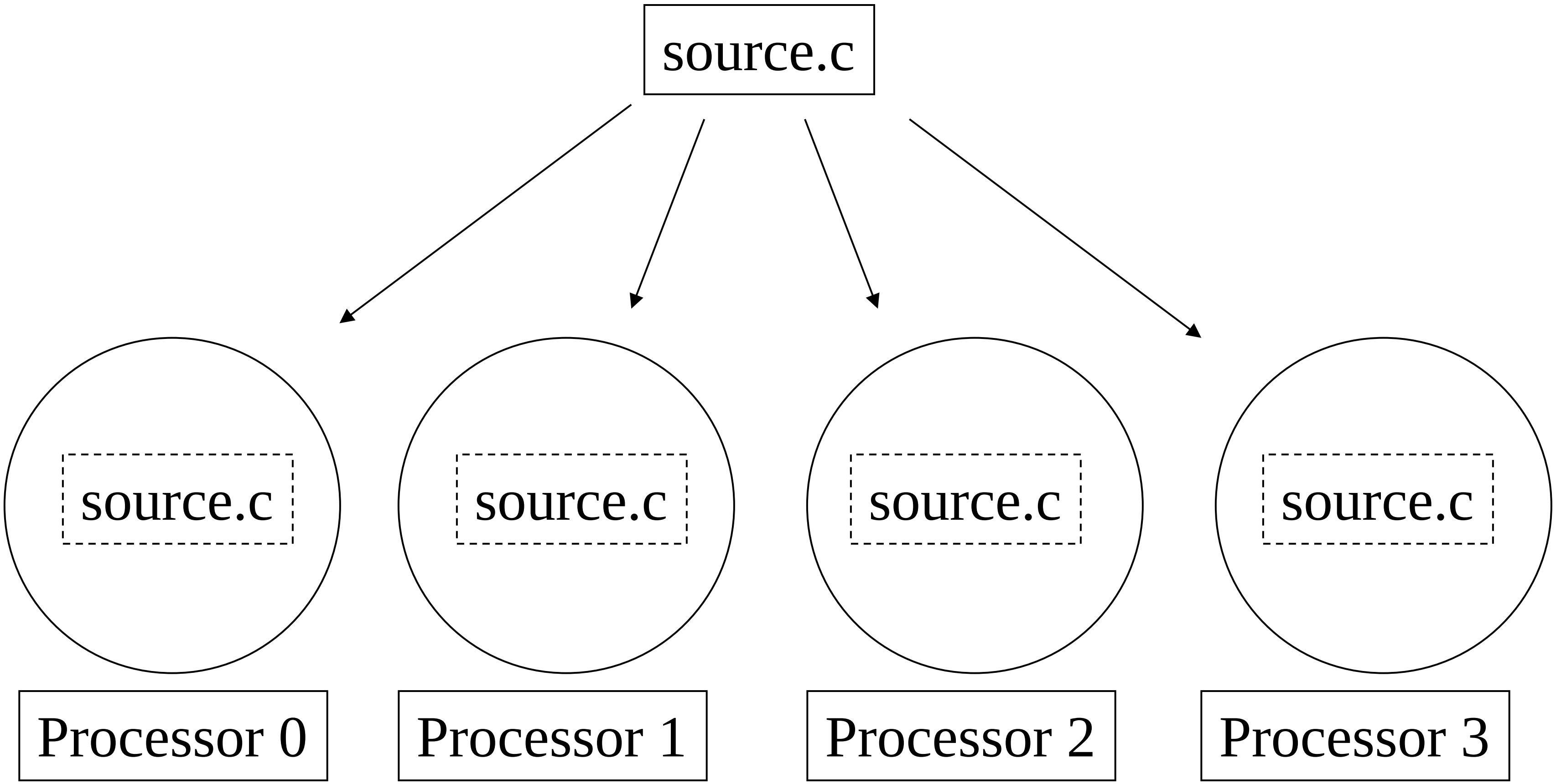
- Programming single-processor systems is (relatively) easy because they have a single thread of execution and a single address space.
- *Programming shared memory systems can benefit from the single* address space
- *Programming distributed memory systems is more difficult due to* multiple address spaces and the need to access remote data
- *Programming hybrid memory systems is even more difficult, but gives the programmer much greater flexibility*

Single Program, Multiple Data (SPMD)

SPMD:

- One source code is written
- Code can have conditional execution based on which processor is executing the copy
- All copies of code are started simultaneously and communicate and sync with each other periodically

SPMD Programming Model



Shared Memory Programming: OpenMP

- Shared memory systems have a single address space:
  - applications can be developed in which loop iterations (with no dependencies) are executed by different processors
  - shared memory codes are mostly data parallel, ‘SIMD’ kinds of codes
  - OpenMP is the new standard for shared memory programming (compiler directives)
  - Vendors offer native compiler directives

Distributed Memory Programming: MPI

Distributed memory systems have separate address spaces for each processor

- Local memory accessed faster than remote memory
- Data must be manually decomposed
- MPI is the standard for distributed memory programming (library of subprogram calls)

Hybrid Memory Programming:

- Systems with multiple shared memory nodes

- Memory is shared at the node level, distributed above that:
  - Applications can be written using OpenMP
  - Applications can be written using MPI
  - Application can be written using both OpenMP and MPI

Questions?