Parallel and concurrent programming
2. Programming Model

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parallel
concurrent
Amdahl's Law
thread of control
processors versus processes
non-deterministic
fork-join parallelism
PROTECTION
data race
synchronization
divide and conquer algorithms
THREAD SAFETY
correctness
MUTUAL EXCLUSION
locks
liveness
DEADLOCK
starvation
HIGH PERFORMANCE COMPUTING
EXECUTORS
thread pools
timing

Overview: How to write parallel programs

To write a parallel program, you (the programmer) need new **primitives** from a programming language or library, that enable you to:

- run multiple operations at once
- share data between operations
- coordinate *(a.k.a. synchronize)* operations

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How this works/is done depends on the **parallel programming model** used in the language/library.

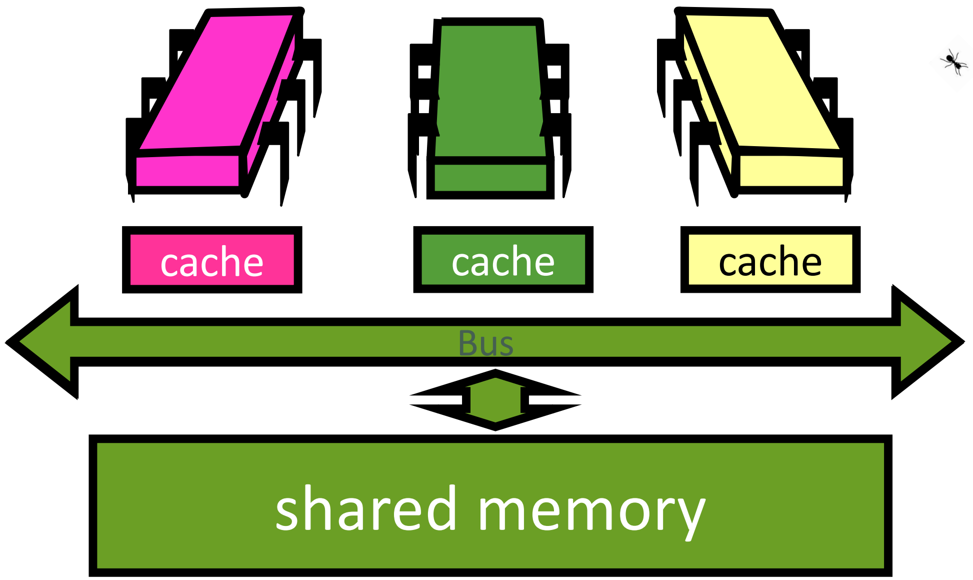
Java uses the *Shared Memory* parallel programming model

The Shared Memory Model

All memory is placed into a single (physical) address space.

- Processors connected by some form of **interconnection network**

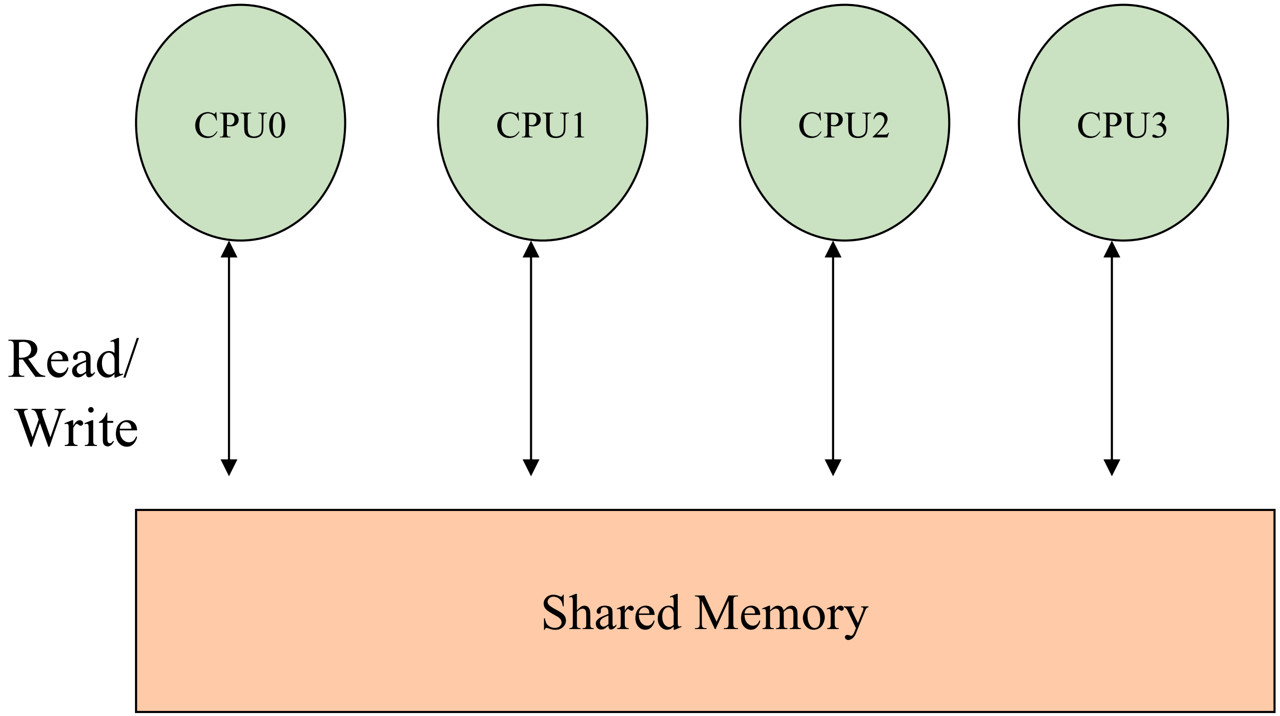
- **Single virtual address space** across **all of memory**. Each processor can access all locations in memory.



from: Art of Multiprocessor Programming

Shared Memory

The **ideal picture** of **shared memory**:



Shared Memory

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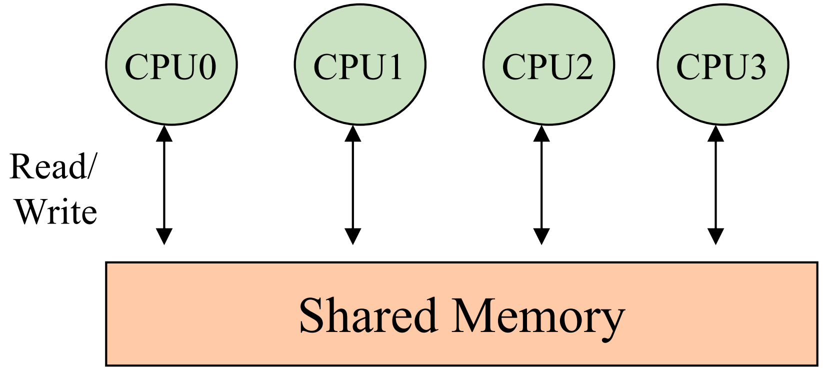

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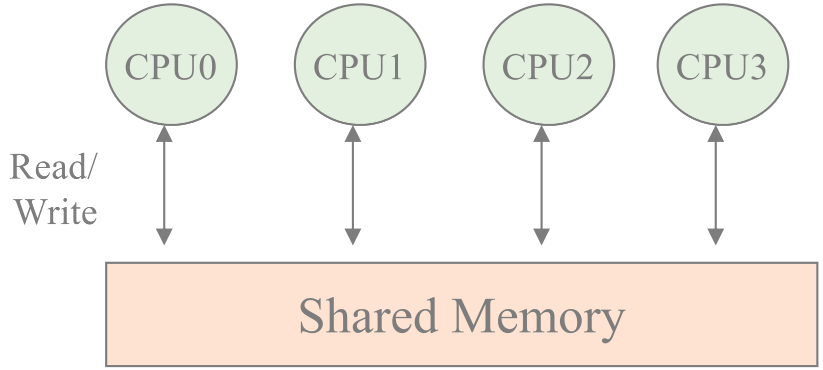
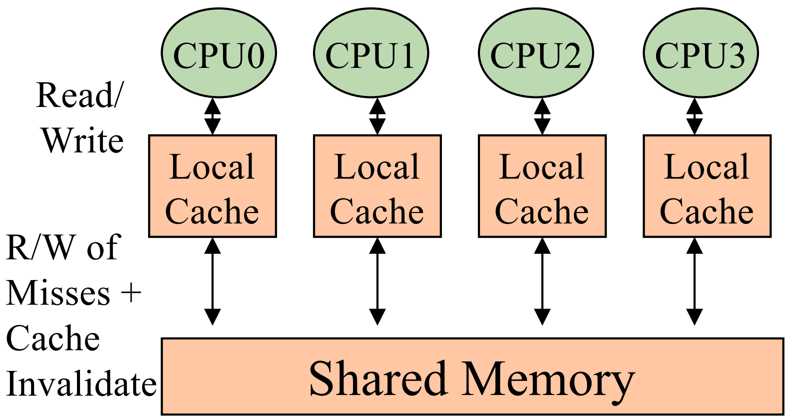
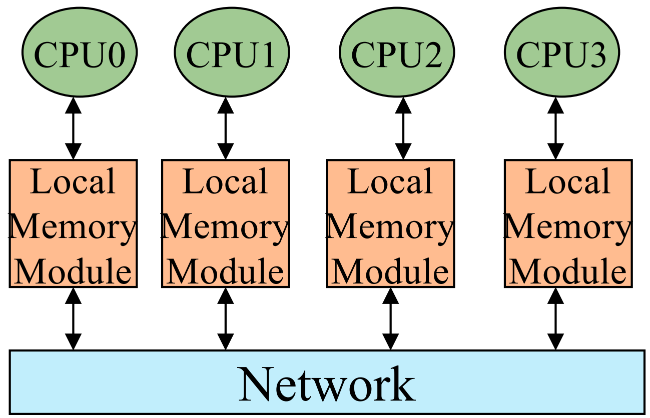


The **actual architecture** of shared memory systems:

Symmetric Multi-Processor (SMP):

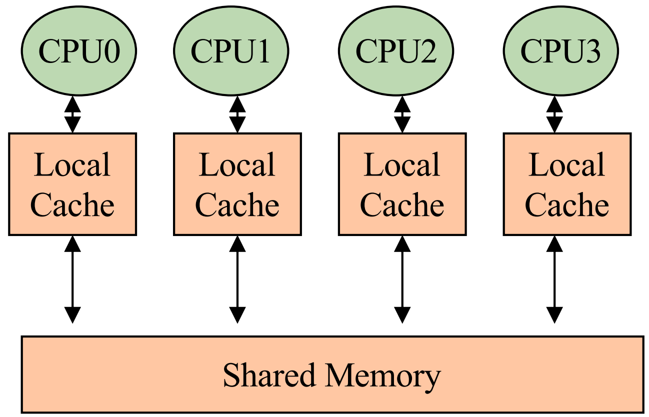


Distributed Shared Memory (DSM):



[Also have Non-uniform Memory Access Symmetric Multi-Processor (NUMA-SMP)]

An aside: cache (Architecture)



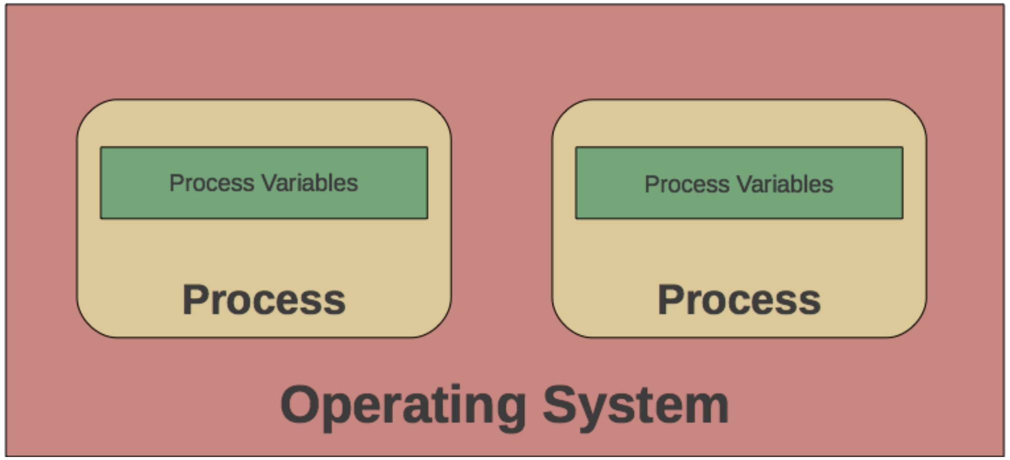
A memory cache, also called a "CPU cache," is a memory bank that bridges main memory and the processor.

- It has faster static RAM (SRAM) chips than the dynamic RAM (DRAM) used for main memory.
- The cache allows instructions to be executed and data to be read and written at **higher speed**.

Can have multiple caches (L1, L2, L3) in modern chips

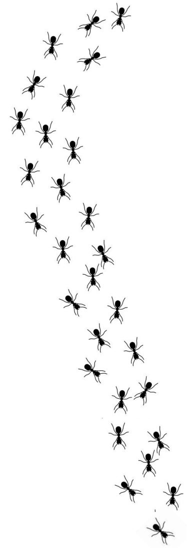
- L1 is the fastest; each subsequent cache is slower and larger than L1, and instructions and data are staged from main memory to L3 to L2 to L1 to the processor.
- On multicore chips, the L3 cache is generally shared among all the processing cores.

A Process (operating system)



Operating system unit of resource allocation both for CPU time and for memory.

- A process is represented by its **code**, **data** and the **state of the machine registers**.
- data of the process divided into
  - global variables and local variables
  - organized as a **stack**.
- Generally, each process in an operating system has its own address space
  - entirely separate entities



It is hard to obtain parallelism or concurrency with separate *processes*… (why?)

… so operating systems created *threads*.

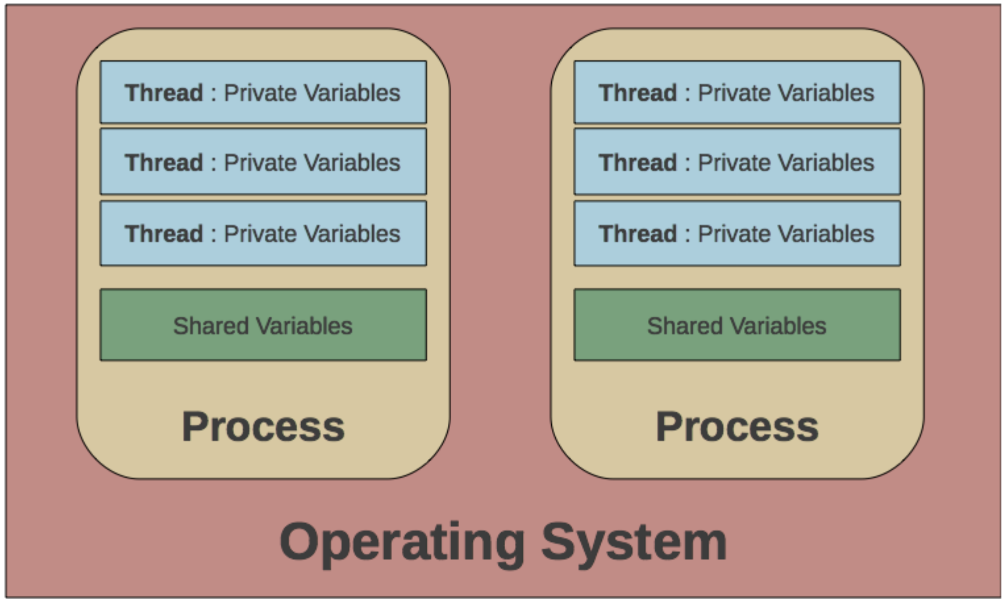
Thread

Process given internal concurrency with multiple *lightweight processes* or ***threads***.

- multiple ***threads of control***

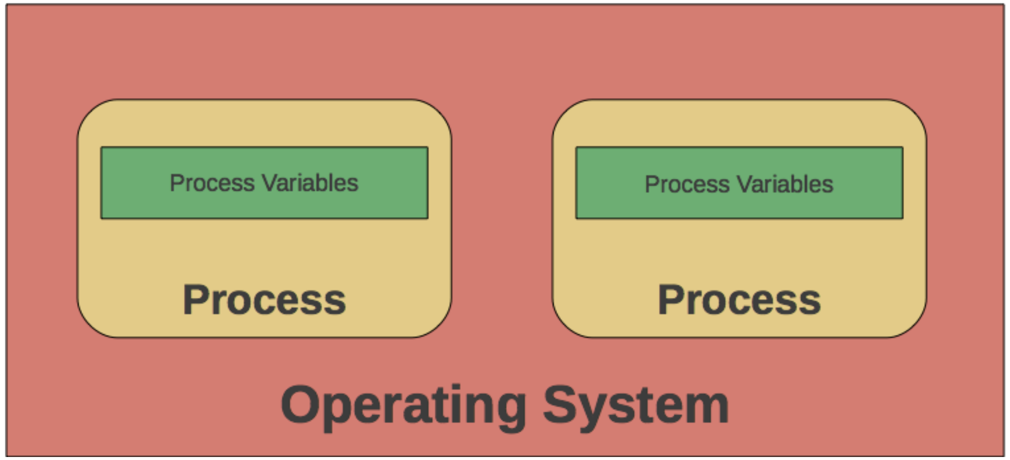
- a process with multiple (lightweight) threads of control has multiple stacks
  - one for each thread.

but access to **shared memory** too.

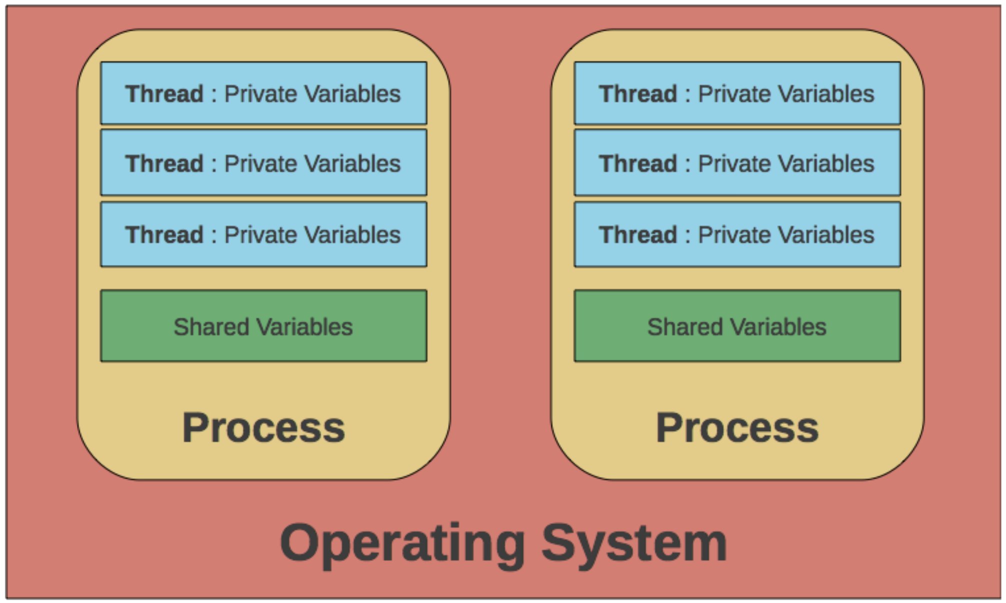


Processes versus threads

Process memory model



Thread memory model



Graphic adapted slides obtained from : www.Intel-Software-Academic-Program.com

What is a parallel program?

The **shared memory model** has multiple **explicit threads** running concurrently.

Threads can:

- perform **multiple computations** in parallel;
- perform separate **simultaneous activities;**
- **communicate easily** and **implicitly** with each other through **shared memory.**

(but this is dangerous if you don't protect your variables correctly)

* This is true for the shared memory model of parallel computing discussed in this module.

Programming Model: Sequential program state

A running serial program has

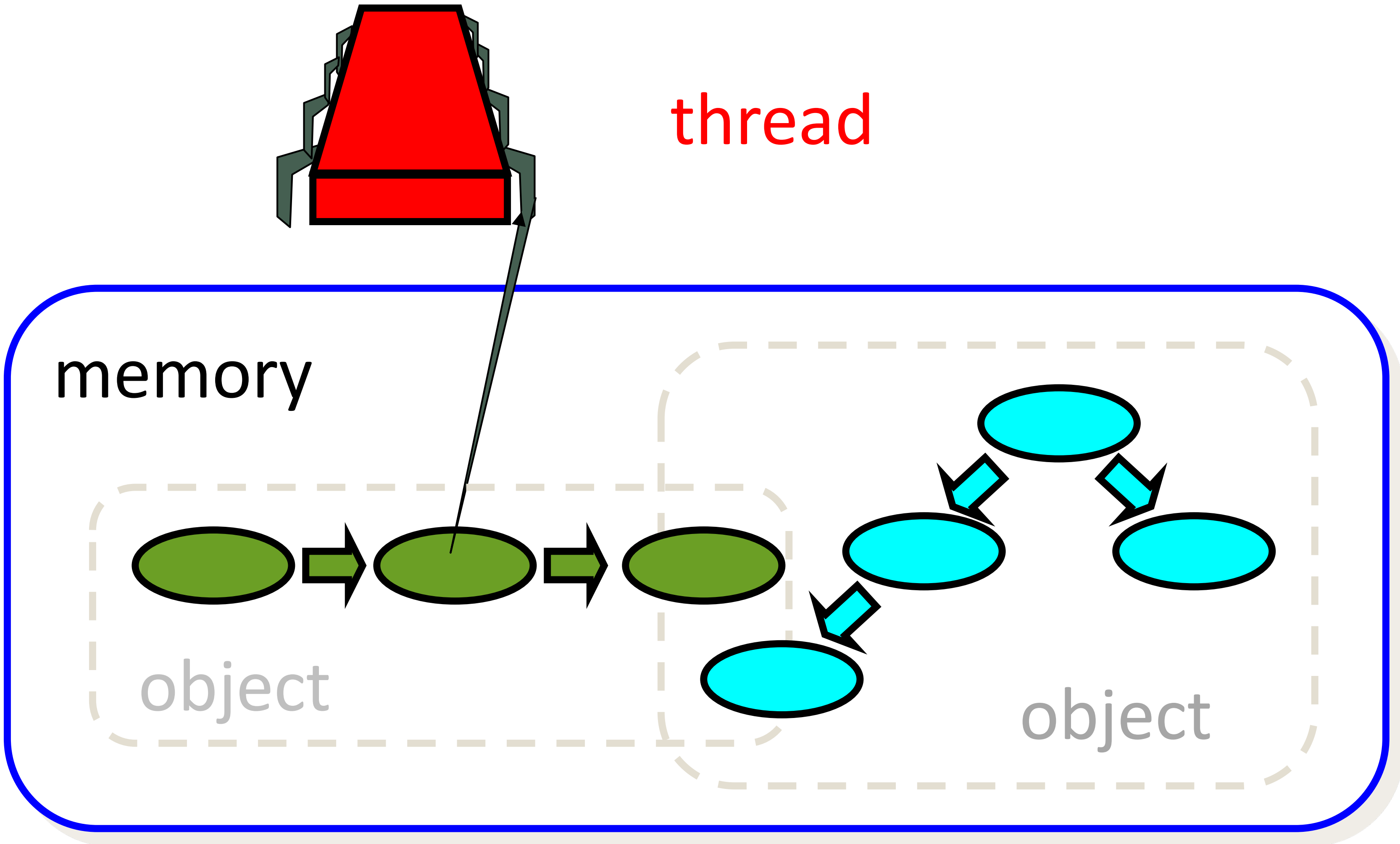
- One *program counter* (current statement executing)
- One *call stack*
  - each stack frame holds the local variables for a method call that has started but not yet finished.
  - Calling a method pushes a new frame and returning from a method pops a frame.
  - Call stacks are why recursion is not "magic."
- *Objects.* Object are created by calling **`new`**. We call the memory that holds all the objects the *heap.*

  (nothing to do with data structure called a heap)
- *Static fields* of classes.

Programming Model: Shared memory

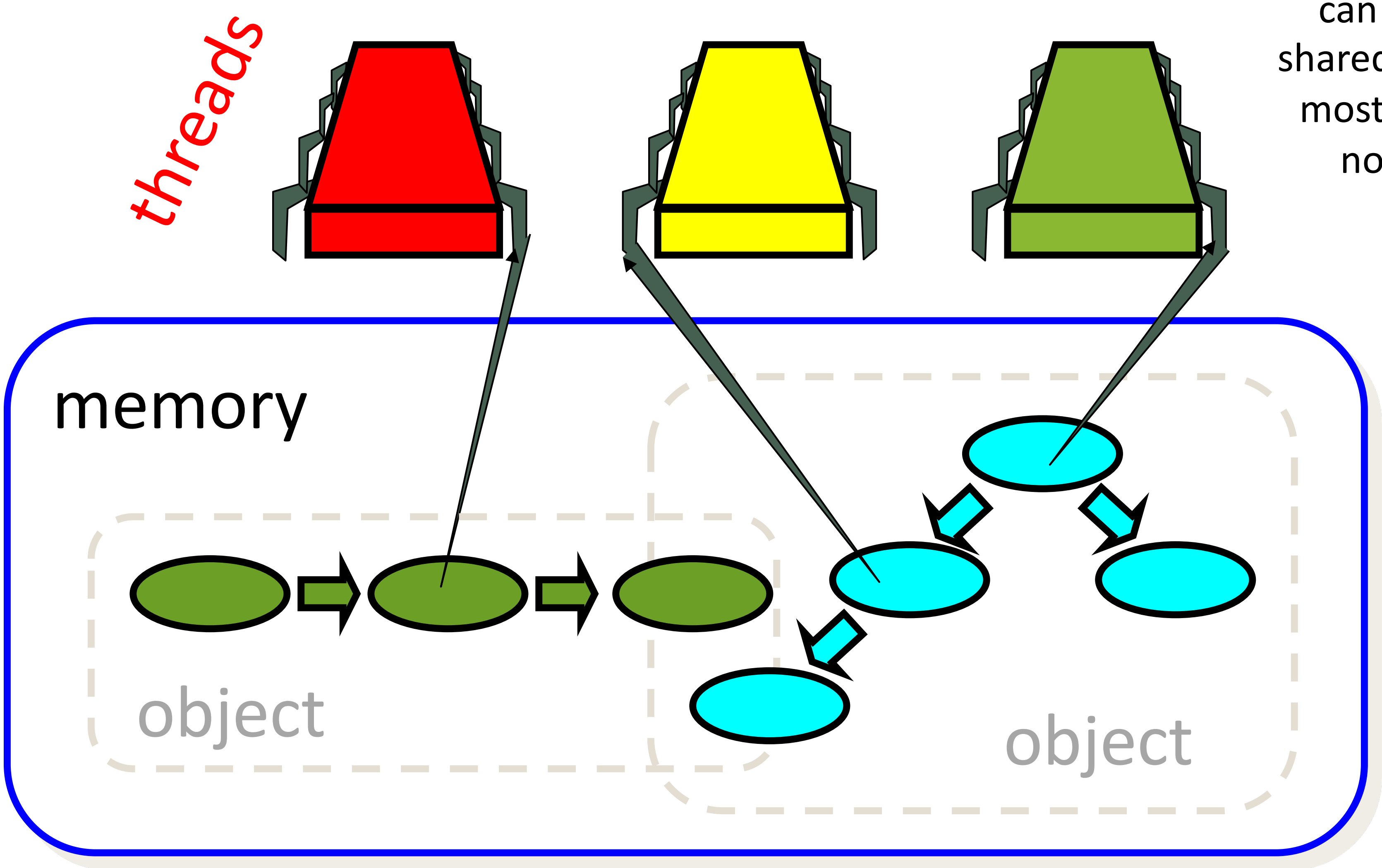
- Each thread has its own program counter, call stack and local variables
- All threads share one collection of objects and static fields
- Static fields of classes are also shared by all threads.
- Threads communicate through shared objects (implicit communication)
  - To *communicate*, **write** somewhere another thread **reads**

Sequential Computation



Concurrent Computation

Any object can be shared, but most are not.



How threads run

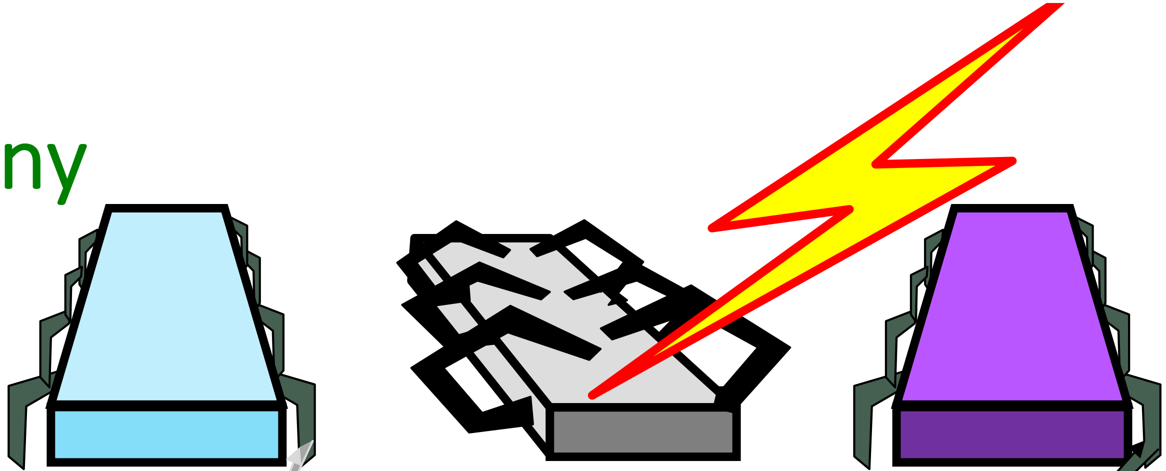
As the programmer, **you create threads**.

- The **Operating System scheduler** determines how and when those threads are run on the available processors
  - Unless you are writing a scheduler, **you don't have control over this**
  - You don't know how many **processors/cores** your program will use

    (though you can guess).
  - You don't know **the order** in which threads will execute

    (you can't even guess).

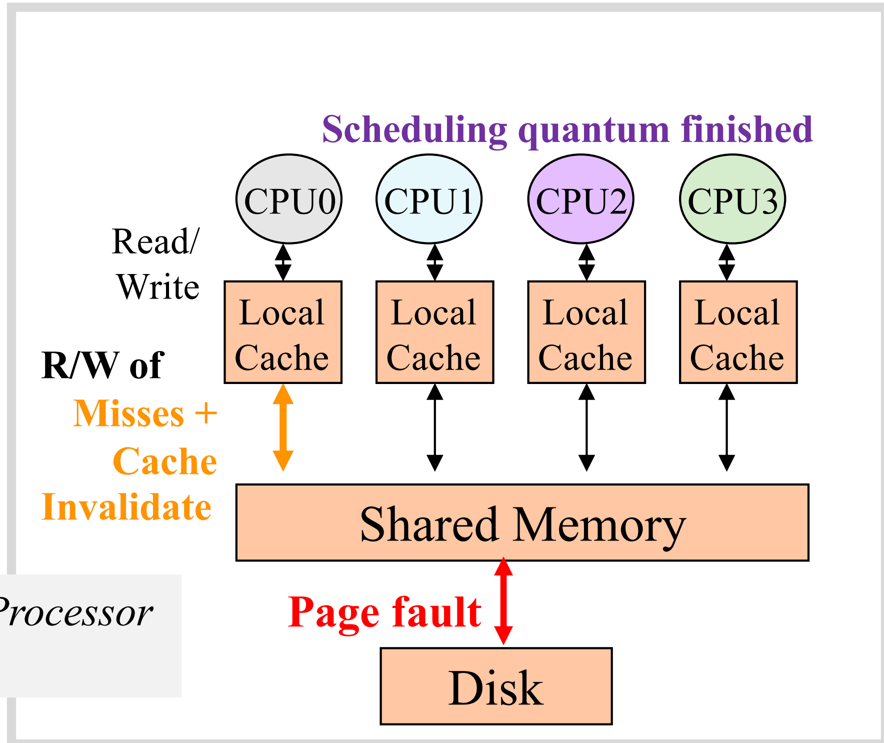
Asynchrony



Threads are subject to **sudden unpredictable delays:**

- **Cache misses** (*short*)
- Page faults (*long*)
- Scheduling quantum finished

  (*really long*)

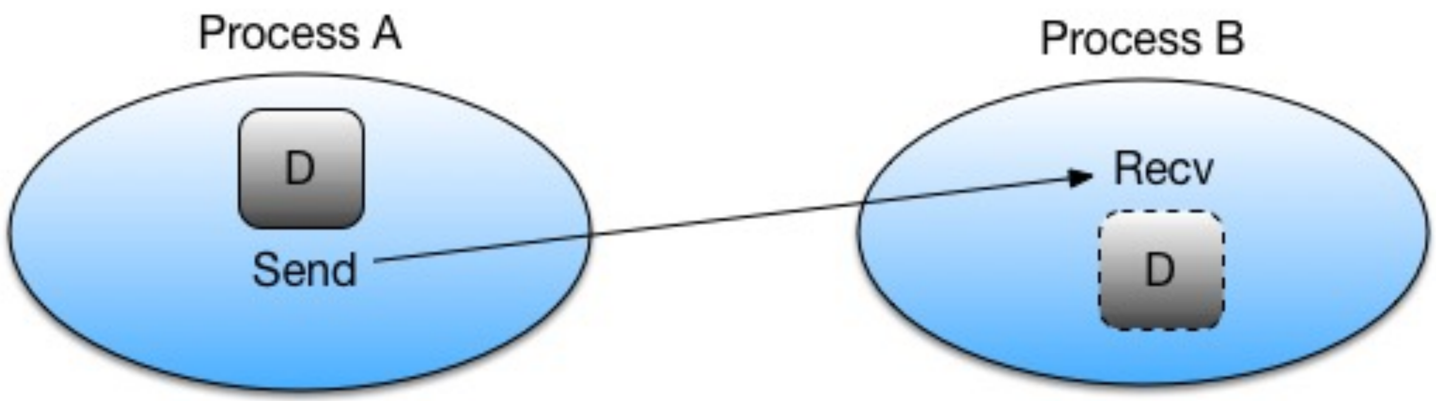


Symmetric Multi-Processor (SMP)

Other parallel programming models

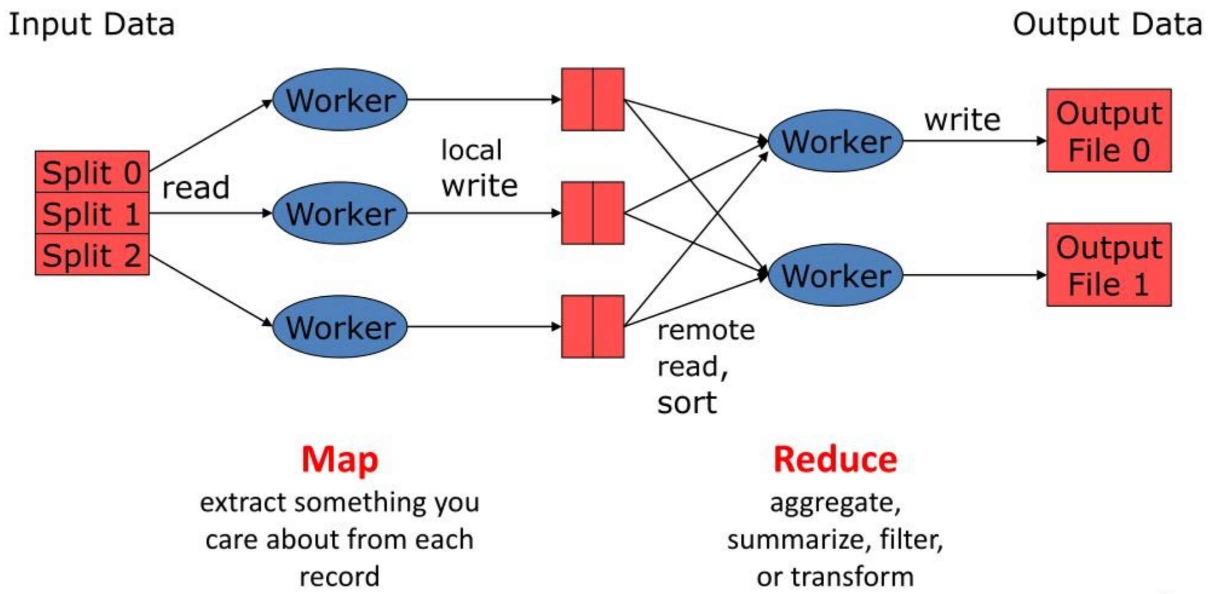
We focus on **shared memory**, but several **other models** exist. Common alternatives are:

- **Message-passing:**
  - Explicit **threads/processes**, each with their own objects/data.
  - Communication is via explicitly **sending/receiving messages**, containing **copies** of the data (share nothing)
  - Most common model on HPC systems (though usually in a hybrid with shared memory)



Other parallel programming models

- **Map reduce:**
  - Data parallelism concept from functional programming languages like LISP
  - Have **primitives** for things like "apply function to every element of an array in parallel".
    - details of the **underlying parallelization** are **hidden** from the programmer, provided you can express your program using the available primitives
  - MapReduce was developed by Google and the programming model has since been adopted by many software frameworks, e.g. Apache's open-source Hadoop



Other parallel programming models

Golang

- Go-routines,
  - Go runtime maps these onto operating system threads
- Channels – used for communication between Go-routines

```
package main

import "fmt"

func main() {
   fmt.Println("Hello, World!")
}
```