CS162
Operating Systems and Systems Programming
Lecture 6

Concurrency (Continued), Synchronization (Start)

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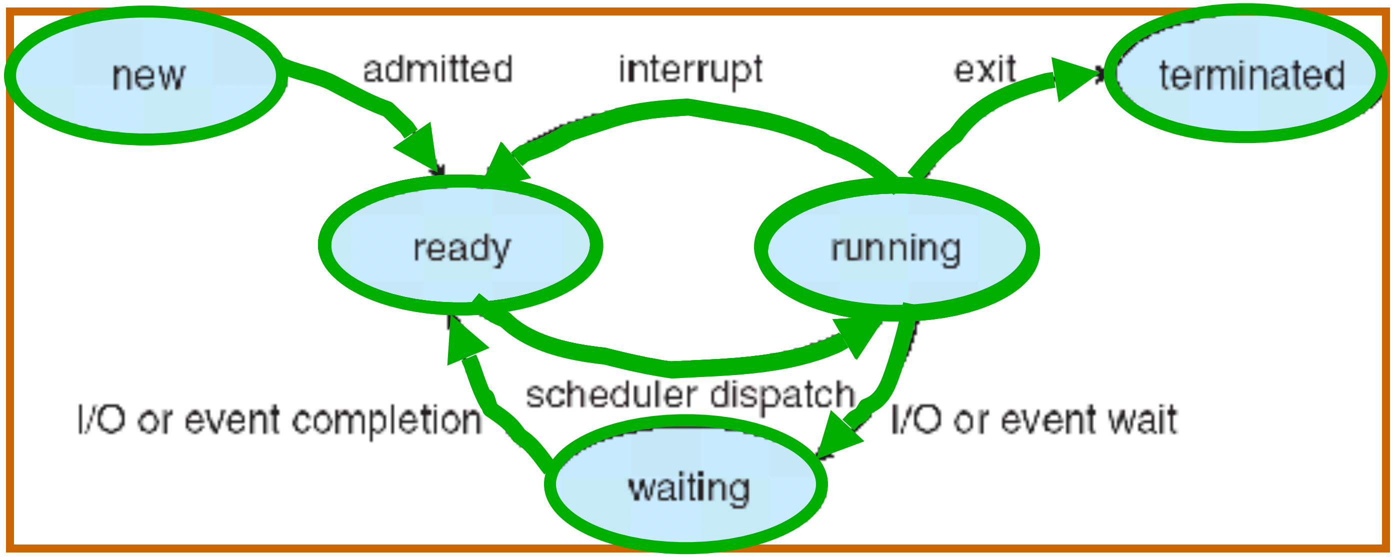
Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

Recall: Lifecycle of a Process



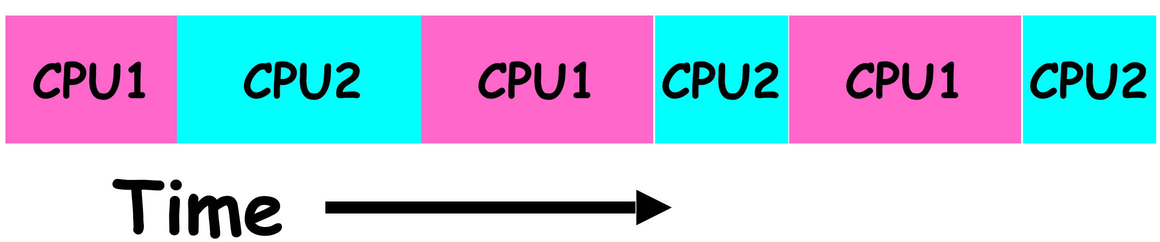
- As a process executes, it changes state:
  - **new**: The process is being created
  - **ready**: The process is waiting to run
  - **running**: Instructions are being executed
  - **waiting**: Process waiting for some event to occur
  - **terminated**: The process has finished execution

Recall: Use of Threads

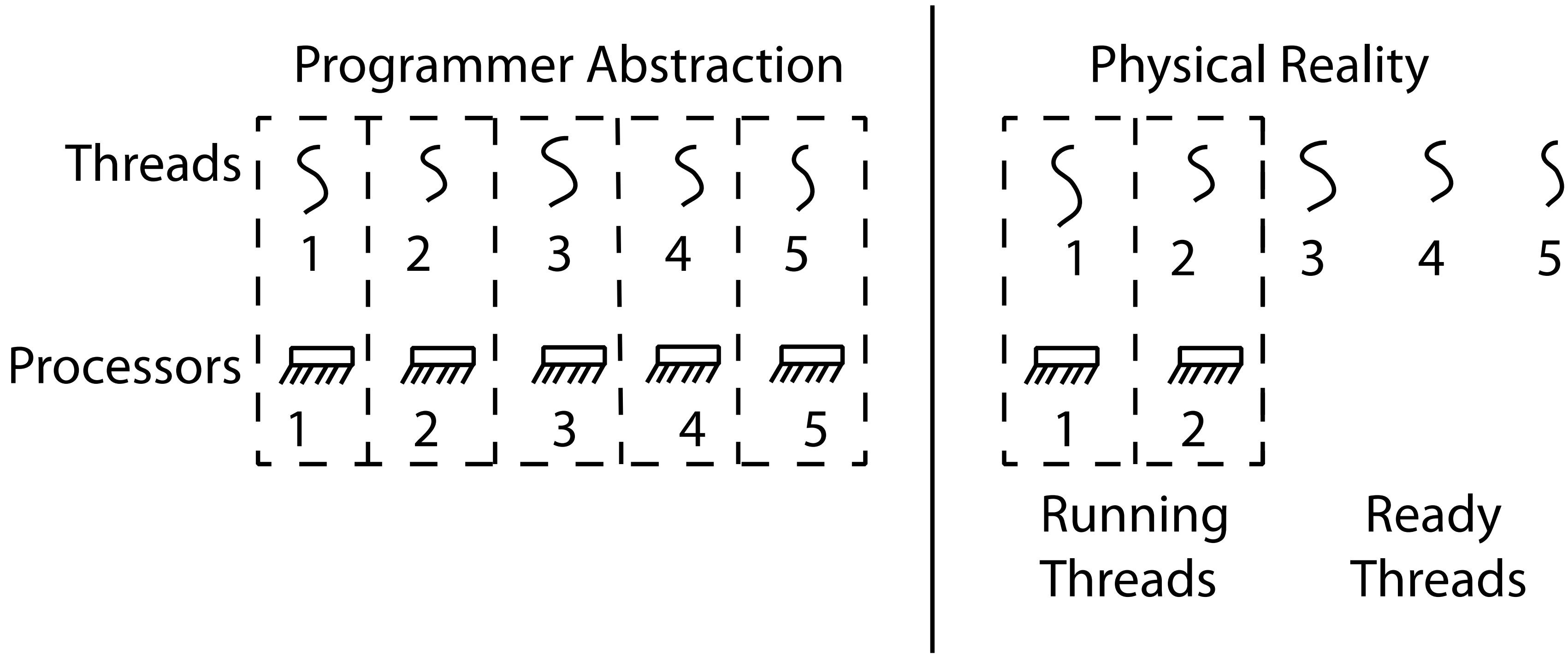
- Version of program with Threads (loose syntax):

```
main() {
    ThreadFork(ComputePI("pi.txt"));
    ThreadFork(PrintClassList("clist.text"));
}
```

- What does "ThreadFork()" do?
  - Start independent thread running given procedure
- What is the behavior here?
  - Now, you would actually see the class list
  - This should behave as if there are two separate CPUs



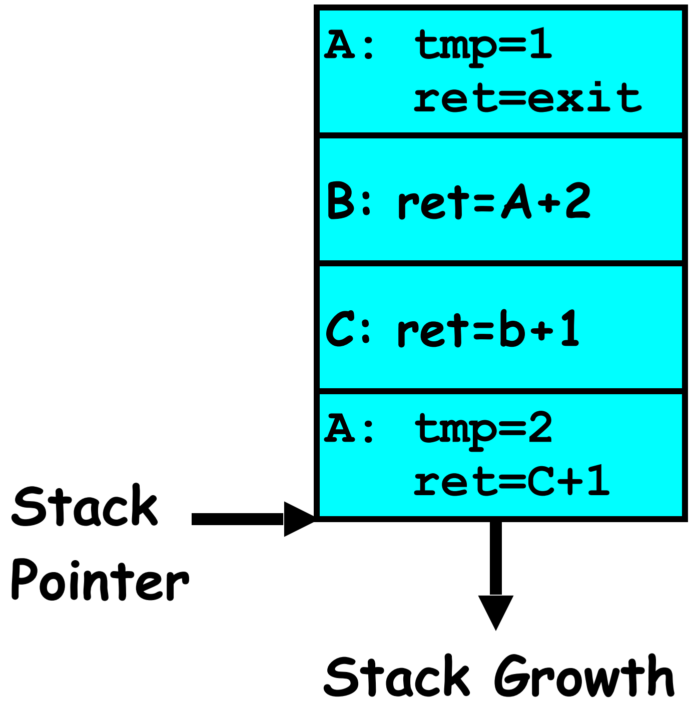
Recall: Thread Abstraction



- Infinite number of processors
- Threads execute with variable speed
  - Programs must be designed to work with any schedule

Recall: Execution Stack Example

```
A(int tmp) {
  if (tmp<2)
    B();
  printf(tmp);
}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

MIPS: Software conventions for Registers

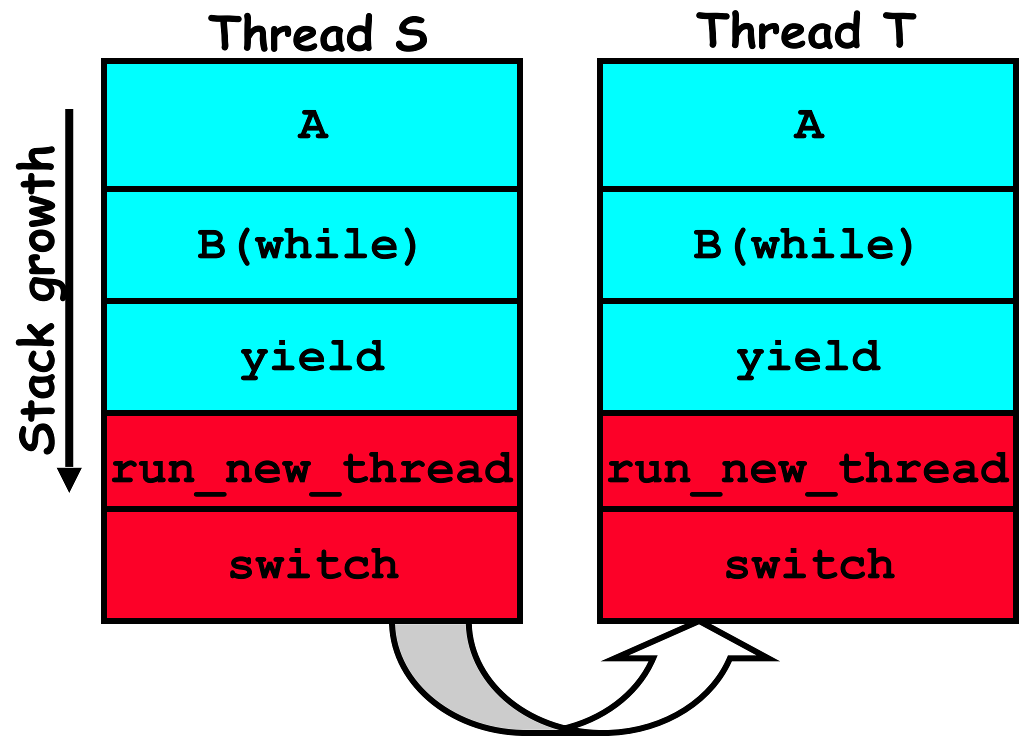
0	zero	constant 0	16	s0	callee saves
1	at	reserved for assembler	. . .		(callee must save)
2	v0	expression evaluation &	23	s7	
3	v1	function results	24	t8	temporary (cont'd)
4	a0	arguments	25	t9	
5	a1		26	k0	reserved for OS kernel
6	a2		27	k1	
7	a3		28	gp	Pointer to global area
8	t0	temporary: caller saves	29	sp	Stack pointer
. . .		(callee can clobber)	30	fp	frame pointer
15	t7		31	ra	Return Address (HW)

- Before calling procedure:
  - Save caller-saves regs
  - Save v0, v1
  - Save ra
- After return, assume
  - Callee-saves reg OK
  - gp,sp,fp OK (restored!)
  - Other things trashed

Recall: Multithreaded stack switching

- Consider the following code blocks:

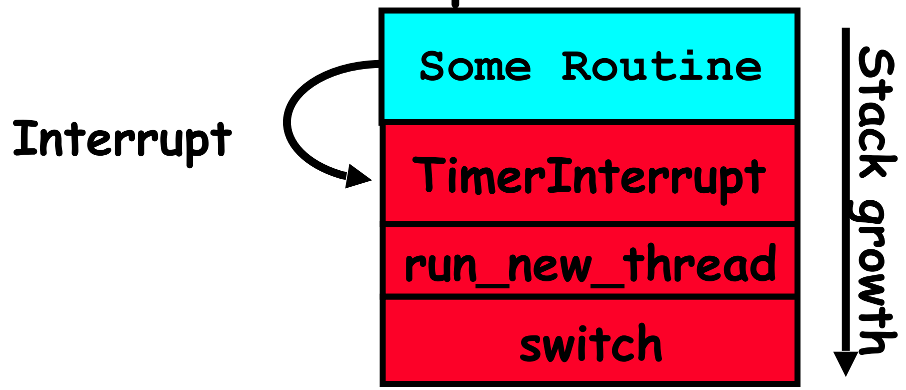
```
proc A() {
    B();
}
proc B() {
    while(TRUE) {
        yield();
    }
}
```



- Suppose we have 2 threads:
  - Threads S and T

Use of Timer Interrupt to Return Control

- Solution to our dispatcher problem
  - Use the timer interrupt to force scheduling decisions

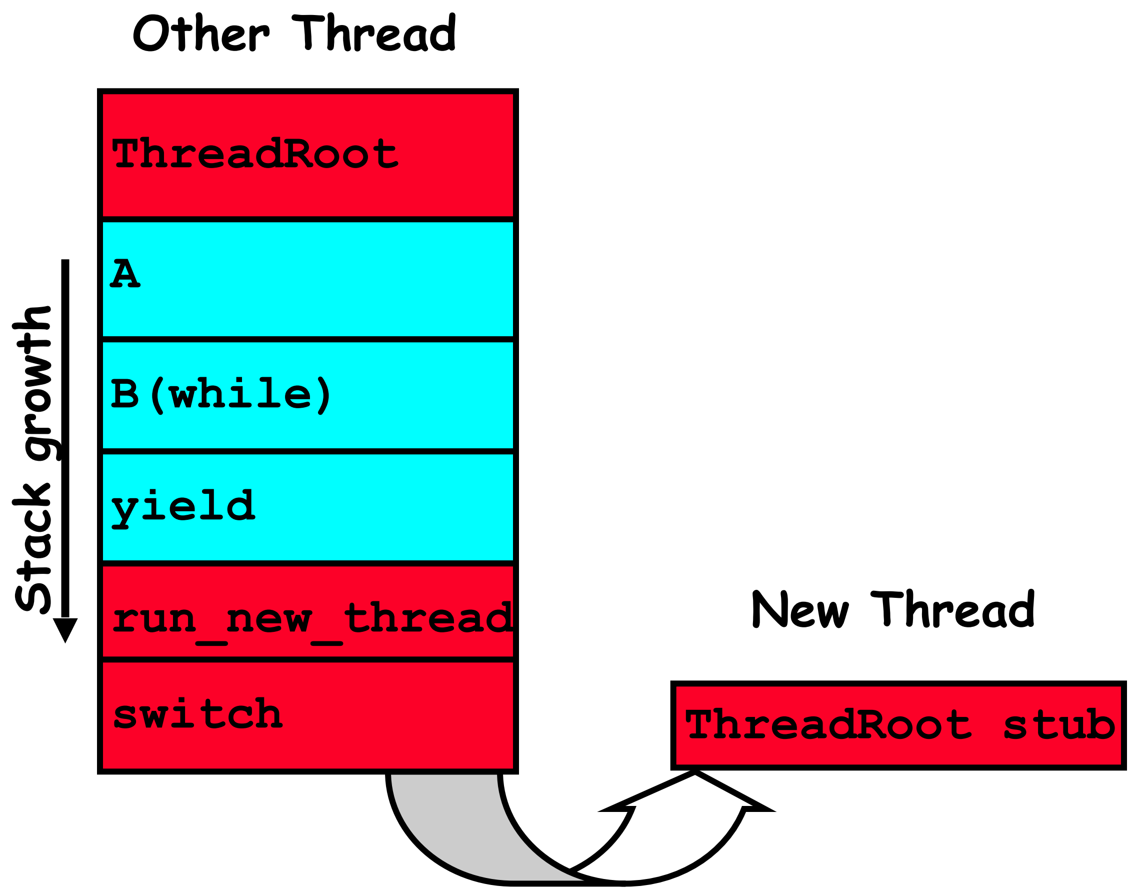


- Timer Interrupt routine:

```
TimerInterrupt() {
    DoPeriodicHouseKeeping();
    run_new_thread();
}
```

- I/O interrupt: same as timer interrupt except that `DoHousekeeping()` replaced by `ServiceIO()`.

How does Thread get started?



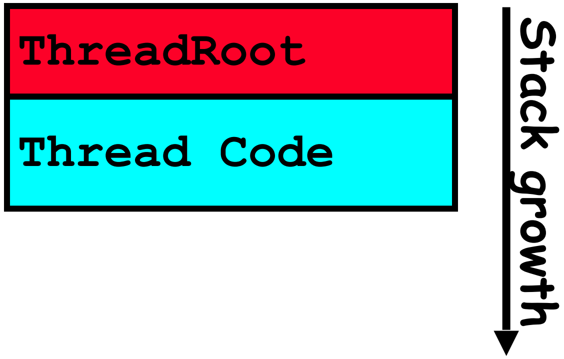
- Eventually, `run_new_thread()` will select this TCB and return into beginning of `ThreadRoot()`
  - This really starts the new thread

What does `ThreadRoot()` look like?

- ThreadRoot() is the root for the thread routine:

```
ThreadRoot() {
   DoStartupHousekeeping();
   UserModeSwitch(); /* enter user mode */
   Call fcnPtr(fcnArgPtr);
   ThreadFinish();
}
```

- Startup Housekeeping
  - Includes things like recording start time of thread
  - Other Statistics
- Stack will grow and shrink with execution of thread
- Final return from thread returns into ThreadRoot() which calls ThreadFinish()
  - ThreadFinish() wake up sleeping threads



Running Stack

Examples multithreaded programs

- Embedded systems
  - Elevators, Planes, Medical systems, Wristwatches
  - Single Program, concurrent operations
- Most modern OS kernels
  - Internally concurrent because have to deal with concurrent requests by multiple users
  - But no protection needed within kernel
- Database Servers
  - Access to shared data by many concurrent users
  - Also background utility processing must be done

Example multithreaded programs (con't)

- Network Servers
  - Concurrent requests from network
  - Again, single program, multiple concurrent operations
  - File server, Web server, and airline reservation systems

- Parallel Programming (More than one physical CPU)
  - Split program into multiple threads for parallelism
  - This is called Multiprocessing

A typical use case

Client Browser
- process for each tab
- thread to render page
- GET in separate thread
- multiple outstanding GETs
- as they complete, render portion

Web Server
- fork process for each client connection
- thread to get request and issue response
- fork threads to read data, access DB, etc
- join and respond

Some Numbers

- Many process are multi-threaded, so thread context switches may be either **within-process** or **across-processes**.

Windows Task Manager

File Options View Help

Applications | Processes | Services | Performance | Networking | Users

Image Name	PID	User Name	CPU	Memory (Private Workin...	Threads	Description
thunderbird.exe *32	5544	jfc	00	422,212 K	28	Thunderbird
firefox.exe *32	6064	jfc	00	362,048 K	49	Firefox
BCU.exe *32	4752	jfc	00	109,012 K	6	Browser Configuration Utility
dwm.exe	4036	jfc	00	105,676 K	5	Desktop Window Manager
POWERPNT.EXE	140	jfc	00	102,204 K	12	Microsoft PowerPoint
explorer.exe	1780	jfc	00	73,244 K	36	Windows Explorer
Dropbox.exe *32	3380	jfc	00	56,792 K	34	Dropbox
CameraHelperShell.exe...	4892	jfc	00	15,068 K	9	Webcam Controller
emacs.exe *32	4856	jfc	00	12,956 K	3	GNU Emacs: The extensible self-doc
FlashPlayerPlugin_11_8...	4260	jfc	00	10,820 K	12	Adobe Flash Player 11.8 r800
nvxdsync.exe	3420		00	10,192 K	10	
emacs.exe *32	2736	jfc	00	10,000 K	3	GNU Emacs: The extensible self-doc
btvStack.exe	2700	jfc	00	9,444 K	43	Bluetooth Stack Server

Kernel Use Cases

- Thread for each user process
- Thread for sequence of steps in processing I/O
- Threads for device drivers
- …

Administrivia

- Group formation: should be completed by tonight!
  – Will handle stragglers tonight
- Group HW #1: Released!
  – Starts today
  – All design reviews will be conducted by TAs
- HW1 due Thursday
  – Must be submitted via the recommended "push" mechanism through git
  – "commit as you make progress" is essential!

Famous Quote WRT Scheduling: Dennis Richie

Dennis Richie,
Unix V6, slp.c:

```
/*
 * If the new process paused because it was
 * swapped out, set the stack level to the last call
 * to savu(u_ssav).  This means that the return
 * which is executed immediately after the call to aretu
 * actually returns from the last routine which did
 * the savu.
 *
 * You are not expected to understand this.
 */
```

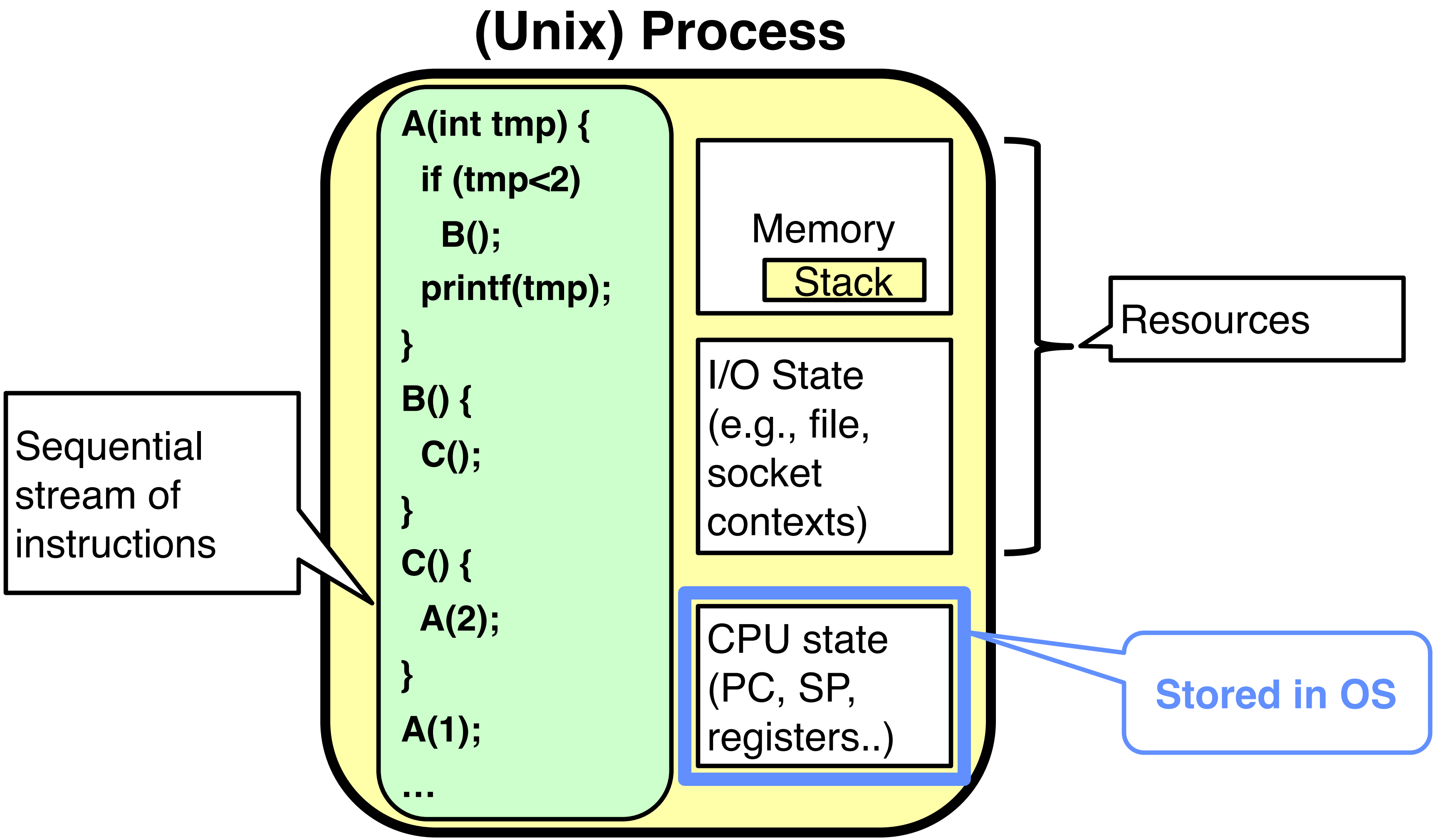
"If the new process paused because it was swapped out, set the stack level to the last call to savu(u_ssav). This means that the return which is executed immediately after the call to aretu actually returns from the last routine which did the savu."

"You are not expected to understand this."

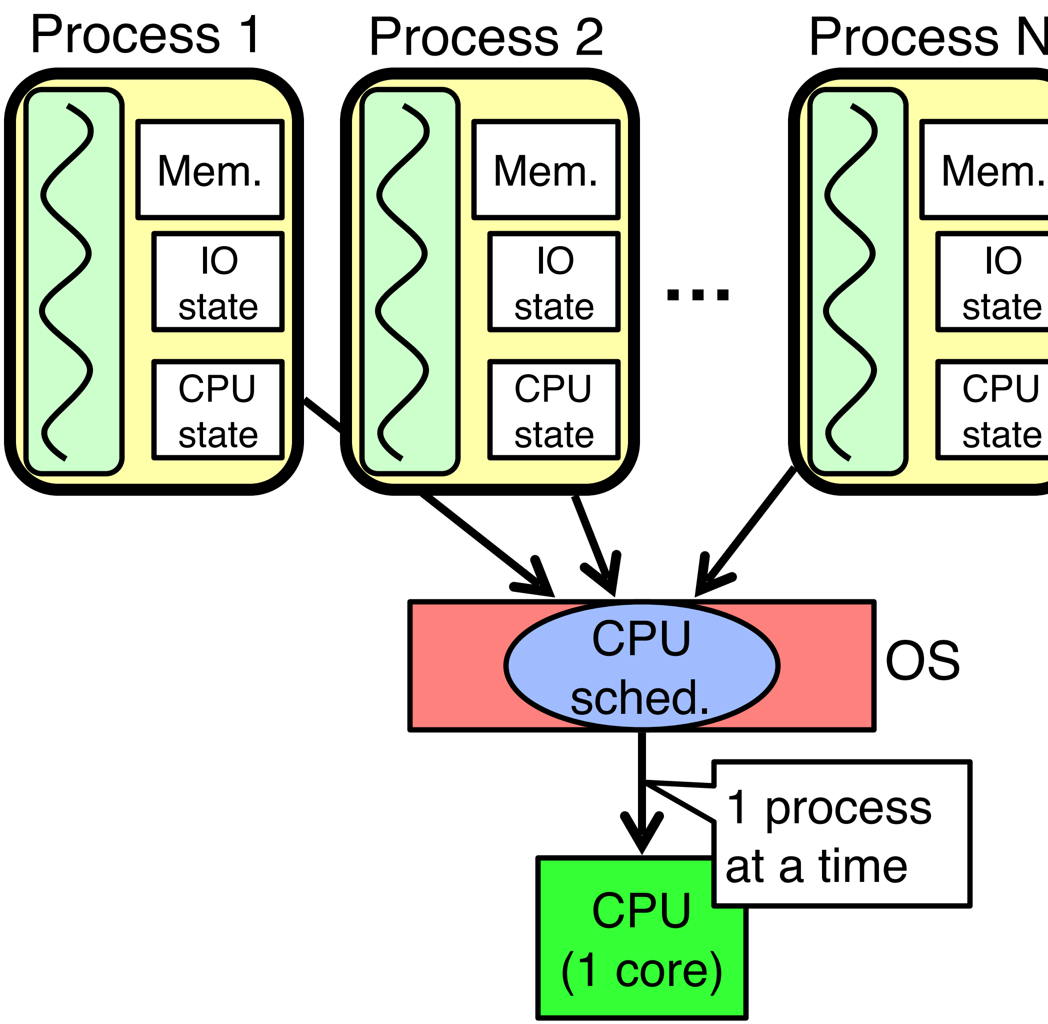
Source: Dennis Ritchie, Unix V6 slp.c (context-switching code) as per The Unix Heritage Society(tuhs.org); gif by Eddie Koehler.

Included by Ali R. Butt in CS3204 from Virginia Tech

Putting it together: Process

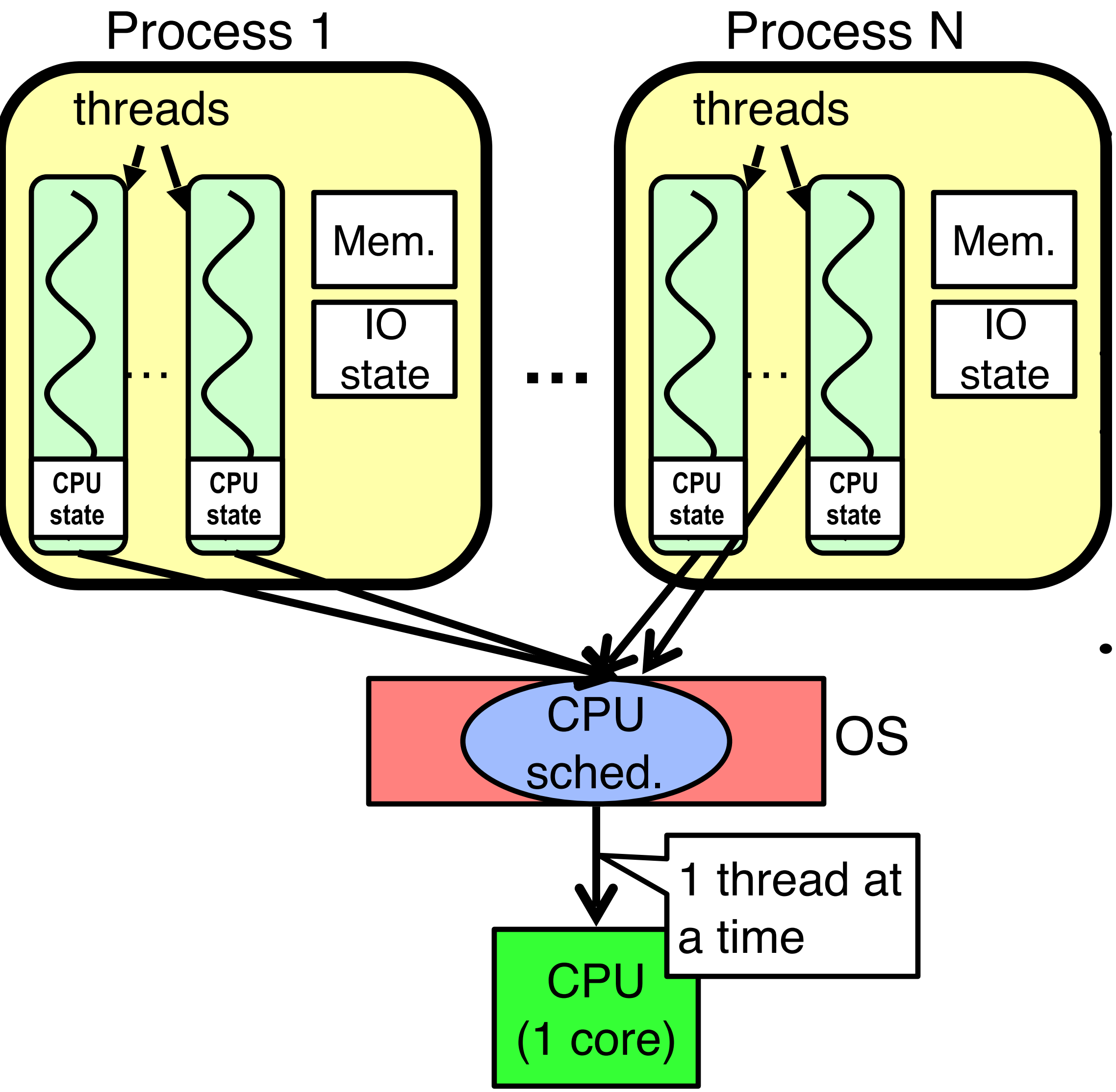


Putting it together: Processes



- Switch overhead: high
  - Kernel entry: low (ish)
  - CPU state: low
  - Memory/IO state: high
- Process creation: high
- Protection
  - CPU: yes
  - Memory/IO: yes
- Sharing overhead: high (involves at least a context switch)

Putting it together: Threads



Switch overhead: medium
- Kernel entry: low(ish)
- CPU state: low

Thread creation: medium

Protection
- CPU: yes
- Memory/IO: No

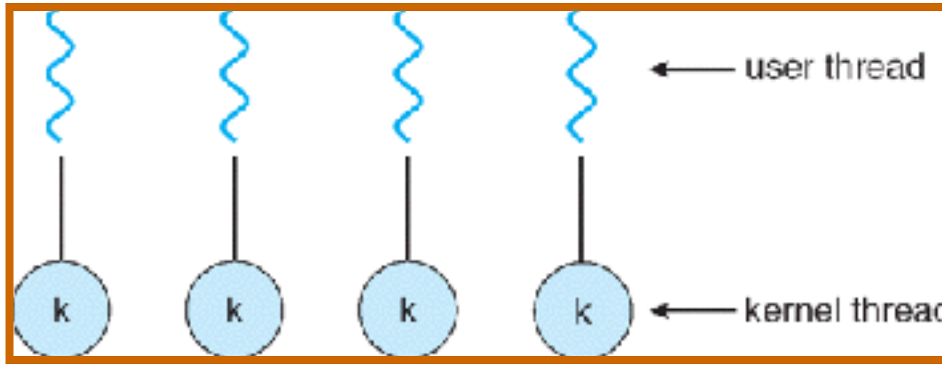
• Sharing overhead: low(ish) (thread switch overhead low)

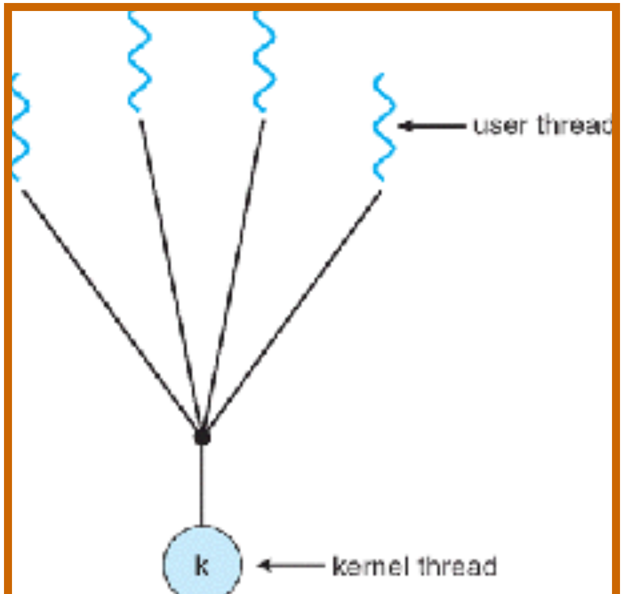
Kernel versus User-Mode threads

- We have been talking about Kernel threads
  - Native threads supported directly by the kernel
  - Every thread can run or block independently
  - One process may have several threads waiting on different things
- Downside of kernel threads: a bit expensive
  - Need to make a crossing into kernel mode to schedule
- Lighter weight option: User Threads
  - User program provides scheduler and thread package
  - May have several user threads per kernel thread
  - User threads may be scheduled non-premptively relative to each other (only switch on yield())
  - Cheap
- Downside of user threads:
  - When one thread blocks on I/O, all threads block
  - Kernel cannot adjust scheduling among all threads
  - Option: Scheduler Activations
    - » Have kernel inform user level when thread blocks…

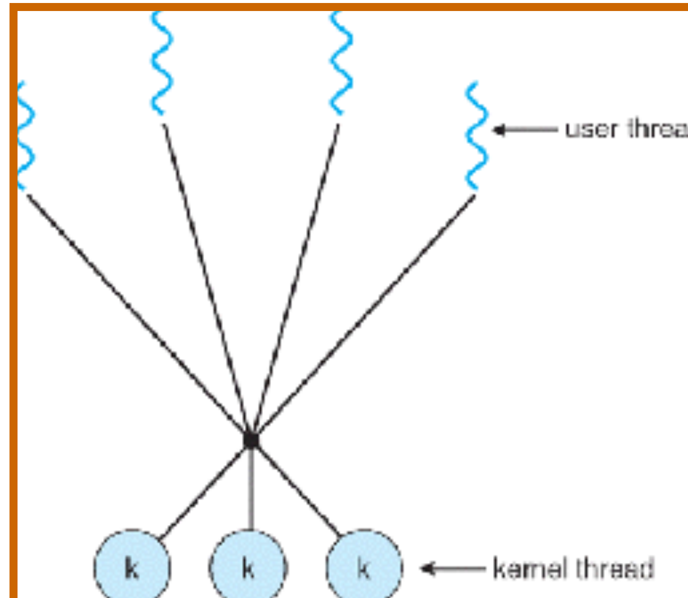
Some Threading Models

Simple One-to-One Threading Model





Many-to-One

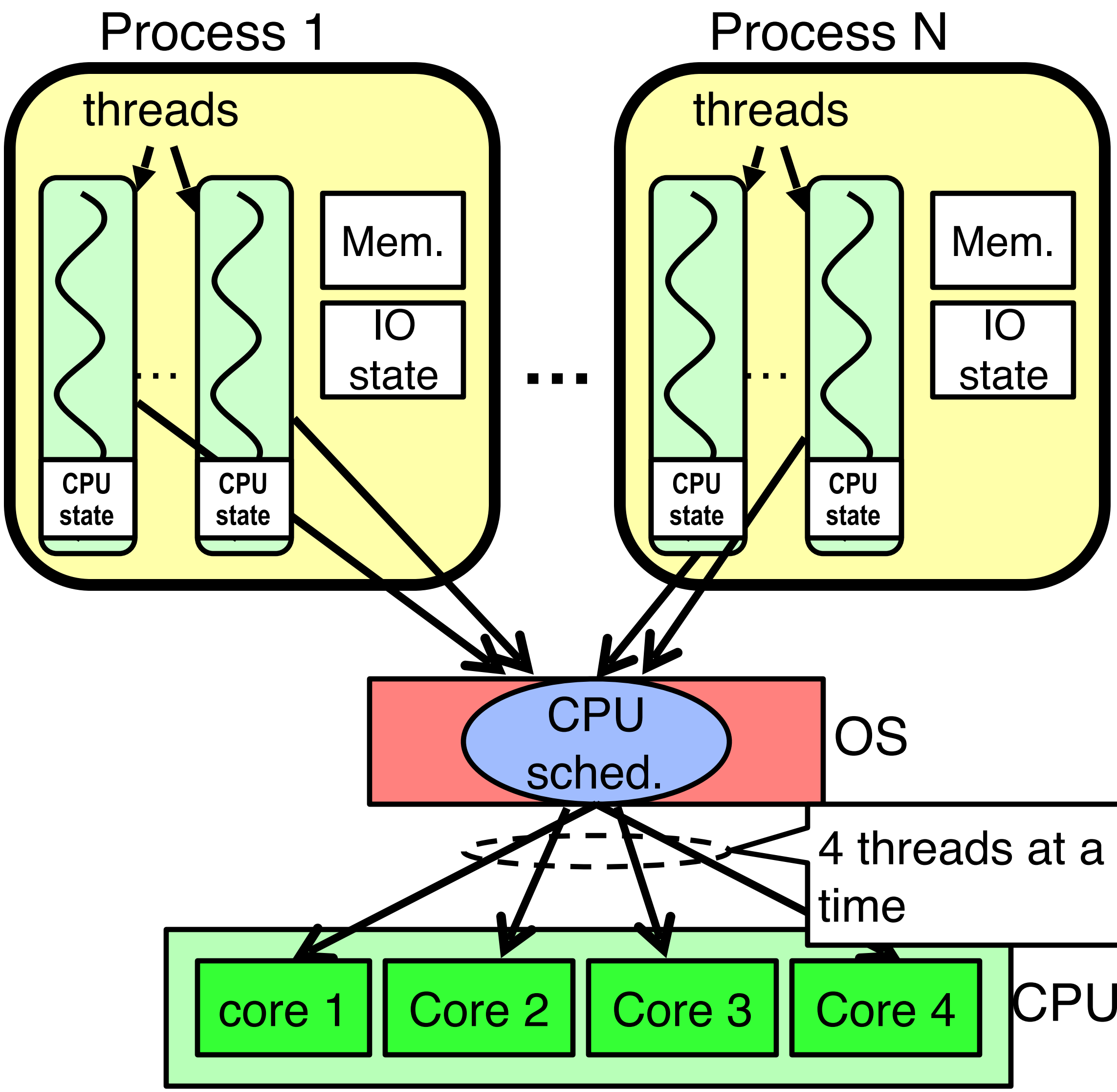


Many-to-Many

Threads in a Process

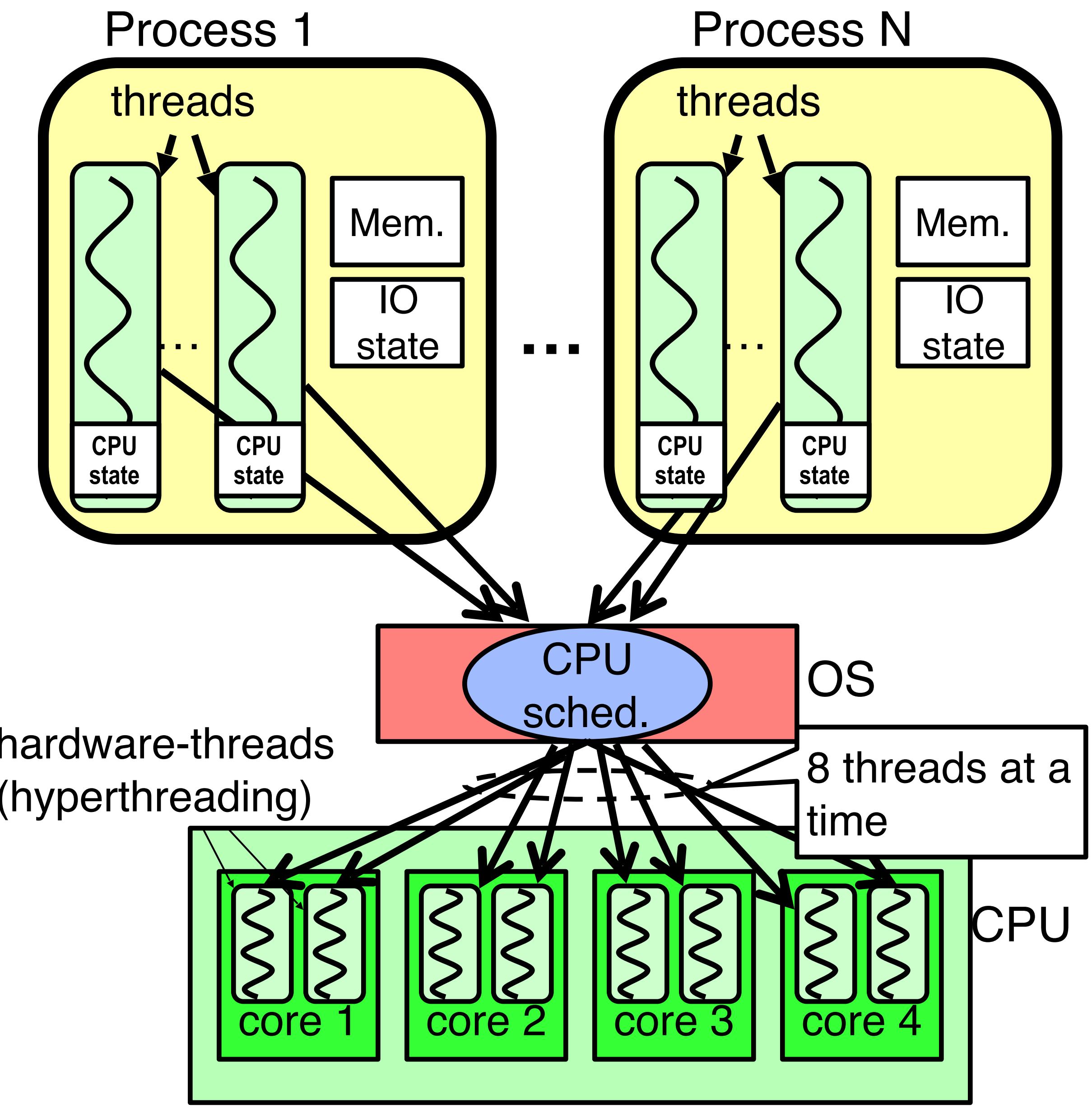
- Threads are useful at user-level
  - Parallelism, hide I/O latency, interactivity
- Option A (early Java): user-level library, within a single-threaded process
  - Library does thread context switch
  - Kernel time slices between processes, e.g., on system call I/O
- Option B (SunOS, Linux/Unix variants): *green Threads*
  - User-level library does thread multiplexing
- Option C (Windows): scheduler activations
  - Kernel allocates processors to user-level library
  - Thread library implements context switch
  - System call I/O that blocks triggers upcall
- Option D (Linux, MacOS, Windows): use kernel threads
  - System calls for thread fork, join, exit (and lock, unlock,…)
  - Kernel does context switching
  - Simple, but a lot of transitions between user and kernel mode

Putting it together: Multi-Cores



- Switch overhead: low (only CPU state)
- Thread creation: low
- Protection
  - CPU: yes
  - Memory/IO: No
- Sharing overhead: low (thread switch overhead low, may not need to switch at all!)

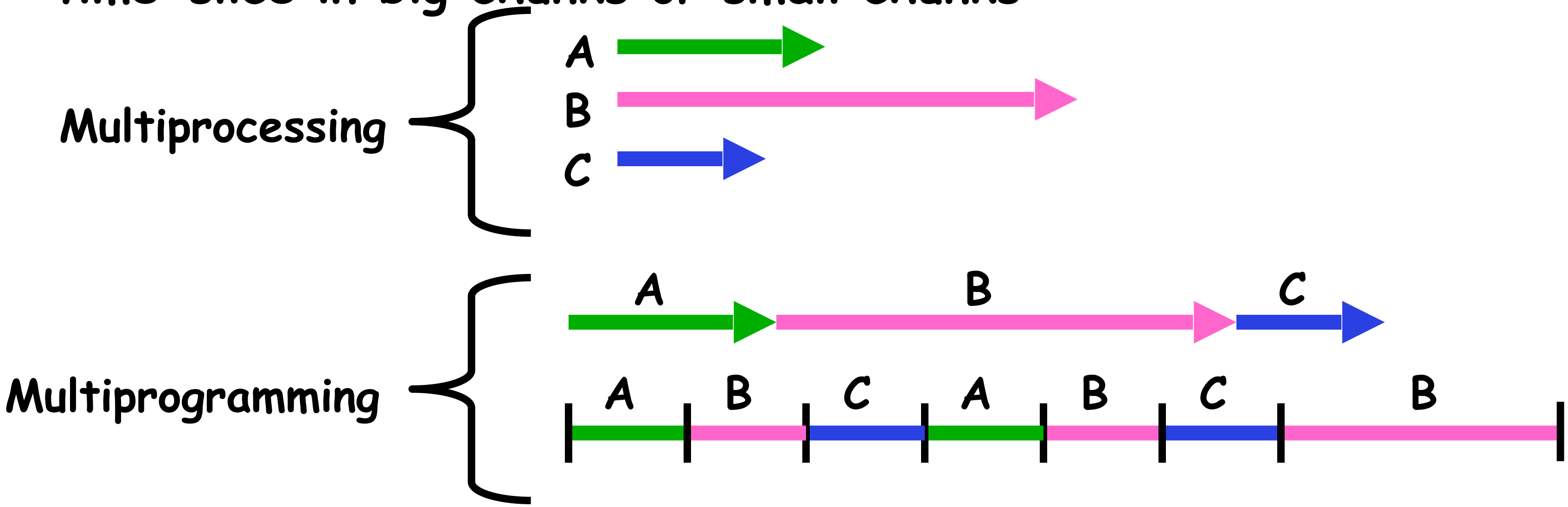
Putting it together: Hyper-Threading



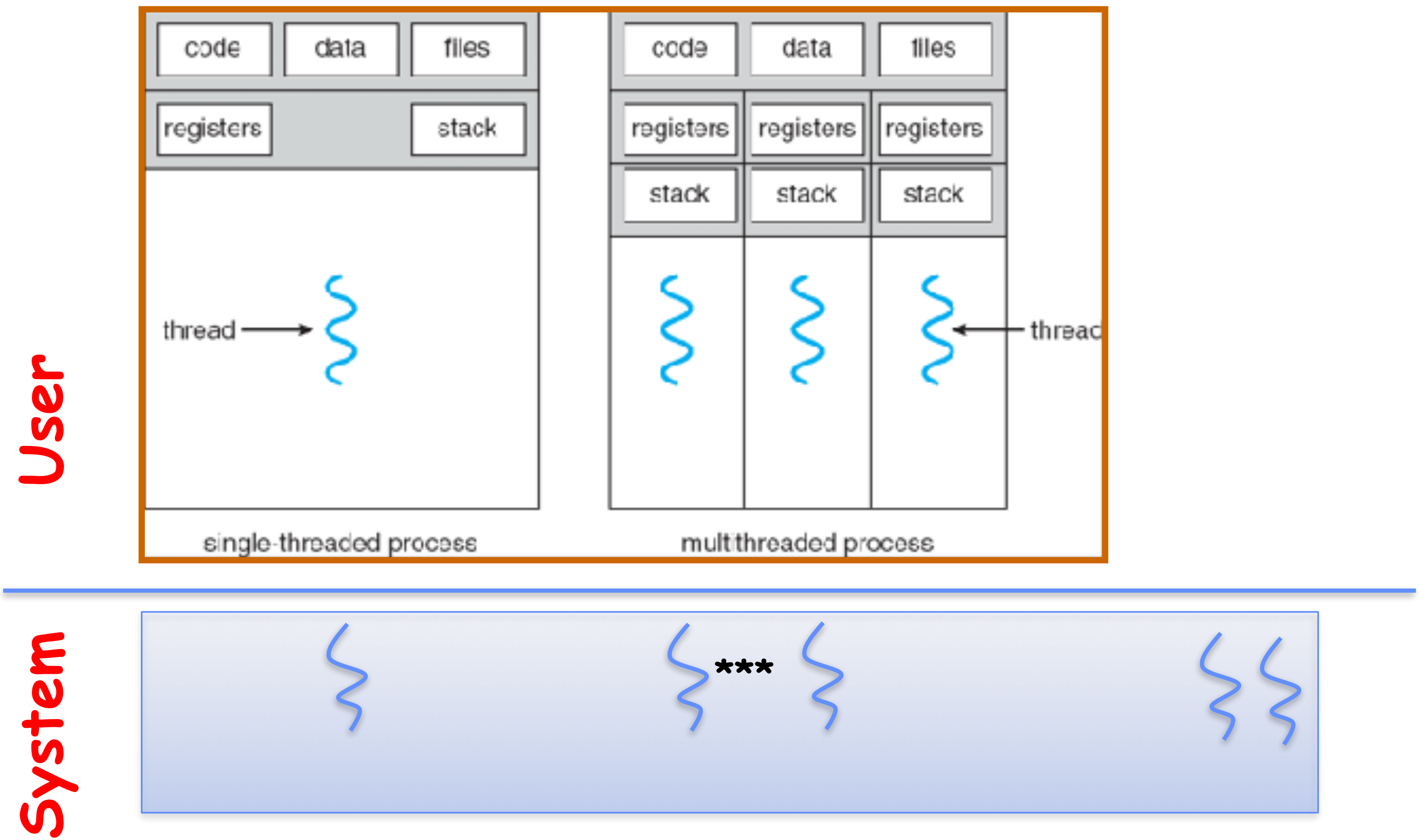
- Switch overhead between hardware-threads: very-low (done in hardware)
- Contention for ALUs/FPUs may hurt performance

Multiprocessing vs Multiprogramming

- Remember Definitions:
  - Multiprocessing ≡ Multiple CPUs
  - Multiprogramming ≡ Multiple Jobs or Processes
  - Multithreading ≡ Multiple threads per Process
- What does it mean to run two threads "concurrently"?
  - Scheduler is free to run threads in any order and interleaving: FIFO, Random, …
  - Dispatcher can choose to run each thread to completion or time-slice in big chunks or small chunks



Supporting 1T and MT Processes



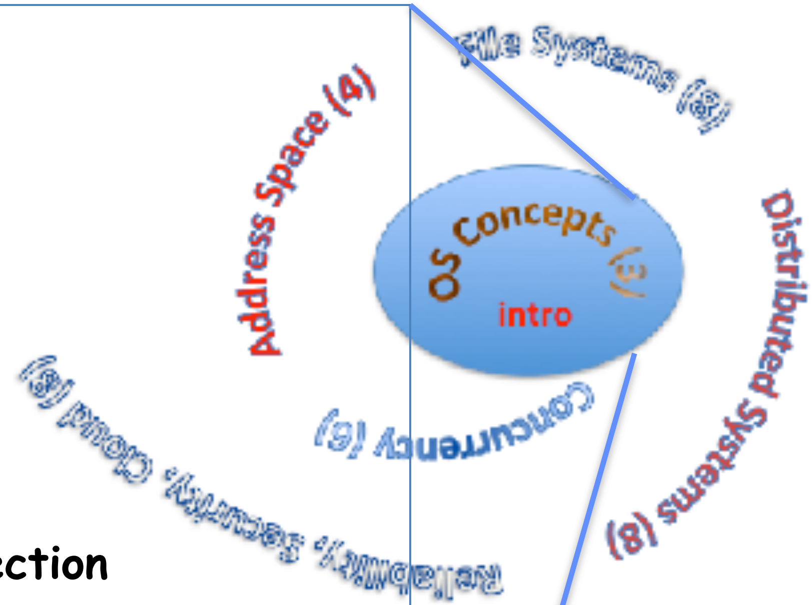
Classification

# threads Per AS: / # of addr spaces:	One	Many
One	MS/DOS, early Macintosh	Traditional UNIX
Many	Embedded systems (Geoworks, VxWorks, JavaOS,etc) JavaOS, Pilot(PC)	Mach, OS/2, Linux Windows 9x??? Win NT to XP, Solaris, HP-UX, OS X

- Real operating systems have either
  - One or many address spaces
  - One or many threads per address space
- Did Windows 95/98/ME have real memory protection?
  - No: Users could overwrite process tables/System DLLs

You are here… why?

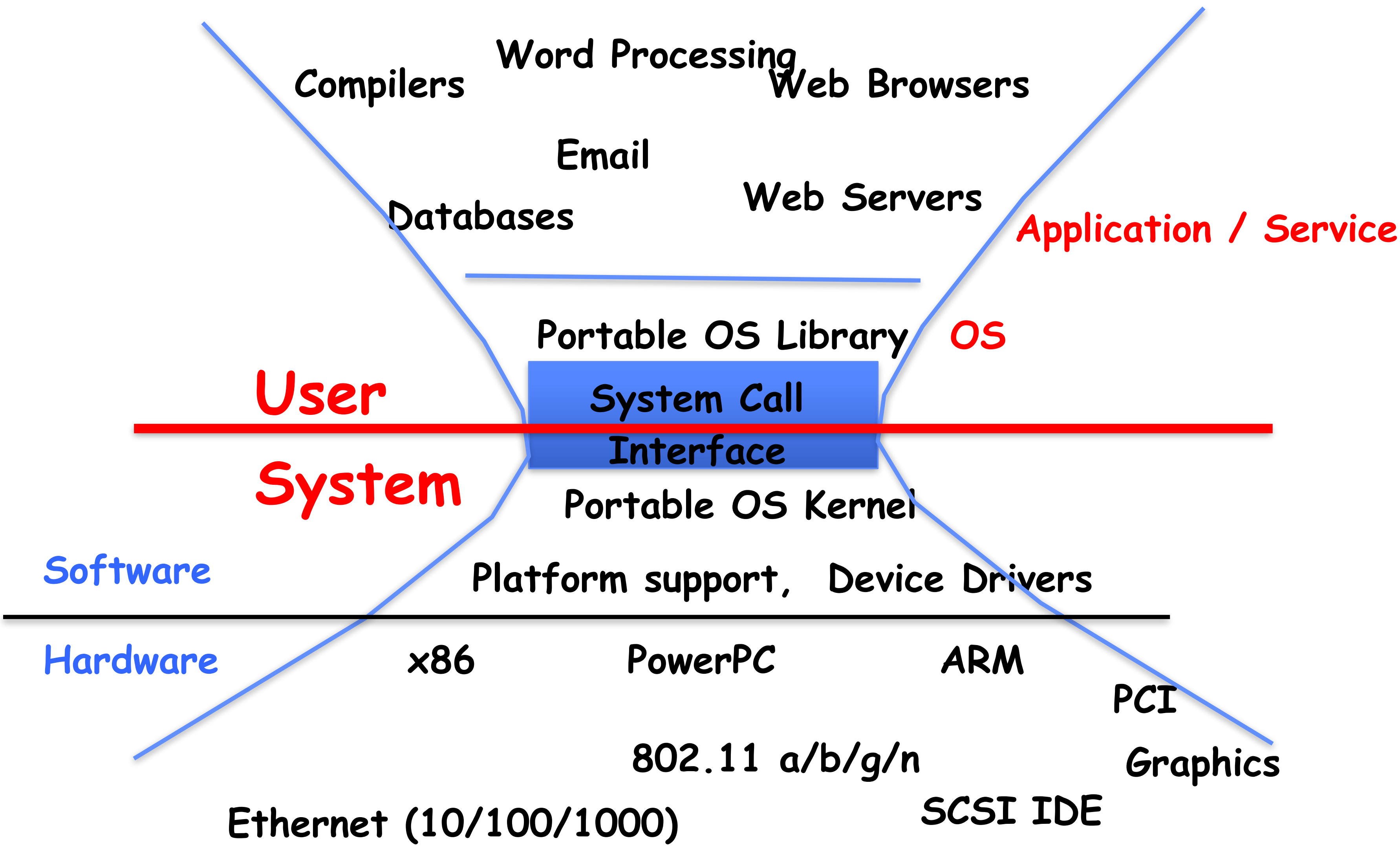
- Processes
  - Thread(s) + address space
- Address Space
- Protection
- Dual Mode
- Interrupt handlers
  - Interrupts, exceptions, syscall
- File System
  - Integrates processes, users, cwd, protection
- Key Layers: OS Lib, Syscall, Subsystem, Driver
  - User handler on OS descriptors
- Process control
  - fork, wait, signal, exec
- Communication through sockets
  - Integrates processes, protection, file ops, concurrency
- Client-Server Protocol
- Concurrent Execution: Threads
- Scheduling



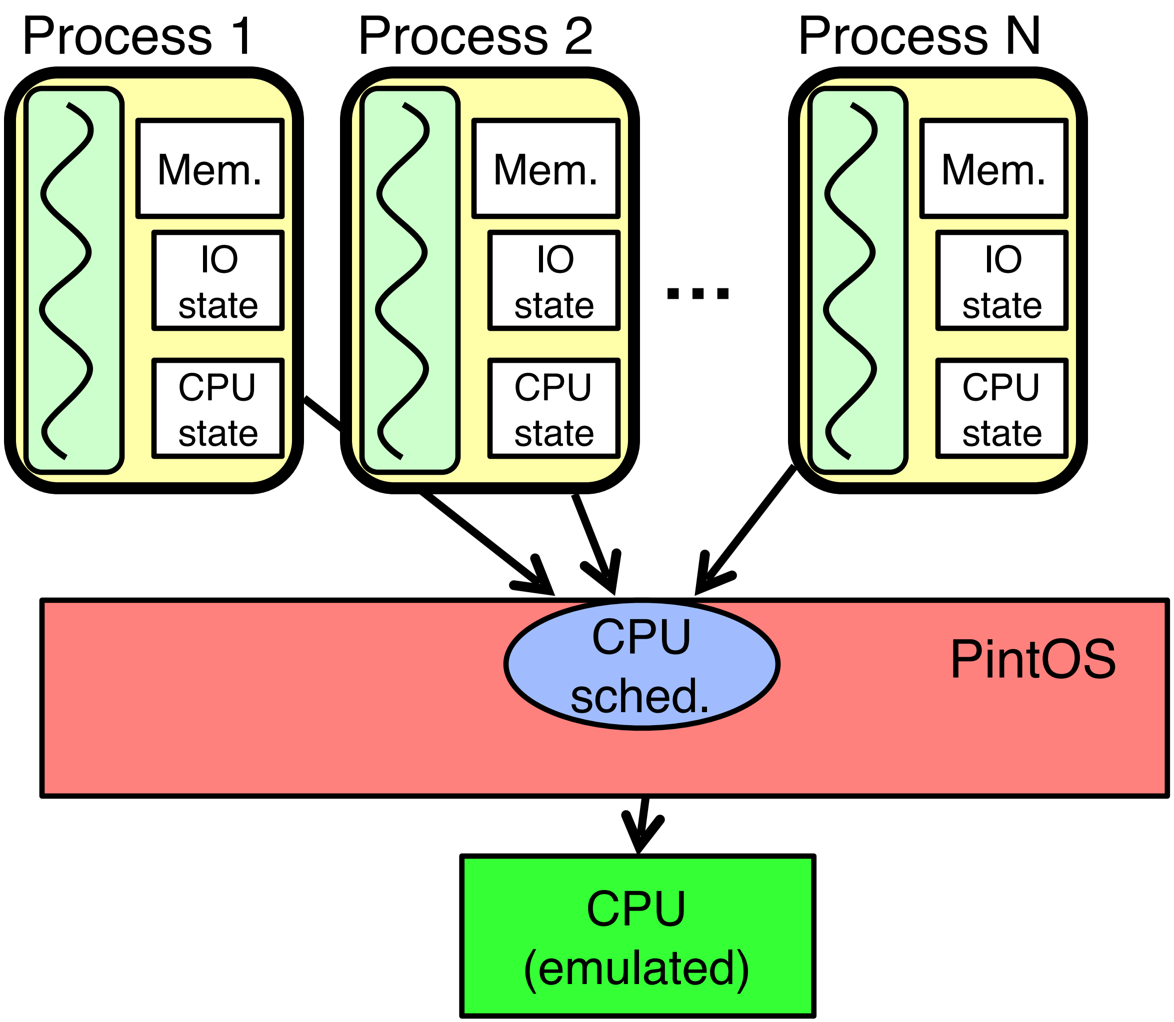
Perspective OS Course

- Historically, OS was the most complex software
  - Concurrency, synchronization, processes, devices, communication,…
  - Core systems concepts developed there
- Today, many "applications" are complex software systems too
  - These concepts appear there
  - But they are realized out of the capabilities provided by the operating system
- Seek to understand how these capabilities are implemented upon the basic hardware.
- See concepts multiple times from multiple perspectives
  - Lecture provides conceptual framework, integration, examples, …
  - Book provides a reference with some additional detail
  - Lots of other resources that you need to learn to use
    - » man pages, google, reference manuals, includes (.h)
- Homework and Group Homework provides detail down to the actual code AND direct hands-on experience

Operating System as Design

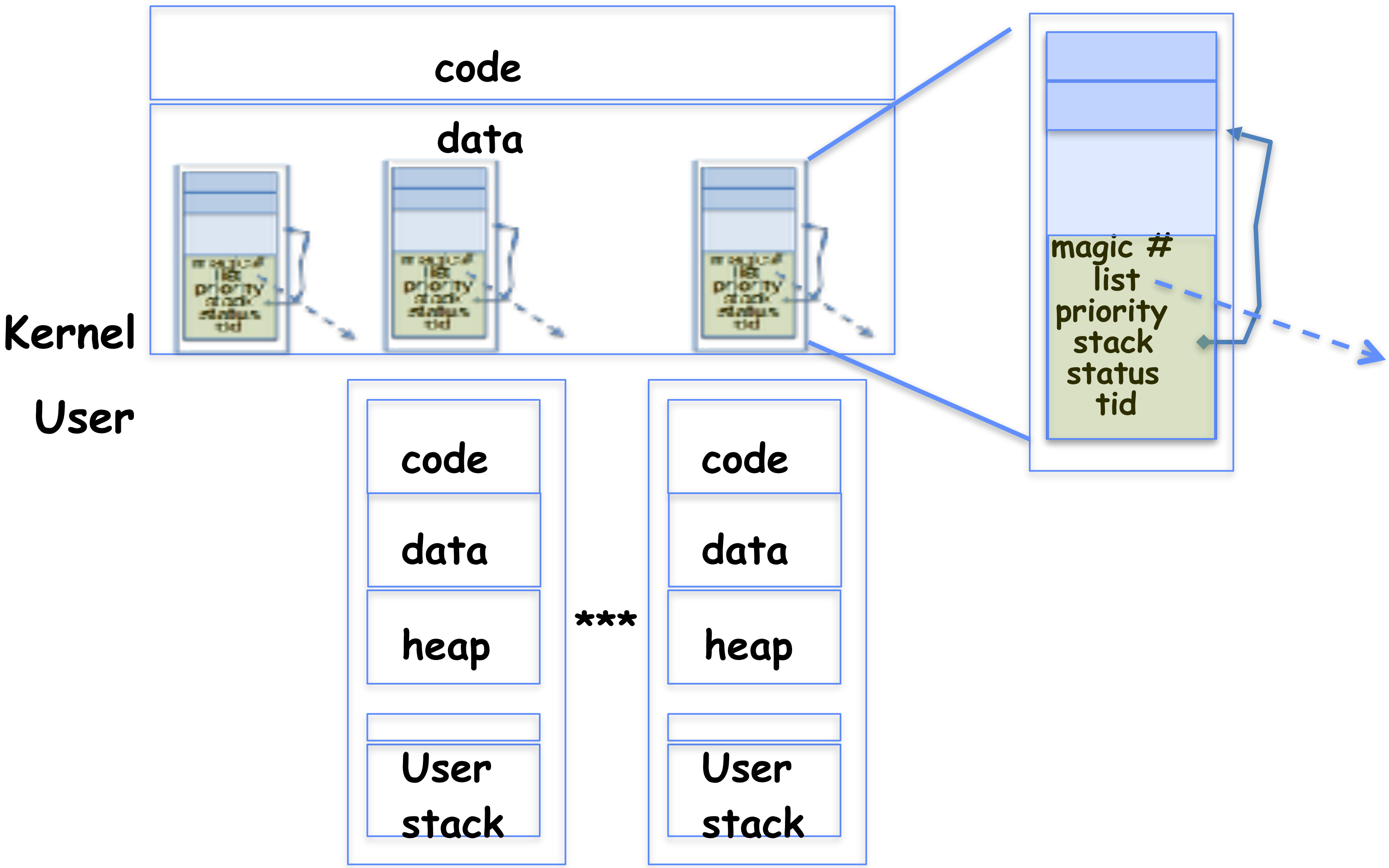


Starting today: Pintos Homeworks



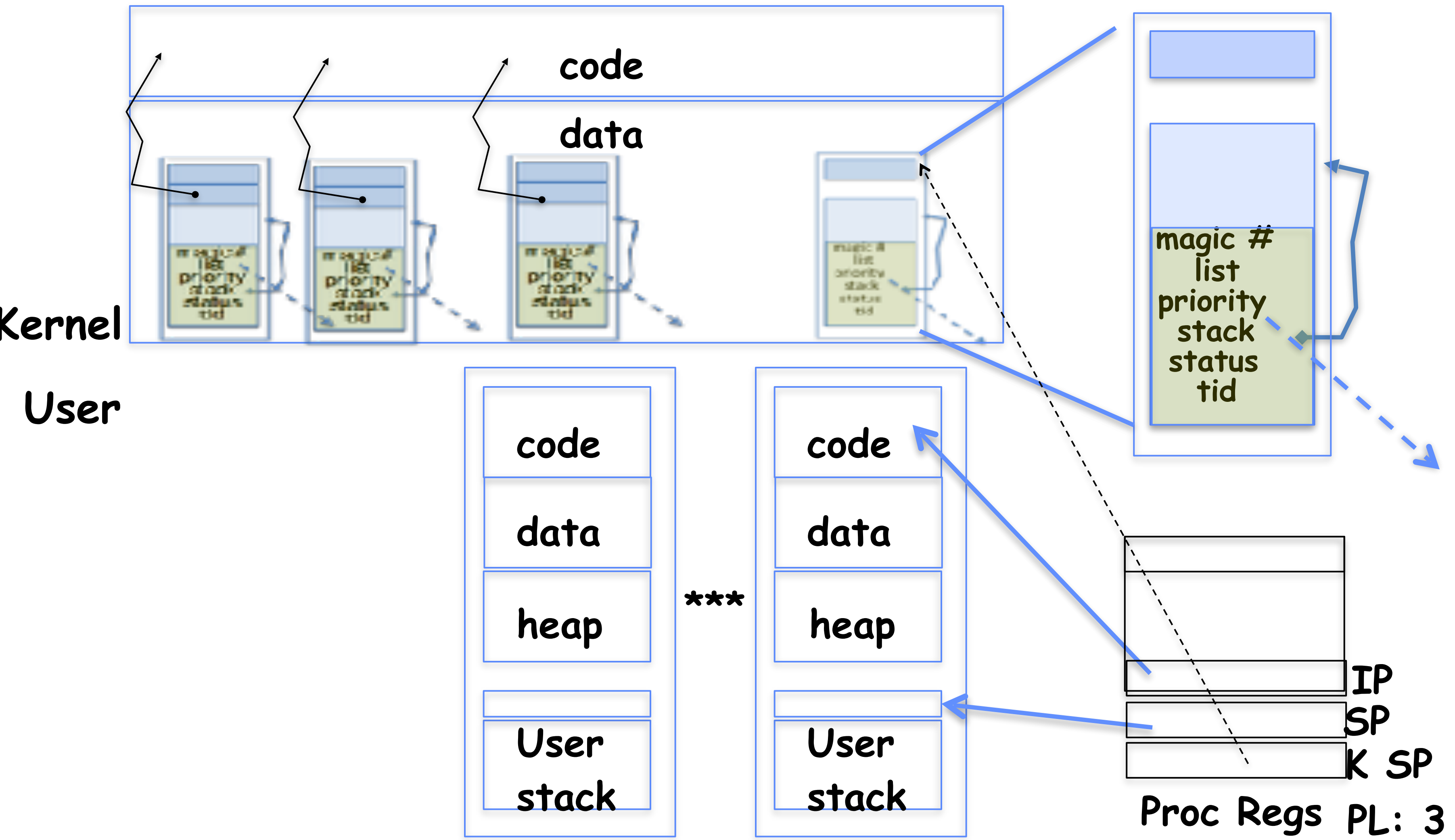
- Groups almost all formed
- Work as one!
- more work than homework!
- P1: threads & scheduler
- P2: user process
- P3: file system

MT Kernel 1T Process ala Pintos/x86



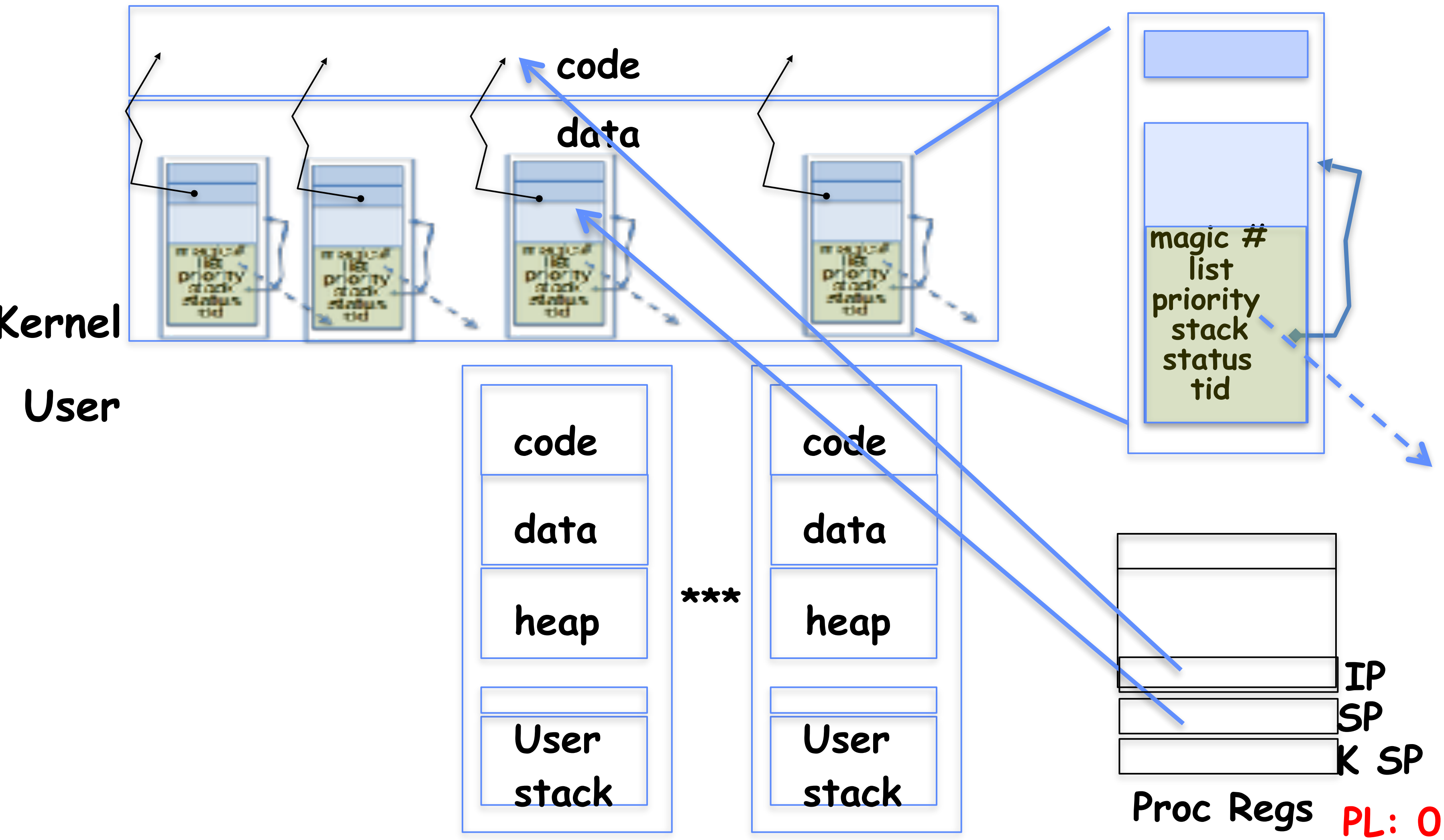
- Each user process/thread associated with a kernel thread, described by a 4kb Page object containing TCB and kernel stack for the kernel thread

In User thread, w/ k-thread waiting



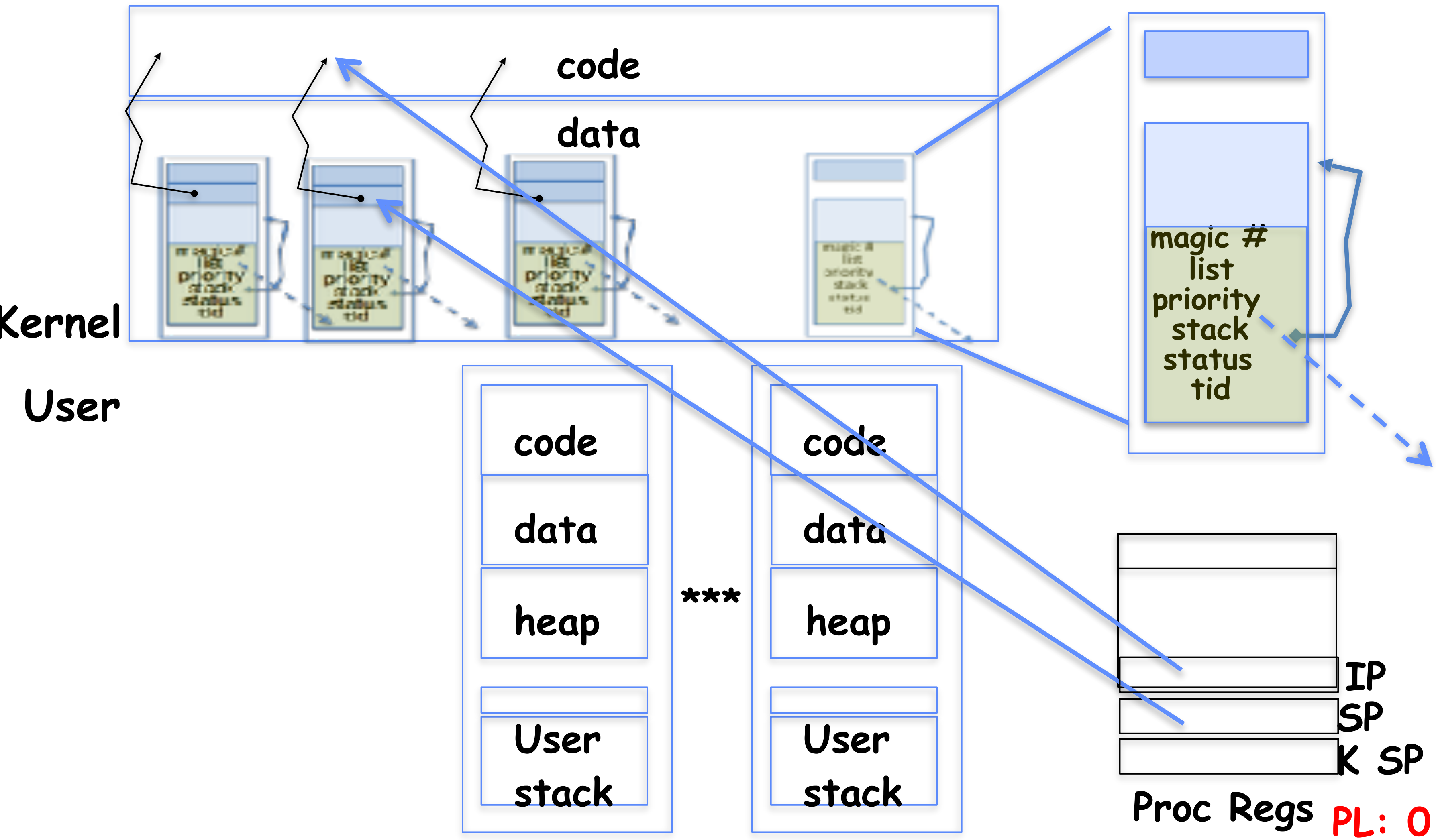
- x86 proc holds interrupt SP high system level
- During user thread exec, associate kernel thread is "standing by"

In Kernel thread



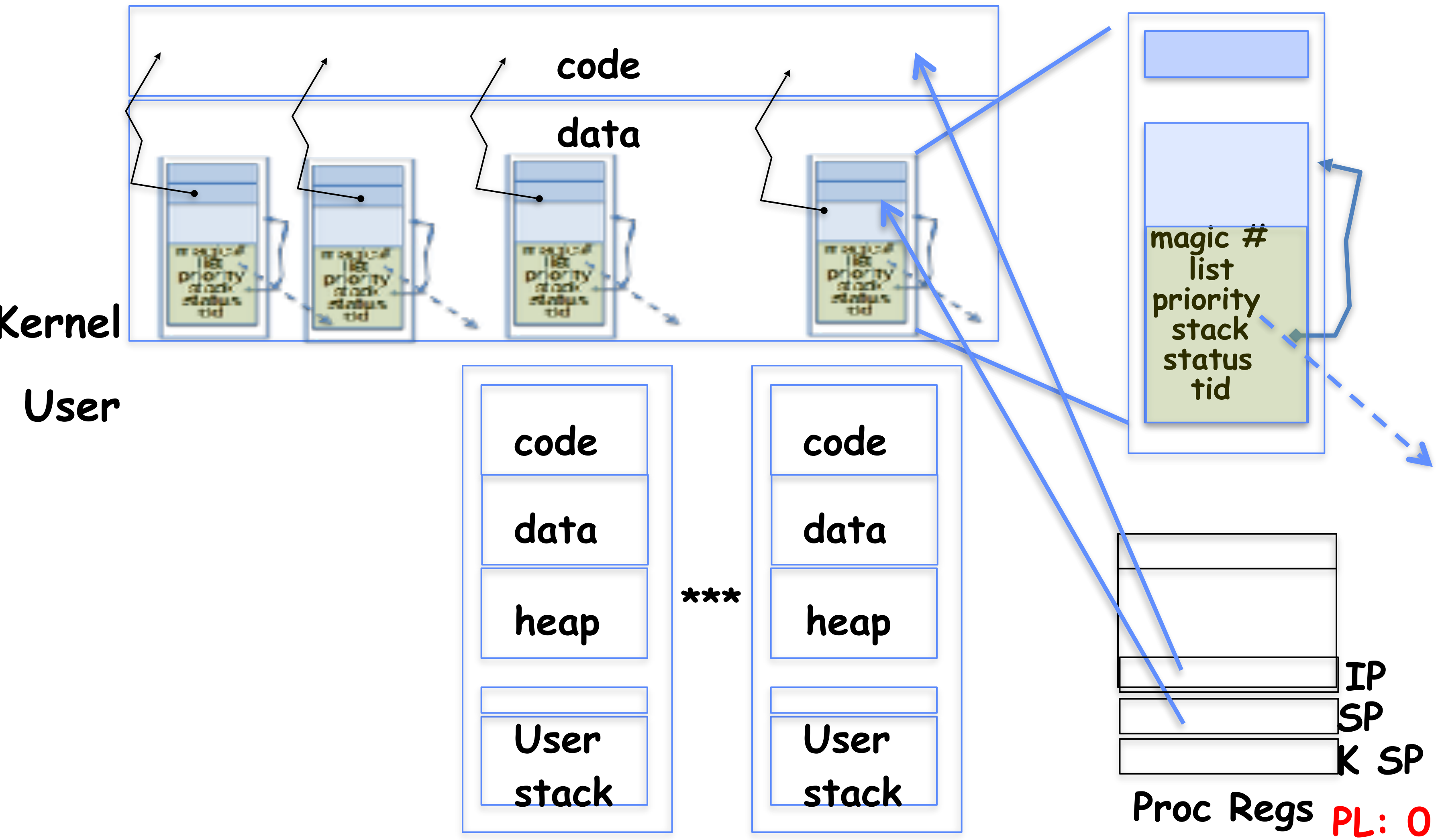
- Kernel threads execute with small stack in thread struct
- Scheduler selects among ready kernel and user threads

Thread Switch (switch.S)

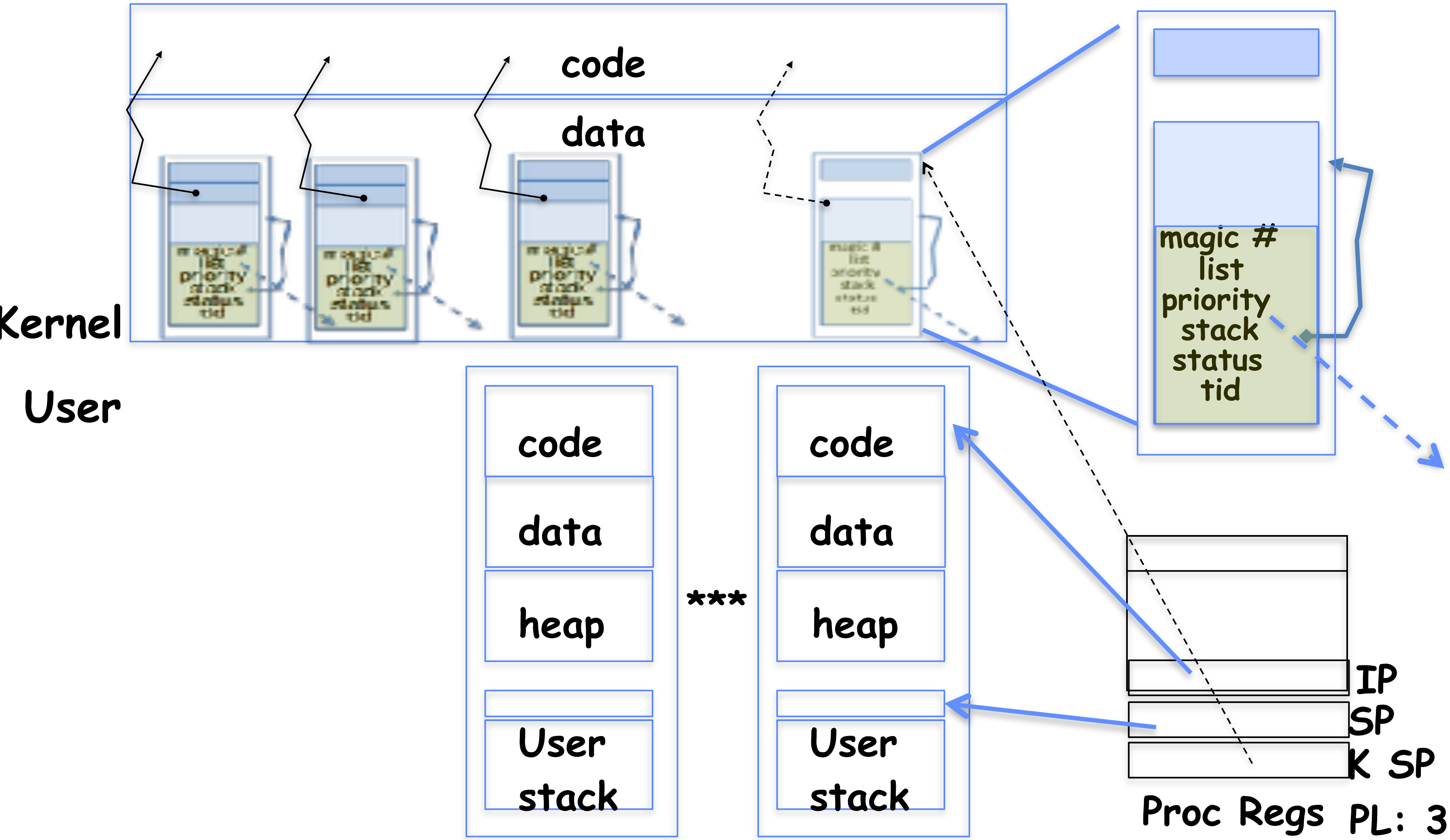


- switch_threads: save regs on current small stack, change SP, return from destination threads call to switch_threads

Switch to Kernel Thread for Process

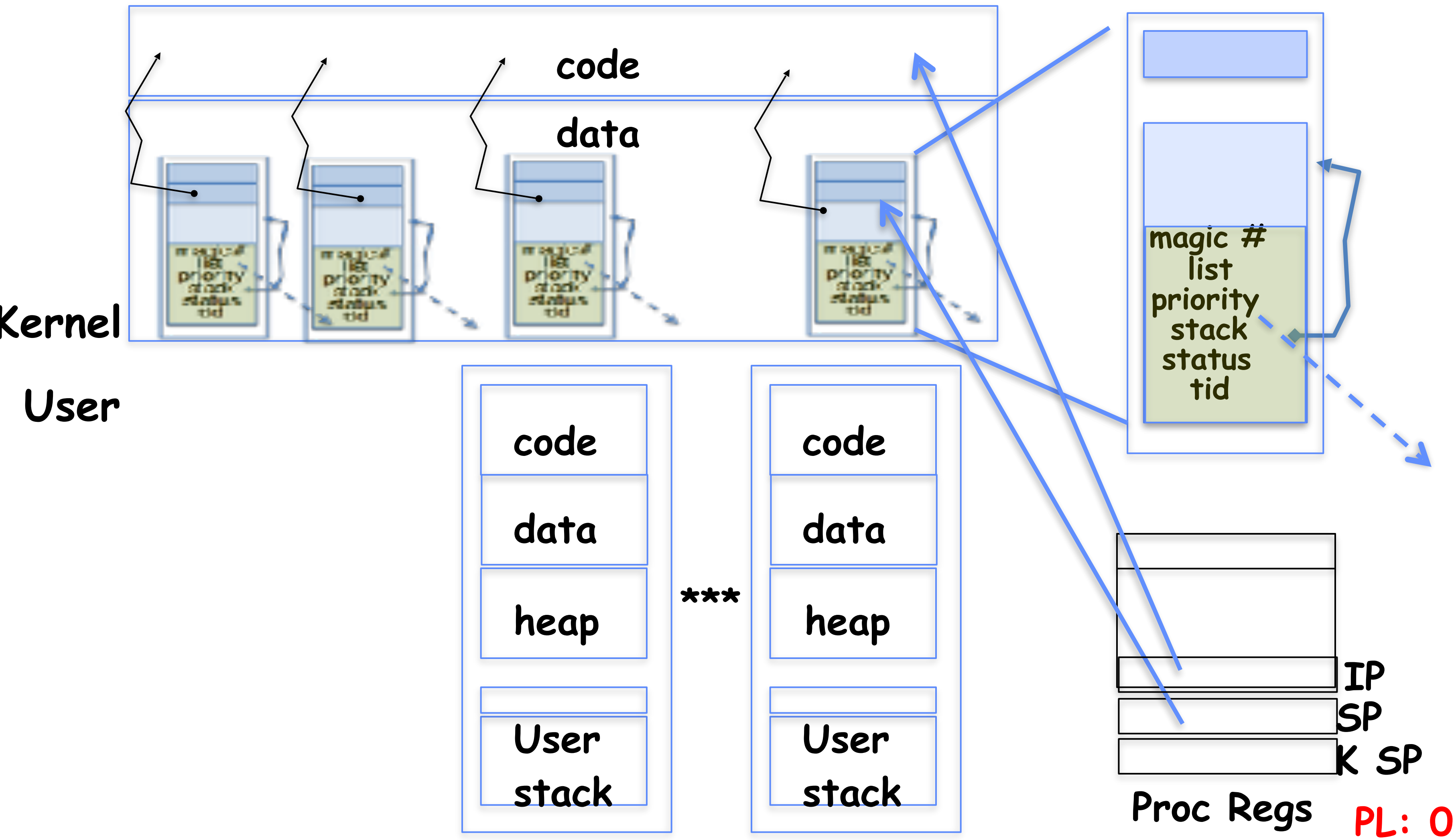


Kernel->User



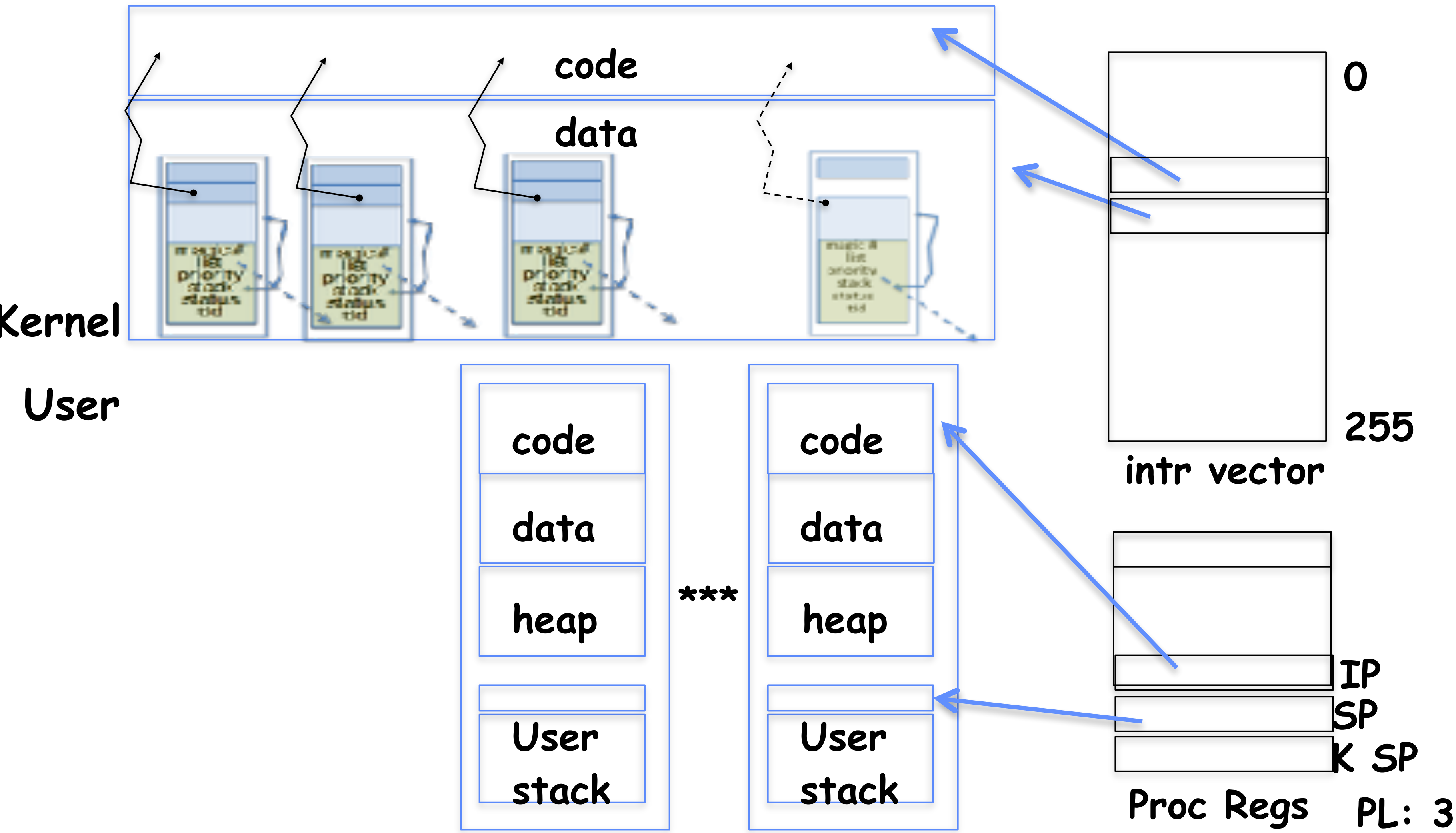
- iret restores user stack and PL

User->Kernel



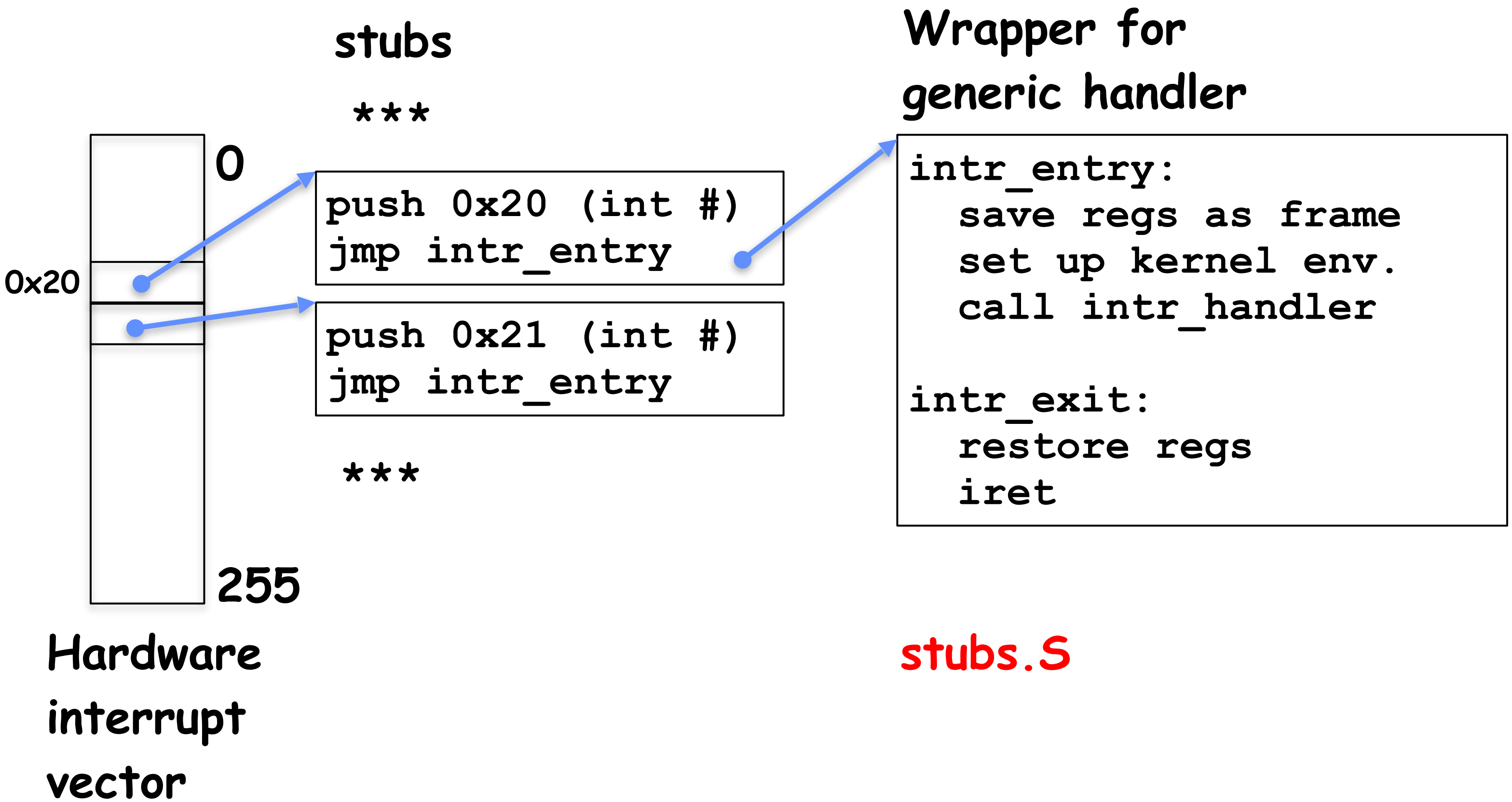
- Mechanism to resume k-thread goes through interrupt vector

User->Kernel via interrupt vector

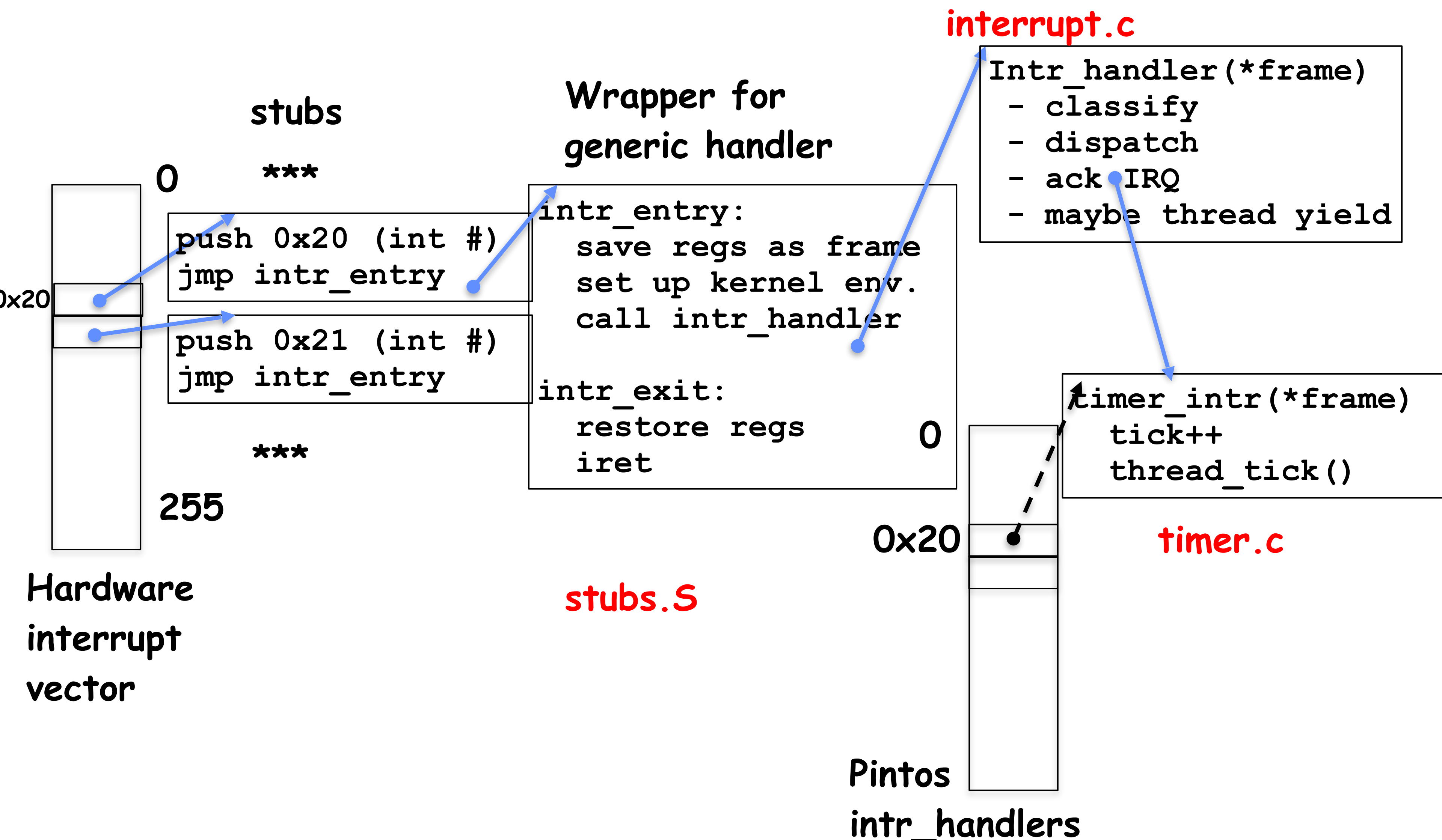


- Interrupt transfers control through the IV (IDT in x86)
- iret restores user stack and PL

Pintos Interrupt Processing



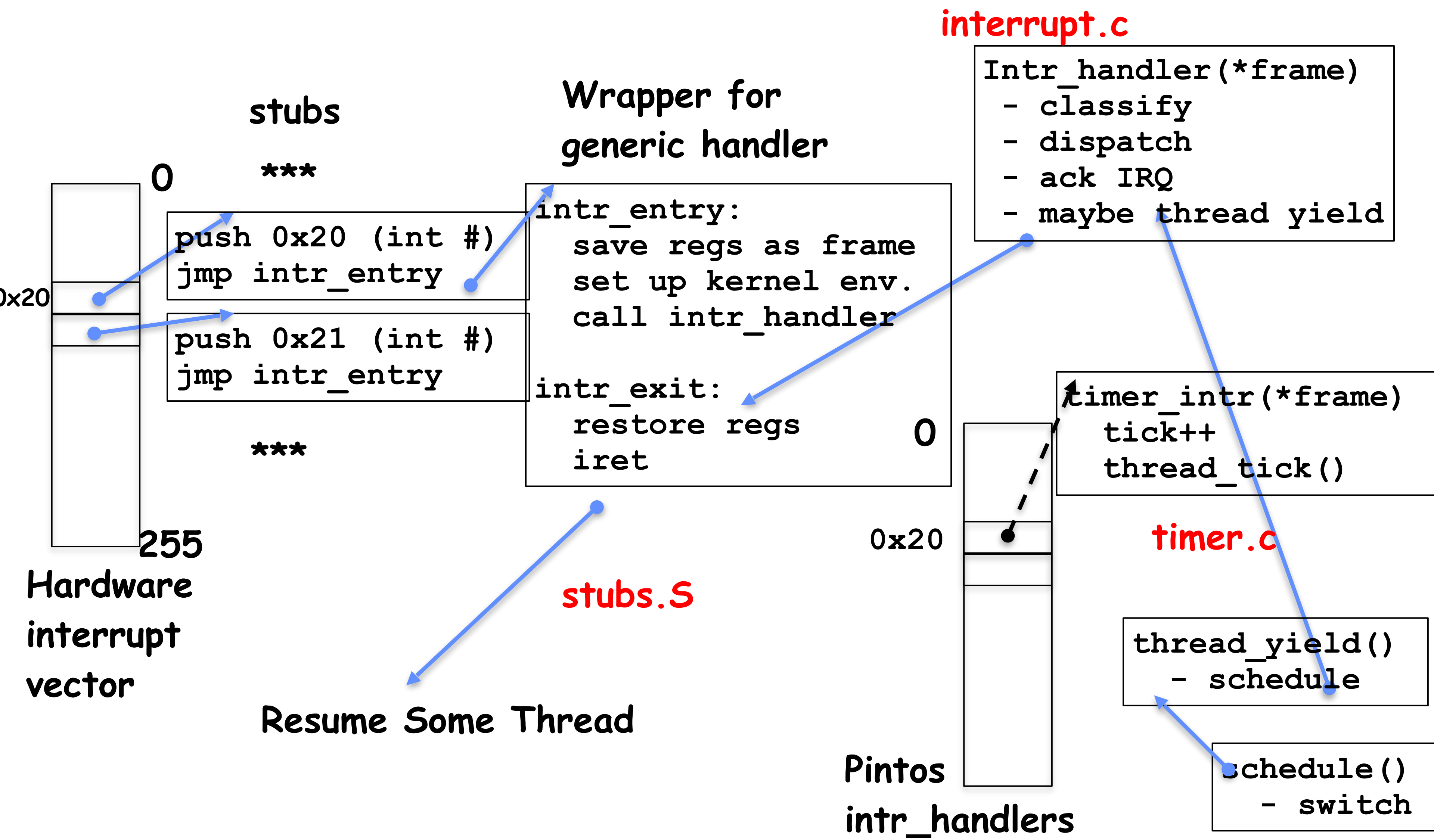
Pintos Interrupt Processing



Timer may trigger thread switch

- thread_tick
  - Updates thread counters
  - If quanta exhausted, sets yield flag
- thread_yield
  - On path to rtn from interrupt
  - Sets current thread back to READY
  - Pushes it back on ready_list
  - Calls schedule to select next thread to run upon iret
- Schedule
  - Selects next thread to run
  - Calls switch_threads to change regs to point to stack for thread to resume
  - Sets its status to RUNNING
  - If user thread, activates the process
  - Returns back to intr_handler

Pintos Return from Processing



Correctness for systems with concurrent threads

- If dispatcher can schedule threads in any way, programs must work under all circumstances
  - Can you test for this?
  - How can you know if your program works?
- Independent Threads:
  - No state shared with other threads
  - Deterministic ⇒ Input state determines results
  - Reproducible ⇒ Can recreate Starting Conditions, I/O
  - Scheduling order doesn't matter (if `switch()` works!!!)
- Cooperating Threads:
  - Shared State between multiple threads
  - Non-deterministic
  - Non-reproducible
- Non-deterministic and Non-reproducible means that bugs can be intermittent
  - Sometimes called "Heisenbugs"

Interactions Complicate Debugging

- Is any program truly independent?
  - Every process shares the file system, OS resources, network, etc
  - Extreme example: buggy device driver causes thread A to crash "independent thread" B
- You probably don't realize how much you depend on reproducibility:
  - Example: Evil C compiler
    - » Modifies files behind your back by inserting errors into C program unless you insert debugging code
  - Example: Debugging statements can overrun stack
- Non-deterministic errors are really difficult to find
  - Example: Memory layout of kernel+user programs
    - » depends on scheduling, which depends on timer/other things
    - » Original UNIX had a bunch of non-deterministic errors

Summary (1 of 2)

- Processes have two parts
  - Threads (Concurrency)
  - Address Spaces (Protection)
- Concurrency accomplished by multiplexing CPU Time:
  - Unloading current thread (PC, registers)
  - Loading new thread (PC, registers)
  - Such context switching may be voluntary (`yield()`, I/O operations) or involuntary (timer, other interrupts)
- Protection accomplished restricting access:
  - Memory mapping isolates processes from each other
  - Dual-mode for isolating I/O, other resources
- Various Textbooks talk about processes
  - When this concerns concurrency, really talking about thread portion of a process
  - When this concerns protection, talking about address space portion of a process

Summary (2 or 2)

- Concurrent threads are a very useful abstraction
  - Allow transparent overlapping of computation and I/O
  - Allow use of parallel processing when available
- Concurrent threads introduce problems when accessing shared data
  - Programs must be insensitive to arbitrary interleavings
  - Without careful design, shared variables can become completely inconsistent
- Important concept: Atomic Operations
  - An operation that runs to completion or not at all
  - These are the primitives on which to construct various synchronization primitives
- Showed how to protect a critical section with only atomic load and store $\Rightarrow$ pretty complex!