

Systems and Networking I

Applied Computer Science and Artificial Intelligence
2024-2025



SAPIENZA
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- All modern operating systems provide features enabling a process to contain **multiple threads** of control
- We introduce many concepts associated with multi-threaded computer systems
- We look at a number of issues related to multi-threaded programming and its effect on the design of operating systems

Threads: Overview

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 - There is only one program counter, and one sequence of instructions that can be carried out at any given time
- Multi-threaded applications have multiple threads within a single process, each having their own program counter, stack, and set of registers
 - But sharing common code, data, and certain structures, such as open files

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- A thread is bound to a specific process

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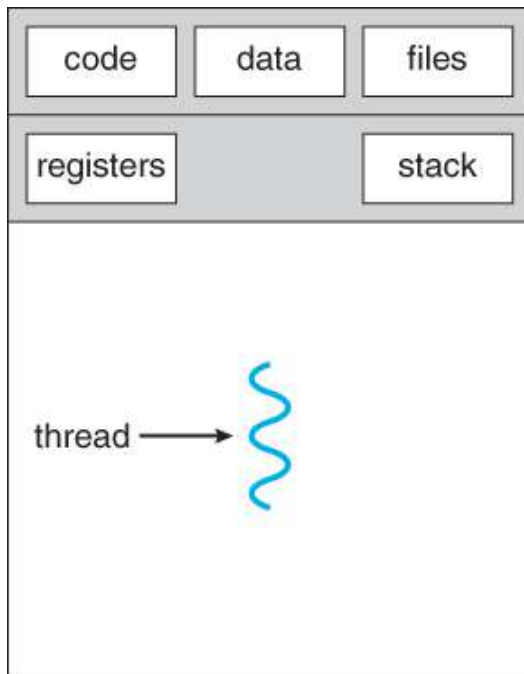
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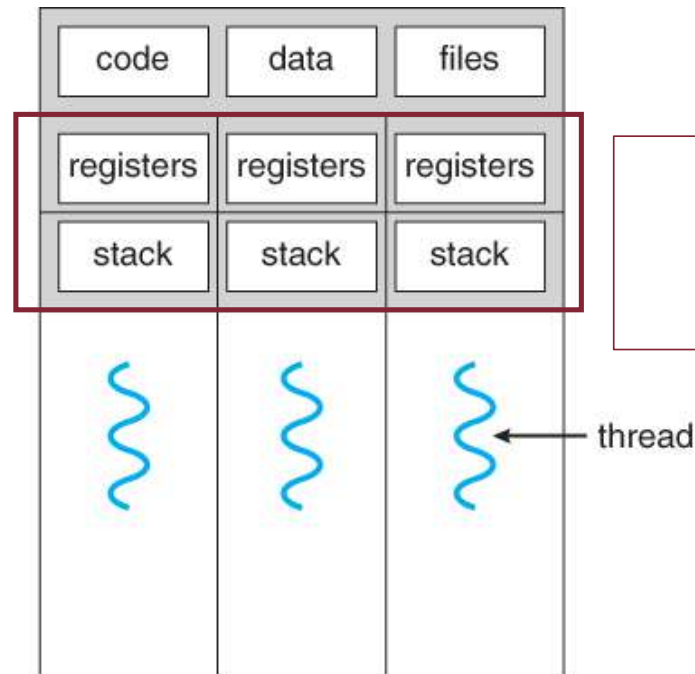
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- Simpler than message passing and shared memory

Single- vs. Multi-Threaded Process



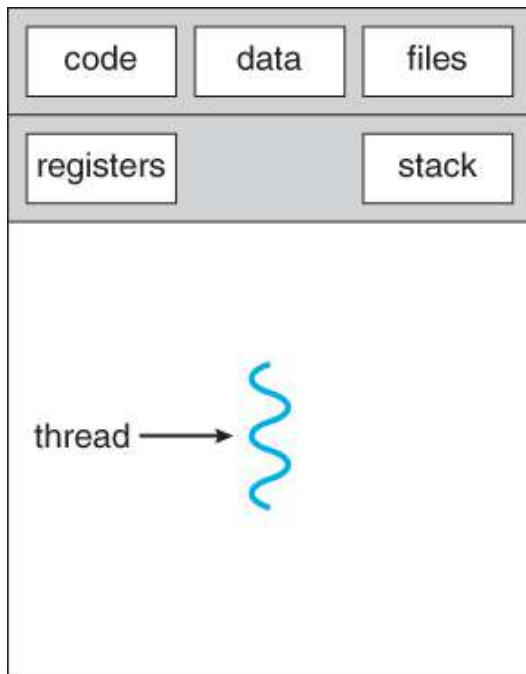
single-threaded process



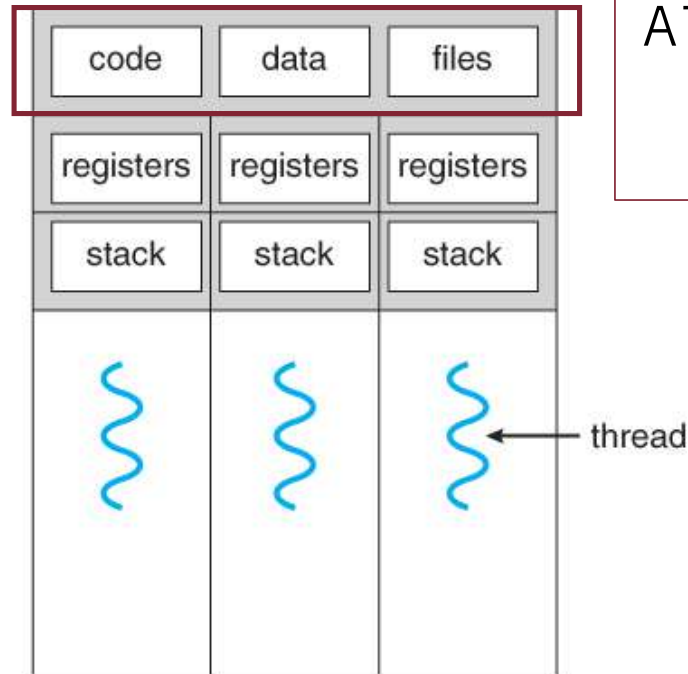
multithreaded process

Each thread has its own independent set of registers and "state"

Single- vs. Multi-Threaded Process



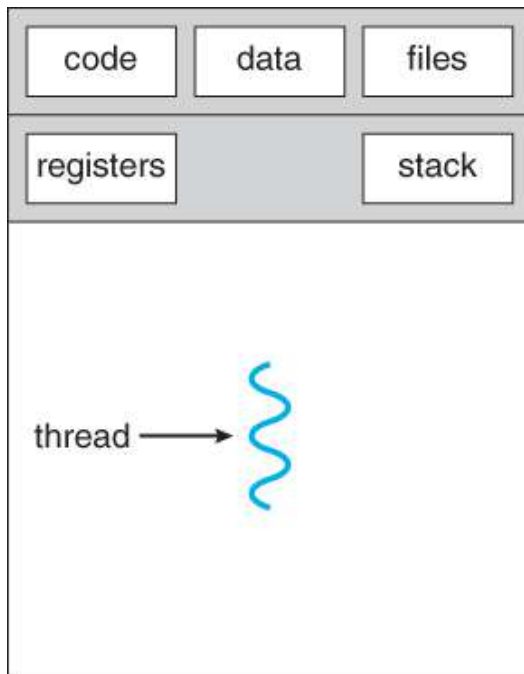
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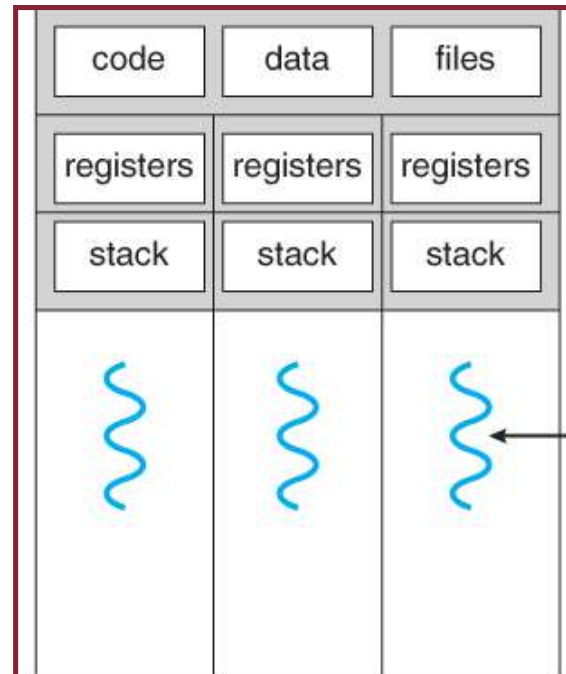
multithreaded process

All the threads of a process share the same code and "global" resources

Single- vs. Multi-Threaded Process



single-threaded process



multithreaded process

Since all the threads live in the same address space, communication between them is easier than communication between processes

Threads: Motivation

- Threads are very useful in modern programming whenever a process has multiple tasks to perform independently of the others

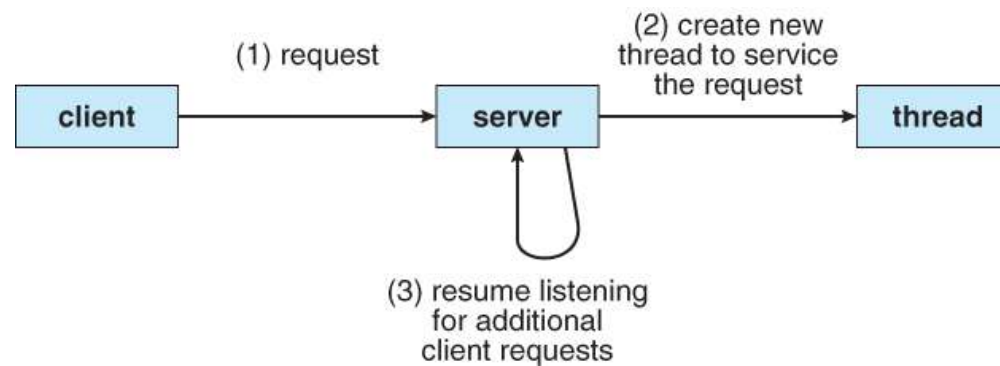
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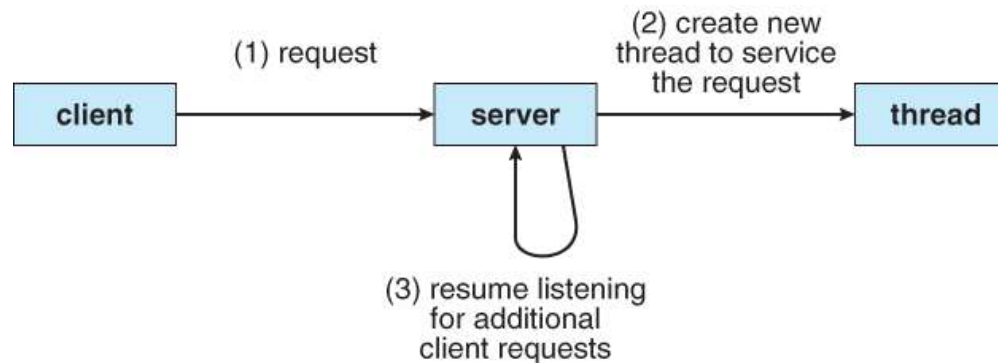
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- **Example: word processor**
 - a thread may check grammar while another thread handles user input (keystrokes), and a third does periodic backups of the file being edited

Multi-threaded Web Server

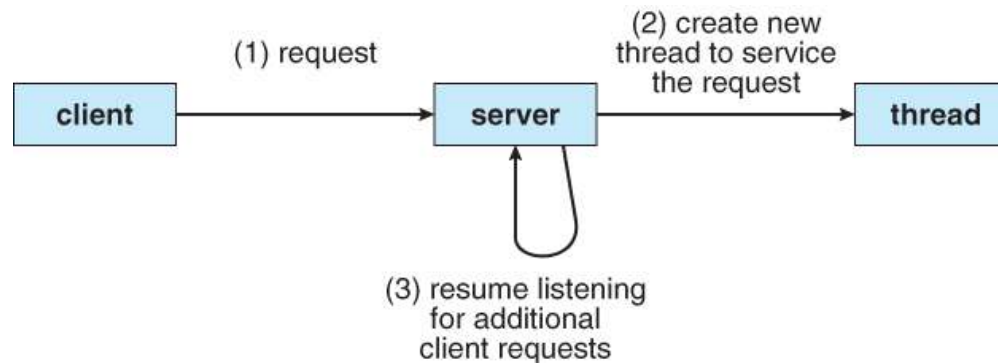


Multi-threaded Web Server



Multiple threads allow for multiple requests to be satisfied simultaneously, without having to serve requests sequentially or to fork off separate processes for every incoming request

Multi-threaded Web Server



What if the server process spawns off a new process for each incoming request rather than a thread?

Multiple Processes vs. Multiple Threads

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 - Context-switches between threads is a lot faster than between processes

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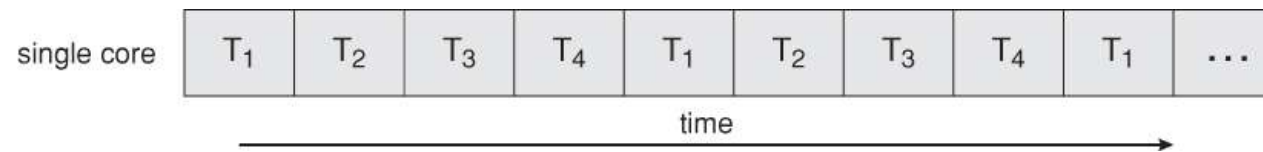
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 - **Economy** → creating and managing threads (and context switches between them) is much faster than performing the same tasks for processes
 - **Scalability** (multi-processor architectures) → A single threaded process can only run on one CPU, whereas a multi-threaded process may be split amongst all available processors/cores

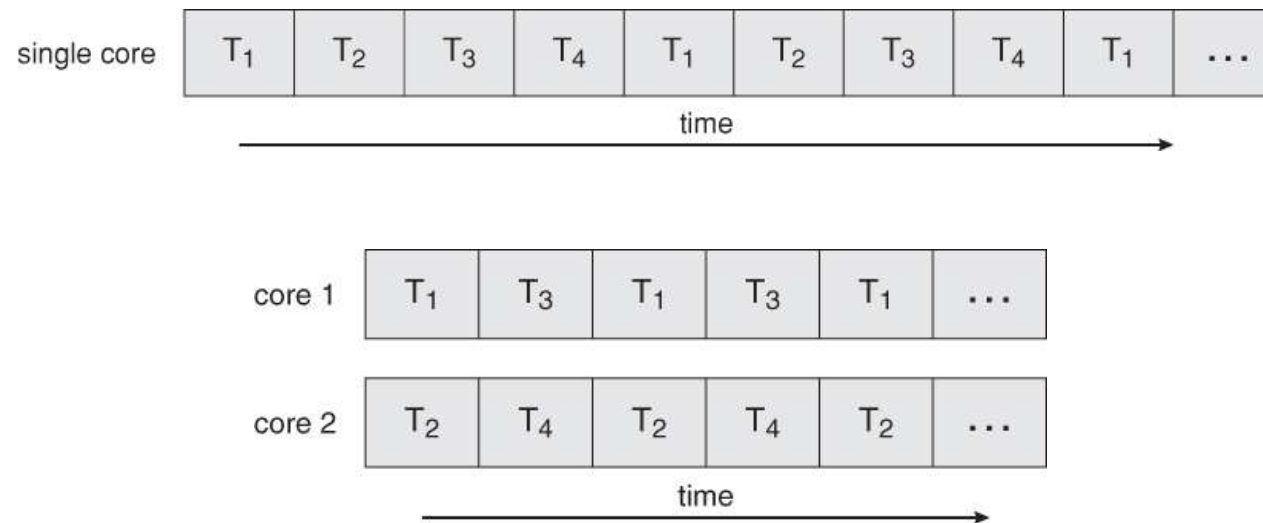
Multi-core Programming

- A recent trend in computer architecture is to produce chips with multiple cores, or CPUs on a single chip
- A multi-threaded application running on a traditional single-core chip would have to interleave the threads
- On a multi-core chip, however, threads could be spread across the available cores, allowing **true parallel processing!**

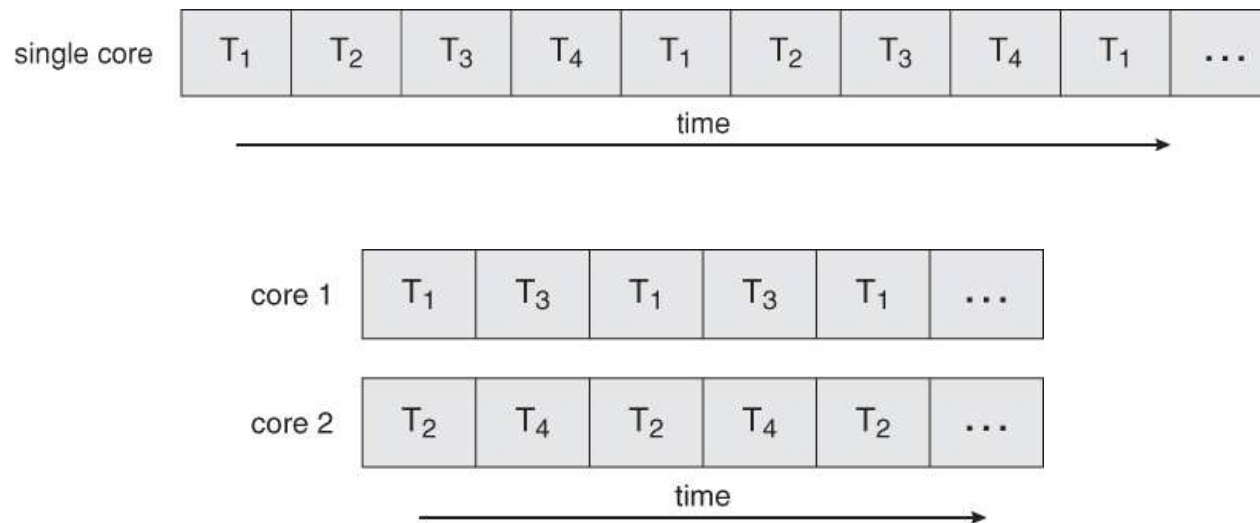
Single- vs. Multi-core Programming



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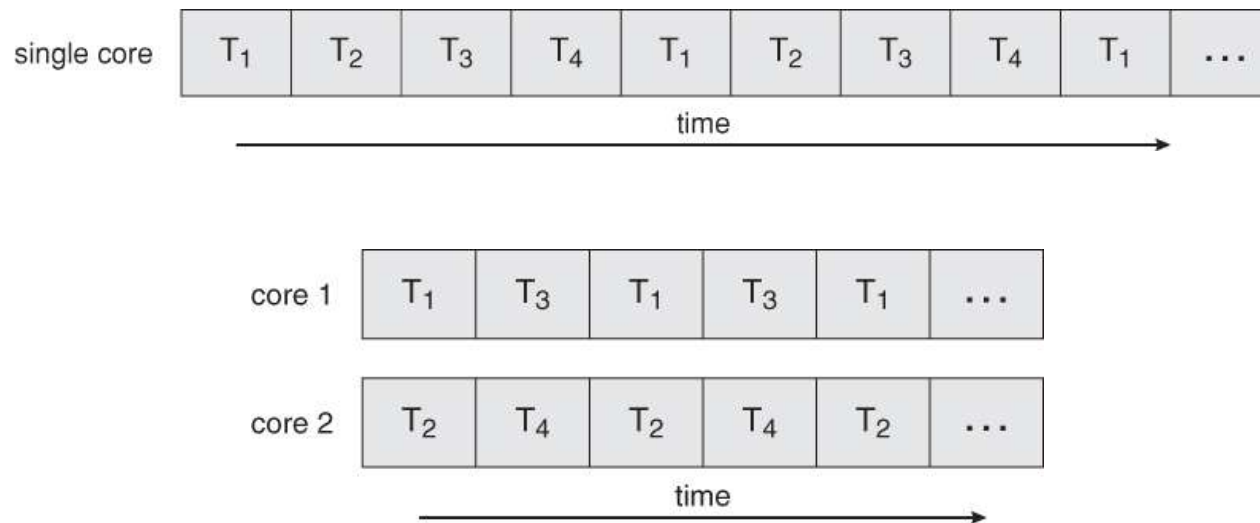


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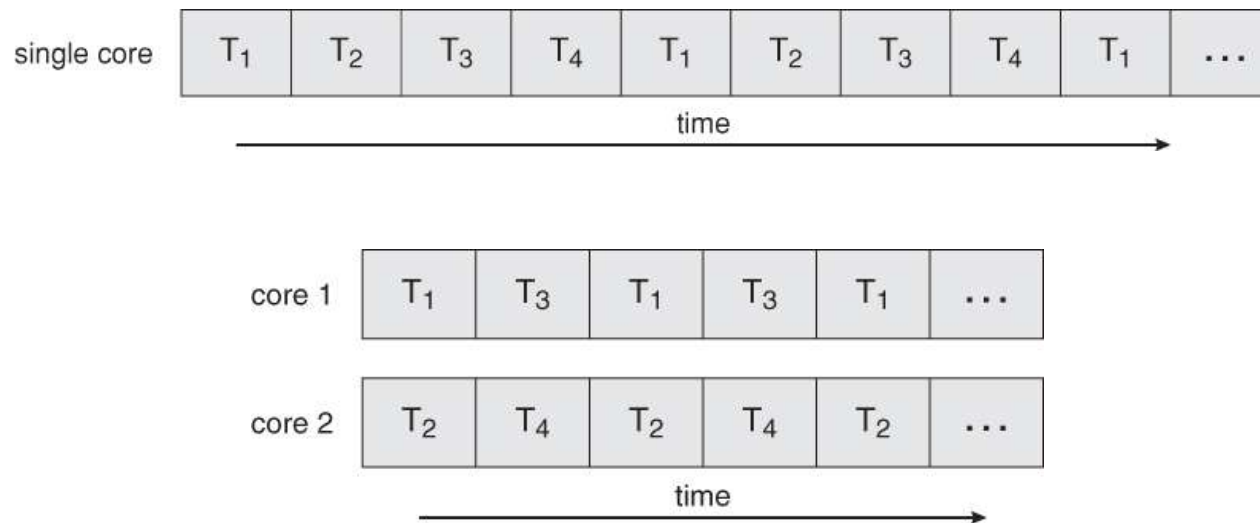
Multi-core chips require new OS scheduling algorithms to make better use of the multiple cores available

Single- vs. Multi-core Programming



CPUs have been developed to support more simultaneous threads per core in hardware (e.g., Intel's **hyper-threading**)

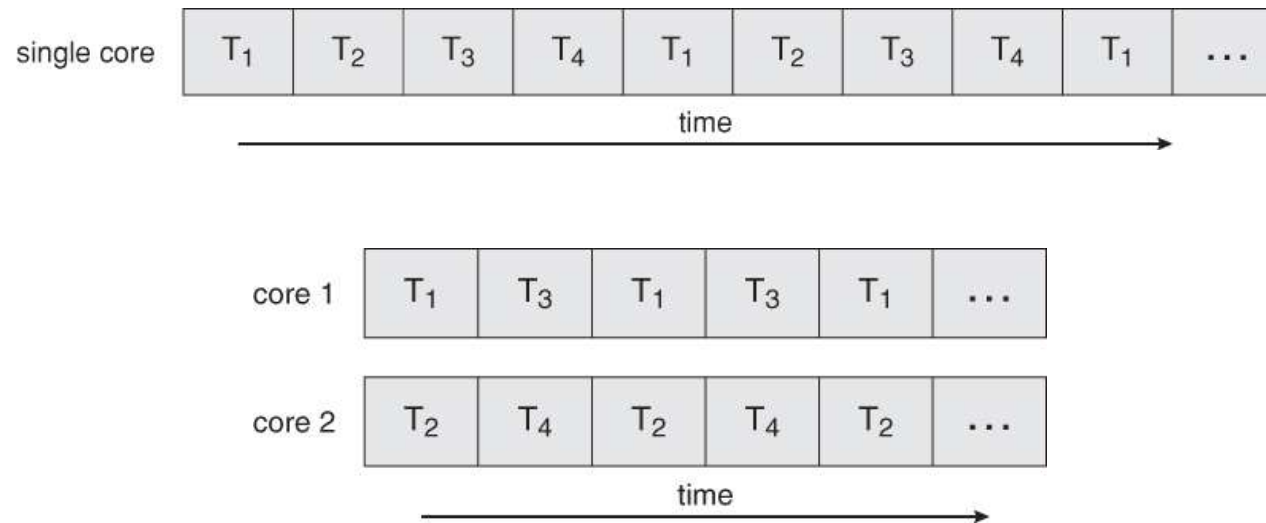
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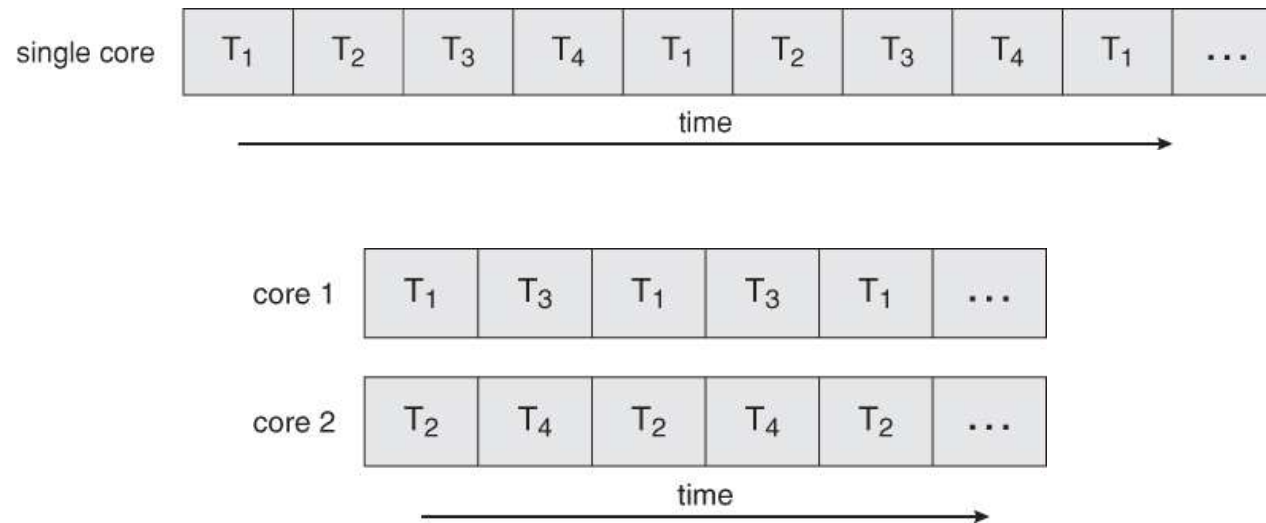
Hyper-threading

Each physical core appears as **two** processors to the OS, allowing **concurrent** scheduling of **two** threads per core

Single- vs. Multi-core Programming



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Concurrency

VS.

Parallelism

Types of Parallelism

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 - **Data parallelism:** divides the data up amongst multiple cores (threads), and performs the same task on each chunk of the data
 - **Task parallelism:** divides the different tasks to be performed among the different cores and performs them simultaneously

Example: A Pure CPU-bound Task

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 - Takes as input a positive integer N
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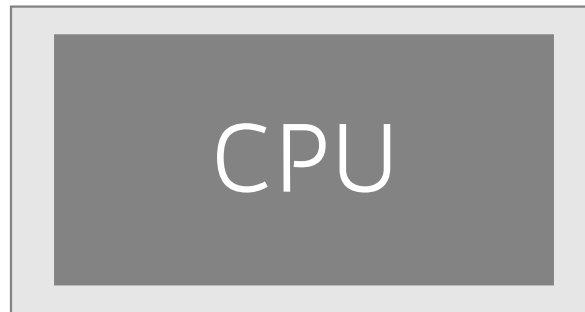
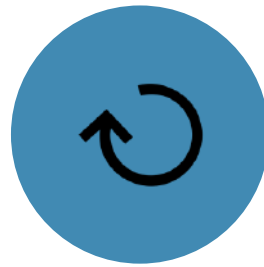
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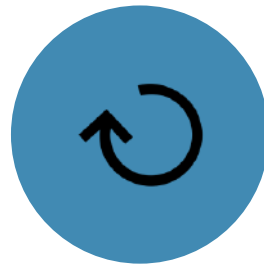
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- If N grows large it may take a while...
- Based on the underlying HW, can we improve the performance of the previously single-threaded process?
- We will consider the following setups:
 - Number of CPU cores: 1 vs. M
 - Processes/Threads: 1/1 vs. $M/1$ vs. $1/M$

1 CPU Core, 1 Process, 1 Thread

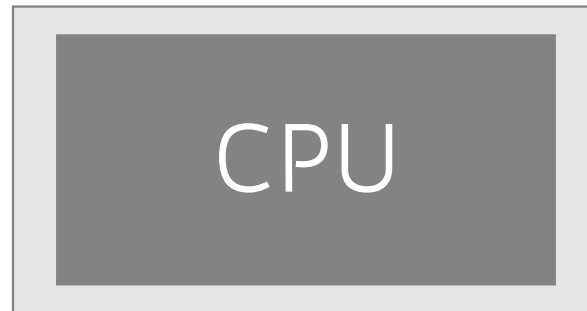


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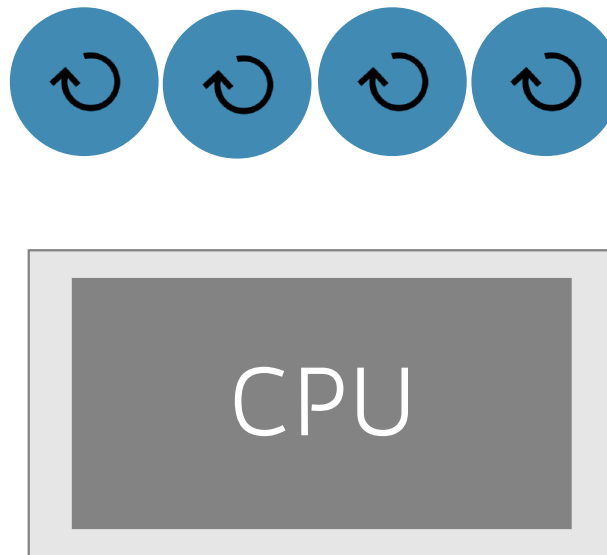
No Parallelism

No Concurrency



1 CPU Core, M Processes, 1 Thread

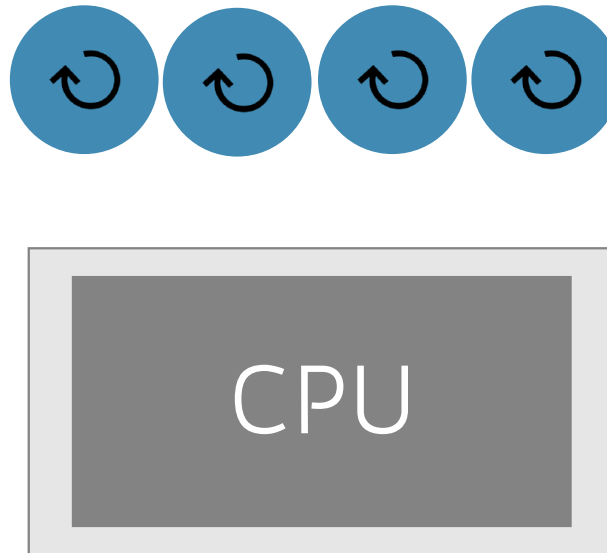
Divide N into M chunks: $\{[1, \dots, N/M], [(N/M)+1, \dots, 2N/M], \dots, [(M-1)(N/M)+1, \dots, N/M]\}$



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e.g., $N = 1000$; $M=8$: $\{[1, \dots, 125], [126, \dots, 250], \dots, [876, \dots, 1000]\}$

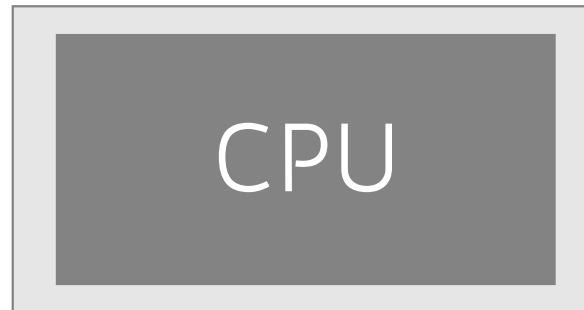
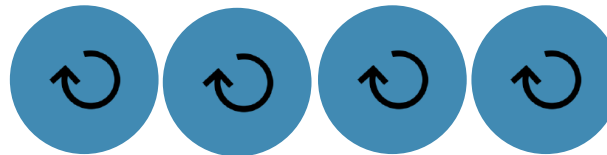


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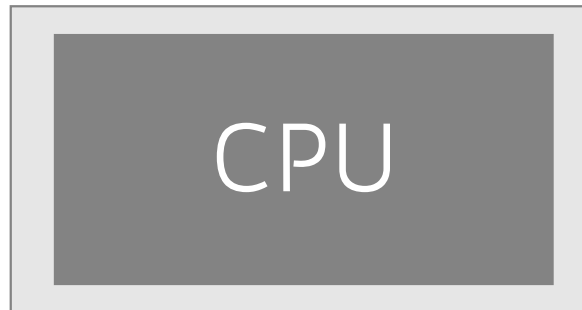
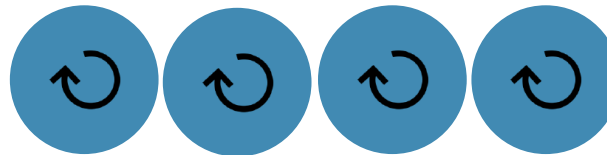


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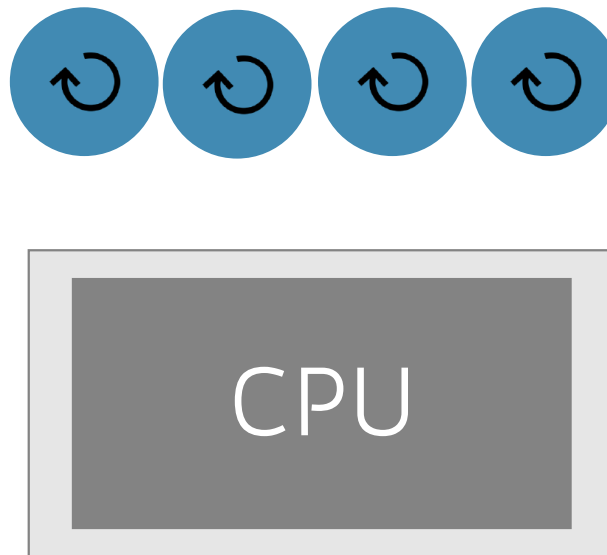


No Parallelism

Concurrency
(among processes)

1 CPU Core, M Processes, 1 Thread

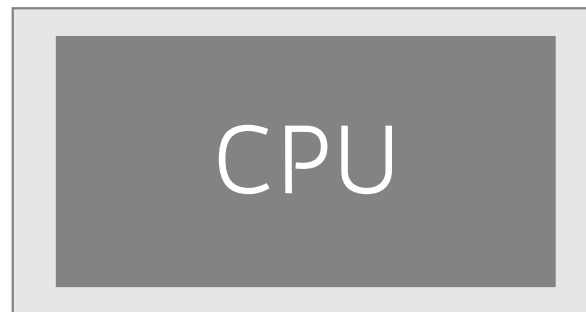
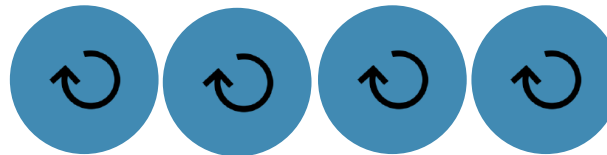
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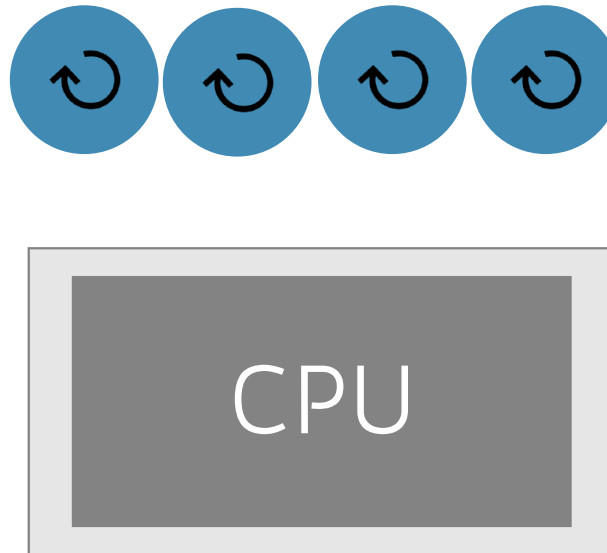
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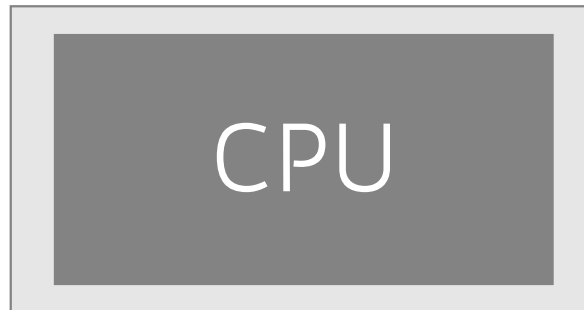
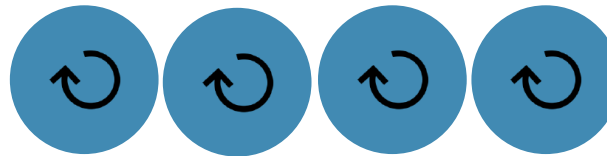


1 CPU Core, M Processes, 1 Thread

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Only one process is running on a single CPU core

All the M processes must finish to get the final result

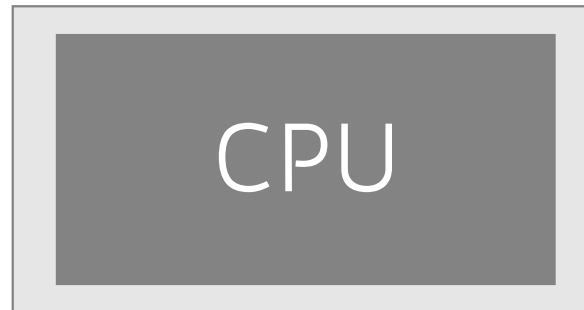
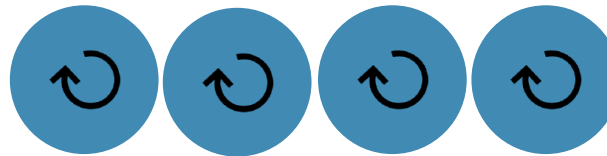


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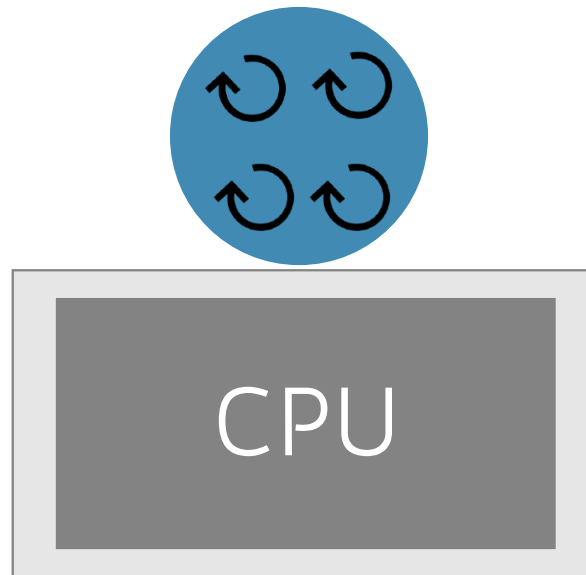


Eventually, each process must communicate its partial sum to the others

**Inter-Process
Communication**

1 CPU Core, 1 Process, M Threads

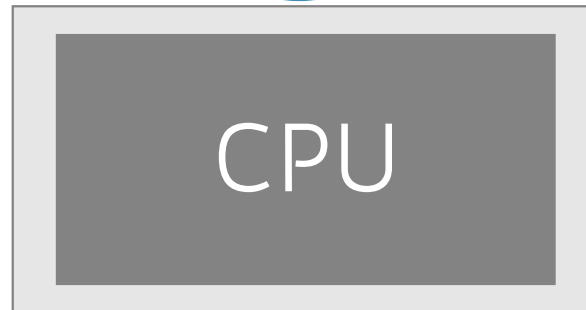
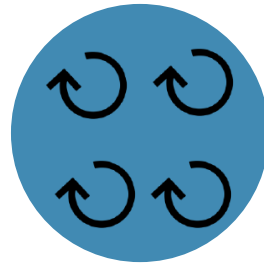
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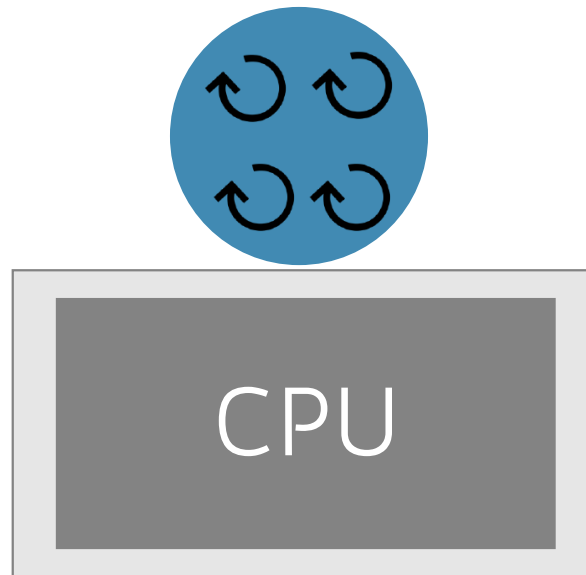
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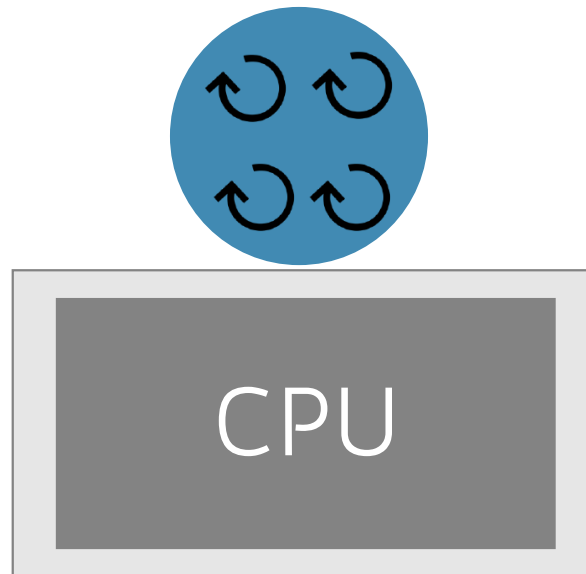
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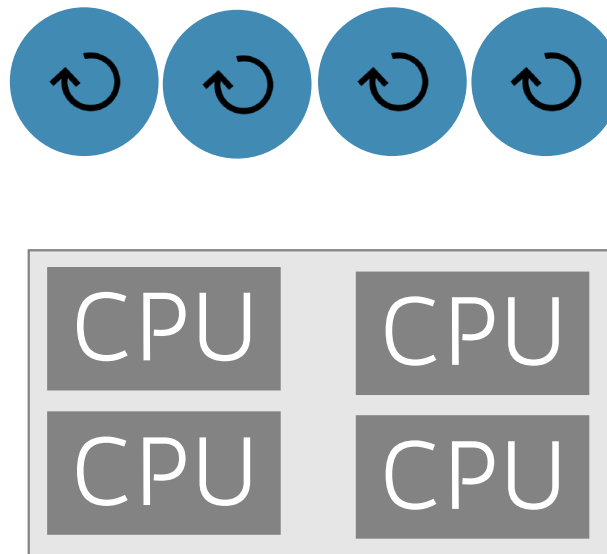


The only advantage is that each thread can easily share its partial sum with the others!

No Inter-Process Communication

M CPU Cores, M Processes, 1 Thread

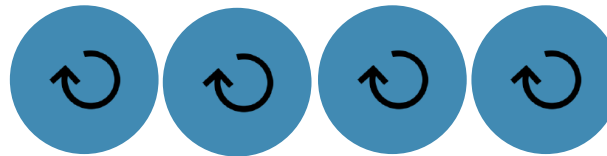
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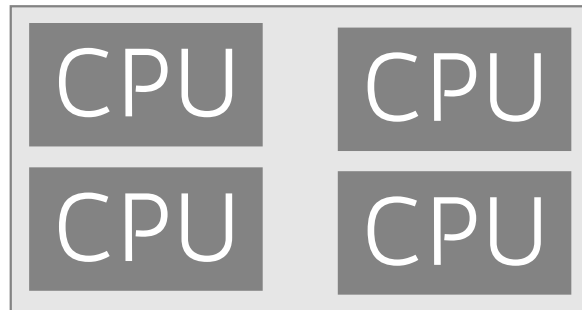
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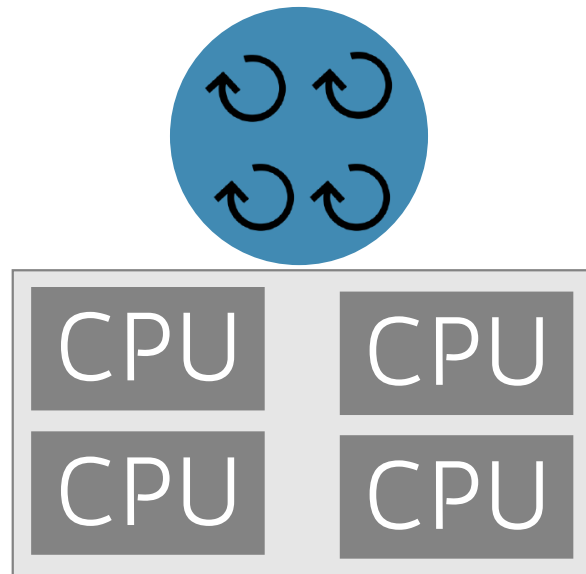
True Parallelism

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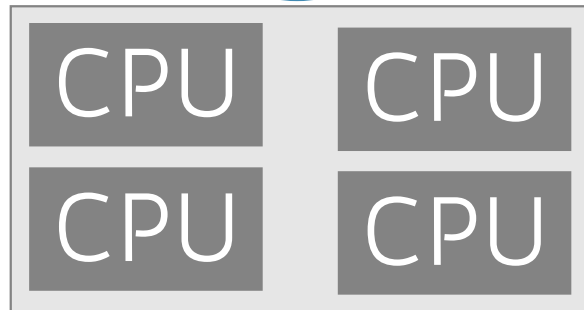
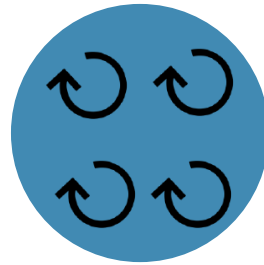
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Communication

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- Indeed, it might pay to split CPU- and I/O-intensive tasks of an application into separate threads
- This way the CPU- and I/O-bound threads can alternate on the CPU
- This slows down the CPU-bound thread a little, but reduces or eliminates the I/O-bound gap


Classifying OSs

 address space

 thread

Classifying OSs


 address space


 thread

single thread

multiple threads

Classifying OSs

 address space

 thread

single address space
(uniprogramming)

multiple address spaces
(multiprogramming)

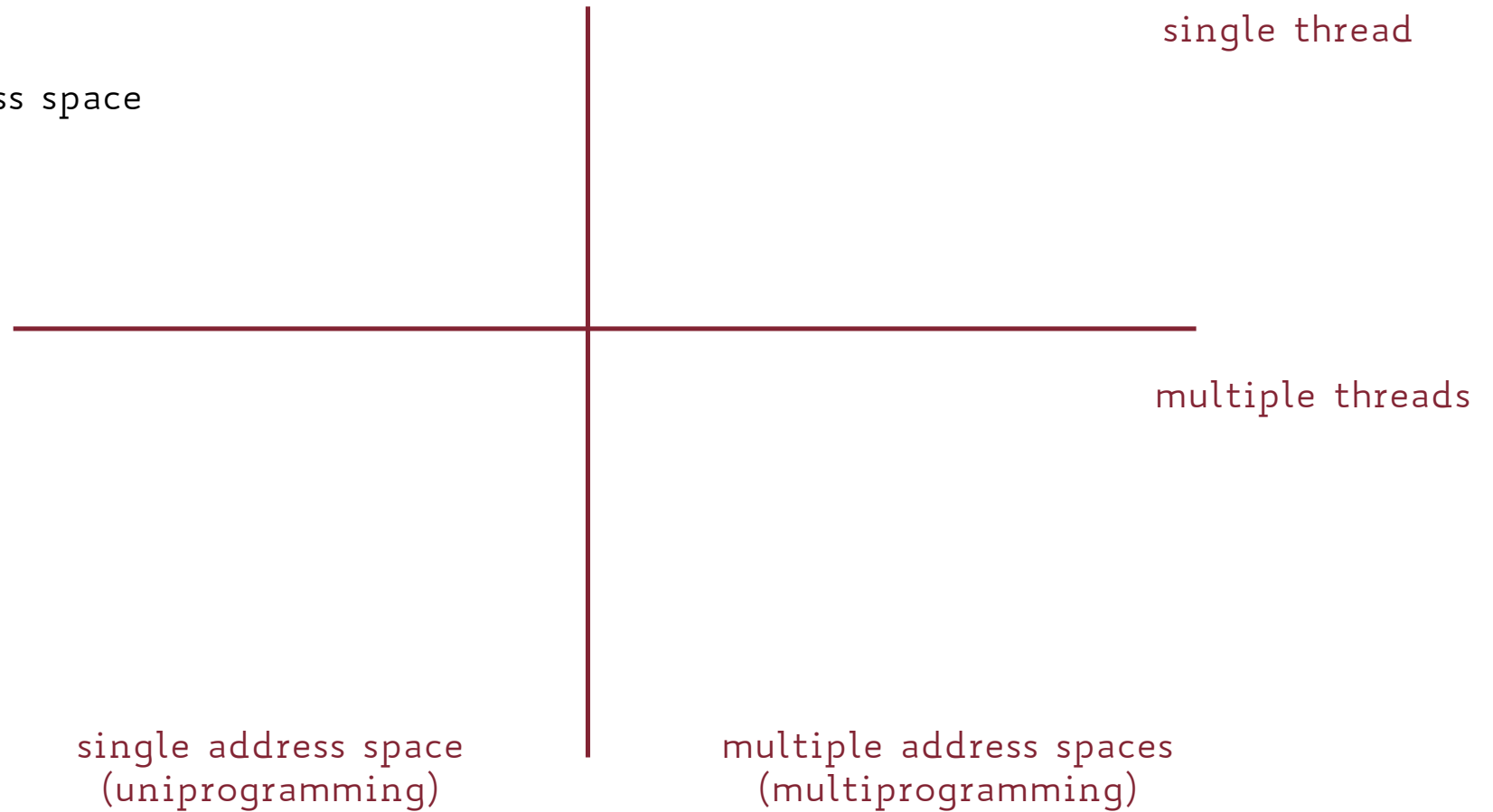
Classifying OSs



address space




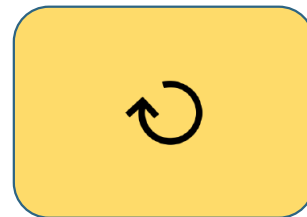
thread



Classifying OSs

 address space

 thread





MS-DOS

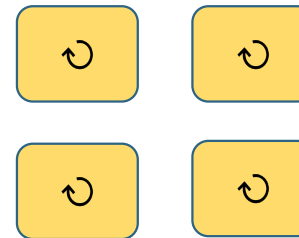
single thread

single address space
(uniprogramming)

Classifying OSs

 address space

 thread



UNIX

single thread

multiple address spaces
(multiprogramming)

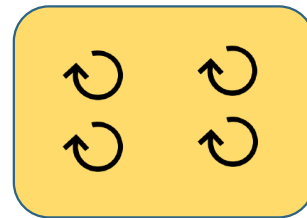
Classifying OSs



address space



thread





Xerox Pilot

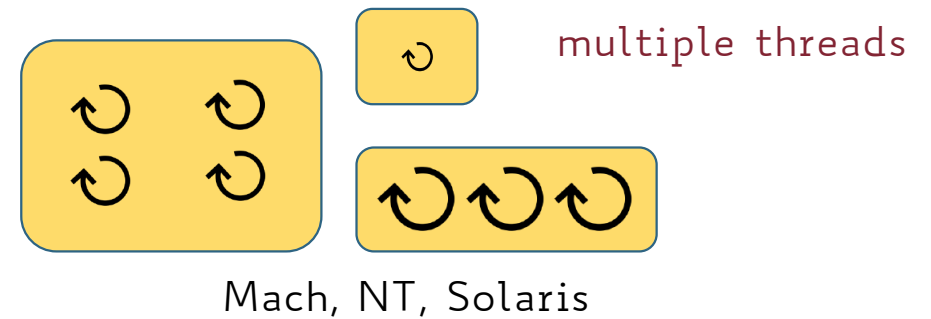
multiple threads

single address space
(uniprogramming)

Classifying OSs

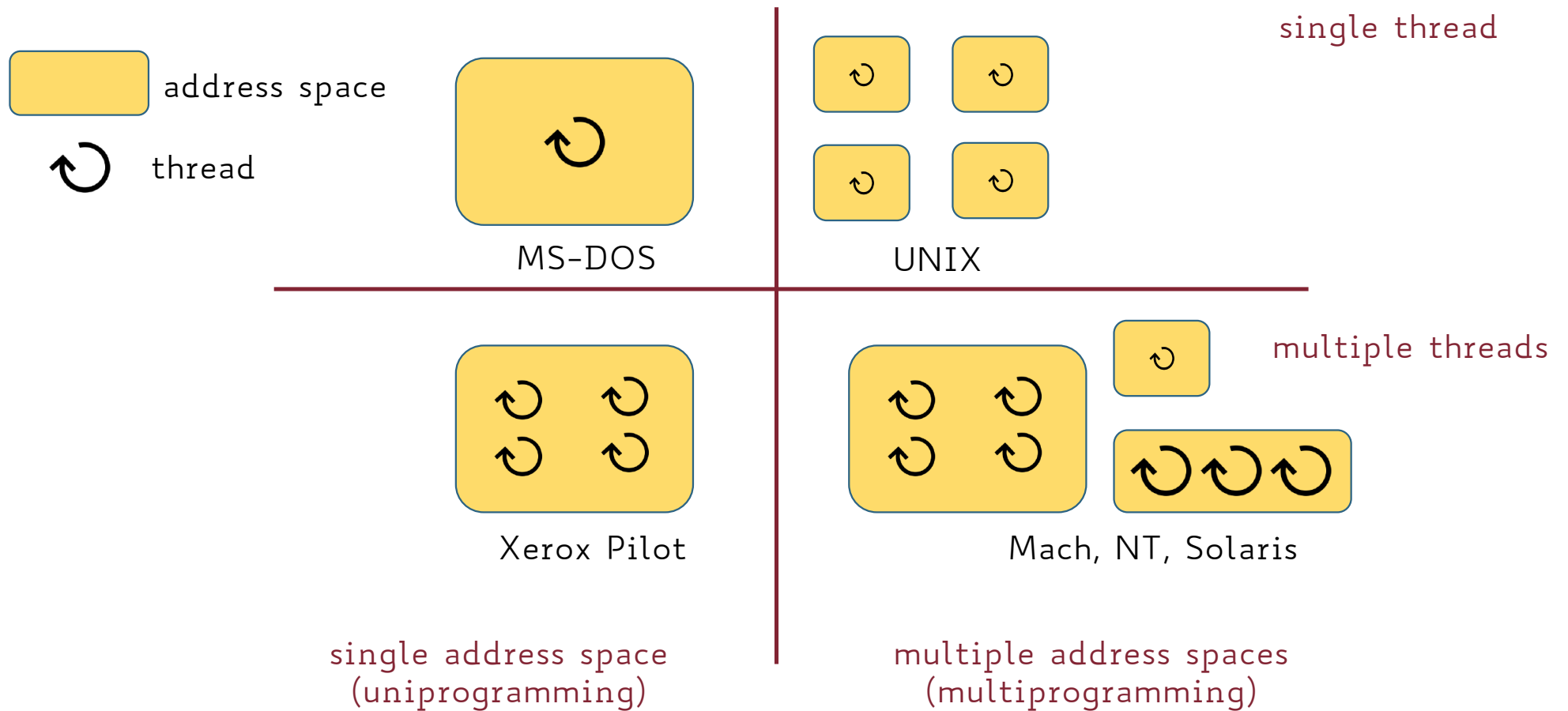
 address space

 thread



multiple address spaces
(multiprogramming)

Classifying OSs



Summary

- A **thread** is a single execution stream within a process

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- A **thread** is a single execution stream within a process
- **Thread** vs. **Process**:
 - common vs. separate address spaces → **quicker communication**
 - lightweight vs. heavyweight → **faster context switching**
- On a single core:
 - Fully CPU-bound processes do not take advantage of multi-threading
 - Concurrency between threads in mixed CPU- and I/O-bound processes