CS162
Operating Systems and Systems Programming
Lecture 7

Synchronization 1: Concurrency, Mutual Exclusion, and Atomic Operations

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Recall: the Dispatch Loop

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

```
Loop {
    RunThread();     // Needs to return to loop every now and then!
    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
- Note: We give control of processor/core to user code!!
  - OS is *not running* because user code *is running*

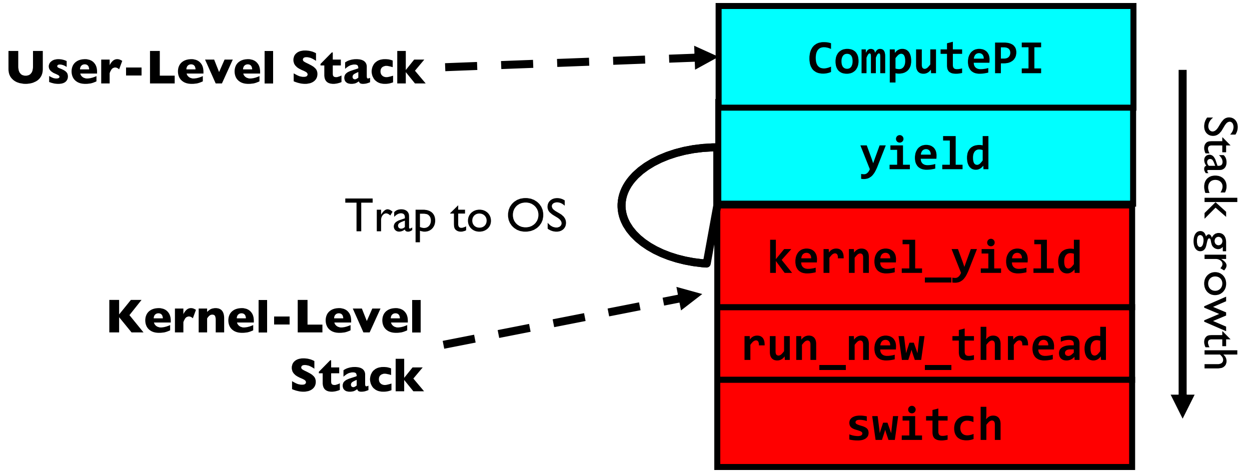
- How does the OS get control back?
  - Internal events: thread returns control *voluntarily*
  - External events: thread gets *preempted*

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 */
}
```

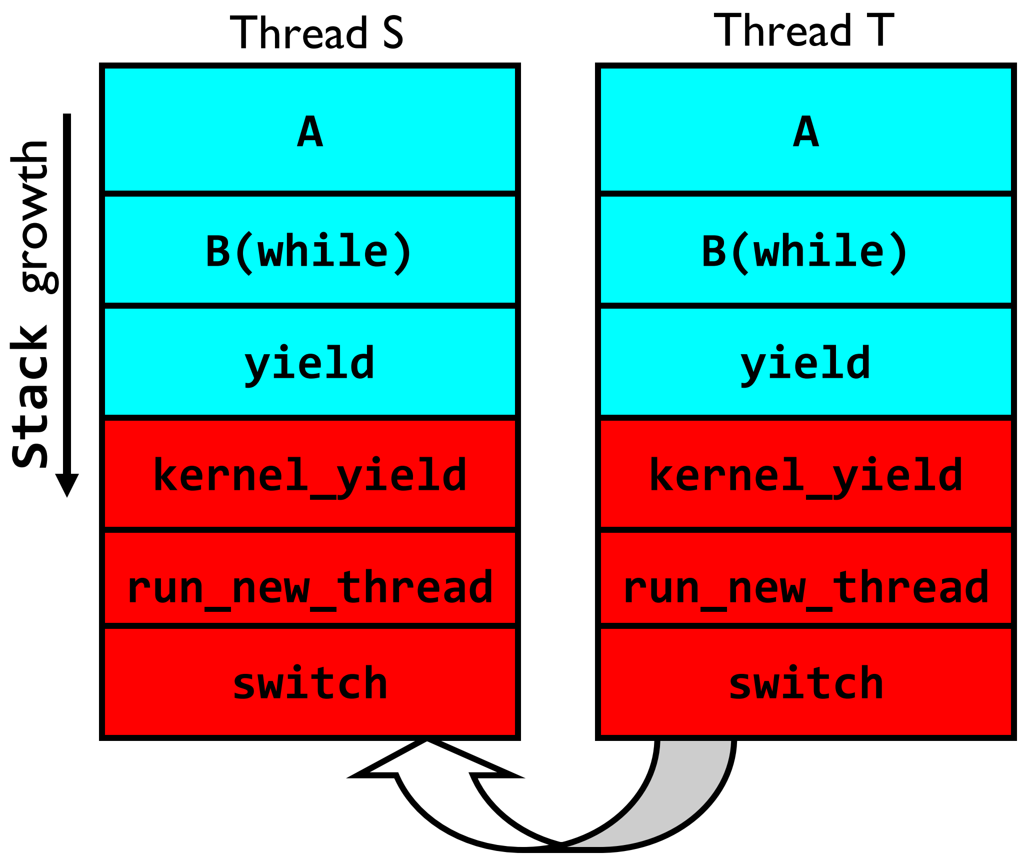
- How does dispatcher switch to a new thread?
  – Save anything next thread may trash: PC, regs, stack pointer
  – Maintain isolation for each thread

Stacks for Yield with Multiple Threads

- Consider the following code blocks:

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

- Suppose we have 2 threads:
  – Threads S and T
  – Assume that both have been running for a while



Thread T's switch returns to Thread S

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 */
}
```

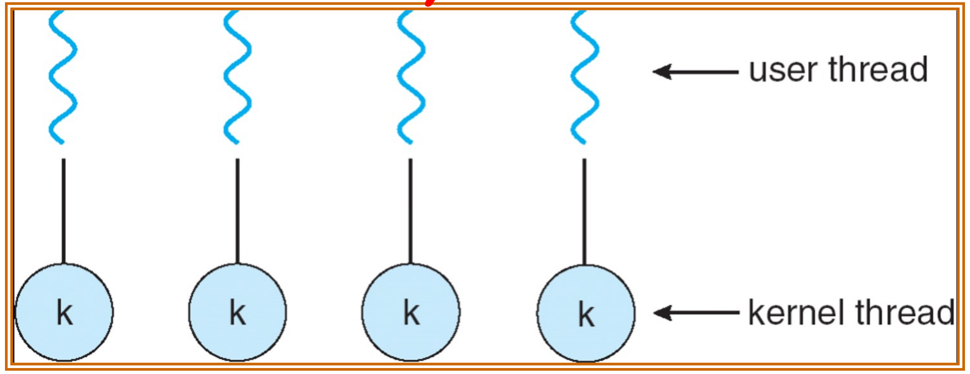
Switch Details (continued)

- 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

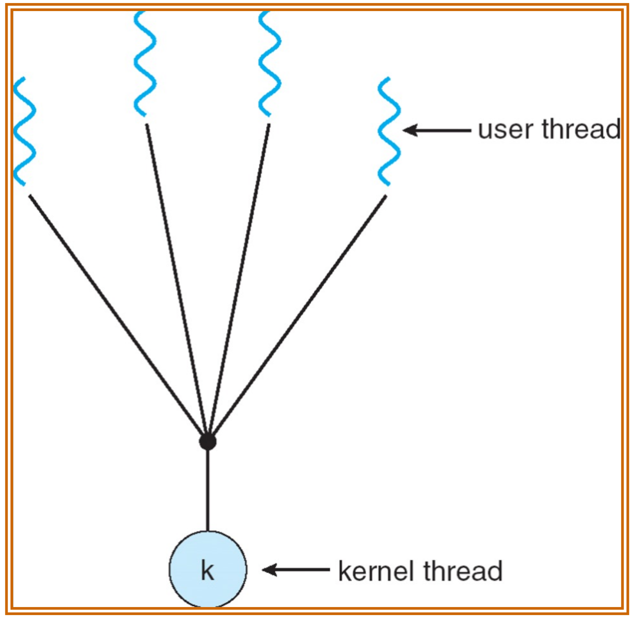
How expensive is context switching?

- Switching between threads in same process similar to switching between threads in different processes, but *much cheaper:*
  - 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!

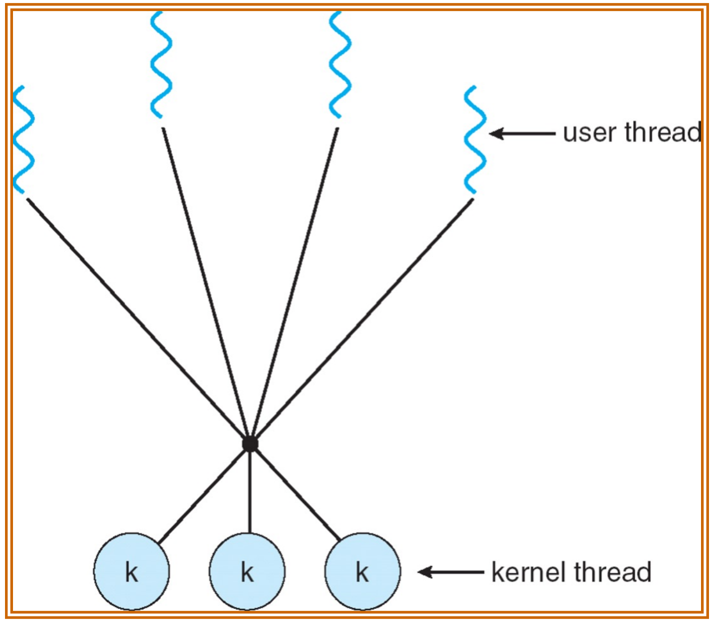
What we are talking about in Today's lecture



Simple One-to-One Threading Model

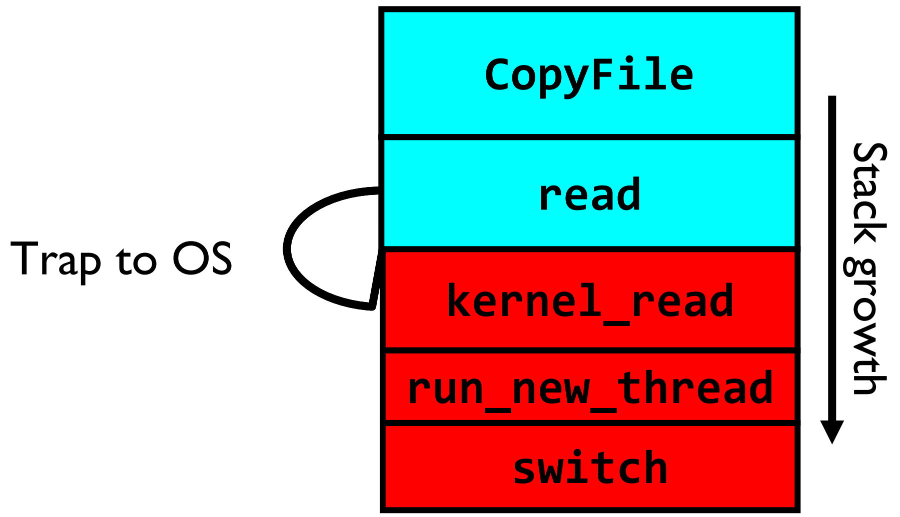


Many-to-One



Many-to-Many

What happens when thread blocks on I/O?

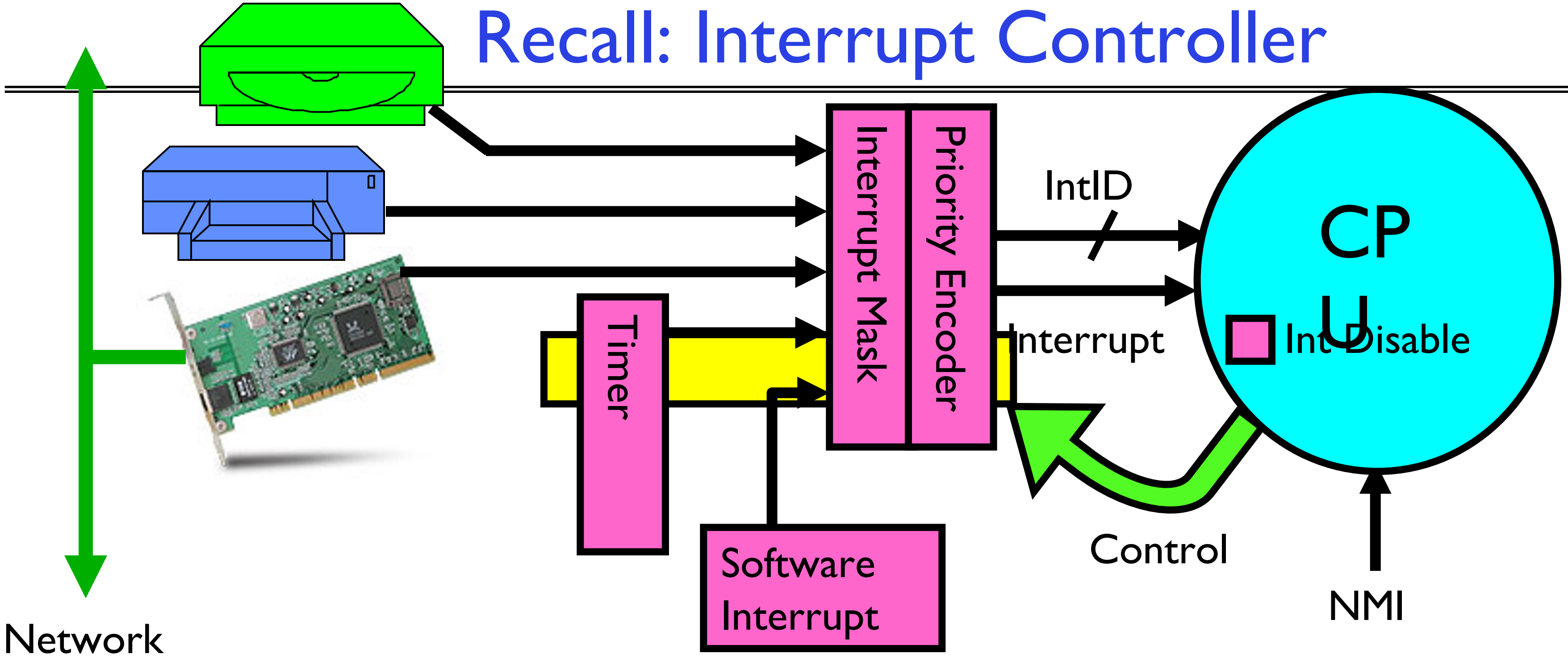


- What happens when a thread requests a block of data from the file system?
  - User code invokes a system call
  - Read operation is initiated
  - Run new thread/switch
- Thread communication similar
  - Wait for Signal/Join
  - Networking

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 few 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

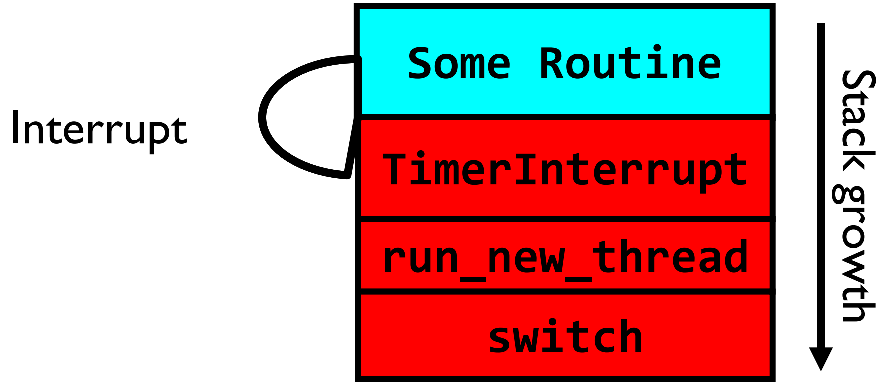
```
Raise priority
       (set mask)
Reenable All Ints
Save registers
Dispatch to Handler
          …
Transfer Network Packet
       from hardware
to Kernel Buffers
          …
Restore registers
Clear current Int
Disable All Ints
Restore priority
       (clear Mask)
RTI
```

"Interrupt Handler"

- 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

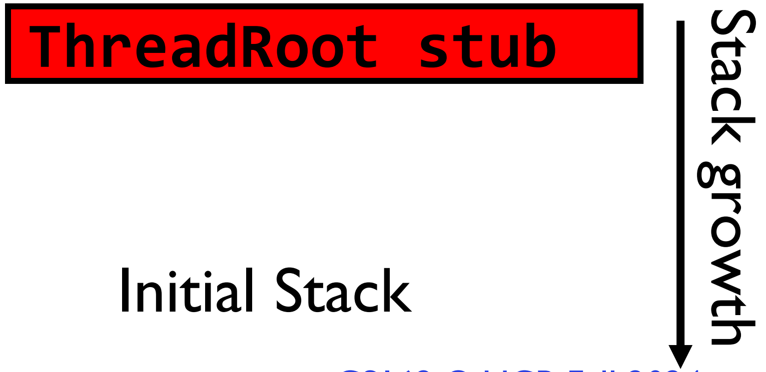
- `ThreadFork()` is a user-level procedure that creates a new thread and places it on ready queue

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

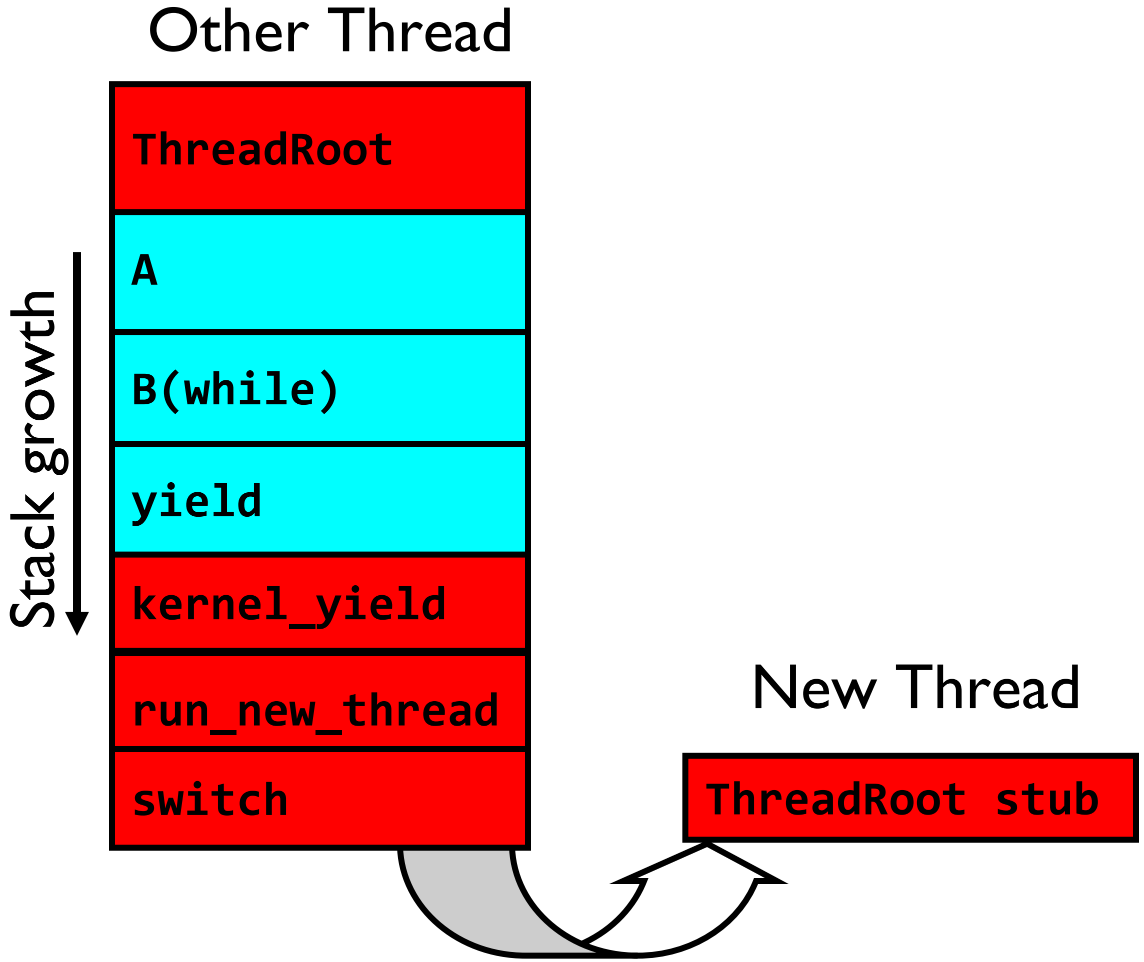
- Implementation
  - Sanity check arguments
  - Enter Kernel-mode and Sanity Check arguments again
  - Allocate new Stack and TCB
  - Initialize TCB and place on ready list (Runnable)

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

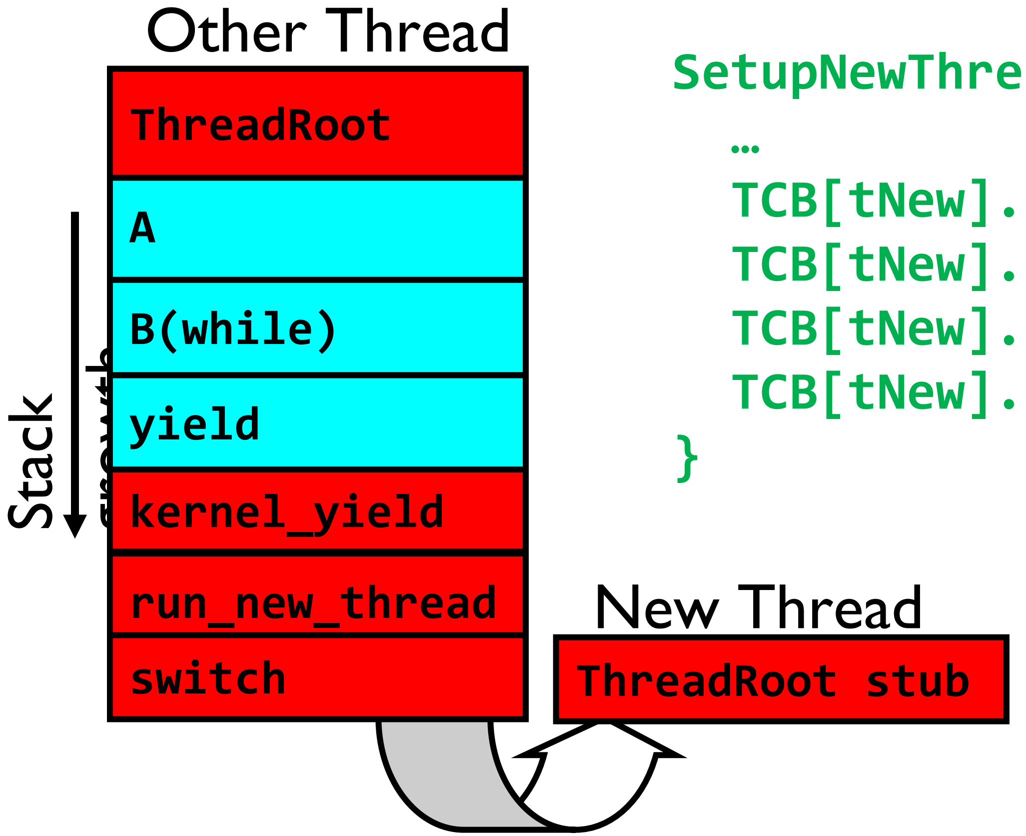


How does Thread get started?



- 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?



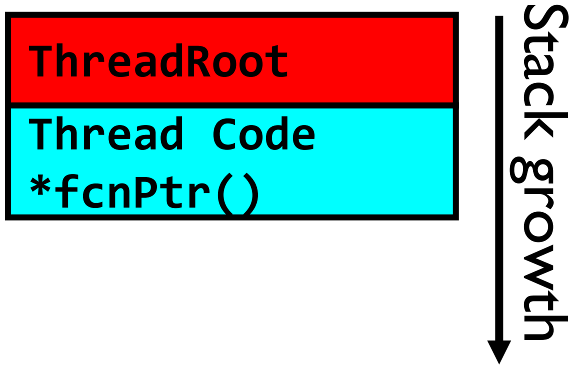

```
SetupNewThread(tNew) {
   …
   TCB[tNew].regs.sp = newStackPtr;
   TCB[tNew].regs.retpc = &ThreadRoot;
   TCB[tNew].regs.r0 = fcnPtr
   TCB[tNew].regs.r1 = fcnArgPtr
}
```

- 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

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

Administrivia

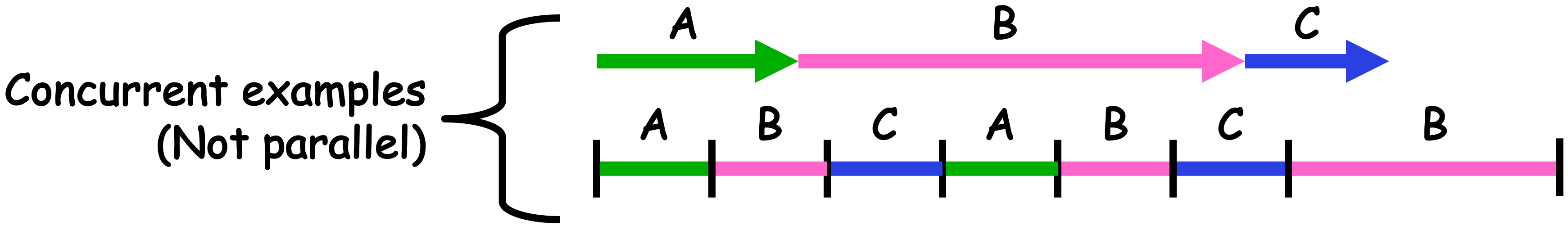
- Midterm Thursday 10/3
  - Closed book, but one page of *handwritten* notes, both sides
  - No class on day of midterm
  - 7-9PM
- Project 1 Design Document due next Thursday 9/26
  - No extensions of any sort on design documents!!!
- Project 1 Design reviews upcoming
  - High-level discussion of your approach
    - » What will you modify?
    - » What algorithm will you use?
    - » How will things be linked together, etc.
    - » Do not need final design (complete with all semicolons!)
  - You will be asked about testing
    - » Understand testing framework
    - » Are there things you are doing that are not tested by tests we give you?
- Do your own work!
  - Please do not try to find solutions from previous terms
  - We will be on the look out for anyone doing this…today

Goals for Rest of Today

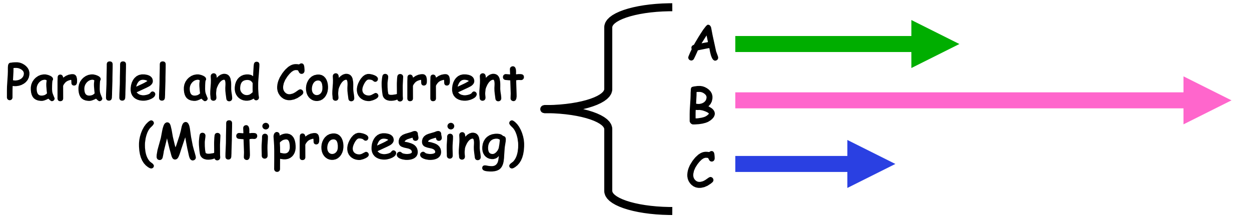
- Challenges and Pitfalls of Concurrency
- Synchronization Operations/Critical Sections
- How to build a lock?
- Atomic Operations

Concurrency vs Parallelism

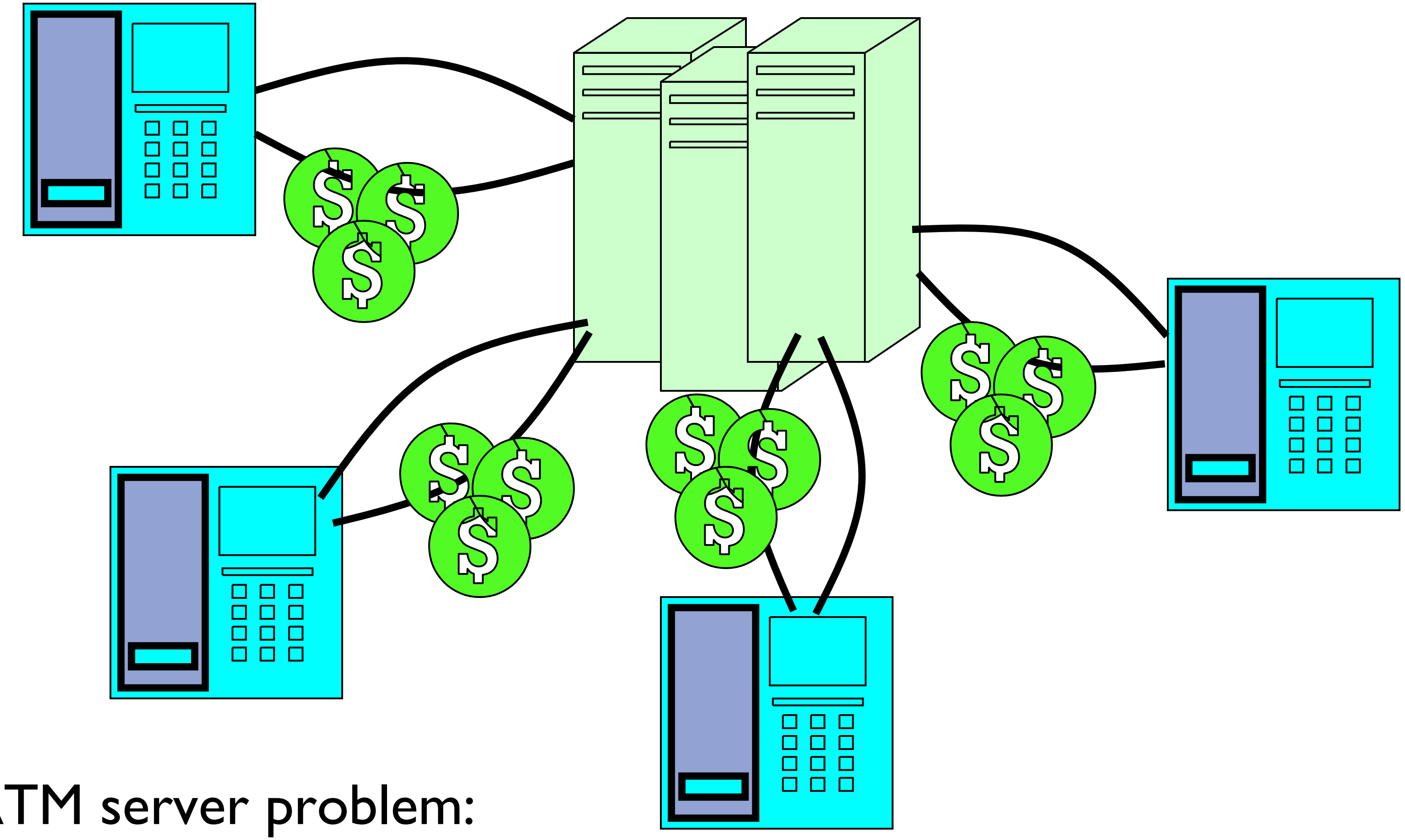
- Multithreading: Multiple threads per Process (*A programming strategy*)
- Multiplexing: Sharing a single resource (such as a core) among multiple threads
- What does it mean to run two threads "concurrently" (*regardless of process*)?
  - Scheduler is free to run threads in any order and interleaving: FIFO, Random, …
  - Unless synchronization is involved, multiple threads are concurrent!
  - Assume: if scheduler can produce the worst possible interleaving, IT WILL!



- What does it mean to run two threads "in parallel" *(regardless of process)?*
  - Threads are *actually running* at the same time
  - Parallel ⇒ Concurrent but Concurrent ⇏ Parallel



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 (in same Process) 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
```

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

Another Concurrent Program Example

- Two threads, A and B, compete with each other
  - One tries to increment a shared counter
  - The other tries to decrement the counter

<u>Thread A</u> <u>Thread B</u>

```
i = 0;            i = 0;
while (i < 10)    while (i > -10)
   i = i + 1;        i = i – 1;
printf("A wins!");  printf("B wins!");
```

- Assume that memory loads and stores are atomic, but incrementing and decrementing are *not* atomic
- Who wins? Could be either
- Is it guaranteed that someone wins? Why or why not?
- What if both threads have their own CPU running at same speed? Is it guaranteed that it goes on forever?

Hand Simulation Multiprocessor Example

- Inner loop looks like this:

```
                        Thread A                        Thread B
r1=0   load   r1, M[i]
                     r1=0   load r1, M[i]
r1=1   add    r1, r1, 1
                     r1=-1 sub r1, r1, 1
M[i]=1       store r1, M[i]
                     M[i]=-1      store r1, M[i]
```

- Hand Simulation:
  - And we're off. A gets off to an early start
  - B says "hmph, better go fast" and tries really hard
  - A goes ahead and writes "1"
  - B goes and writes "-1"
  - A says "HUH??? I could have sworn I put a 1 there"
- Could this happen on a uniprocessor? With Hyperthreads?
  - Yes! Unlikely, but if you are depending on it not happening, it will and your system will break…

Definitions

- Synchronization: using atomic operations to ensure cooperation between threads
  - For now, only loads and stores are atomic
  - We are going to show that its hard to build anything useful with only reads and writes
- Mutual Exclusion: ensuring that only one thread does a particular thing at a time
  - One thread *excludes* the other while doing its task
- Critical Section: piece of code that only one thread can execute at once. Only one thread at a time will get into this section of code
  - Critical section is the result of mutual exclusion
  - Critical section and mutual exclusion are two ways of describing the same thing

Locks

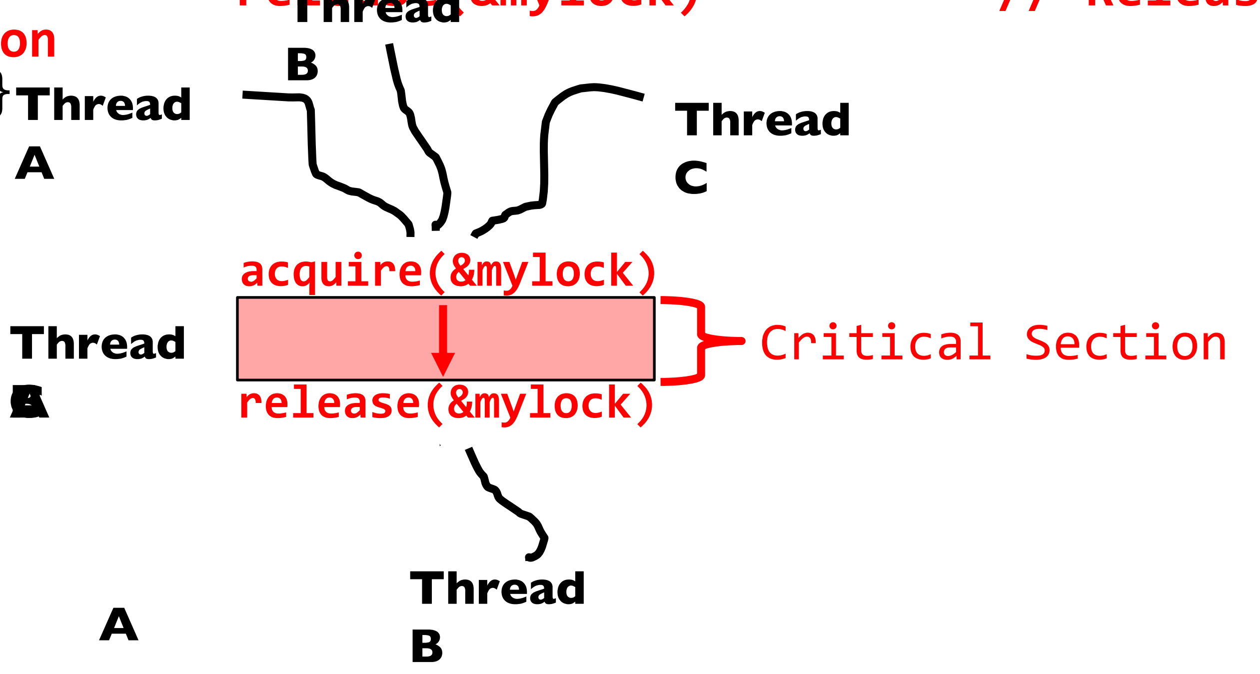
- Lock: prevents someone from doing something
  - `Lock()` before entering critical section and before accessing shared data
  - `Unlock()` when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting
- Locks need to be allocated and initialized:
  - `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!

Correctness Requirements

- Threaded programs must work for all interleavings of thread instruction sequences
  - Cooperating threads inherently non-deterministic and non-reproducible
  - Really hard to debug unless carefully designed!
- Example: Therac-25
  - Machine for radiation therapy
    - » Software control of electron accelerator and electron beam/ Xray production
    - » Software control of dosage
  - Software errors caused the death of several patients
    - » A series of race conditions on shared variables and poor software design
    - » "They determined that data entry speed during editing was the key factor in producing the error condition: If the prescription data was edited at a fast pace, the overdose occurred."

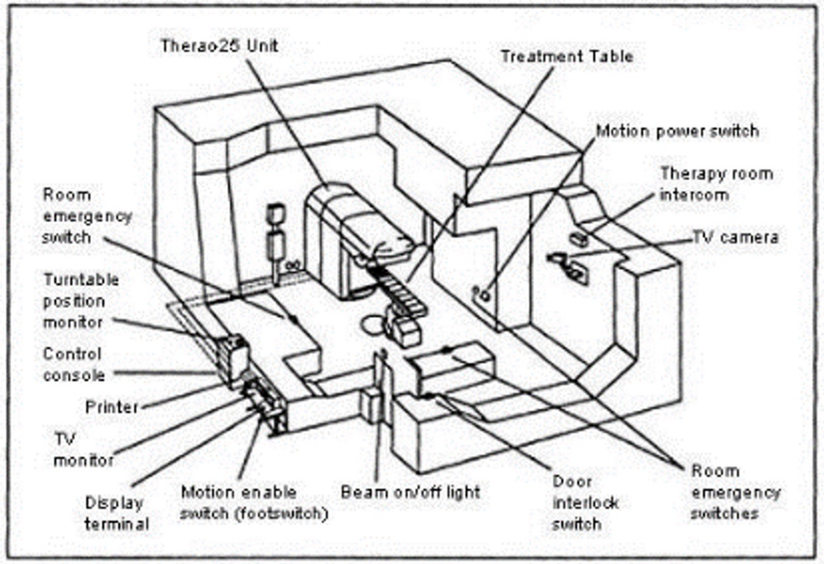


Figure 1. Typical Therac-25 facility

Conclusion

- Every thread has both a user and kernel stack
  - Showed more details about context-switching mechanisms
- 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
- Introduced the Lock API: `acquire()` and `release()`
  - Next time: How do we make a lock?