CS162
Operating Systems and Systems Programming
Lecture 6

Synchronization 1: Concurrency and Mutual Exclusion

February 4th, 2021

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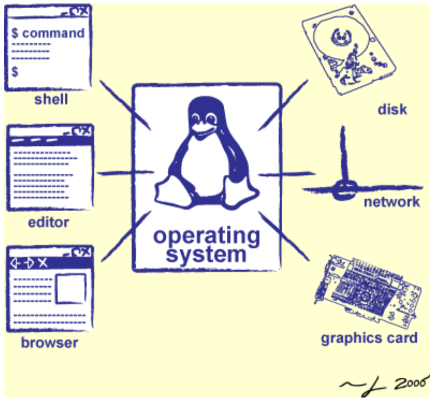
Goals for Today: Synchronization

- How does an OS provide concurrency through threads?
  - Brief discussion of process/thread states and scheduling
  - High-level discussion of how stacks contribute to concurrency
- Introduce needs for synchronization
- Discussion of Locks and Semaphores



Recall: Inter-Process Communication (IPC)

- Mechanism to create communication channel between distinct processes
  - Same or different machines, same or different programming language…
- Requires serialization format understood by both
- Failure in one process isolated from the other
  - Sharing is done in a controlled way through IPC
  - Still have to be careful handling what is received via IPC
- Later in the term: Many uses and interaction patterns
  - Logging process, window management, …
  - Potentially allows us to move some system functions outside of kernel to userspace

Recall: POSIX/Unix PIPE

```
write(wfd, wbuf, wlen);
```


```
n = read(rfd, rbuf, rmax);
```

- Memory Buffer is finite:
  - If producer (A) tries to write when buffer full, it *blocks* (Put sleep until space)
  - If consumer (B) tries to read when buffer empty, it *blocks* (Put to sleep until data)

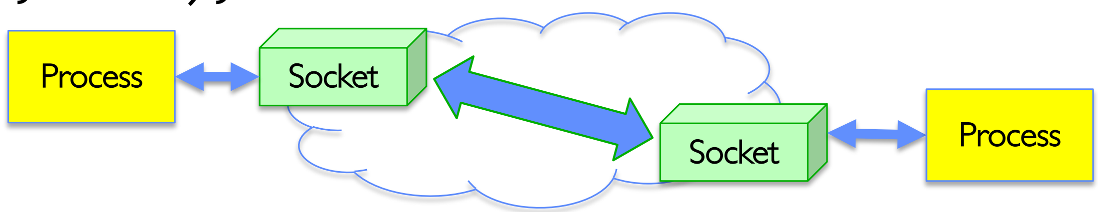
```
int pipe(int fileds[2]);
```

- Allocates two new file descriptors in the process
- Writes to `fileds[1]` read from `fileds[0]`
- Implemented as a fixed-size queue

Recall: Socket Endpoint for Communication

- **Key Idea:** Communication across the world looks like File I/O

```
write(wfd, wbuf, wlen);
```

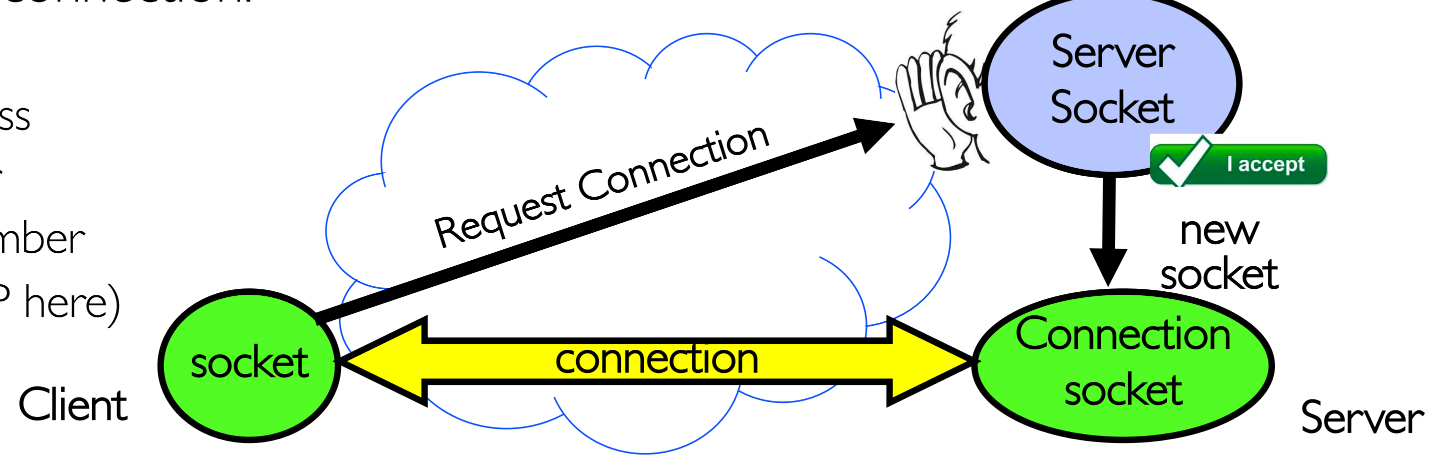



```
n = read(rfd, rbuf, rmax);
```

- Sockets: Bidirectional Endpoint for Communication
  – Queues to temporarily hold results
  – Queues are NOT Pipes!
- Connection: Two Sockets Connected Over the network ⇒ IPC over network!
  – How to **open()**?
  – What is the namespace?
  – How are they connected in time?

Recall: Connection Setup over 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 (v1)

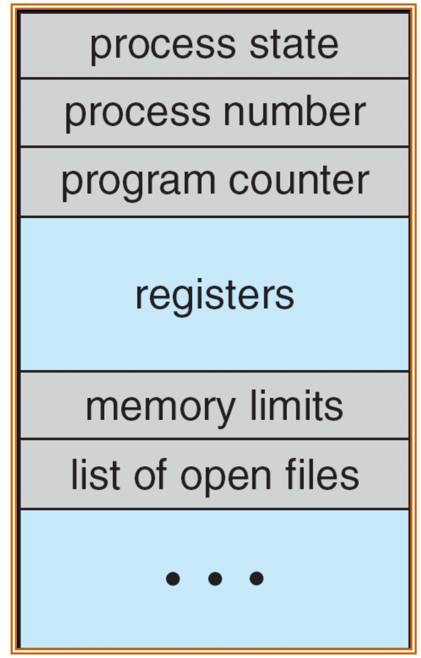
```
// Create socket to listen for client connections
char *port_name;
struct addrinfo *server = setup_address(port_name);
int server_socket = socket(server->ai_family,
      server->ai_socktype, server->ai_protocol);
// Bind socket to specific port
bind(server_socket, server->ai_addr, server->ai_addrlen);
// Start listening for new client connections
listen(server_socket, MAX_QUEUE);

while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  serve_client(conn_socket);
  close(conn_socket);
}
close(server_socket);
```

[redacted]

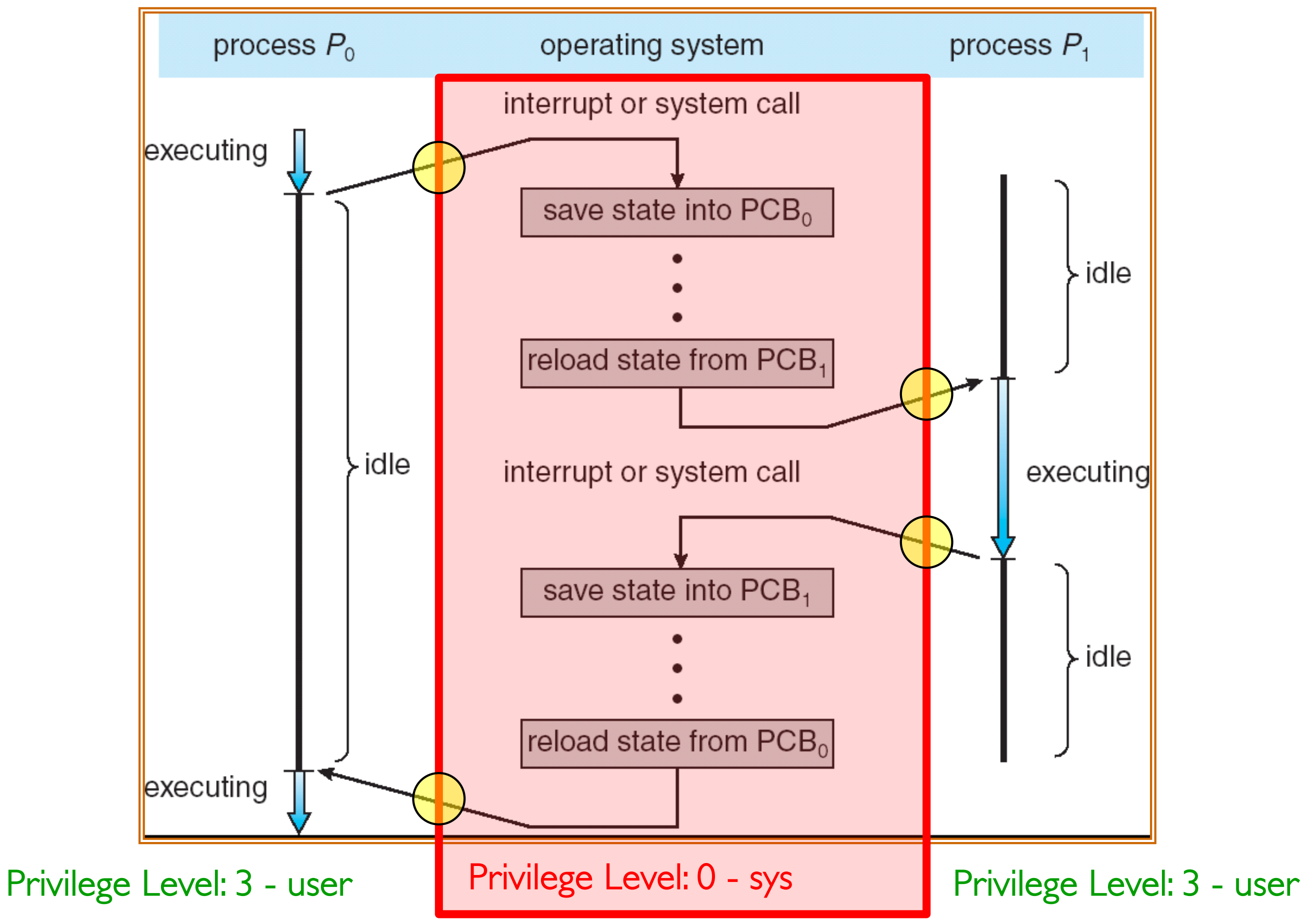
Multiplexing Processes: The Process Control Block

- 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

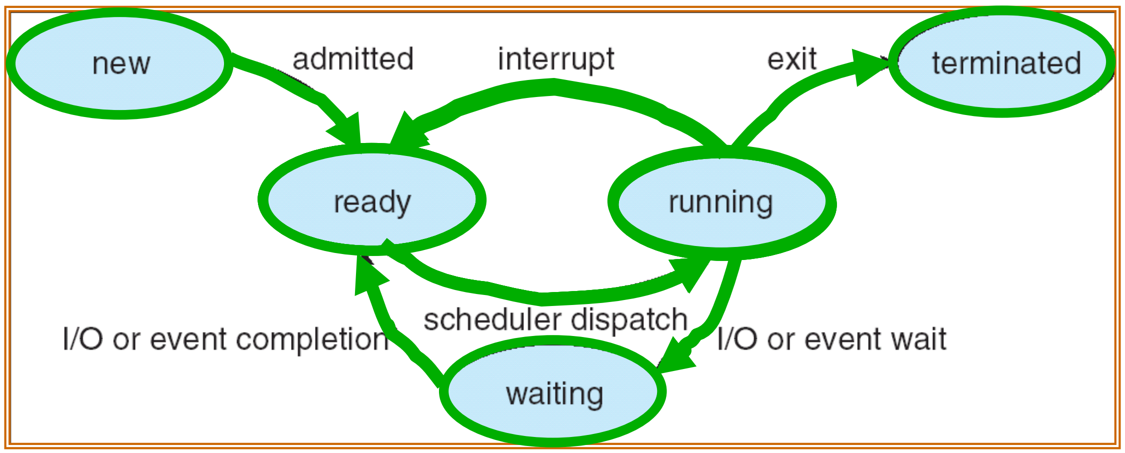


Process Control Block

Context Switch

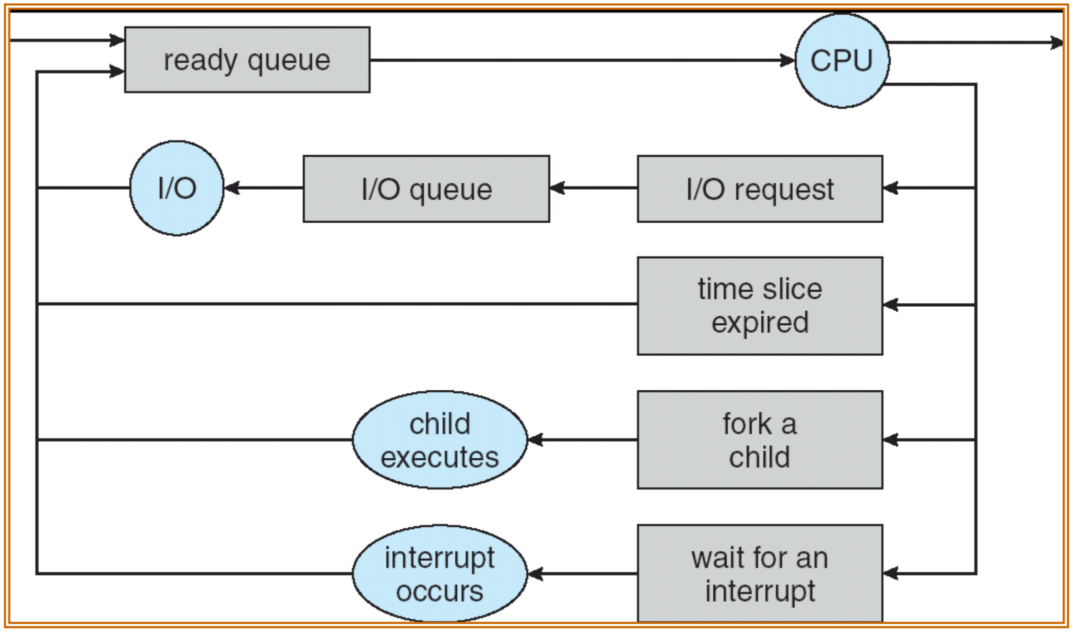


Lifecycle of a Process or Thread



- 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

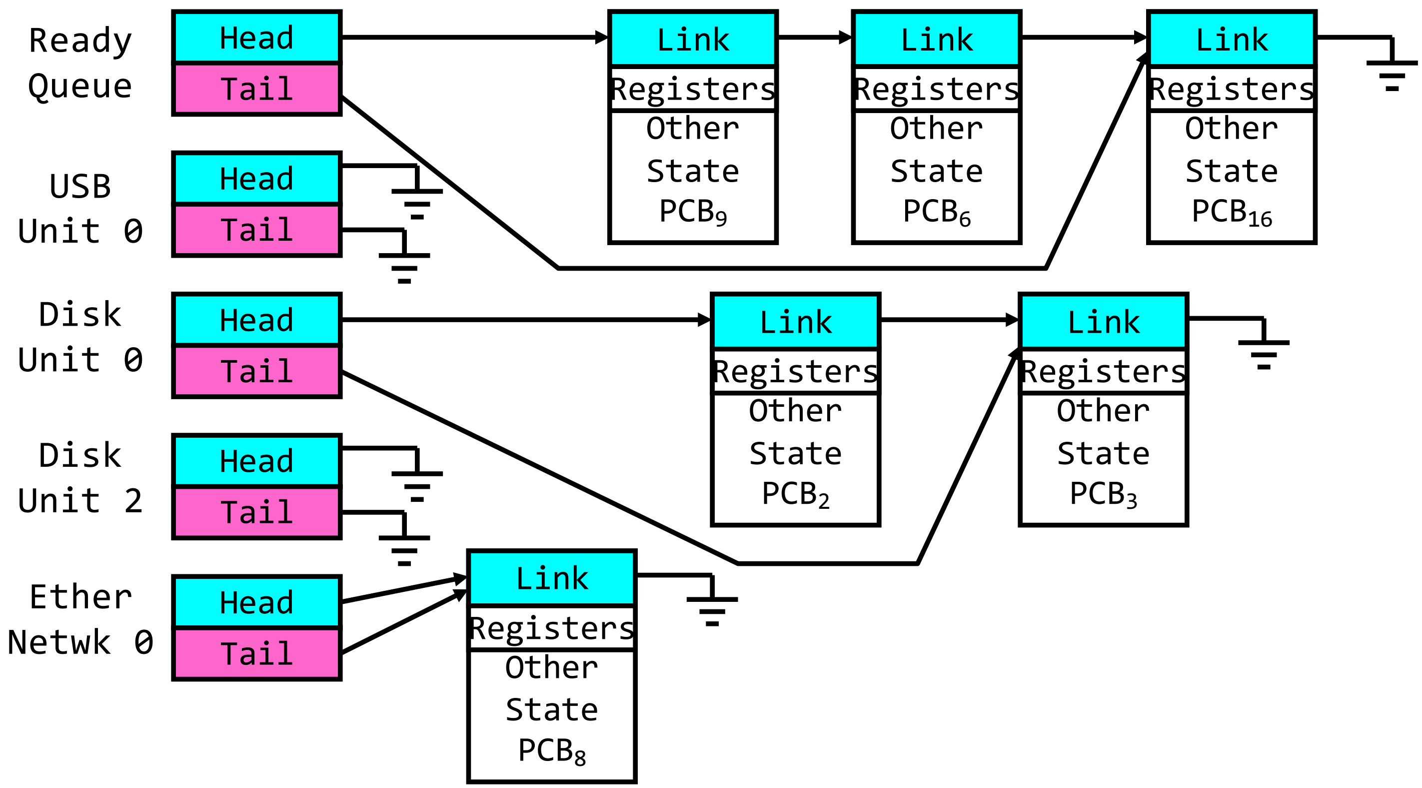
Scheduling: All About Queues



- PCBs move from queue to queue
- **Scheduling:** which order to remove from queue
  – Much more on this soon

Ready Queue And Various I/O Device Queues

- Process not running ⇒ PCB is in some scheduler queue
  - Separate queue for each device/signal/condition
  - Each queue can have a different scheduler policy

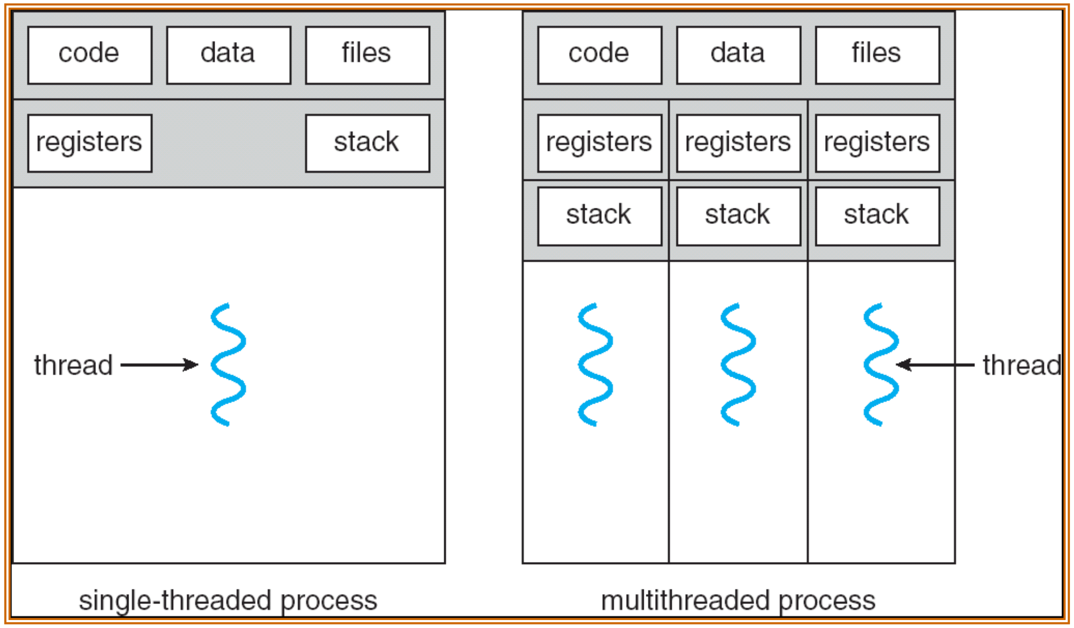


Scheduler

```
if ( readyProcesses(PCBs) ) {
    nextPCB = selectProcess(PCBs);
    run( nextPCB );
} else {
    run_idle_process();
}
```

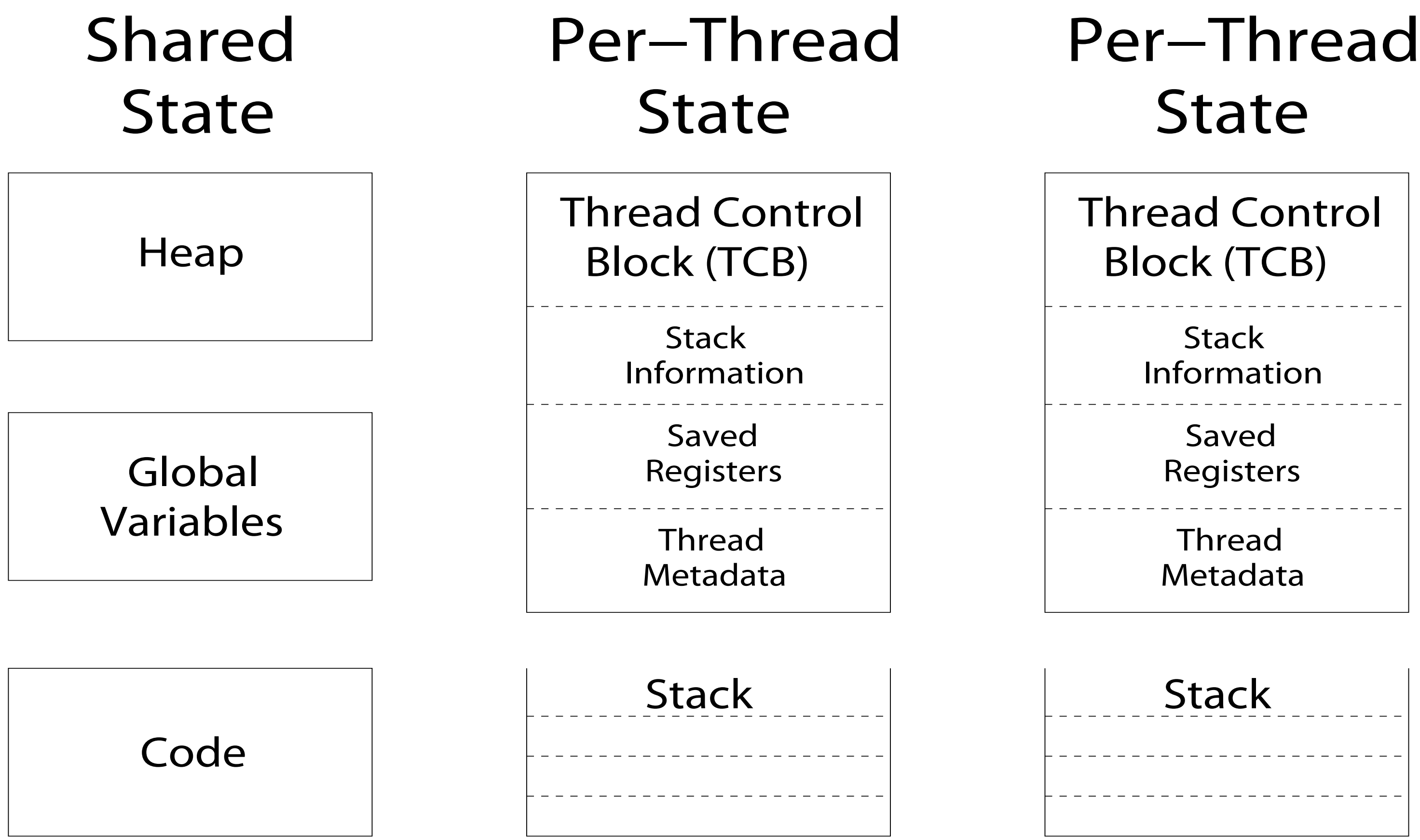
- Scheduling: Mechanism for deciding which processes/threads receive the CPU
- Lots of different scheduling policies provide …
  – Fairness or
  – Real-time guarantees or
  – Latency optimization or ..

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?

[redacted]

Administrivia

- Homework 1 due Wed 2/10
- Project 1 in full swing! (Design doc due Tue 2/9)
  - We expect that your design document will give intuitions behind your designs, not just a dump of pseudo-code
  - Think of this you are in a company and your TA is you manager
- Paradox: need code for design document?
  - Not full code, just enough prove you have thought through complexities of design
- Should be attending your permanent discussion section!
  - Remember to turn on your camera in Zoom
  - Discussion section attendance is mandatory
- Midterm 1: Thu February 18th, 5-6:30PM (Two weeks from today!)
  - Video Proctored, Use of computer to answer questions
  - More details as we get closer to exam

[redacted]

The Core of Concurrency: the Dispatch Loop

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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();
    }
}
```

Recall: POSIX API for Threads: *pthreads*

```
int pthread_create(pthread_t *thread, const pthread_attr_t *attr,
                   void *(*start_routine)(void*), void *arg);
```

– thread is created executing *start_routine* with *arg* as its sole argument.

– return is implicit call to pthread_exit

```
void pthread_exit(void *value_ptr);
```

– terminates the thread and makes *value_ptr* available to any successful join

```
int pthread_join(pthread_t thread, void **value_ptr);
```

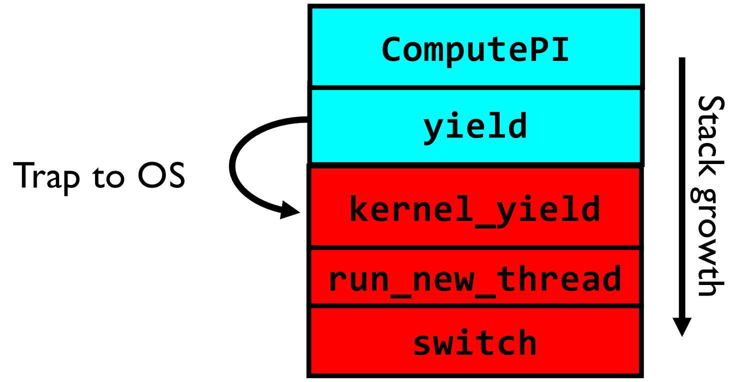
– suspends execution of the calling thread until the target *thread* terminates.

– On return with a non-NULL *value_ptr* the value passed to pthread_exit() by the terminating thread is made available in the location referenced by *value_ptr*.

```
void pthread_yield(void);
void sched_yield(void);
```

– Current thread *yields* (gives up) CPU so that another thread can run

Stack for Yielding Thread



- How do we run a new thread?

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

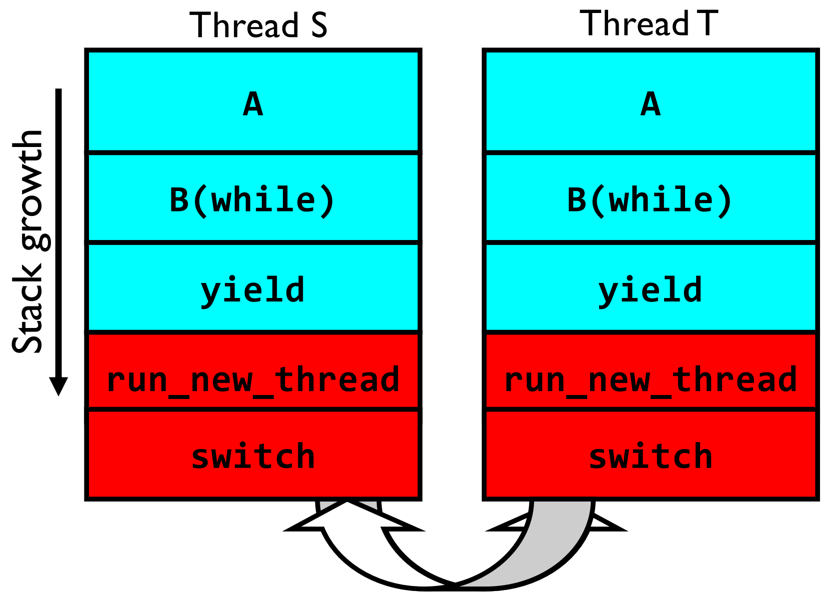
- How does dispatcher switch to a new thread?
  – Save anything next thread may trash: PC, regs, stack pointer
  – Maintain isolation for each thread

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)

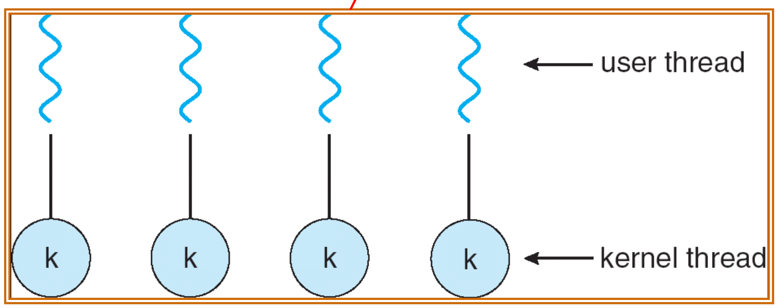
```
Switch(tCur,tNew) {
   /* Unload old thread */
   TCB[tCur].regs.r7 = CPU.r7;
         …
   TCB[tCur].regs.r0 = CPU.r0;
   TCB[tCur].regs.sp = CPU.sp;
   TCB[tCur].regs.retpc = CPU.retpc; /*return addr*/

   /* 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)

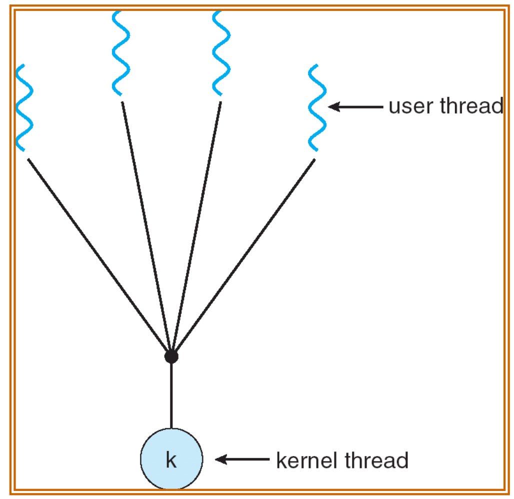
- What if you make a mistake in implementing switch?
  - Suppose you forget to save/restore register 32
  - Get intermittent failures depending on when context switch occurred and whether new thread uses register 32
  - System will give wrong result without warning
- Can you devise an exhaustive test to test switch code?
  - No! Too many combinations and inter-leavings
- 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

Aren't we still switching contexts?

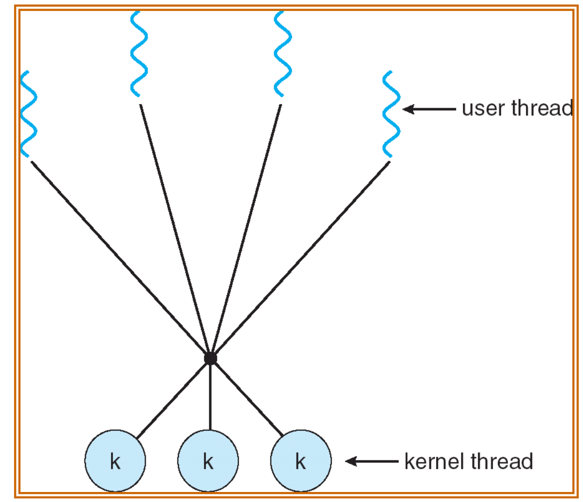
What we are talking about
in Today's lecture



Simple One-to-One Threading Model



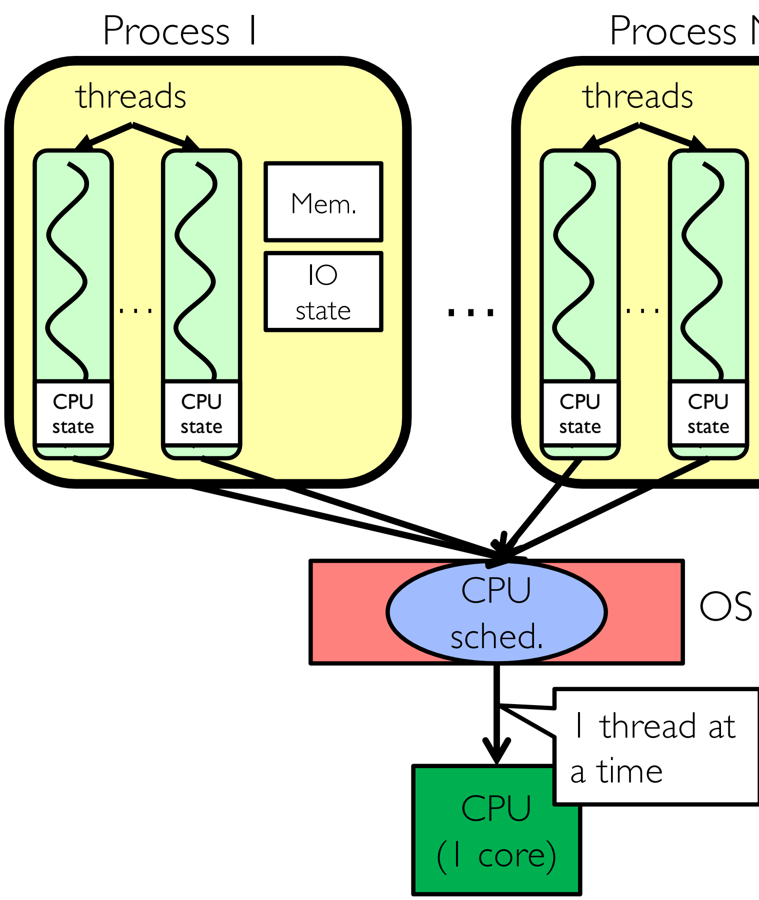
Many-to-One



Many-to-Many

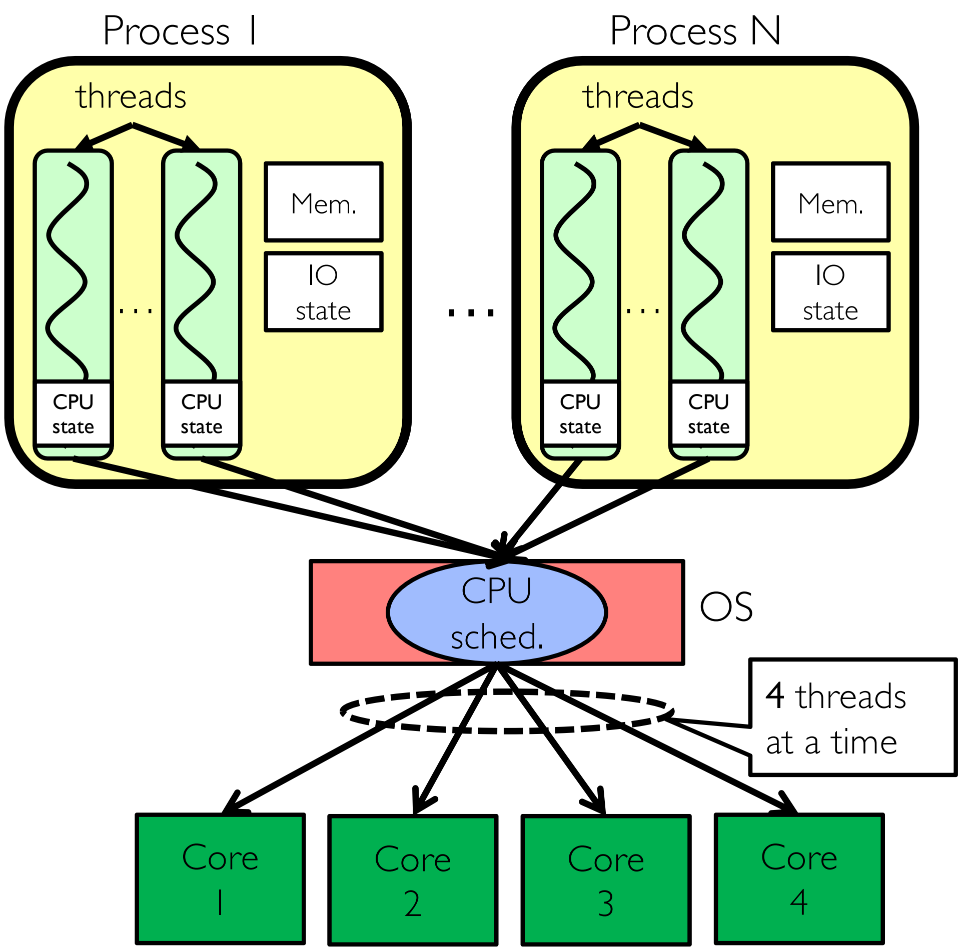
- Yes, but much cheaper than switching processes
  - No need to change address space
- Some numbers from Linux:
  - Frequency of context switch: 10-100ms
  - Switching between processes: 3-4 μsec.
  - Switching between threads: 100 ns
- Even cheaper: switch threads (using "yield") in user-space!

Processes vs. Threads



- 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

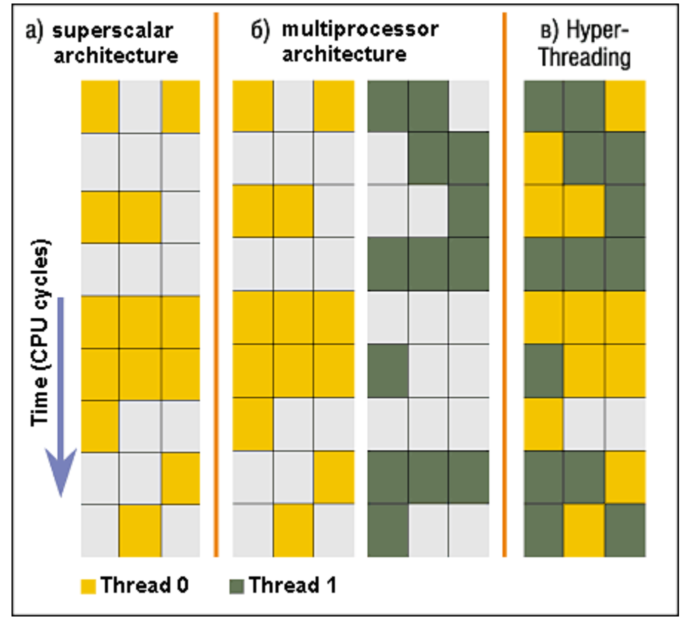
Processes vs. Threads



- 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**

Simultaneous MultiThreading/Hyperthreading

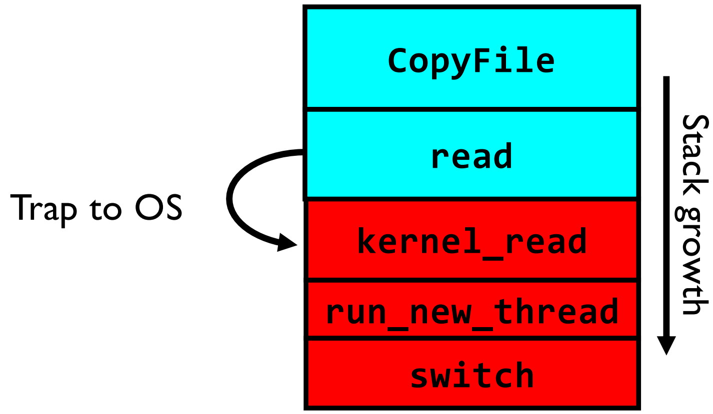
- Hardware scheduling technique
  - Superscalar processors can execute multiple instructions that are independent.
  - Hyperthreading duplicates register state to make a second "thread," allowing more instructions to run.
- Can schedule each thread as if were separate CPU
  - But, sub-linear speedup!



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

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

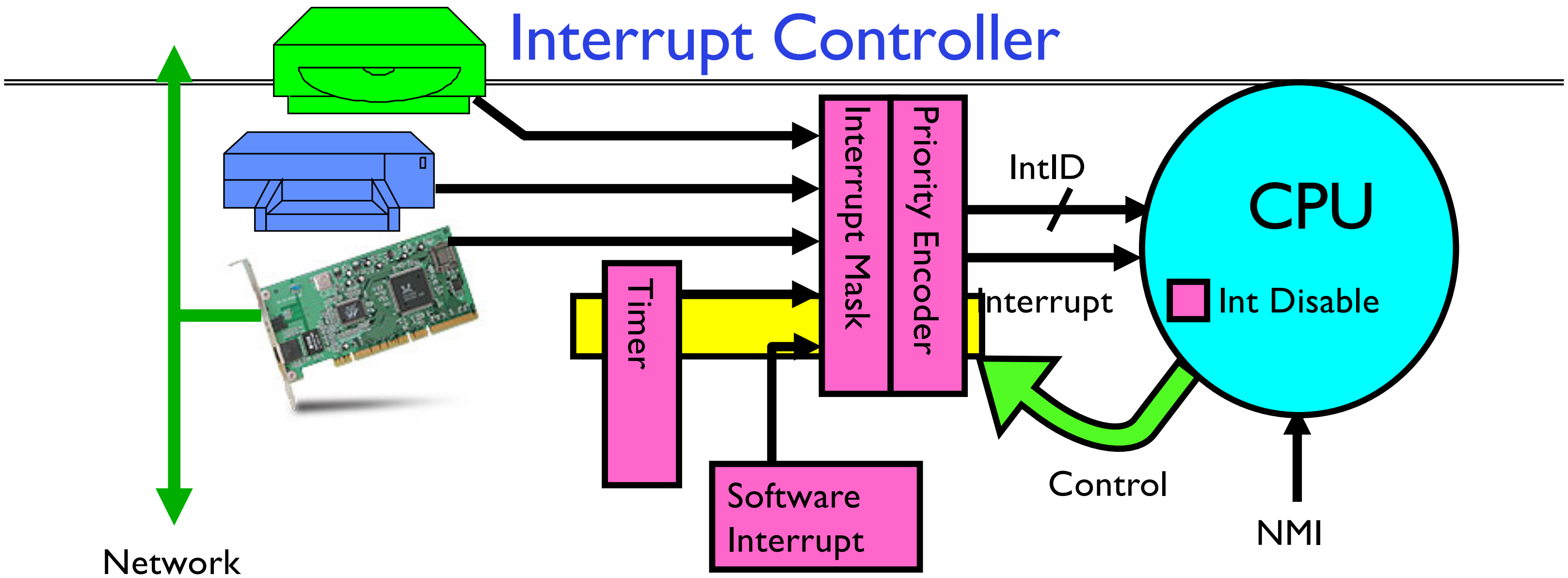
External Events

- 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

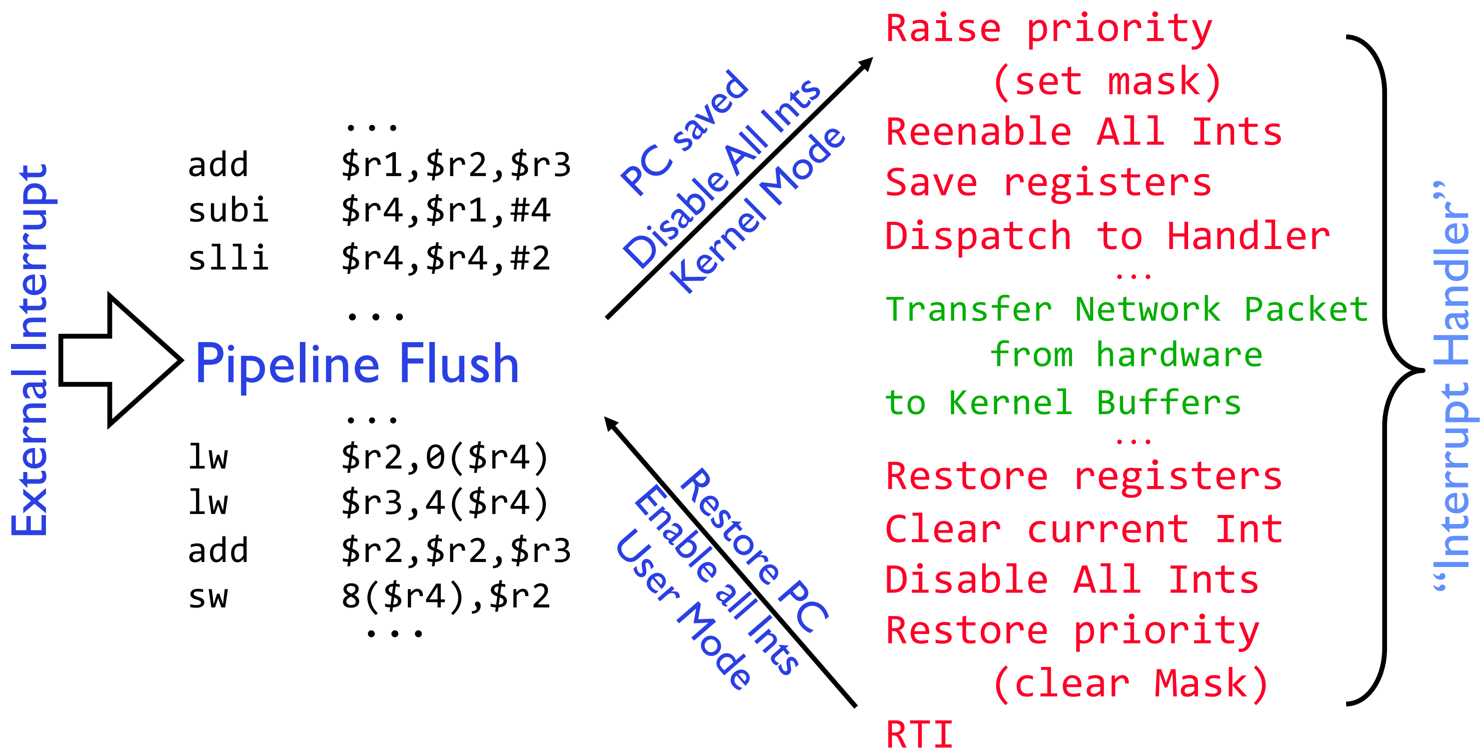
- If we make sure that external events occur frequently enough, can ensure dispatcher runs

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

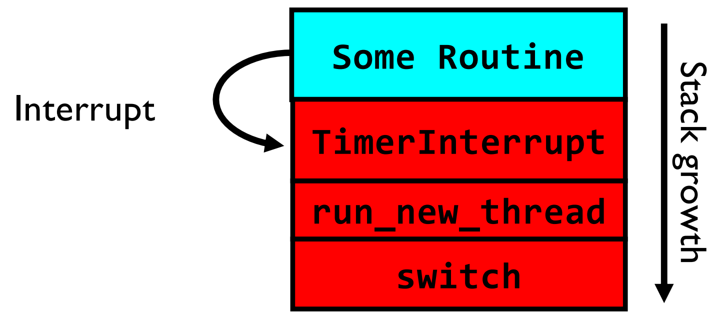
Example: Network Interrupt



- 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

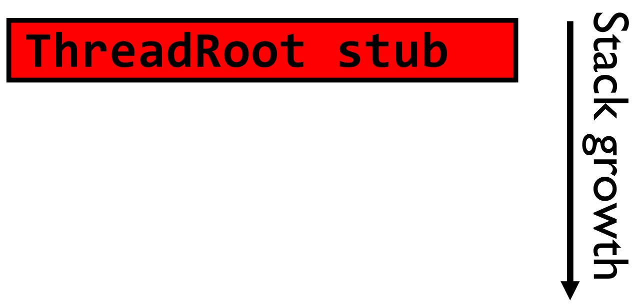


- Timer Interrupt routine:

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

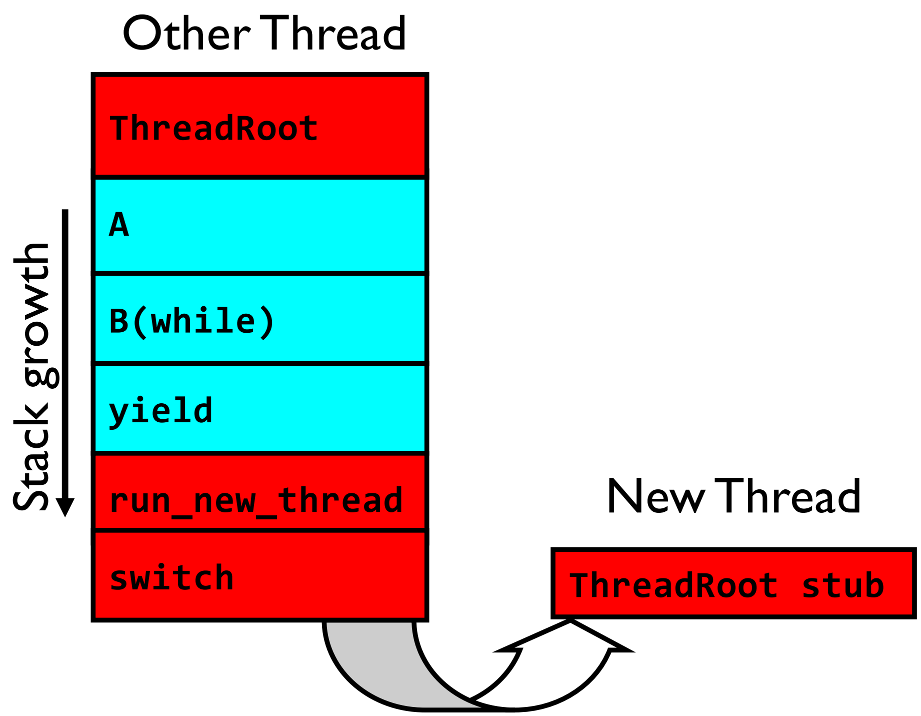
How do we initialize TCB and Stack?

- 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



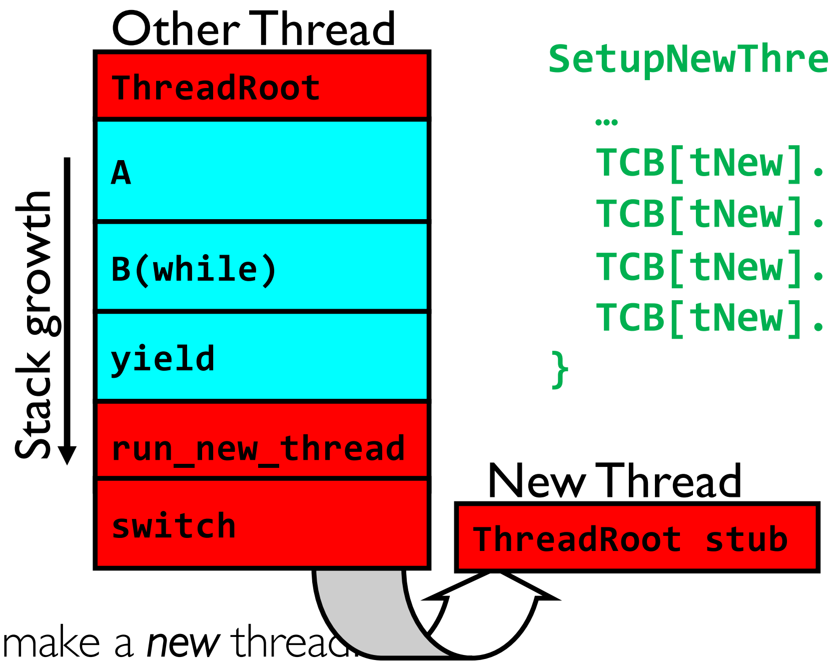
Initial Stack

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

How does a thread get started?



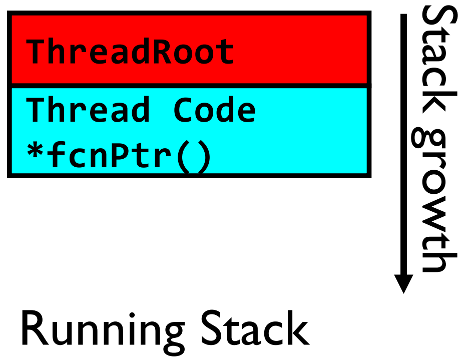

```
SetupNewThread(tNew) {
   …
   TCB[tNew].regs.sp = newStackPtr;
   TCB[tNew].regs.retpc = &ThreadRoot;
   TCB[tNew].regs.r0 = fcnPtr
   TCB[tNew].regs.r1 = fcnArgPtr
}
```

- 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
  - 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();
}
```



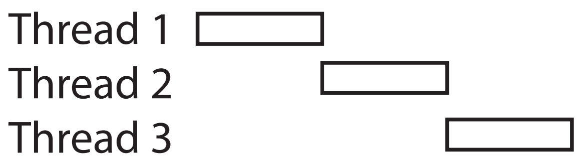
- Startup Housekeeping
  – Includes things like recording start time of thread
  – Other statistics
- Stack will grow and shrink with execution of thread
- Final return from thread returns into `ThreadRoot()` which calls `ThreadFinish()`
  – `ThreadFinish()` wake up sleeping threads

[redacted]

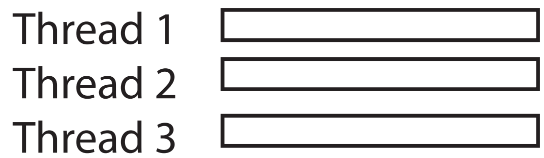
Correctness with Concurrent Threads?

- 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**

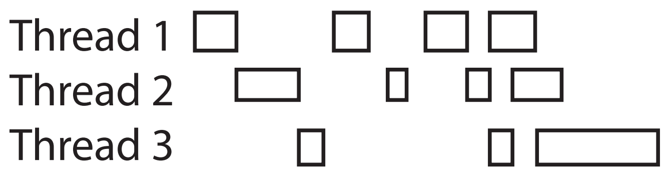
Recall: Possible Executions



a) One execution

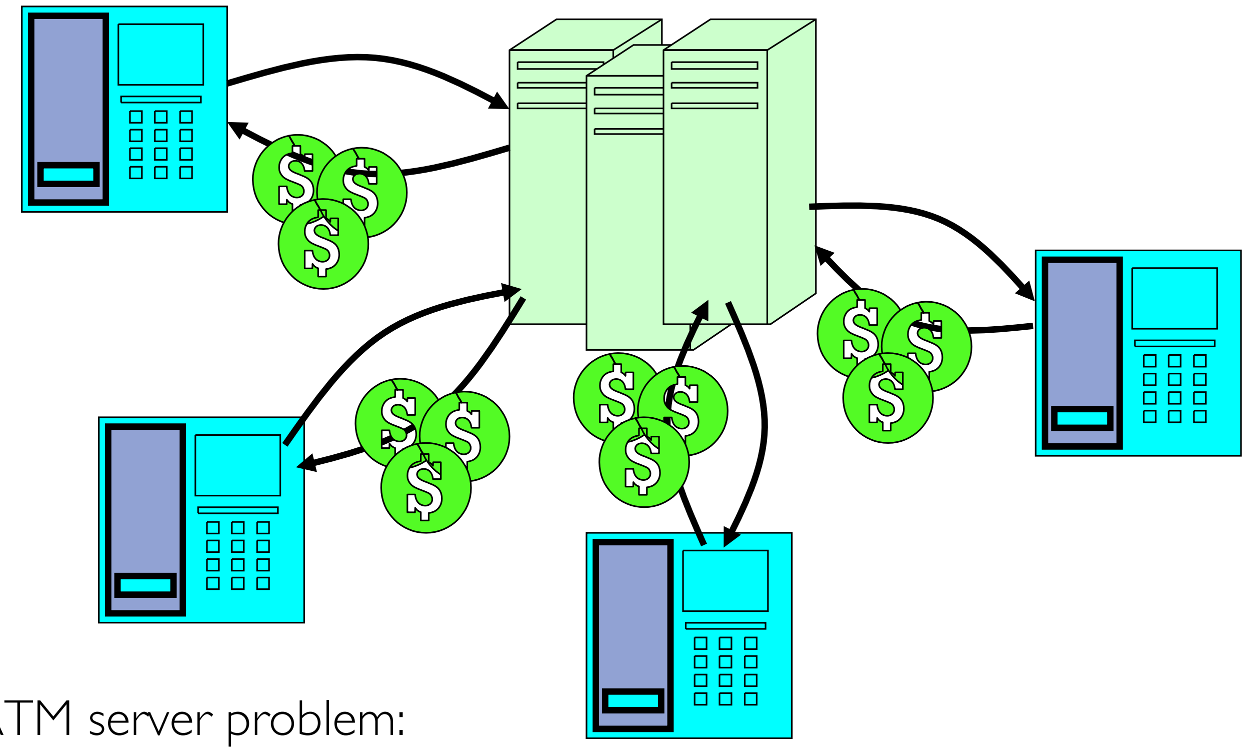


b) Another execution



c) Another execution

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();
   }
}
```

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

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
```

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;

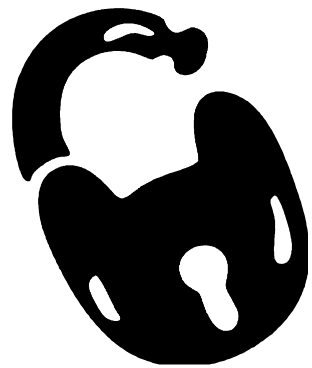
  – X could be 1 or 2 (non-deterministic!)
  – Could even be 3 for serial processors:
    » Thread A writes 0001, B writes 0010
    → scheduling order ABABABBA yields 3!

[redacted]

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

Recall: Locks



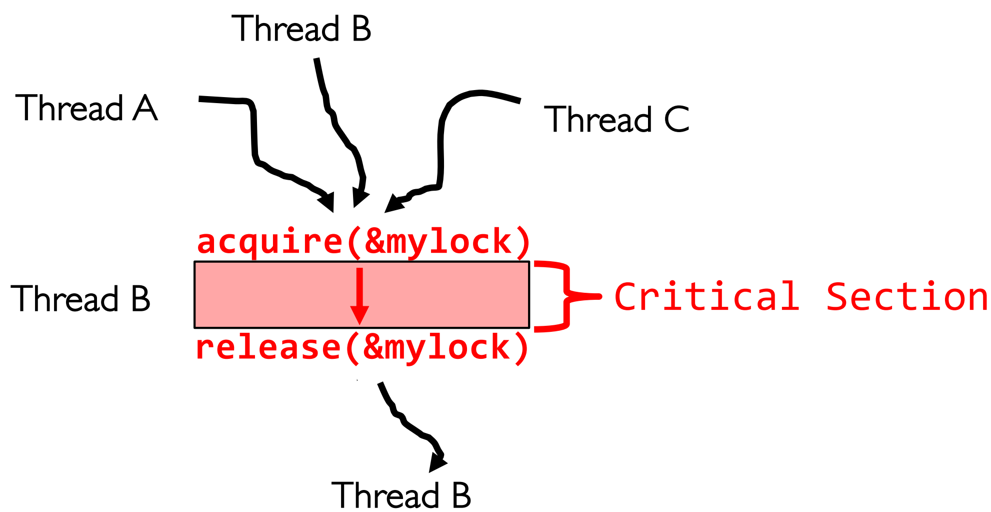
- Lock: prevents someone from doing something
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting
- Locks need to be allocated and initialized:
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

Recall: 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

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

Thread A	Thread B

```
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
  – No difference between: "i=i+1" and "i++"
  – Same instruction sequence, the ++ operator is just syntactic sugar
- 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"
- Uncontrolled race condition: two threads attempting to access same data *simultaneously* with one of them performing a write
  - Here "simultaneous" is defined even with one CPU as "could access at same time if only there were two CPUs

So – does this fix it?

- Put locks around increment/decrement:

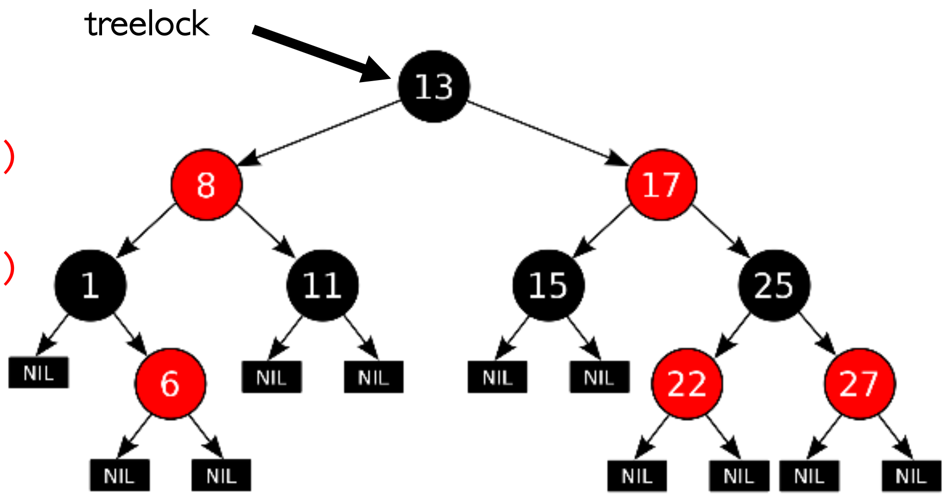
```
Thread A                   Thread B
i = 0;                     i = 0;
while (i < 10)             while (i > -10)
   acquire(&mylock)           acquire(&mylock)
   i = i + 1;                 i = i - 1;
   release(&mylock)           release(&mylock)
printf("A wins!");         printf("B wins!");
```

- What does this do? Is it better???
- Each increment or decrement operation is now atomic. Good!
  – Technically, no race conditions, since lock prevents simultaneous reads/writes
- Program is likely still broken. Not so good…
  – May or may not be what you intended (probably not)
  – Still unclear who wins – it is a nondeterministic result: different on each run
- When might something like this make sense?
  – If each thread needed to get a unique integer for some reason

Recall: Red-Black tree example

Thread A

```
Insert(3) {
  acquire(&treelock)
  Tree.Insert(3)
  release(&treelock)
}
```



Tree-Based Set Data Structure

Thread B

```
Insert(4) {
  acquire(&treelock)
  Tree.insert(4)
  release(&treelock)
}
Get(6) {
  acquire(&treelock)
  Tree.search(6)
  release(&treelock)
}
```

- Here, the Lock is associated with the root of the tree
  - Restricts parallelism but makes sure that tree *always* consistent
  - No races at the operation level
- Threads are exchange information through a consistent data structure
- Could you make it faster with one lock per node? Perhaps, but must be careful!
  - Need to define invariants that are always true despite many simultaneous threads…

Concurrency is Hard!

- Even for practicing engineers trying to write mission-critical, bulletproof code!
  - 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!
- Therac-25: Radiation Therapy Machine with Unintended Overdoses (reading on course site)
  - Concurrency errors caused the death of a number of patients by misconfiguring the radiation production
  - Improper synchronization between input from operators and positioning software
- Mars Pathfinder Priority Inversion (JPL Account)
- Toyota Uncontrolled Acceleration (CMU Talk)
  - 256.6K Lines of C Code, ~9-11K global variables
  - Inconsistent mutual exclusion on reads/writes

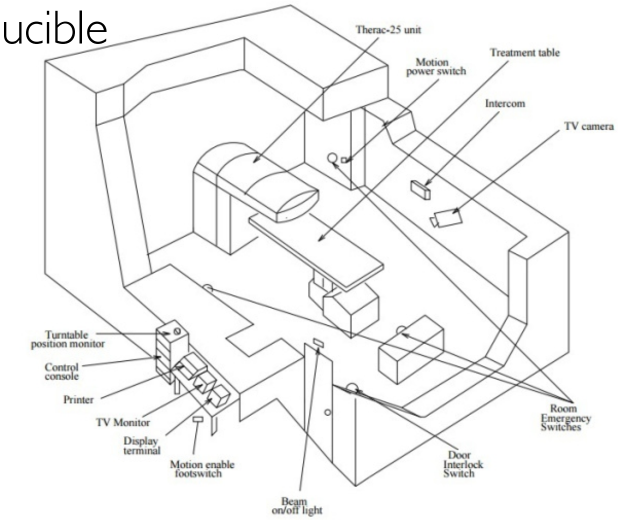


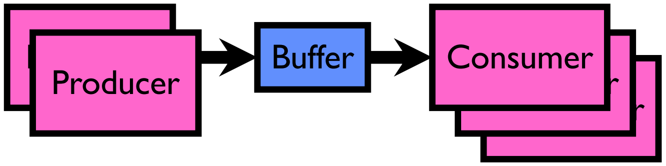
Figure 5: A typical Therac-25 facility after the final CAP.

Conclusion

- 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) or involuntary (interrupts)
- TCB + Stacks hold complete state of thread for restarting
- Atomic Operation: an operation that always runs to completion or not at all
- Synchronization: using atomic operations to ensure cooperation between threads
- 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
- Locks: synchronization mechanism for enforcing mutual exclusion on critical sections to construct atomic operations

[redacted]

Producer-Consumer with a Bounded Buffer



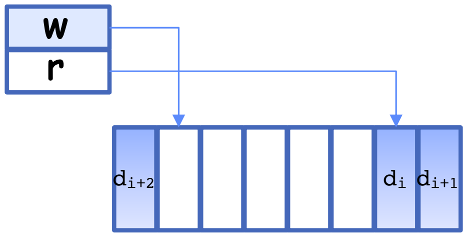
- Problem Definition
  – Producer(s) put things into a shared buffer
  – Consumer(s) take them out
  – Need synchronization to coordinate producer/consumer

- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  – Need to synchronize access to this buffer
  – Producer needs to wait if buffer is full
  – Consumer needs to wait if buffer is empty

- Example 1: GCC compiler
  – `cpp | cc1 | cc2 | as | ld`
- Example 2: Coke machine
  – Producer can put limited number of Cokes in machine
  – Consumer can't take Cokes out if machine is empty
- Others: Web servers, Routers, ….

Circular Buffer Data Structure (sequential case)

```
typedef struct buf {
  int write_index;
  int read_index;
  <type> *entries[BUFSIZE];
} buf_t;
```



- Insert: write & bump write ptr (enqueue)
- Remove: read & bump read ptr (dequeue)
- *How to tell if Full (on insert) Empty (on remove)?*
- *And what do you do if it is?*
- *What needs to be atomic?*

Circular Buffer – first cut

```
mutex buf_lock = <initially unlocked>

Producer(item) {
  acquire(&buf_lock);
  while (buffer full) {}; // Wait for a free slot
  enqueue(item);
  release(&buf_lock);
}

Consumer() {
  acquire(&buf_lock);
  while (buffer empty) {}; // Wait for arrival
  item = dequeue();
  release(&buf_lock);
  return item
}
```

Will we ever come out of the wait loop?

Circular Buffer – 2nd cut

```
mutex buf_lock = <initially unlocked>

Producer(item) {
  acquire(&buf_lock);
  while (buffer full) {release(&buf_lock); acquire(&buf_lock);}
  enqueue(item);
  release(&buf_lock);
}
```

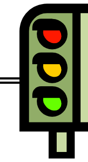
What happens when one is waiting for the other?
- Multiple cores ?
- Single core ?

```
Consumer() {
  acquire(&buf_lock);
  while (buffer empty) {release(&buf_lock); acquire(&buf_lock);}
  item = dequeue();
  release(&buf_lock);
  return item
}
```

Higher-level Primitives than Locks

- What is right abstraction for synchronizing threads that share memory?
  – Want as high a level primitive as possible
- Good primitives and practices important!
  – Since execution is not entirely sequential, really hard to find bugs, since they happen rarely
  – UNIX is pretty stable now, but up until about mid-80s (10 years after started), systems running UNIX would crash every week or so – concurrency bugs
- Synchronization is a way of coordinating multiple concurrent activities that are using shared state
  – This lecture and the next presents a some ways of structuring sharing

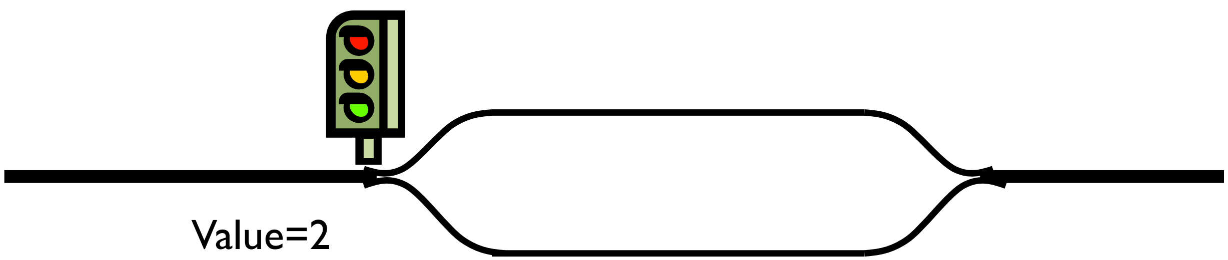
Recall: Semaphores



- Semaphores are a kind of generalized lock
  - First defined by Dijkstra in late 60s
  - Main synchronization primitive used in original UNIX
- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
  - `Down()` or `P()`: an atomic operation that waits for semaphore to become positive, then decrements it by 1
    - » Think of this as the wait() operation
  - `Up()` or `V()`: an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
    - » This of this as the signal() operation
  - Note that `P()` stands for "*proberen*" (to test) and `V()` stands for "*verhogen*" (to increment) in Dutch

Semaphores Like Integers Except…

- Semaphores are like integers, except:
  - No negative values
  - Only operations allowed are P and V – can't read or write value, except initially
  - Operations must be atomic
    - » Two P's together can't decrement value below zero
    - » Thread going to sleep in P won't miss wakeup from V – even if both happen at same time
- POSIX adds ability to read value, but technically not part of proper interface!
- Semaphore from railway analogy
  - Here is a semaphore initialized to 2 for resource control:



Two Uses of Semaphores

Mutual Exclusion (initial value = 1)

- Also called "Binary Semaphore" or "mutex".
- Can be used for mutual exclusion, just like a lock:

```
semaP(&mysem);
  // Critical section goes here
semaV(&mysem);
```

Scheduling Constraints (initial value = 0)

- Allow thread 1 to wait for a signal from thread 2
  - thread 2 schedules thread 1 when a given event occurs
- Example: suppose you had to implement ThreadJoin which must wait for thread to terminate:

```
Initial value of semaphore = 0
ThreadJoin {
   semaP(&mysem);
}
ThreadFinish {
   semaV(&mysem);
}
```

Revisit Bounded Buffer: Correctness constraints for solution

- Correctness Constraints:
  - Consumer must wait for producer to fill buffers, if none full (scheduling constraint)
  - Producer must wait for consumer to empty buffers, if all full (scheduling constraint)
  - Only one thread can manipulate buffer queue at a time (mutual exclusion)
- Remember why we need mutual exclusion
  - Because computers are stupid
  - Imagine if in real life: the delivery person is filling the machine and somebody comes up and tries to stick their money into the machine
- General rule of thumb: Use a separate semaphore for each constraint

```
– Semaphore fullBuffers; // consumer's constraint
– Semaphore emptyBuffers;// producer's constraint
– Semaphore mutex;       // mutual exclusion
```

Full Solution to Bounded Buffer (coke machine)


```
Semaphore fullSlots = 0;      // Initially, no coke
Semaphore emptySlots = bufSize;
                              // Initially, num empty slots
Semaphore mutex = 1;          // No one using machine

Producer(item) {
    semaP(&emptySlots);       // Wait until space
    semaP(&mutex);            // Wait until machine free
    Enqueue(item);
    semaV(&mutex);
    semaV(&fullSlots);        // Tell consumers there is
                              // more coke
}
Consumer() {
    semaP(&fullSlots);        // Check if there's a coke
    semaP(&mutex);            // Wait until machine free
    item = Dequeue();
    semaV(&mutex);
    semaV(&emptySlots);       // tell producer need more
    return item;
}
```

`fullSlots` signals coke

`emptySlots` signals space

Critical sections using mutex protect integrity of the queue

Discussion about Solution

- Why asymmetry?
  - Producer does: **semaP(&emptyBuffer), semaV(&fullBuffer)**
  - Consumer does: **semaP(&fullBuffer), semaV(&emptyBuffer)**

Decrease # of empty slots

Increase # of occupied slots

Decrease # of occupied slots

Increase # of empty slots

- Is order of P's important?
- Is order of V's important?
- What if we have 2 producers or 2 consumers?

```
Producer(item) {
  semaP(&mutex);
  semaP(&emptySlots);
  Enqueue(item);
  semaV(&mutex);
  semaV(&fullSlots);
}
Consumer() {
  semaP(&fullSlots);
  semaP(&mutex);
  item = Dequeue();
  semaV(&mutex);
  semaV(&emptySlots);
  return item;
}
```

Where are we going with synchronization?

Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- We are going to implement various higher-level synchronization primitives using atomic operations
  - Everything is pretty painful if only atomic primitives are load and store
  - Need to provide primitives useful at user-level
- Talk about how to structure programs so that they are correct
  - Under any scheduling and number of processors

Conclusion

- Concurrency accomplished by multiplexing CPU time:
  - Unloading current thread (PC, registers)
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  - Such context switching may be voluntary (yield(), I/O) or involuntary (interrupts)
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