Systems and Networking – Unit I

B.Sc. in Applied Computer Science and Artificial Intelligence

2021-2022

Gabriele Tolomei

Department of Computer Science

Sapienza Università di Roma

tolomei@di.uniroma1.it

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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

Process vs. Thread

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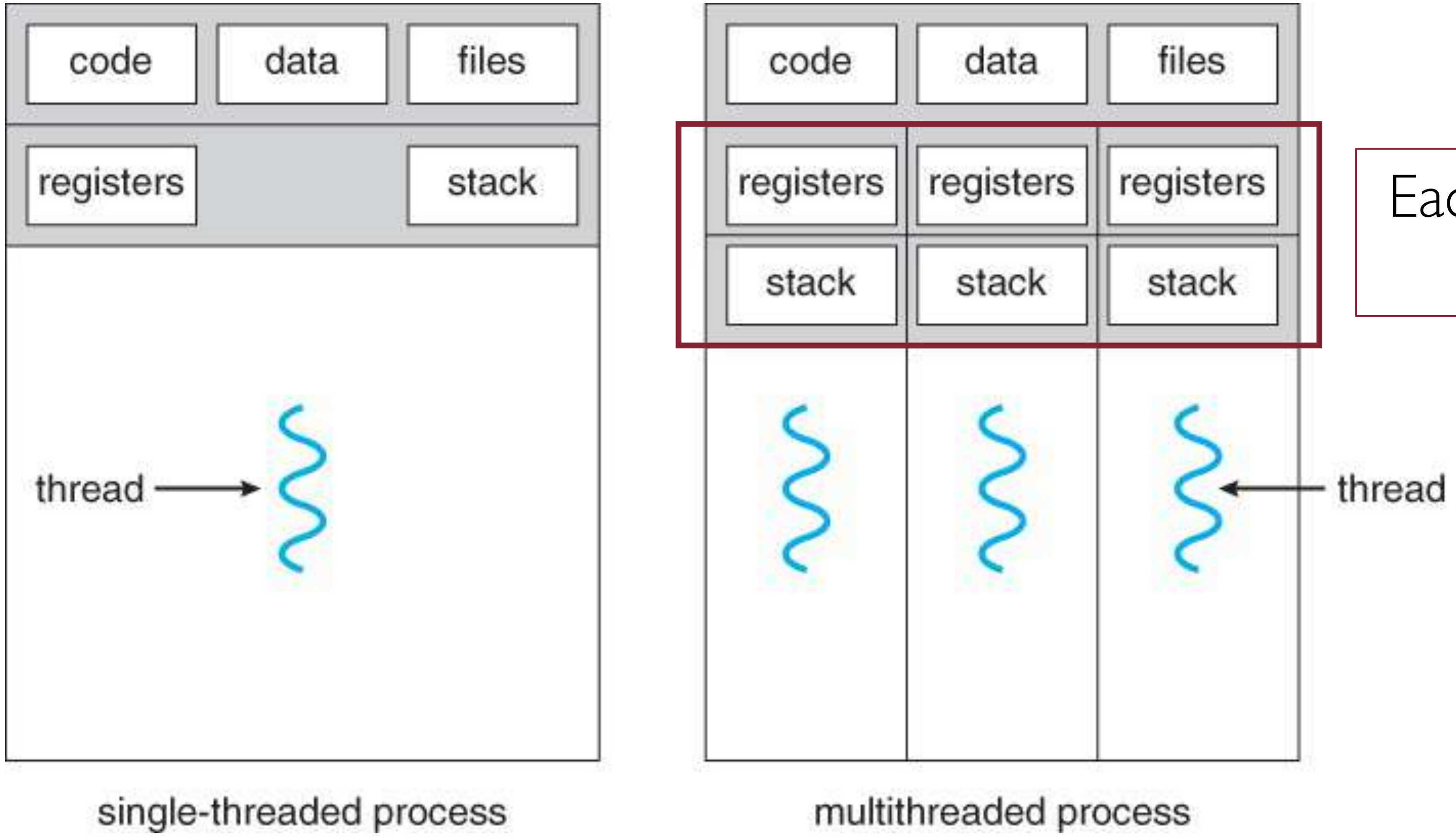
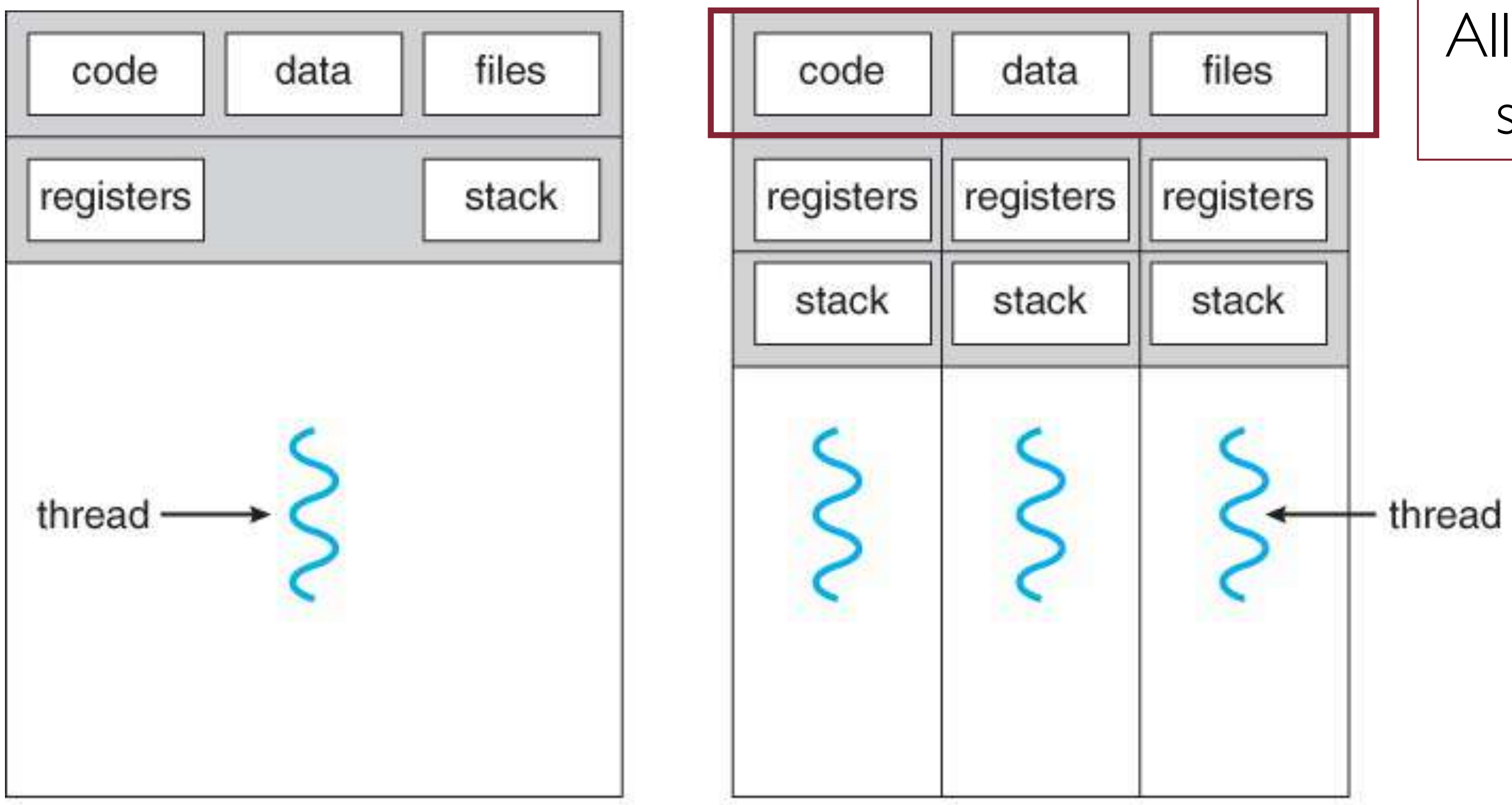
- A thread defines a single sequential execution stream *within* a process (i.e., program counter, stack, registers)
- A thread is bound to a specific process
- Each process may have several threads of control within it
  - The process' address space is shared among all its threads
  - No system calls 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

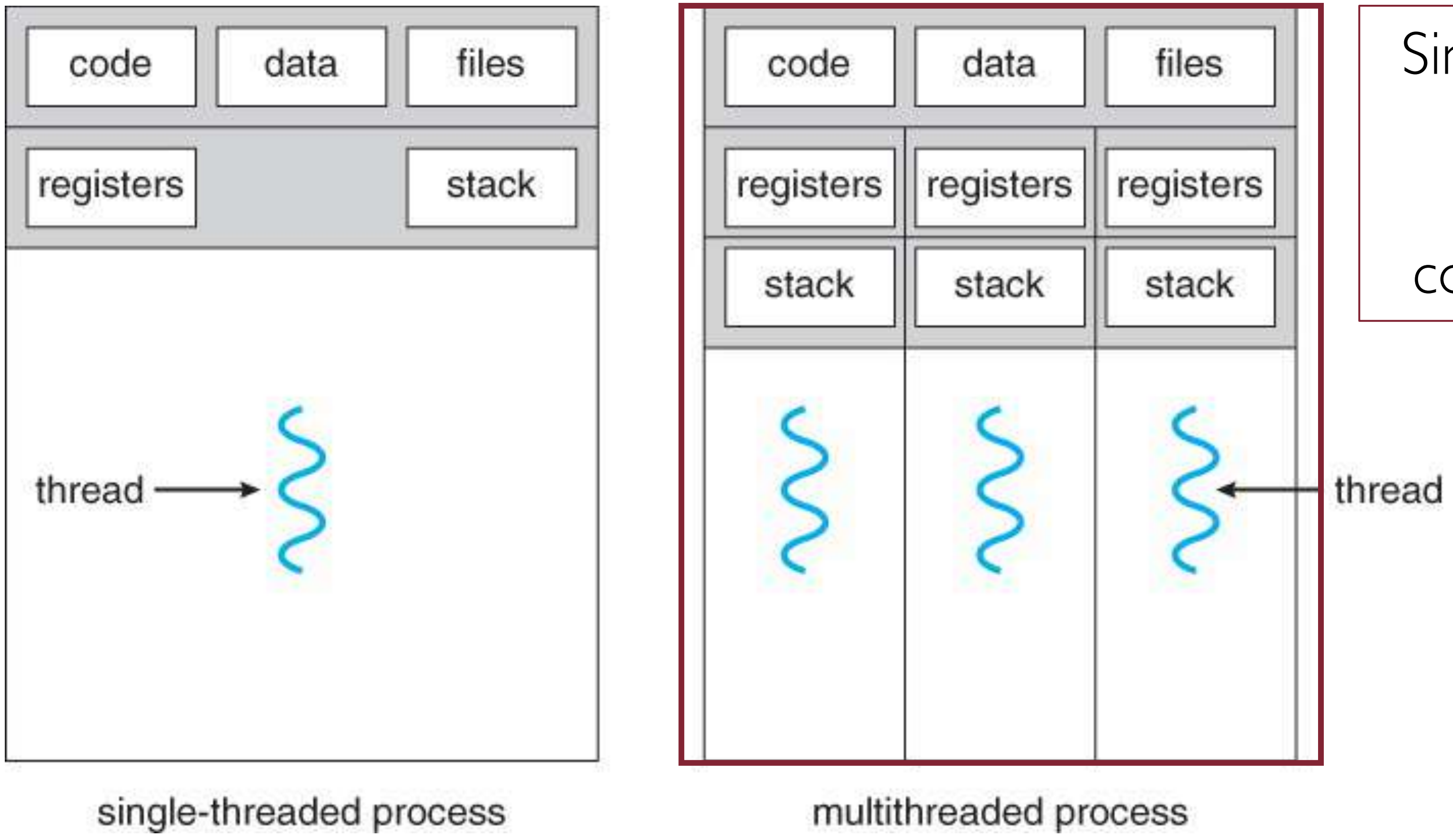


single-threaded process

multithreaded process

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

Single- vs. Multi-Threaded Process



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

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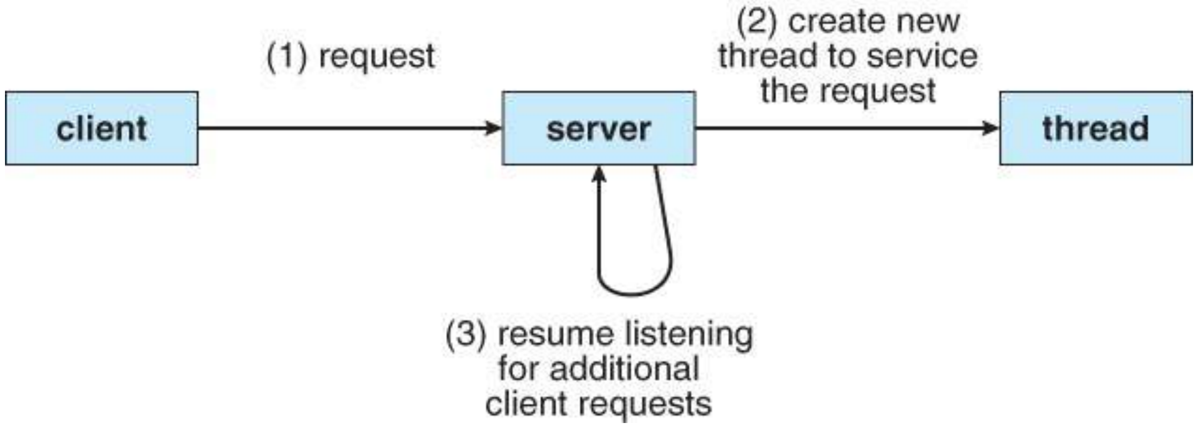
- This is particularly true when one of the tasks may block, and it is desired to allow the other tasks to proceed without blocking
- Example: word processor
  - a thread may check spelling and grammar while another thread handles user input (keystrokes), and a third does periodic backups of the file being edited

Multi-threaded Web Server



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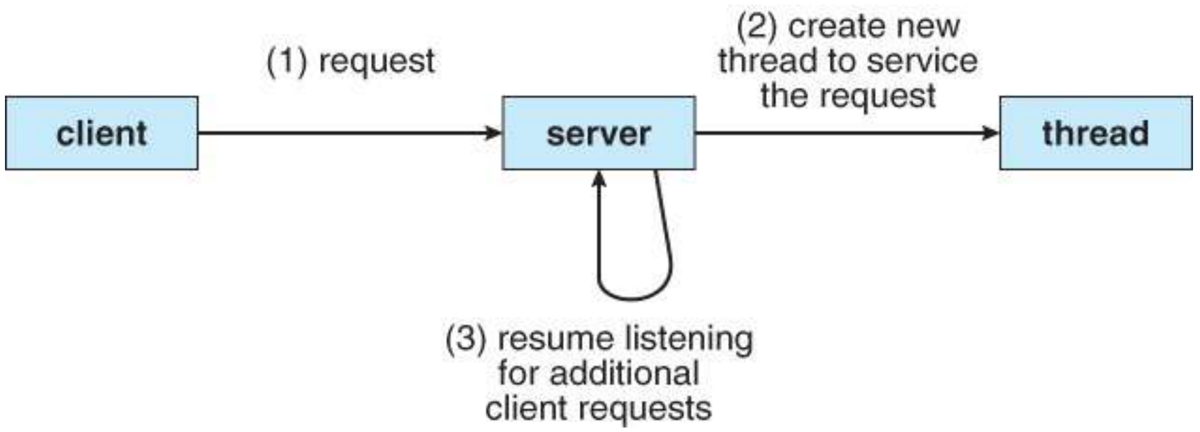
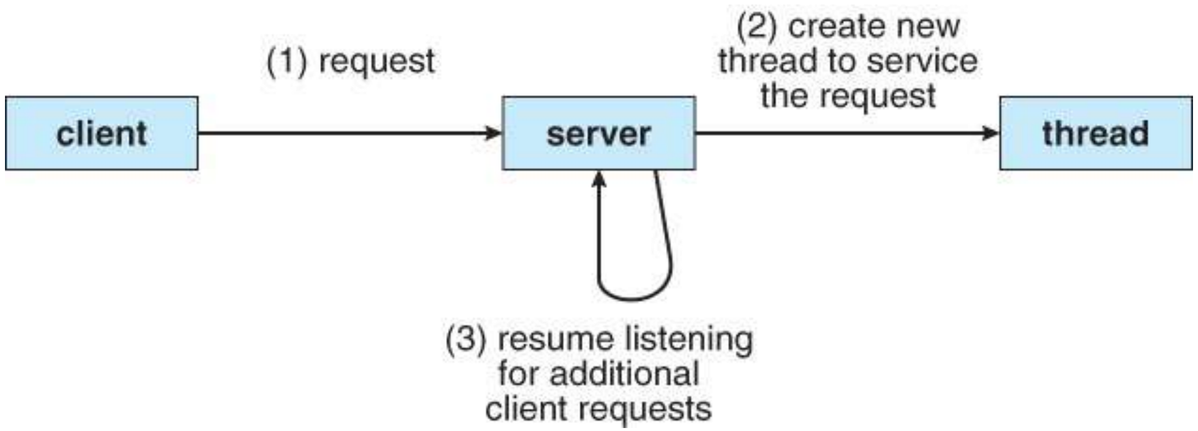


Multiple threads allow for multiple requests to be satisfied simultaneously, without having to serve requests sequentially or to fork off separate processes for every incoming request

Multi-threaded Web Server



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

Multiple Processes vs. Multiple Threads

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  - Inter-thread communication is significantly quicker than inter-process one
  - Context-switches between threads is a lot faster than between processes

Threads: Benefits

- 4 main benefits:
  - Responsiveness → one thread may provide rapid response while other threads are blocked or slowed down doing intensive computations

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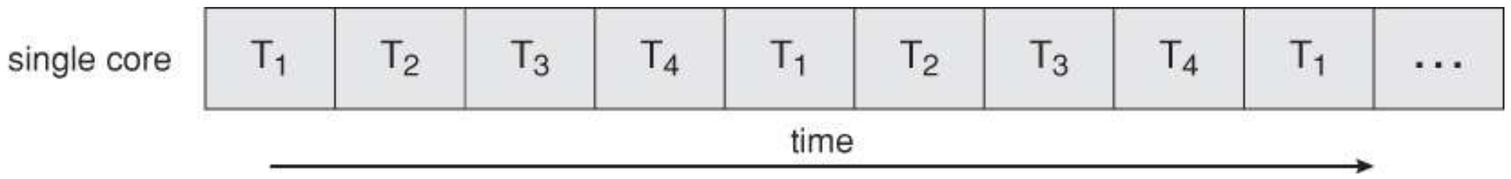
  - Economy → creating and managing threads (and context switches between them) is much faster than performing the same tasks for processes
  - Scalability (multi-processor architectures) → A single threaded process can only run on one CPU, whereas a multi-threaded process may be split amongst all available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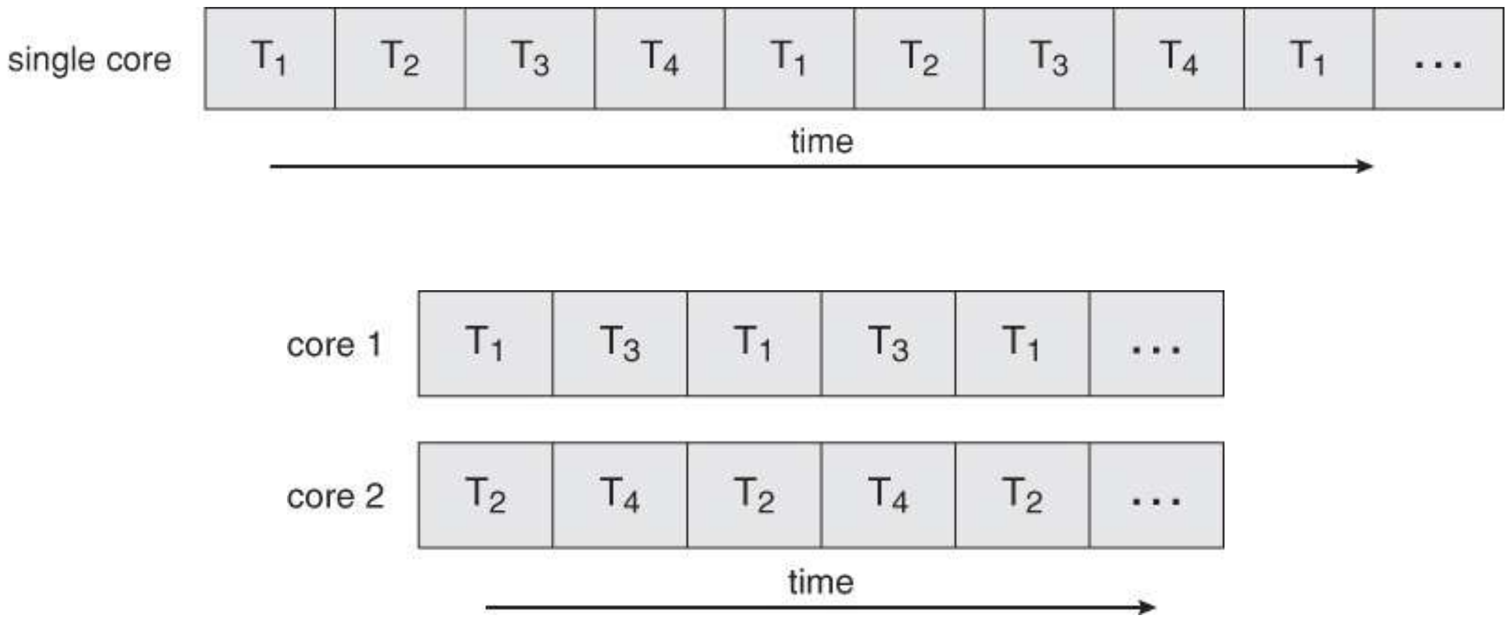

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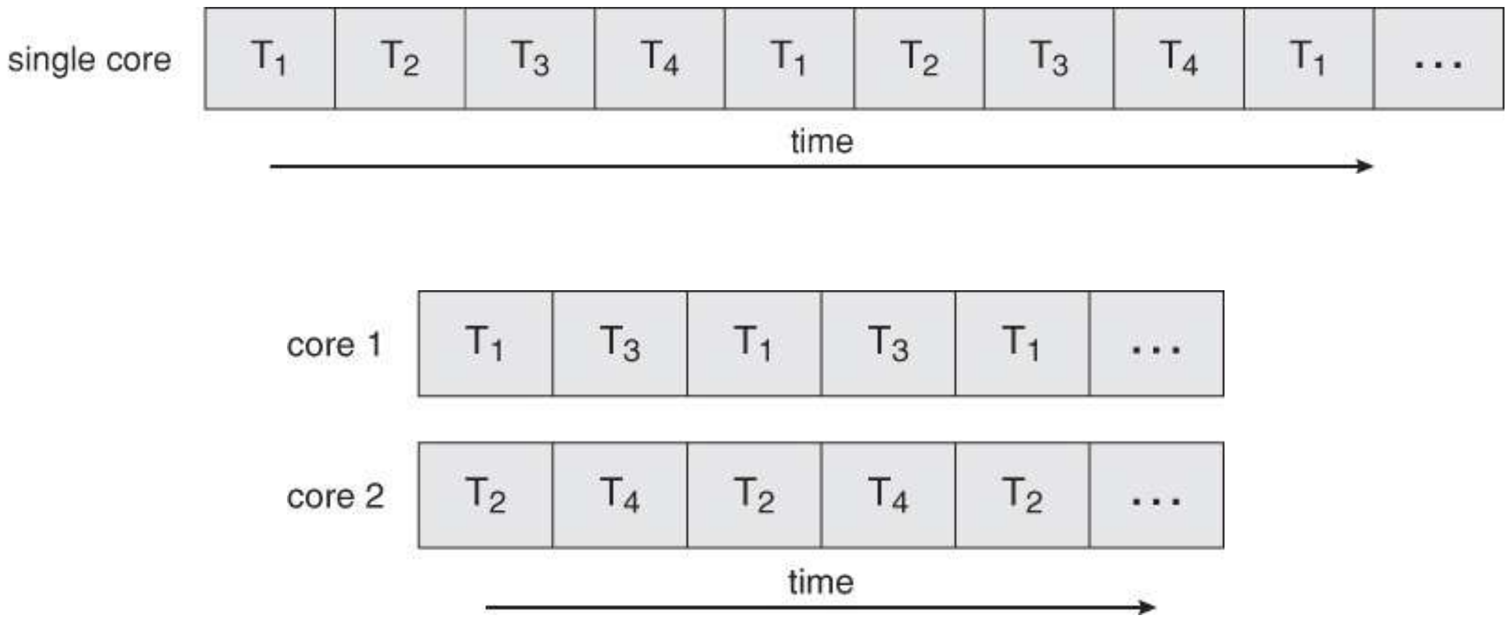

Multi-core chips require new OS scheduling algorithms to make better use of the multiple cores available

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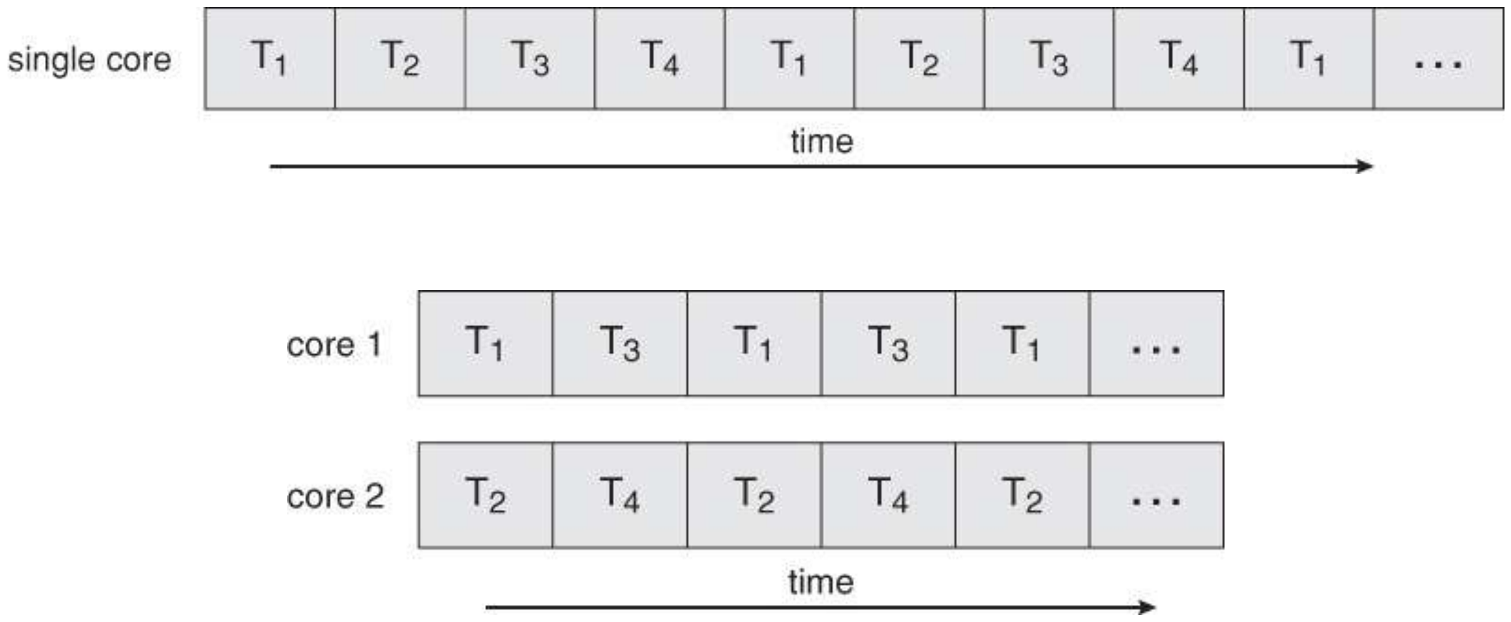

CPUs have been developed to support more simultaneous threads per core in hardware (e.g., Intel's hyper-threading)

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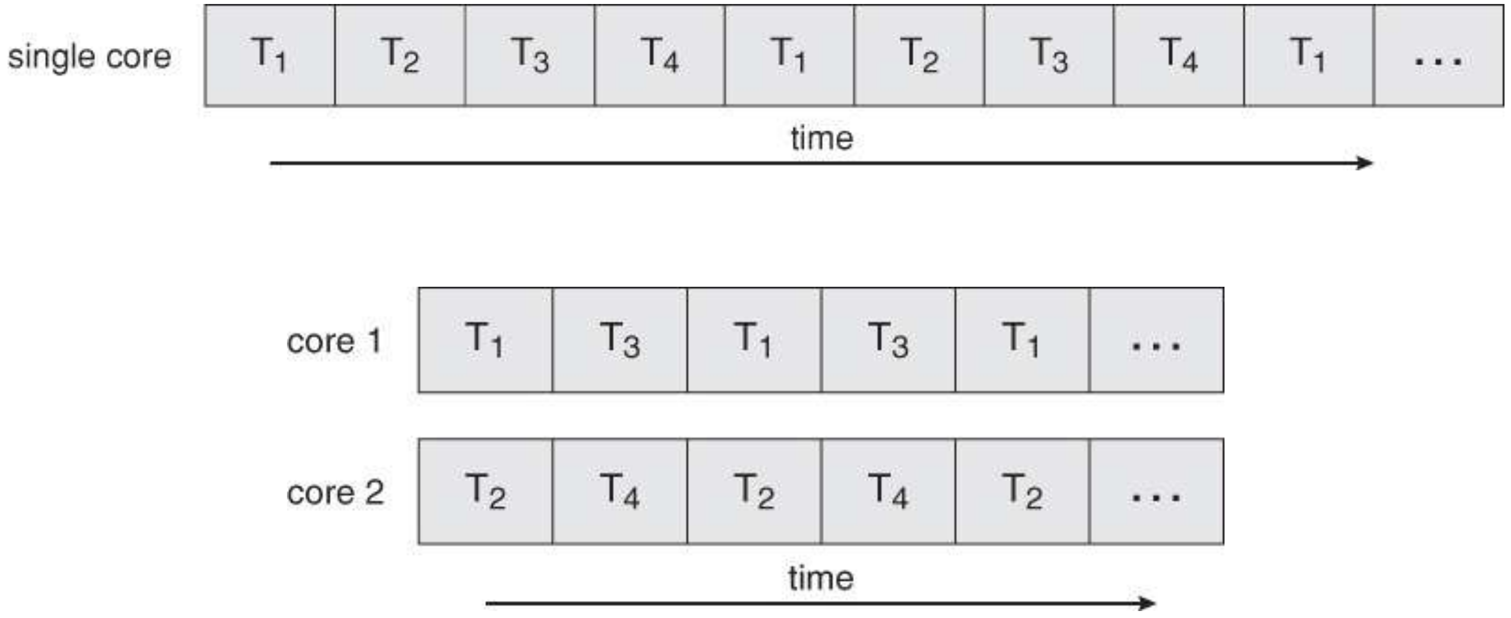
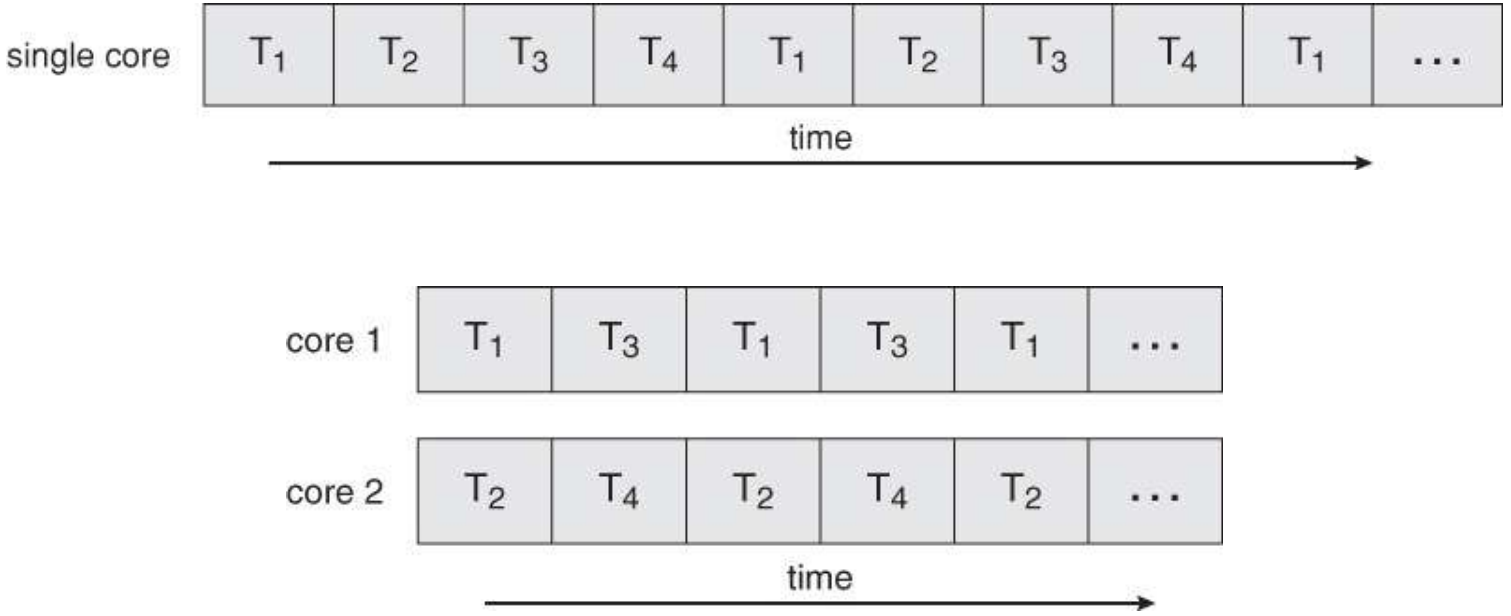


Hyper-threading

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

Single- vs. Multi-core Programming



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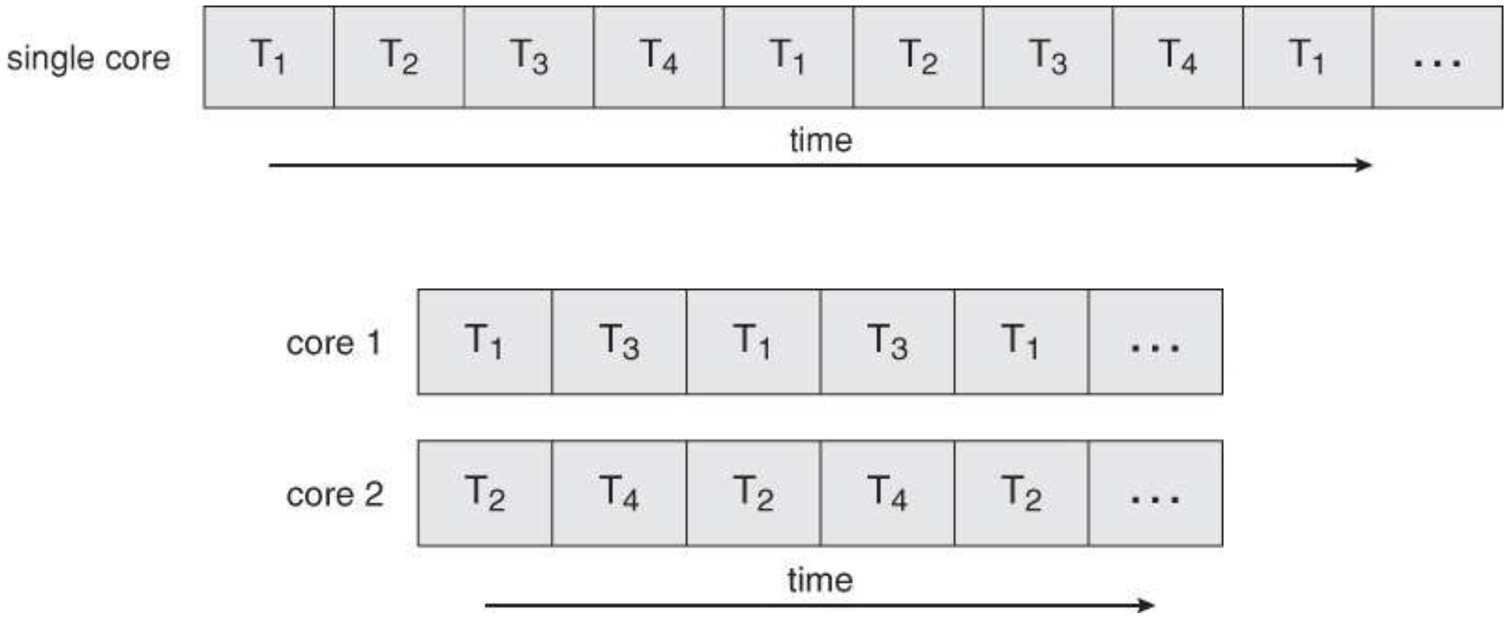

Concurrency

vs.

Parallelism

Types of Parallelism

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  - Task parallelism: divides the different tasks to be performed among the different cores and performs them simultaneously
- In practice, no program is ever divided up solely by one or the other of these, but instead by some sort of hybrid combination

Classifying OSs

address space

thread

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address space

thread

single thread

multiple threads

Classifying OSs

address space

thread

single address space
(uniprogramming)

multiple address spaces
(multiprogramming)

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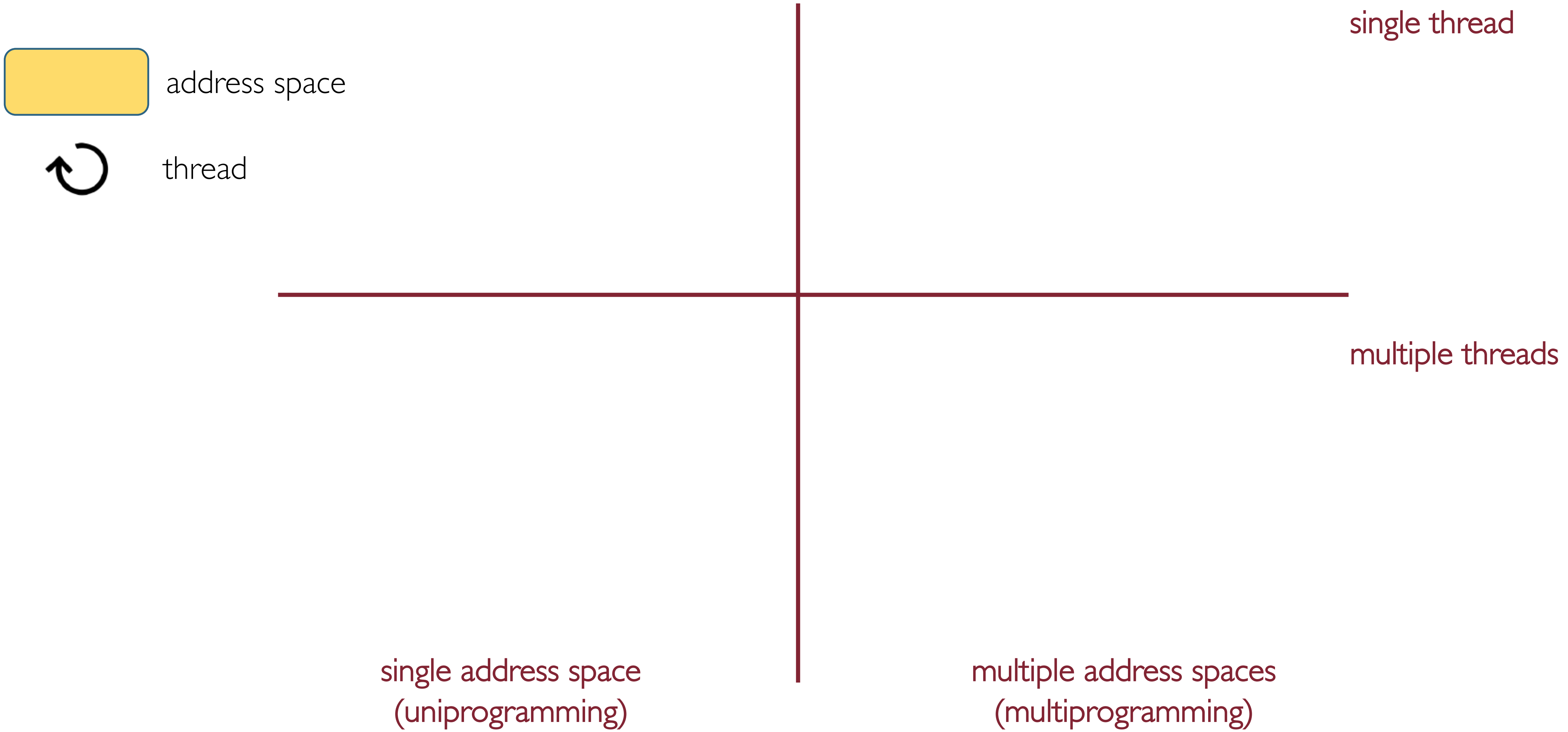

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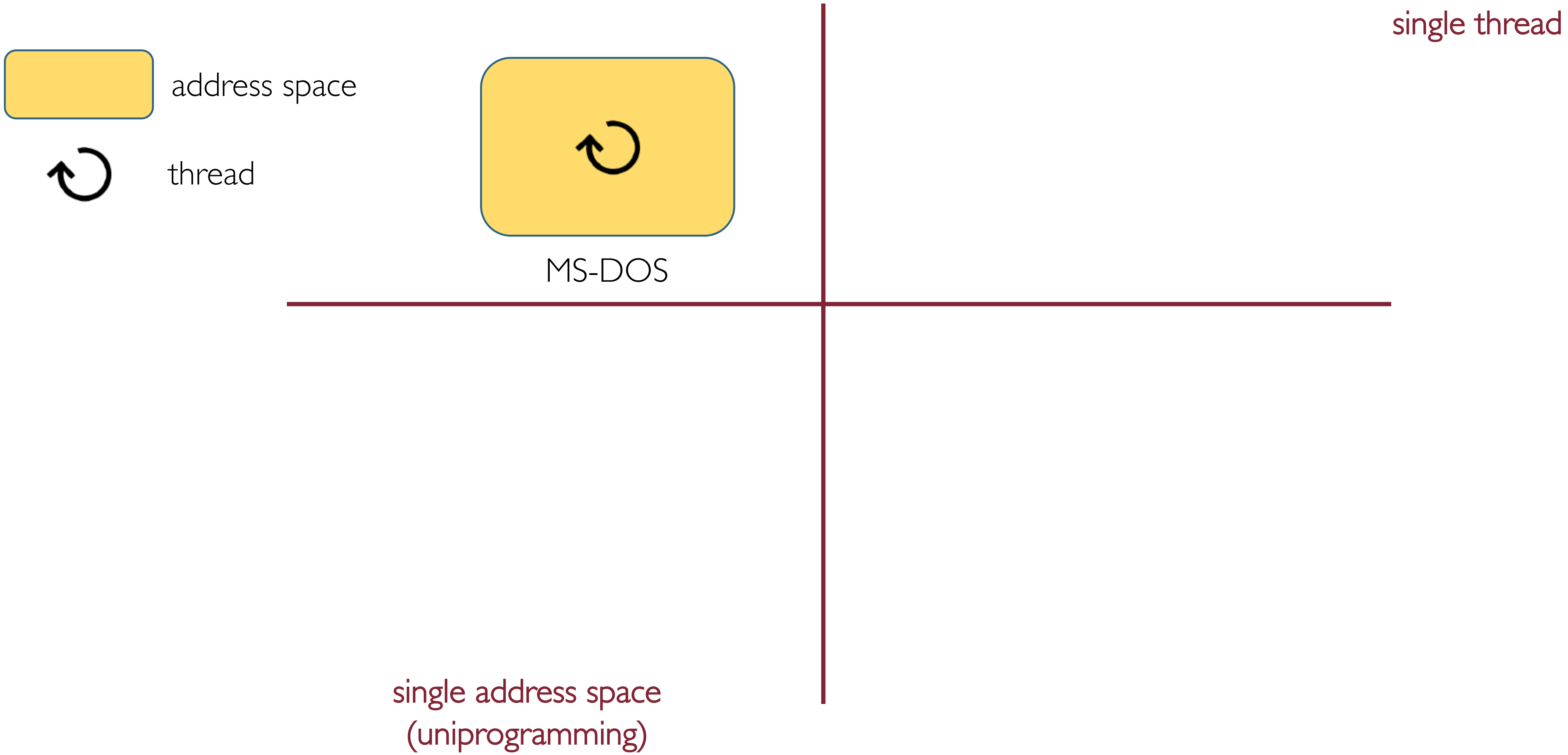

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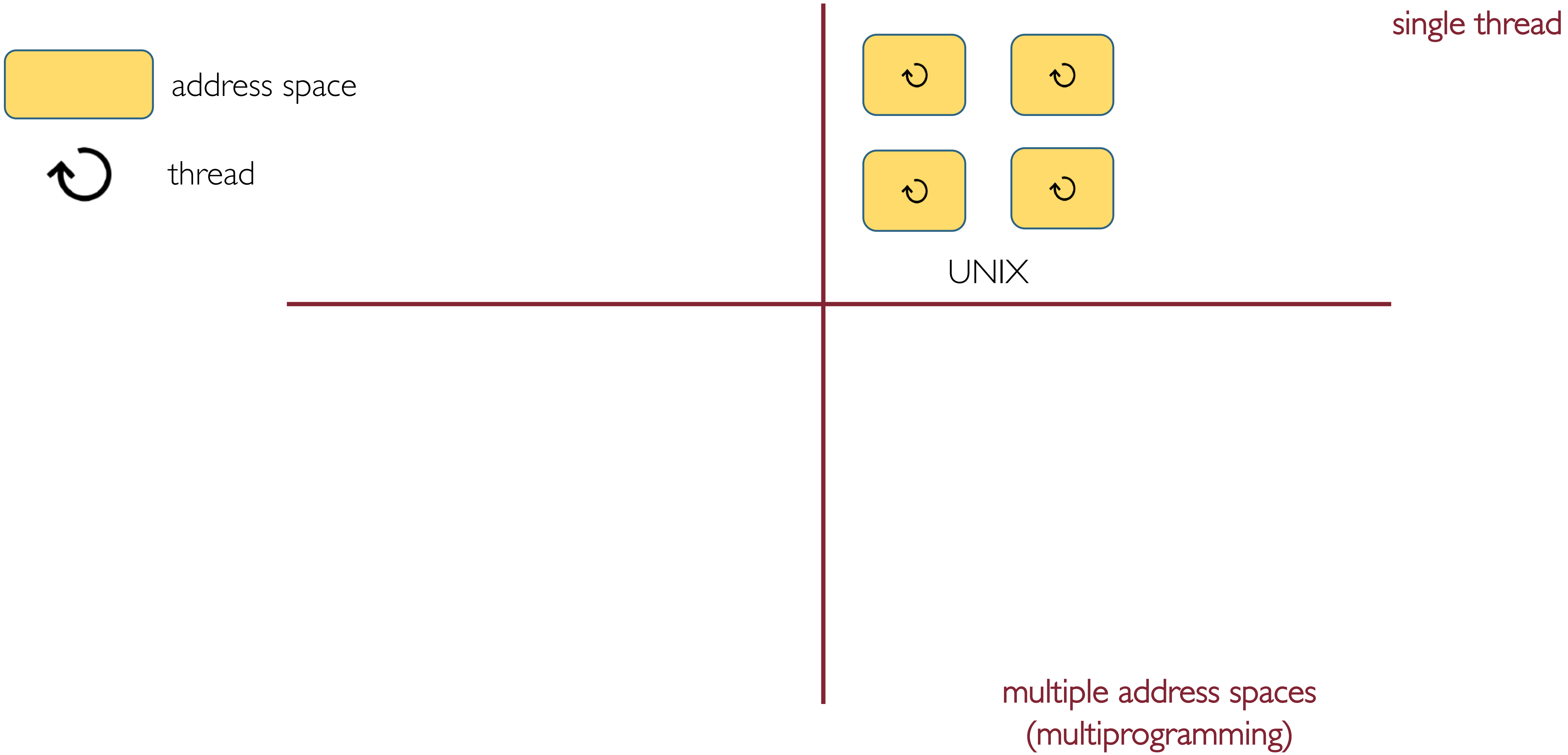

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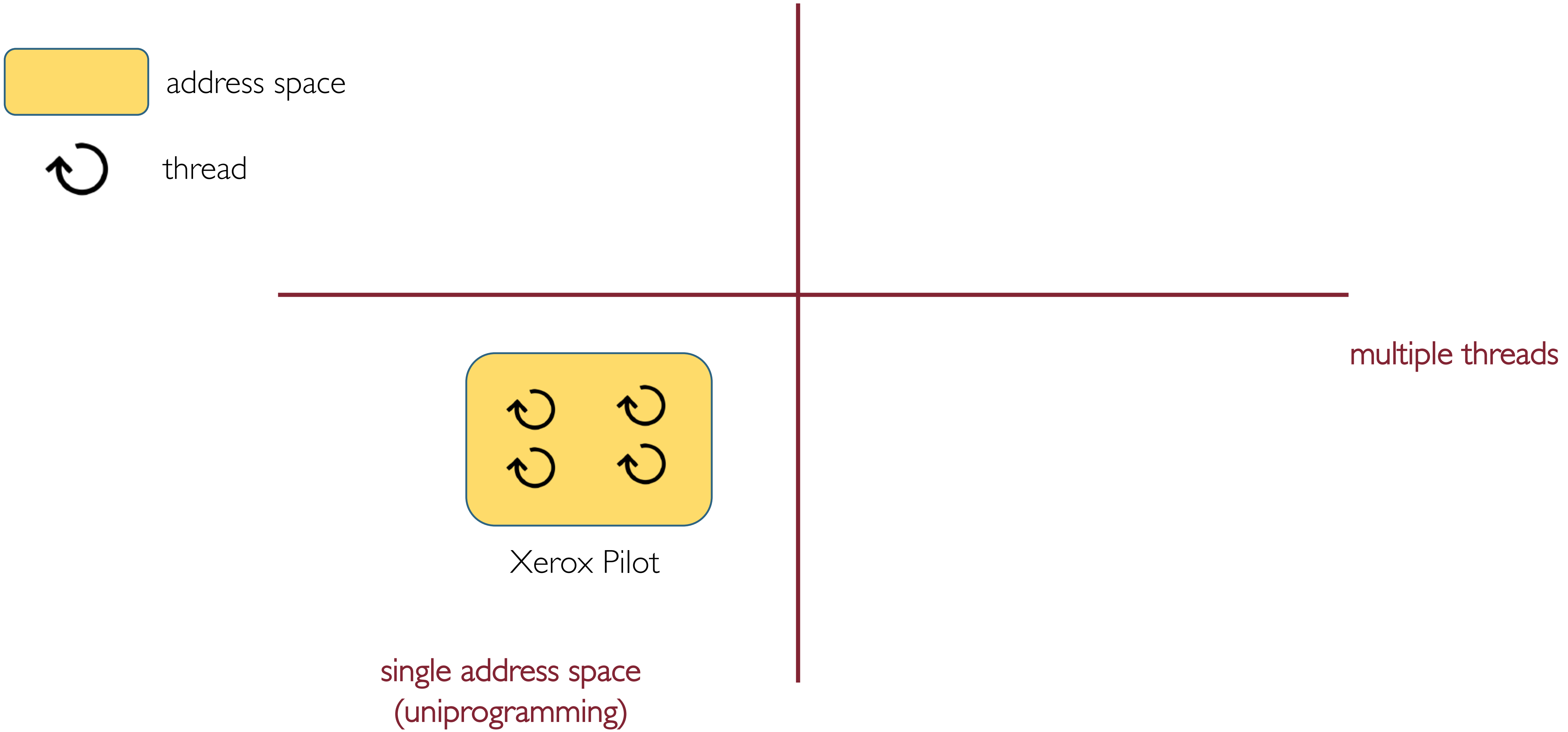

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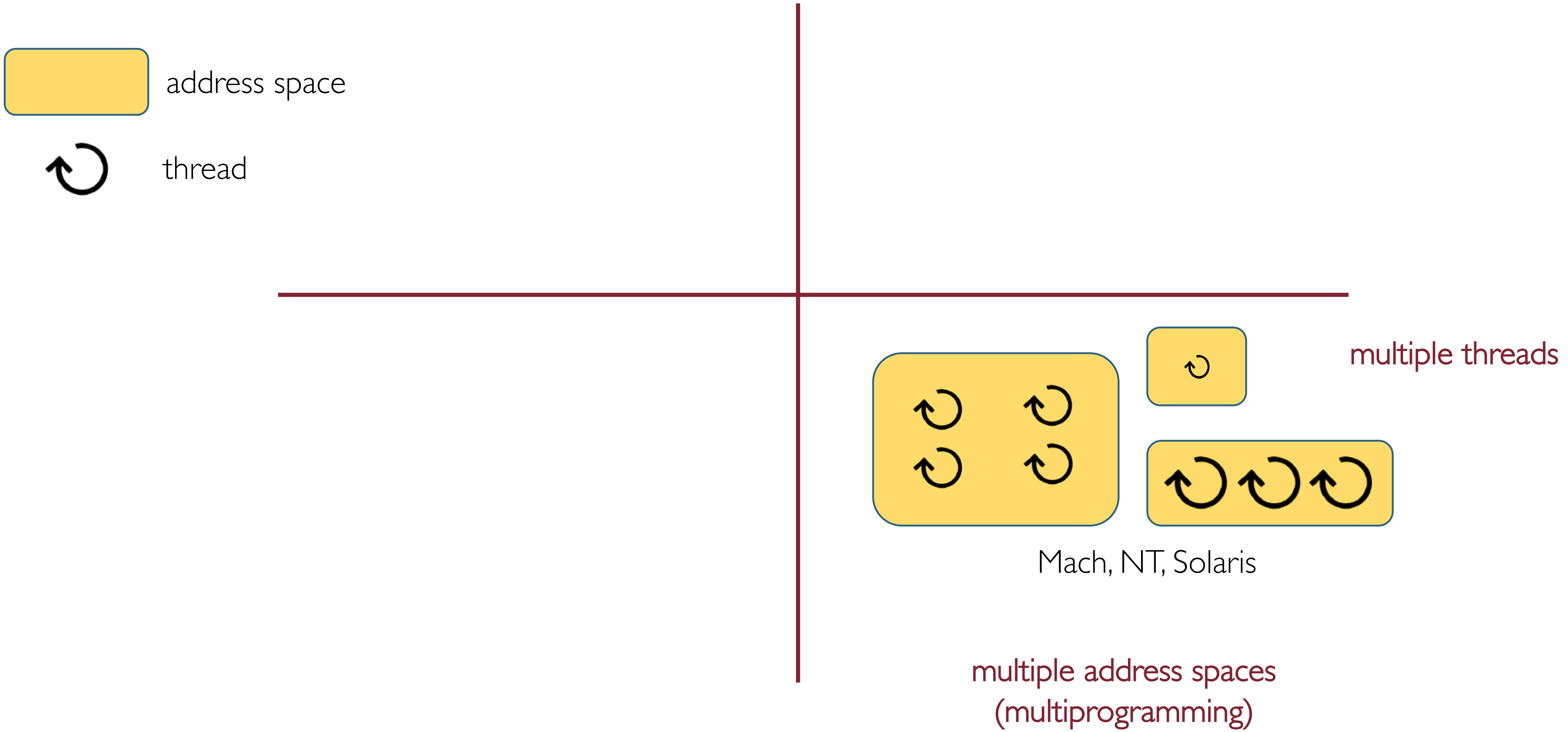

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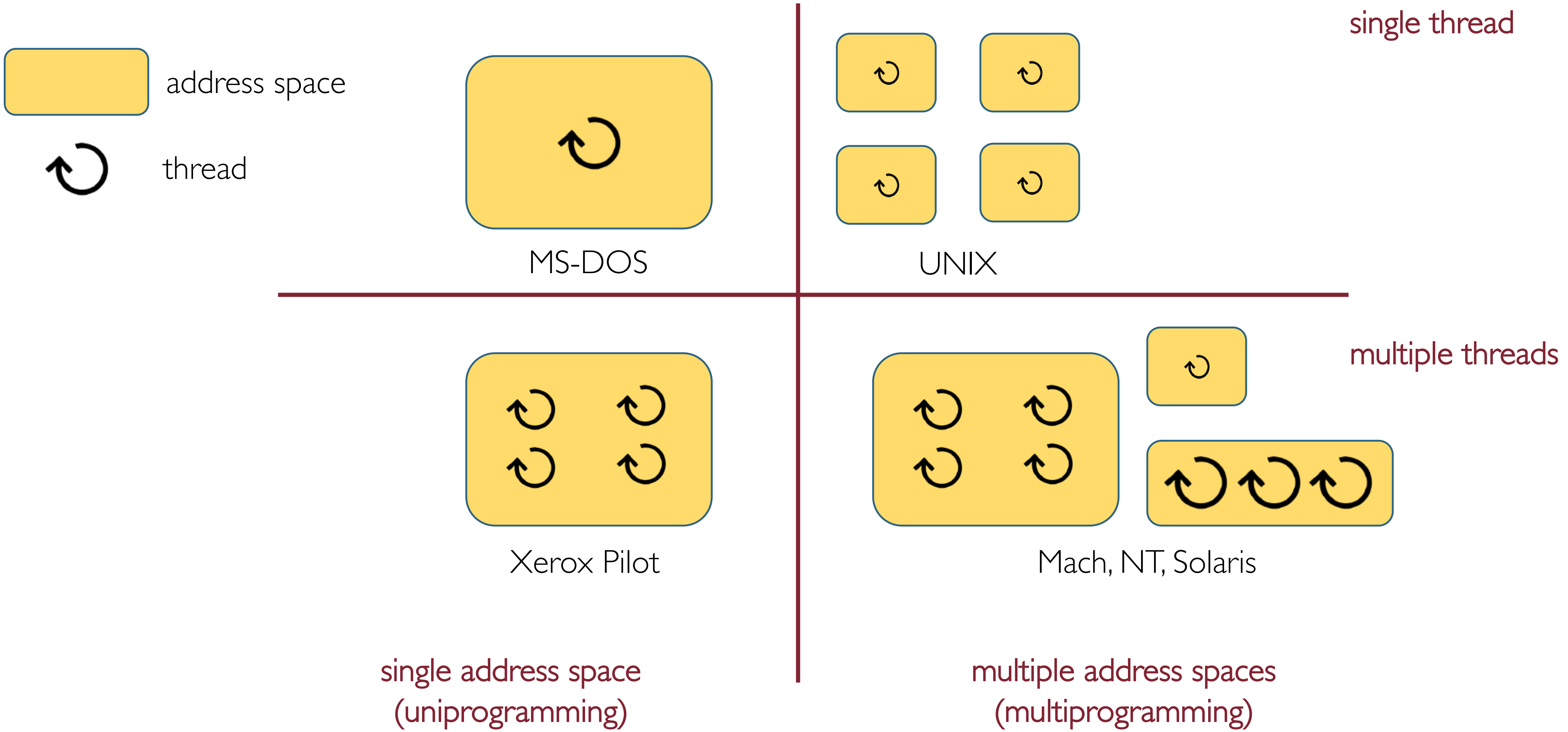

Multi-threading: Support and Management

- Support for (multiple) threads can be provided in 2 ways:
  - at the kernel level → kernel threads
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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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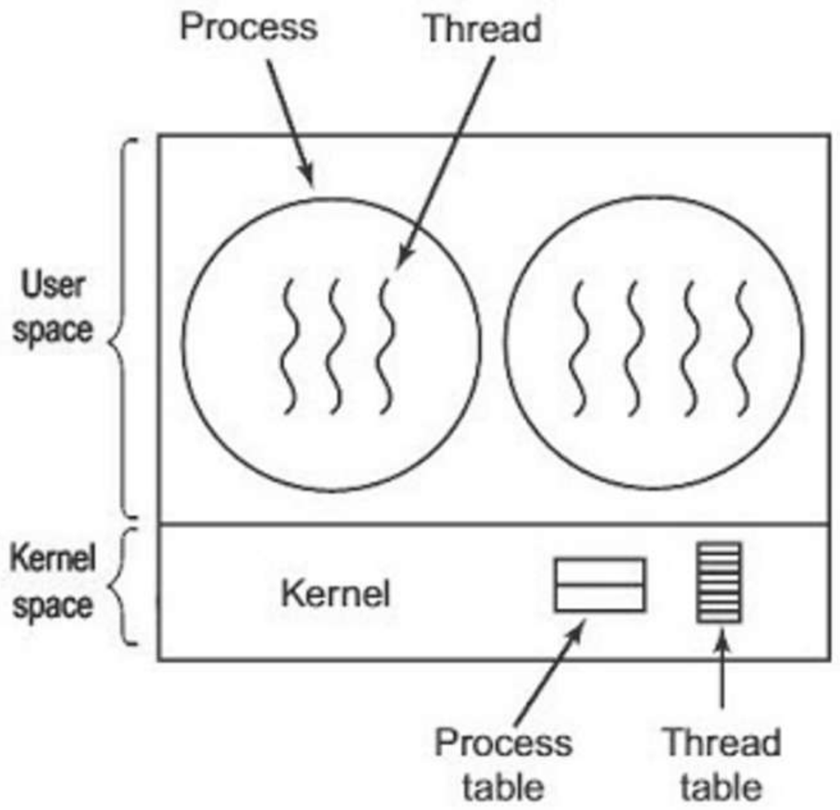
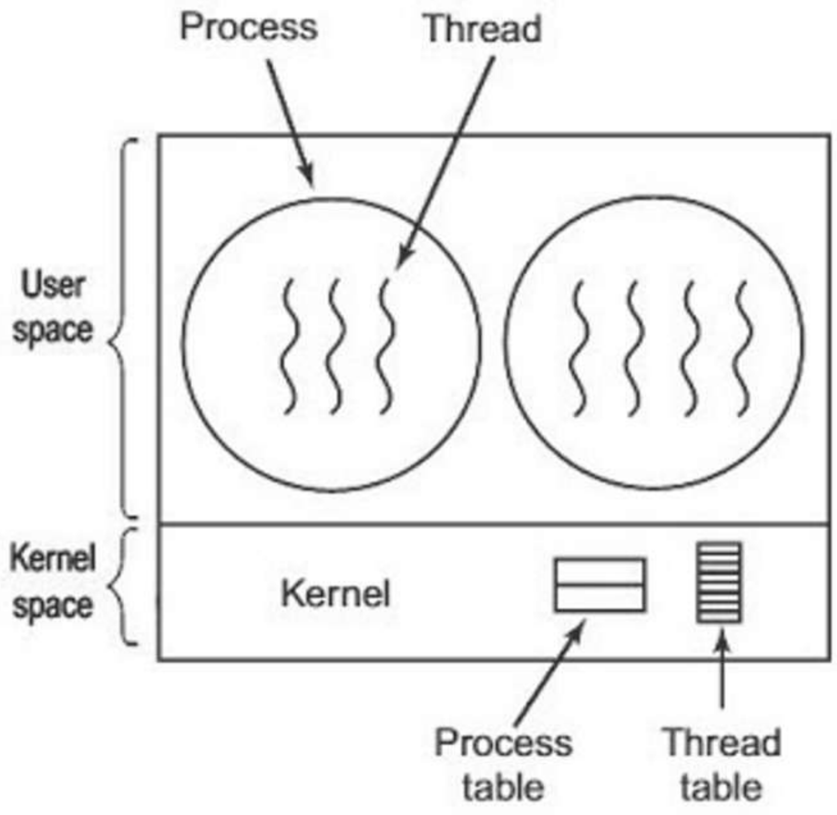
- The OS usually provides system calls to create and manage threads from user space

Kernel Threads: PROs



- PROs
  - The kernel has full knowledge of all threads
  - Scheduler may decide to give more CPU time to a process having a large numer of threads
  - Good for applications that frequently block
  - Switching between threads is faster than switching between processes

Kernel Threads: CONs



- CONs
  - Significant overhead and increase in kernel complexity
  - Slow and inefficient (need kernel invocations)
  - Context switching, although lighter, is managed by the kernel

User Threads

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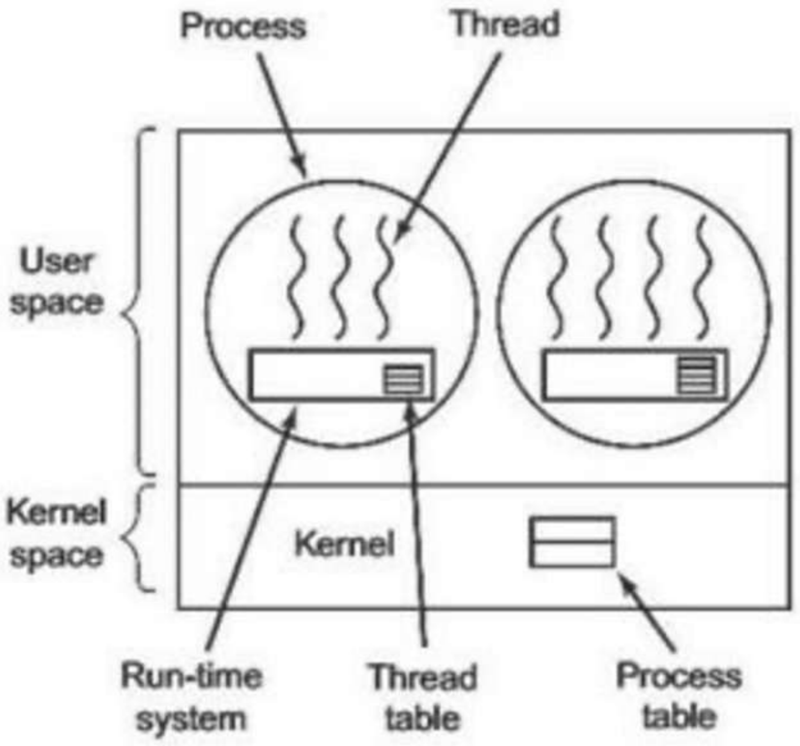
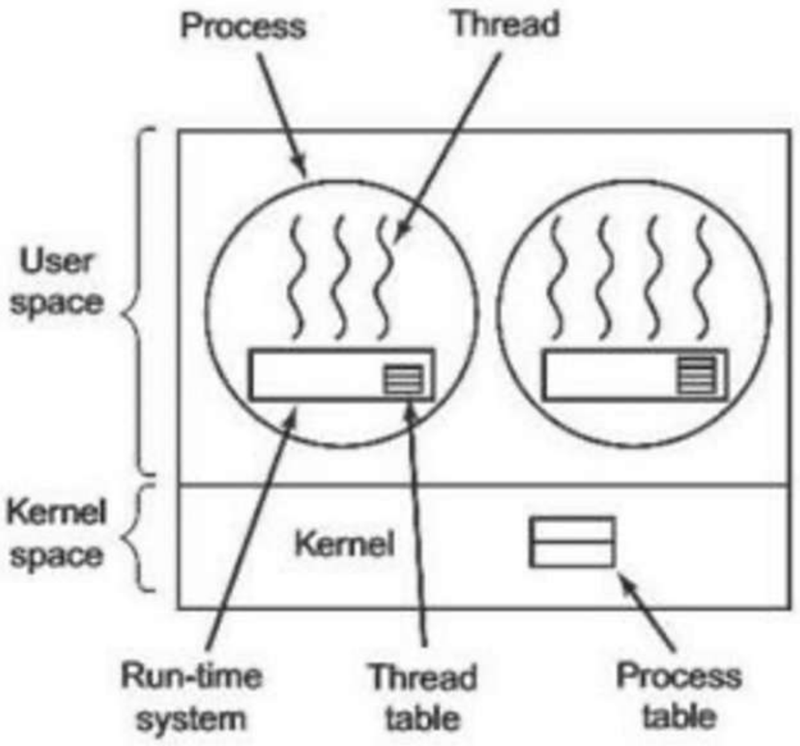
- Ideally, thread operations should be as fast as a function call

User Threads: PROs



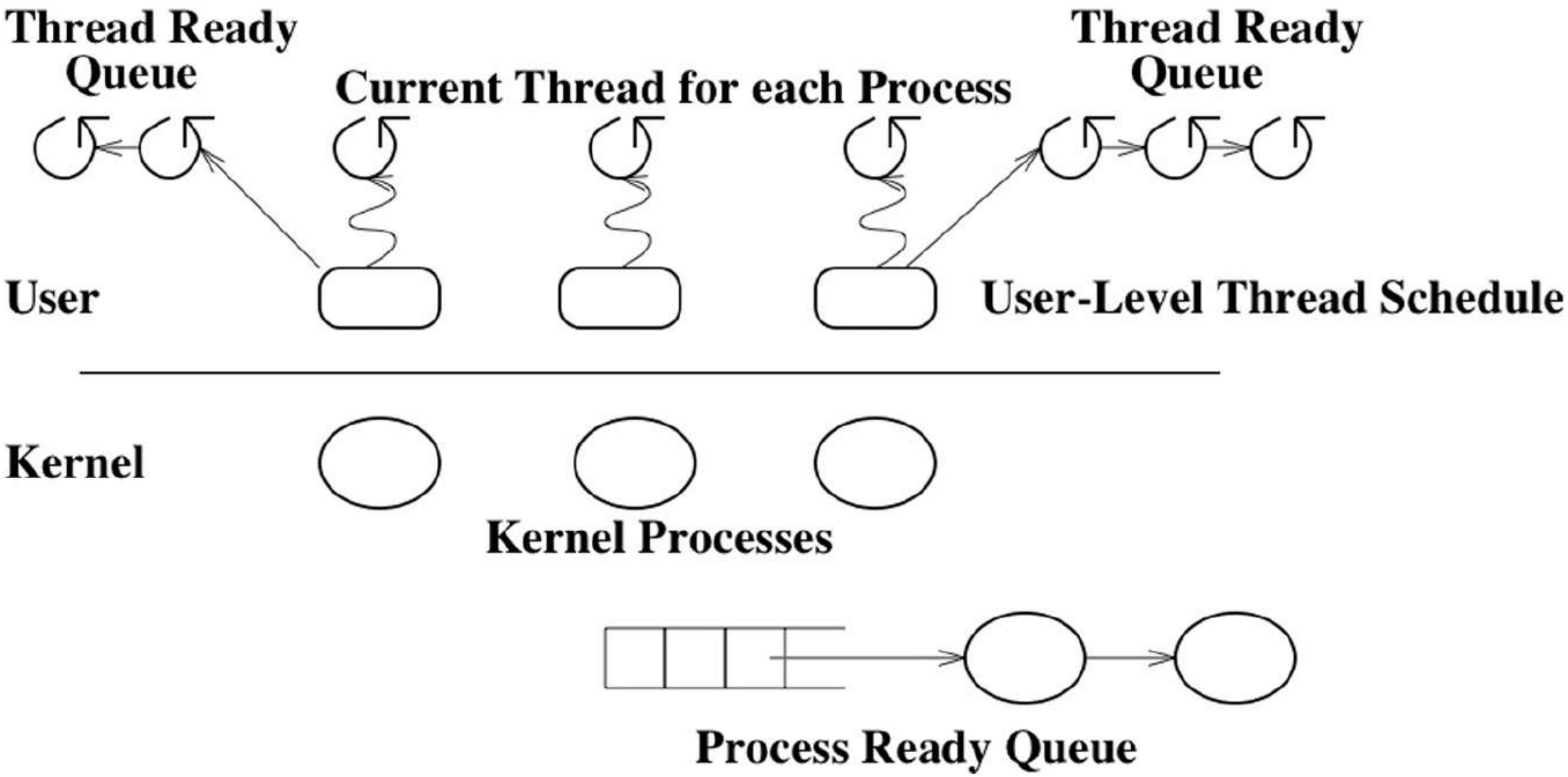
- PROs
  - Really fast and lightweight
  - Scheduling policies are more flexible
  - Can be implemented in OSs that do not support threading
  - No system calls involved, just user-space function calls
  - No actual context switch

User Threads: CONs

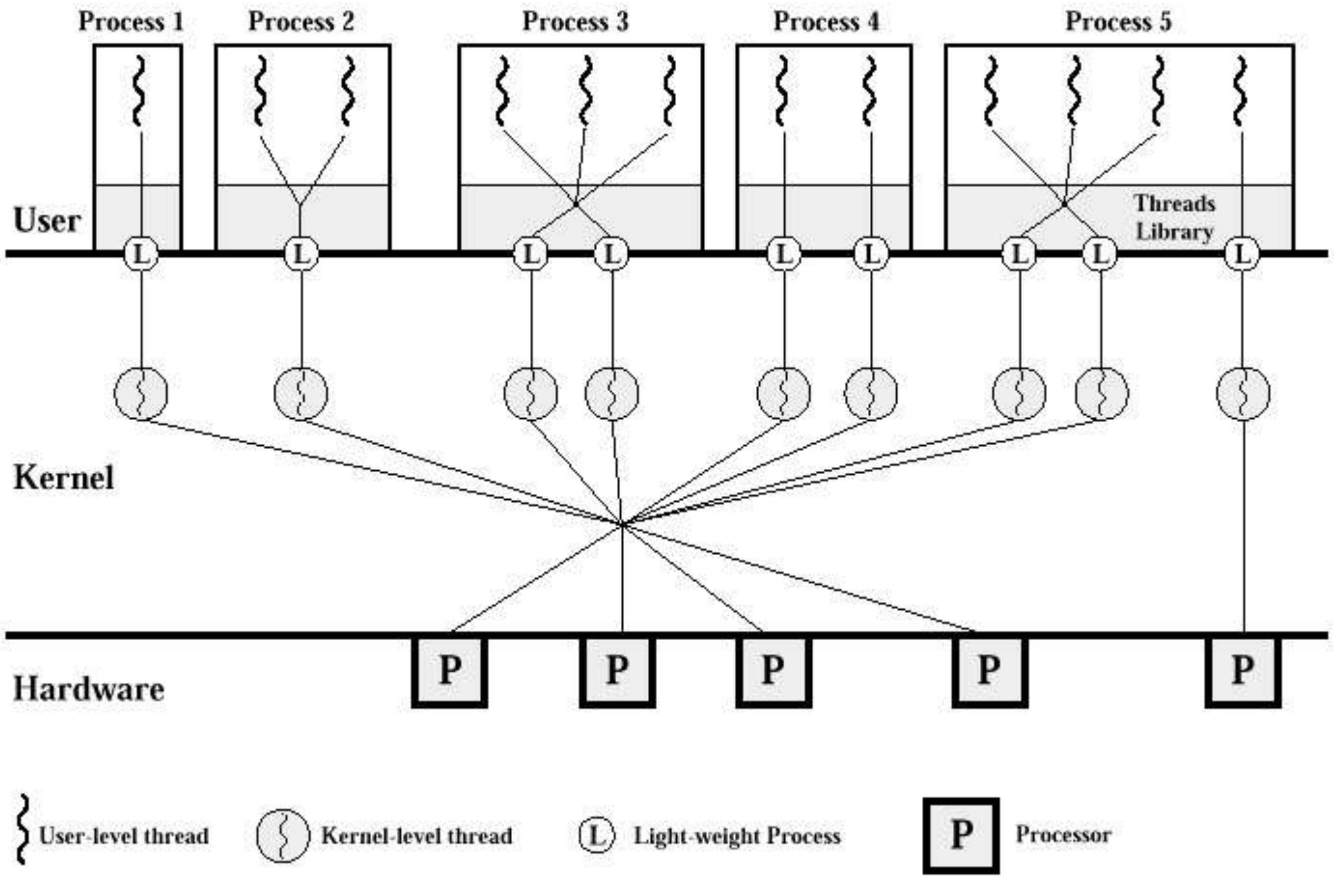


- CONs
  - No true concurrency of multi-threaded processes
  - Poor scheduling decisions
  - Lack of coordination between kernel and threads
    - A process with 100 threads competes for a time slice with a process with just 1 thread
  - Requires non-blocking system calls, otherwise all threads within a process have to wait

User Threads



Hybrid Management: Lightweight Processes



Multi-threading Models

- In a specific implementation, user threads must be mapped to kernel threads in one of the following ways:
  - Many-to-One
  - One-to-One
  - Many-to-Many
  - Two-level

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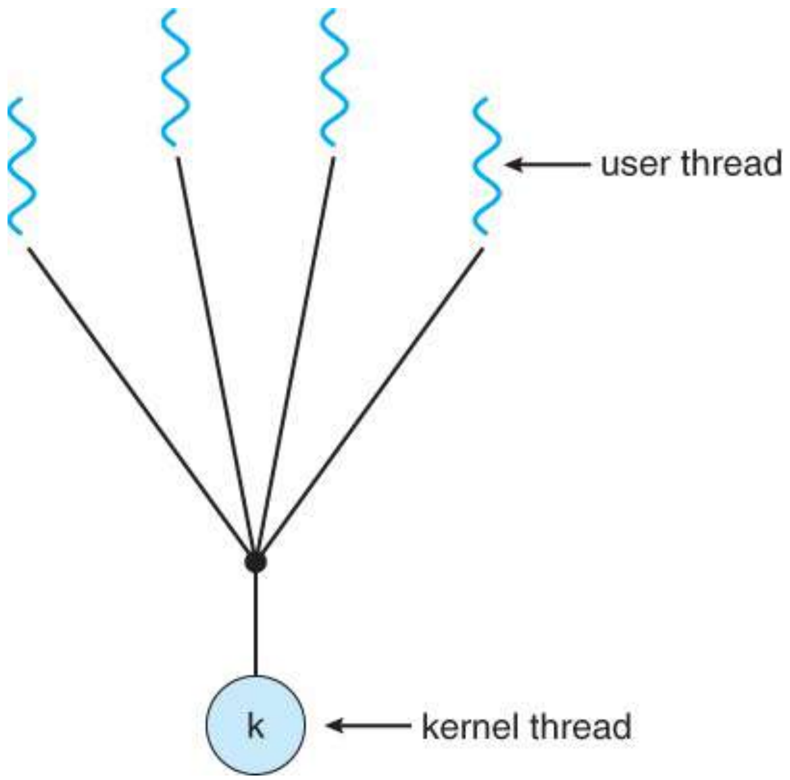
Remember:
A kernel thread is the unit of execution that is scheduled by the OS to run on the CPU (similar to single-threaded process)

Many-to-One Model



- 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
- As single kernel thread can operate on a single CPU, multi-user-thread processes cannot be split across multiple CPUs
- If a blocking system call is made, the entire process blocks, even if other user threads would be able to continue

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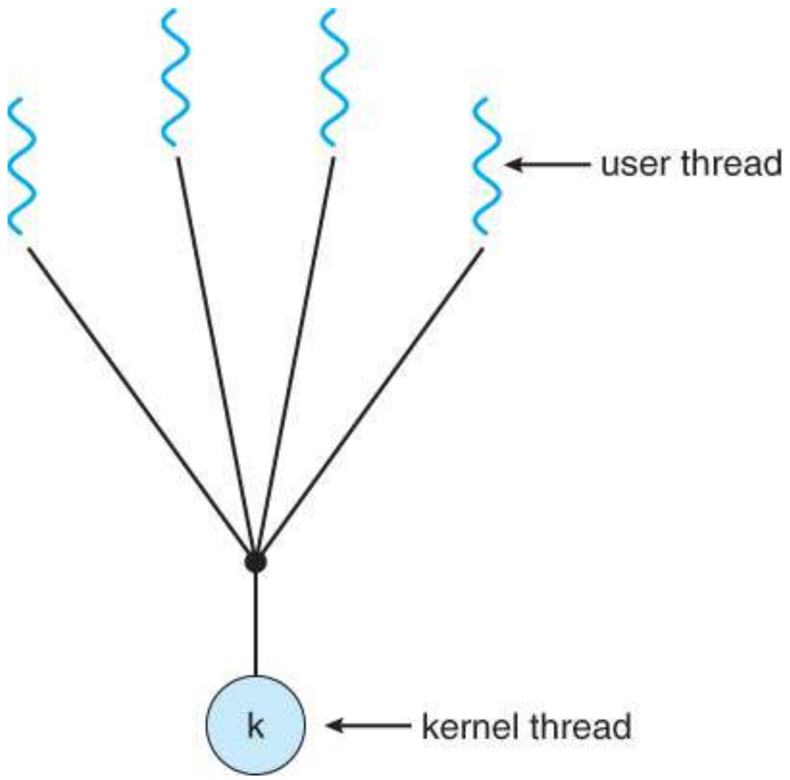

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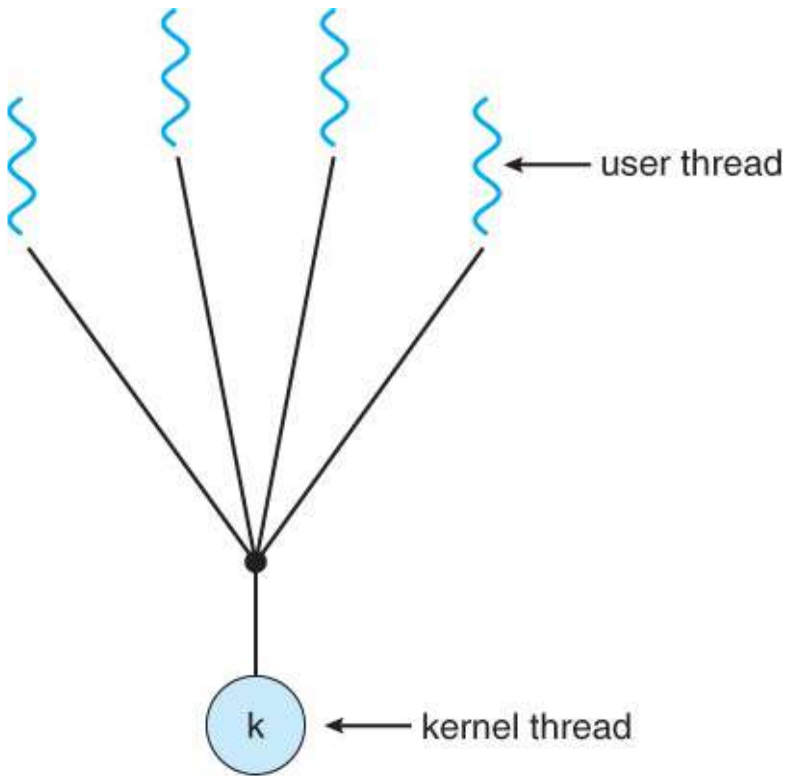

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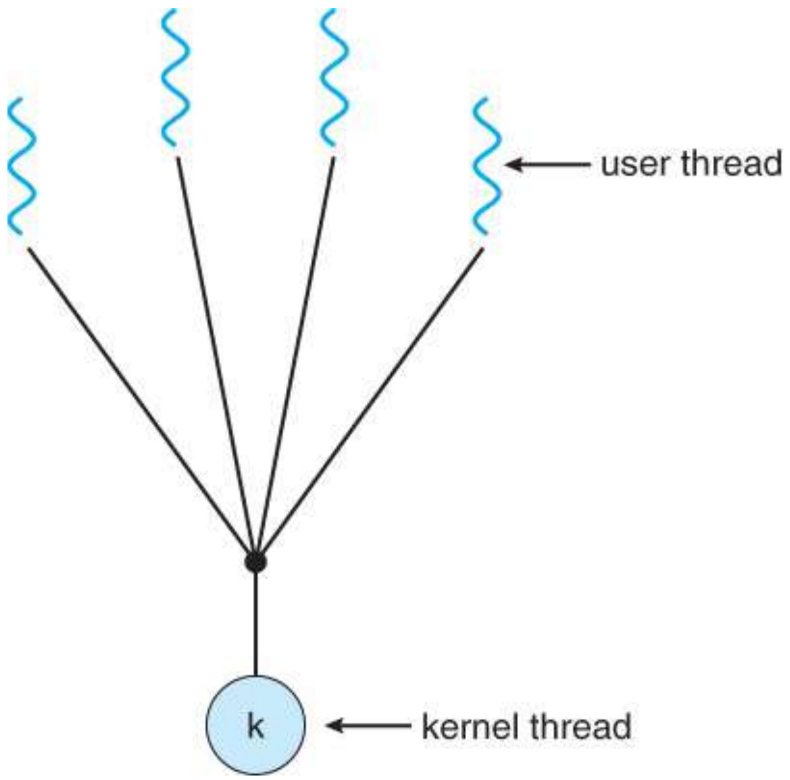

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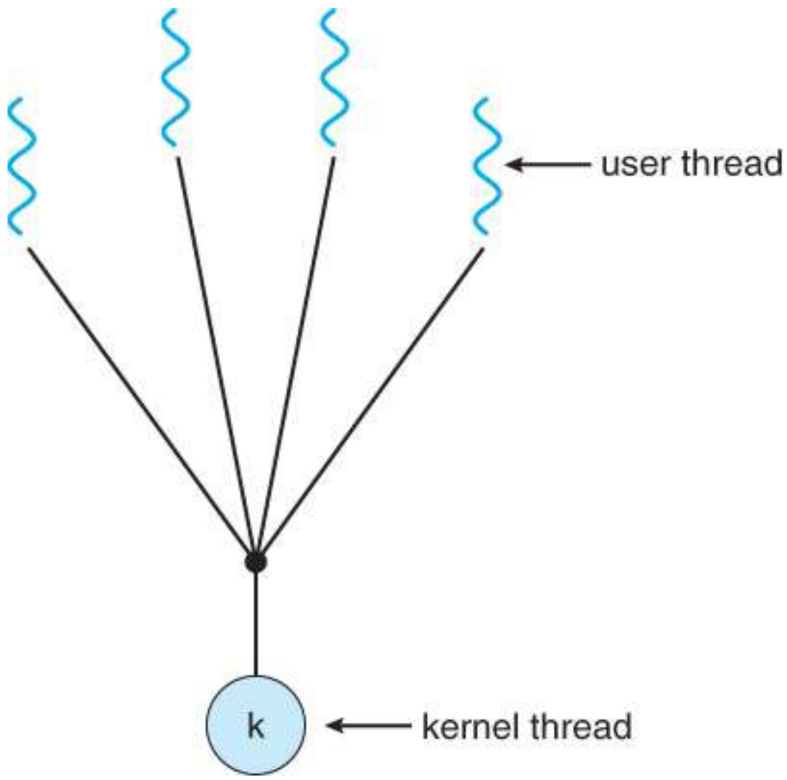

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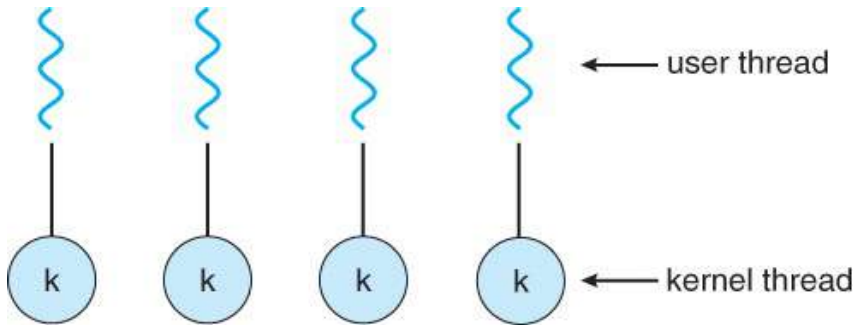
pure user-level

One-to-One Model



- A separate kernel thread to handle each user thread
- Overcomes the limitations of blocking system calls and splitting of processes across multiple CPUs
- The overhead of managing the one-to-one model is more significant and may slow down the system
- Most implementations of this model place a limit on how many threads can be created

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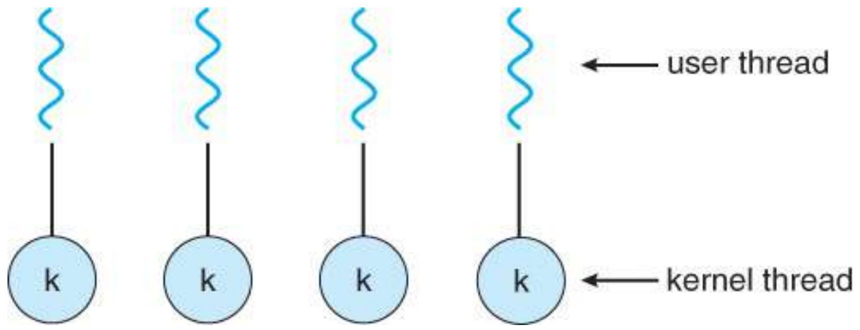

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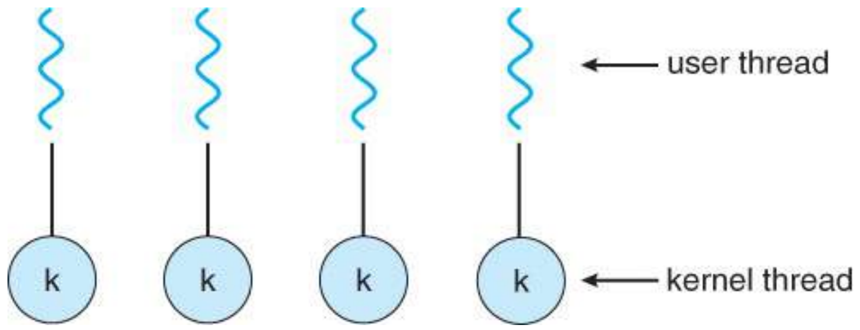

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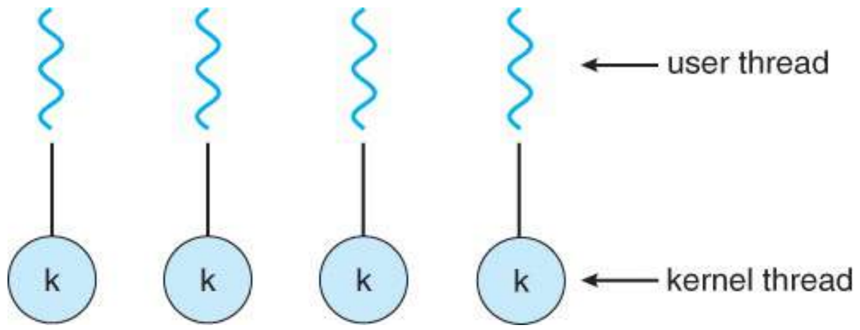

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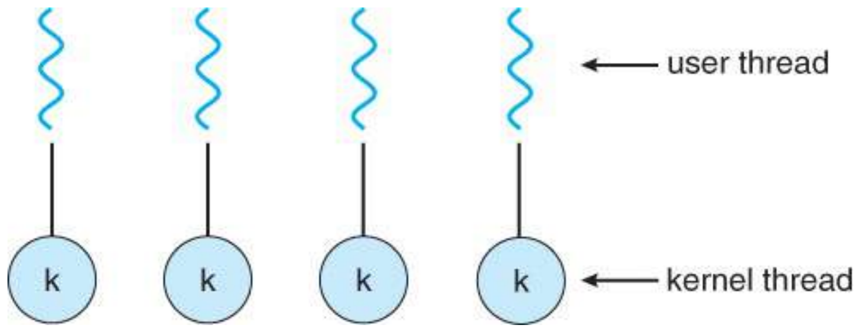

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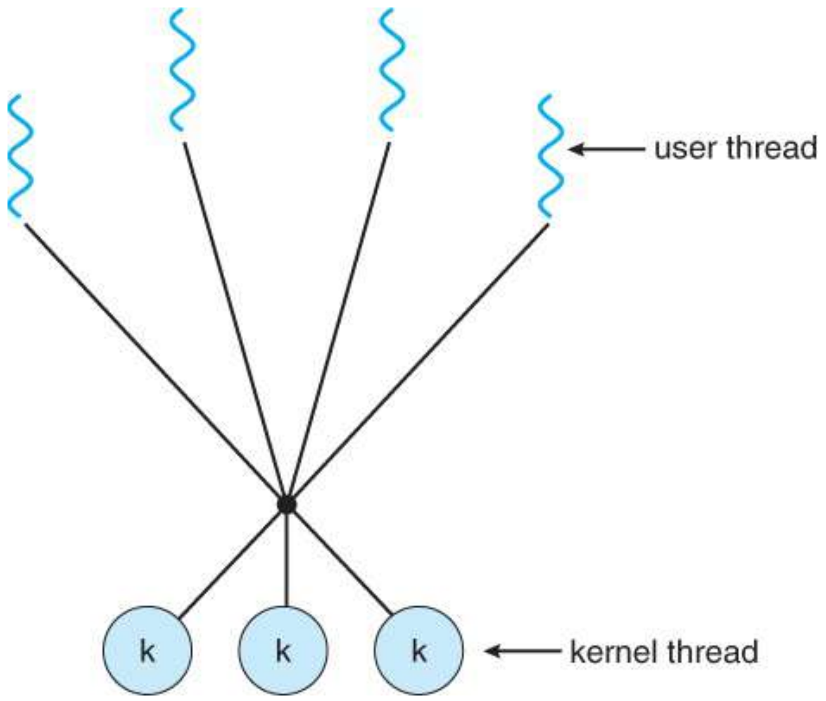
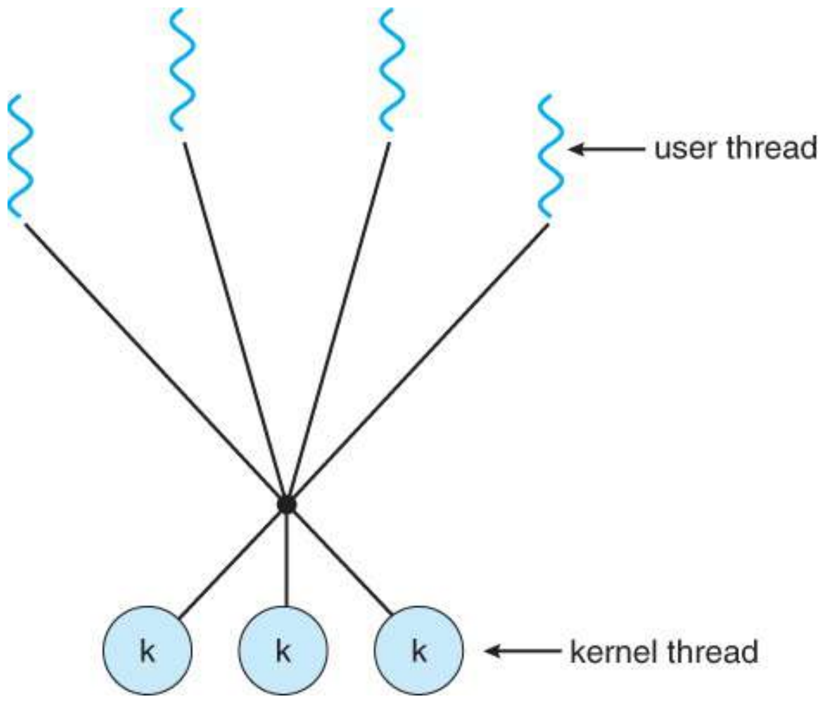
pure kernel-level

Many-to-Many Model



- Multiplexes any number of user threads onto an equal or smaller number of kernel threads
- Users have no restrictions on the number of threads created
- Processes can be split across multiple processors
- Blocking kernel system calls do not block the entire process

Many-to-Many Model



- Multiplexes any number of user threads onto an equal or smaller number of kernel threads
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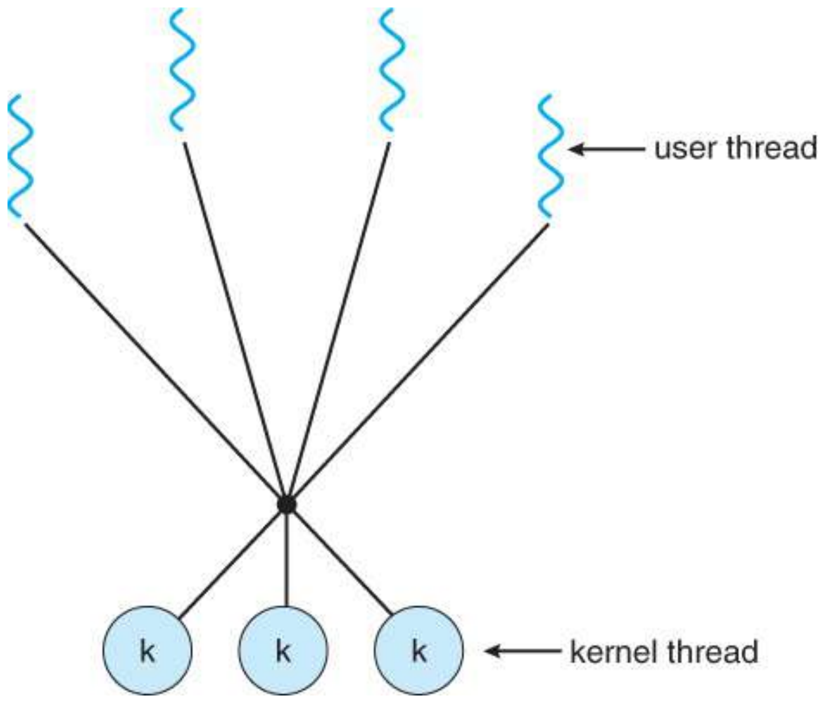

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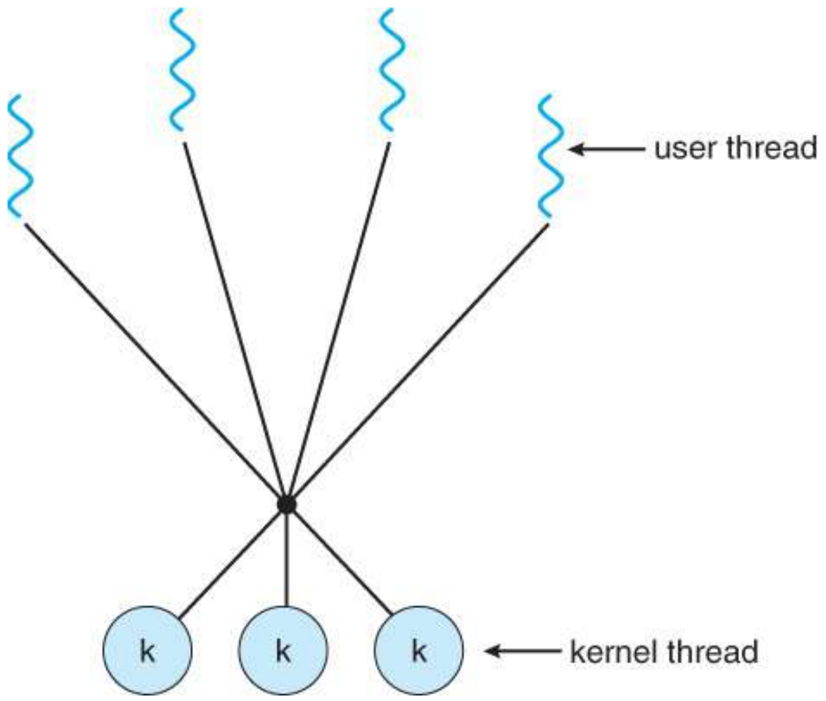

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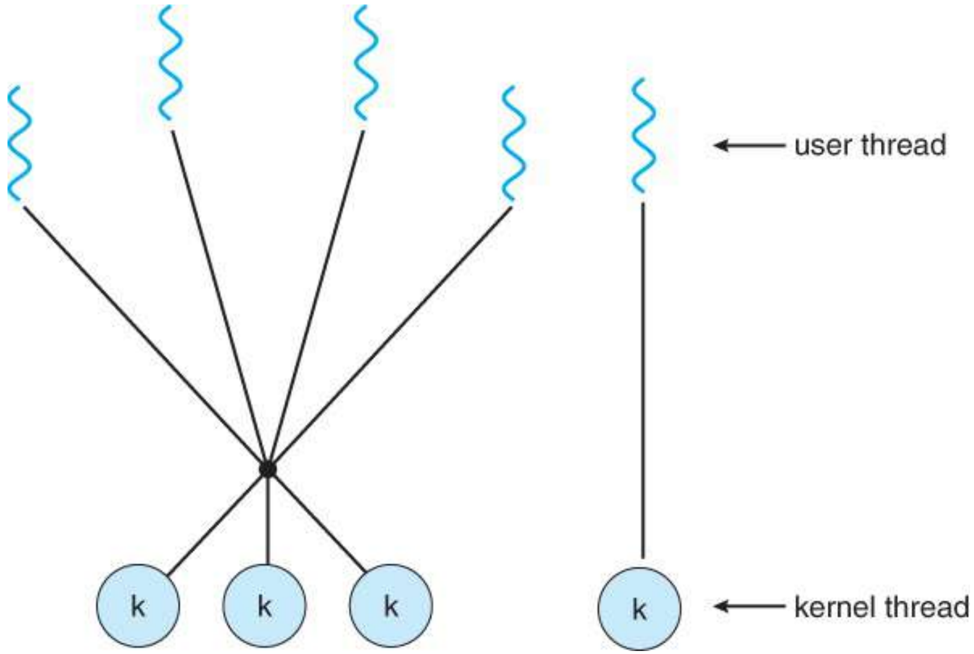

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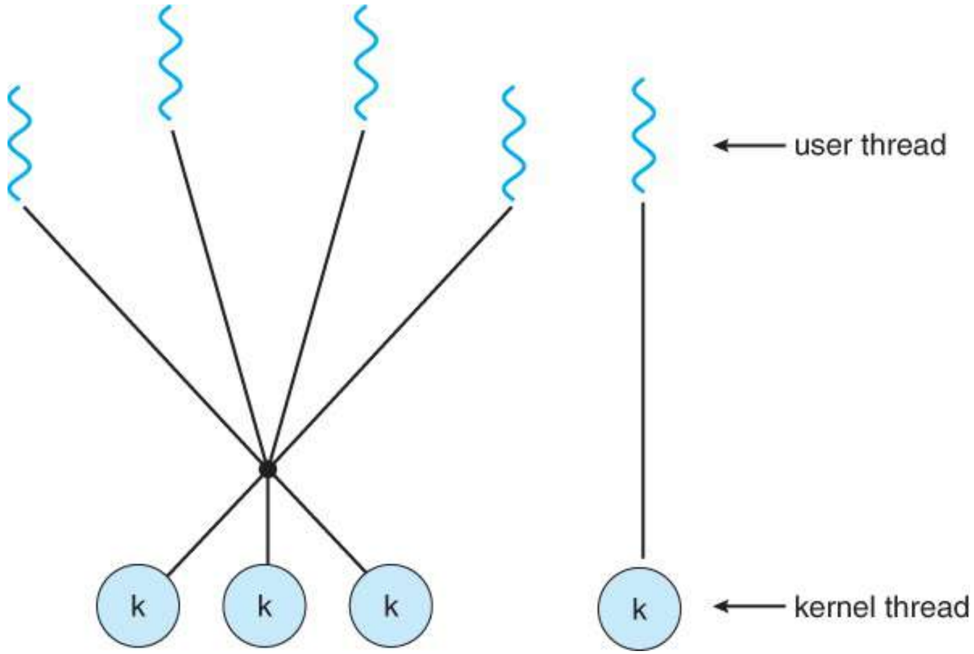

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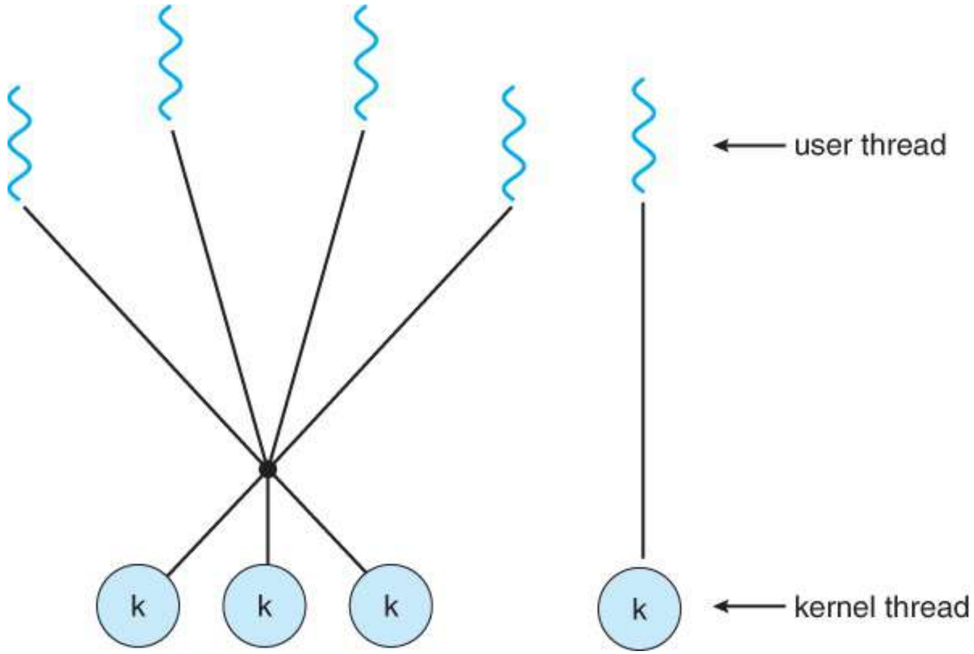

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Thread Libraries

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- 2 primary ways of implementing it:
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  - kernel space → implemented in kernel space within a kernel that supports threads (system calls)

Thread Libraries: Examples

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Thread Libraries: Examples

- There are 3 main thread libraries in use today:
  - POSIX Pthreads → may be provided as either a user or kernel library, as an extension to the POSIX standard
  - Win32 threads → provided as a kernel-level library on Windows systems
  - 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

Pthreads

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Pthreads: Sum Example

Compute the sum of the first *N* integers on a separate thread

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int sum; /* this data is shared by the thread(s) */
void *runner(void *param); /* the thread */

int main(int argc, char *argv[])
{
  pthread_t tid; /* the thread identifier */
  pthread_attr_t attr; /* set of thread attributes */

  if (argc != 2) {
    fprintf(stderr,"usage: a.out <integer value>\n");
    return -1;
  }
  if (atoi(argv[1]) < 0) {
    fprintf(stderr,"%d must be >= 0\n",atoi(argv[1]));
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  }

  /* get the default attributes */
  pthread_attr_init(&attr);
  /* create the thread */
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  /* wait for the thread to exit */
  pthread_join(tid,NULL);

  printf("sum = %d\n",sum);
}

/* The thread will begin control in this function */
void *runner(void *param)
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  int i, upper = atoi(param);
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  for (i = 1; i <= upper; i++)
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Figure 4.6 Multithreaded C program using the Pthreads API.

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Java Threads

- Java Threads can be created in 2 ways:
  - Extending the **`Thread`** class
  - Implementing the **`Runnable`** Interface
- Both solutions require to override the **`run()`** method
- Note that Java doesn't support multiple inheritance!
  - If your class extends the **`Thread`** class, it cannot extend any other class
  - In such a situation, implementing **`Runnable`** is preferable

Java Threads: Single-Threaded Web Server

```java
public class SingleThreadedServer implements Runnable {

    protected int          serverPort    = 8080;
    protected ServerSocket serverSocket  = null;
    protected boolean      isStopped     = false;

    public SingleThreadedServer(int port){
        this.serverPort = port;
    }

    public void run() {

        try {
            this.serverSocket = new ServerSocket(this.serverPort);
        }
        catch (IOException e) {
            throw new RuntimeException("Cannot open port " + this.serverPort, e);
        }

        while(!this.isStopped) {
            Socket clientSocket = null;
            try {
                clientSocket = this.serverSocket.accept();
            } catch (IOException e) {
                if(this.isStopped) {
                    System.out.println("Server Stopped.") ;
                    return;
                }
                throw new RuntimeException(
                    "Error accepting client connection", e);
            }
            try {
                processClientRequest(clientSocket);
            } catch (Exception e) {
                //log exception and go on to the next request.
            }
        }

        System.out.println("Server Stopped.");
    }

    private void processClientRequest(Socket clientSocket) throws Exception {
        // Process client request here ...
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This is the simplest (although not optimal) single-threaded implementation of a Java web server

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This is not a good idea as clients can connect to the server <u>only</u> when this is inside the `serverSocket.accept()` method call

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The risk of clients being denied access to the server because the listening thread is outside the `accept()` call is minimized

Java Threads: Multi-Threaded Web Server

```java
public class WorkerRunnable implements Runnable{

    protected Socket clientSocket = null;
    protected String serverText   = null;

    public WorkerRunnable(Socket clientSocket, String serverText) {
        this.clientSocket = clientSocket;
        this.serverText   = serverText;
    }

    public void run() {
        // process client request here ...
    }
}
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  - overhead to create a thread for each request
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- Solution → use a **thread pool**

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- When the web server gets a request it awakens a thread from the pool
- The worker thread processes the request and goes back to the pool once terminated
- If no threads are available in the pool the server simply waits for one

Thread Pools: Benefits

- Servicing a request with an existing thread is faster than waiting to create a thread
- A thread pool limits the number of threads that exist at any one point
- Separating the task to be performed from the mechanics of creating the task allows us to use different strategies for running the task
  - For example, the task could be scheduled to execute after a time delay or to execute periodically

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Threading Issues: `fork()` and `exec()`

- Q: *If one thread forks, is the entire process copied, or is the new process single-threaded?*
- A1: System dependent
- A2: If the new process execs right away, there is no need to copy all the other threads, otherwise the entire process should be copied
- A3: Many versions of UNIX provide multiple versions of the fork call for this purpose

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Threading Issues: Signal Handling

- Q: *When a multi-threaded process receives a signal, to what thread should that signal be delivered?*
- A: There are 4 major options:
  - Deliver the signal to the thread to which the signal applies
  - Deliver the signal to every thread in the process
  - Deliver the signal to certain threads in the process
  - Assign a specific thread to receive all signals in a process

Threading Issues: Signal Handling (UNIX)

- UNIX allows individual threads to indicate which signals they are accepting and which they are ignoring
- Provides 2 separate system calls for delivering signals to process/threads, respectively:
  - `kill(pid, signal)`
  - `pthread_kill(tid, signal)`

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  - on systems implementing many-to-one and many-to-many threads
- System Contention Scope (SCS)
  - involves the system scheduler scheduling kernel threads to run on one or more CPUs
  - on systems implementing one-to-one threads

Thread Scheduling: Activation

- Many implementations of threads provide a virtual processor as an interface between user thread and the kernel thread (many-to-many or two-tier)
- This virtual processor is known as a Lightweight Process (LWP)
- There is a one-to-one correspondence between LWPs and kernel threads
- The number of kernel threads available may change dynamically
- The application (user-level thread library) maps user threads onto available LWPs
- Kernel threads are scheduled onto the real processor(s) by the OS

Thread Scheduling: Activation

- The kernel communicates to the user-level thread library when certain events occur (e.g., a thread is blocking) via an upcall
- The upcall is handled in the thread library by an upcall handler
- The upcall also provides a new LWP for the upcall handler to run on, which it can then use to reschedule the user thread that is about to become blocked
- The OS will also issue upcalls when a thread unblocks, so the thread library can make appropriate adjustments
- If the kernel thread blocks then the LWP blocks, which blocks the user thread

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- Scheduling algorithms operates (almost) transparently with threads