CSC 112: Computer Operating Systems
Lecture 6

Synchronization 1: Concurrency and Mutual Exclusion

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Acknowledgement: Lecture slides based on UC Berkeley CS 162: Operating Systems and System Programming

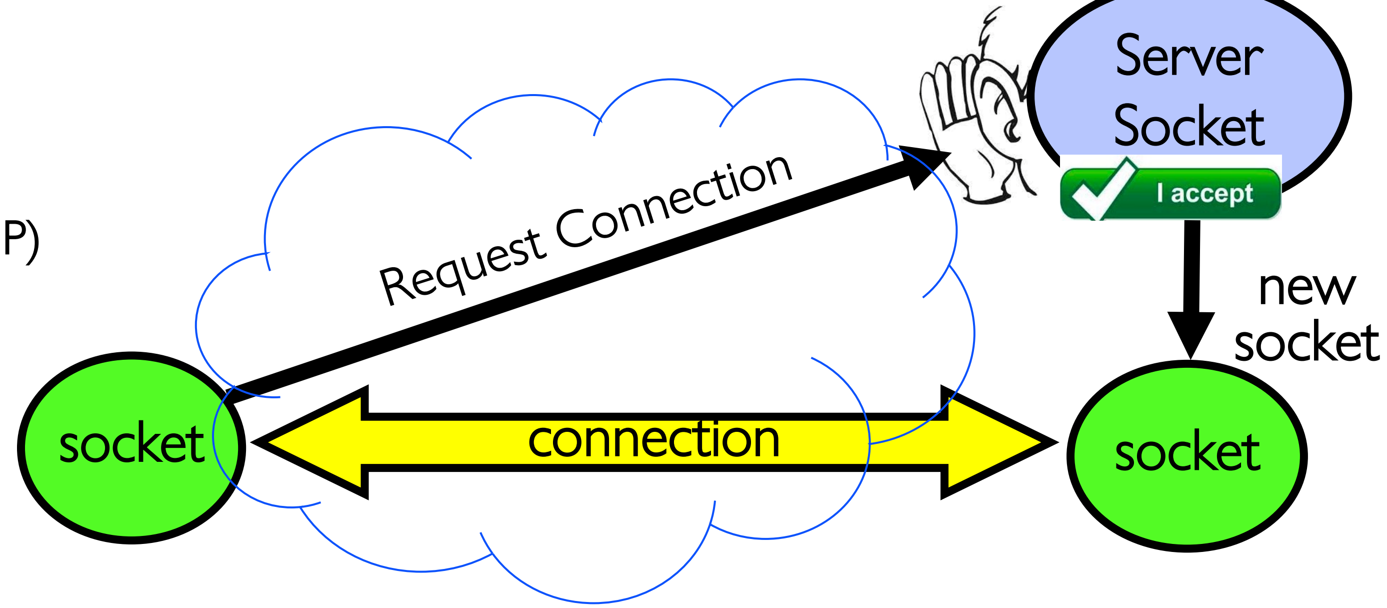
Recall: Connection Setup over TCP/IP

Client Side

Connection request:
1. Client IP addr
2. Client Port
3. Protocol (TCP/IP)

Server Side

Server Listening:
1. Server IP addr
2. well-known port,
3. Protocol (TCP/IP)



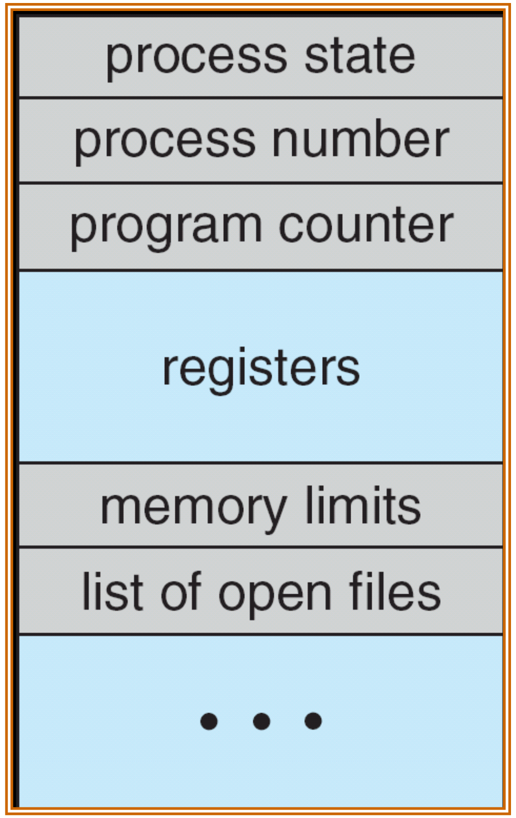
- 5-Tuple identifies each connection:
  1. Source IP Address
  2. Destination IP Address
  3. Source Port Number
  4. Destination Port Number
  5. Protocol (always TCP here)
- Often, Client Port “randomly” assigned
  – Done by OS during client socket setup
- Server Port often “well known”
  – 80 (web), 443 (secure web), 25 (sendmail), etc
  – Well-known ports from 0—1023

Recall: Server Protocol (v3)

```
// Socket setup code elided…
listen(server_socket, MAX_QUEUE);
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);
    exit(0);
  } else {
    close(conn_socket);
    // wait(NULL);
  }
}
close(server_socket);
```

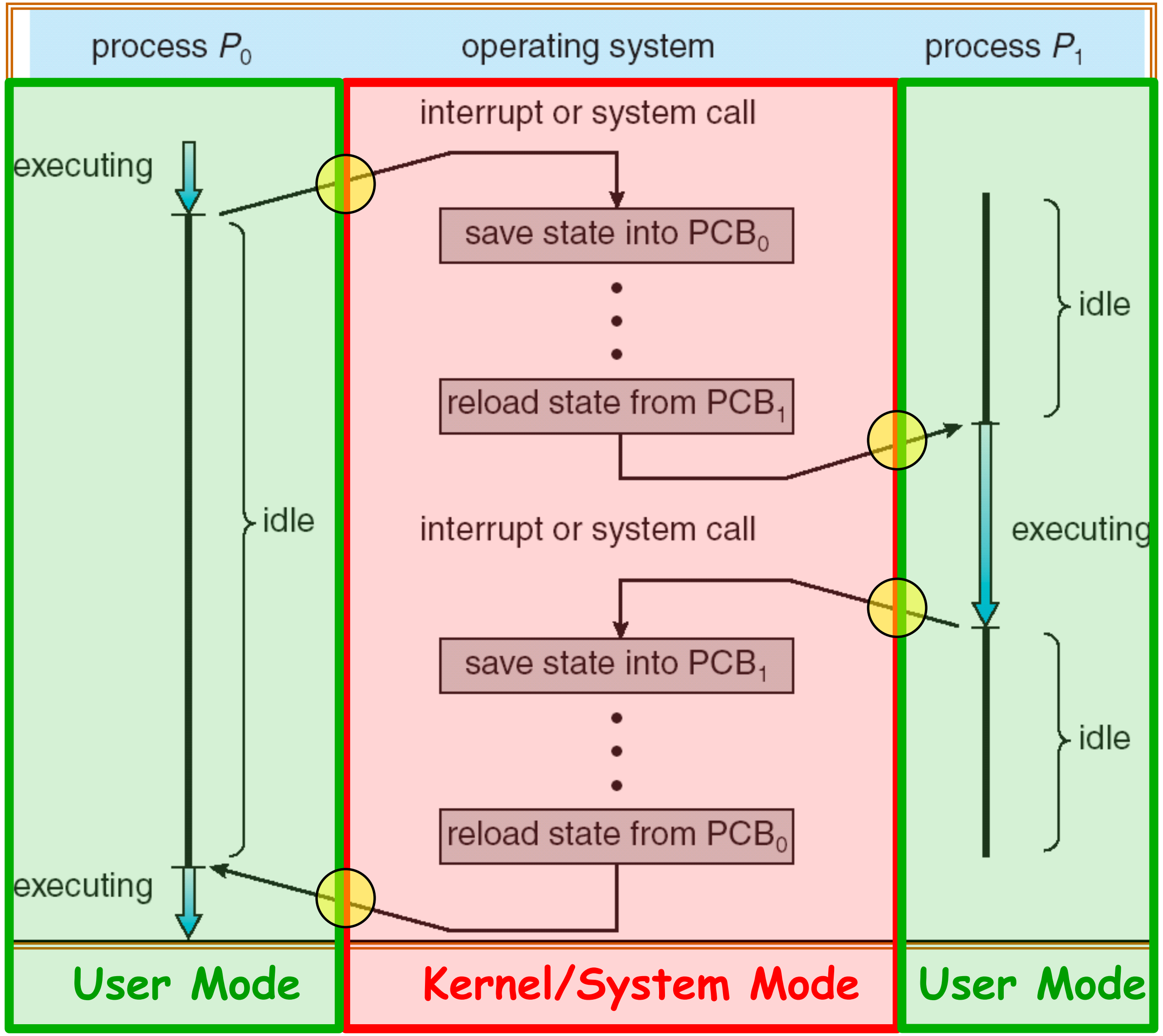
Recall: Multiplexing Processes: The Process Control Block

- Kernel represents each process as a process control block (PCB)
  - Status (running, ready, blocked, …)
  - Register state (when not ready)
  - Process ID (PID), User, Executable, Priority, …
  - Execution time, …
  - Memory space, translation, …
- Kernel *Scheduler* maintains a data structure containing the PCBs
  - Give out CPU to different processes
  - This is a Policy Decision
- Give out non-CPU resources
  - Memory/IO
  - Another policy decision

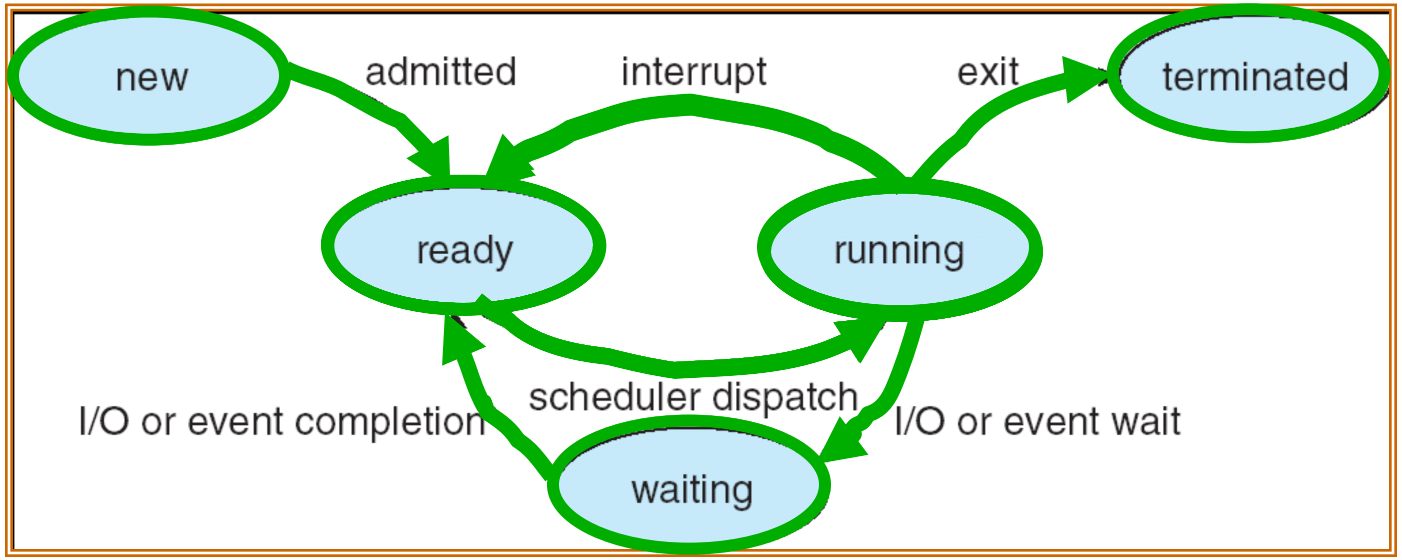


Process Control Block

Recall: CPU Switch From Process A to Process B

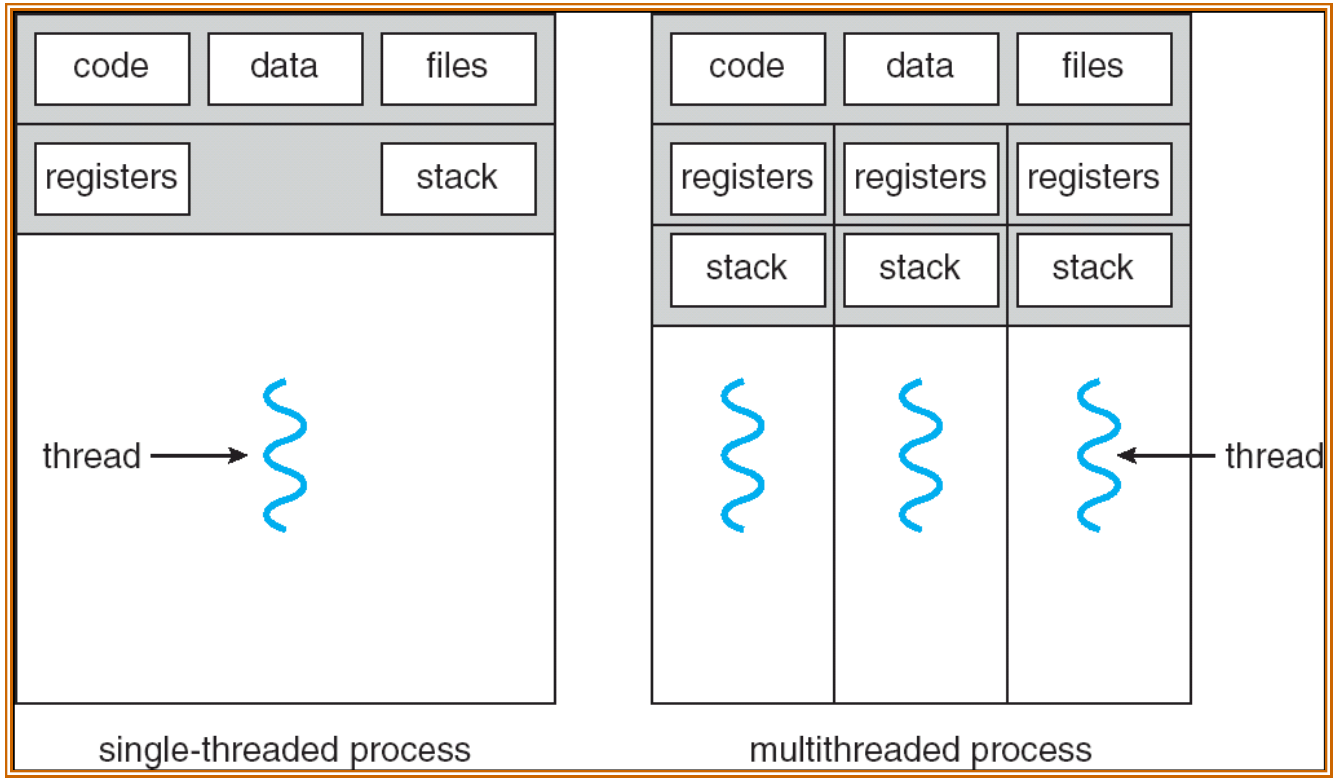


Recall: Lifecycle of a Process or Thread



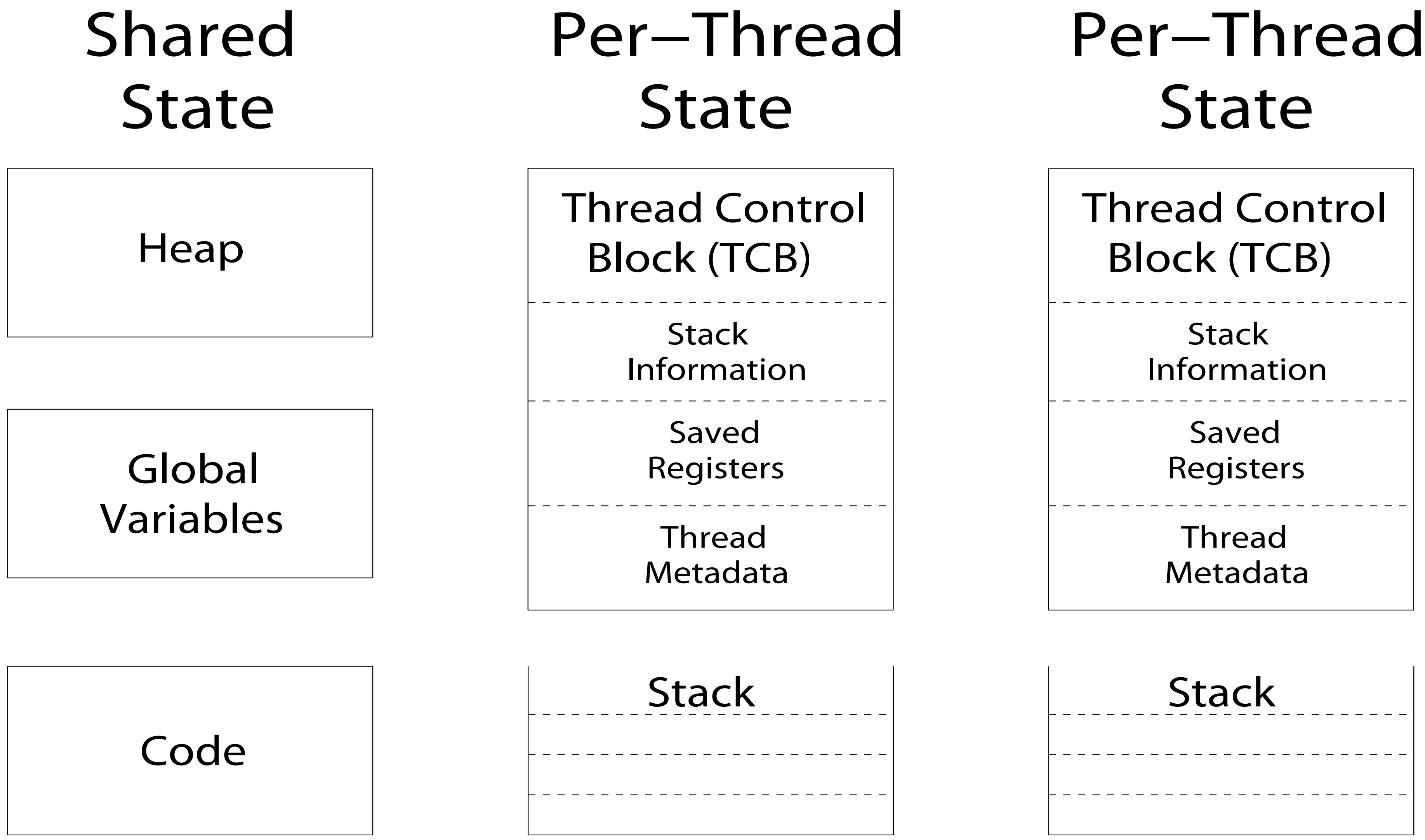
- As a process executes, it changes state:
  - new: The process/thread is being created
  - ready: The process is waiting to run
  - running: Instructions are being executed
  - waiting: Process waiting for some event to occur
  - terminated: The process has finished execution

Recall: Single and Multithreaded Processes



- Threads encapsulate concurrency: "Active" component
- Address spaces encapsulate protection: "Passive" part
  - Keeps buggy program from trashing the system
- Why have multiple threads per address space?

Recall: Shared vs. Per-Thread State



The Core of Concurrency: the Dispatch Loop

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

```
Loop {
   RunThread();
   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()`

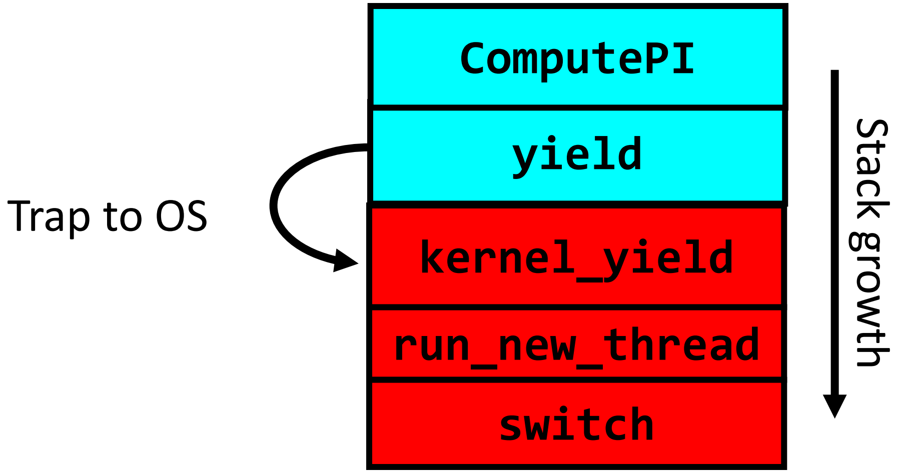
- How do I run a thread?
  - Load its state (registers, PC, stack pointer) into CPU
  - Load environment (virtual memory space, etc)
  - Jump to the PC
- How does the dispatcher get control back?
  - Internal events: thread returns control voluntarily
  - External events: thread gets *preempted*

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

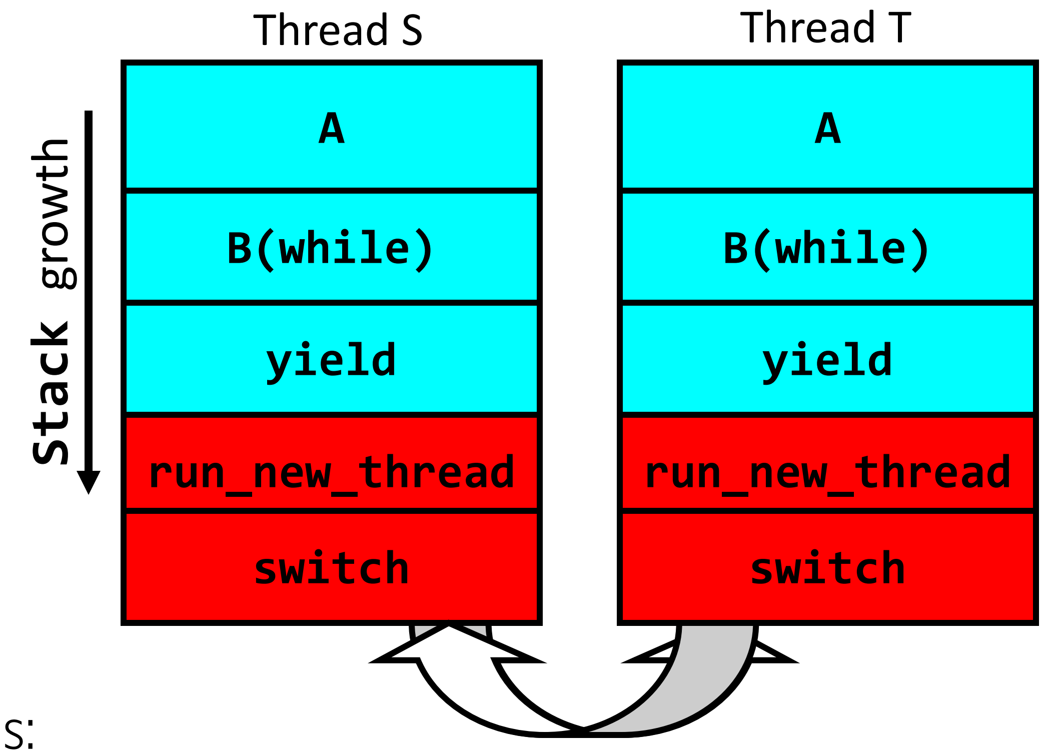
What Do the Stacks Look Like?

- Consider the following code blocks:

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

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

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



Thread S's switch returns to Thread T's (and vice versa)

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 */
}
```

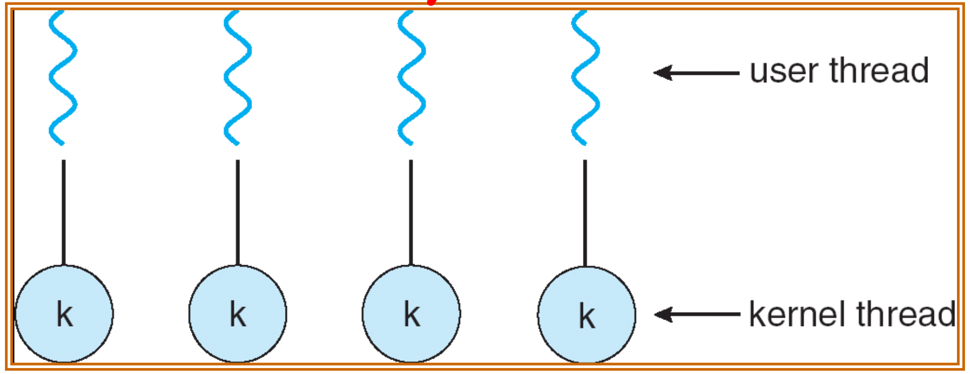
Switch Details (continued)

- 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

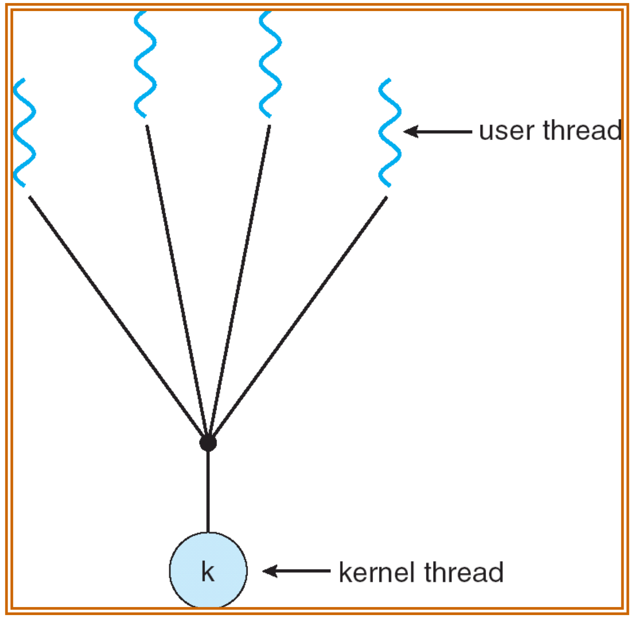
Are we still switching contexts with previous examples?

- Yes, but much cheaper than switching processes
  - No need to change address space
- Some numbers from Linux:
  - Frequency of context switch: 10-100ms
  - Switching between processes: 3-4 μsec.
  - Switching between threads: 100 ns
- Even cheaper: switch threads (using "yield") in user-space!

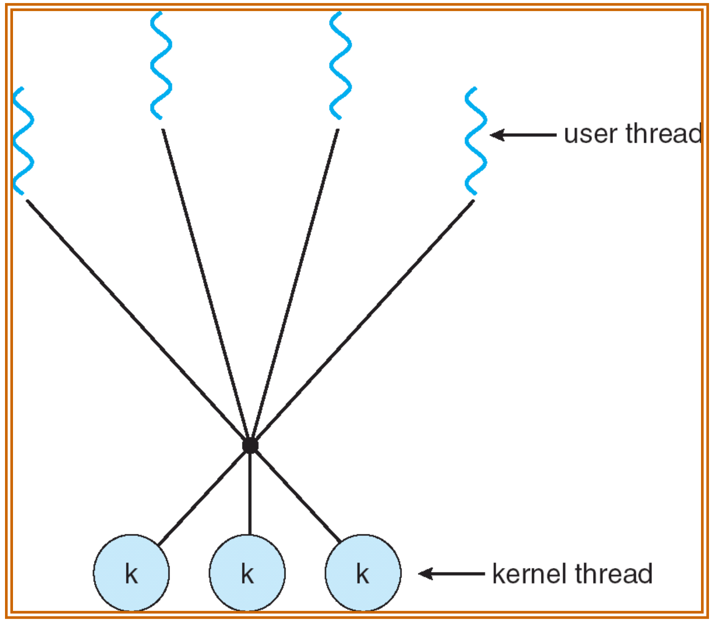
What we are talking about in Today's lecture



Simple One-to-One Threading Model

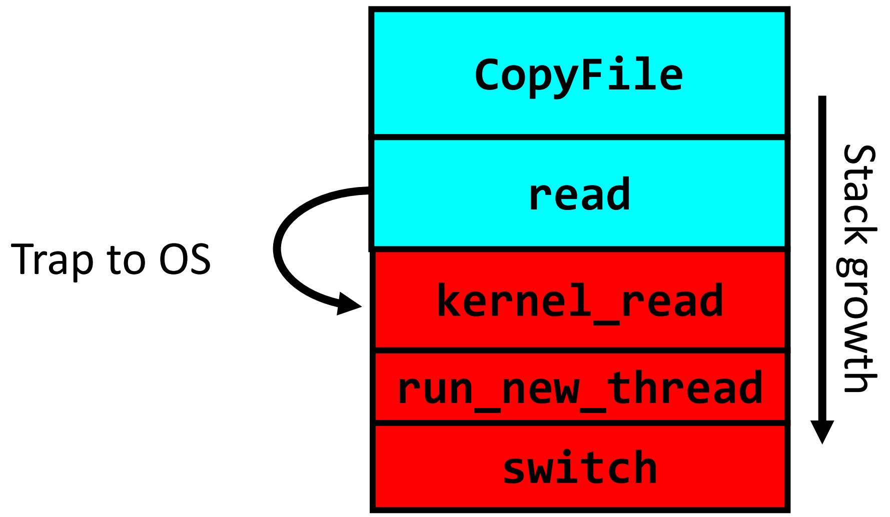


Many-to-One



Many-to-Many

What happens when thread blocks on I/O?

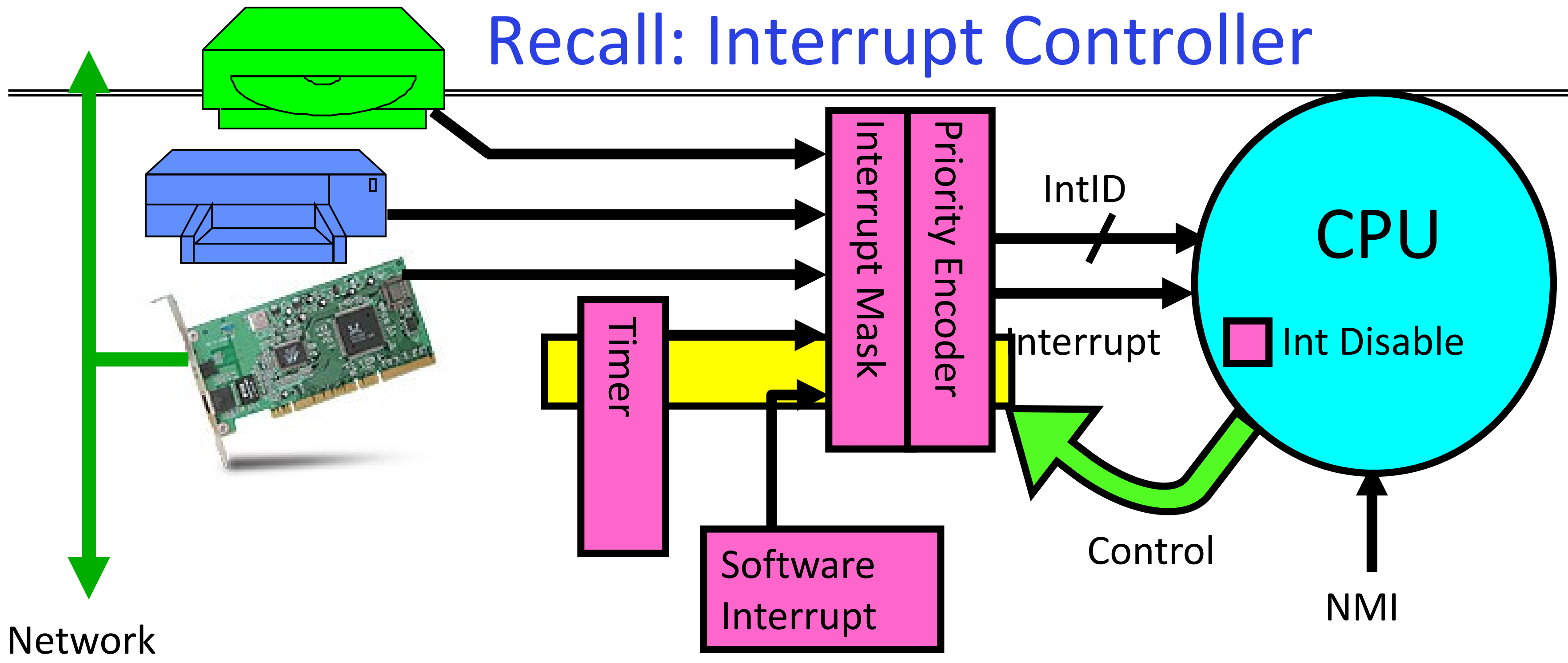


- What happens when a thread requests a block of data from the file system?
  - User code invokes a system call
  - Read operation is initiated
  - Run new thread/switch
- Thread communication similar
  - Wait for Signal/Join
  - Networking

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 milliseconds
- If we make sure that external events occur frequently enough, can ensure dispatcher runs

Recall: Interrupt Controller



- Interrupts invoked with interrupt lines from devices
- Interrupt controller chooses interrupt request to honor
  - Interrupt identity specified with ID line
  - Mask enables/disables interrupts
  - Priority encoder picks highest enabled interrupt
  - Software Interrupt Set/Cleared by Software
- CPU can disable all interrupts with internal flag
- Non-Maskable Interrupt line (NMI) can't be disabled

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
Kernel Mode

Restore PC
Enable all Ints
User Mode

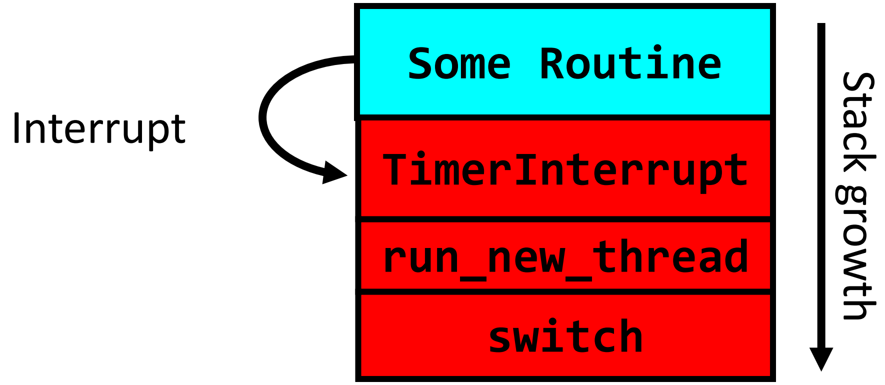
"Interrupt Handler"

```
Raise priority
    (set mask)
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
    (clear Mask)
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();
}
```

`ThreadFork()`: Create a New Thread

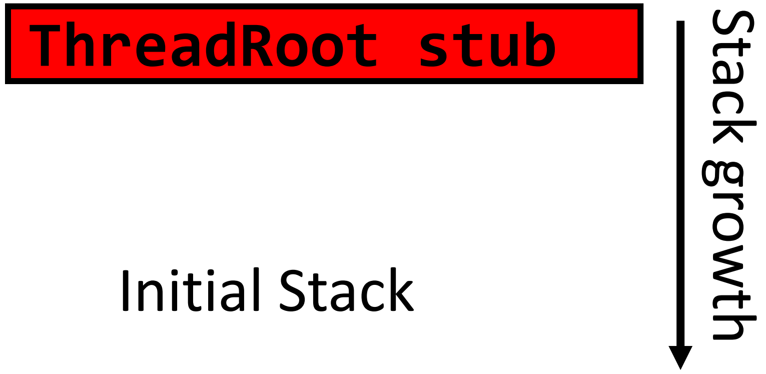
- `ThreadFork()` is a user-level procedure that creates a new thread and places it on ready queue

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

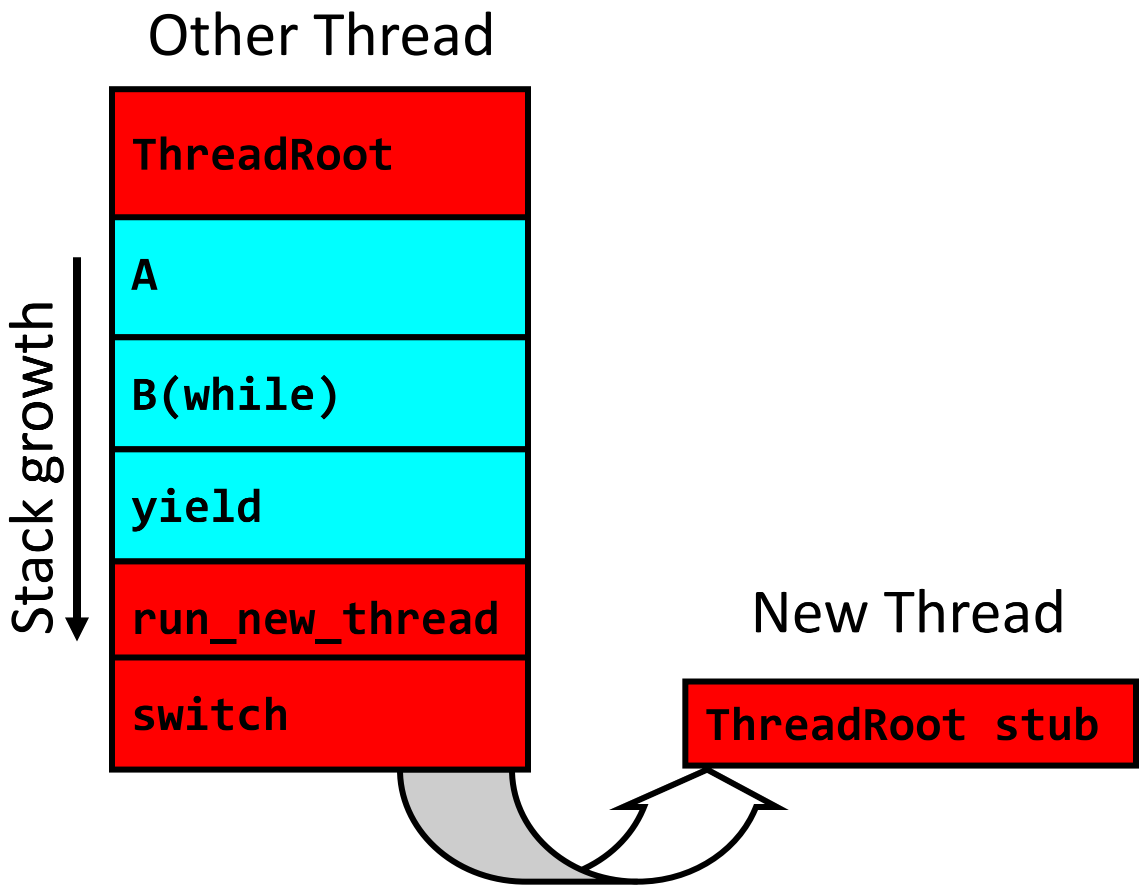
- Implementation
  - Sanity check arguments
  - Enter Kernel-mode and Sanity Check arguments again
  - Allocate new Stack and TCB
  - Initialize TCB and place on ready list (Runnable)

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?
  - Minimal initialization ⇒setup return to go to beginning of ThreadRoot()
    - » Important part of stack frame is in registers for RISC-V (ra)
    - » X86: need to push a return address on stack
  - Think of stack frame as just before body of **`ThreadRoot()`** really gets started

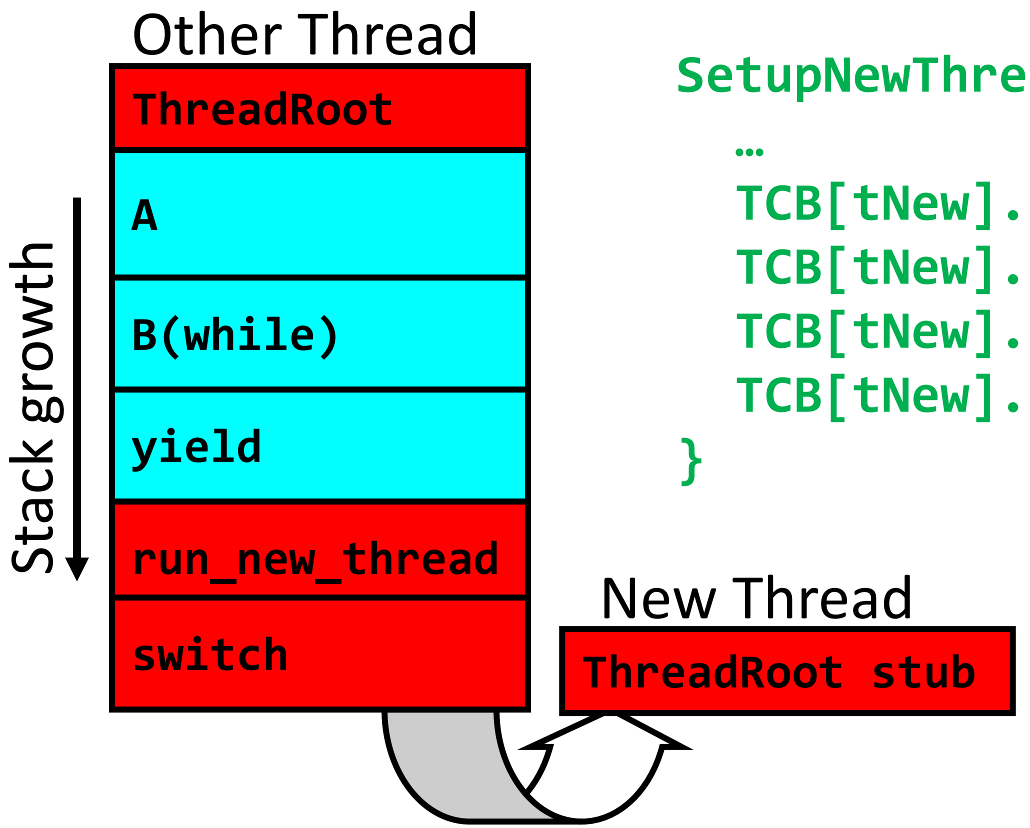


How does Thread get started?



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

How does a thread get started?



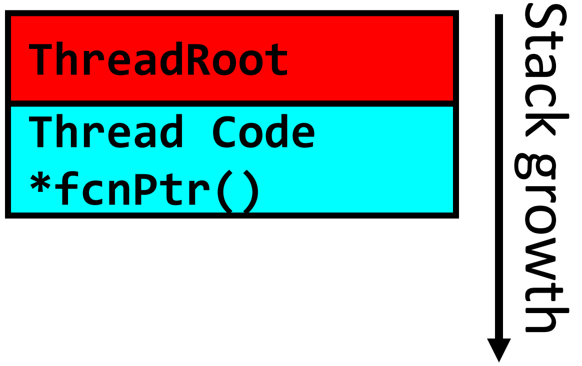

```
SetupNewThread(tNew) {
   …
   TCB[tNew].regs.sp = newStackPtr;
   TCB[tNew].regs.retpc = &ThreadRoot;
   TCB[tNew].regs.r0 = fcnPtr
   TCB[tNew].regs.r1 = fcnArgPtr
}
```

- How do we make a *new* thread?
  - Setup TCB/kernel thread to point at new user stack and ThreadRoot code
  - Put pointers to start function and args in registers or top of stack
    - » This depends heavily on the calling convention (i.e. RISC-V vs x86)
- 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:

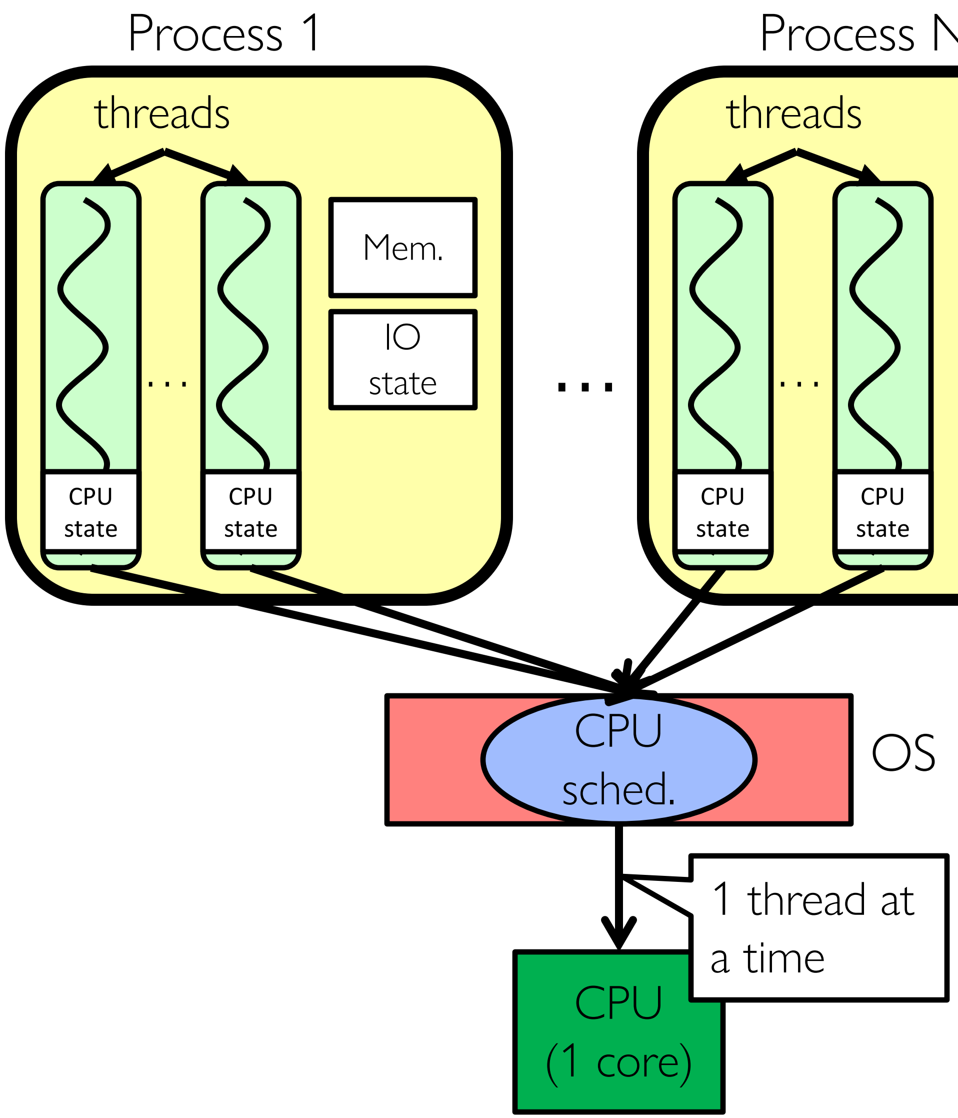
```
ThreadRoot(fcnPTR,fcnArgPtr) {
    DoStartupHousekeeping();
    UserModeSwitch(); /* enter user mode */
    Call fcnPtr(fcnArgPtr);
    ThreadFinish();
}
```



Running Stack

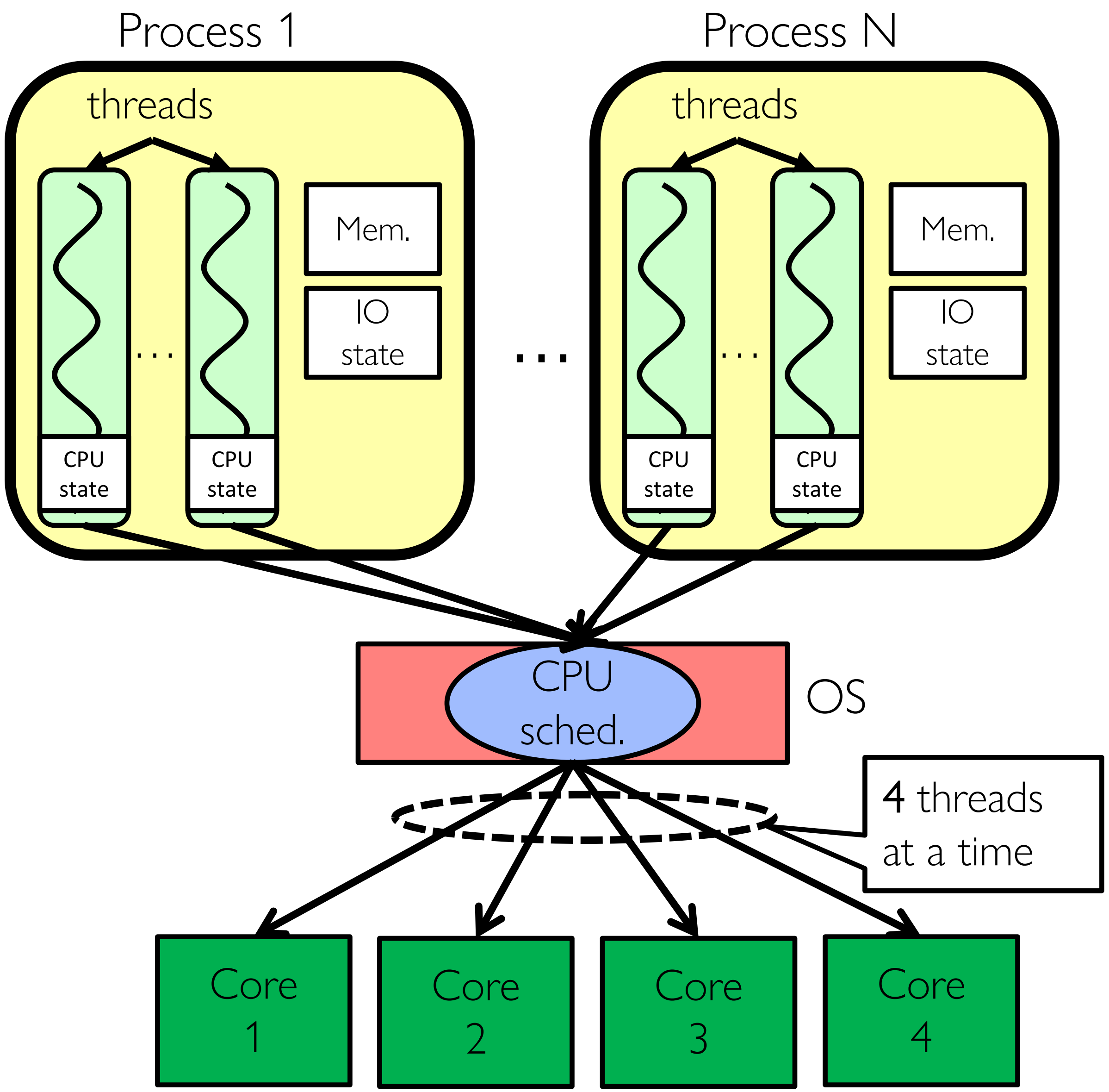
- Startup Housekeeping
  – Includes things like recording start time of thread
  – Other statistics
- Stack will grow and shrink with execution of thread
- Final return from thread returns into `ThreadRoot()` which calls `ThreadFinish()`
  – `ThreadFinish()` wake up sleeping threads

Processes vs. Threads: One Core



- Switch overhead:
  - Same process: low
  - Different proc.: high
- Protection
  - Same proc: low
  - Different proc: high
- Sharing overhead
  - Same proc: low
  - Different proc: high
- Parallelism: no

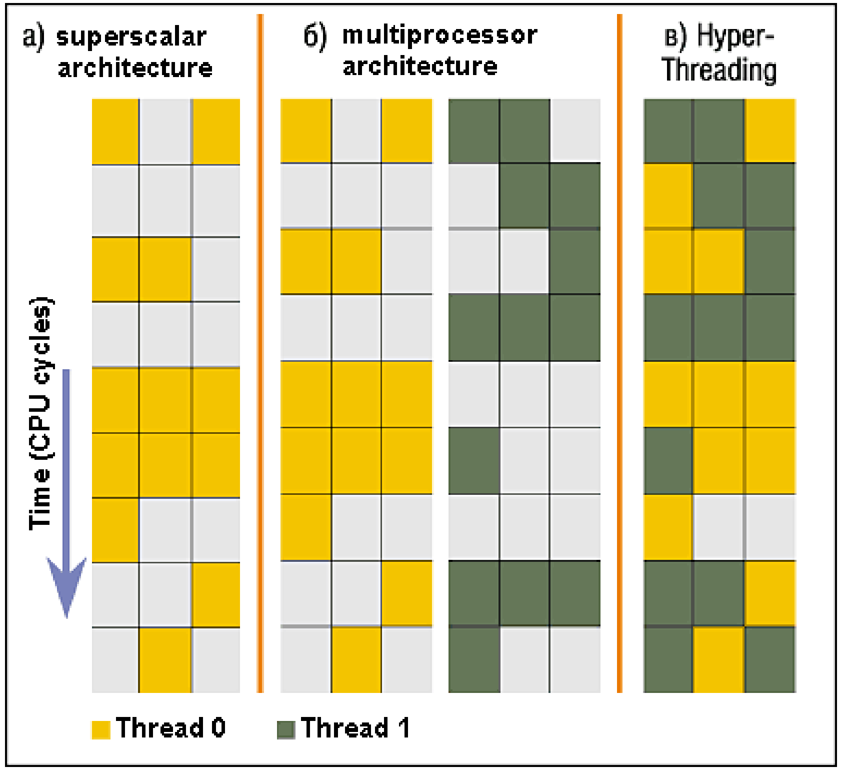
Processes vs. Threads: MultiCore



- Switch overhead:
  – Same process: **low**
  – Different proc.: **high**
- Protection
  – Same proc: **low**
  – Different proc: **high**
- Sharing overhead
  – Same proc: **low**
  – Different proc, simultaneous core: **medium**
  – Different proc, offloaded core: high
- Parallelism: **yes**

Recall: Simultaneous MultiThreading/Hyperthreading

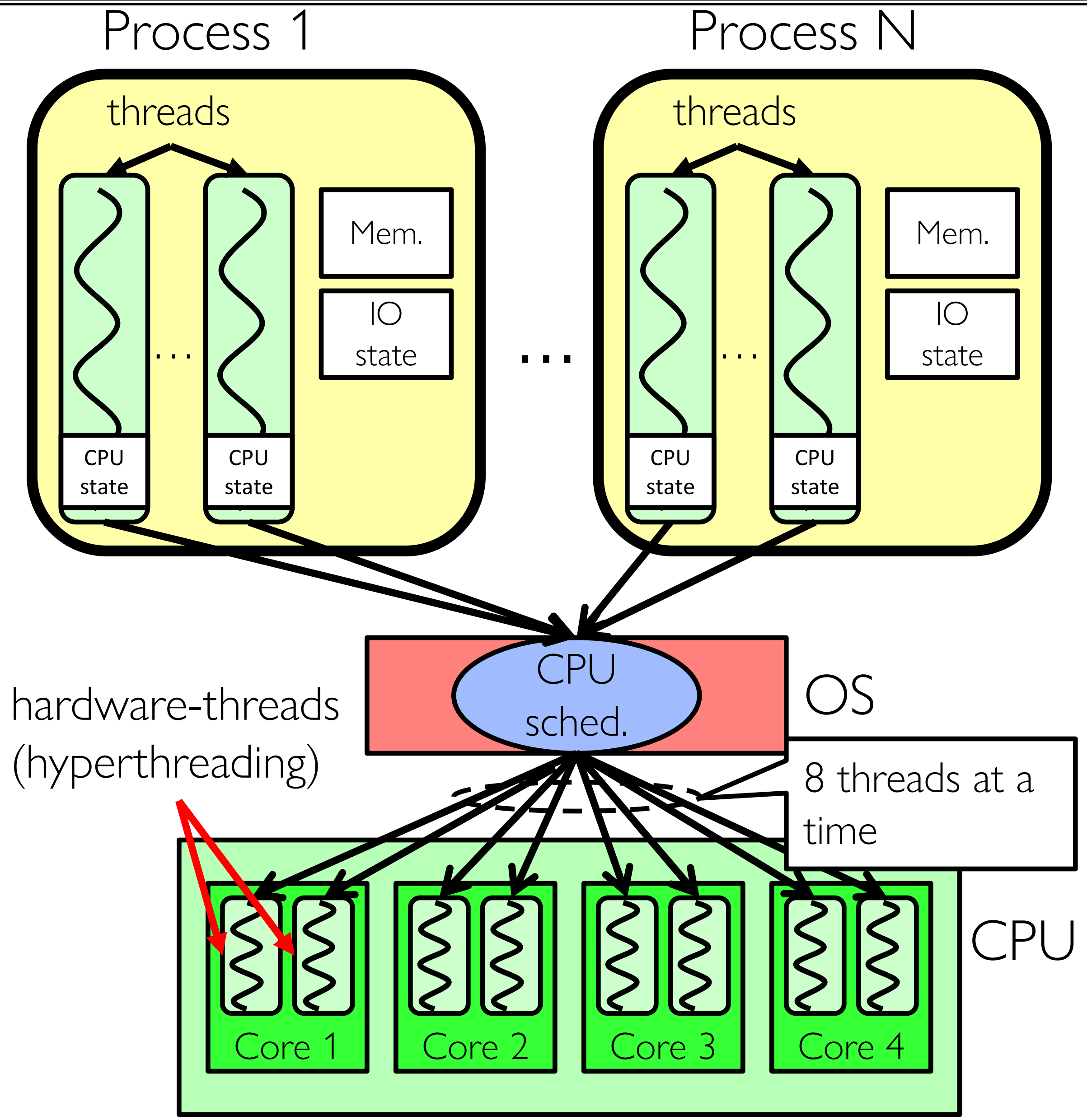
- Hardware scheduling technique
  - Superscalar processors can execute multiple instructions that are independent.
  - Hyperthreading duplicates register state to make a second "thread," allowing more instructions to run.
- Can schedule each thread as if were separate CPU
  - But, sub-linear speedup!



Colored blocks show instructions executed

- Original technique called "Simultaneous Multithreading"
  - http://www.cs.washington.edu/research/smt/index.html
  - SPARC, Pentium 4/Xeon ("Hyperthreading"), Power 5

Processes vs. Threads: Hyper-Threading



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

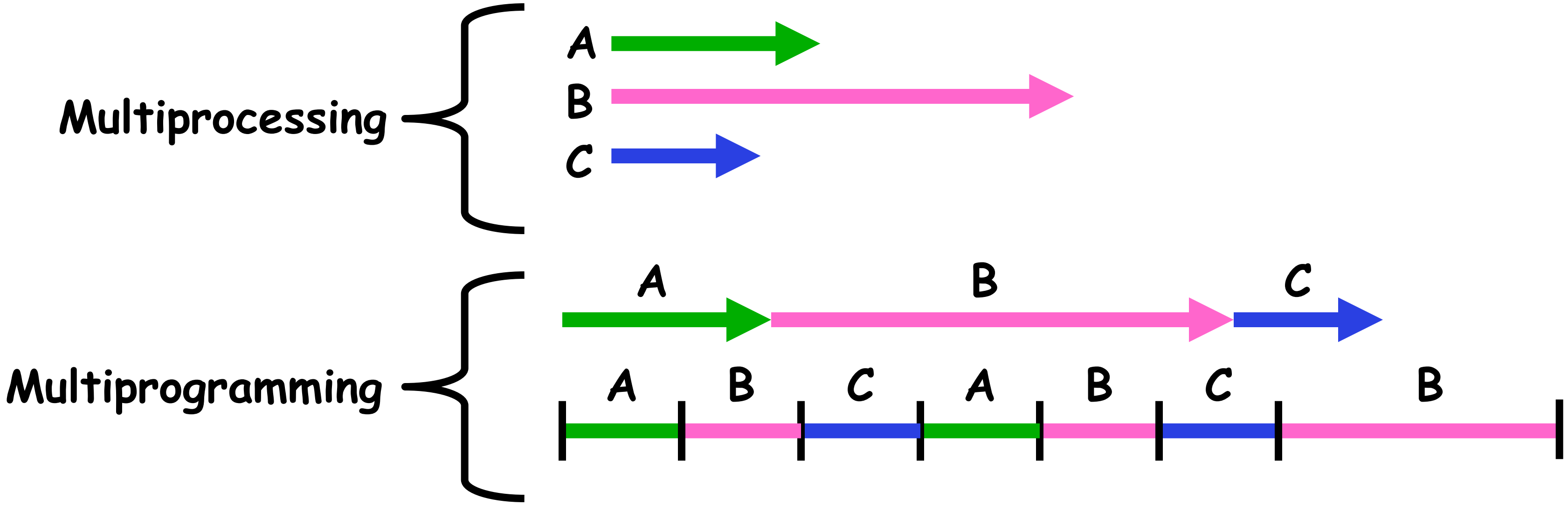
Threads vs Address Spaces: Options

# 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

Multiprocessing vs Multiprogramming

- Some 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



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 $\Rightarrow$ Input state determines results
  – Reproducible $\Rightarrow$ 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"

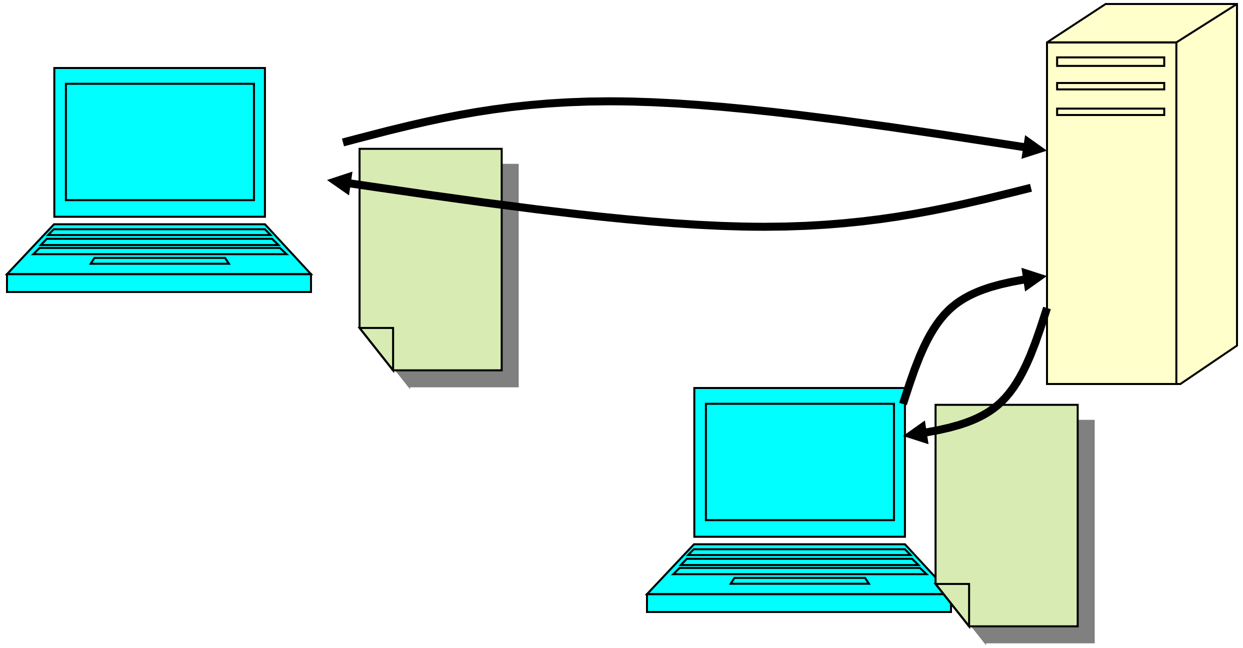
Interactions Complicate Debugging

- 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
  - Example: Something which does interesting I/O
    - » User typing of letters used to help generate secure keys

Why allow cooperating threads?

- People cooperate; computers help/enhance people's lives, so computers must cooperate
  - By analogy, the non-reproducibility/non-determinism of people is a notable problem for "carefully laid plans"
- Advantage 1: Share resources
  - One computer, many users
  - One bank balance, many ATMs
    - » What if ATMs were only updated at night?
  - Embedded systems (robot control: coordinate arm & hand)
- Advantage 2: Speedup
  - Overlap I/O and computation
    - » Many different file systems do read-ahead
  - Multiprocessors – chop up program into parallel pieces
- Advantage 3: Modularity
  - More important than you might think
  - Chop large problem up into simpler pieces
    - » To compile, for instance, gcc calls cpp | cc1 | cc2 | as | ld
    - » Makes system easier to extend

Recall: High-level Example: Web Server



- Server must handle many requests
- Non-cooperating version:

```
serverLoop() {
    con = AcceptCon();
    ProcessFork(ServiceWebPage(),con);
}
```

- What are some disadvantages of this technique?

Recall: Threaded Web Server

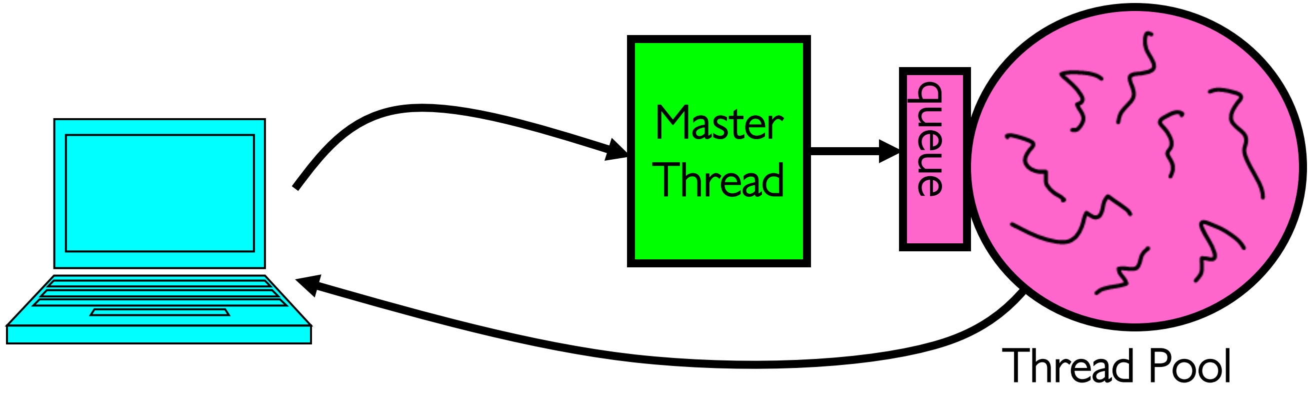
- Now, use a single process
- Multithreaded (cooperating) version:

```
serverLoop() {
     connection = AcceptCon();
     ThreadFork(ServiceWebPage(),connection);
  }
```

- Looks almost the same, but has many advantages:
  – Can share file caches kept in memory, results of CGI scripts, other things
  – Threads are *much* cheaper to create than processes, so this has a lower per-request overhead
- Question: would a user-level (say one-to-many) thread package make sense here?
  – When one request blocks on disk, all block…
- What about Denial of Service attacks or digg / Slash-dot effects?

Thread Pools: Bounded Concurrency

- Problem with previous version: Unbounded Threads
  – When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded "pool" of worker threads, representing the maximum level of multiprogramming



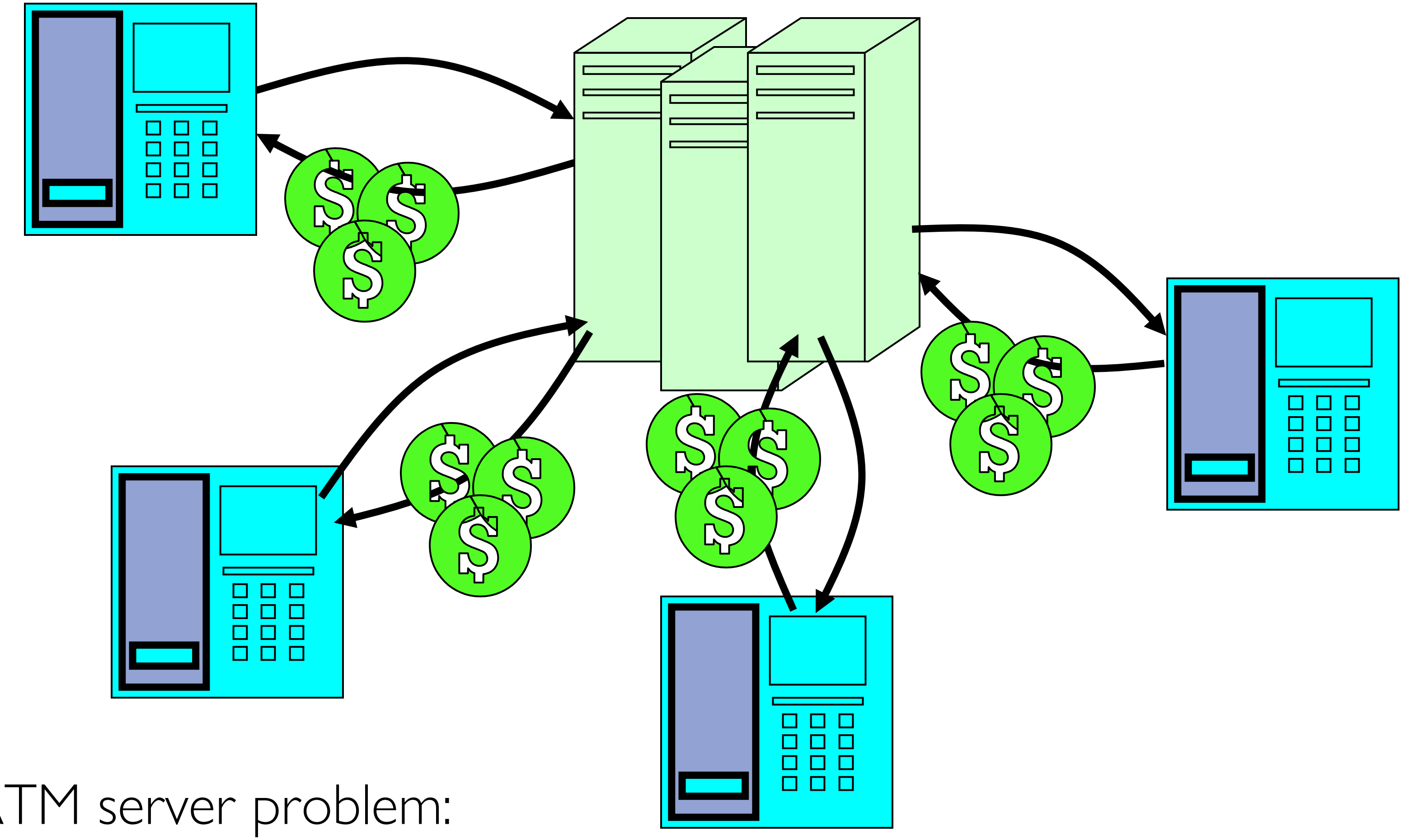

```
master() {
   allocThreads(worker,queue);
   while(TRUE) {
      con=AcceptCon();
      Enqueue(queue,con);
      wakeUp(queue);
   }
}
```

```
worker(queue) {
   while(TRUE) {
      con=Dequeue(queue);
      if (con==null)
         sleepOn(queue);
      else
         ServiceWebPage(con);
   }
}
```

Correctness with Concurrent Threads?

- Non-determinism:
  - Scheduler can run threads in **any order**
  - Scheduler can switch threads **at any time**
  - This can make testing very difficult
- *Independent Threads*
  - No state shared with other threads
  - Deterministic, reproducible conditions
- *Cooperating Threads*
  - Shared state between multiple threads
- **Goal: Correctness by Design**

ATM Bank Server



- ATM server problem:
  - Service a set of requests
  - Do so without corrupting database
  - Don't hand out too much money

ATM bank server example

- Suppose we wanted to implement a server process to handle requests from an ATM network:

```
BankServer() {
   while (TRUE) {
      ReceiveRequest(&op, &acctId, &amount);
      ProcessRequest(op, acctId, amount);
   }
}
ProcessRequest(op, acctId, amount) {
   if (op == deposit) Deposit(acctId, amount);
   else if …
}
Deposit(acctId, amount) {
   acct = GetAccount(acctId); /* may use disk I/O */
   acct->balance += amount;
   StoreAccount(acct); /* Involves disk I/O */
}
```

- How could we speed this up?
  - More than one request being processed at once
  - Event driven (overlap computation and I/O)
  - Multiple threads (multi-proc, or overlap comp and I/O)

Event Driven Version of ATM server

- Suppose we only had one CPU
  - Still like to overlap I/O with computation
  - Without threads, we would have to rewrite in event-driven style
- Example

```
BankServer() {
   while(TRUE) {
      event = WaitForNextEvent();
      if (event == ATMRequest)
         StartOnRequest();
      else if (event == AcctAvail)
         ContinueRequest();
      else if (event == AcctStored)
         FinishRequest();
   }
}
```

  - This technique is used for graphical programming
- Complication:
  - What if we missed a blocking I/O step?
  - What if we have to split code into hundreds of pieces which could be blocking?

Can Threads Make This Easier?

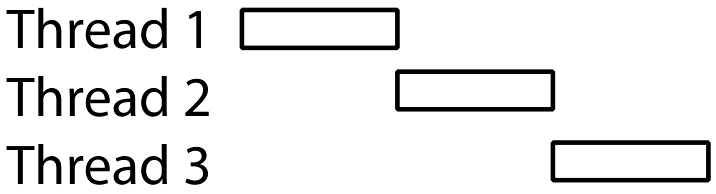
- Threads yield overlapped I/O and computation without "deconstructing" code into non-blocking fragments
  - One thread per request
- Requests proceeds to completion, blocking as required:

```
Deposit(acctId, amount) {
  acct = GetAccount(actId); /* May use disk I/O */
  acct->balance += amount;
  StoreAccount(acct);      /* Involves disk I/O */
}
```

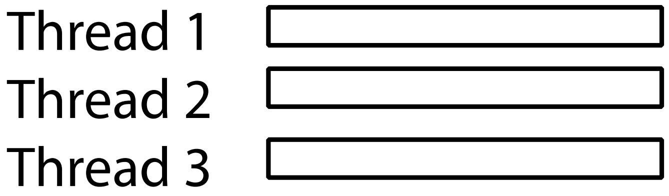
- Unfortunately, shared state can get corrupted:

```
          Thread 1                          Thread 2
load r1, acct->balance
                                  load r1, acct->balance
                                  add r1, amount2
                                  store r1, acct->balance
add r1, amount1
store r1, acct->balance
```

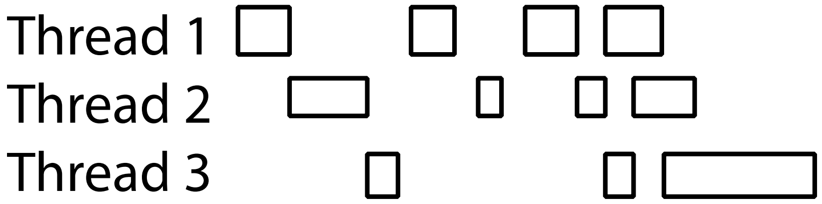
Recall: Possible Executions



a) One execution



b) Another execution



c) Another execution

Problem is at the Lowest Level

- Most of the time, threads are working on separate data, so scheduling doesn't matter:

Thread A	Thread B
x = 1;	y = 2;

- However, what about (Initially, y = 12):

Thread A	Thread B
x = 1;	y = 2;
x = y+1;	y = y*2;

  – What are the possible values of x?
- Or, what are the possible values of x below?

Thread A	Thread B
x = 1;	x = 2;

  – X could be 1 or 2 (non-deterministic!)
  – Could even be 3 for serial processors:
    » Thread A writes 0001, B writes 0010 → scheduling order ABABABBA yields 3!

Atomic Operations

- To understand a concurrent program, we need to know what the underlying indivisible operations are!
- Atomic Operation: an operation that always runs to completion or not at all
  – It is *indivisible:* it cannot be stopped in the middle and state cannot be modified by someone else in the middle
  – Fundamental building block – if no atomic operations, then have no way for threads to work together
- On most machines, memory references and assignments (i.e. loads and stores) of words are atomic
  – Consequently – weird example that produces "3" on previous slide can't happen
- Many instructions are not atomic
  – Double-precision floating point store often not atomic
  – VAX and IBM 360 had an instruction to copy a whole array

Locks

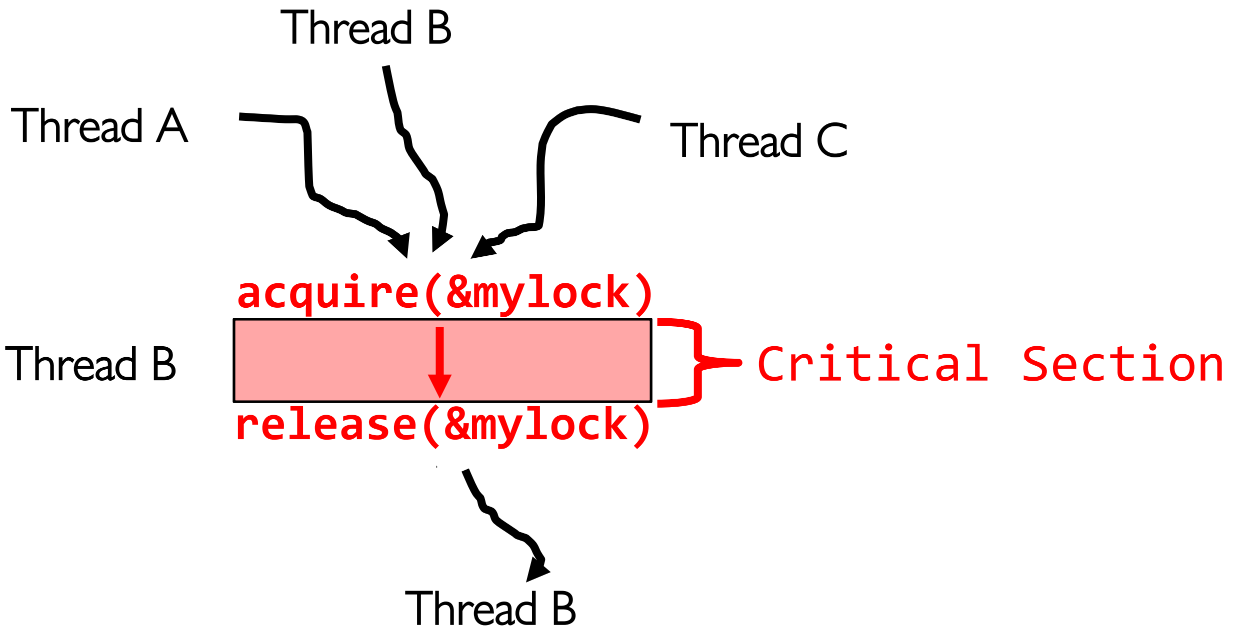
- Lock: prevents someone from doing something
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting
- Locks need to be allocated and initialized:
  - `structure Lock mylock` or `pthread_mutex_t mylock;`
  - `lock_init(&mylock)` or `mylock = PTHREAD_MUTEX_INITIALIZER;`
- Locks provide two **atomic** operations:
  - acquire(&mylock) – wait until lock is free; then mark it as busy
    - » After this returns, we say the calling thread *holds* the lock
  - release(&mylock) – mark lock as free
    - » Should only be called by a thread that currently holds the lock
    - » After this returns, the calling thread no longer holds the lock

Fix banking problem with Locks!

- Identify critical sections (atomic instruction sequences) and add locking:

```
Deposit(acctId, amount) {
  acquire(&mylock)            // Wait if someone else in critical section!
  acct = GetAccount(actId);
  acct->balance += amount;
  StoreAccount(acct);
  release(&mylock)            // Release someone into critical section
}
```

Critical Section



Threads serialized by lock through critical section.
Only one thread at a time

- Must use SAME lock (`mylock`) with all of the methods (Withdraw, etc…)
  – Shared with all threads!

Conclusion

- 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