Systems and Networking I

Applied Computer Science and Artificial Intelligence

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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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- Traditional (heavyweight) processes have a single thread of control
  - 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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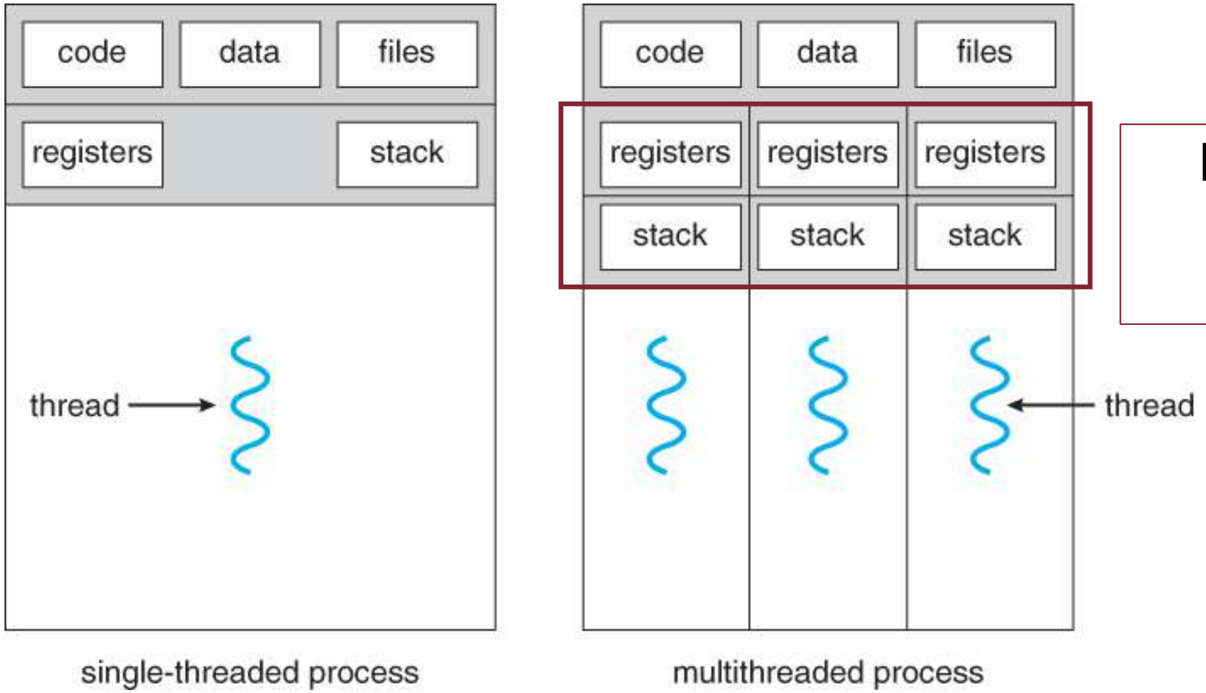
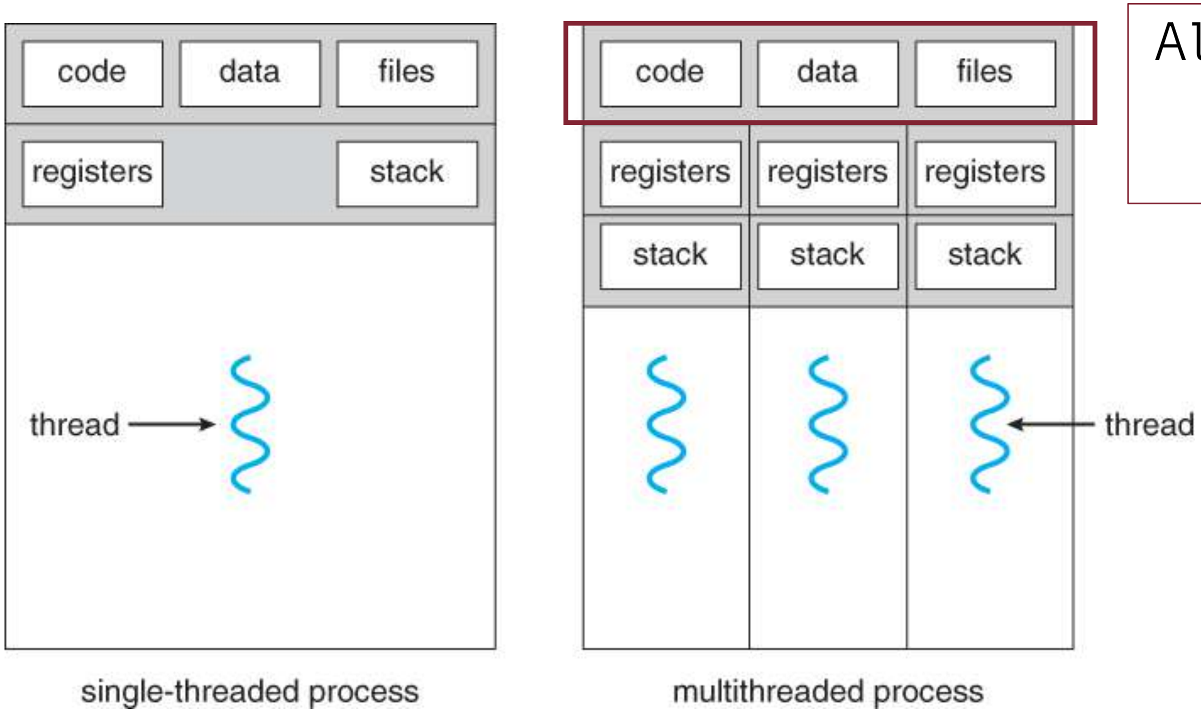
- No system calls are required for threads to cooperate with each other
- Simpler than message passing and shared memory

Single- vs. Multi-Threaded Process



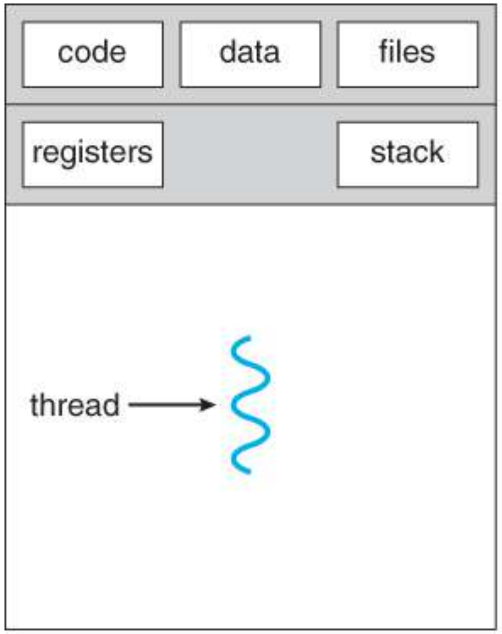
Each thread has its own independent set of registers and "state"

Single- vs. Multi-Threaded Process

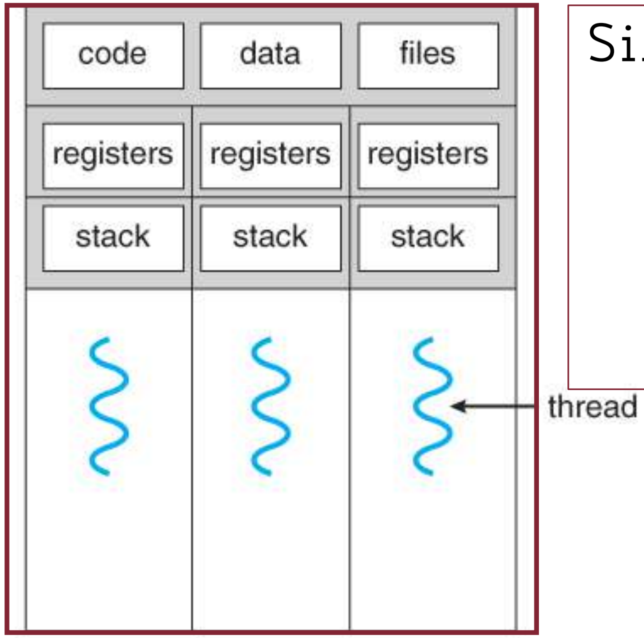


All the threads of a process share the same code and "global" resources

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

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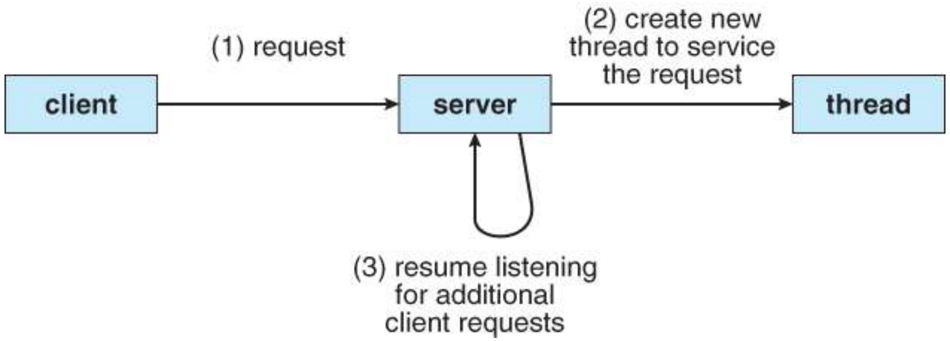
- Threading allows overlap of I/O with other tasks within the same program
  - Similar to what multiprogramming does across different processes
- **Example: word processor**
  - a thread may check grammar while another thread handles user input (keystrokes), and a third does periodic backups of the file being edited

Multi-threaded Web Server



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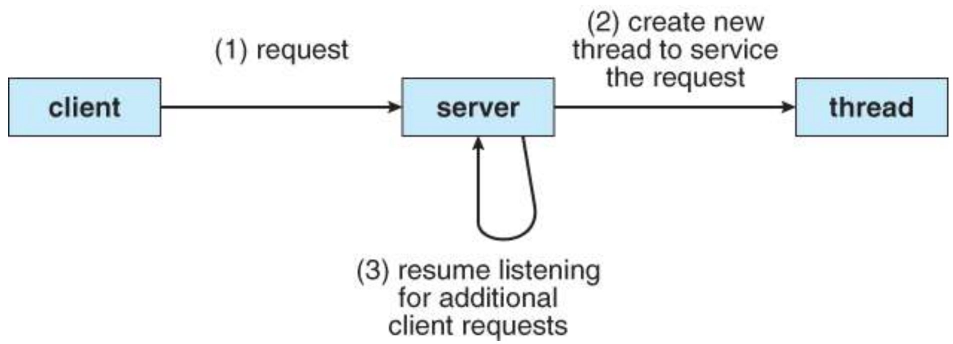
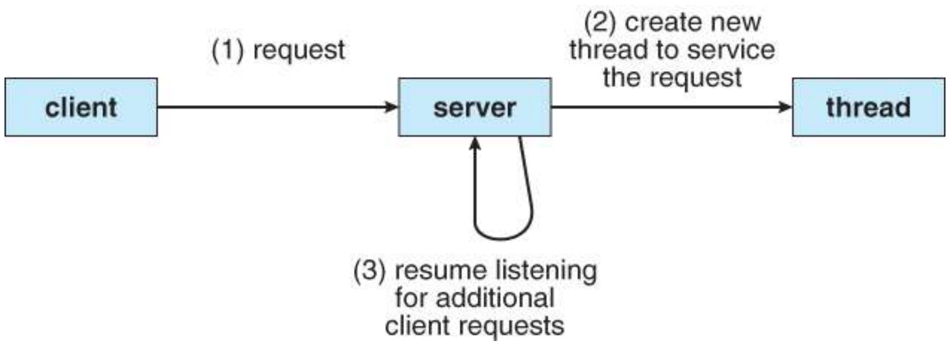


Multiple threads allow for multiple requests to be satisfied simultaneously, without having to serve requests sequentially or to fork off separate processes for every incoming request

Multi-threaded Web Server



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

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

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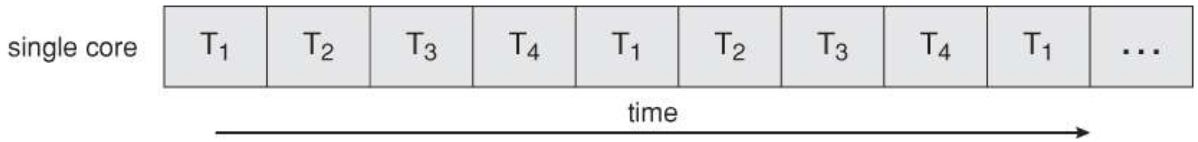
  - **Scalability** (multi-processor architectures) → A single threaded process can only run on one CPU, whereas a multi-threaded process may be split amongst all available processors/cores

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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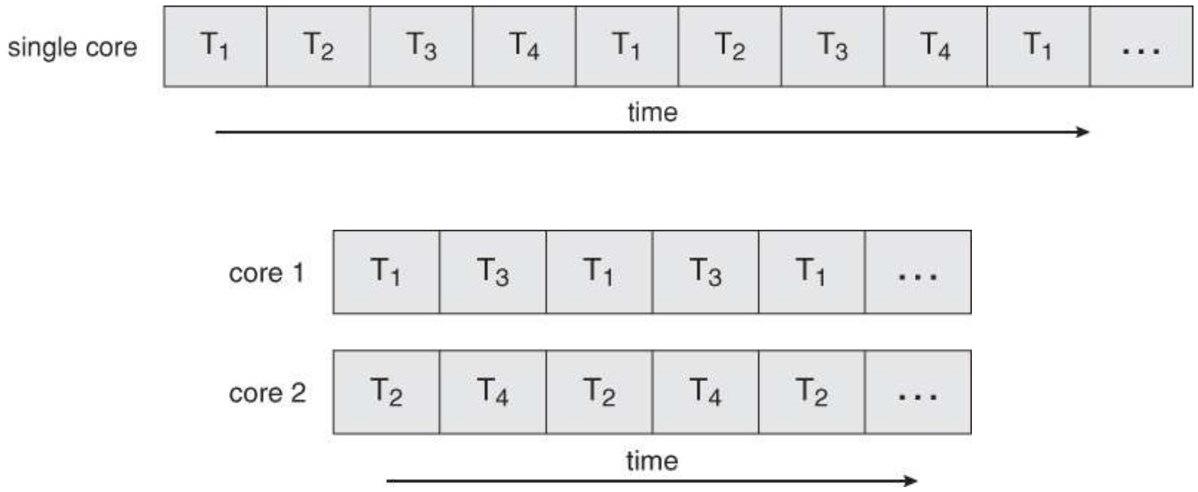

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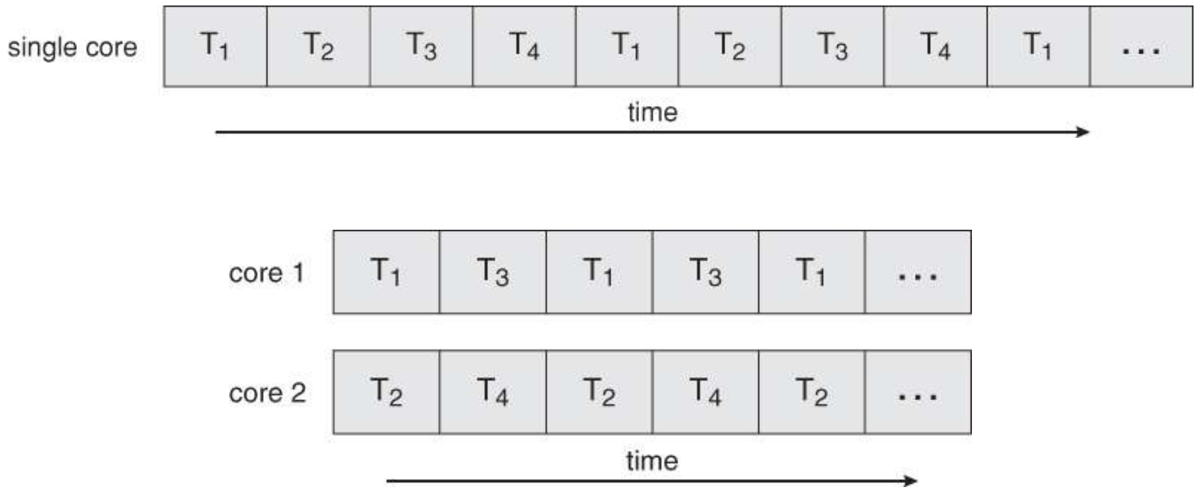

Multi-core chips require new OS scheduling algorithms to make better use of the multiple cores available

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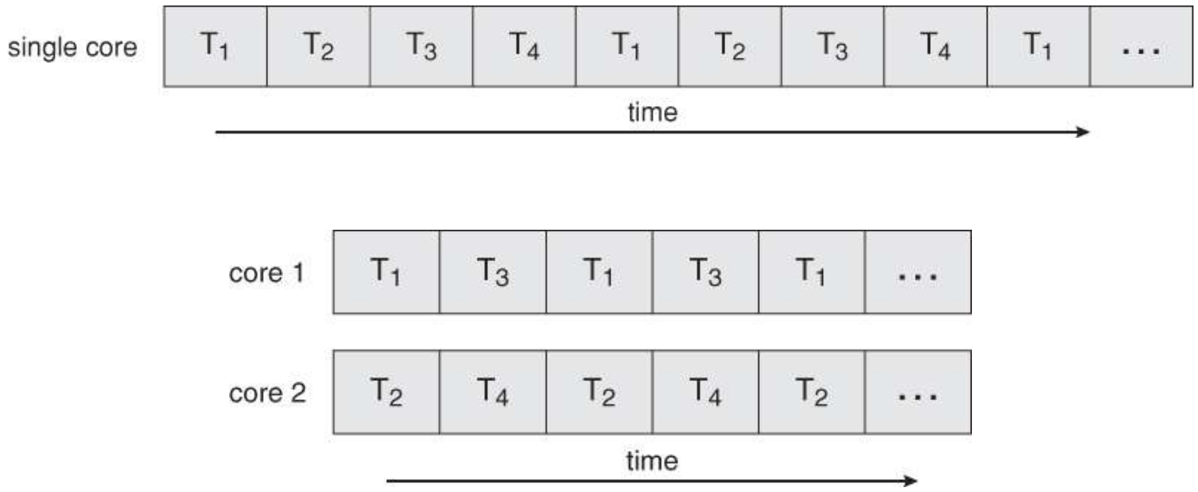

CPUs have been developed to support more simultaneous threads per core in hardware (e.g., Intel's hyper-threading)

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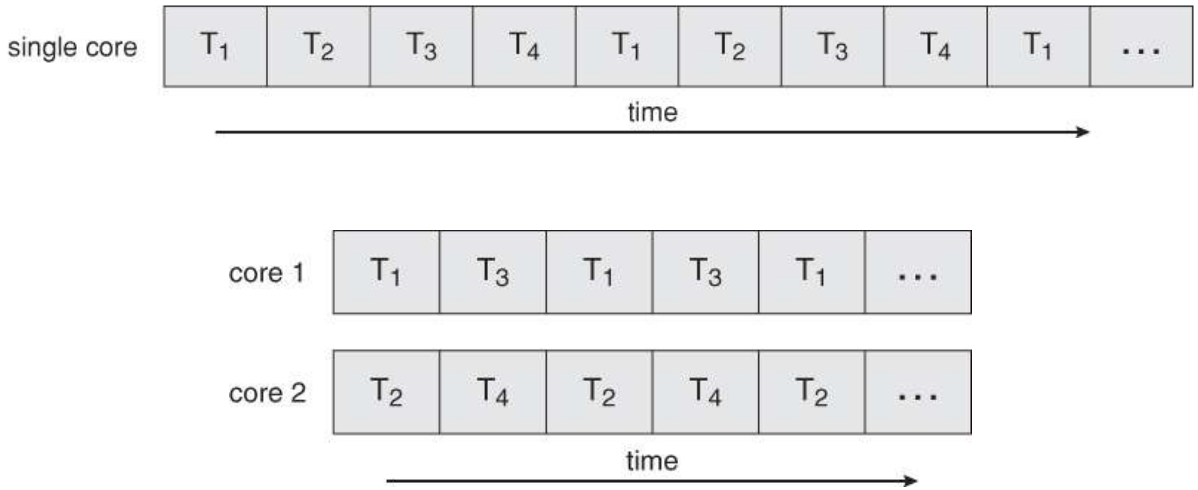
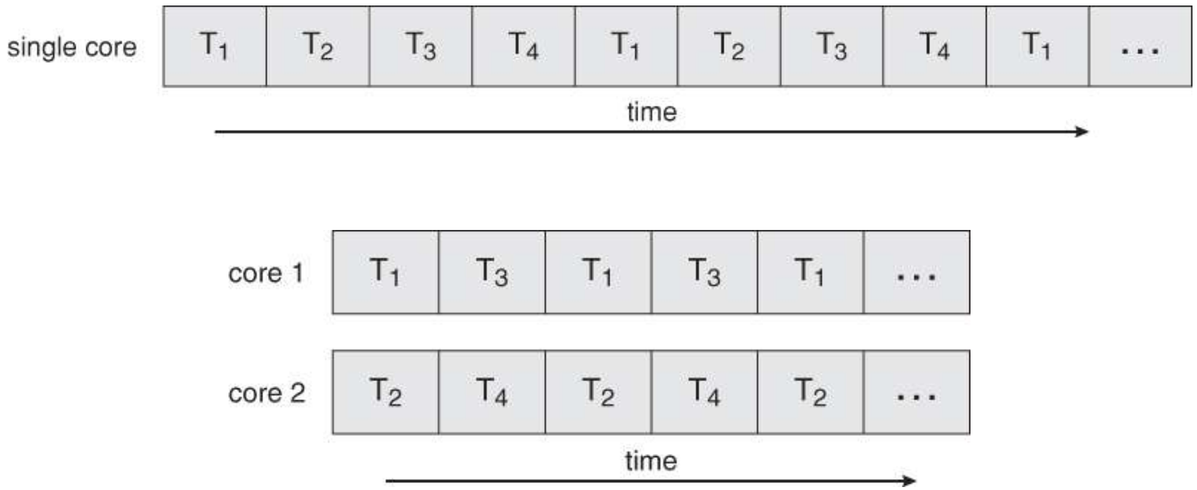


Hyper-threading

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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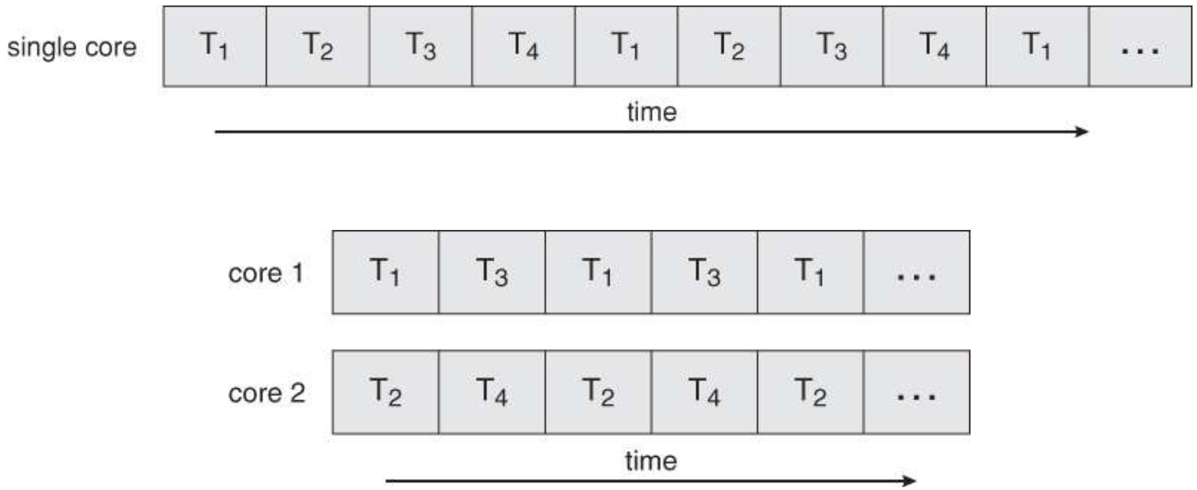

Concurrency

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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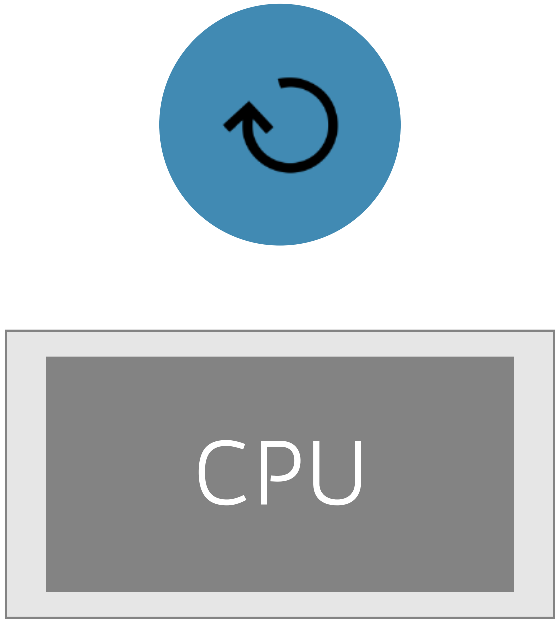
- Based on the underlying HW, can we improve the performance of the previously single-threaded process?
- We will consider the following setups:
  - Number of CPU cores: 1 vs. M
  - Processes/Threads: 1/1 vs. M/1 vs. 1/M

1 CPU Core, 1 Process, 1 Thread



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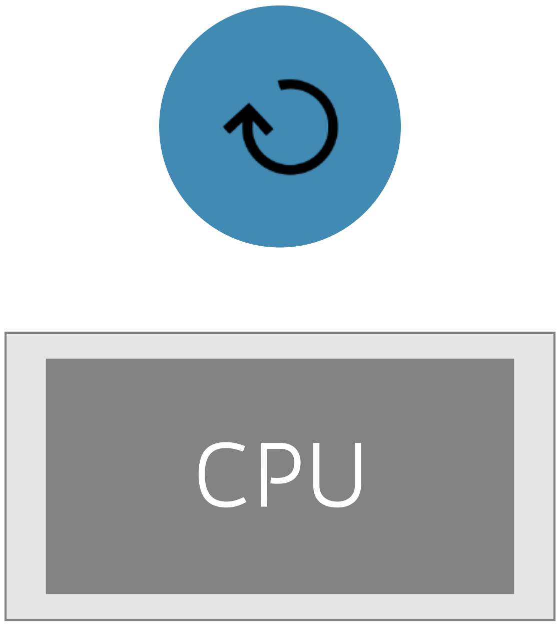
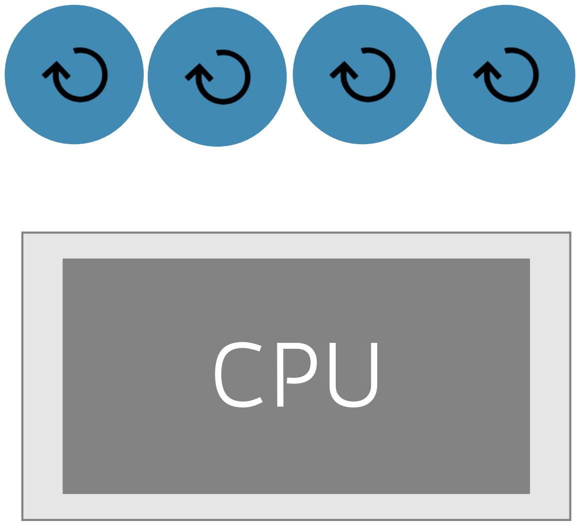


No Parallelism

No Concurrency

1 CPU Core, M Processes, 1 Thread

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



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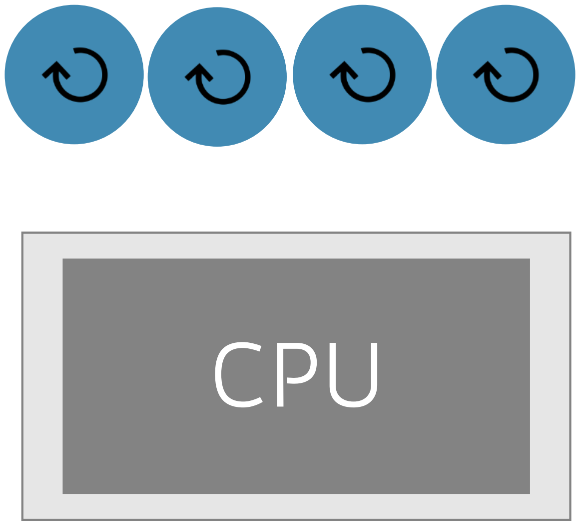
e.g., N = 1000; M=8: {[1, ..., 125], [126, ..., 250], ..., [876, ..., 1000]}



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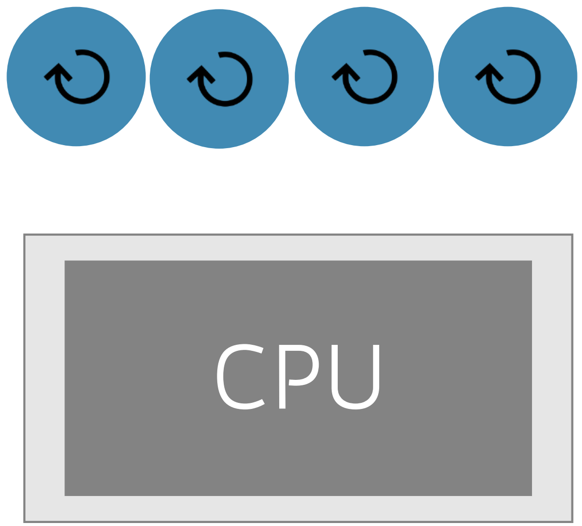

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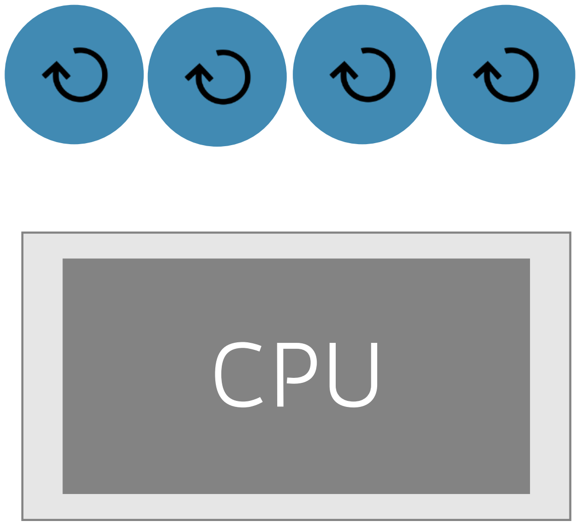

No Parallelism

Concurrency (among processes)

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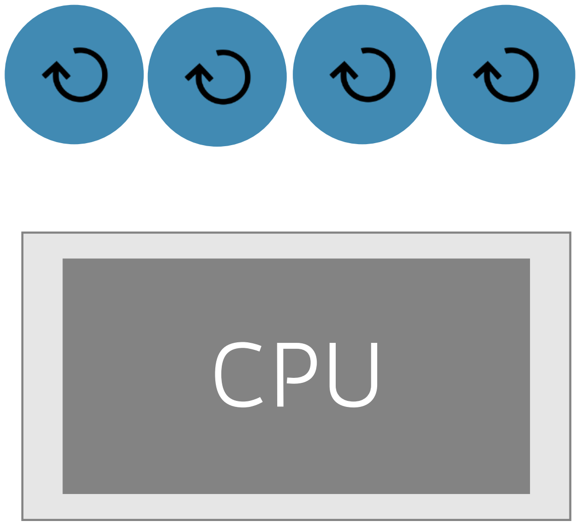
Will this solution get any speedup to the whole computation?



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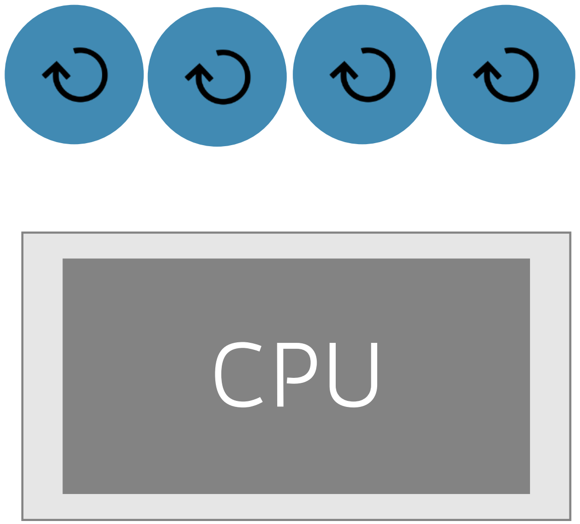

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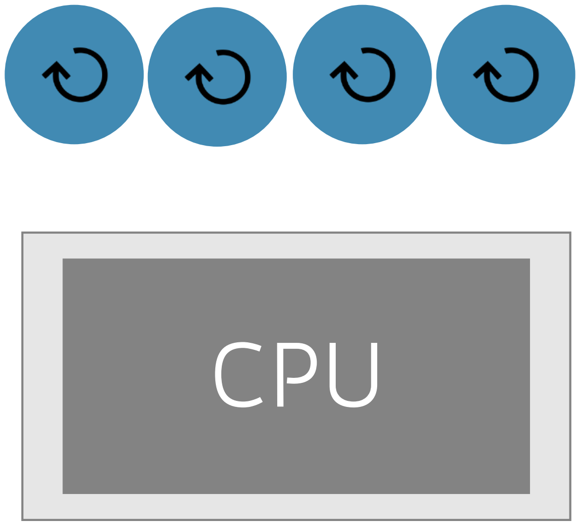

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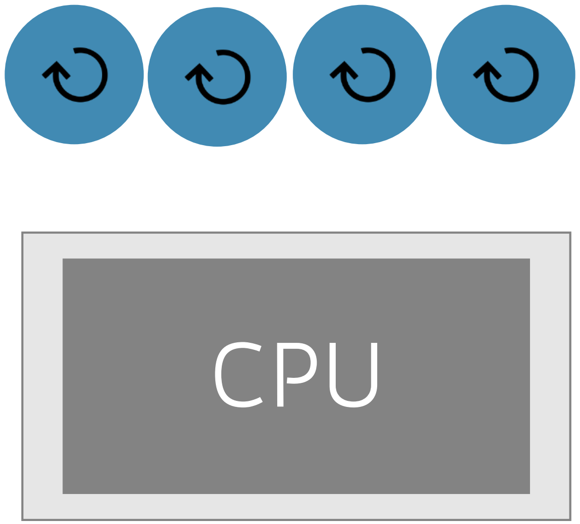

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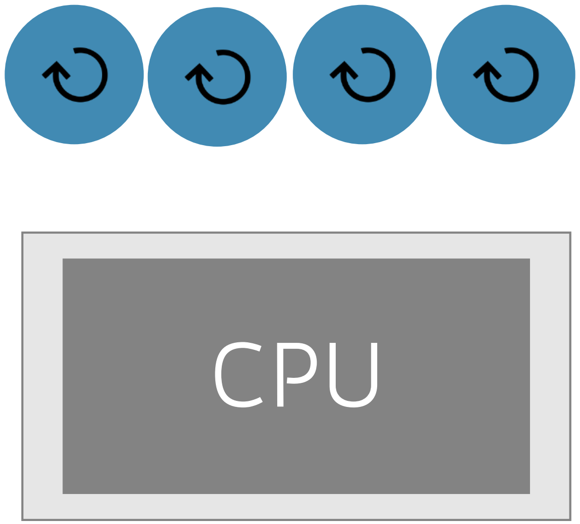

Eventually, each process must communicate its partial sum to the others

Inter-Process Communication

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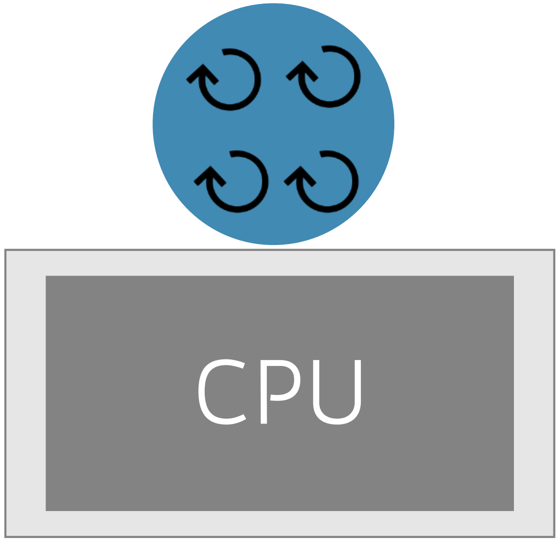

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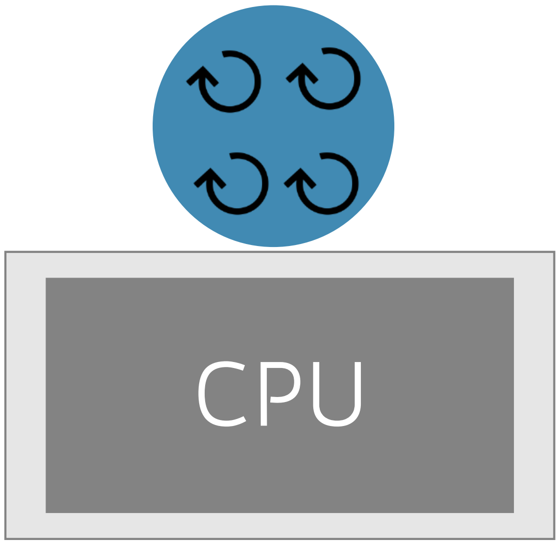

1 CPU Core, 1 Process, M Threads

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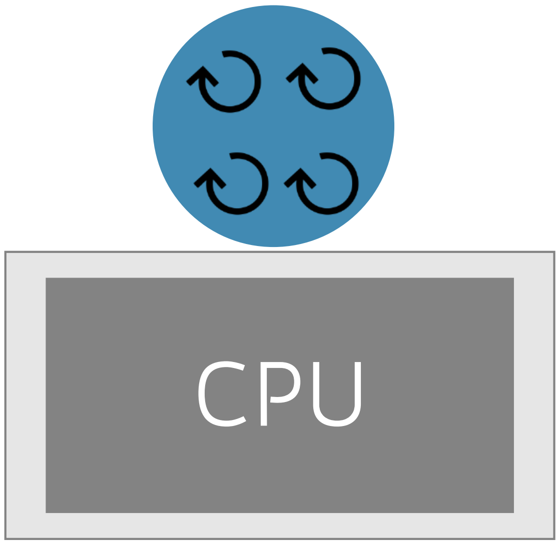

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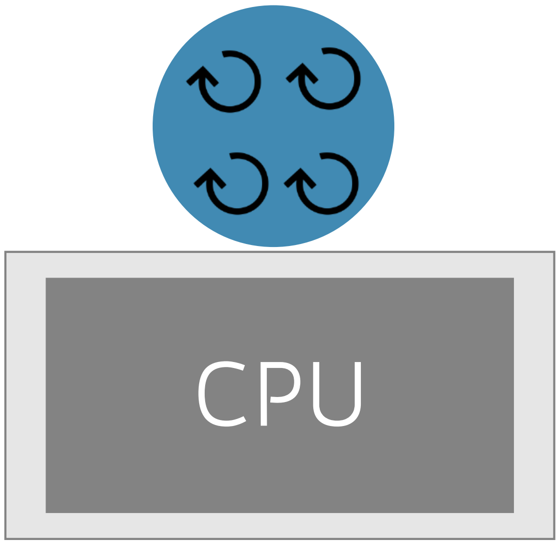

The only advantage is that each thread can easily share its partial sum with the others!

No Inter-Process Communication

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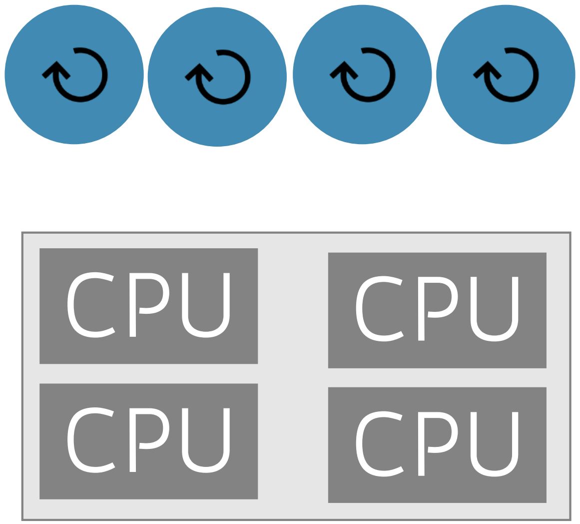

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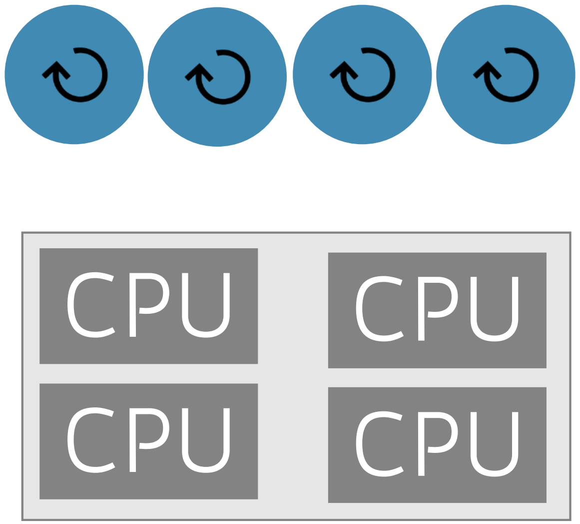

True Parallelism

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

M CPU Cores, 1 Process, M Threads

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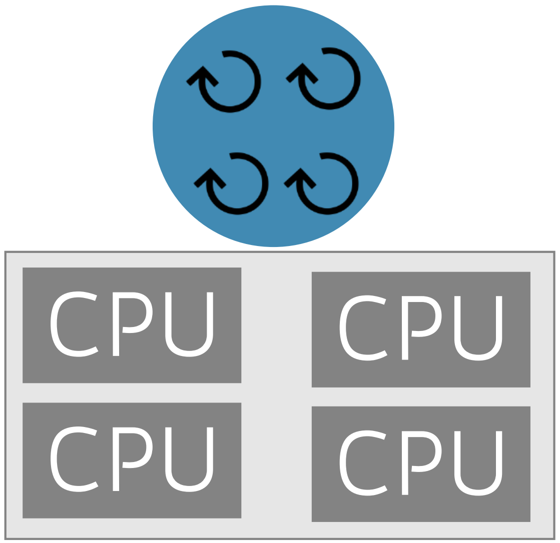

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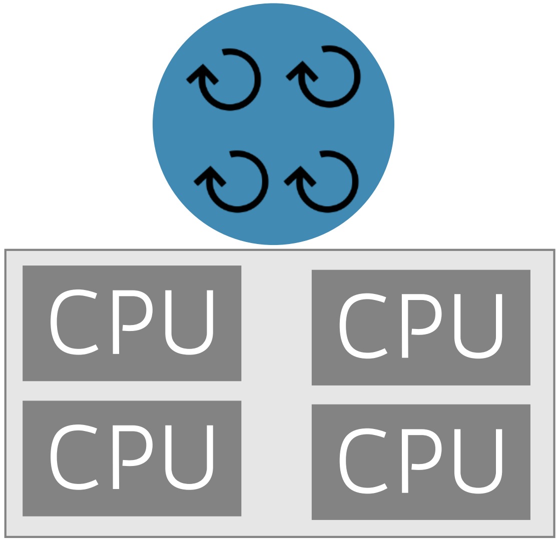

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  - Compression/Decompression algorithms (side-by-side)

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

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  - 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

Multi-threading: Support and Management

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- User threads
  - managed in user space by a user-level thread library, without OS intervention

Kernel Threads

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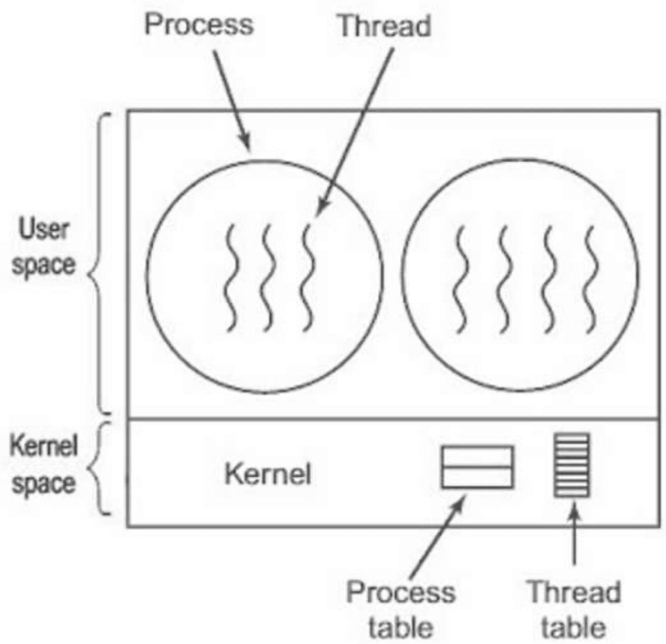
Kernel Threads: PROs



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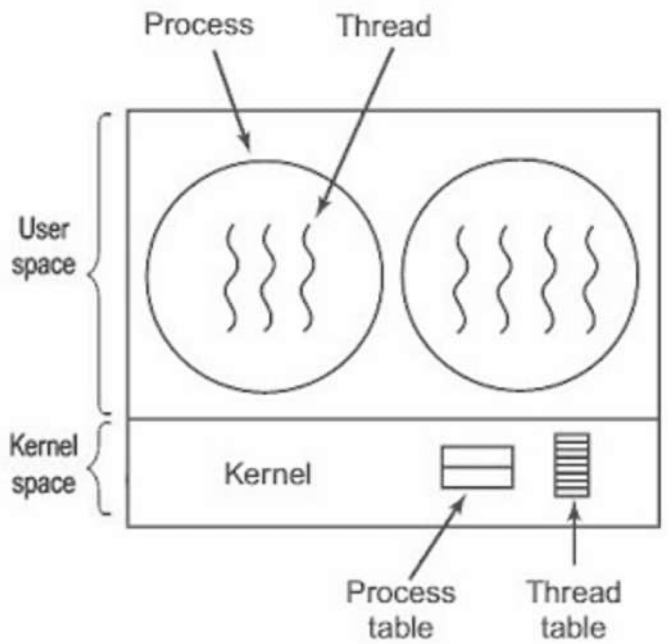

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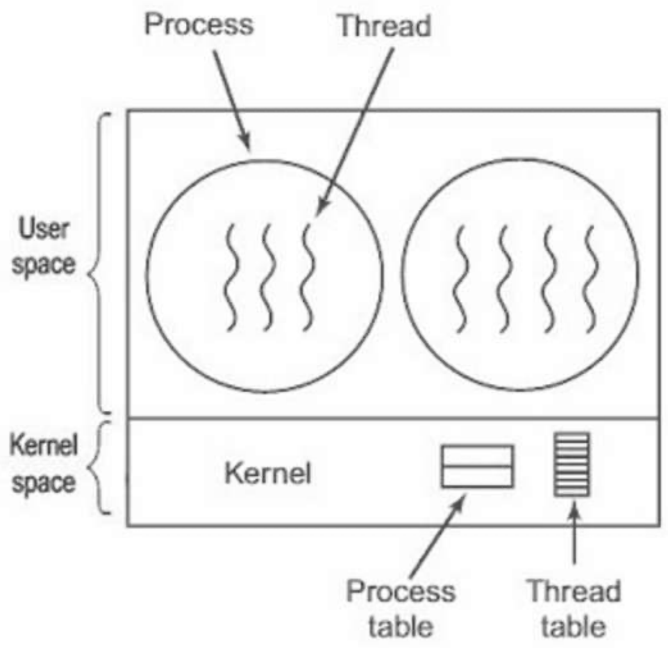

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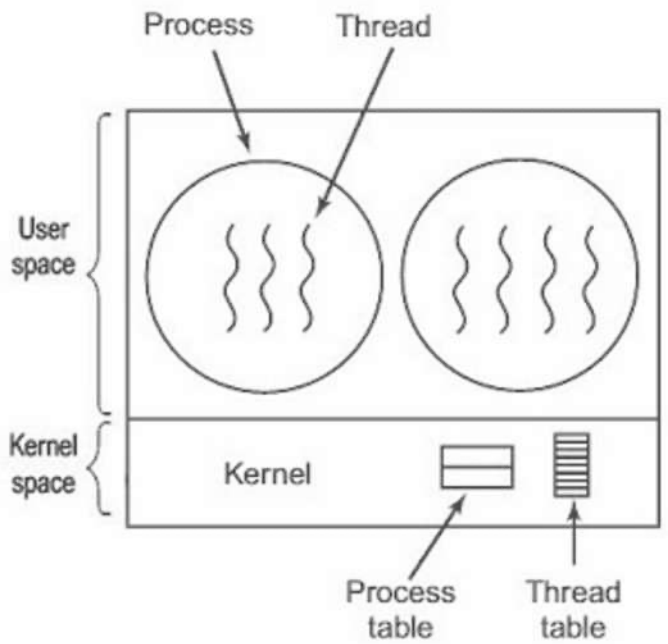

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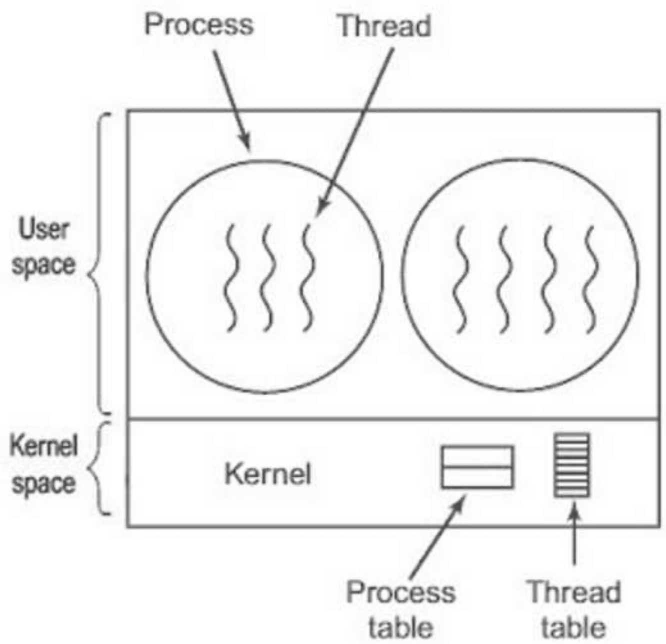

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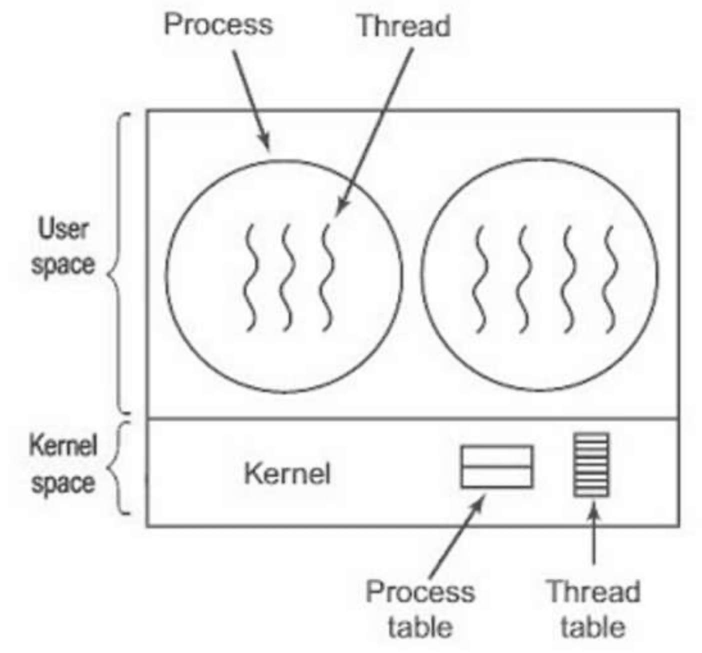

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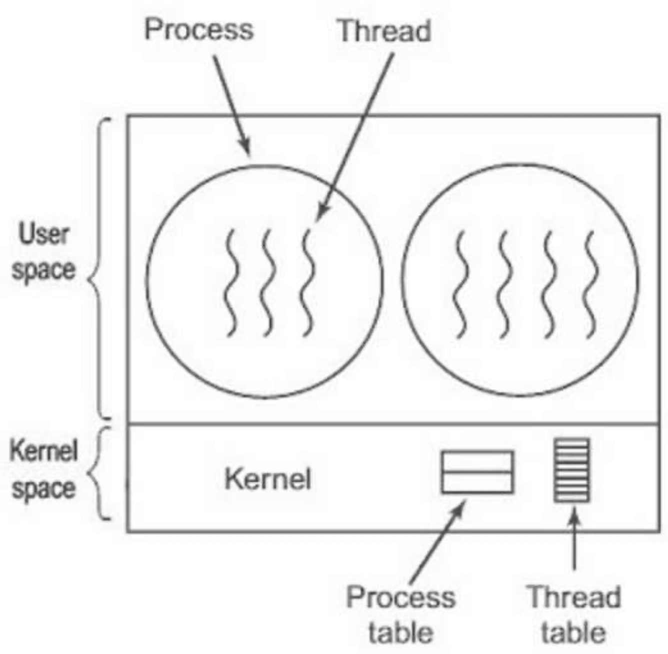

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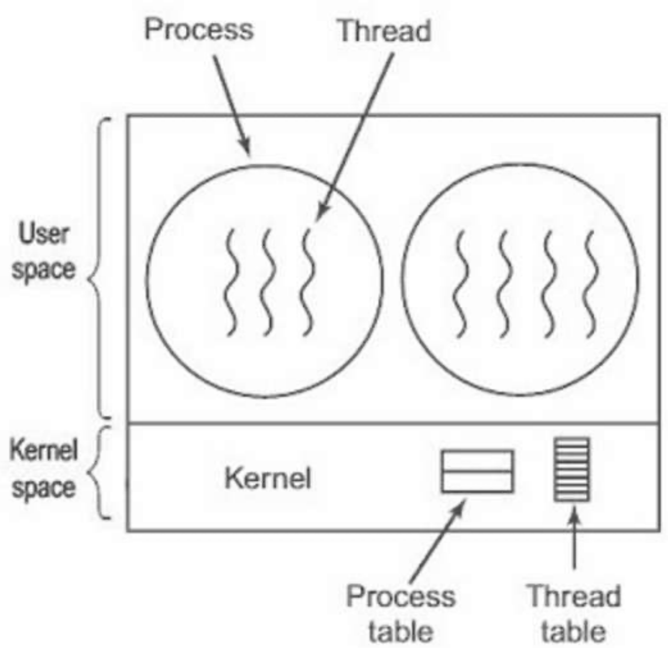

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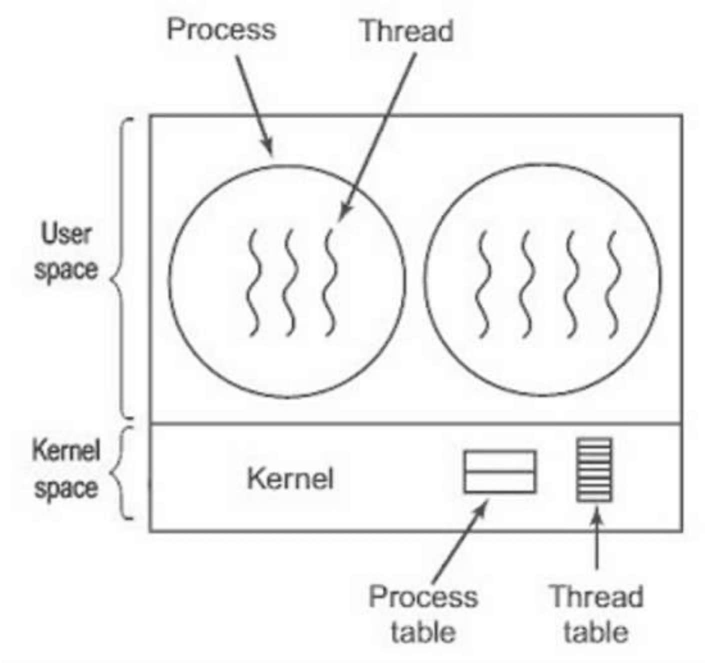

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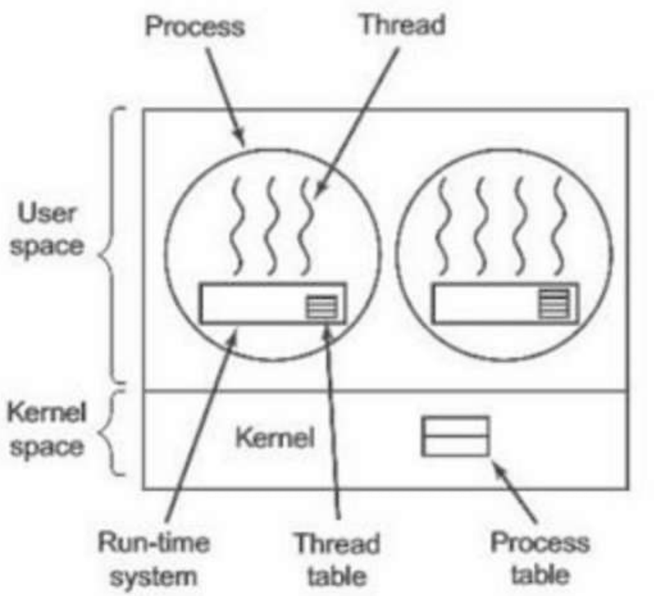

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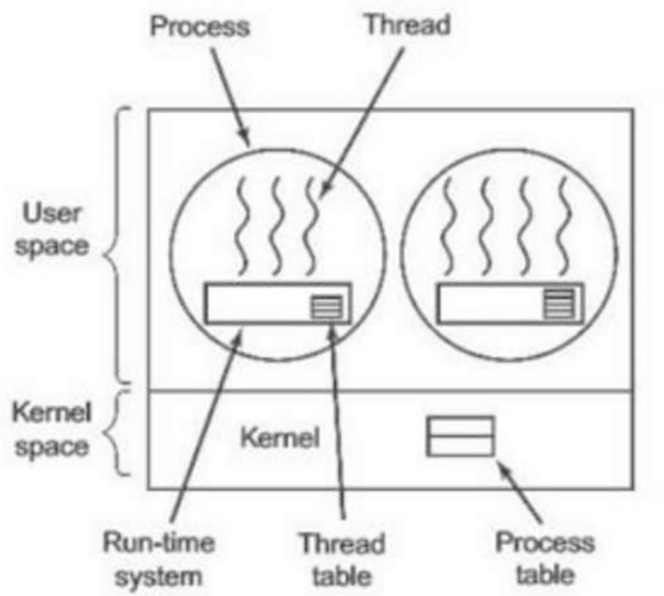

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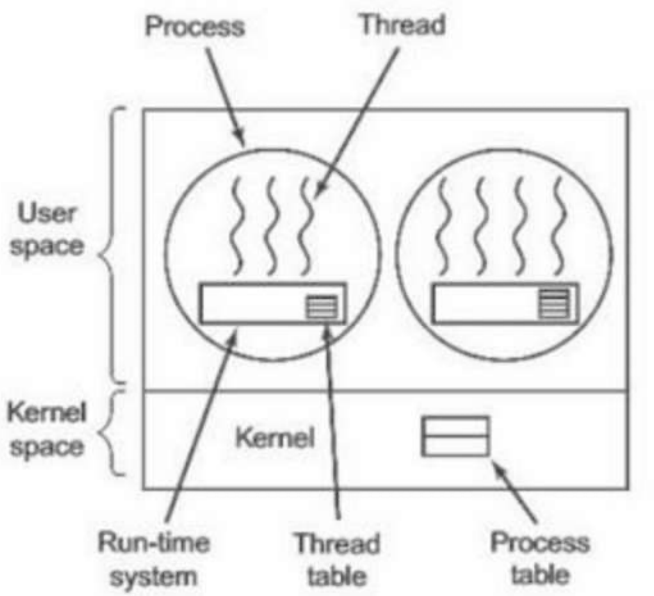

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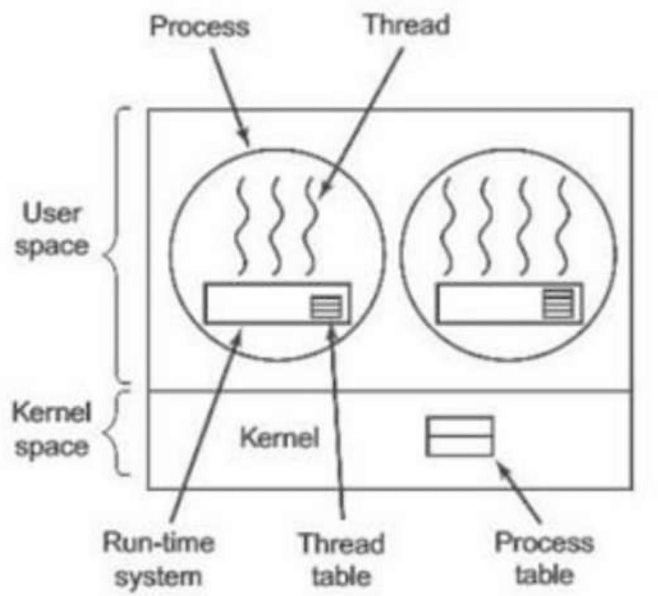

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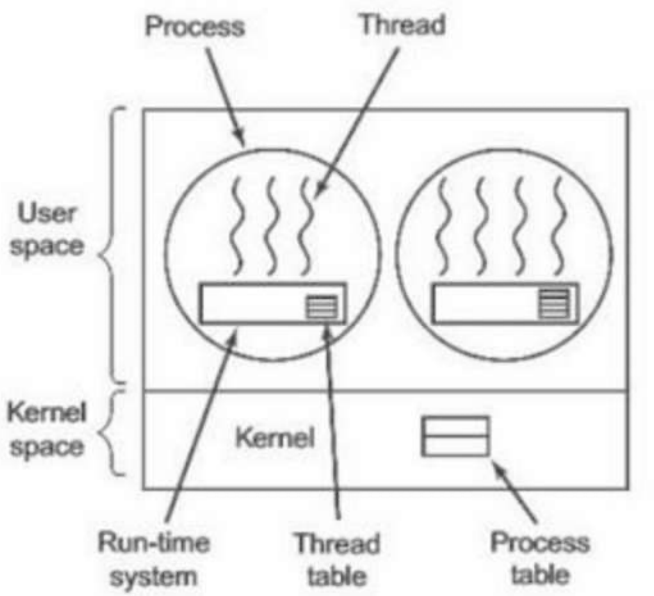

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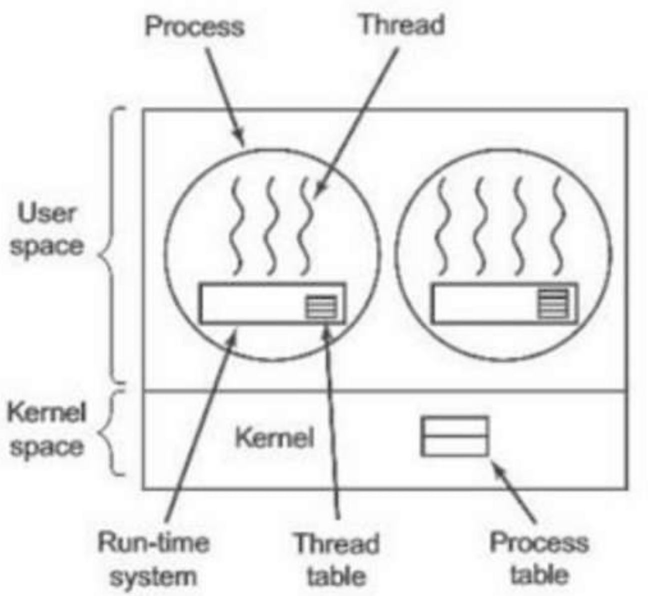

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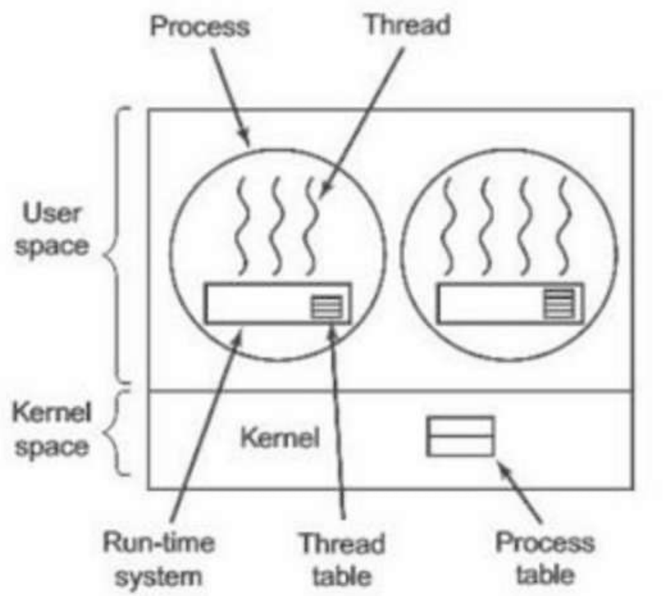

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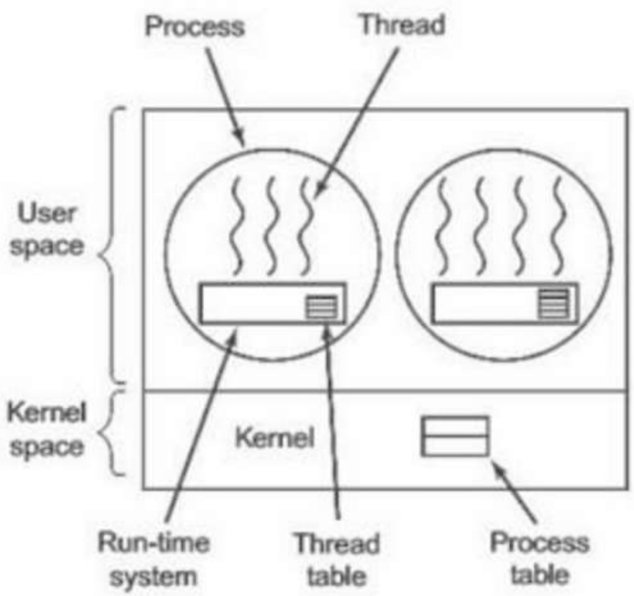

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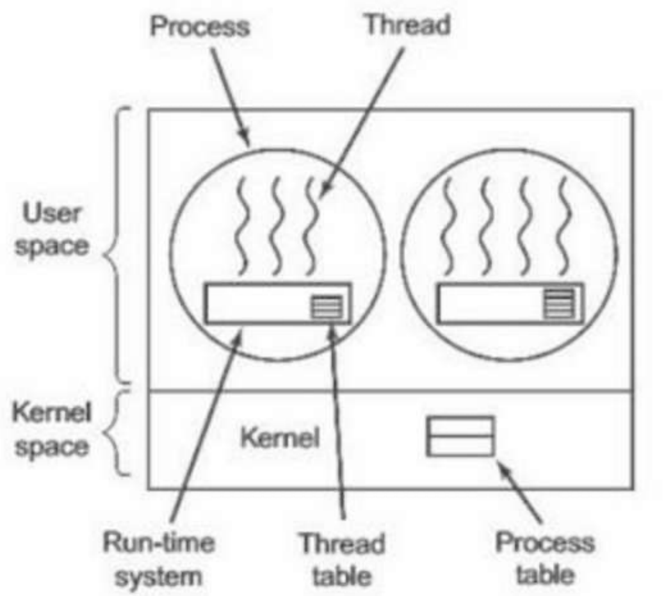

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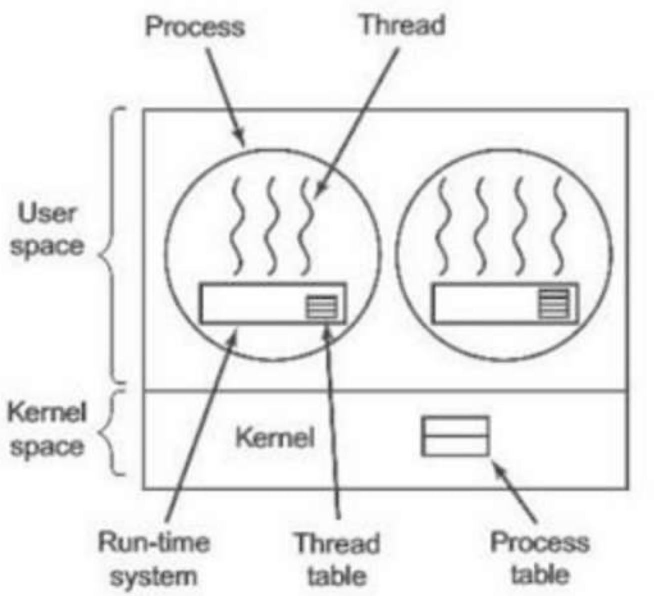

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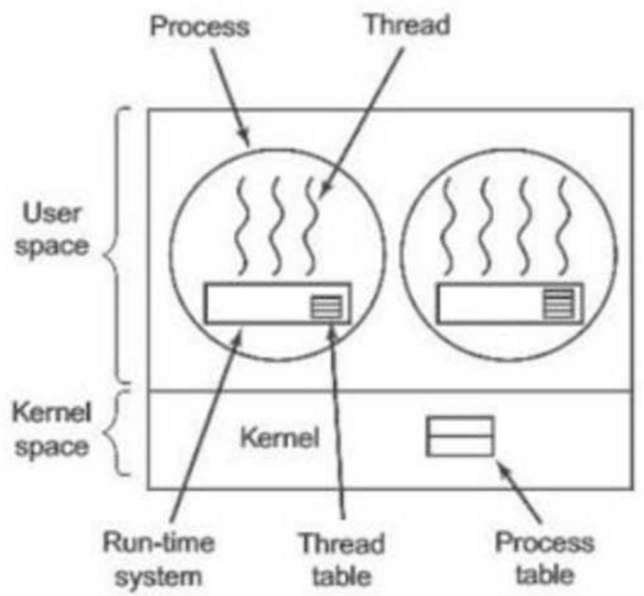

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Multi-threading Models

- In a specific implementation, user threads must be mapped to kernel threads in one of the following ways:
  - Many-to-One (N:1)
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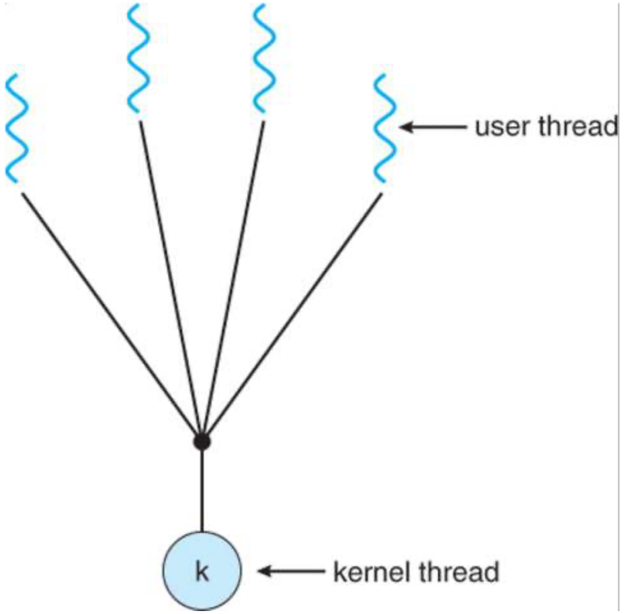
Remember:

A kernel thread is the unit of execution that is scheduled by the OS to run on the CPU (similar to single-threaded process)

Many-to-One Model (N:1)



- Many user threads are all mapped onto a single kernel thread
- The process can only run one user thread at a time because there is only one kernel thread associated with it
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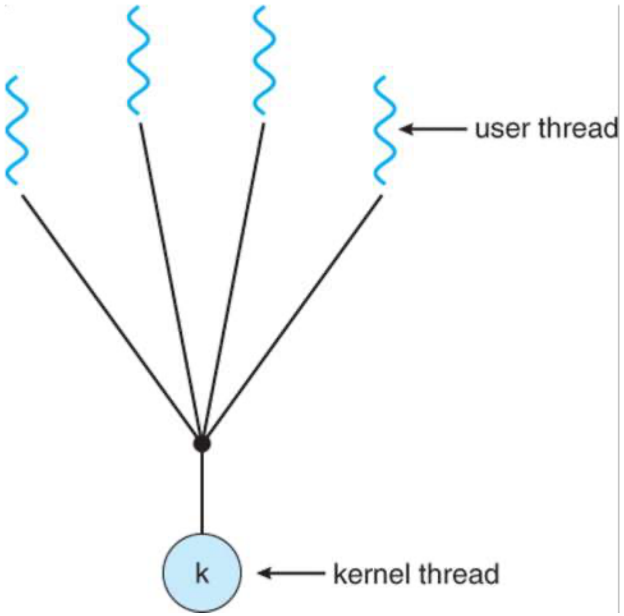

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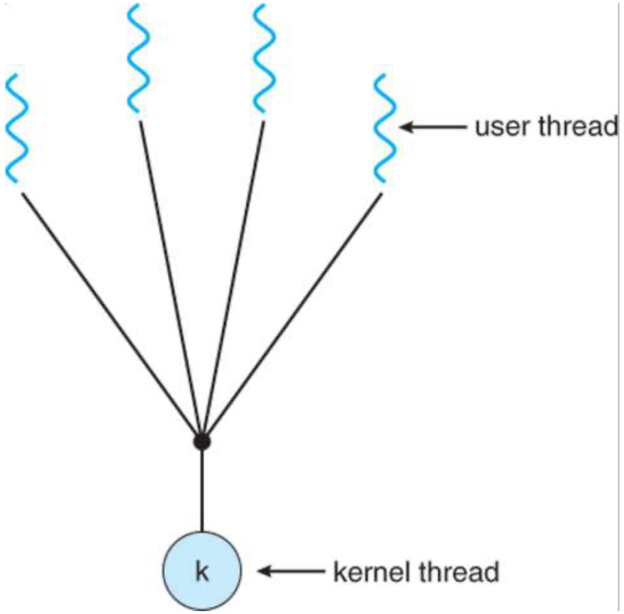

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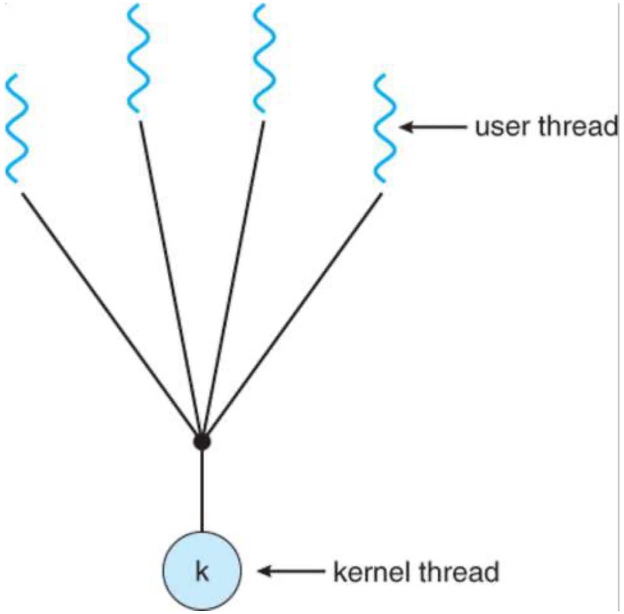

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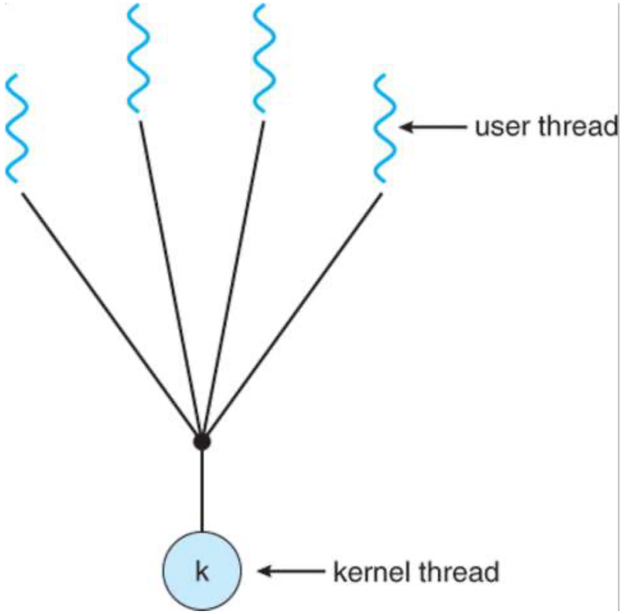

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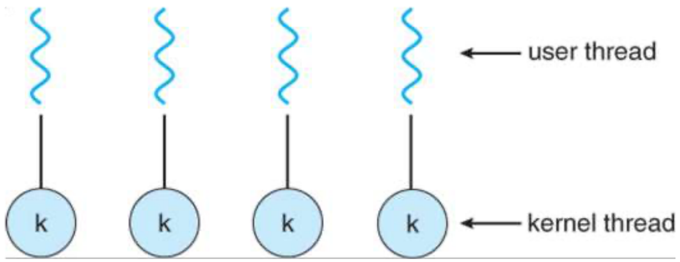

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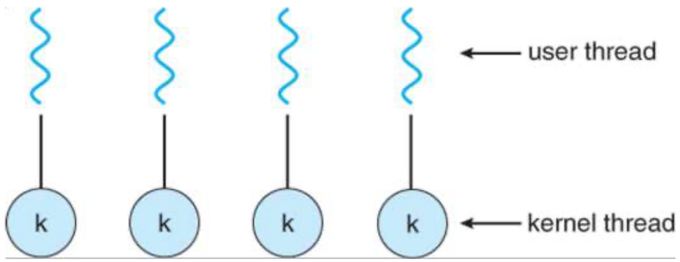

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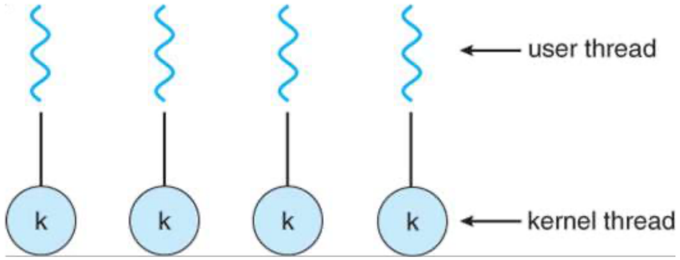

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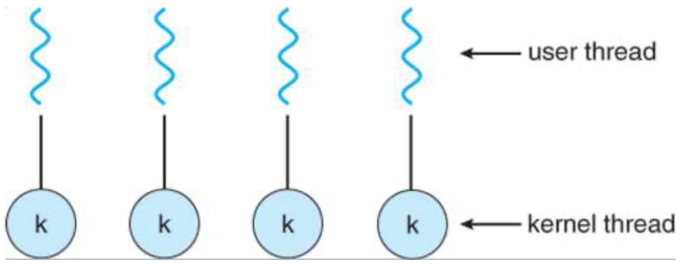

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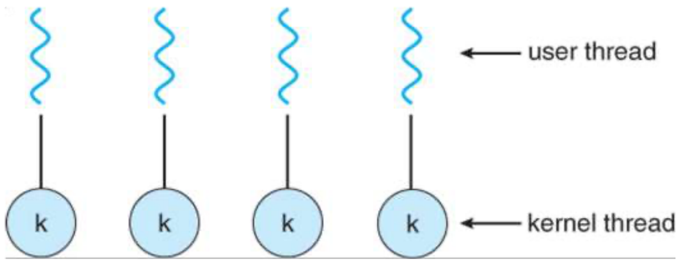

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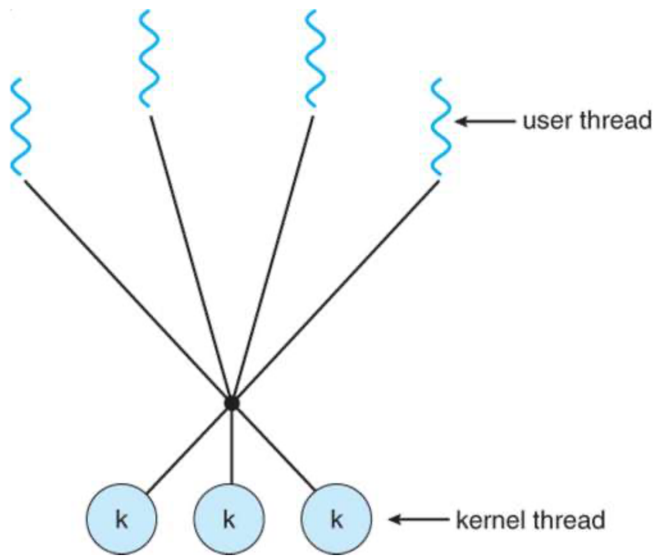

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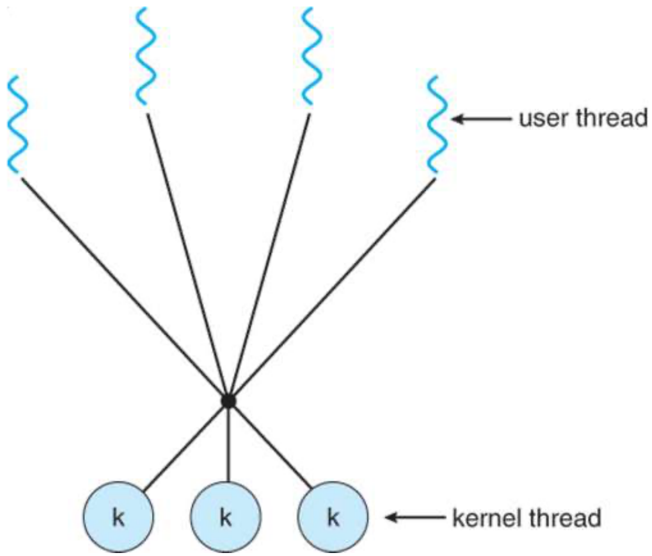

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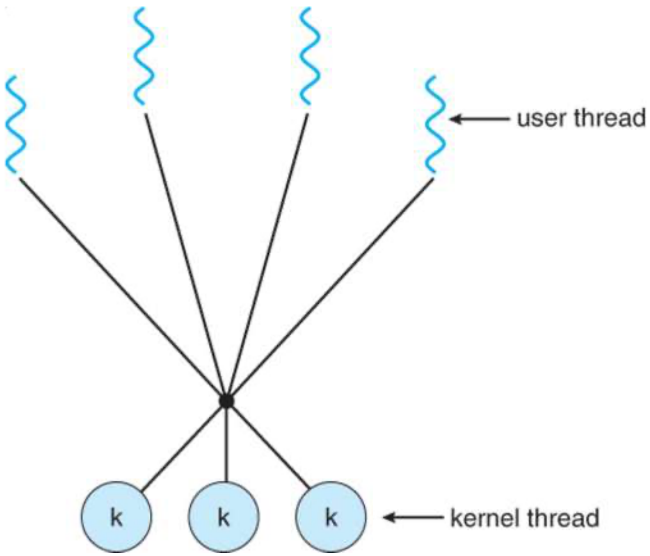

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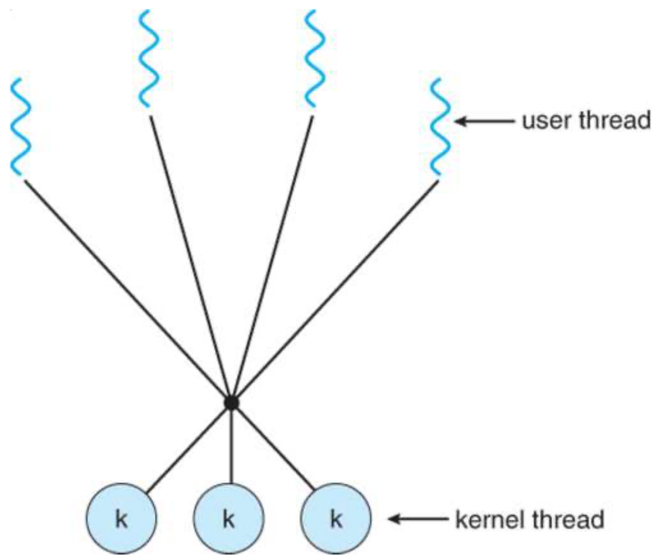

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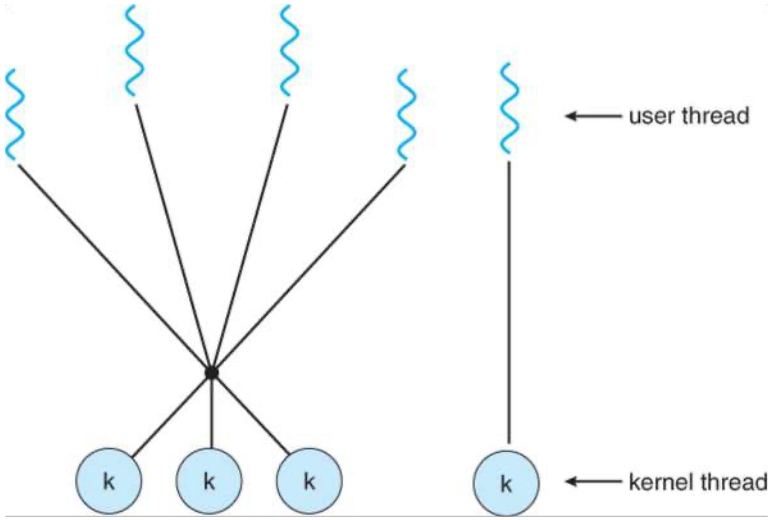

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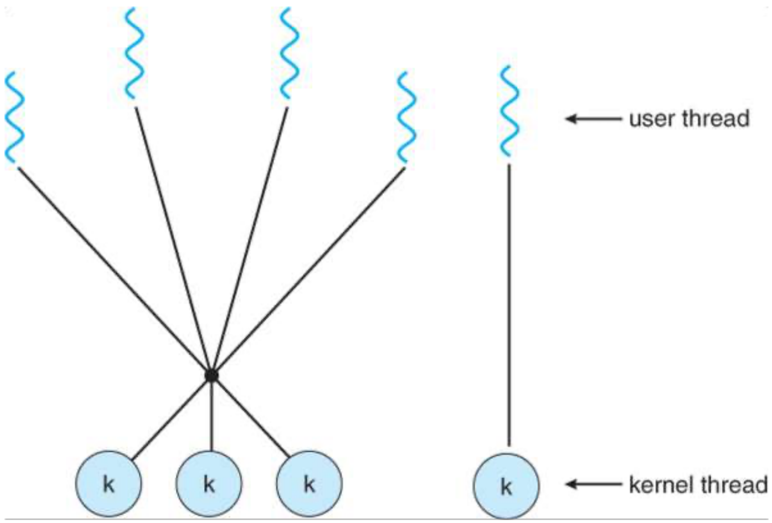

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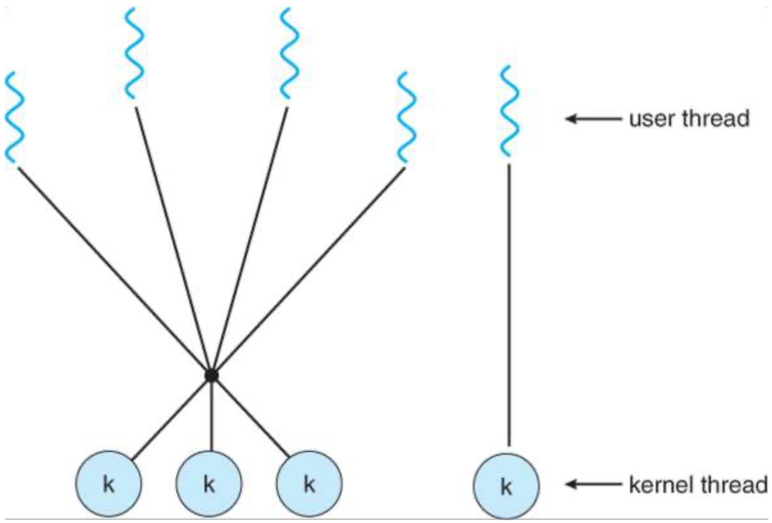

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  - Java threads → the implementation of threads is based upon whatever OS and hardware the JVM is running on, e.g., either Pthreads or Win32 threads

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To Wrap Up

Threading Model	Where Threads Run	Scheduling Responsibility	Preemption Possible?	Key Notes	Real-world Examples
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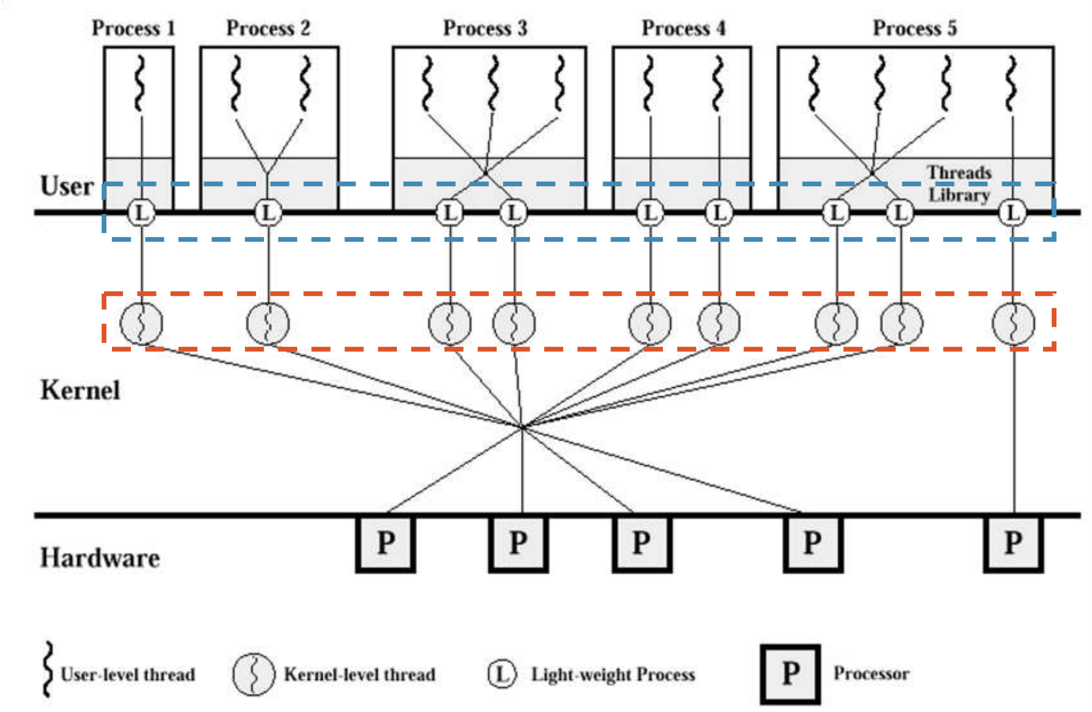
1:1 (Kernel-level threads)	Each user thread maps to one kernel thread	Managed by the OS kernel scheduler	Fully preemptive – kernel can interrupt and schedule any thread	Higher overhead (kernel context switch), true concurrency on multiprocessors	Windows threads, Linux Pthreads (NPTL), Solaris threads

To Wrap Up

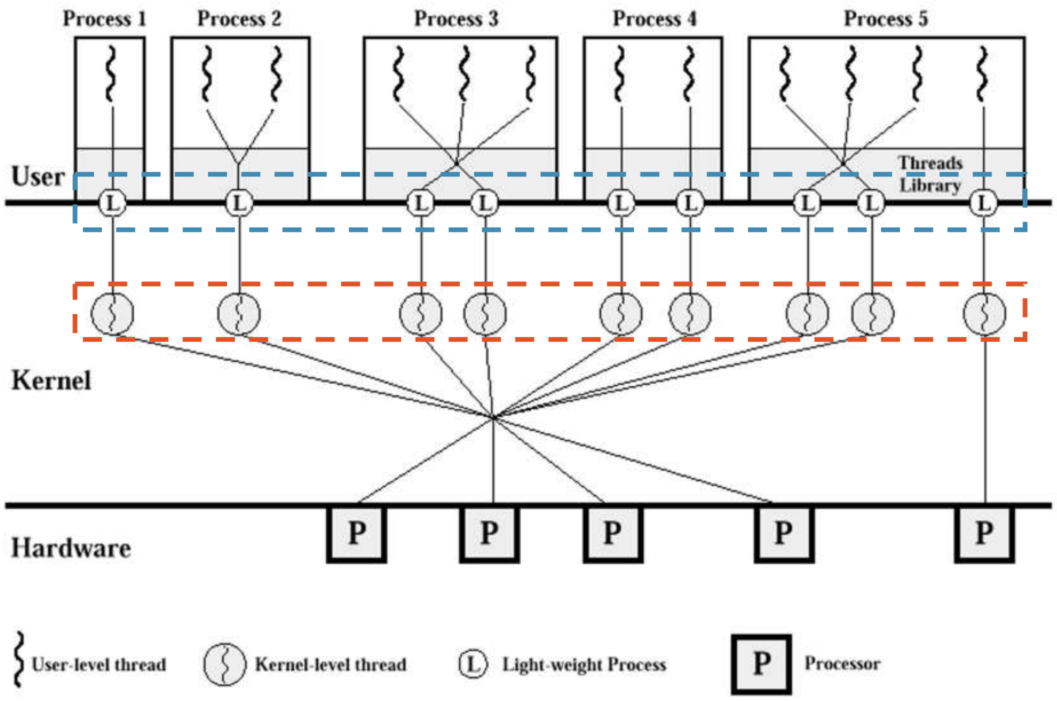
Threading Model	Where Threads Run	Scheduling Responsibility	Preemption Possible?	Key Notes	Real-world Examples
N:1 (User-level threads)	All threads run in user space on a single kernel thread	Managed entirely by the user-level library	No preemption between user threads within the same kernel thread – if one thread blocks (e.g., I/O), all threads block	Fast context switches, low kernel involvement, limited concurrency on multiprocessors	Early versions of GNU Portable Threads, green threads in older Java VMs
1:1 (Kernel-level threads)	Each user thread maps to one kernel thread	Managed by the OS kernel scheduler	Fully preemptive – kernel can interrupt and schedule any thread	Higher overhead (kernel context switch), true concurrency on multiprocessors	Windows threads, Linux Pthreads (NPTL), Solaris threads
M:N (Hybrid)	Multiple user threads mapped onto multiple kernel threads	User-level library schedules user threads onto kernel threads; kernel schedules kernel threads on CPU	Preemption possible for kernel threads; user-level library can implement additional scheduling policies	Combines flexibility of user-level scheduling with kernel-level concurrency; complexity in coordination	Solaris Scheduler Activations, older versions of GNU Portable Threads

Thread Scheduling (M:N)



M:N thread implementations provide a virtual processor (L) as an interface between user and kernel threads

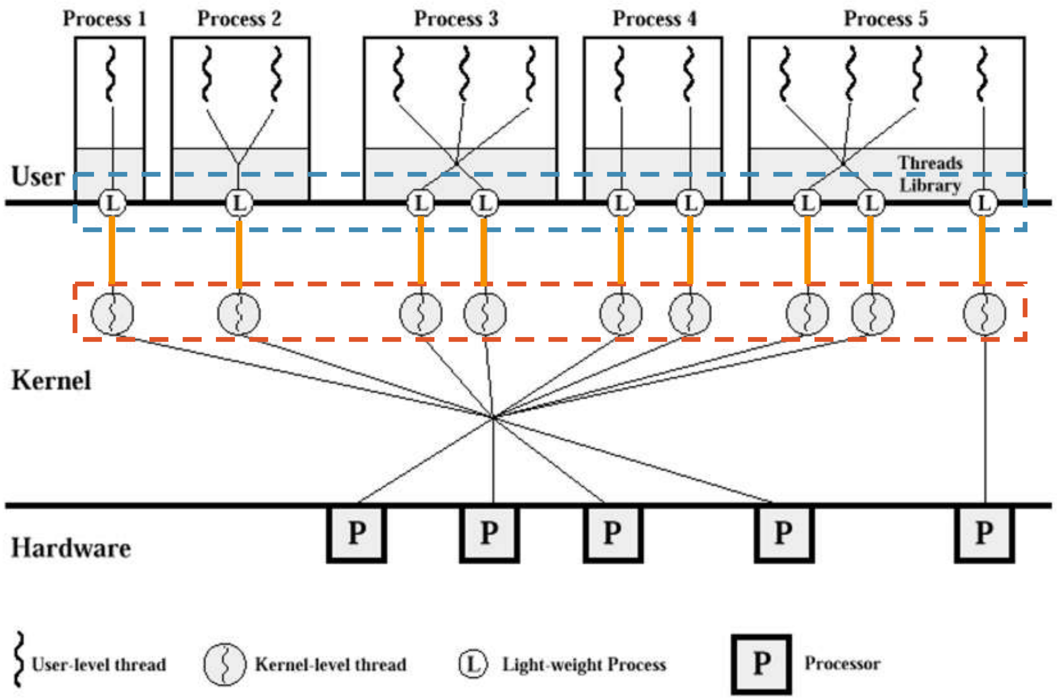
Thread Scheduling (M:N)



M:N thread implementations provide a virtual processor (L) as an interface between user and kernel threads

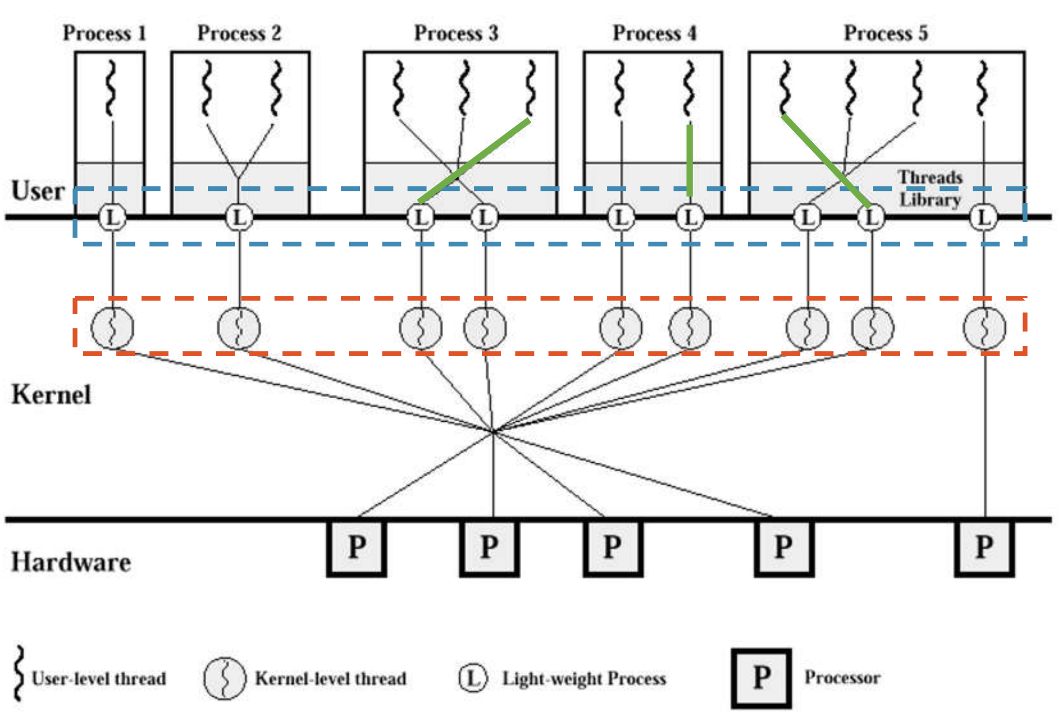
Light-Weight Process (LWP)

Thread Scheduling (M:N)



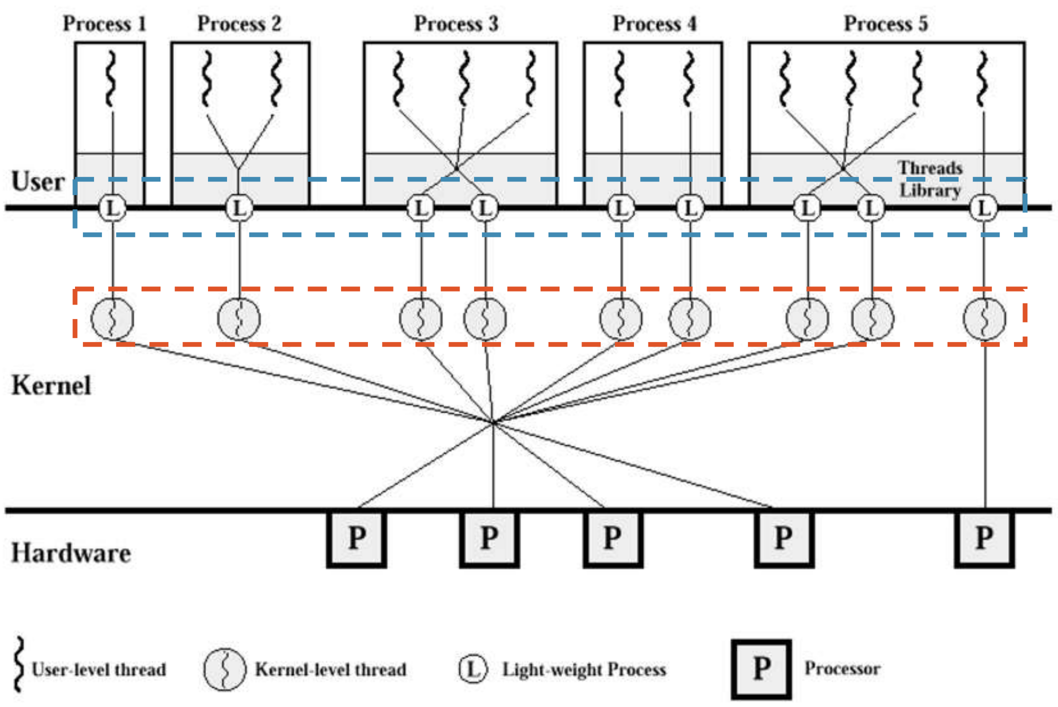
1:1 correspondence between LWPs and kernel threads

Thread Scheduling (M:N)



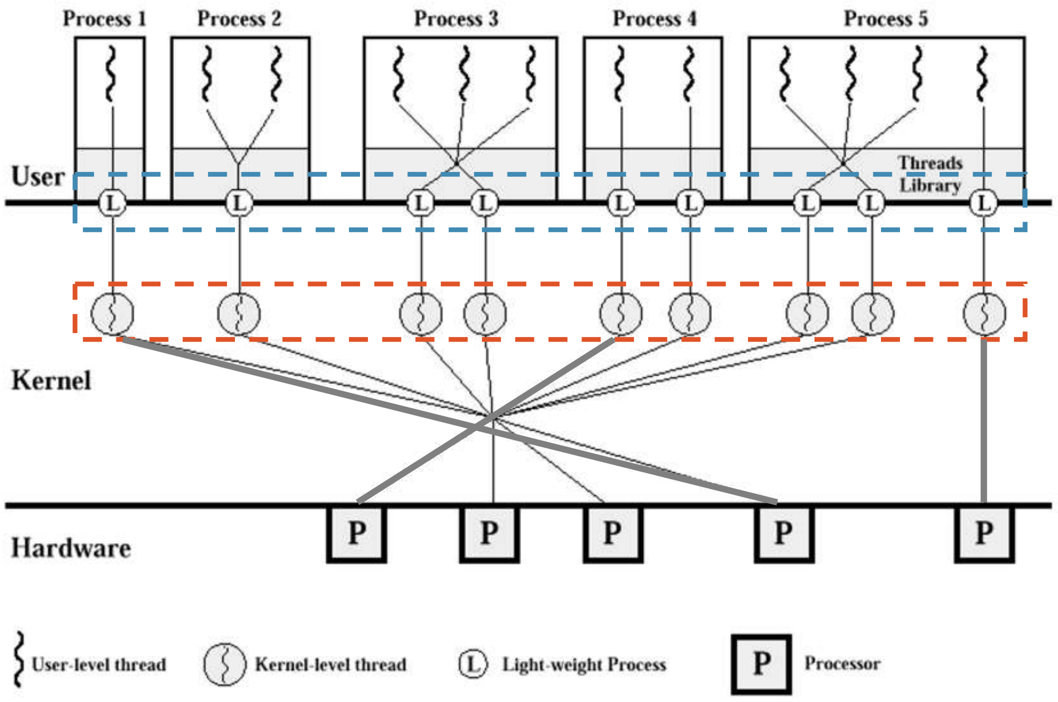
The application (user-level thread library) maps user threads onto available LWPs

Thread Scheduling (M:N)



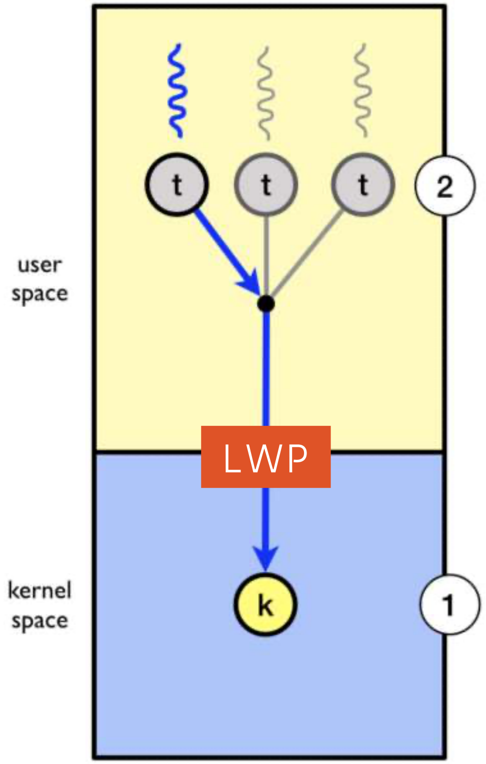
The number of kernel threads available in the system may change dynamically

Thread Scheduling (M:N)



Kernel threads are scheduled onto the real processor(s) by the OS

Scheduler Activations: Example



The kernel has allocated one kernel thread (1) to a process (i.e., an LWP) with three user-level threads (2)

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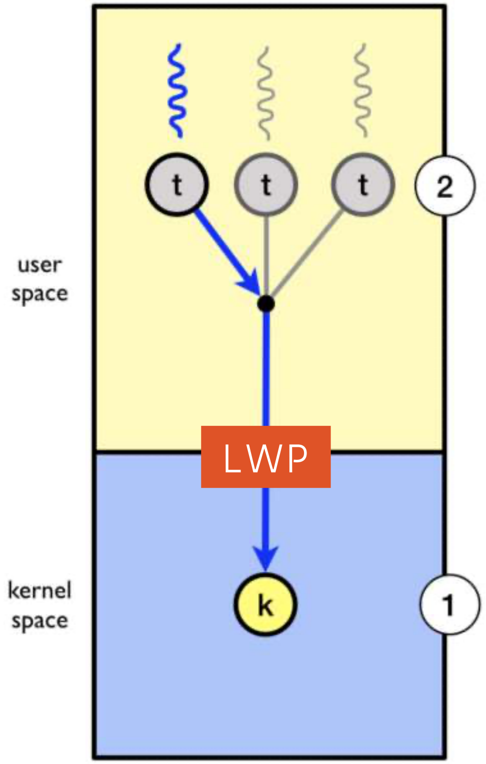
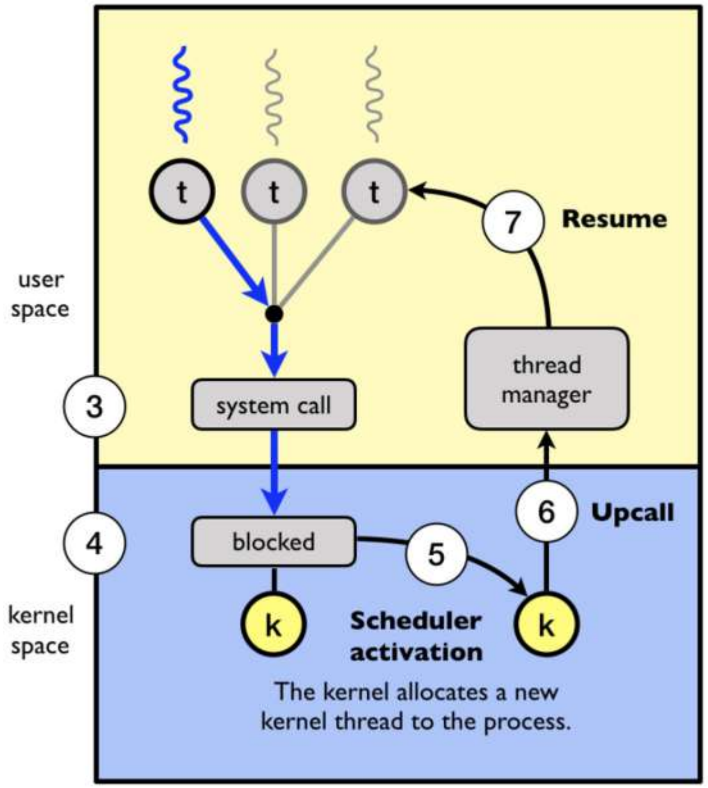


The kernel has allocated one kernel thread (1) to a process (i.e., an LWP) with three user-level threads (2)

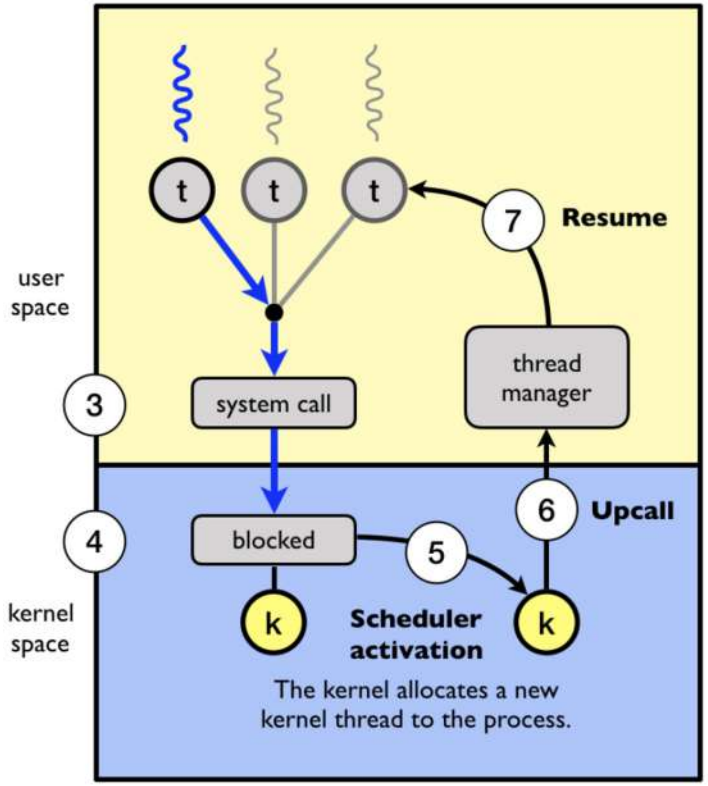
The three user level threads take turn executing on the single kernel-level thread

Scheduler Activations: Example



The executing thread makes a blocking system call (3)

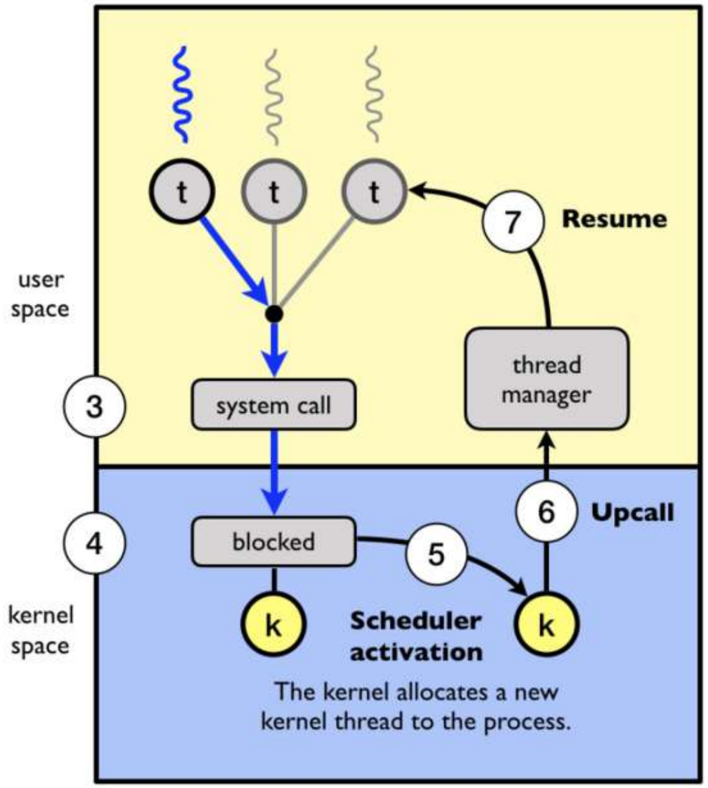
Scheduler Activations: Example



The executing thread makes a blocking system call (3)

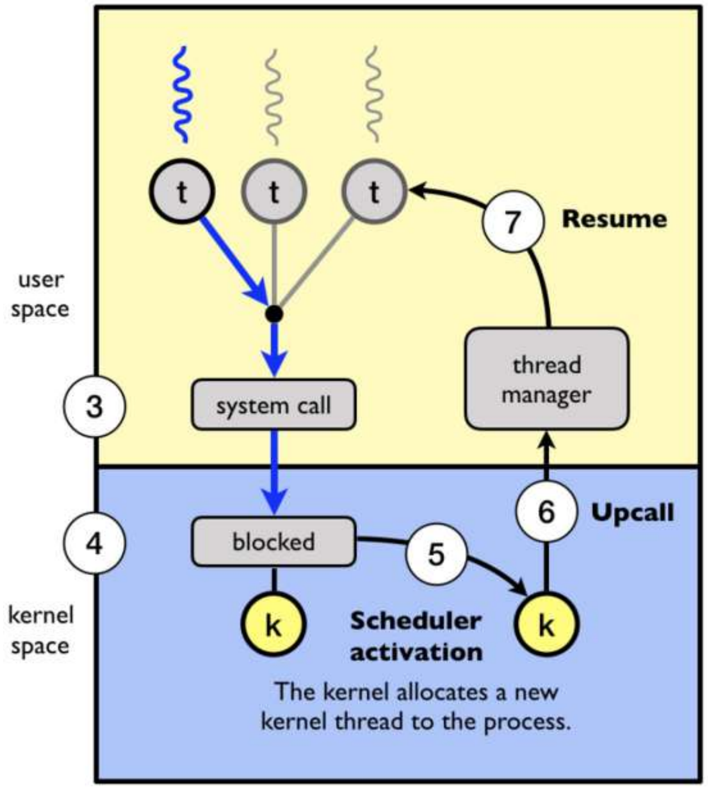
The kernel blocks the calling user-level thread and the kernel-level thread (LWP) used to execute the user-level thread (4)

Scheduler Activations: Example



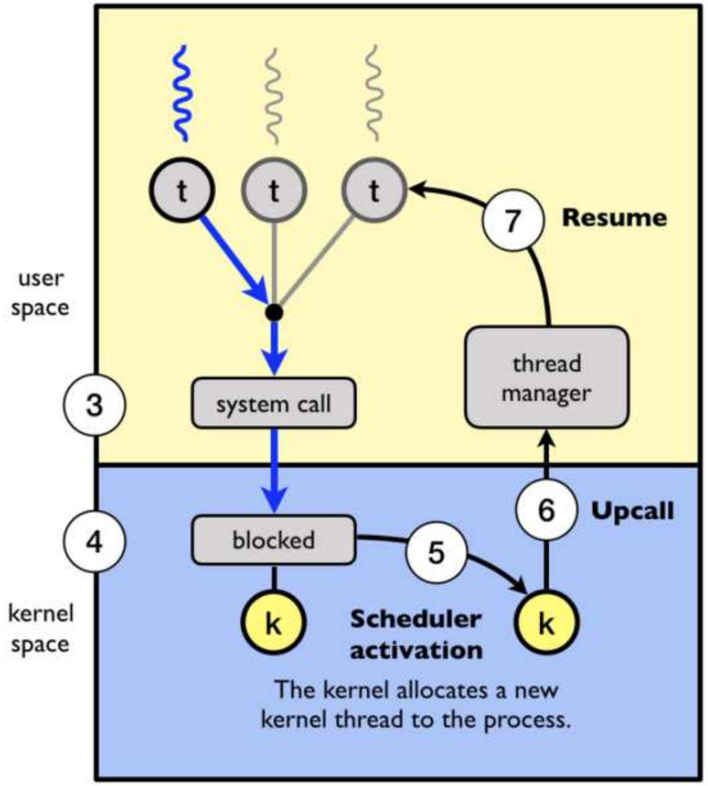
Scheduler activation: the kernel decides to allocate a new kernel-level thread to the process (5)

Scheduler Activations: Example



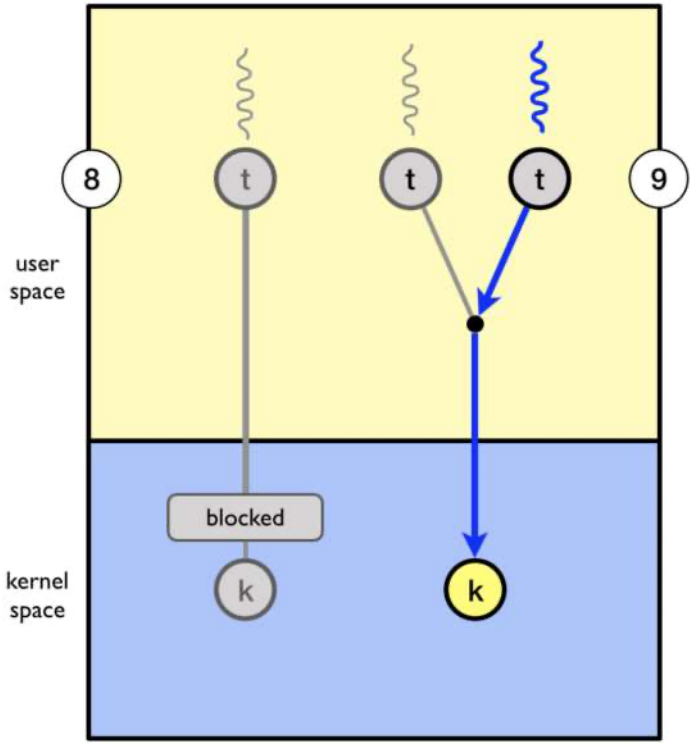
Upcall: The kernel notifies the user-level thread library which user-level thread that is now blocked and that a new kernel-level thread is available (6)

Scheduler Activations: Example



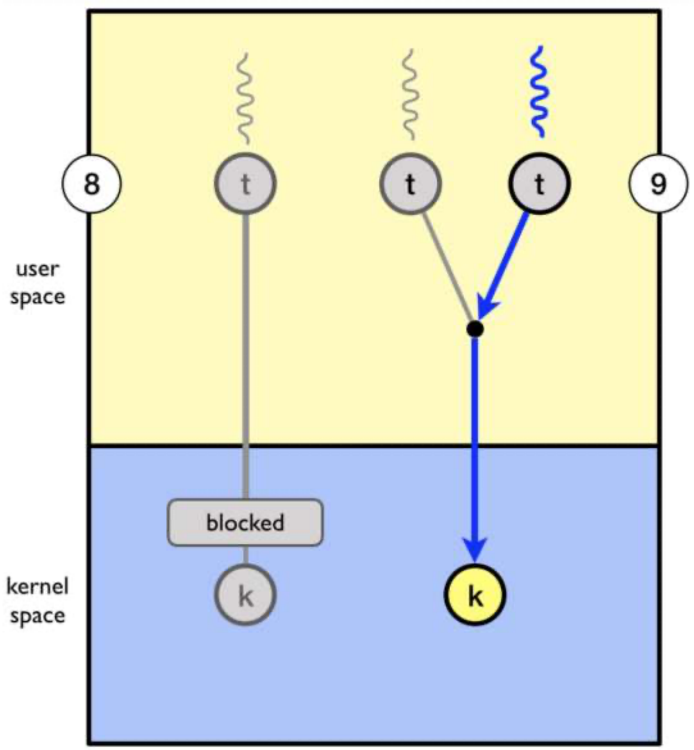
Upcall handler: The user-level thread library resumes one of the ready threads on to the new kernel thread (7)

Scheduler Activations: Example



While one user-level thread is blocked (8) the other threads can take turn executing on the new kernel thread (9)

Scheduler Activations: Example



When the first thread wakes up, the kernel will notify the user thread library via another upcall

User-Level Thread Scheduling

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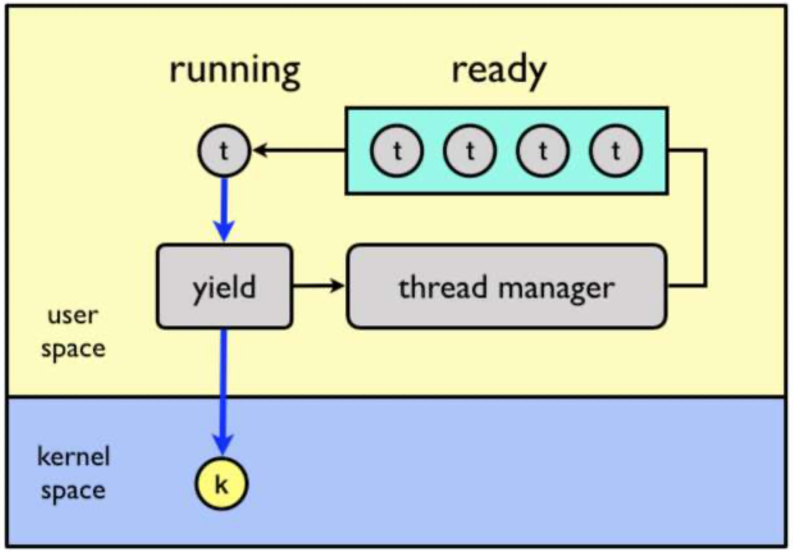
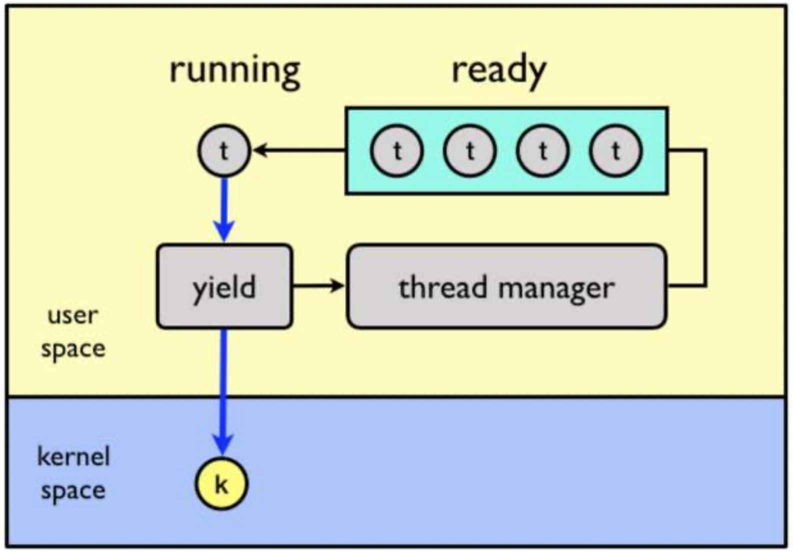
- Two main scheduling methods:
  - Cooperative
  - Preemptive

Cooperative Thread Scheduling



Similar to multiprogramming where a process executes on the CPU until making a I/O request

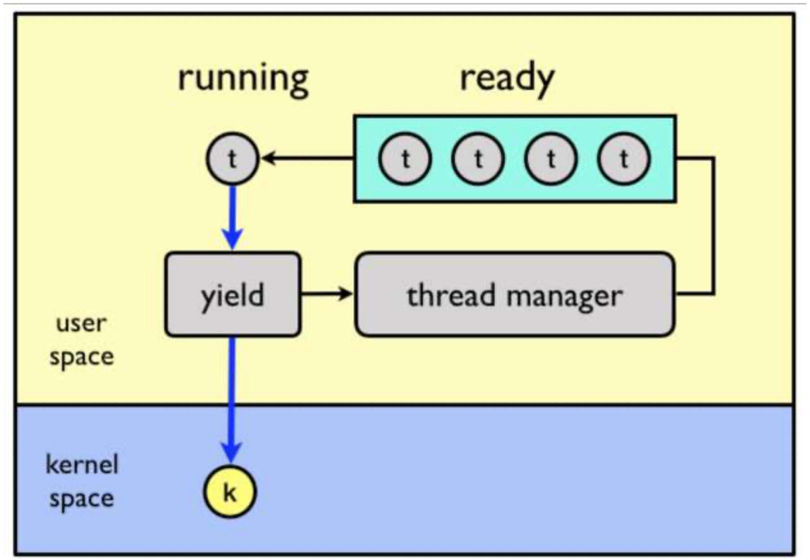
Cooperative Thread Scheduling



Similar to multiprogramming where a process executes on the CPU until making a I/O request

Cooperative user-level threads execute on the assigned kernel-level thread until they voluntarily give back the kernel thread to the library

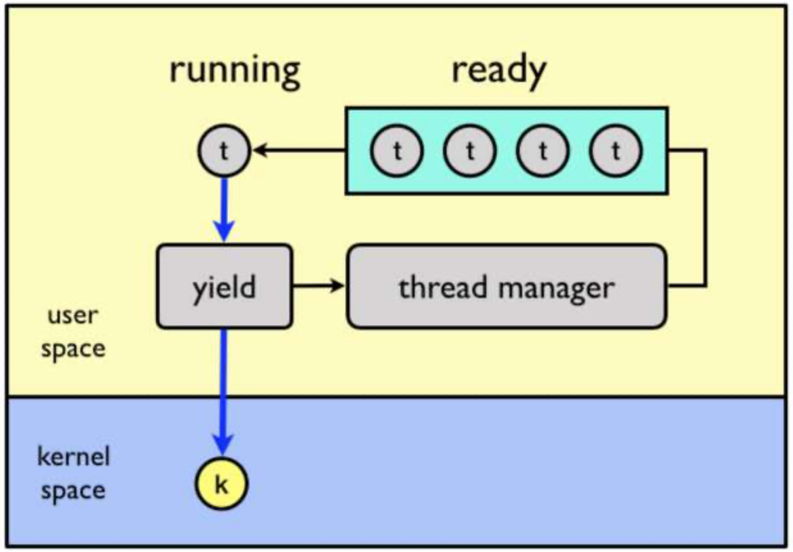
Cooperative Thread Scheduling



Threads yield to each other, either

- explicitly (e.g., by calling a yield() provided by the user-level thread library) or

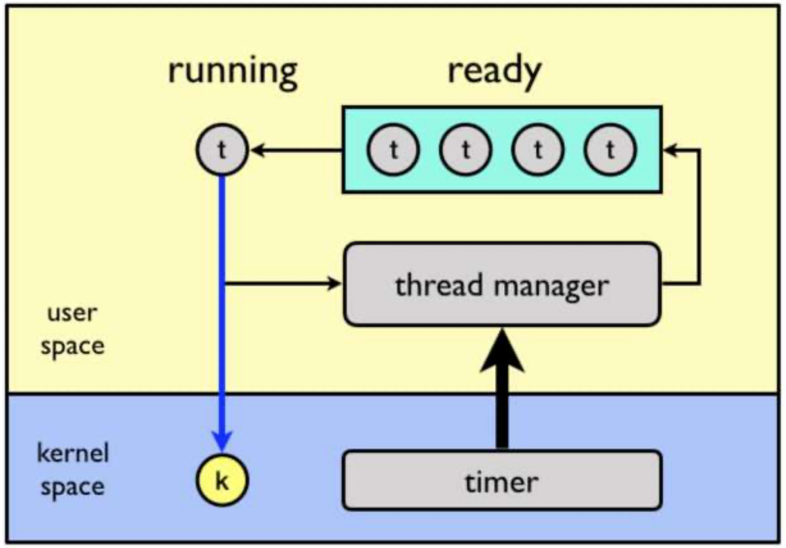
Cooperative Thread Scheduling



Threads yield to each other, either

- explicitly (e.g., by calling a yield() provided by the user-level thread library) or
- implicitly (e.g., requesting a lock held by another thread)

Preemptive Thread Scheduling



Similar to multitasking (a.k.a. time sharing), where a timer is set to cause an interrupt at a regular time interval

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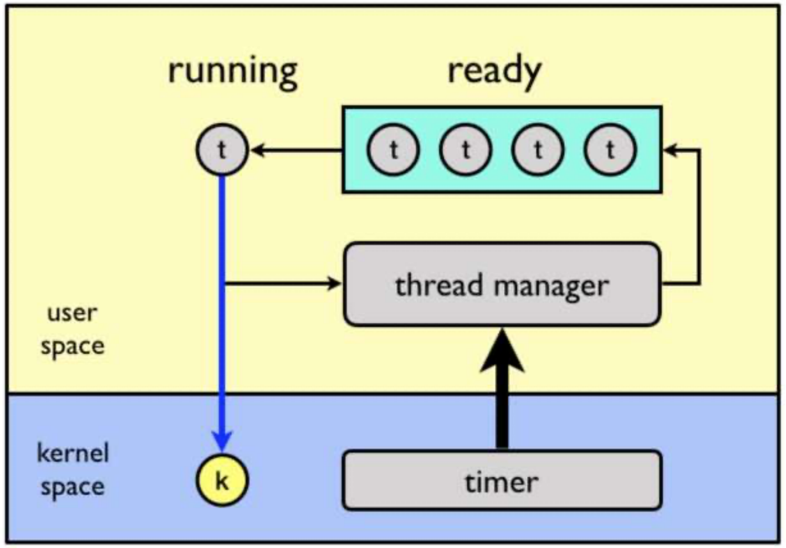

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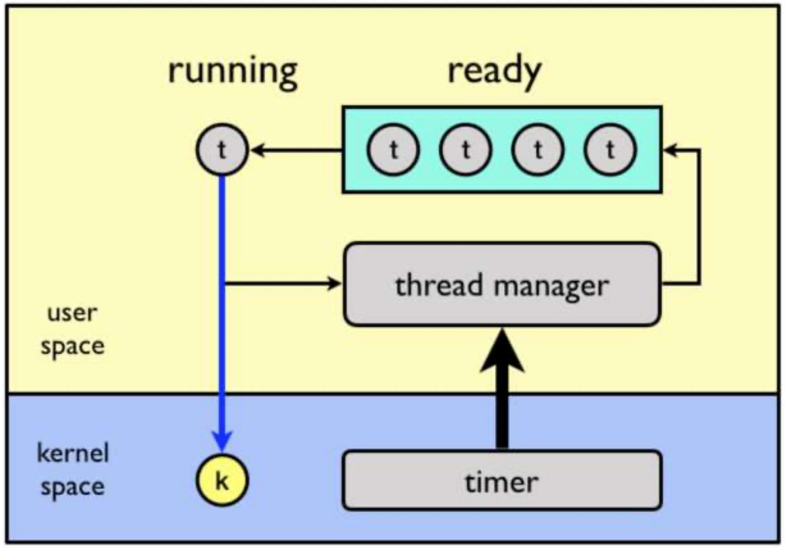

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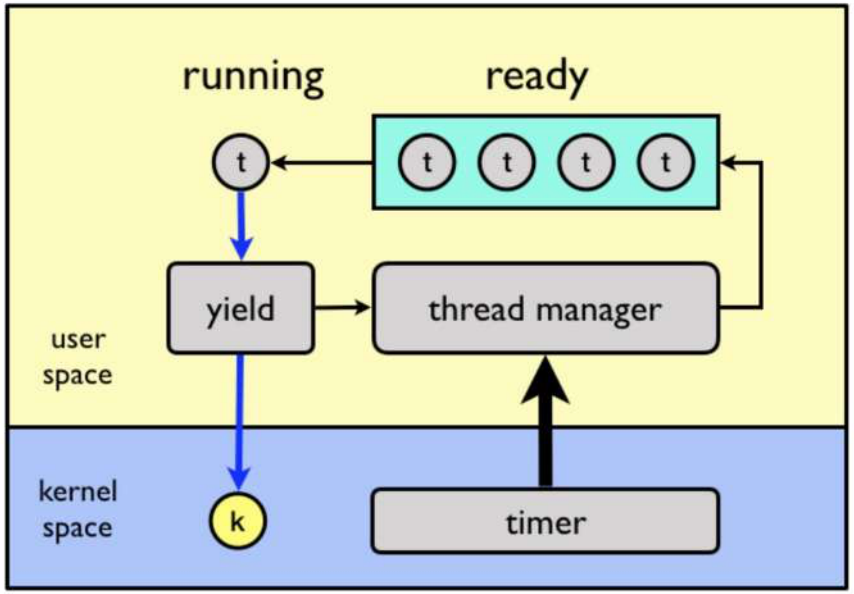
The running process is replaced if the job requests I/O or if the job is interrupted by the timer

The timer is used to cause execution flow to jump to a central dispatcher thread (in the user-level library), which chooses the next thread to run

Hybrid Thread Scheduling



Cooperative + Preemptive

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