CSC 112: Computer Operating Systems
Lecture 3

Threads

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What's in a process?

- A process consists of:
  - an address space
  - the code for the running program
  - the data for the running program
  - at least one thread
    - » Registers, IP
    - » Floating point state
    - » Stack and stack pointer
  - a set of OS resources
    - » open files, network connections, sound channels, …
- Today: decompose …
  - threads of control
  - (other resources…)

Concurrency

- Imagine a web server that handles 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
- Imagine a parallel program running on a multiprocessor, which might like to employ "physical concurrency"
  – For example, multiplying a large matrix – split the output matrix into k regions and compute the entries in each region concurrently using k processors

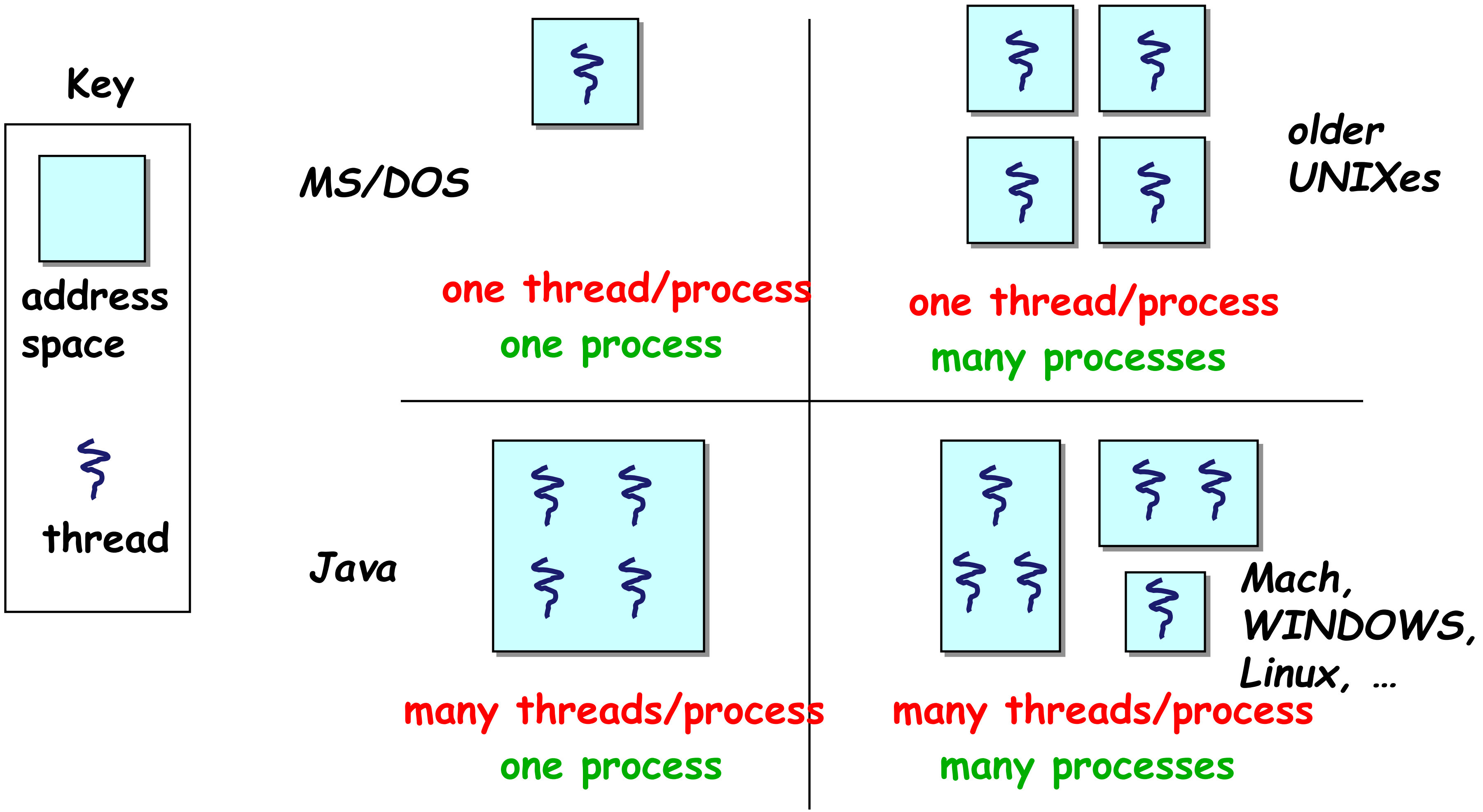
What's needed?

- In each of these examples of concurrency (web server, web client, parallel program):
  - Everybody wants to run the same code
  - Everybody wants to access the same data
  - Everybody has the same privileges
  - Everybody uses the same resources (open files, network connections, etc.)
- But you'd like to have multiple hardware execution states:
  - an execution stack and stack pointer (SP)
    - » traces state of procedure calls made
  - program counter (PC), indicating the next instruction
  - a set of general-purpose processor registers and their values
- Creating multiple processes is inefficient
- Key idea: separate the concept of a process (address space, etc.) from that of a minimal "thread of control" (execution state: PC, etc.)
- This execution state is usually called a thread, or sometimes, a lightweight process

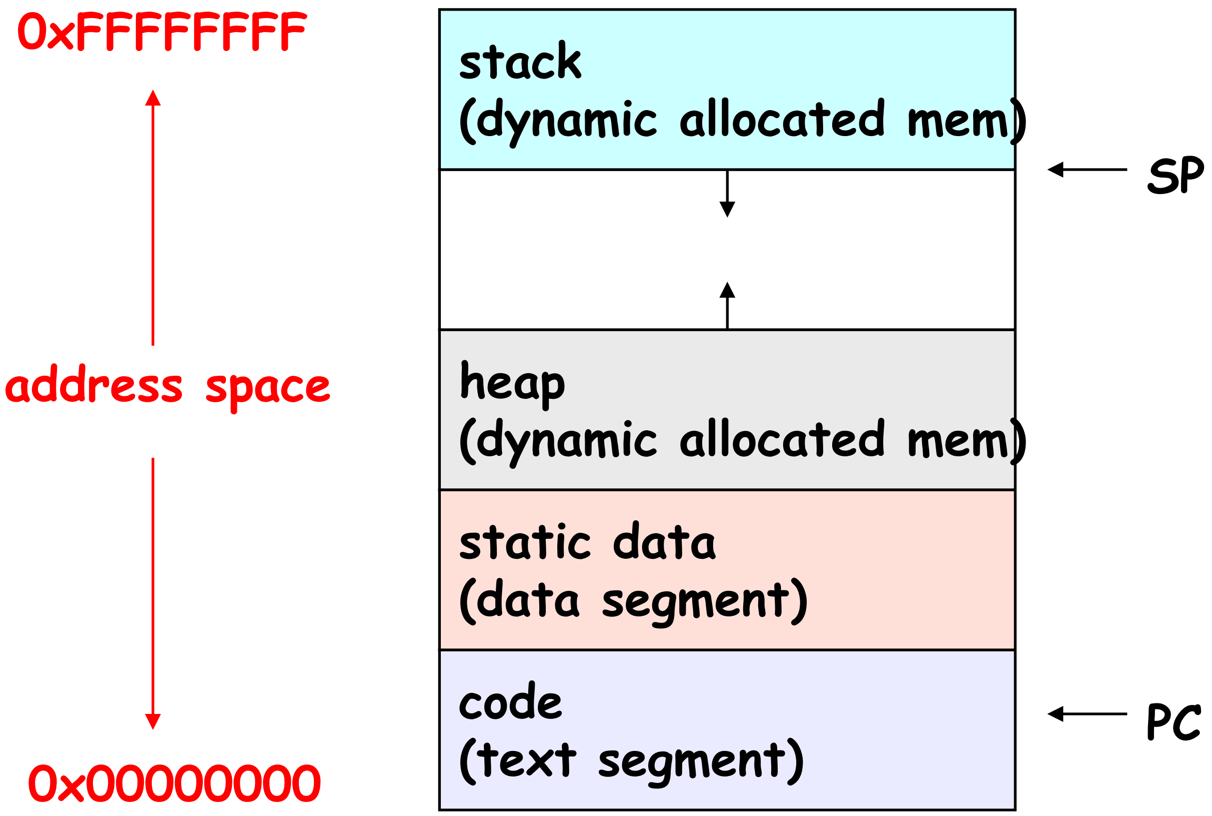
Processes and Threads

- Modern OSes 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, however, 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
  - processes / address spaces are just containers in which threads execute

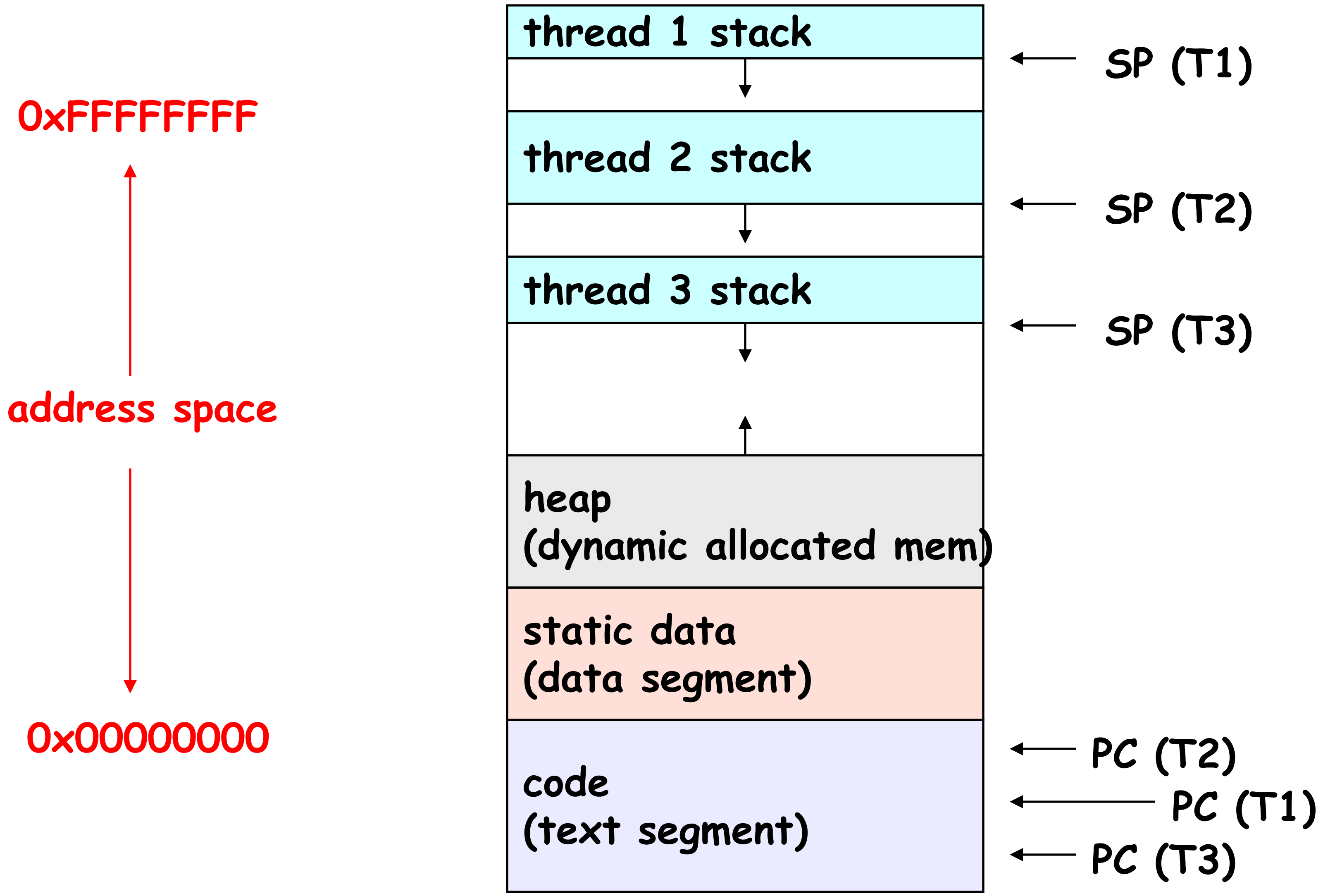
The design space



(old) Process address space



(new) Process address space with threads



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 uniprocessor
  - even though only one thread can run at a time
- 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?”

- The kernel 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

"Where do threads come from?" (2)

- 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 Linux thread package multiplexes user-level threads on top of kernel thread(s), which it treats as "virtual processors"
  - we call these user-level threads

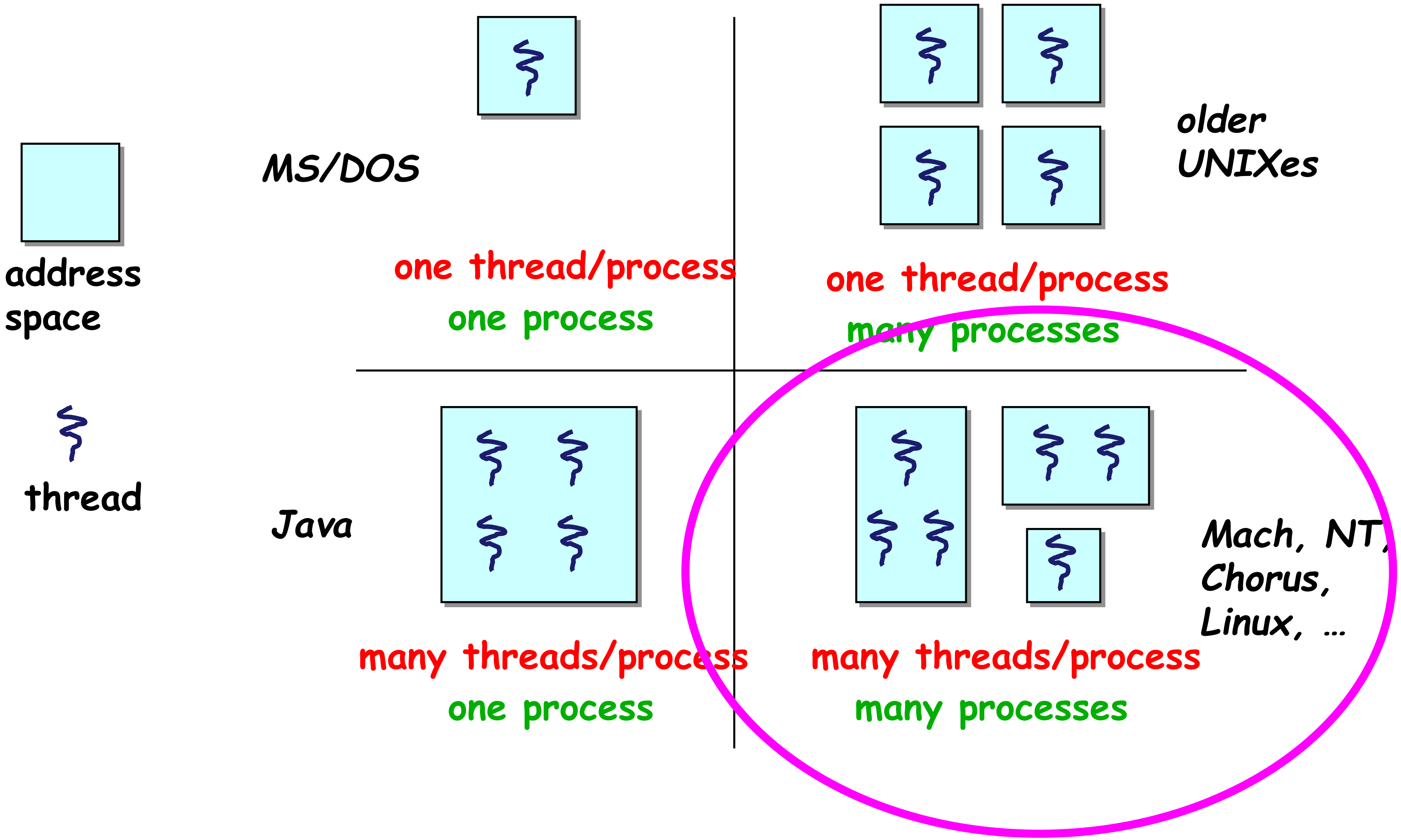
Kernel threads

- OS now manages threads *and* processes
  - 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
- Kernel threads are cheaper than processes
  - less state to allocate and initialize
- But, they're still expensive for fine-grained use (e.g., orders of magnitude more expensive than a procedure call)
  - thread operations are all system calls
    - » context switch
    - » argument checks
  - must maintain kernel state for each thread

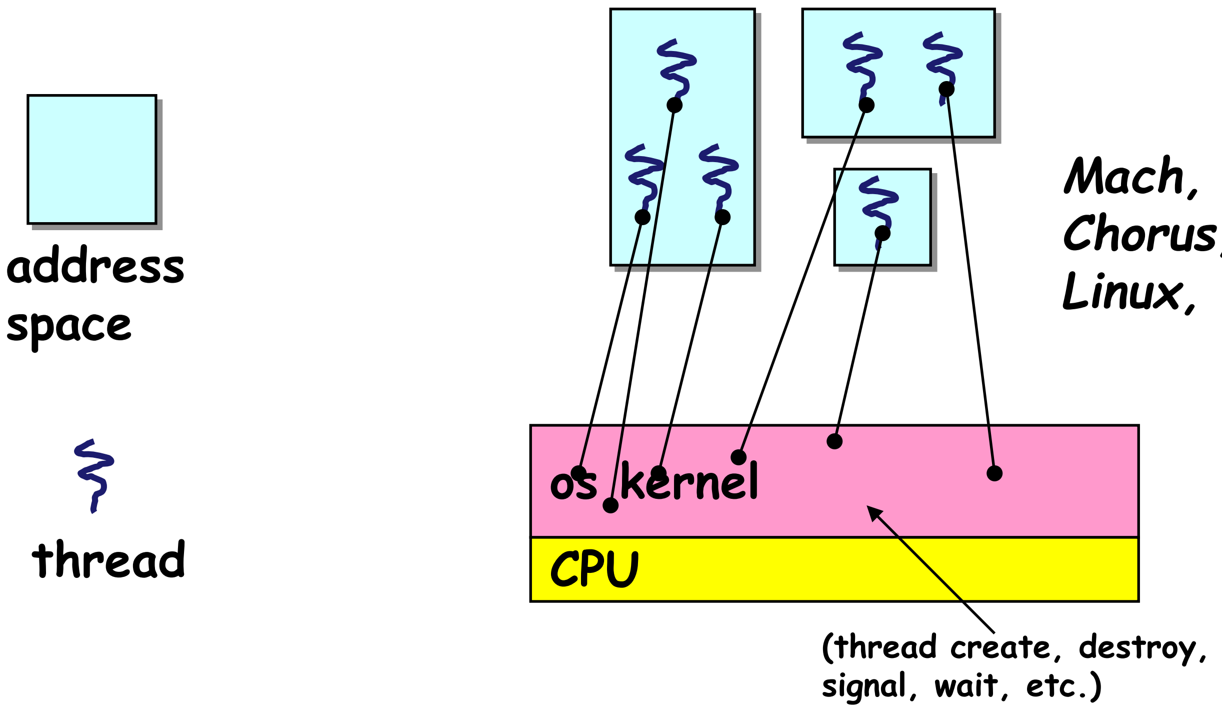
User-level threads

- To make threads cheap and fast, they may be implemented at the user level
  - managed entirely by user-level library, e.g., **`libpthreads.a`**
- User-level threads are small and fast
  - each thread is represented simply by a PC, registers, a stack, and a small thread control block (user-space 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

The design space

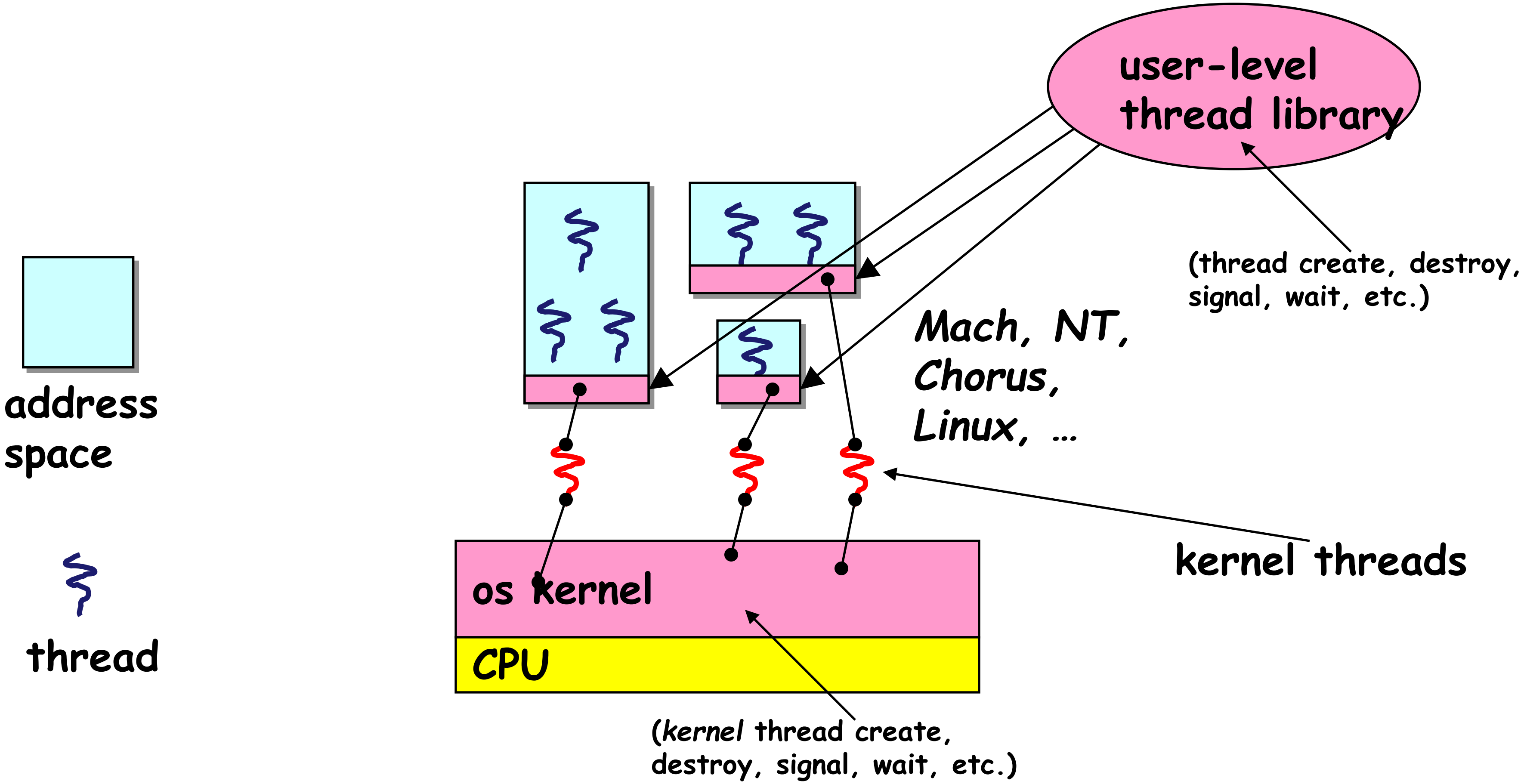


Kernel threads



Mach, NT,
Chorus,
Linux, …

User-level threads



User-level thread implementation

- The kernel believes the user-level process is just a normal process running code
  - But, this code includes the thread support library and its associated thread scheduler
- The thread scheduler determines when a 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
- Example implementations of user-level threads
  - Fibers, co-routines

FANG Interview Question | Process vs Thread
https://www.youtube.com/watch?v=4rLW7zg21gI

Thread interface

- The POSIX `pthreads` API:
  - `t = pthread_create(attributes, start_procedure)`
    - » creates a new thread of control
    - » new thread begins executing at start_procedure
  - `pthread_cond_wait(condition_variable)`
    - » the calling thread blocks, sometimes called thread_block()
  - `pthread_signal(condition_variable)`
    - » starts the thread waiting on the condition variable
  - `pthread_exit()`
    - » terminates the calling thread
  - `pthread_wait(t)`
    - » waits for the named thread to terminate

How to prevent 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

Thread context switch

- Very simple for user-level threads:
  - save context of currently running thread
    - » push machine state onto thread stack
  - restore context of the next thread
    - » pop machine state from next thread's stack
  - return as the new thread
    - » execution resumes at PC of next thread
- 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
    - » e.g., a thread might be preempted (and then resumed) in the middle of a procedure call

What if a thread tries to do I/O?

- The kernel thread is lost for the duration of the (synchronous) I/O operation!
- Could have one kernel thread for each user-level thread
  – no real difference from kernel threads – "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

Summary

- We 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 verification
- User-level threads are:
  - fast
  - great for common-case operations
    - » creation, synchronization, destruction
  - can suffer in uncommon cases due to kernel obliviousness
    - » I/O
    - » preemption of a lock-holder