# CSE 451: Operating Systems
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## Module 5
## Threads

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# What's "in" a process?

- A process consists of (at least):
  - An address space, containing
    - the code (instructions) for the running program
    - the data for the running program
  - Thread state, consisting of
    - The program counter (PC), indicating the next instruction
    - The stack pointer register (implying the stack it points to)
    - Other general purpose register values
  - A set of OS resources
    - open files, network connections, sound channels, …
- Today: decompose …
  - address space
  - thread of control (stack, stack pointer, program counter, registers)
  - OS resources

# Module overview

- Big picture:  Achieving concurrency/parallelism
- Kernel threads
- User-level threads

# The Big Picture

- Threads are about concurrency and parallelism
  - Parallelism: physically simultaneous operations for performance
  - Concurrency: logically (and possibly physically) simultaneous operations for convenience/simplicity

- One way to get concurrency and parallelism is to use multiple processes
  - The programs (code) of distinct processes are isolated from each other

- Threads are another way to get concurrency and parallelism
  - Threads “share a process” – same address space, same OS resources
  - Threads have private stack, CPU state – are schedulable

# Concurrency/Parallelism

- Imagine a web server, which might like to handle multiple requests concurrently
  - *While waiting for the credit card server to approve a purchase for one client, it could be retrieving the data requested by another client from disk, and assembling the response for a third client from cached information*
- Imagine a web client (browser), which might like to initiate multiple requests concurrently
  - *The CSE home page has dozens of "src= …" html commands, each of which is going to involve a lot of sitting around! Wouldn't it be nice to be able to launch these requests concurrently?*
- Imagine a parallel program running on a multiprocessor, which might like to employ "physical concurrency"
  - *For example, multiplying two large matrices – split the output matrix into k regions and compute the entries in each region concurrently, using k processors*

# What's the goal?

- If I want more than one thing running at a time, I already have a mechanism to achieve that
  - Processes
- What's wrong with processes?
  - IPC (inter-process communication) is slow
    - Why?
- What's right with processes?
  - Convenient abstraction of CPU, memory, I/O

# What's needed?

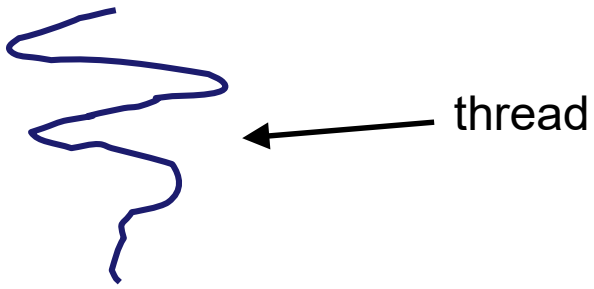
- You'd like to have multiple hardware execution states:
  - an execution stack and stack pointer (SP)
    - traces state of procedure calls made
  - the program counter (PC), indicating the next instruction
  - a set of general-purpose processor registers and their values
- That's a *thread*

- You'd like to have very fast communication among the separate execution contexts
  - Use shared memory
    - All threads run in the same virtual address space
  - Globals are shared
  - Locals are "private"
    - Except there is no enforcement of that

# How could we achieve this?

- Key idea:
  - separate the concept of a process (address space, OS resources)
  - … from that of a "thread of control" (execution state: stack, stack pointer, program counter, registers)

- This execution state is usually called a thread

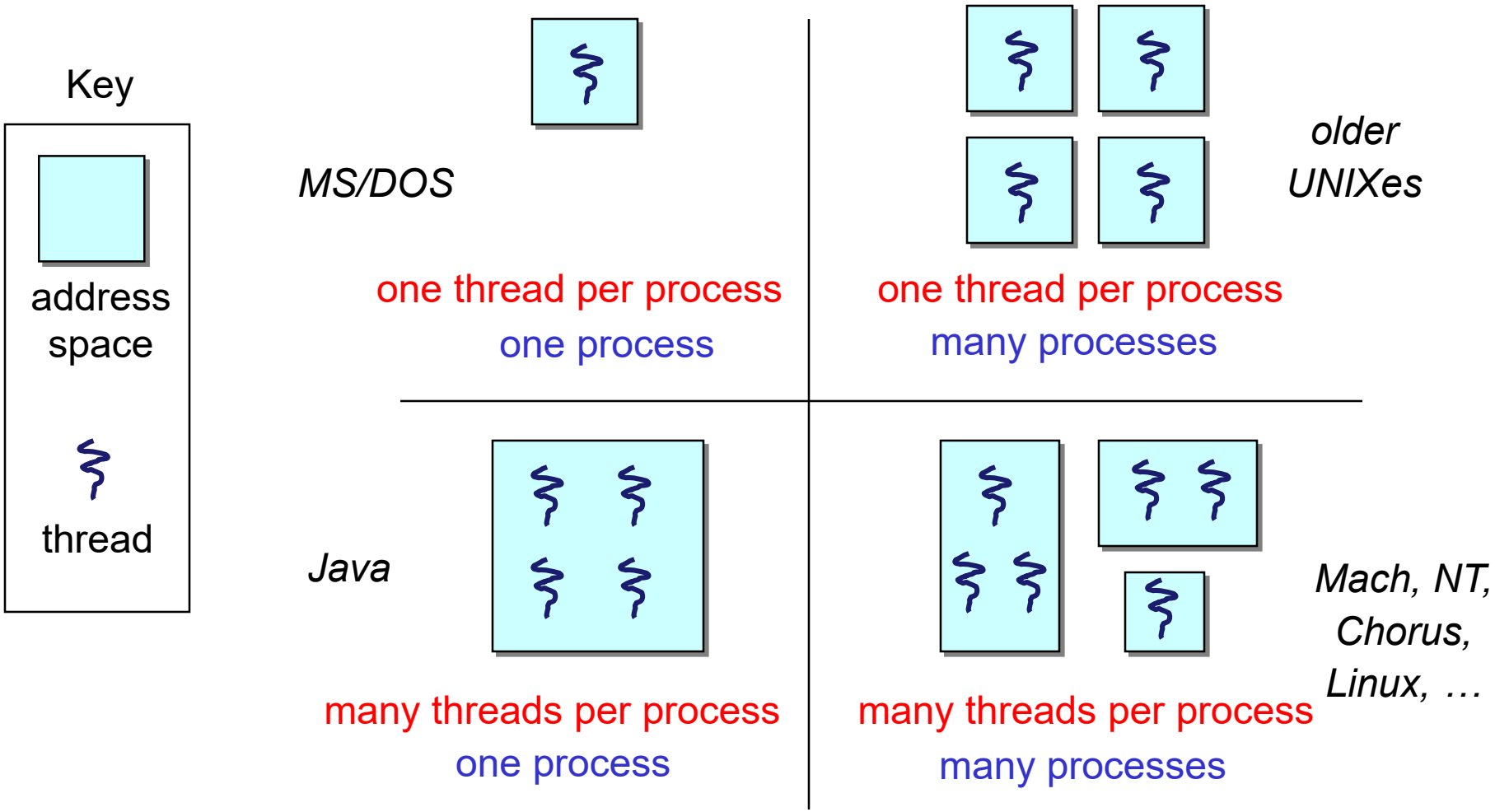


# Threads and processes

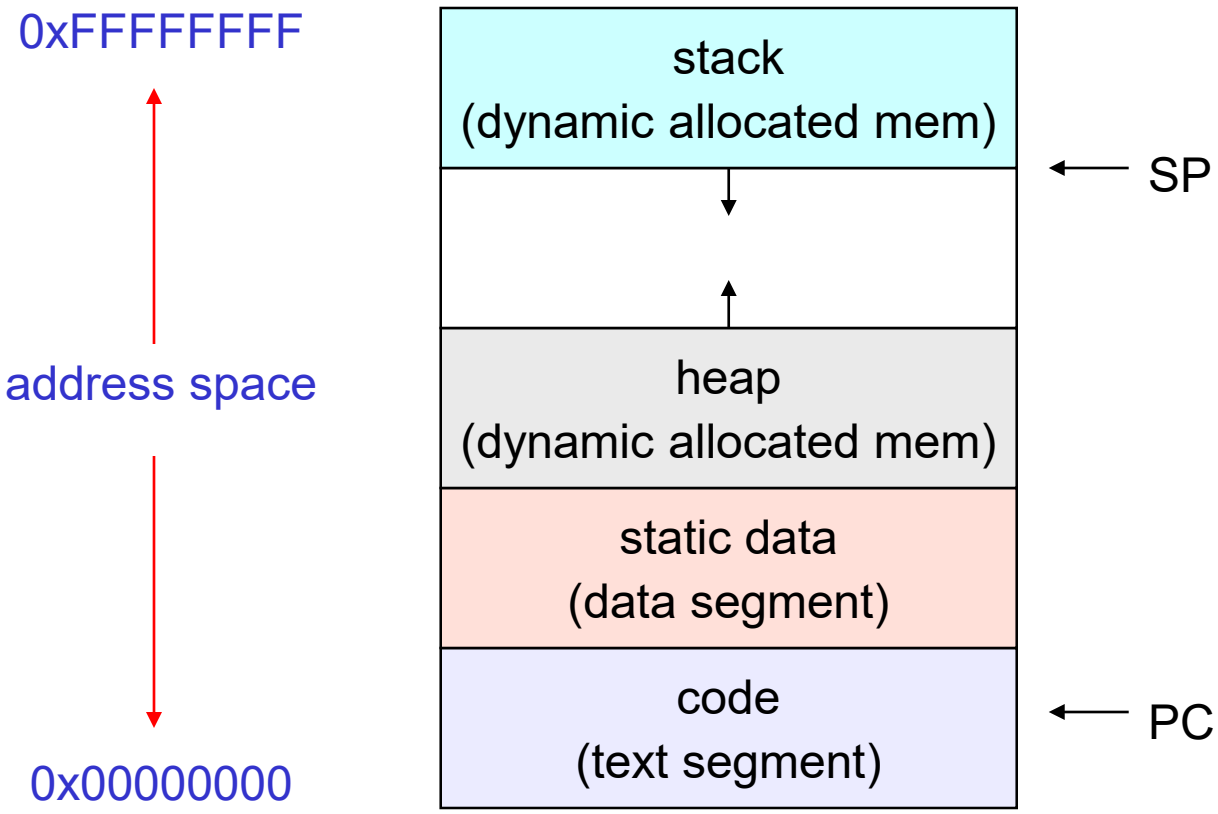
- Most modern OS's therefore support two entities:
  - the process, which defines the address space and general process attributes (such as open files, etc.)
  - the thread, which defines a sequential execution stream within a process
- A thread is bound to a single process / address space
  - address spaces can have multiple threads executing within them
  - sharing data among threads is cheap: all see the same address space
  - creating threads is cheap too!
- Threads become the unit of scheduling
  - processes / address spaces are just containers in which threads execute

- Threads are concurrent executions sharing an address space (and some OS resources)
  - Address spaces provide isolation
    - If you can't name it, you can't read or write it
  - Hence, communicating between processes is expensive
    - Must go through the OS to move data from one address space to another
  - Because threads are in the same address space, communication is simple/cheap
    - Just update a shared variable!

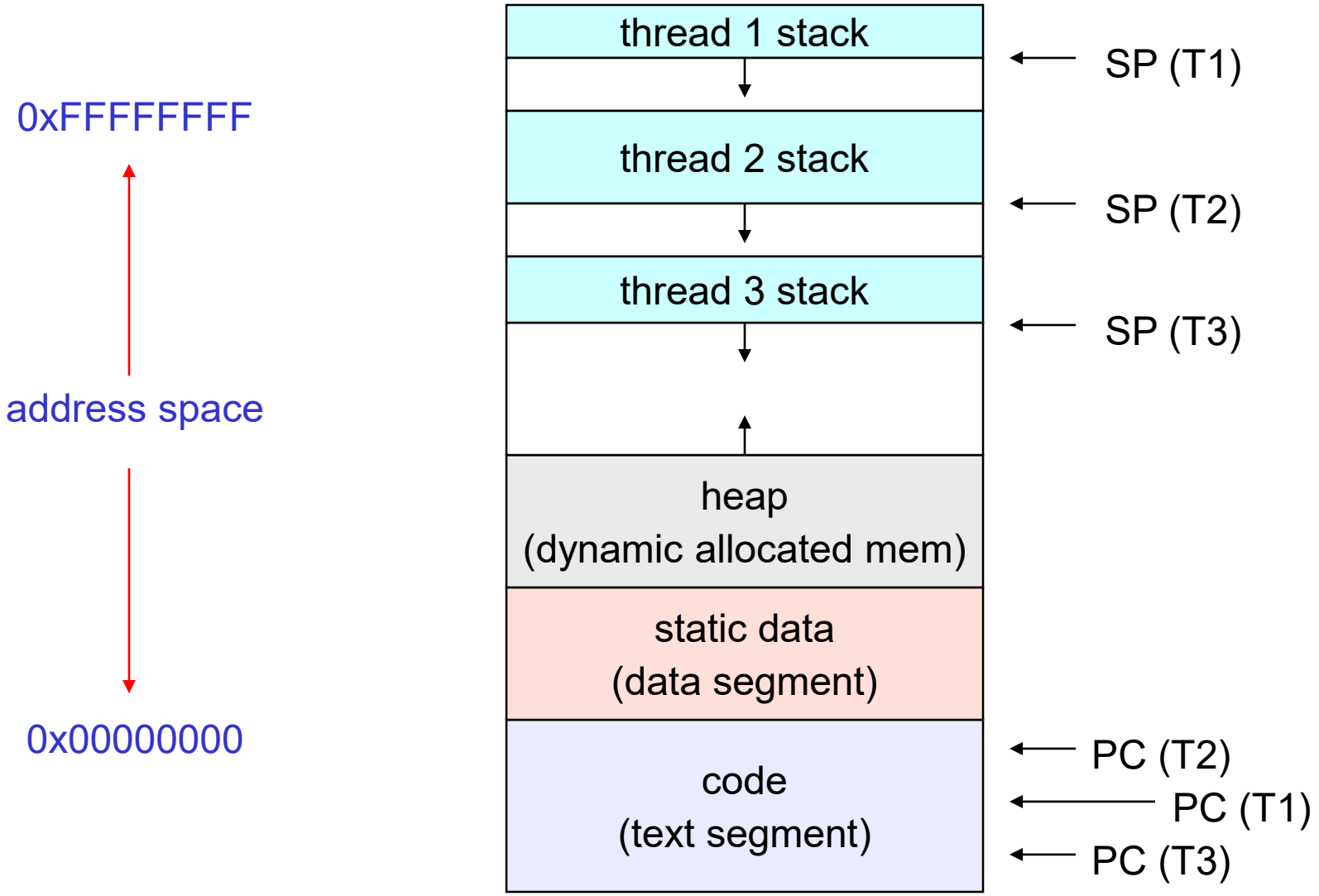
# The design space



# (old) Process address space



# (new) Address space with threads



# Value of process/thread separation

- Concurrency (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 (the Java argument)

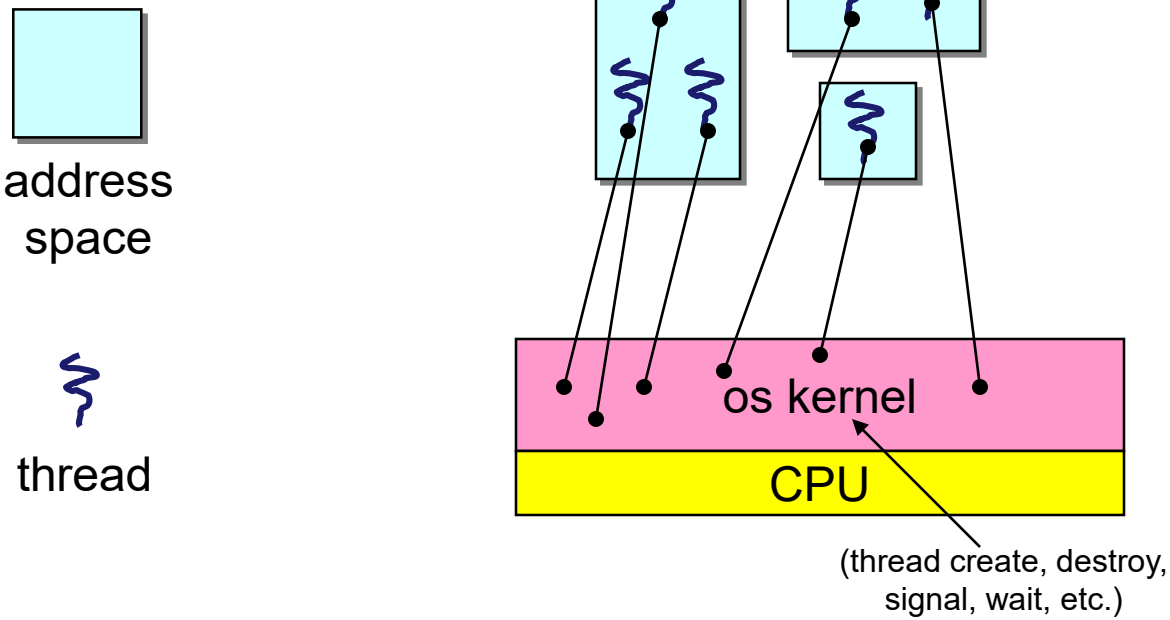
- Multithreading is useful even on a single core processor
  - even though only one thread can run at a time
  - Why?

- Supporting multithreading – that is, separating the concept of a process (address space, files, etc.) from that of a minimal thread of control (execution state), is a big win
  - creating concurrency does not require creating new processes
  - “faster / better / cheaper”

# “Where do threads come from?”

- Natural answer: the OS is responsible for creating/managing threads
  - For example, the kernel call to create a new thread would
    - allocate an execution stack within the process address space
    - create and initialize a Thread Control Block
      - stack pointer, program counter, register values
    - stick it on the ready queue
  - We call these kernel threads
  - There is a “thread name space”
    - Thread id’s (TID’s)
    - TID’s are integers (surprise!)
- Why “must” the kernel be responsible for creating/managing threads?

# Kernel threads



# Kernel threads

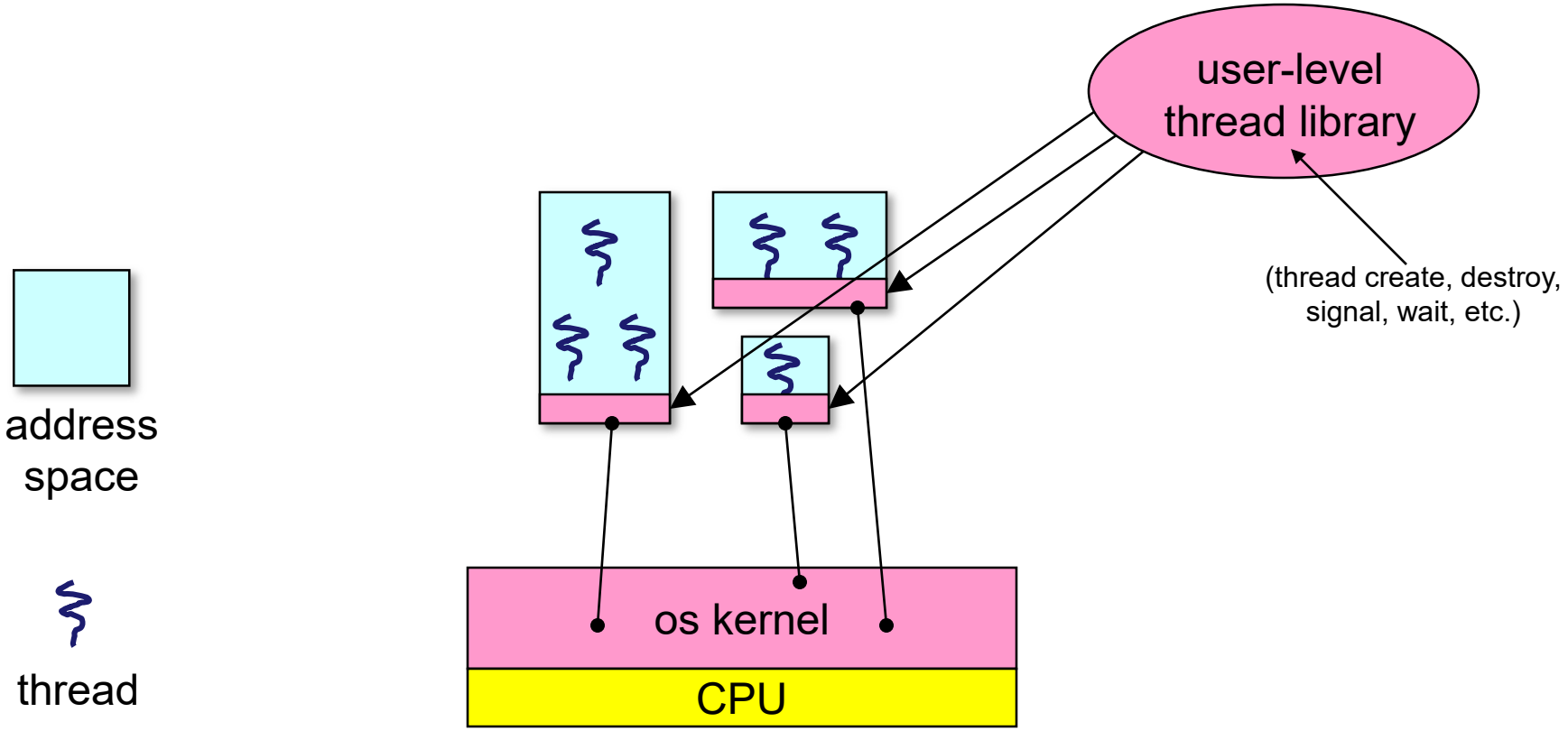
- OS now manages threads *and* processes / address spaces
  - all thread operations are implemented in the kernel
  - OS schedules all of the threads in a system
    - if one thread in a process blocks (e.g., on I/O), the OS knows about it, and can run other threads from that process
    - possible to overlap I/O and computation inside a process
      - that is, under programmer control
- Kernel threads are cheaper than processes
  - less state to allocate and initialize
- But, they're still pretty expensive for fine-grained use
  - orders of magnitude more expensive than a procedure call
  - thread operations are all system calls
    - context switch
    - argument checks

# “Where do threads come from?” (2)

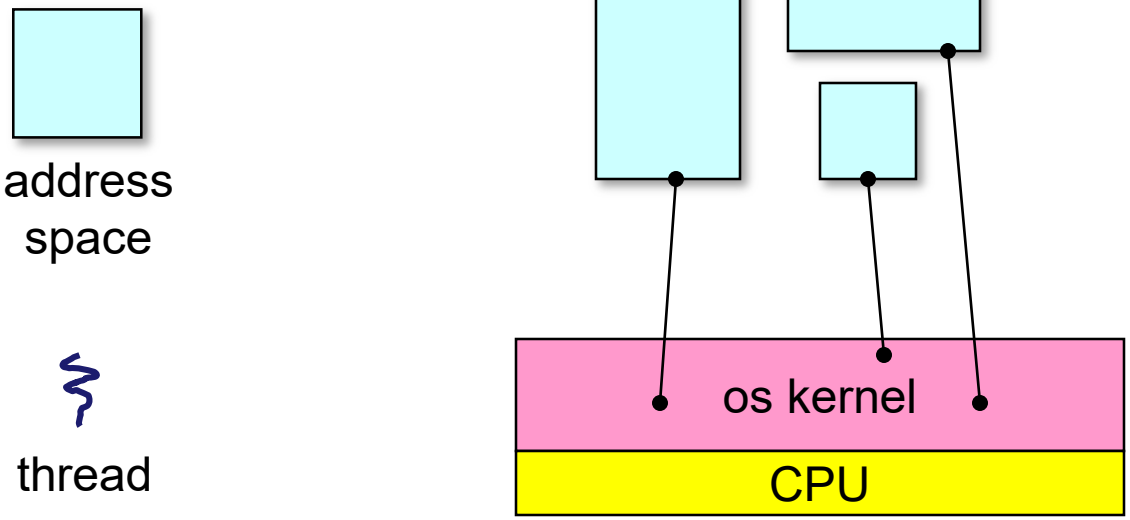
- There is an alternative to kernel threads
  - Note that thread management isn’t doing anything that feels privileged

- Threads can also be managed at the user level (that is, entirely from within the process)
  - a library linked into the program manages the threads
    - because threads share the same address space, 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 on top of kernel thread(s)
    - each kernel thread is treated as a “virtual processor”
  - we call these user-level threads

# User-level threads



# User-level threads: what the kernel sees



# User-level threads

- User-level threads are small and fast
  - managed entirely by user-level library
    - E.g., pthreads (**`libpthreads.a`**)
  - each thread is represented simply by a PC, registers, a stack, and a small thread control block (TCB)
  - creating a thread, switching between threads, and synchronizing threads are done via procedure calls
    - no kernel involvement is necessary!
  - user-level thread operations can be 10-100x faster than kernel threads as a result

# Performance example

- On a 700MHz Pentium running Linux 2.2.16 (only the relative numbers matter; ignore the ancient CPU!):
  - Processes
    - **`fork/exit`**: 251 μs
  - Kernel threads
    - **`pthread_create()/pthread_join()`**: 94 μs **(2.5x faster – ~150μs faster)**

    Why?
  - User-level threads
    - **`pthread_create()/pthread_join`**: 4.5 μs **(another 20x faster - ~100μs faster)**

    Why?

# User-level thread implementation

- The OS schedules the kernel thread
- The kernel thread executes user code, including the thread support library and its associated thread scheduler
- The thread scheduler determines when a user-level thread runs
  - it uses queues to keep track of what threads are doing: run, ready, wait
    - just like the OS and processes
    - but, implemented at user-level as a library

# Thread interface

- This is taken from the POSIX `pthreads` API:
  - `rcode = 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, sometimes called thread_block()
  - `pthread_signal(condition_variable)`
    - starts a thread waiting on the condition variable
  - `pthread_exit()`
    - terminates the calling thread
  - `pthread_wait(t)`
    - waits for the named thread to terminate

# Thread context switch

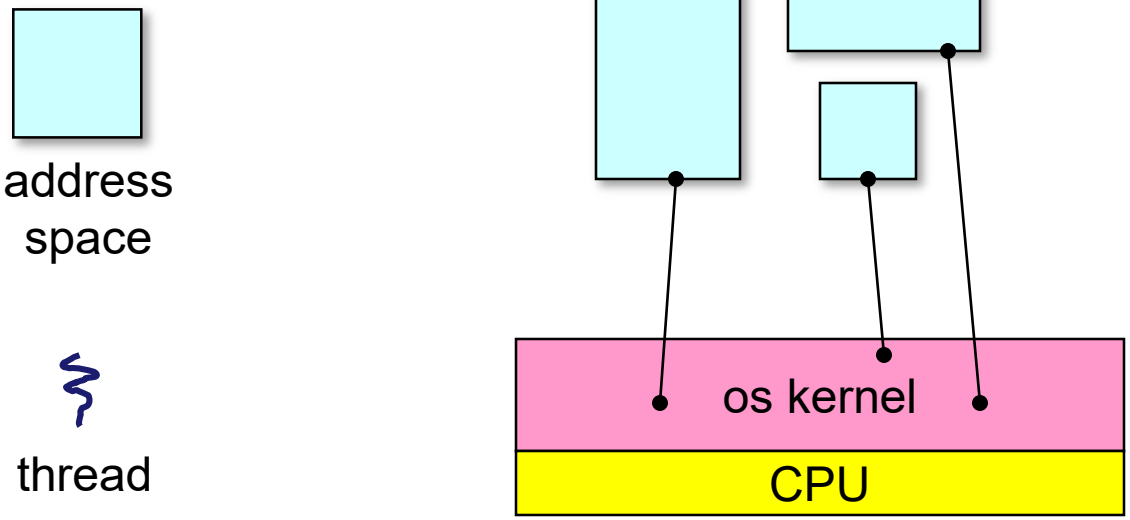
- Very simple for user-level threads:
  - save context of currently running thread
    - push CPU state onto thread stack
  - restore context of the next thread
    - pop CPU state from next thread's stack
  - return as the new thread
    - execution resumes at PC of next thread
  - Note: no changes to memory mapping required!
- This is all done by assembly language
  - it works at the level of the procedure calling convention
    - thus, it cannot be implemented using procedure calls

# 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

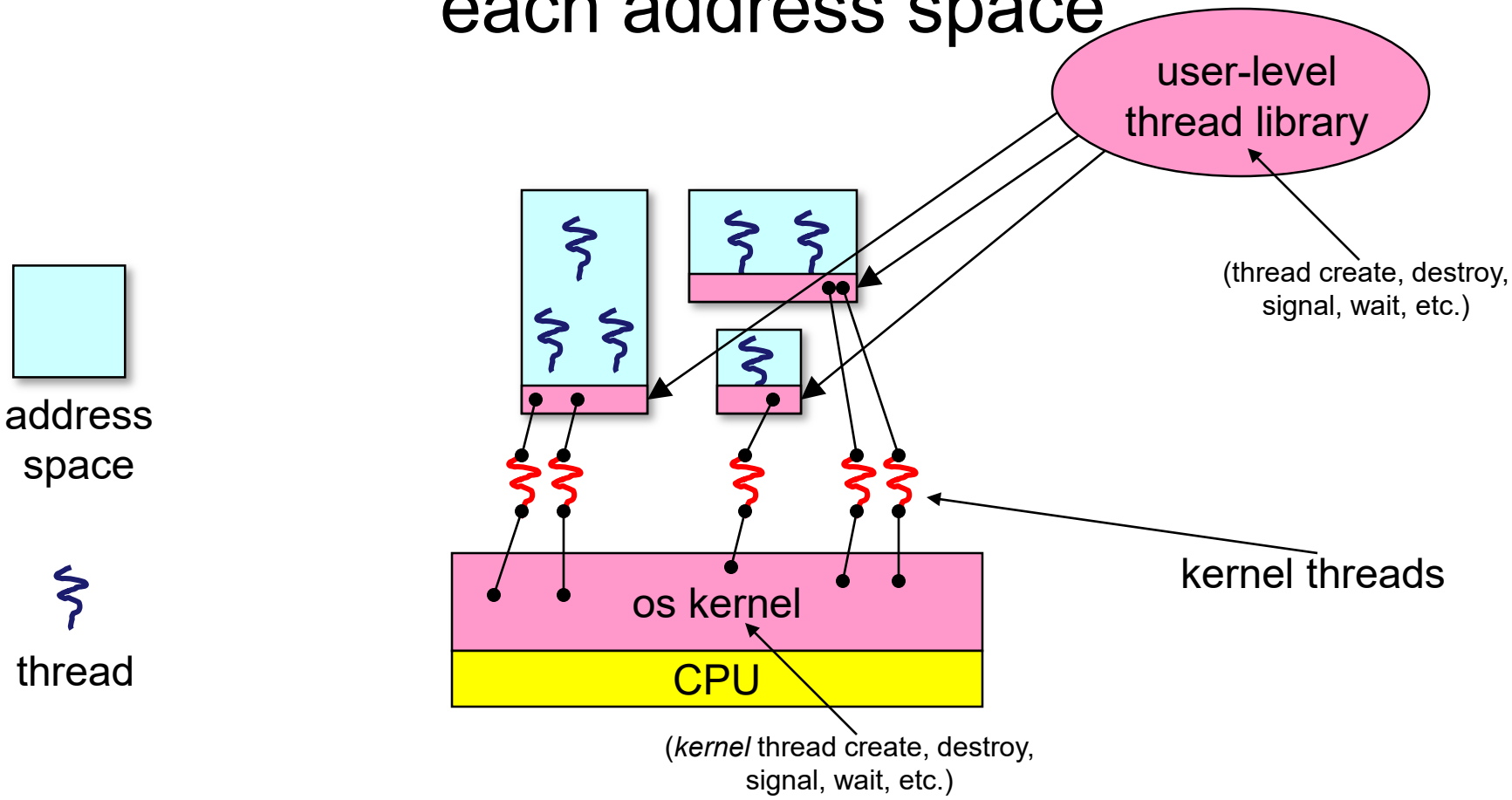
# What if a thread tries to do IO?



# What if a thread tries to do I/O?

- The kernel thread "powering" it is lost for the duration of the (synchronous) I/O operation!
  - The kernel thread blocks in the OS, as always
  - It maroons with it the state of the user-level thread
- Could have one kernel thread "powering" each user-level thread
  - "common case" operations (e.g., synchronization) would be quick
- Could have a limited-size "pool" of kernel threads "powering" all the user-level threads in the address space
  - the kernel will be scheduling these threads, obliviously to what's going on at user-level

# Multiple kernel threads “powering” each address space



# What if the kernel preempts a thread holding a lock?

- Other threads will be unable to enter the critical section and will block (stall)

# Addressing these problems

- Effective coordination of kernel decisions and user-level threads requires OS-to-user-level communication
  - OS notifies user-level that it has suspended a kernel thread
- This is called “scheduler activations”
    - a research paper from UW with huge effect on practice
    - each process can request one or more kernel threads
      - process is given responsibility for mapping user-level threads onto kernel threads
      - kernel promises to notify user-level before it suspends or destroys a kernel thread

# Summary

- You really want multiple threads per address space
- Kernel threads are much more efficient than processes, but they're still not cheap
  - all operations require a kernel call and parameter validation
- User-level threads are:
  - really fast/cheap
  - great for common-case operations
    - creation, synchronization, destruction
  - can suffer in uncommon cases due to kernel obliviousness
    - I/O
    - preemption of a lock-holder
- Scheduler activations are an answer
  - pretty subtle though