CS162
Operating Systems and Systems Programming
Lecture 6

Concurrency (Continued), Thread and Processes

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Motivational Example for Threads

- Consider the following C program:

```
main() {
    ComputePI("pi.txt");
    PrintClassList("classlist.txt");
}
```

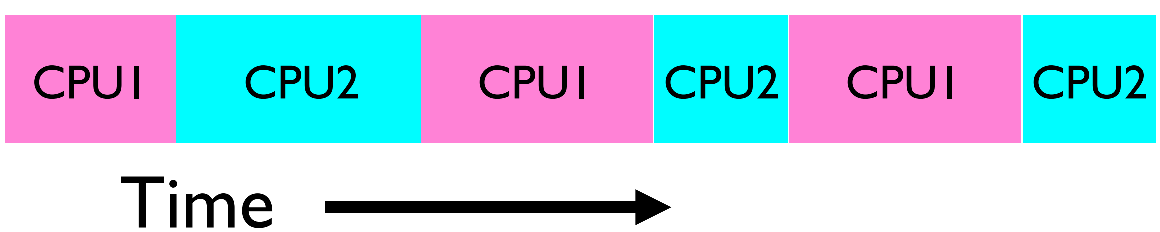
- What is the behavior here?
  – Program would never print out class list
  – Why? **`ComputePI`** would never finish

Use of Threads

- Version of program with Threads (loose syntax):

```
main() {
    ThreadFork(ComputePI, "pi.txt"));
    ThreadFork(PrintClassList, "classlist.txt"));
}
```

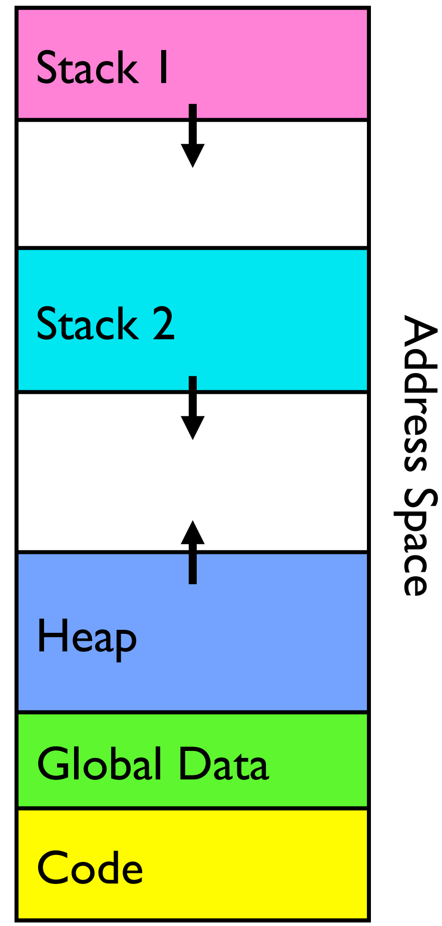
- What does **`ThreadFork()`** do?
  - Start independent thread running given procedure
- What is the behavior here?
  - Now, you would actually see the class list
  - This *should* behave as if there are two separate CPUs



Memory Footprint: Two-Threads

- If we stopped this program and examined it with a debugger, we would see
  – Two sets of CPU registers
  – Two sets of Stacks

- Questions:
  – How do we position stacks relative to each other?
  – What maximum size should we choose for the stacks?
  – What happens if threads violate this?
  – How might you catch violations?



Actual Thread Operations

- `thread_fork(func, args)`
  - Create a new thread to run func(args)
  - Pintos: `thread_create`
- `thread_yield()`
  - Relinquish processor voluntarily
  - Pintos: `thread_yield`
- `thread_join(thread)`
  - In parent, wait for forked thread to exit, then return
  - Pintos: `thread_join`
- `thread_exit()`
  - Quit thread and clean up, wake up joiner if any
  - Pintos: `thread_exit`

- `pThreads`: POSIX standard for thread programming [POSIX.1c, Threads extensions (IEEE Std 1003.1c-1995)]

Dispatch Loop

- Conceptually, the dispatching loop of the operating system looks as follows:

```
Loop {
    RunThread();
    newTCB = ChooseNextThread();
    SaveStateOfCPU(curTCB);
    LoadStateOfCPU(newTCB);
}
```

- This is an *infinite* loop
  – One could argue that this is all that the OS does
- Should we ever exit this loop???
  – When would that be?

Running a thread

Consider first portion: `RunThread()`

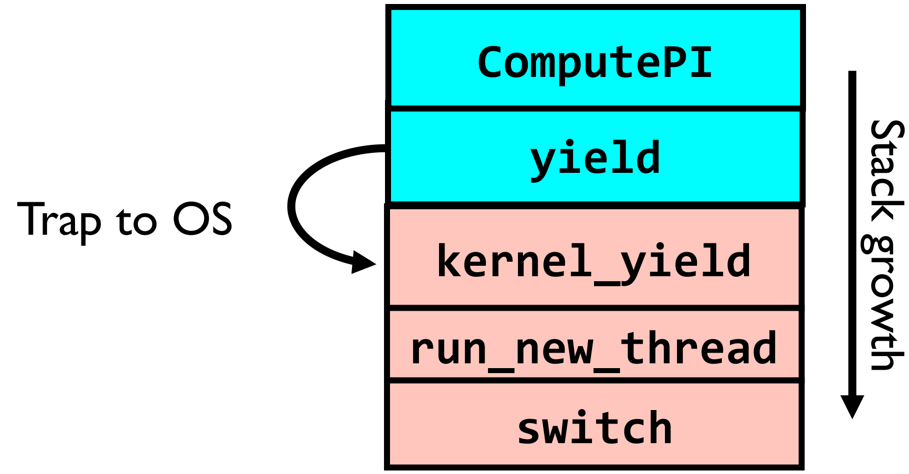
- How do I run a thread?
  - Load its state (registers, PC, stack pointer) into CPU
  - Load environment (virtual memory space, etc)
  - Jump to the PC
- How does the dispatcher get control back?
  - Internal events: thread returns control voluntarily
  - External events: thread gets *preempted*

Internal Events

- Blocking on I/O
  - The act of requesting I/O implicitly yields the CPU
- Waiting on a "signal" from other thread
  - Thread asks to wait and thus yields the CPU
- Thread executes a **`yield()`**
  - Thread volunteers to give up CPU

```
computePI() {
   while(TRUE) {
      ComputeNextDigit();
      yield();
   }
}
```

Stack for Yielding Thread



- How do we run a new thread?

```
run_new_thread() {
   newThread = PickNewThread();
   switch(curThread, newThread);
   ThreadHouseKeeping(); /* Do any cleanup */
}
```

- How does dispatcher switch to a new thread?
  – Save anything next thread may trash: PC, regs, stack pointer
  – Maintain isolation for each thread

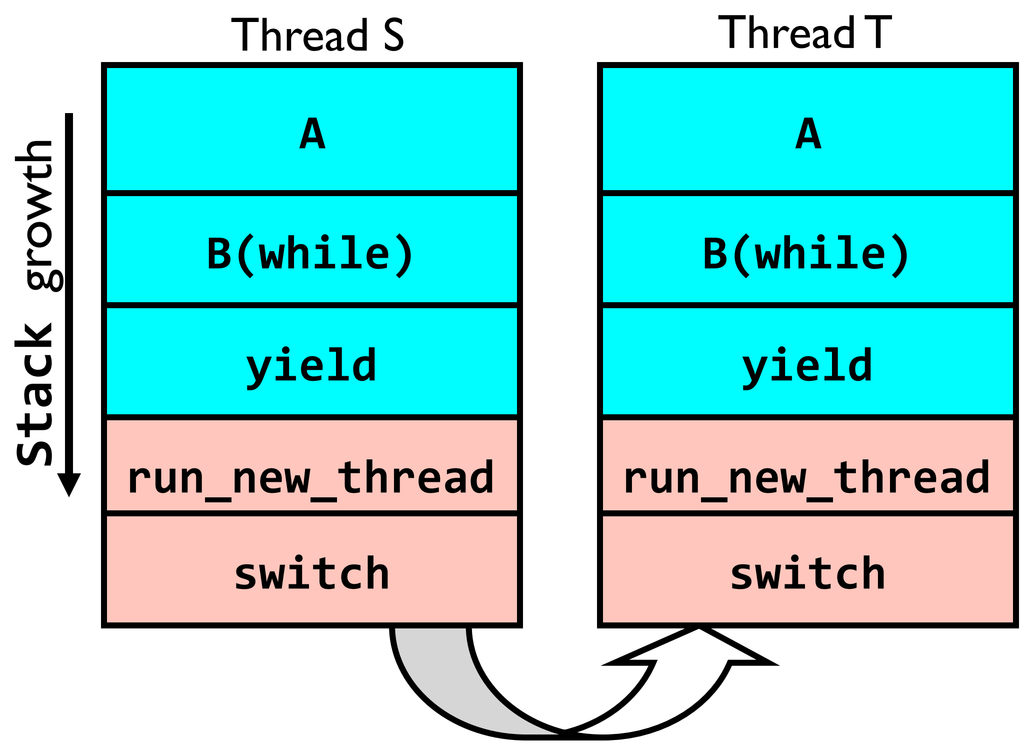
What Do the Stacks Look Like?

- Consider the following code blocks:

```
proc A() {
    B();

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

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



Saving/Restoring state (often called "Context Switch)

```
Switch(tCur,tNew) {
    /* Unload old thread */
    TCB[tCur].regs.r7 = CPU.r7;
          …
    TCB[tCur].regs.r0 = CPU.r0;
    TCB[tCur].regs.sp = CPU.sp;
    TCB[tCur].regs.retpc = CPU.retpc; /*return addr*/

    /* Load and execute new thread */
    CPU.r7 = TCB[tNew].regs.r7;
          …
    CPU.r0 = TCB[tNew].regs.r0;
    CPU.sp = TCB[tNew].regs.sp;
    CPU.retpc = TCB[tNew].regs.retpc;
    return; /* Return to CPU.retpc */
}
```

Switch Details (continued)

- What if you make a mistake in implementing switch?
  - Suppose you forget to save/restore register 32
  - Get intermittent failures depending on when context switch occurred and whether new thread uses register 32
  - System will give wrong result without warning
- Can you devise an exhaustive test to test switch code?
  - No! Too many combinations and inter-leavings
- Cautionary tale:
  - For speed, Topaz kernel saved one instruction in switch()
  - Carefully documented! Only works as long as kernel size < 1MB
  - What happened?
    - » Time passed, People forgot
    - » Later, they added features to kernel (no one removes features!)
    - » Very weird behavior started happening
  - Moral of story: Design for simplicity

Some Numbers

- Frequency of performing context switches: 10-100ms
- Context switch time in Linux: 3-4 μsecs (Intel i7 & E5)
  - Thread switching faster than process switching (100 ns)
  - But switching across cores ~2x more expensive than within-core
- Context switch time increases sharply with size of working set*
  - Can increase 100x or more

  *The working set is subset of memory used by process in a time window

- Moral: context switching depends mostly on cache limits and the process or thread's hunger for memory

Some Numbers

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

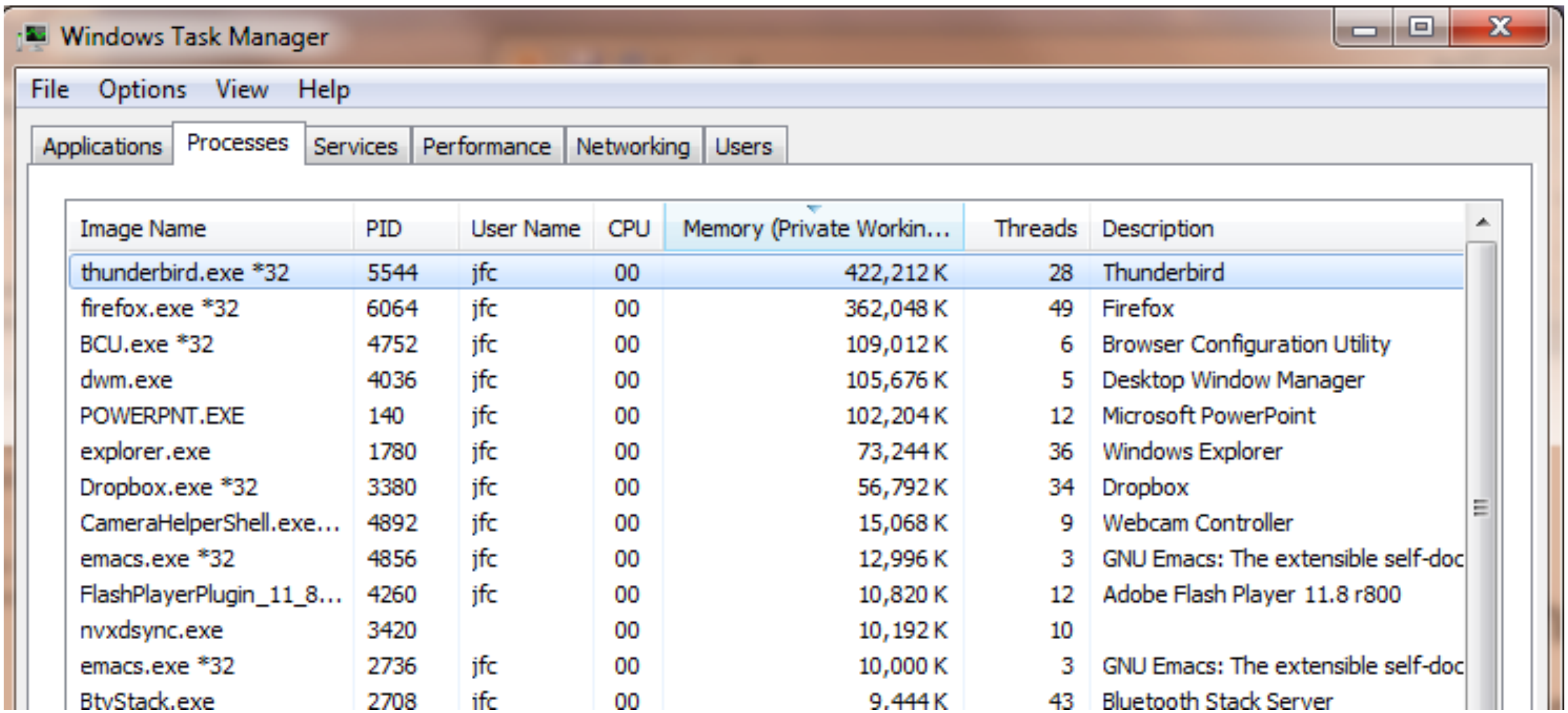
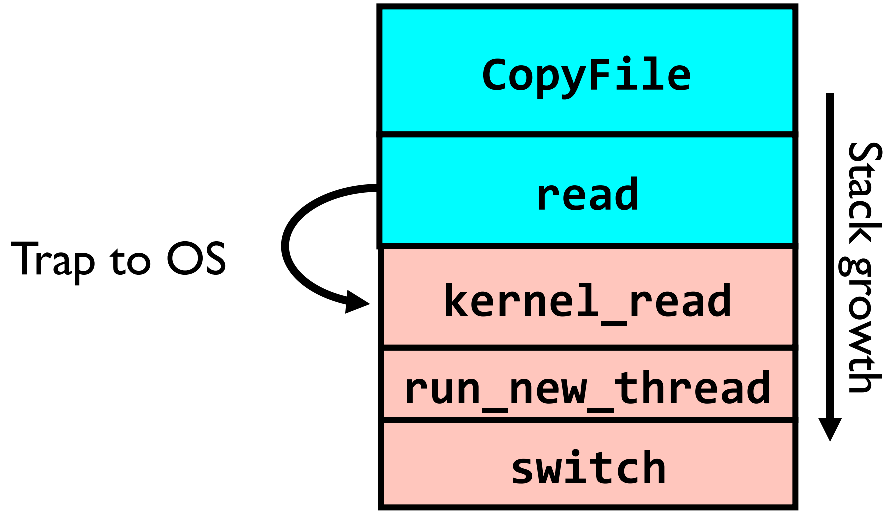


Image Name	PID	User Name	CPU	Memory (Private Workin...	Threads	Description
thunderbird.exe *32	5544	jfc	00	422,212 K	28	Thunderbird
firefox.exe *32	6064	jfc	00	362,048 K	49	Firefox
BCU.exe *32	4752	jfc	00	109,012 K	6	Browser Configuration Utility
dwm.exe	4036	jfc	00	105,676 K	5	Desktop Window Manager
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	12,996 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	2708	jfc	00	9,444 K	43	Bluetooth Stack Server

What happens when thread blocks on I/O?



- What happens when a thread requests a block of data from the file system?
  – User code invokes a system call
  – Read operation is initiated
  – Run new thread/switch
- Thread communication similar
  – Wait for Signal/Join
  – Networking

External Events

- What happens if thread never does any I/O, never waits, and never yields control?
  - Could the `ComputePI` program grab all resources and never release the processor?
    - » What if it didn't print to console?
  - Must find way that dispatcher can regain control!
- Answer: utilize external events
  - Interrupts: signals from hardware or software that stop the running code and jump to kernel
  - Timer: like an alarm clock that goes off every some many milliseconds
- If we make sure that external events occur frequently enough, can ensure dispatcher runs

Example: Network Interrupt

External Interrupt

```
        ...
add     $r1,$r2,$r3
subi    $r4,$r1,#4
slli    $r4,$r4,#2
        ...
```

Pipeline Flush

```
        ...
lw      $r2,0($r4)
lw      $r3,4($r4)
add     $r2,$r2,$r3
sw      8($r4),$r2
        ...
```

PC saved
Disable All Ints
Supervisor Mode

Restore PC
User Mode

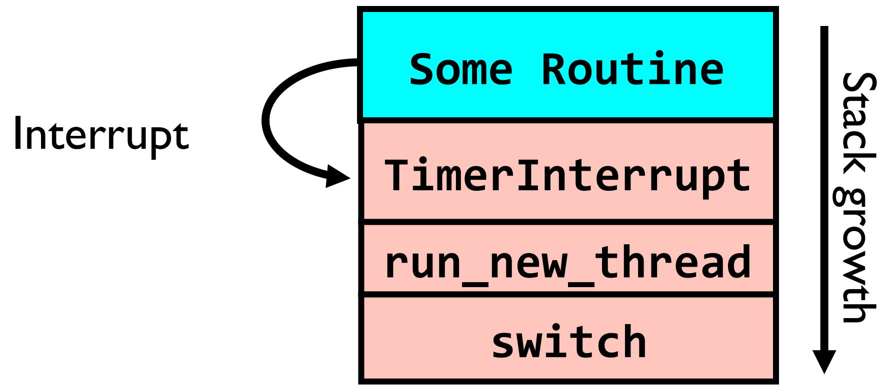
"Interrupt Handler"

```
Raise priority
Reenable All Ints
Save registers
Dispatch to Handler
  ...
Transfer Network Packet
from hardware
to Kernel Buffers
  ...
Restore registers
Clear current Int
Disable All Ints
Restore priority
RTI
```

- An interrupt is a hardware-invoked context switch
  - No separate step to choose what to run next
  - Always run the interrupt handler immediately

Use of Timer Interrupt to Return Control

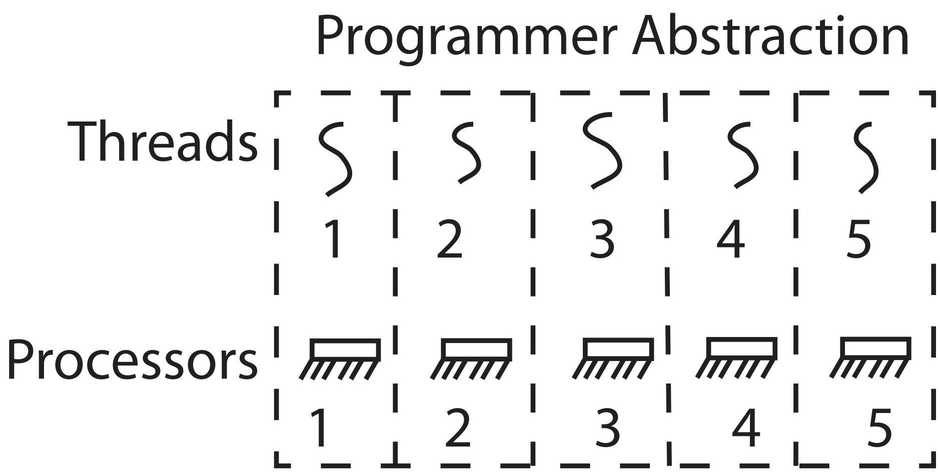
- Solution to our dispatcher problem
  – Use the timer interrupt to force scheduling decisions



- Timer Interrupt routine:

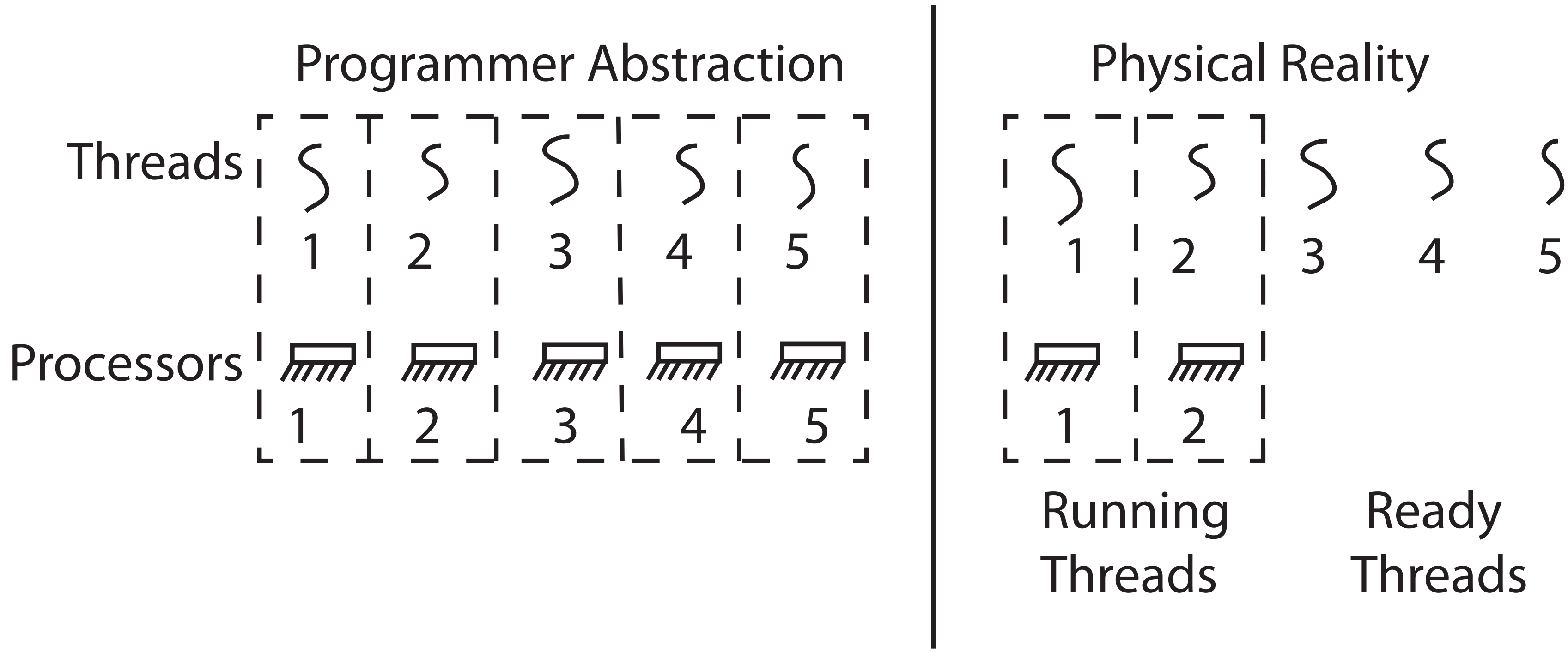
```
TimerInterrupt() {
   DoPeriodicHouseKeeping();
   run_new_thread();
}
```

Thread Abstraction



- Illusion: Infinite number of processors

Thread Abstraction



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

Programmer vs. Processor View

Programmer's View	Possible Execution #1
.	.
.	.
.	.
x = x + 1;	x = x + 1;
y = y + x;	y = y + x;
z = x +5y;	z = x + 5y;
.	.
.	.
.	.

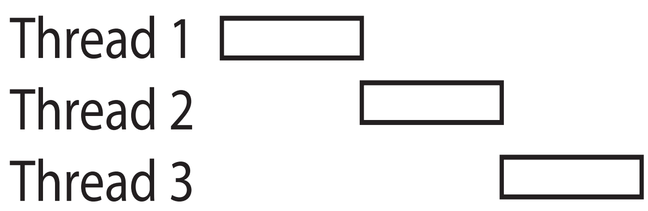
Programmer vs. Processor View

Programmer's View	Possible Execution #1	Possible Execution #2
.	.	.
.	.	.
.	.	.
x = x + 1;	x = x + 1;	x = x + 1
y = y + x;	y = y + x;	....
z = x +5y;	z = x + 5y;	thread is suspended
.	.	other thread(s) run
.	.	thread is resumed
.	.	....
		y = y + x
		z = x + 5y

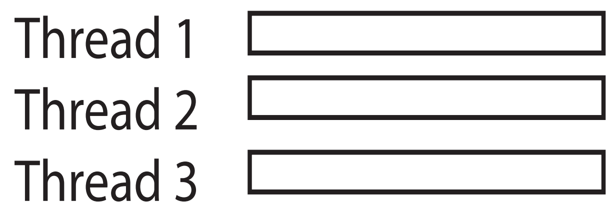
Programmer vs. Processor View

Programmer's View	Possible Execution #1	Possible Execution #2	Possible Execution #3
.	.	.	.
.	.	.	.
.	.	.	.
$x = x + 1;$	$x = x + 1;$	$x = x + 1$	$x = x + 1$
$y = y + x;$	$y = y + x;$	....	$y = y + x$
$z = x + 5y;$	$z = x + 5y;$	thread is suspended	....
.	.	other thread(s) run	thread is suspended
.	.	thread is resumed	other thread(s) run
.	.	....	thread is resumed
		$y = y + x$	....
		$z = x + 5y$	$z = x + 5y$

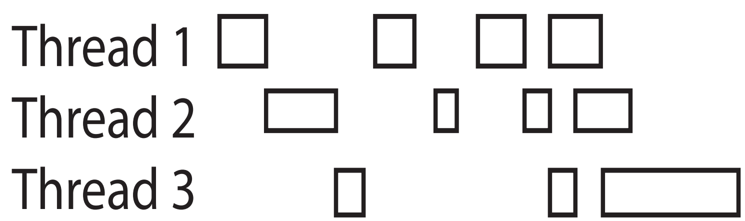
Possible Executions



a) One execution

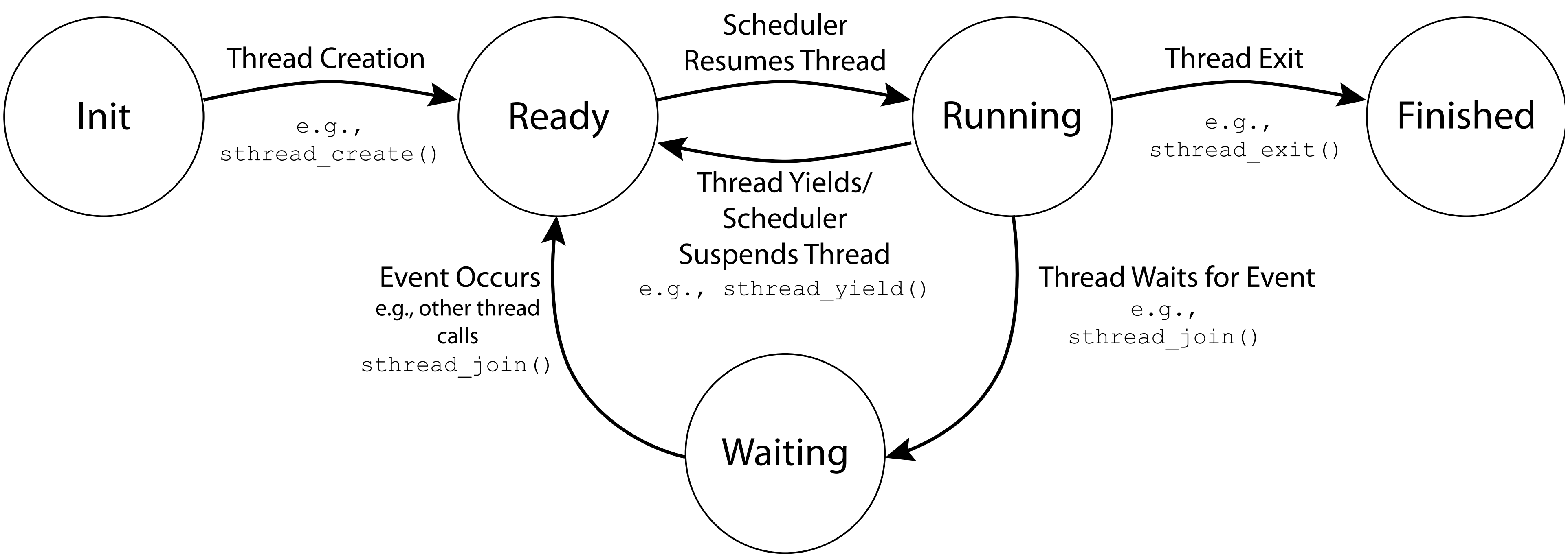


b) Another execution



c) Another execution

Thread Lifecycle



Administrivia

- Group TA Preference Deadline tonight at 11:59:59pm
- Your section is your home for CS162
  - The TA needs to get to know you to judge participation
  - All design reviews will be conducted by your TA
  - You can attend alternate section by same TA, but try to keep the amount of such cross-section movement to a minimum
- Project #1: Starts today!
- Ion will be away Tuesday and Wednesday
  - Nathan will teach on Wednesday
  - Ion's Wednesday OH cancelled

Per Thread Descriptor (Kernel Supported Threads)

- Each Thread has a *Thread Control Block* (TCB)
  - Execution State: CPU registers, program counter (PC), pointer to stack (SP)
  - Scheduling info: state, priority, CPU time
  - Various Pointers (for implementing scheduling queues)
  - Pointer to enclosing process (PCB) – user threads
  - Etc (add stuff as you find a need)

- OS Keeps track of TCBs in "kernel memory"
  - In Array, or Linked List, or …
  - I/O state (file descriptors, network connections, etc)

ThreadFork(): Create a New Thread

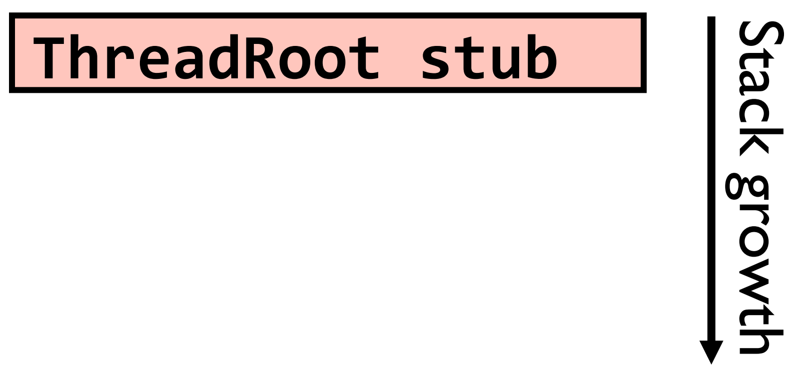
- `ThreadFork()` is a user-level procedure that creates a new thread and places it on ready queue

- Arguments to `ThreadFork()`
  - Pointer to application routine (`fcnPtr`)
  - Pointer to array of arguments (`fcnArgPtr`)
  - Size of stack to allocate

- Implementation
  - Sanity Check arguments
  - Enter Kernel-mode and Sanity Check arguments again
  - Allocate new Stack and TCB
  - Initialize TCB and place on ready list (Runnable)

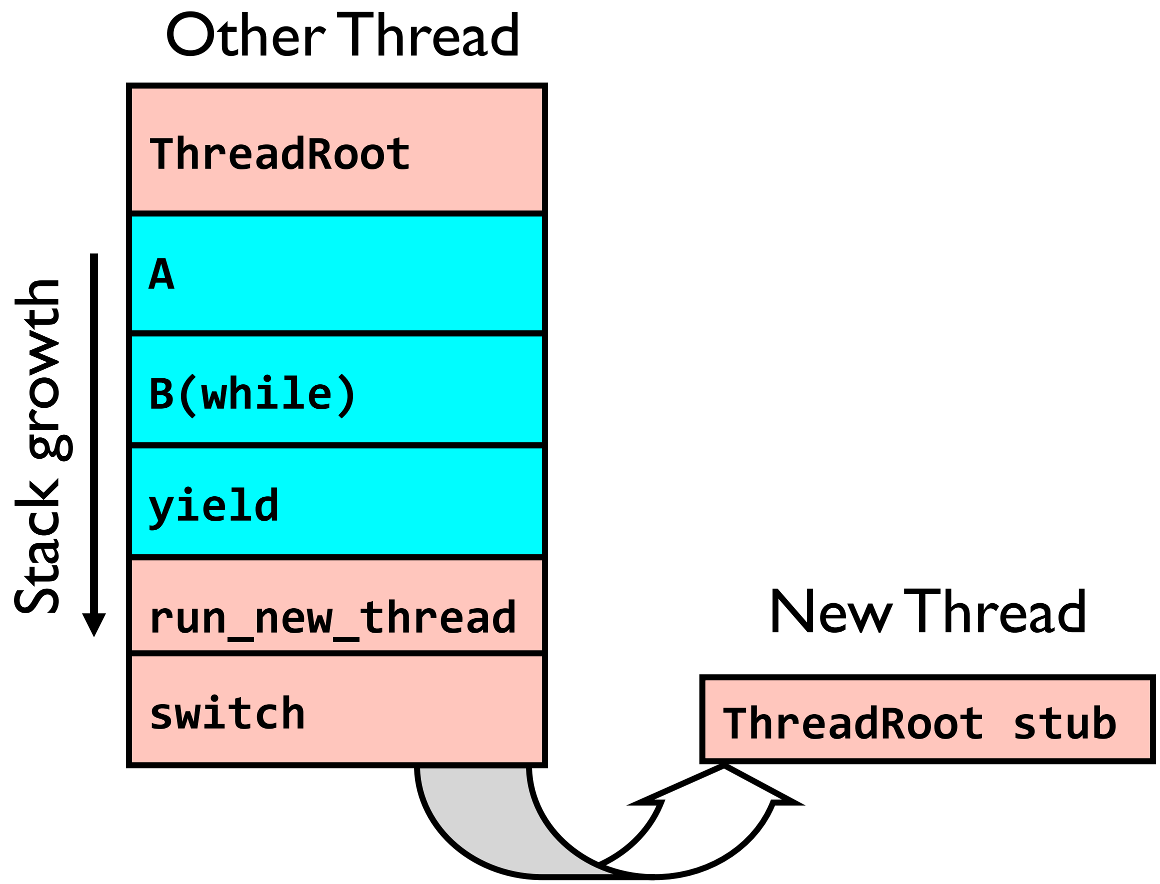
How do we initialize TCB and Stack?

- Initialize Register fields of TCB
  - Stack pointer made to point at stack
  - PC return address ⇒ OS (asm) routine `ThreadRoot()`
  - Two arg registers (a0 and a1) initialized to `fcnPtr` and `fcnArgPtr`, respectively
- Initialize stack data?
  - No. Important part of stack frame is in registers (ra)
  - Think of stack frame as just before body of `ThreadRoot()` really gets started



Initial Stack

How does Thread get started?



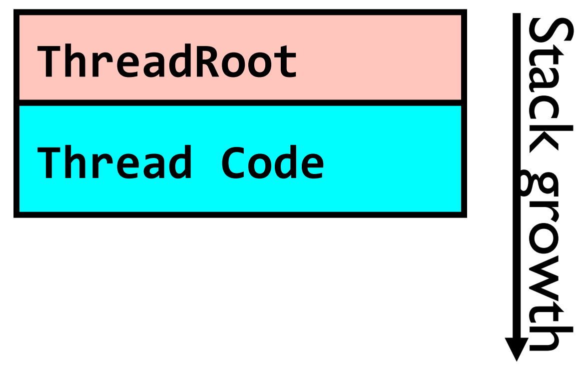
- Eventually, `run_new_thread()` will select this TCB and return into beginning of `ThreadRoot()`
  - This really starts the new thread

What does ThreadRoot() look like?

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

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

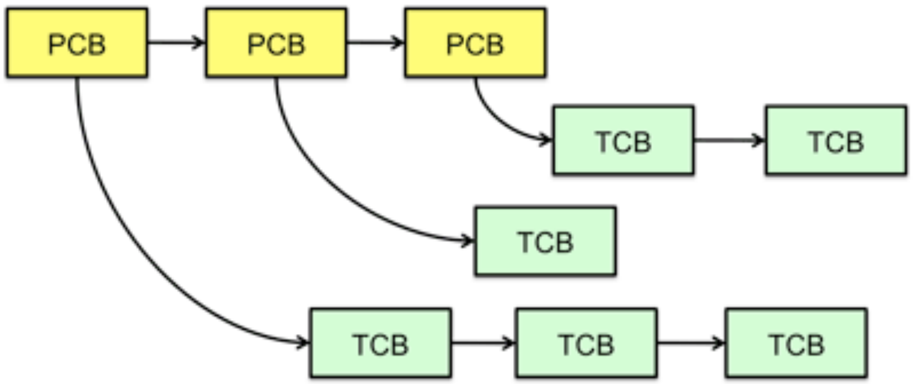
- Startup Housekeeping
  - Includes things like recording start time of thread
  - Other Statistics
- Stack will grow and shrink with execution of thread
- Final return from thread returns into `ThreadRoot()` which calls `ThreadFinish()`
  - `ThreadFinish()` wake up sleeping threads



Running Stack

Multithreaded Processes

- Process Control Block (PCBs) points to multiple Thread Control Blocks (TCBs):



- Switching threads within a block is a simple thread switch
- Switching threads across blocks requires changes to memory and I/O address tables

Examples multithreaded programs

- Embedded systems
  - Elevators, planes, medical systems, smart watches
  - 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)

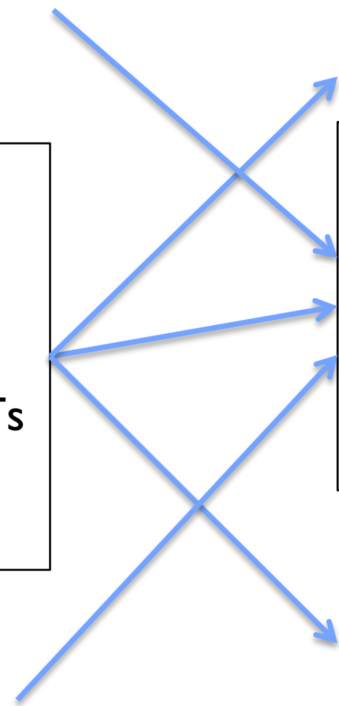
- Network servers
  - Concurrent requests from network
  - Again, single program, multiple concurrent operations
  - File server, Web server, and airline reservation systems

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

- Some multiprocessors are actually uniprogrammed:
  - Multiple threads in one address space but one program at a time

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

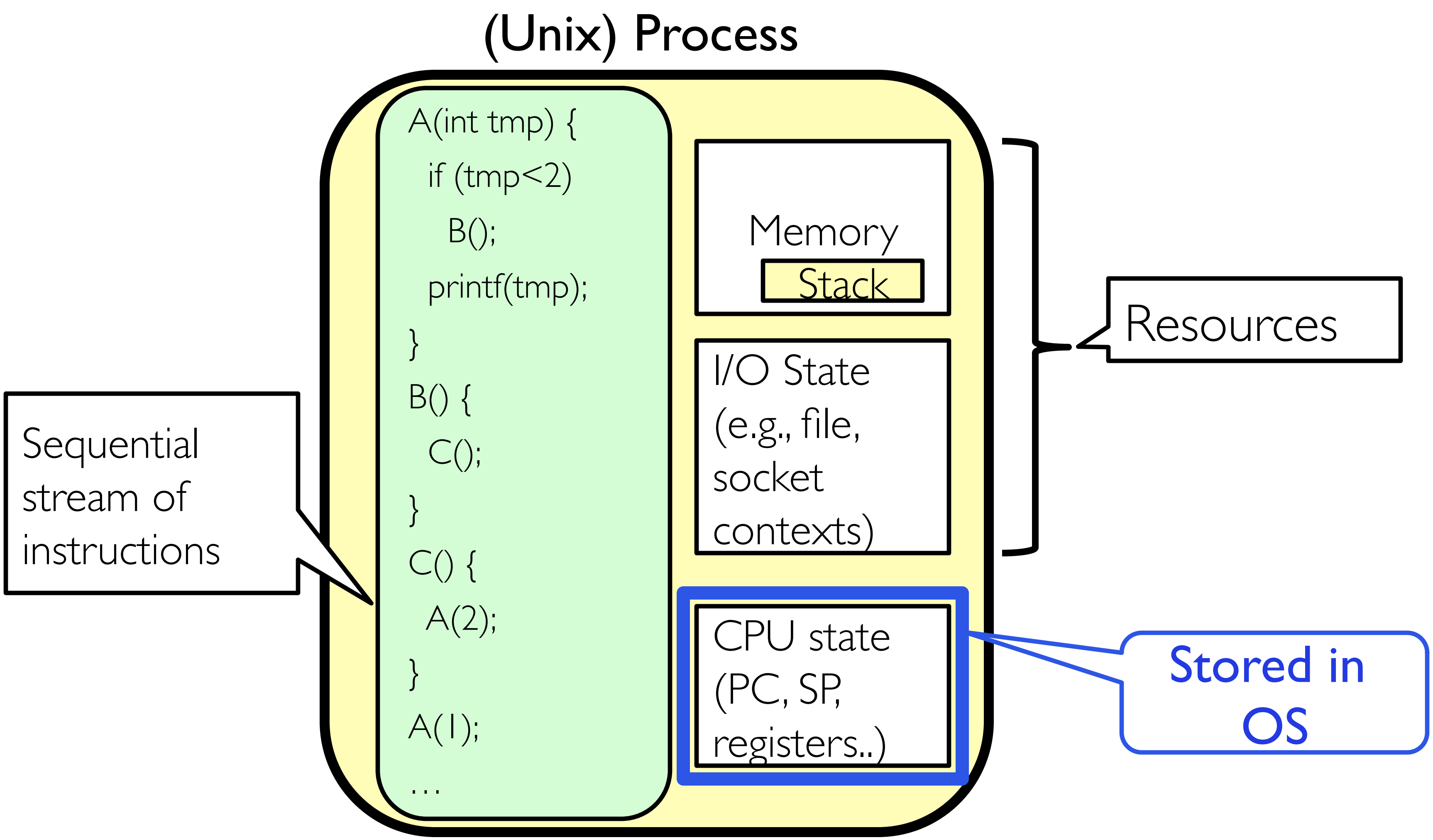


Web Server
- fork process for each client connection
- thread to get request and issue response
- fork threads to read data, access DB, etc
- join and respond

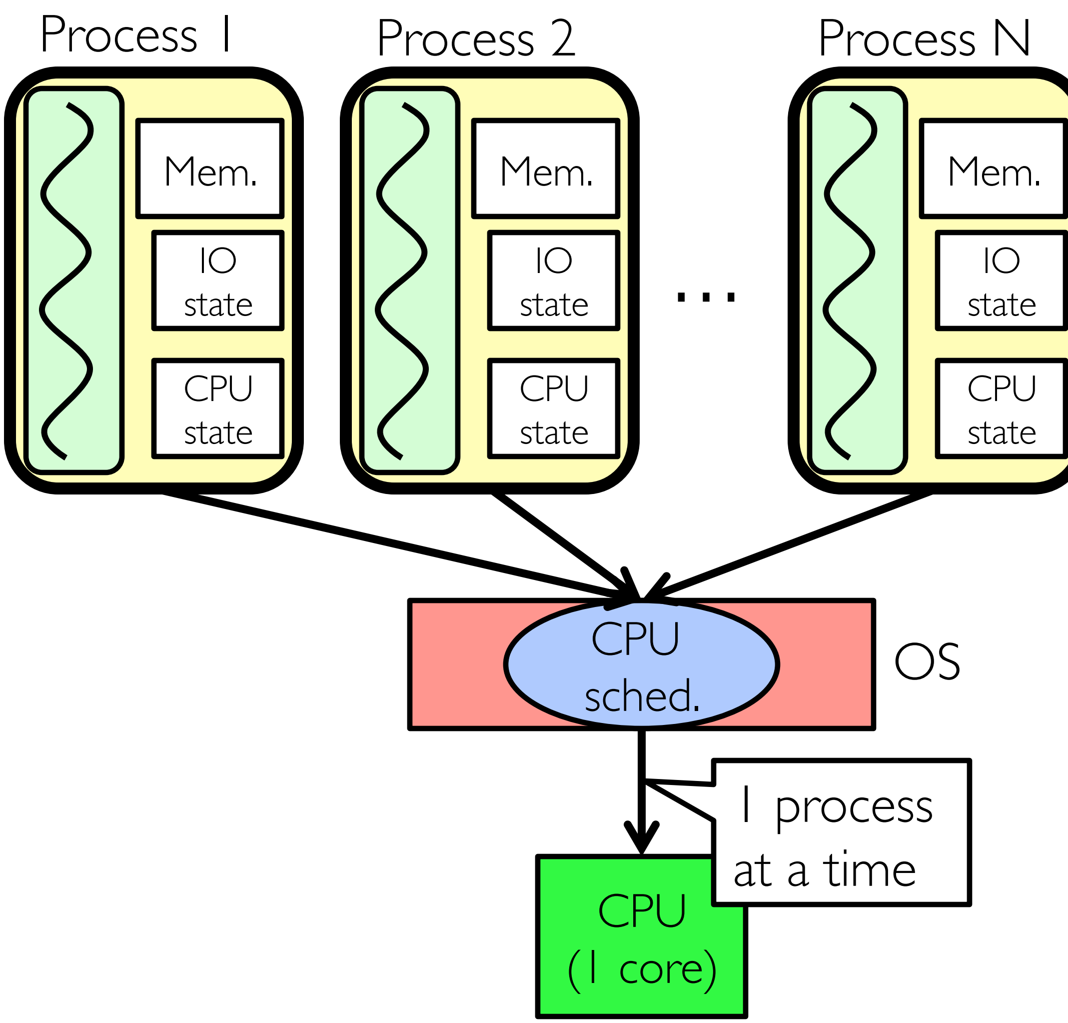
Kernel Use Cases

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

Putting it Together: Process

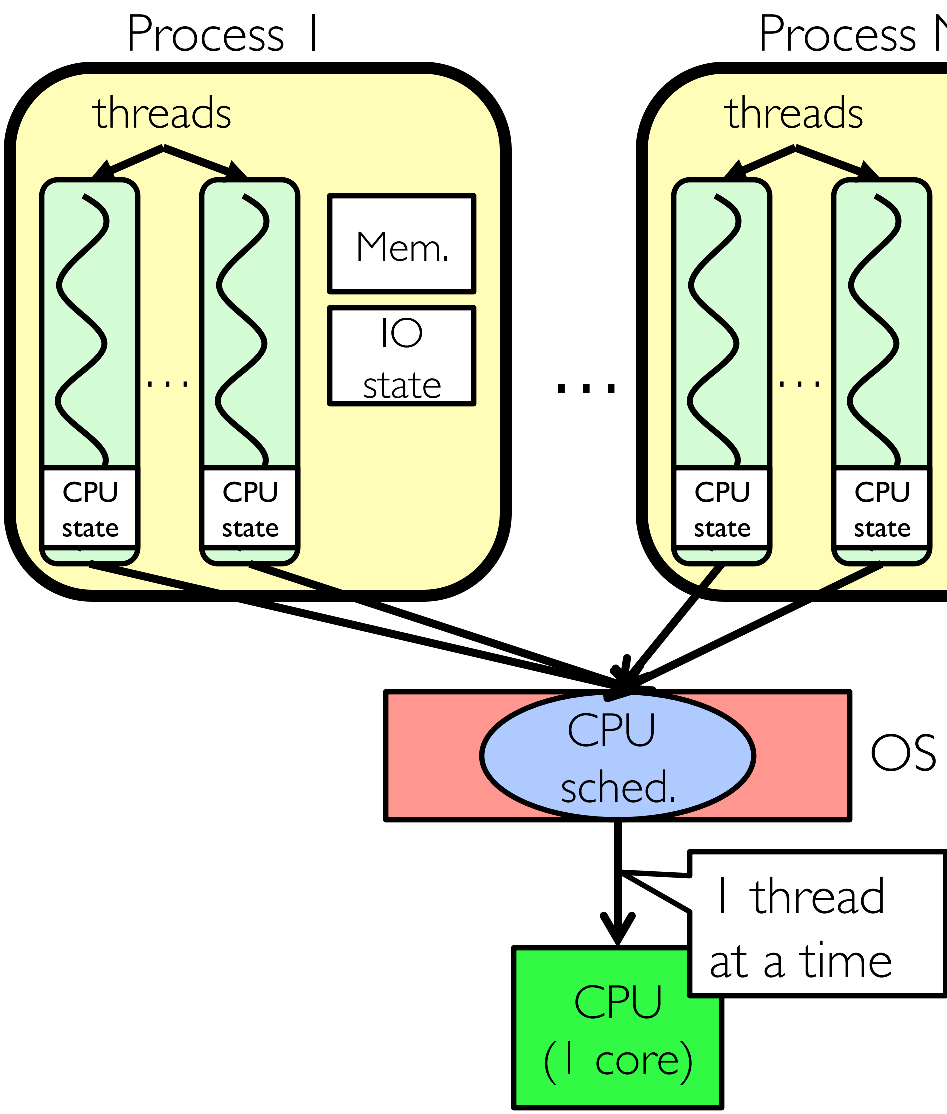


Putting it Together: Processes



- 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



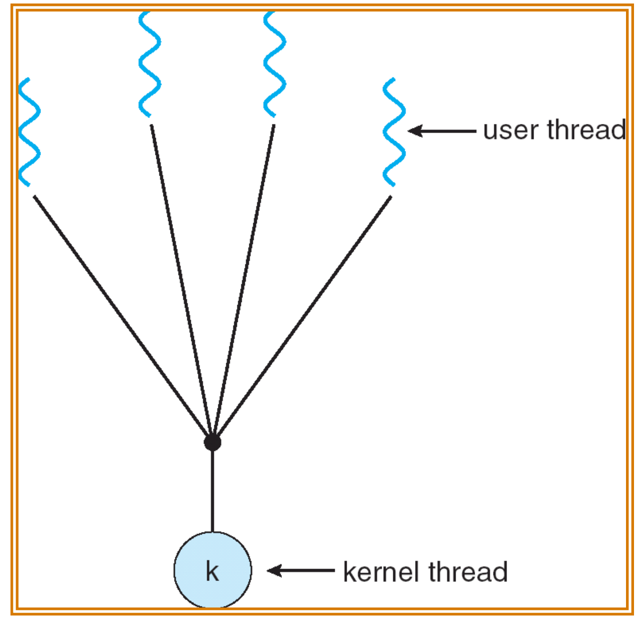
- Switch overhead: medium
  - Kernel entry: *low(ish)*
  - CPU state: *low*
- Thread creation: medium
- Protection
  - CPU: *yes*
  - Memory/IO: No
- Sharing overhead: *low(ish)* (thread switch overhead low)

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-Mode Threads

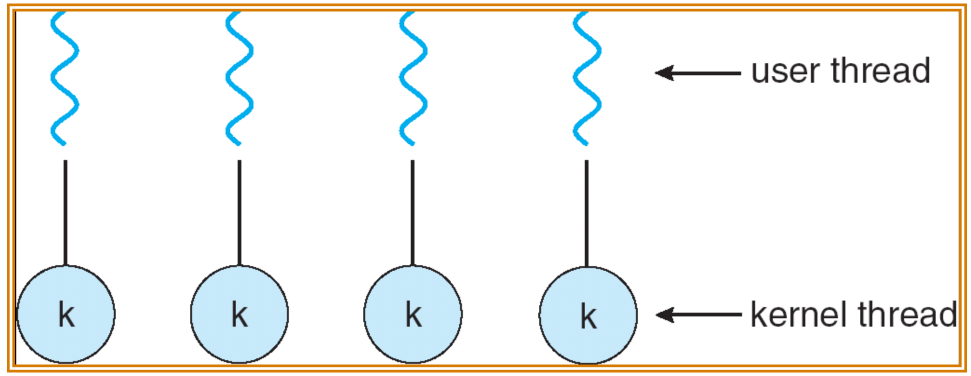
- Lighter weight option:
  - User program provides scheduler and thread package
  - May have several user threads per kernel thread
  - User threads may be scheduled non-preemptively relative to each other (only switch on yield())
  - Cheap

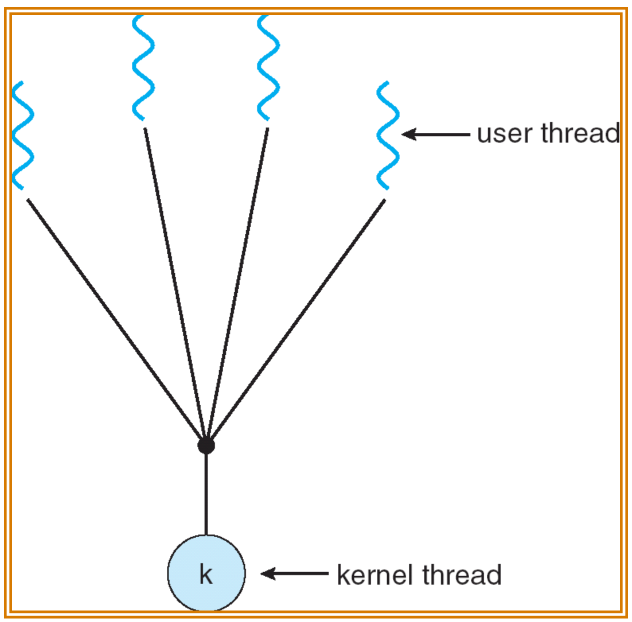


- Downside of user threads:
  - When one thread blocks on I/O, all threads block
  - Kernel cannot adjust scheduling among all threads
  - Option: *Scheduler Activations*
    - » Have kernel inform user level when thread blocks…

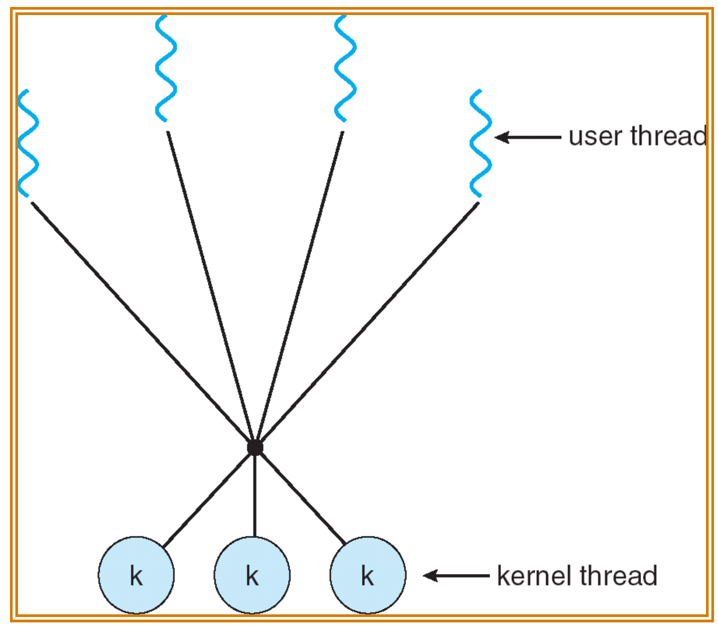
Some Threading Models

Simple One-to-One Threading Model





Many-to-One

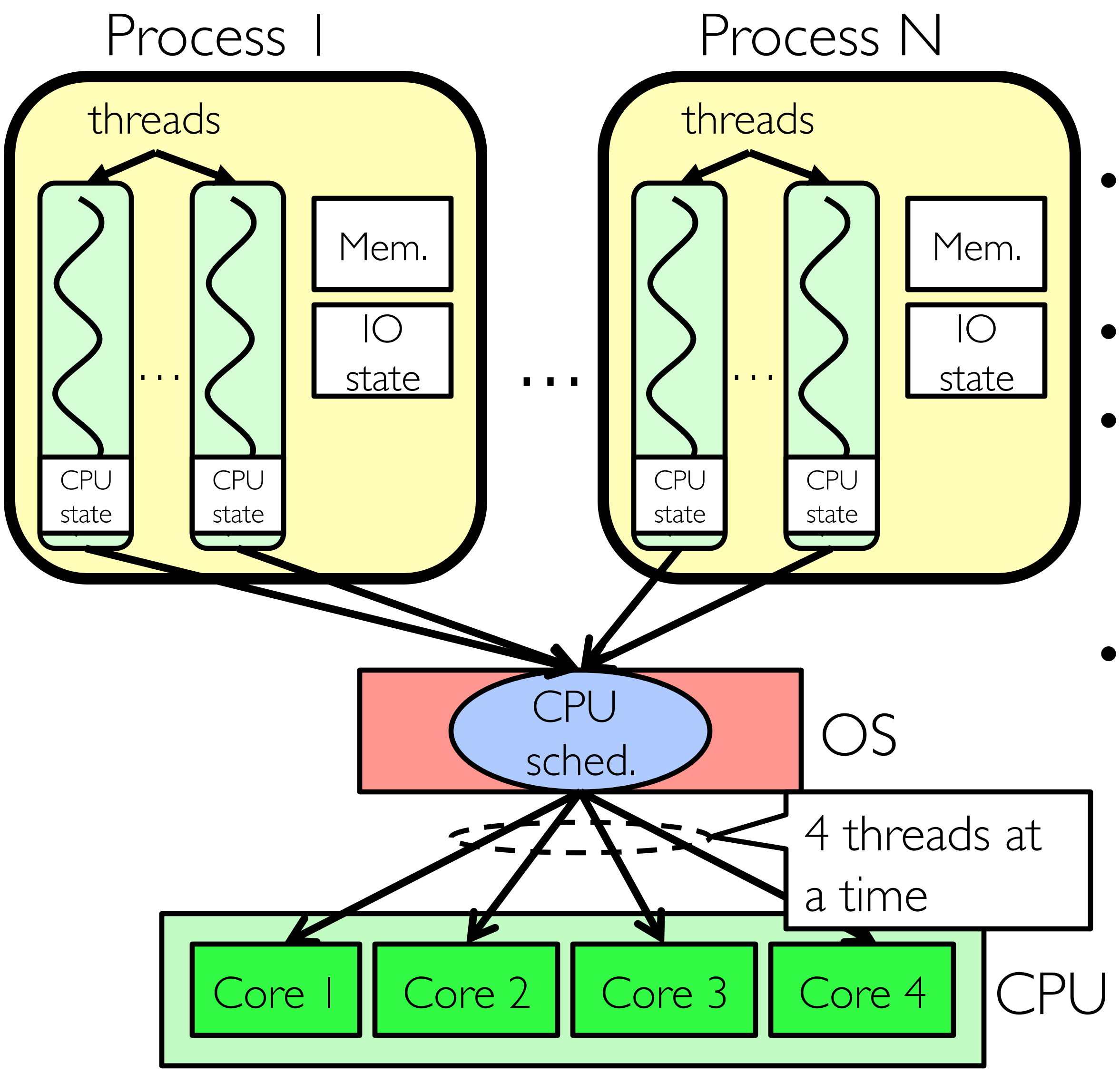


Many-to-Many

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

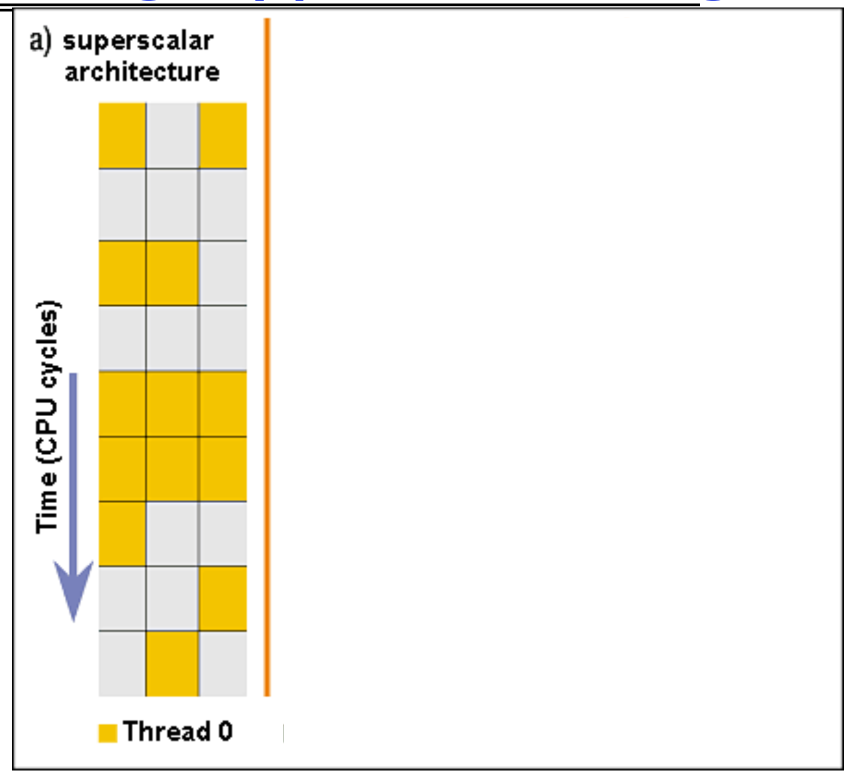
Putting it Together: Multi-Cores



- 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!)

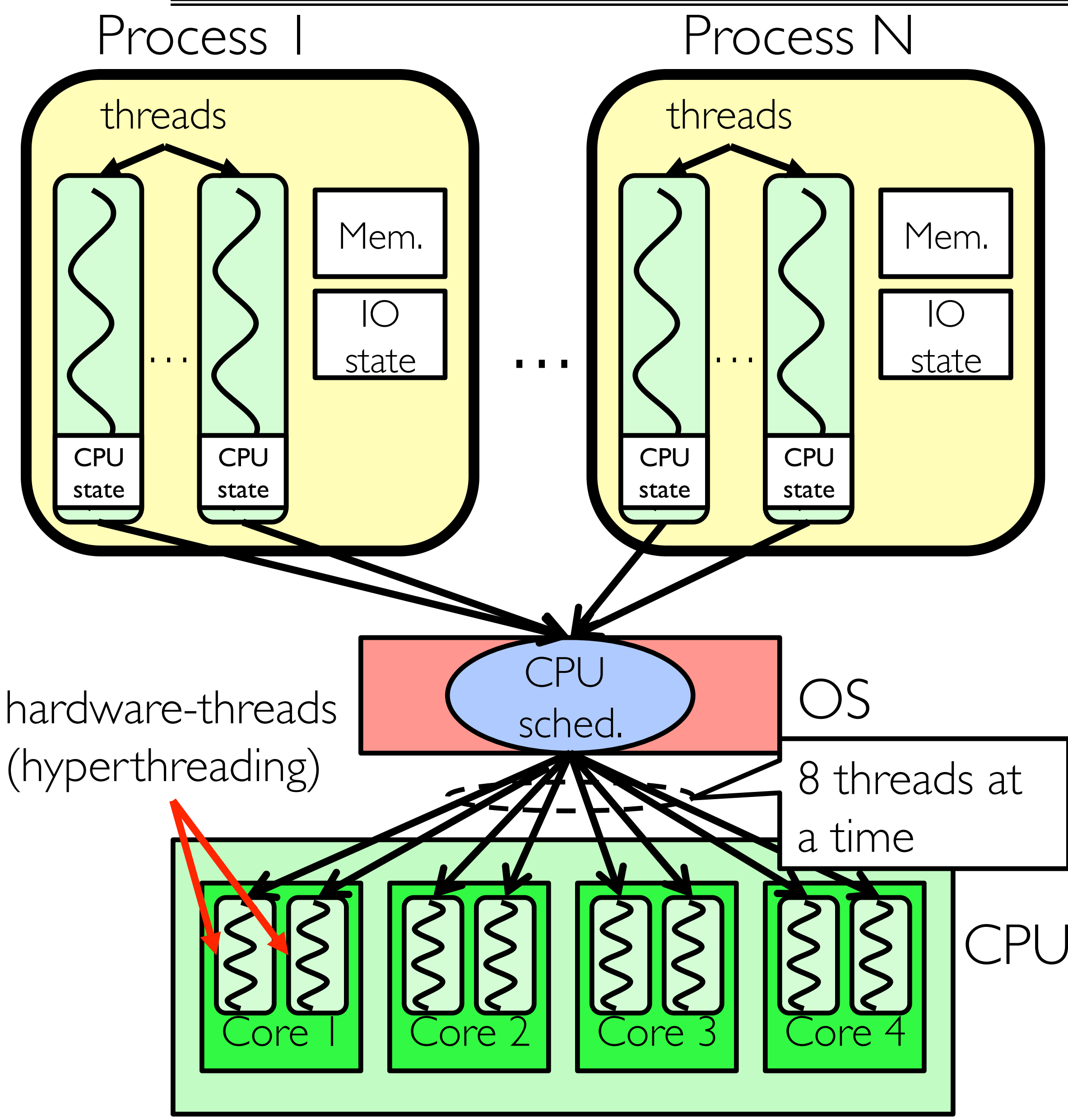
Simultaneous MultiThreading/Hyperthreading

- Hardware technique
  - Superscalar processors can execute multiple instructions that are independent
  - Hyperthreading duplicates register state to make a second "thread," allowing more instructions to run
- Can schedule each thread as if were separate CPU
  - But, sub-linear speedup!
- Original called "Simultaneous Multithreading"
  - http://www.cs.washington.edu/research/smt/index.html
  - Intel, SPARC, Power (IBM)
  - A virtual core on AWS' EC2 is basically a hyperthread



Colored blocks show instructions executed

Putting it Together: Hyper-Threading



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

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 10 Win NT to XP, Solaris, HP-UX, OS X

- Most operating systems have either
  - One or many address spaces
  - One or many threads per address space

Summary

- Processes have two parts
  - Threads (Concurrency)
  - Address Spaces (Protection)
- 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
- 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