# Operating Systems (INFR09047)

2019/2020 Semester 2

# Threads

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Chapter 4

# Overview

- Concurrency vs Parallelism
- Process vs Thread
- Threads
- Kernel-level Threading
- User-level Threading
- Explicit and Implicit Thread Interfaces

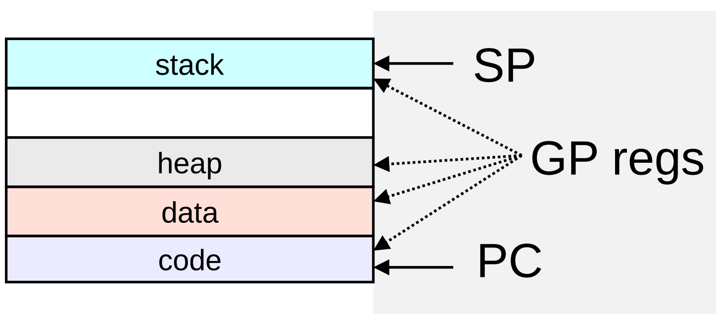
# What's "in" a process?

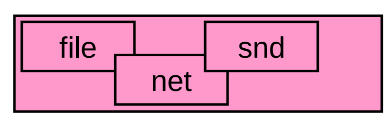
**From previous slide-set**

- A process consists of (at least)
  - An **address space**, containing
    - Code (instructions) for the running program
    - Data for the running program (static data, heap data, stack)
  - A **CPU state**, consisting of
    - Program counter (PC), indicating the next instruction
    - Stack pointer, current stack position
    - Other general-purpose register values
  - A set of **OS resources**
    - Open files, network connections, sound channels, …

instruction flow

Process address space

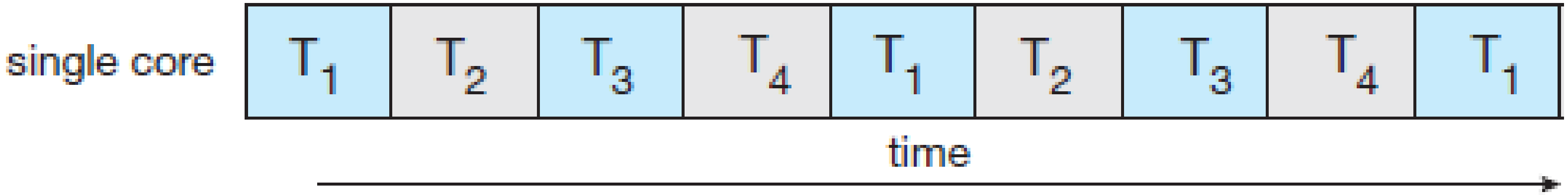


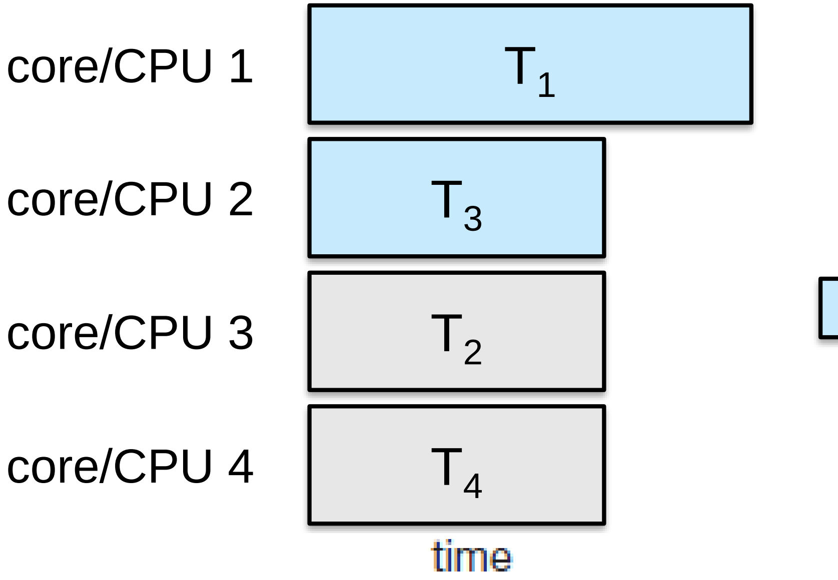

OS kernel address space

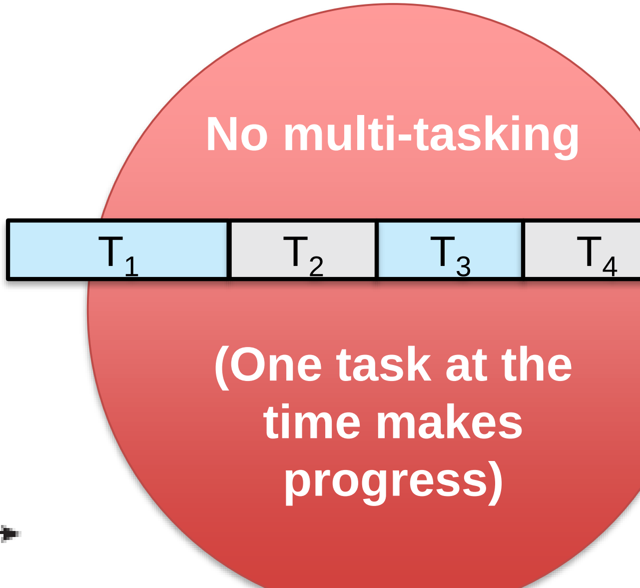
# Concurrency **vs** Parallelism

- **Multiple tasks:** Task 1 ($T_1$), Task 2 ($T_2$), Task 3 ($T_3$), Task 4 ($T_4$)
- **Concurrent** execution on a **single-core system**



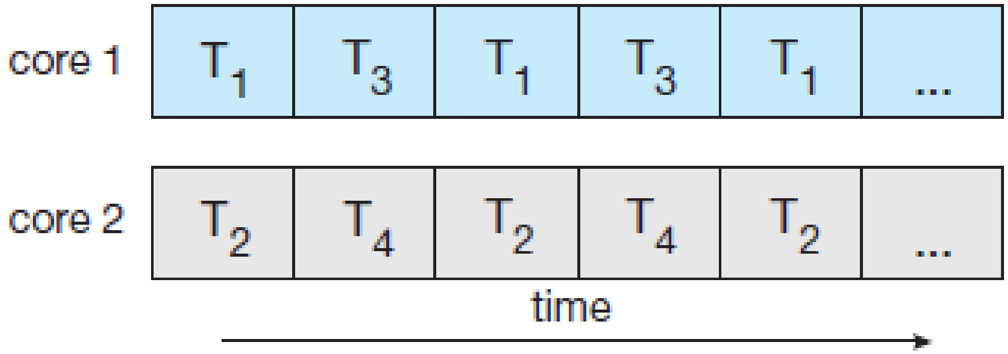

- **Parallel execution** on a **multicore/multiprocessor** system



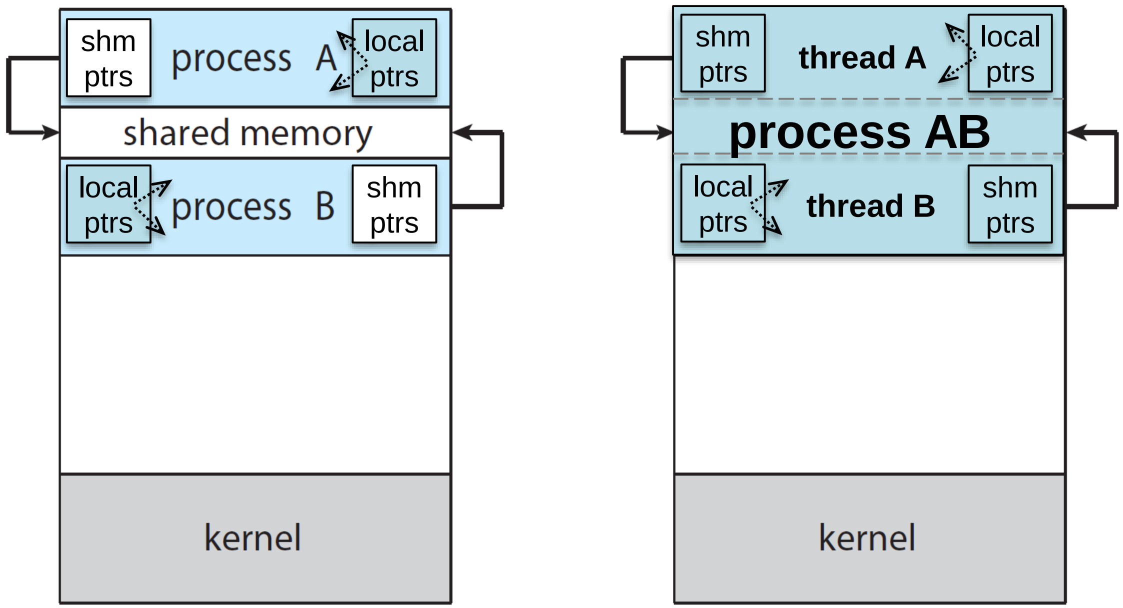
# Concurrency **and** Parallelism

- **Both Concurrency** and **Parallelism**




- Multiple **processes** to get *concurrency* and *parallelism*
  - Programs (code) of distinct processes are isolated from each other
- *What if they need to communicate/share data?*
  - Message passing, OS in the middle – **slow**
  - Shared memory, not all pointers work – **limited shareability**
    OS resources not shared by default – **cumbersome**

# From Processes **to Threads**




- Multiple **processes** to get *concurrency* and *parallelism*
  - Programs (code) of distinct processes are isolated from each other
- Multiple **threads** to get *concurrency* and *parallelism*
  - Threads **“share a process”** – same address space, OS resources
  - Threads have **different instruction flow** – private stack, CPU state

# Use Case Scenario

- Various **instruction flows**
  - run the *same* **code** (same or different instruction order)
  - access the *same* **data** (or part of it)
  - have the *same* **privileges**
  - use the *same* **OS resources**

- Each **instruction flow** has **hardware execution state**
  - Execution stack and stack pointer (SP)
    - Traces state of procedure calls made
  - Program counter (PC)
    - Next instruction to be executed
  - Set of general-purpose processor registers and their values

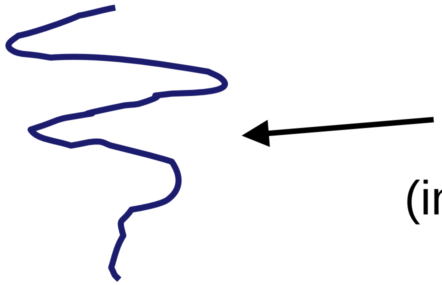
# Can be Achieved that with Processes?

- Given the **process abstraction**
  1. Fork several processes
  2. Cause each of them to *map* to the same memory to share data
     - See **`shmget()`** API for one way to do this
  3. Make them both to *open* the same OS resources

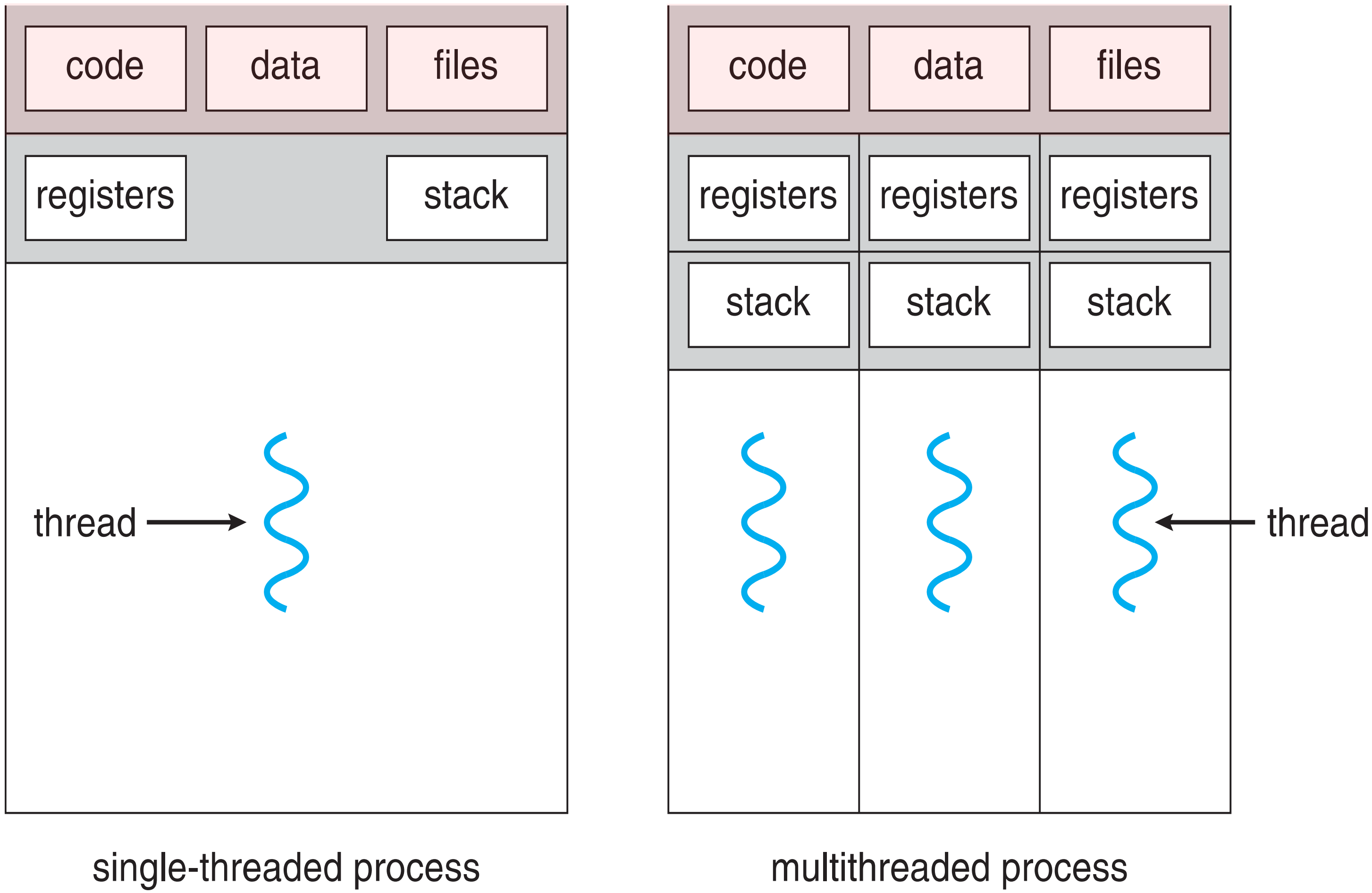
- Cumbersome
- Inefficient
  - **Space**: PCB, page tables, etc.
  - **Time**: creating OS structures, fork/copy address space, etc.
- Limited shareability
  - Not all pointers work

# Anything Better?

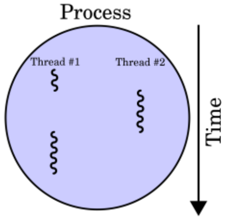
- Key **idea**
  - **Separate** the foundational components of a *process* (address space, execution state, OS resources)
  - Into different **abstractions/entities**
    - **PROCESS:** address space, OS resources
    - **THREAD:** CPU state (execution state)
      - program counter, stack pointer, other registers



# Single-**threaded** and Multi**threaded** Processes



# Threads and Processes

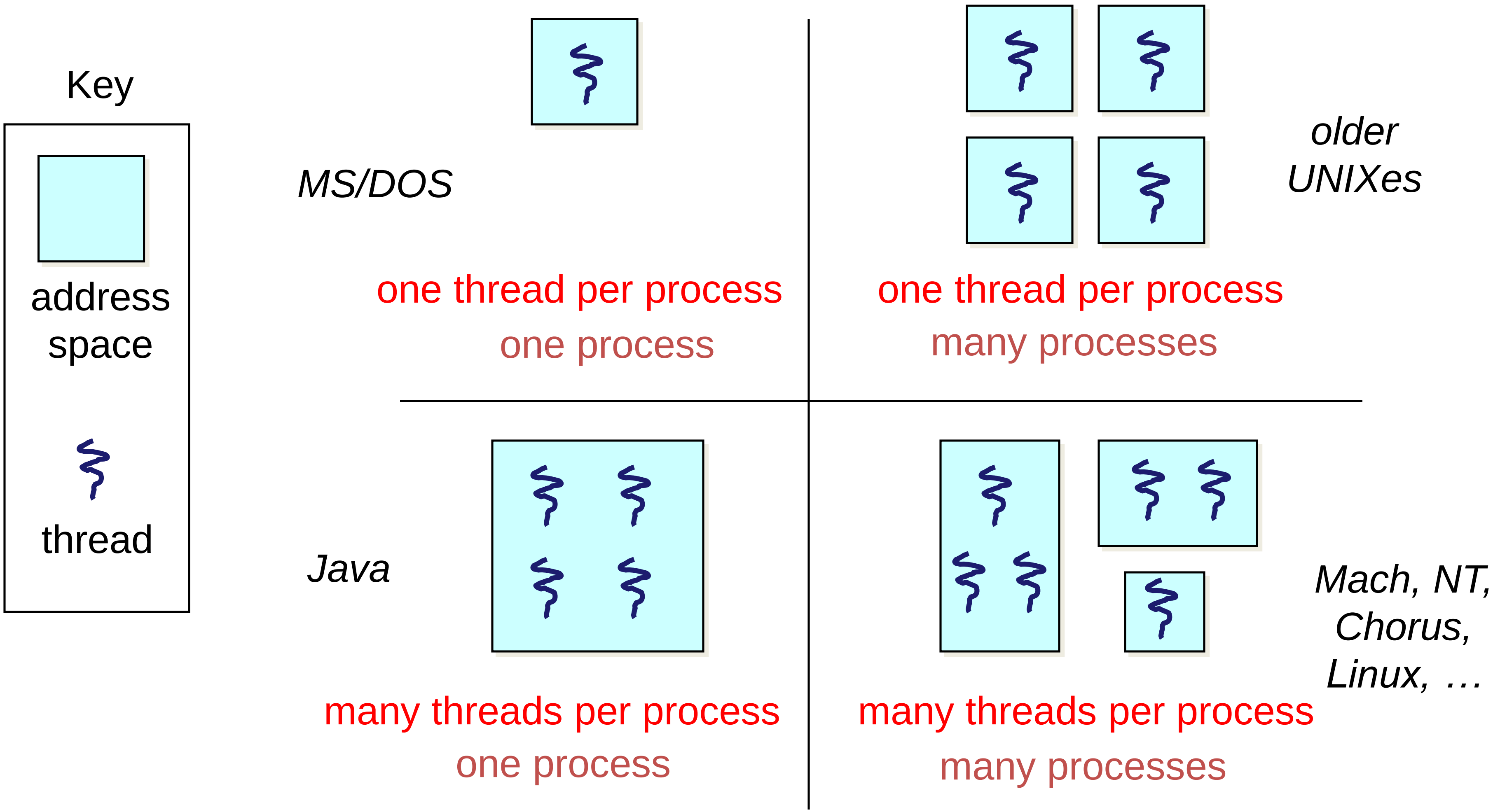



- Most modern OS's (Mach (Mac OS), Chorus, Windows, UNIX) support
  - **Process:** defines the address space and process' OS resources
  - **Thread:** defines a sequential **execution flow** within a process
- A **thread** **is bound to** a single process (thus address space)
  - However, processes (and address spaces) can have **multiple threads** executing within them
  - Sharing data between threads is **cheap**: all see the same address space
  - Creating threads is **cheap** too!
- **Threads** become the **unit of scheduling**
  - But depends on implementation (see next slides)
  - Processes are just **containers** in which threads execute

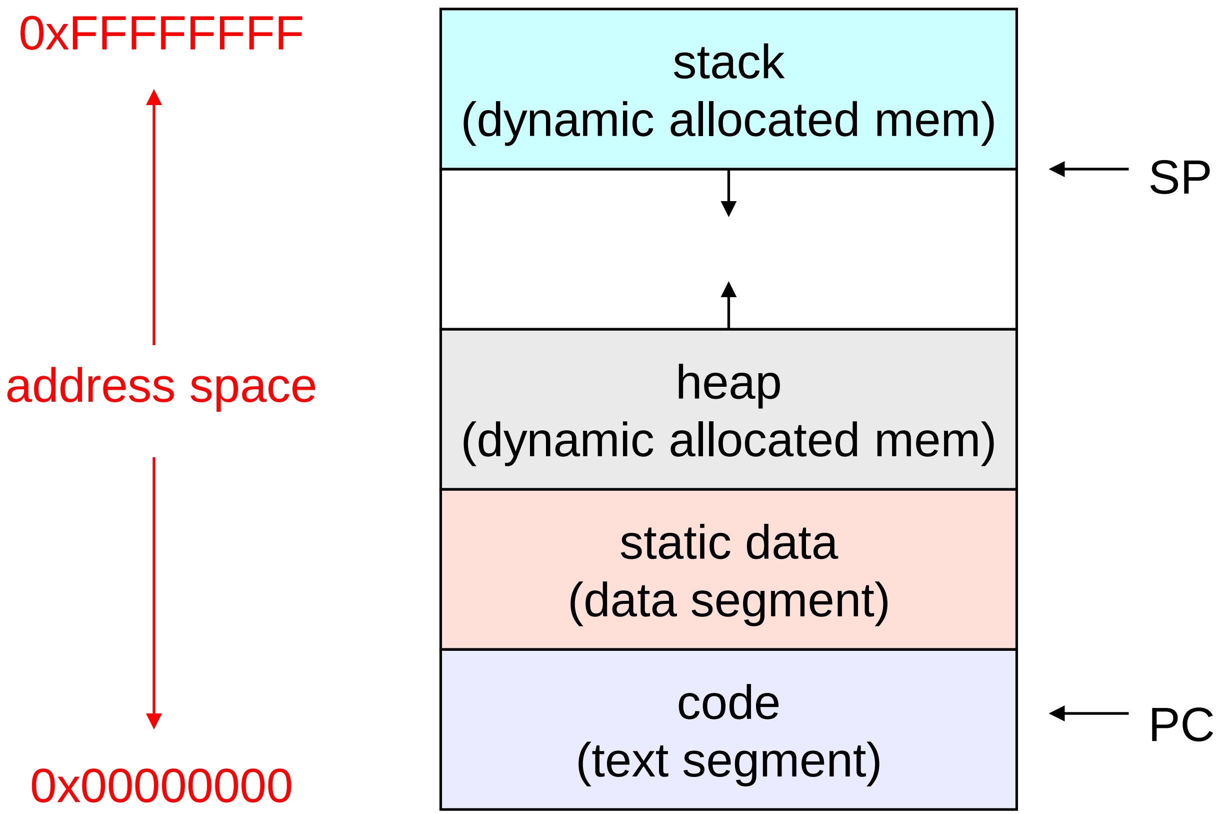
# Communication

- **Threads** are diverse execution flows sharing an address space (and OS resources)
- Address spaces provide **isolation**
  - If you can’t name it, you can’t read nor write it
- **Threads** are in the same address space
  - Same name space (memory addresses)
  - Update a **shared variable**

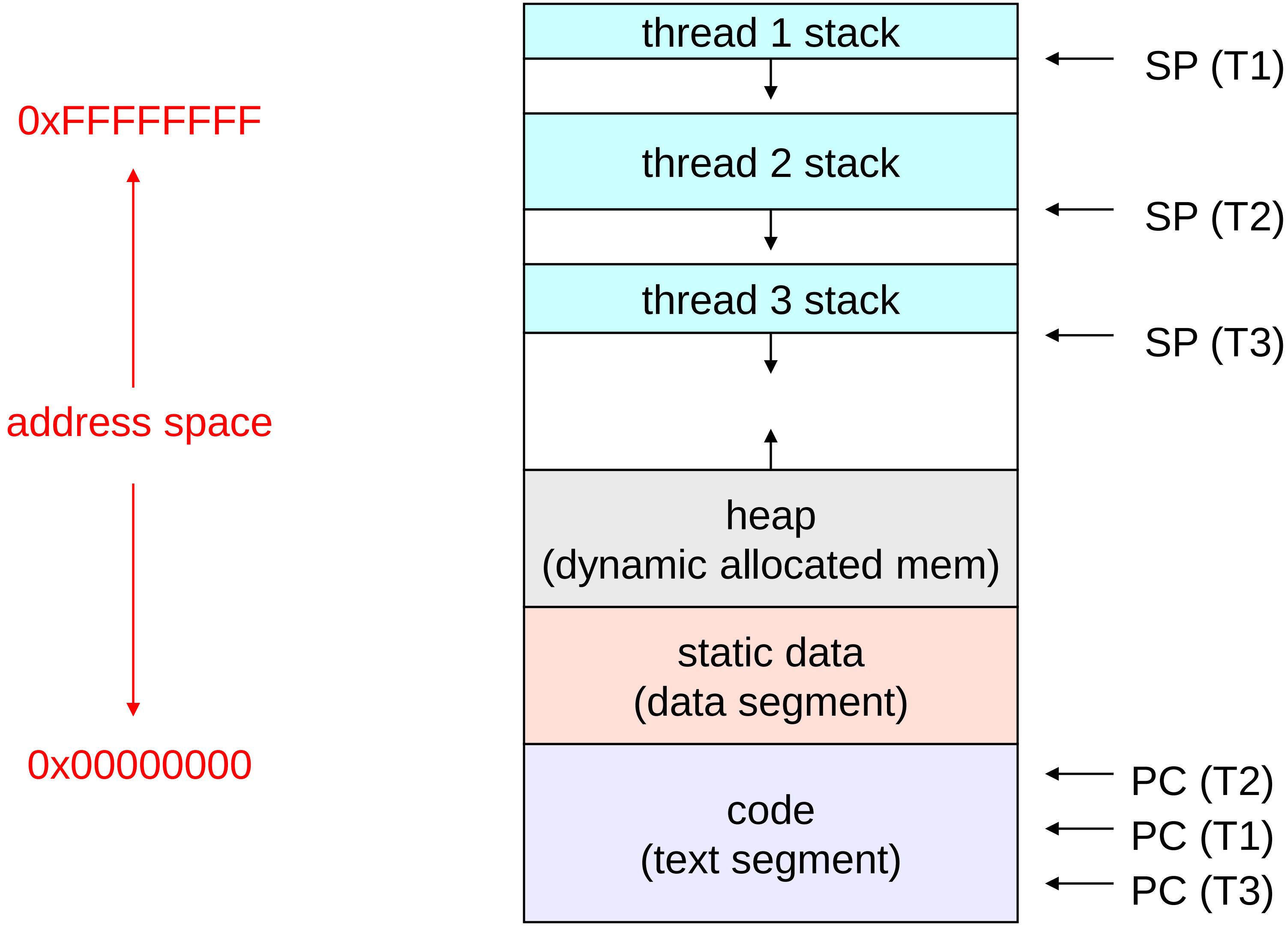
# Historical Design Space



# (Old) Process Address Space (32bit)



# (New) Address Space with Threads (32bit)



# Example Applications

- Multithreading is useful for
  - Handling concurrent events (e.g., web servers and clients)
  - Building parallel programs (e.g., matrix multiply, ray tracing)
  - Improving program structure (divide and conqueror)

- Multithreading is useful **on a uniprocessor**
  - Even though only one thread can run at a time

# Terminology Note

- There is the potential for some confusion
  - “process” == “address space + OS resources + single execution flow”
  - **OR**
  - “process” == “address space + system resources + multiple execution flows”

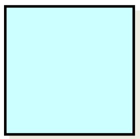
- Single-threaded process: 1 thread
- Multi-threaded process: N>1 threads

# Who is Creating/Managing Threads?

- **OS kernel** is responsible for creating/managing threads
  - The kernel call to create a new thread would
    1. Allocate an execution stack within the process address space
    2. Create and initialize a Thread Control Block (TCB)
       - Stack pointer, program counter, register values
    3. Stick it on the ready queue

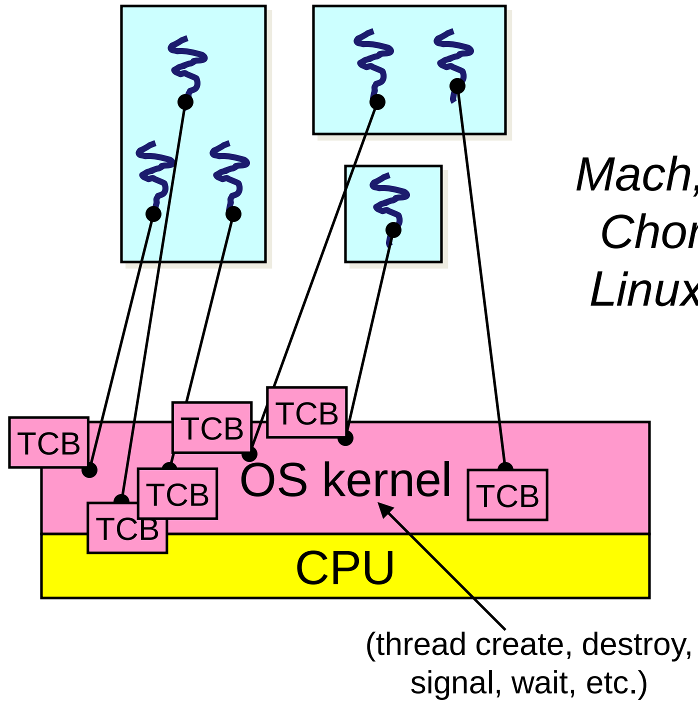
- This is **kernel-level threading**, or **1:1** threading
  - There is a "thread name space"
    - Thread's identifier (TID)
    - TIDs are integers, similar to PIDs
    - For each thread, a TCB, similar to PCB

# Kernel-level Threading #1



address space

thread




*Mach, NT, Chorus, Linux, …*

There are still PCBs to describe each address space and their OS resources

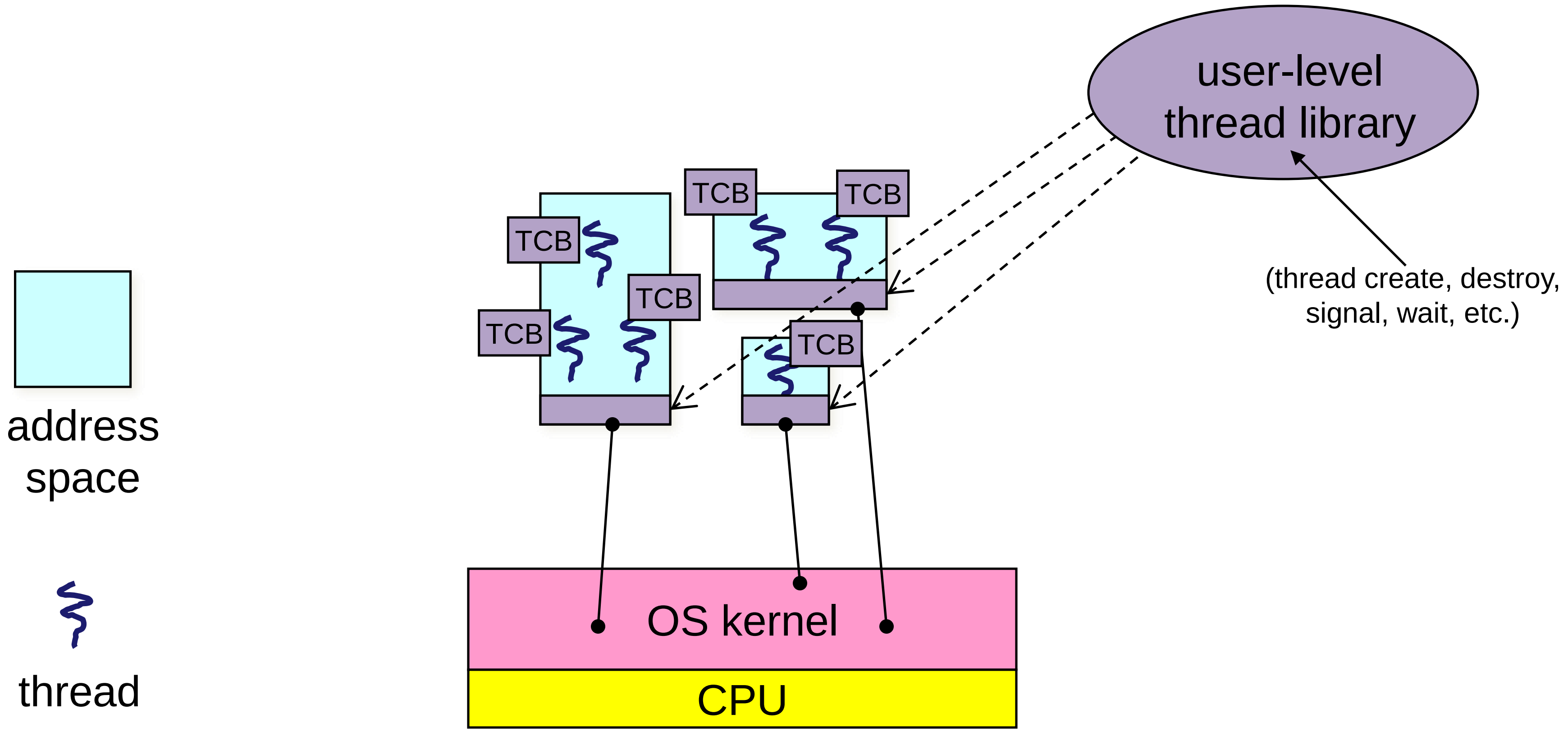
# Kernel-level Threading #2

- OS manages **threads and processes**
  - All thread operations implemented in the kernel
  - OS schedules all threads in a system
    - If one thread in a process blocks (e.g., on I/O)
      - the OS knows about it, can run other threads from that process
    - Possible to **overlap I/O** and computation **within a process**
- (Kernel-managed) **Threads** are **cheaper than processes**
  - Less state to allocate and initialize
- But, **pretty expensive** for fine-grained use
  - Orders of magnitude more expensive than a procedure call
  - Thread operations are **system calls**
    - Context switch
    - Argument checks
  - Must maintain kernel state for each thread

# User-level Threading

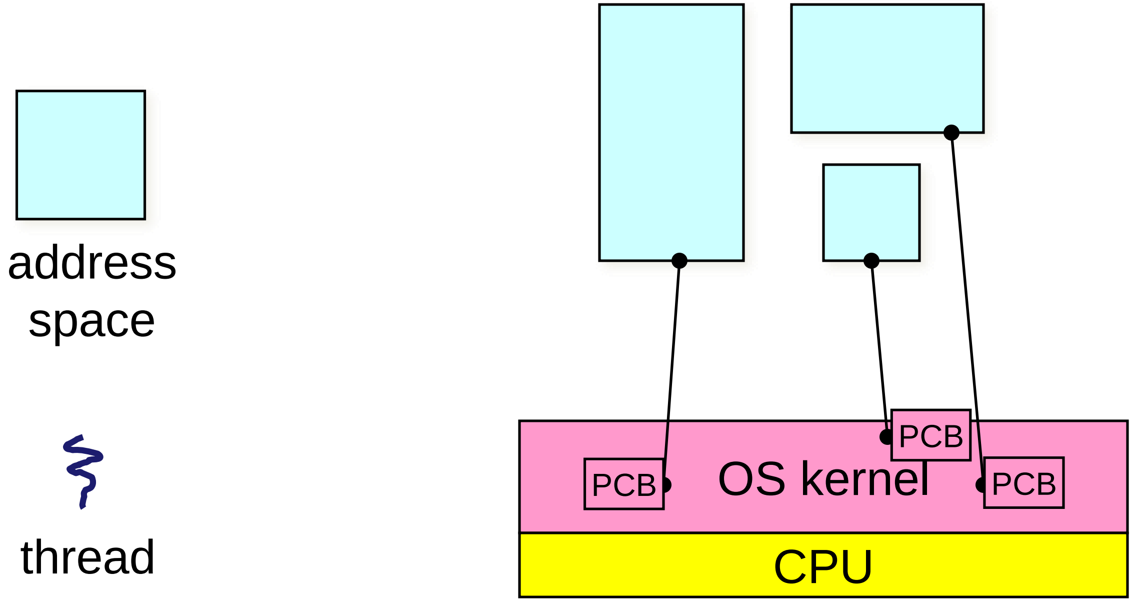
- **Alternative** to kernel-level threading
- Threads managed at the user level, **within the process**
  - **A library** into the program manages the threads
    - The thread manager **doesn’t** need to manipulate **address spaces** (which only the kernel can do)
    - Threads differ (roughly) only in hardware contexts (PC, SP, registers), which can be manipulated by user-level code
    - The **thread package** multiplexes user-level threads in a process
- This is **user-level threading**, or **1:N** threading
  - Kernel is unaware of threads existence
  - Thread control blocks (TCBs) at user level

# User-level Threading




Now thread id is unique within the context of a process, not unique system-wide

# User-level Threading: What the Kernel Sees



# Why User-level Threading?

- User-level threading is **lightweight** and **fast**
  - Managed entirely by user-level library
  - Each thread is represented simply by
    - PC, registers, a stack
    - Small thread control block
  - Creating a thread, switching between threads, and synchronizing threads are done via procedure calls
    - **No kernel involvement** is necessary
- User-level threading **operations** can be 10-100x faster than kernel threads

# (Old) Performance Example

- On a 700MHz Intel Pentium, running Linux 2.2.16 (only the relative numbers matter; ignore the ancient CPU and kernel)


  – Processes
    - **`fork/exit`**: 251 μs
  – Kernel-level threading
    - **`pthread_create()/pthread_join()`**: 94 μs **(2.5x faster)**
  – User-level threading
    - **`pthread_create()/pthread_join`**: 4.5 μs **(another 20x faster)**

# User-level Threading Implementation

1. **OS schedules** the process
2. Process executes user code (at user-level)
   - Including the thread support library and its thread scheduler
3. **Thread scheduler** determines when a user-level thread runs
   - Uses queues to keep track of what threads do (run, ready, wait, …)
     - Like the OS, but in user-space as a library
4. **Context switch** at the user-level
   1. Save context of currently running thread
      - push CPU state onto thread stack
   2. Restore context of the next thread
      - pop CPU state from next thread's stack
   3. Return as the new thread
      - execution resumes at PC of next thread
   - It works at the level of the **procedure calling convention**
     - **No changes** to memory mapping required

# How to Keep a User-level Thread from Hogging the CPU?

- Strategy 1: **force everyone** to cooperate
  - A thread willingly gives up the CPU by calling **`yield()`**
  - **`yield()`** calls into the scheduler, which context switches to another ready thread
  - What happens if a thread never calls **`yield()`**?

- Strategy 2: use **preemption**
  - Scheduler requests that a **timer interrupt** be delivered by the OS periodically
    - Usually delivered as a UNIX signal (`man signal`)
    - Signals are just like software interrupts, but delivered to user-level by the OS instead of delivered to OS by hardware
  - At each timer interrupt, scheduler gains control and context switches as appropriate

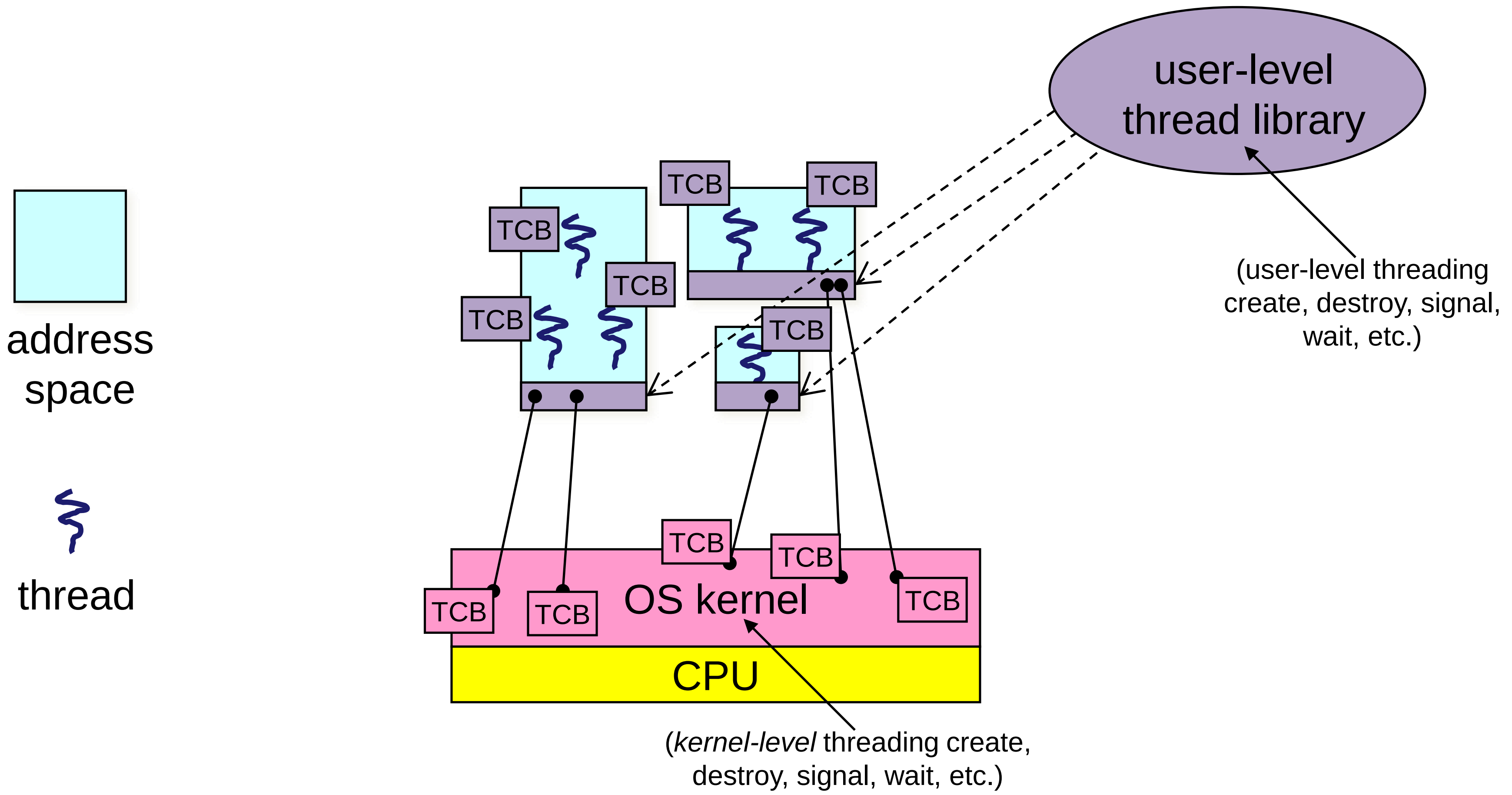
# What if a Thread Tries to do I/O?

- The process "powering" it **"is lost"** for the duration of the (synchronous) I/O operation!
  - The process blocks in the OS
  - The OS is not aware of the threads, OS sees one thread/process
  - No process' thread makes progress
  - Other processes can progress tho

- This is **not the case** with kernel-level threading
  - Kernel knows about each process' thread
  - Another thread can be schedule

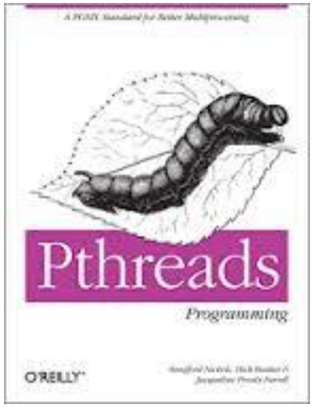
- *Can kernel-level threading and user-level threading be merged?*

# The N:M Threading Model
# (Merges 1:1 and 1:N Models)



# Explicit Thread Interface (User- or Kernel- level)

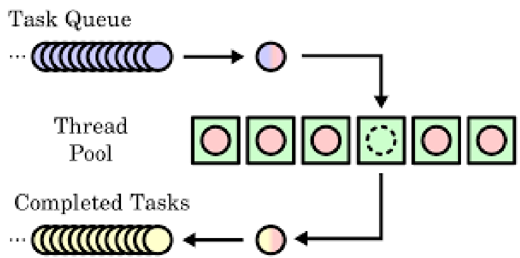
- POSIX Thread (pthread) APIs
  - `ret = pthread_create(&t, attributes, start_procedure)`
    - Creates a new thread of control
    - New thread begins executing at start_procedure
  - `pthread_cond_wait(condition_variable, mutex)`
    - The calling thread blocks on a conditional variable
  - `pthread_signal(condition_variable)`
    - Starts a thread waiting on the condition variable
  - `pthread_exit()`
    - Terminates the calling thread
  - `pthread_join(t)`
    - Waits for the named thread to terminate



# Implicit Thread Interface (User-level)

- Thread management to library/runtime
- Identify application's tasks, not threads
- Compiler-level support (in most cases)
  - Code annotation
  - Pragmas
  - Templates

- Examples
  - Thread pools
  - Fork-join
  - OpenMP
  - Grand Central Dispatch
  - Intel Thread building blocks



# Summary

- Multiple threads per process (and address space)
  - **Real resource sharing** for multiple instruction flows
- **Kernel-level threading (1:1)** implemented in OS kernel
  - All operations require a kernel call and parameter validation
  - Enables concurrency and parallelism
- **User-level threading (1:N)** implemented in application
  - Cheaper and faster
  - Enables concurrency
  - Great for common-case operations
    - Creation, synchronization, destruction
  - May block all threads on the same process
    - Blocking IO
- **N:M threading**
  - Best of both the previous