CS162
Operating Systems and Systems Programming
Lecture 7

Concurrency (Continued), Synchronization

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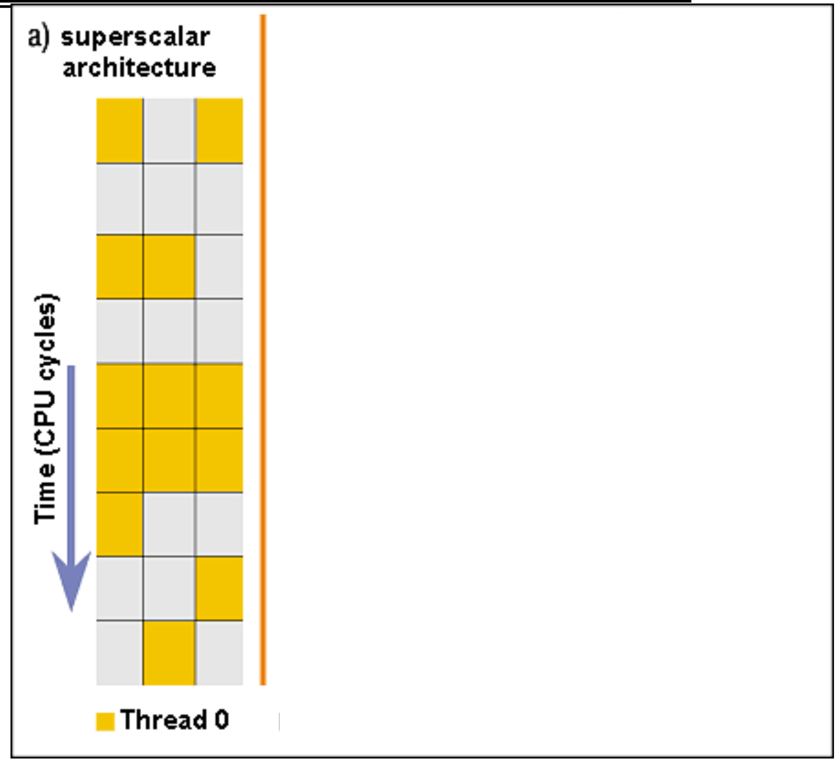
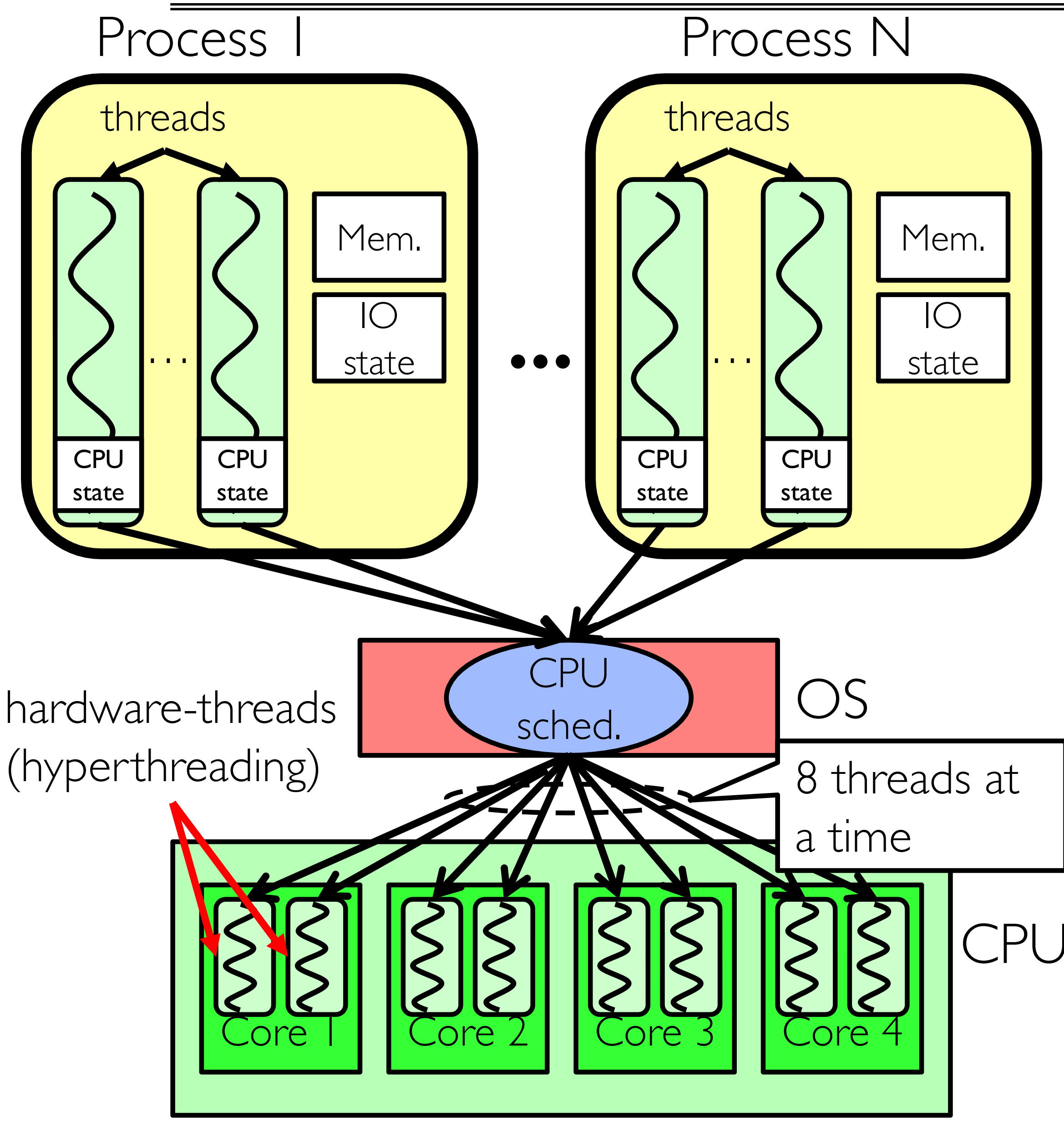
Recall: Simultaneous MultiThreading/Hyperthreading

- 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

Recall: Putting it Together: Hyper-Threading



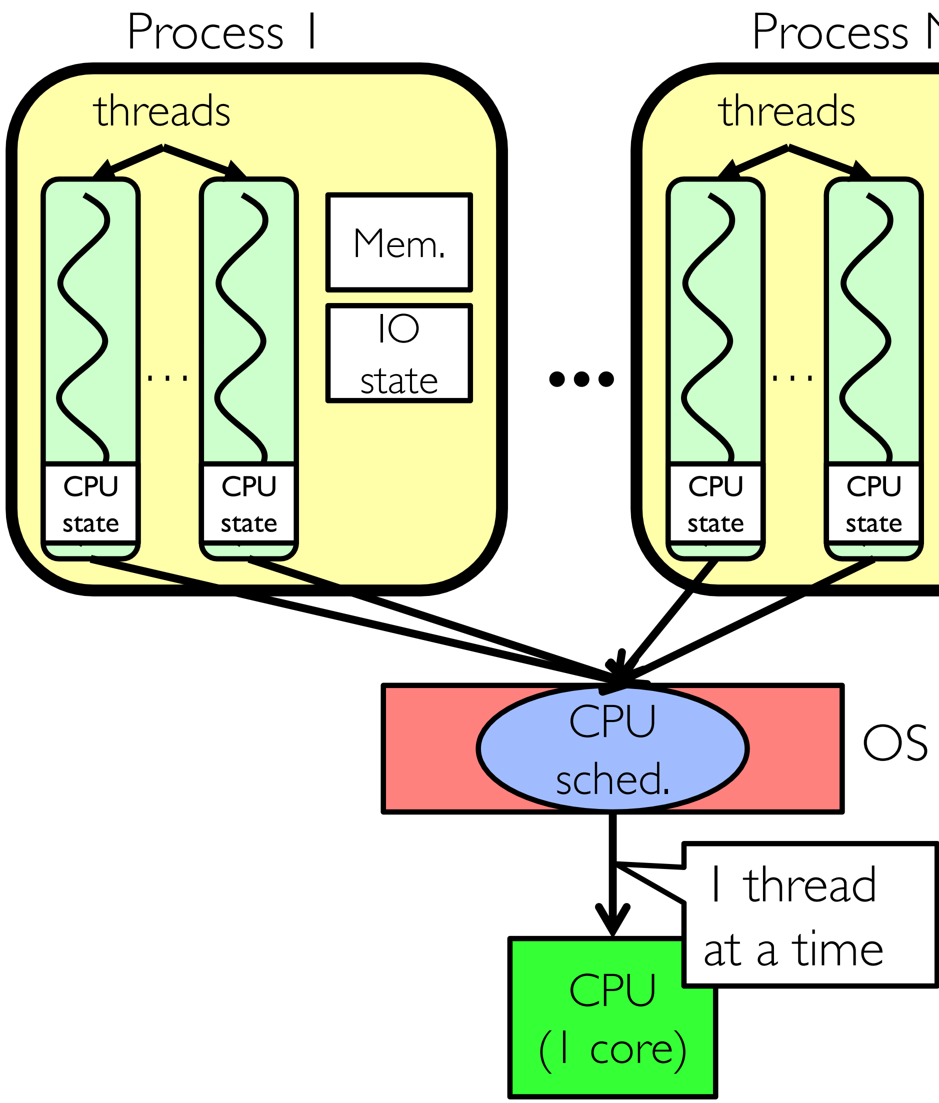
- Switch overhead between hardware-threads: *very-low* (done in hardware)
- Contention for ALUs/FPUs may hurt performance

Recall: 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

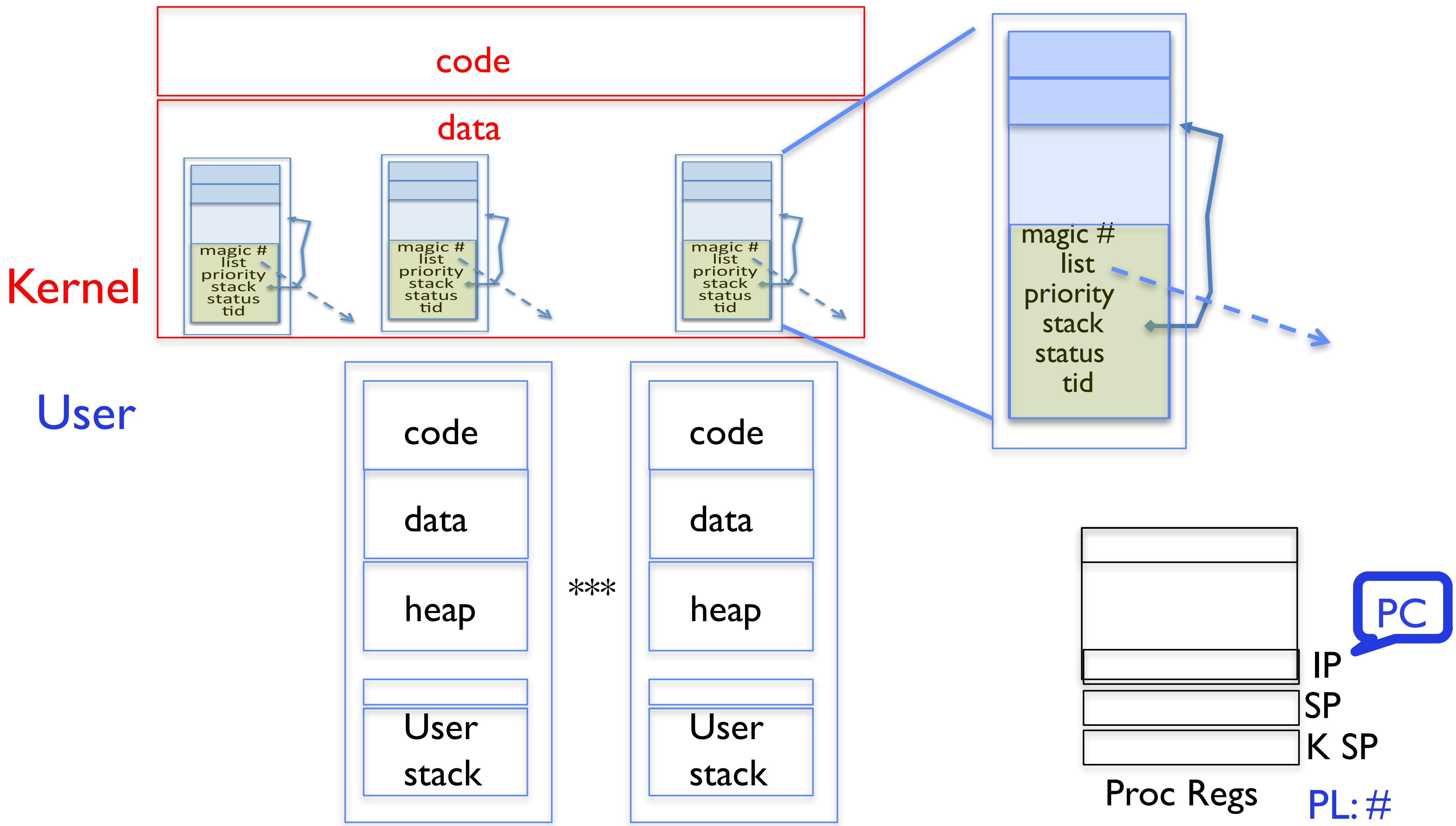
- Most operating systems have either
  – One or many address spaces
  – One or many threads per address space

Summary: Conceptual Framework



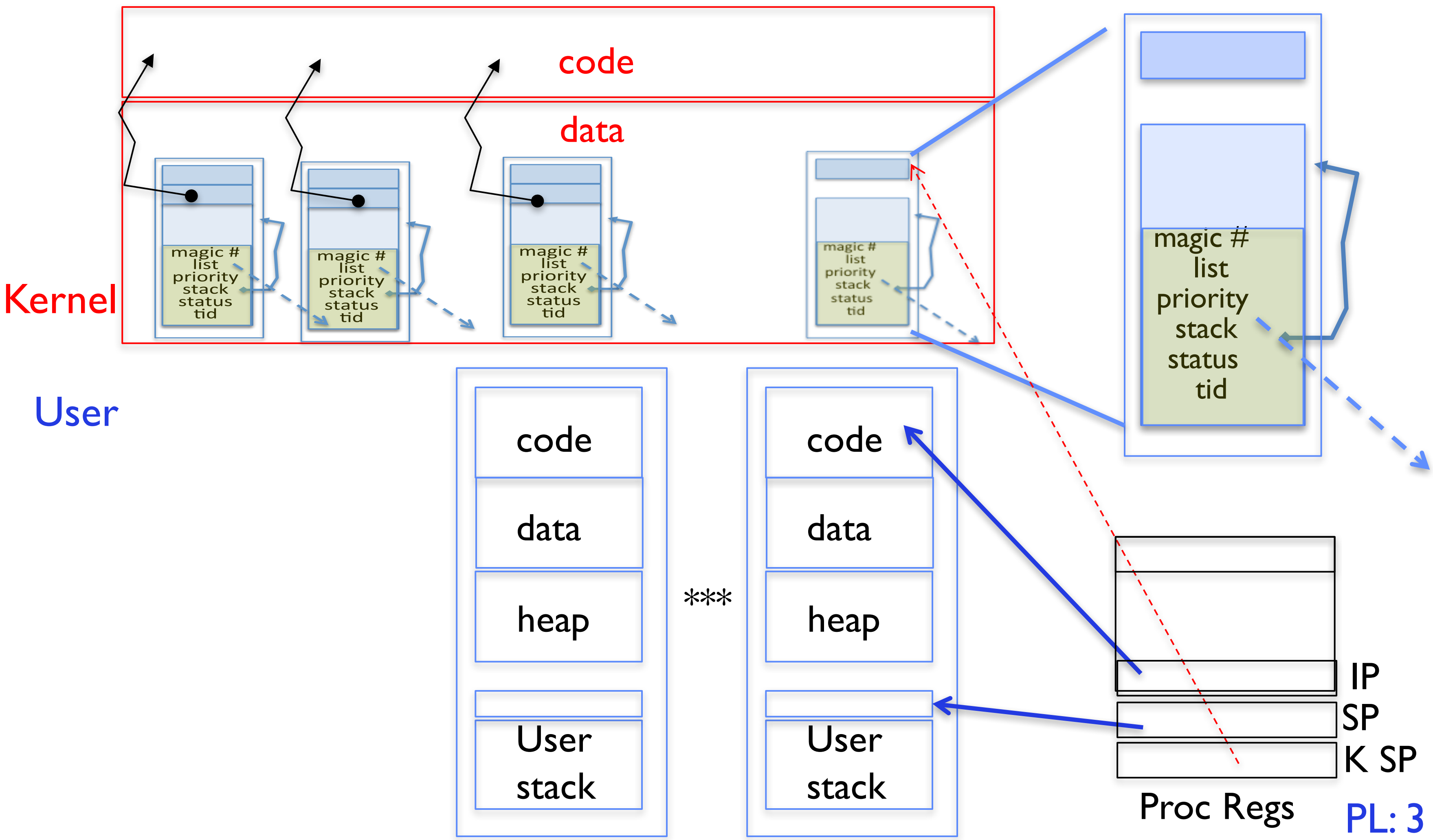
- Physical addresses shared
  - **So:** Processes and Address Translation
- CPU must be Shared
  - **So:** Threads
- Processes aren't trusted
  - **So:** Kernel/Userspace Split
- Threads might not cooperate
  - **So:** Use timer interrupts to context switch ("preemption")

Recall: MT Kernel 1T Process ala Pintos/x86



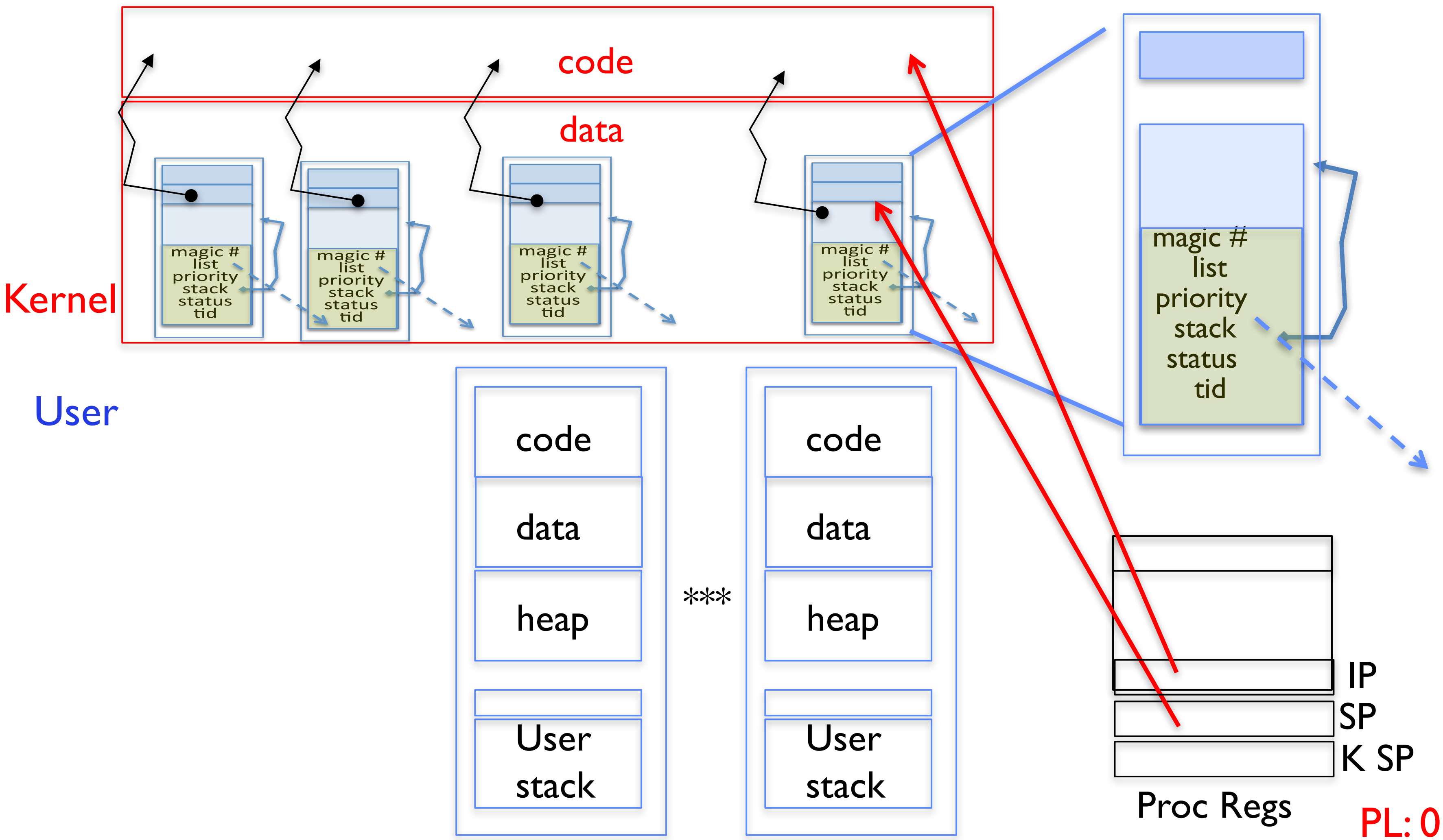
- Each user process/thread associated with a kernel thread, described by a 4KB page object containing TCB and kernel stack for the kernel thread

In User thread, w/ Kernel thread waiting



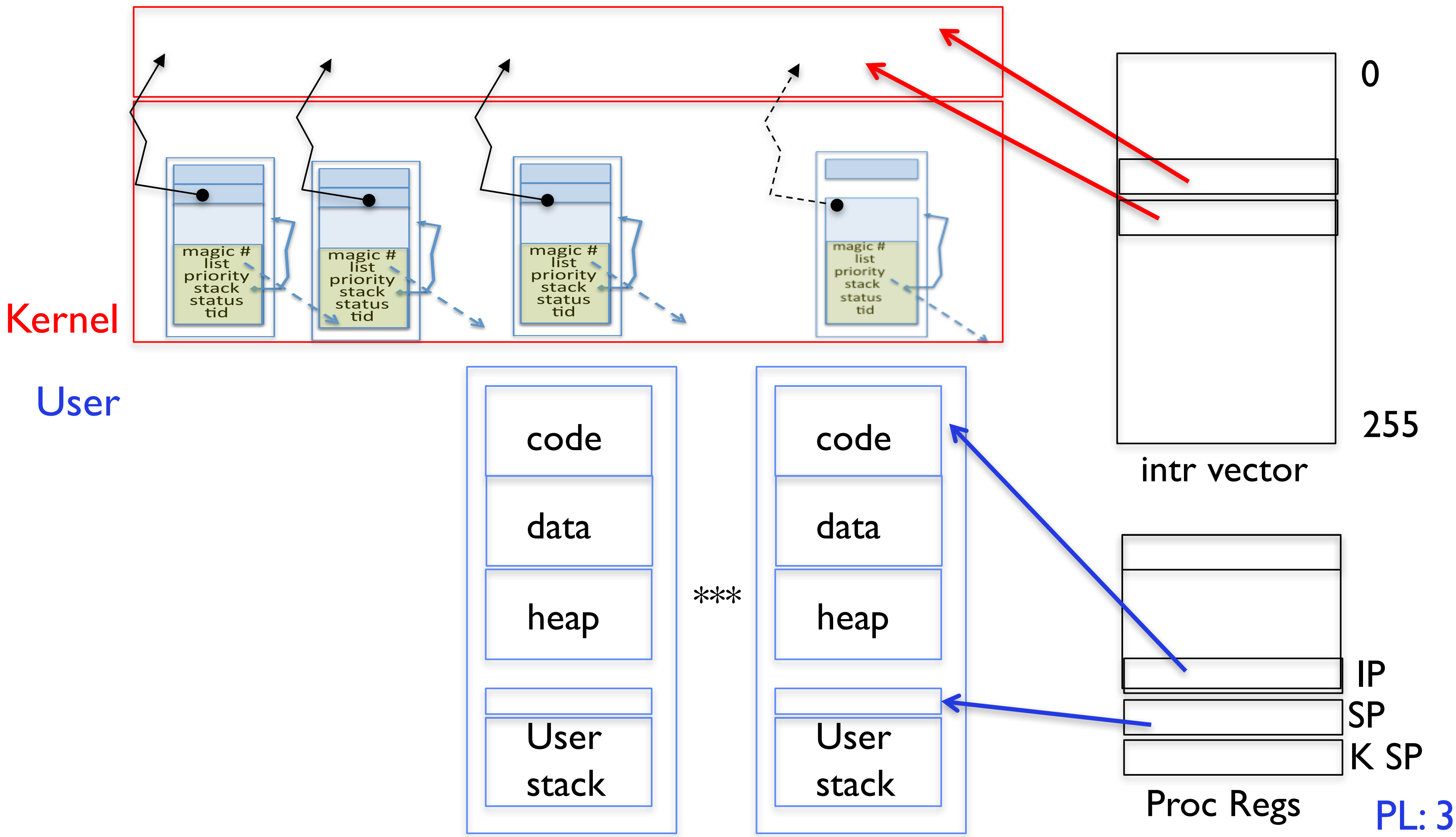
- x86 CPU holds interrupt SP in register
- During user thread execution, associated kernel thread is "standing by"

User → Kernel



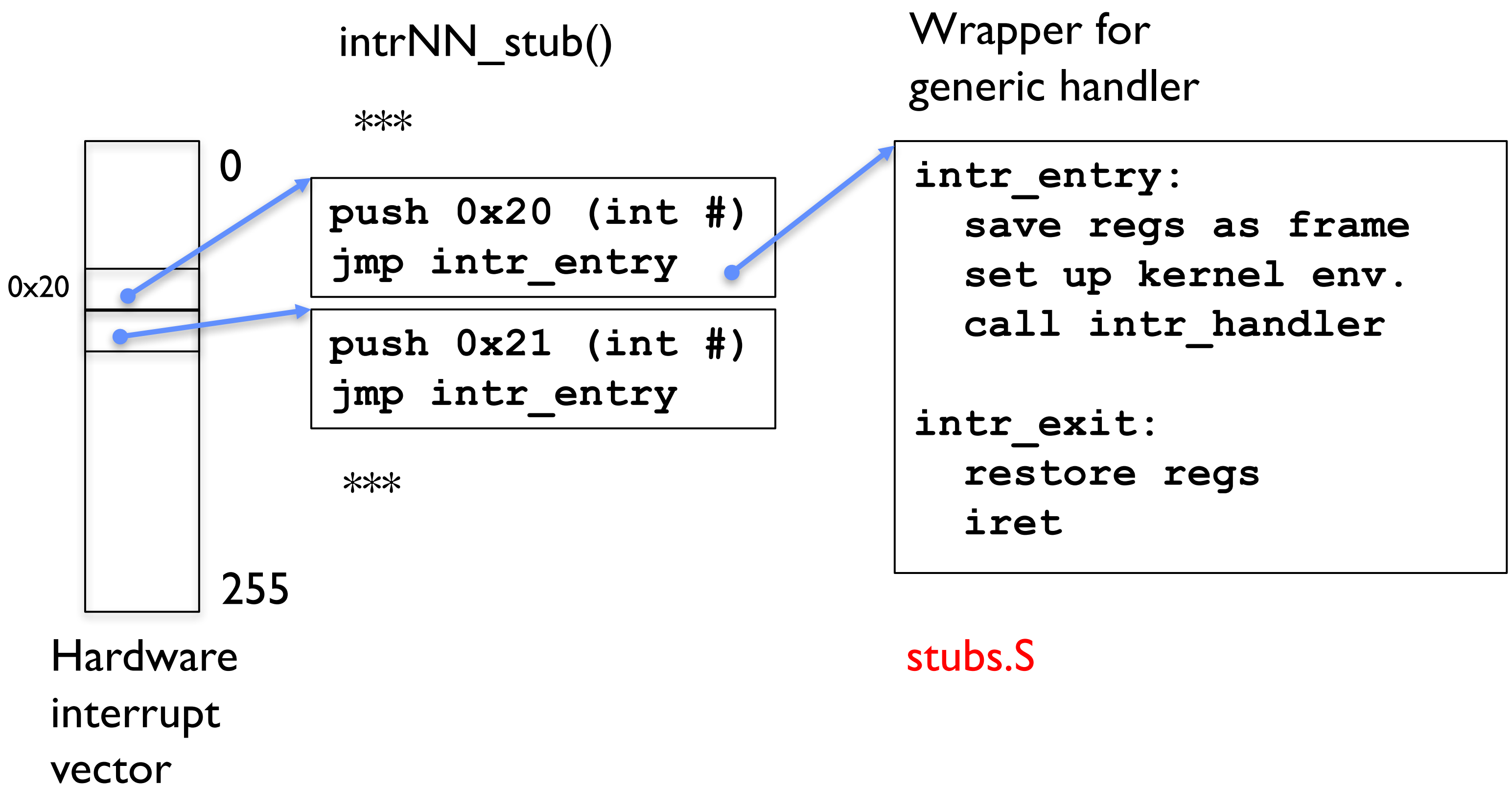
- Mechanism to resume k-thread goes through interrupt vector

User → Kernel via interrupt vector



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

Pintos Interrupt Processing



Recall: cs61C THE STACK FRAME

Basic Structure of a Function

Prologue

```
entry_label:
addi $sp,$sp, -framesize
sw $ra, framesize-4($sp)  # save $ra
save other regs if need be
```

Body . . .   (call other functions…)

ra

memory

Epilogue

```
restore other regs if need be
lw $ra, framesize-4($sp)  # restore $ra
addi $sp,$sp, framesize
jr $ra
```

CS61C L10 Introduction to MIPS : Procedures I (18)   Garcia, Spring 2014

The Stack (review)

- Stack frame includes:
  - Return "instruction" address
  - Parameters
  - Space for other local variables
- Stack frames contiguous blocks of memory; stack pointer tells where bottom of stack frame is
- When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames

0xFFFFFFFF →

frame

frame

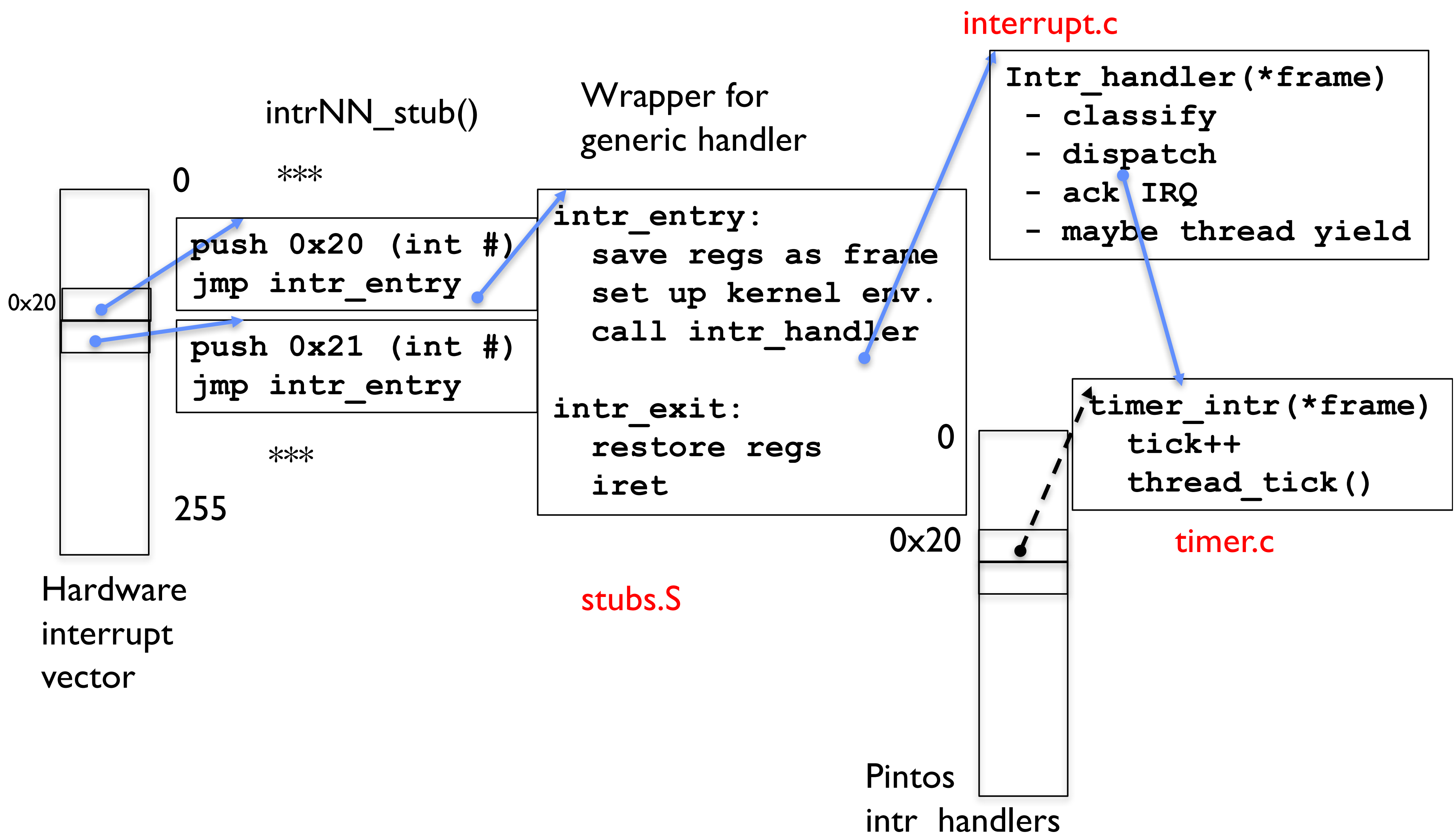
frame

frame

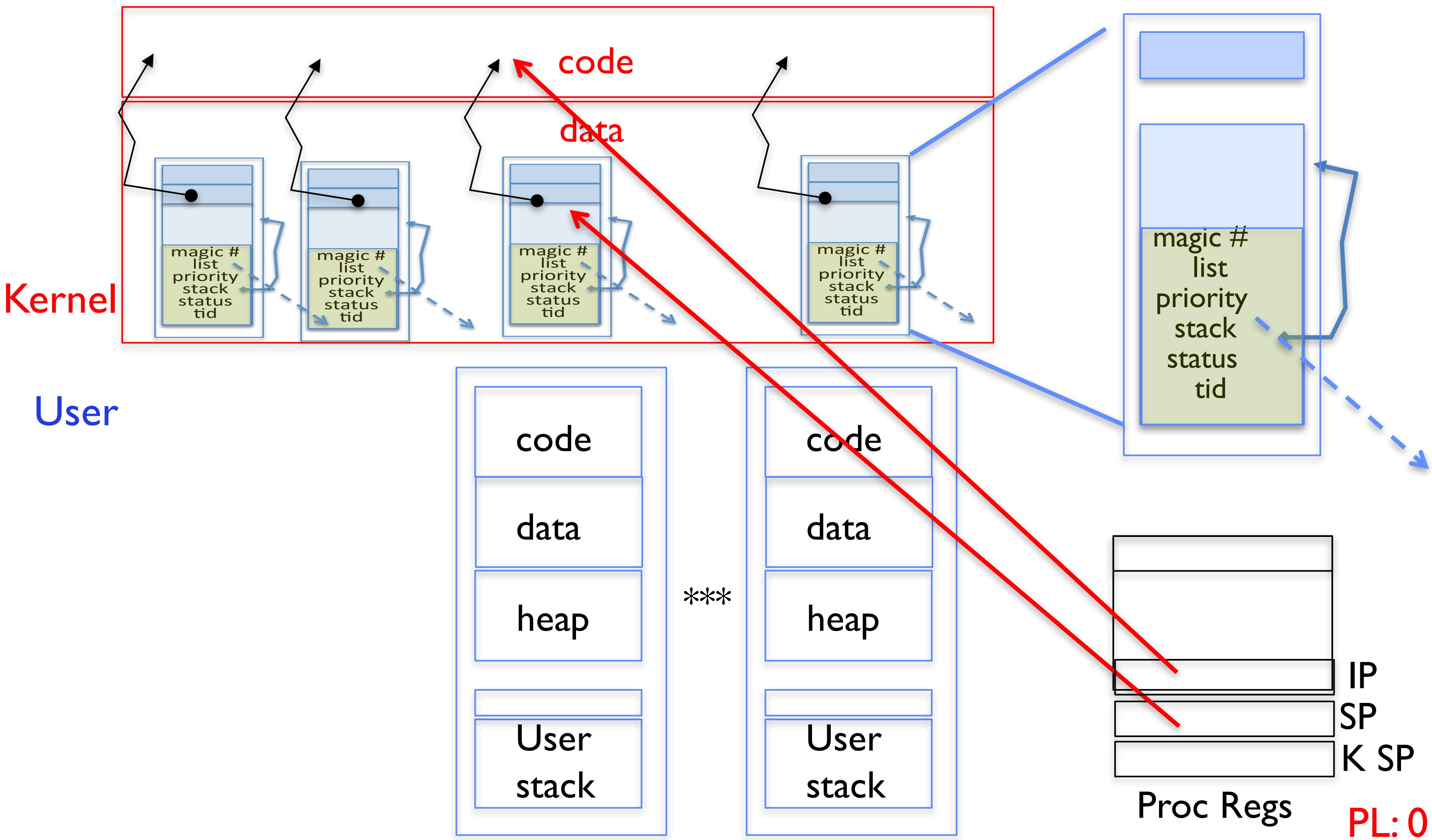
$sp →

CS61C L11 Introduction to MIPS : Procedures II & Logical Ops (3)   Garcia, Spring 2014 © UCB

Pintos Interrupt Processing



In Kernel thread

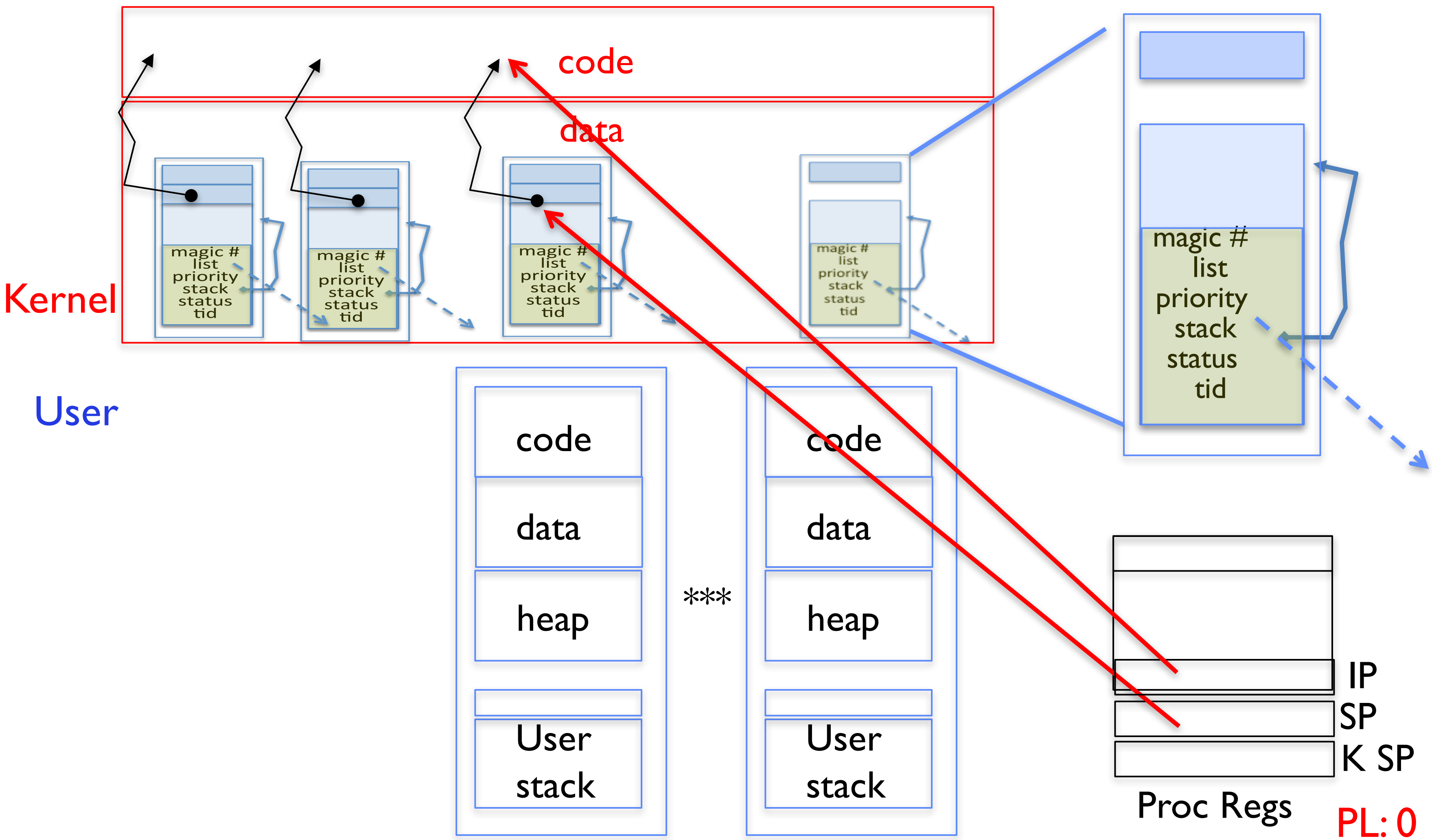


- Kernel threads execute with small stack in thread structure
- Scheduler selects among ready kernel and user threads

Timer may trigger thread switch

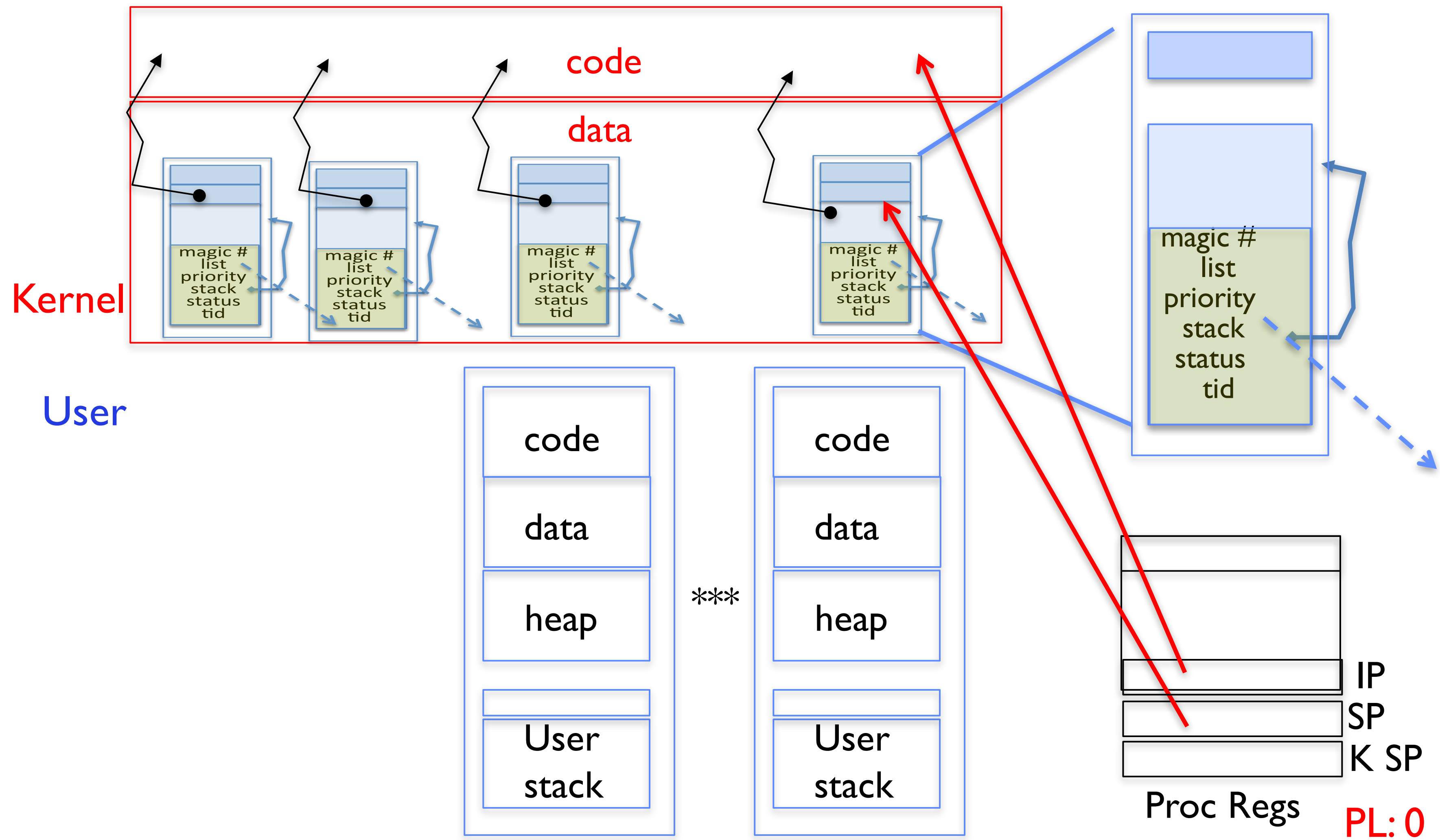
- thread_tick
  - Updates thread counters
  - If quanta exhausted, sets yield flag
- thread_yield
  - On path to rtn from interrupt
  - Sets current thread back to READY
  - Pushes it back on ready_list
  - Calls schedule to select next thread to run upon iret
- Schedule
  - Selects next thread to run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

Thread Switch (switch.S)

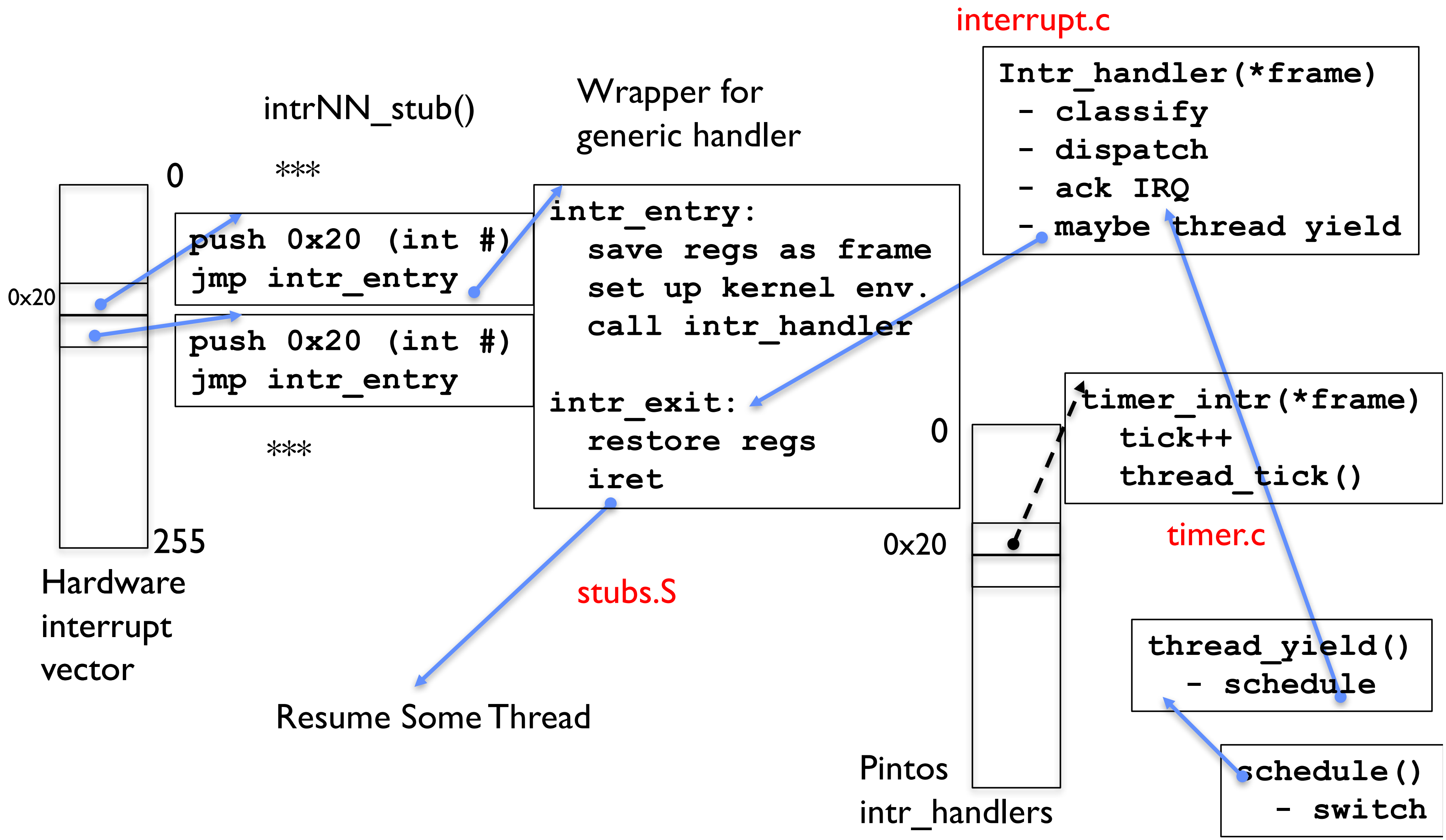


- switch_threads: save regs on current small stack, change SP, return from destination threads call to switch_threads

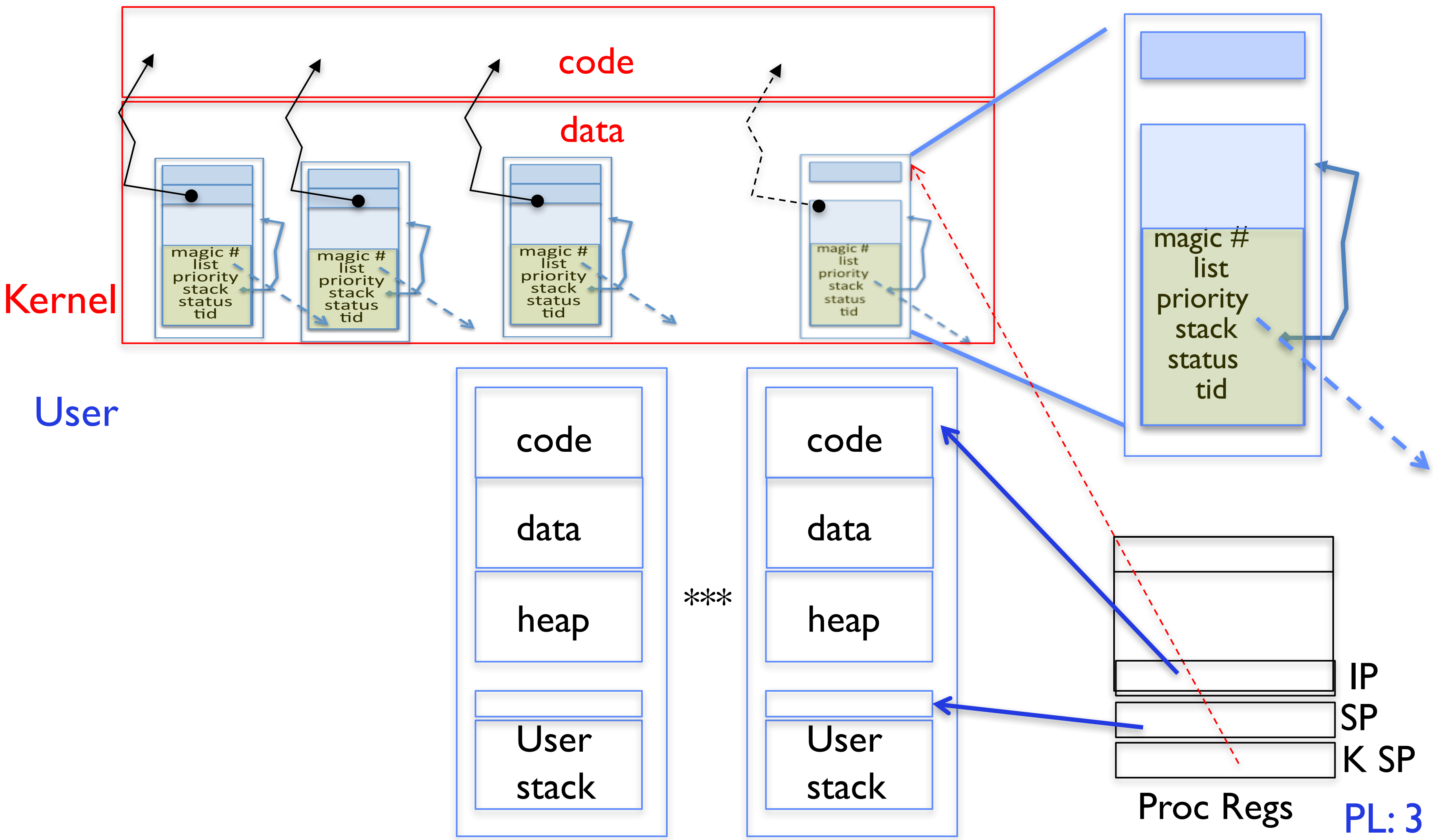
Switch to Kernel Thread for Process



Pintos Return from Processing



Kernel → User

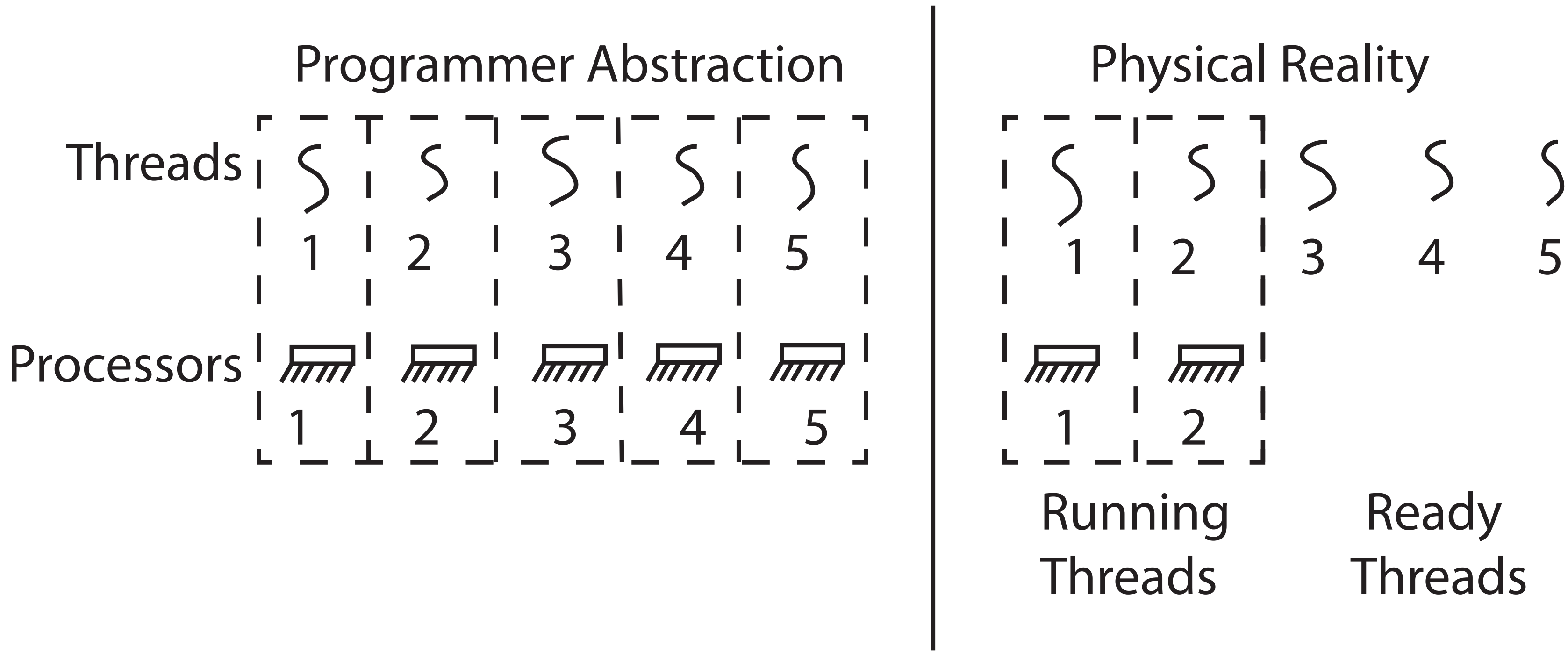


- Interrupt return (iret) restores user stack and PL

Rest of Today's Lecture

- The Concurrency Problem
- Synchronization Operations
- Higher-level Synchronization Abstractions
  - Semaphores, monitors, and condition variables

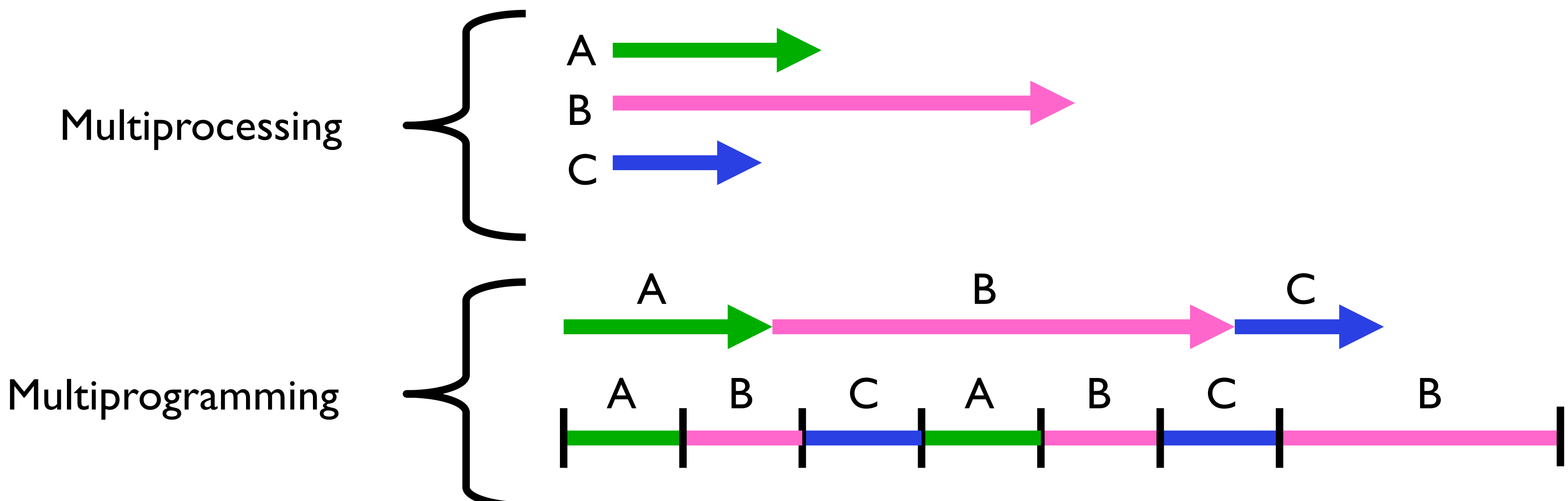
Recall: Thread Abstraction



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

Multiprocessing vs Multiprogramming

- Remember Definitions:
  - Multiprocessing ≡ Multiple CPUs or cores or hyperthreads (HW per-instruction interleaving)
  - 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, …



Correctness for systems with concurrent threads

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

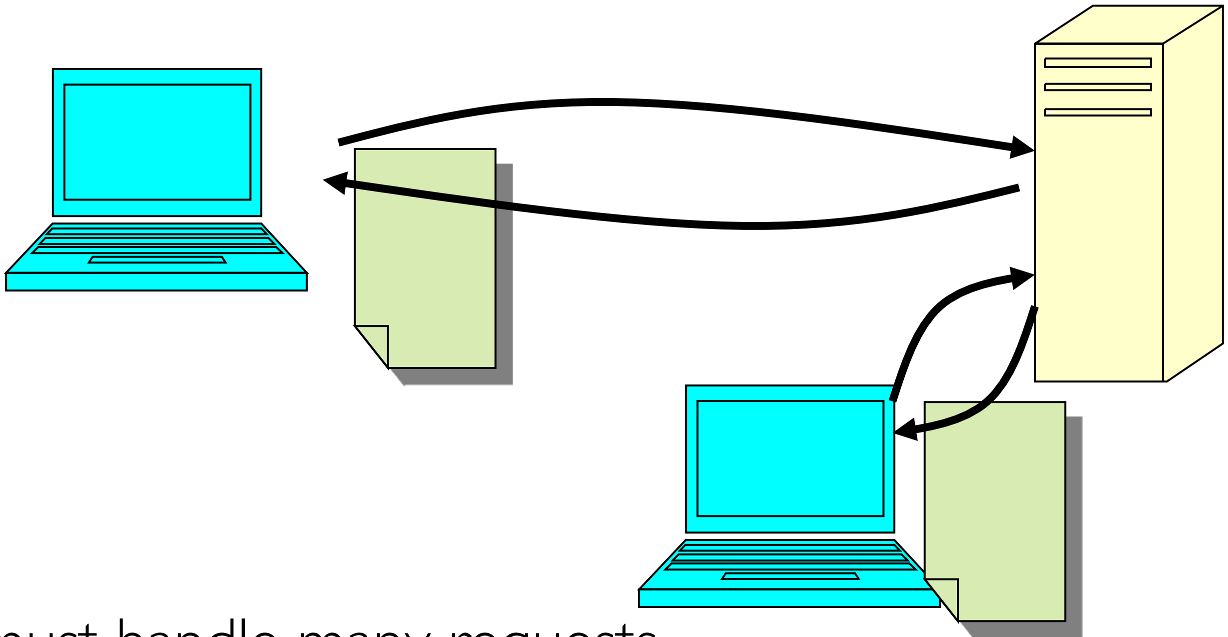
Interactions Complicate Debugging

- Is any program truly independent?
  - Every process shares the file system, OS resources, network, etc.
  - Extreme example: buggy device driver causes thread A to crash "independent thread" B
- 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?

- 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

High-level Example: Web Server



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

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

- What are some disadvantages of this technique?

Threaded Web Server

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

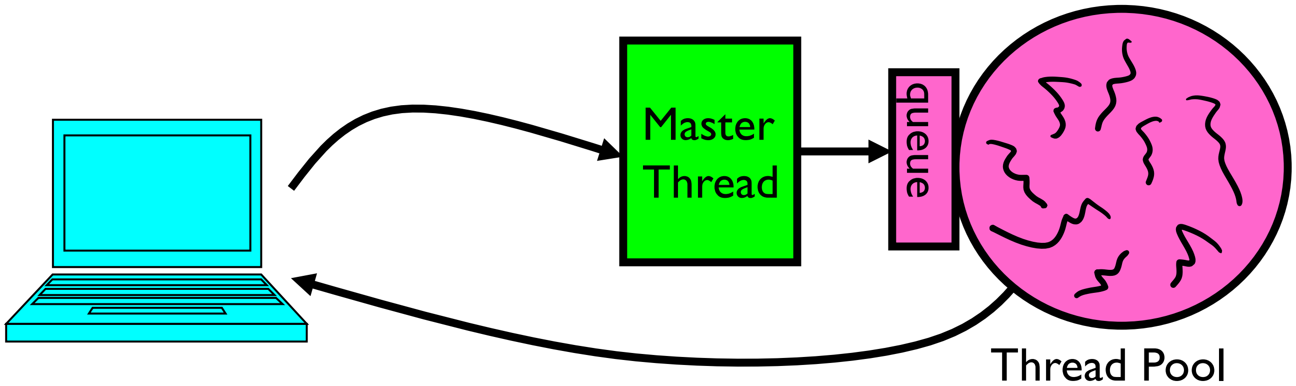
```
serverLoop() {
        connection = AcceptCon();
        ThreadFork(ServiceWebPage(), connection);
  }
```

- 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

- What about Denial of Service attacks or digg / Slashdot effects?

Thread Pools

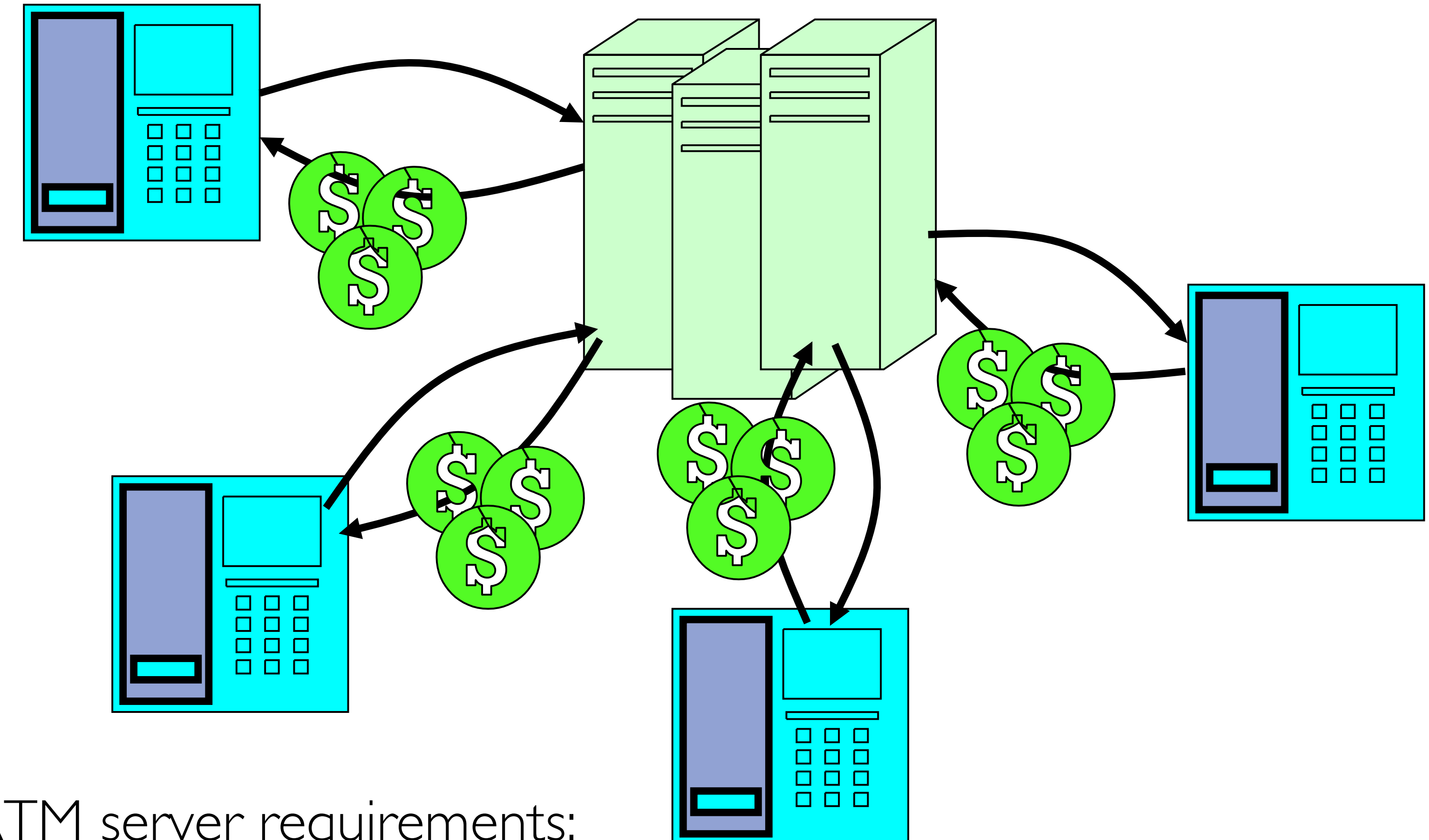
- Problem with previous version: Unbounded Threads
  - When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded "pool" of worker threads, representing the maximum level of multiprogramming




```
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);
   }
}
```

ATM Bank Server



- ATM server requirements:
  - 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 programming GPUs (Graphics Processing Unit)

Can Threads Make This Easier?

- Threads yield overlapped I/O and computation without having to "deconstruct" 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

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!
- Examples:

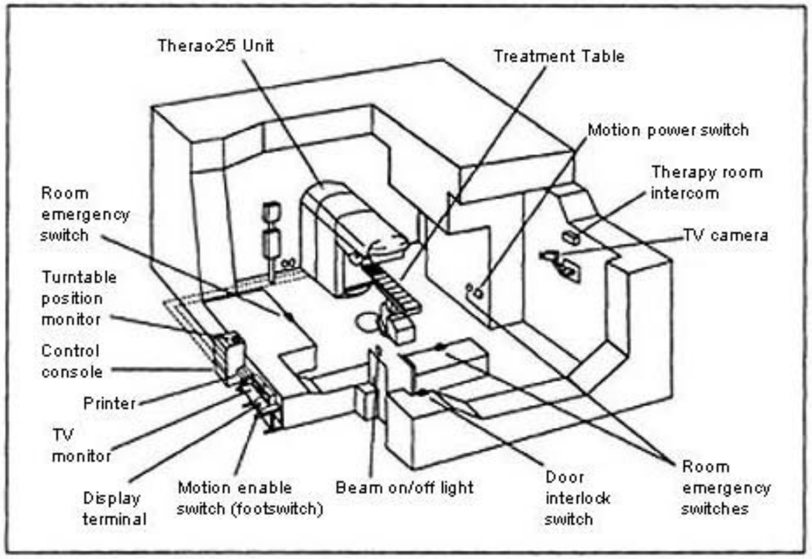


Figure 1. Typical Therac-25 facility

Administrivia

- Group/Section assignments finalized!
  - If you are not in group, talk to us immediately!
- Attend assigned sections
  - Need to know your TA!
    - » Participation is 8% of your grade
    - » Should attend section with your TA
- First design doc due next Wednesday
  - This means you should be well on your way with Project 1
  - Watch for notification from your TA to sign up for design review
- Basic semaphores work in PintOS!
  - However, you will need to implement priority scheduling behavior both in semaphore and ready queue

- BREAK

Motivation: "Too Much Milk"

- Great thing about OS's – analogy between problems in OS and problems in real life
  – Help you understand real life problems better
  – But, computers are much stupider than people
- Example: People need to coordinate:

Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

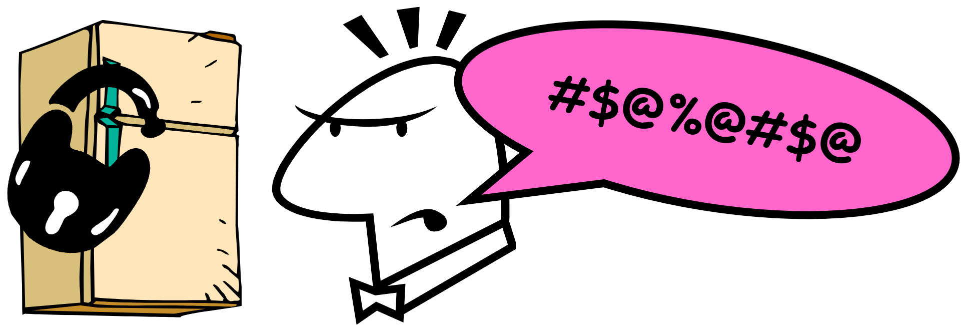
Definitions

- 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

More Definitions

- 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

- For example: fix the milk problem by putting a key on the refrigerator
  – Lock it and take key if you are going to go buy milk
  – Fixes too much: roommate angry if only wants OJ



  – Of Course – We don't know how to make a lock yet

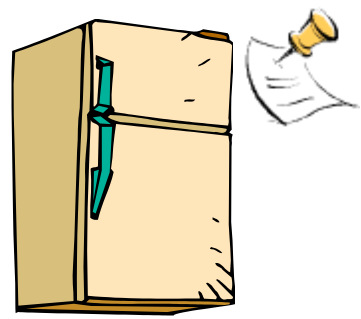
Too Much Milk: Correctness Properties

- Need to be careful about correctness of concurrent programs, since non-deterministic
  - Impulse is to start coding first, then when it doesn't work, pull hair out
  - Instead, think first, then code
  - Always write down behavior first
- What are the correctness properties for the "Too much milk" problem???
  - Never more than one person buys
  - Someone buys if needed
- Restrict ourselves to use only atomic load and store operations as building blocks

Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
  - Leave a note before buying (kind of "lock")
  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

```
if (noMilk) {
   if (noNote) {
      leave Note;
      buy milk;
      remove note;
   }
}
```



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  - Remove note after buying (kind of "unlock")
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- Suppose a computer tries this (remember, only memory read/write are atomic):

Thread A

```
if (noMilk) {


   if (noNote) {
     leave Note;
     buy Milk;
     remove Note;
   }
}
```

Thread B

```
if (noMilk) {
   if (noNote) {







      leave Note;
      buy Milk;
      remove Note;
   }
}
```

Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
  - Leave a note before buying (kind of "lock")
  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

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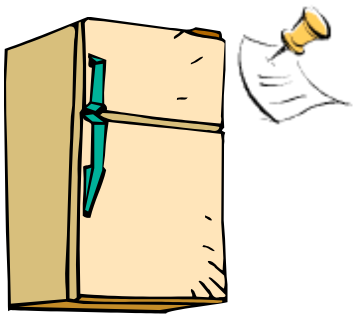
      buy milk;
      remove note;
   }
}
```



- Result?
  - Still too much milk but only occasionally!
  - Thread can get context switched after checking milk and note but before buying milk!
- Solution makes problem worse since fails intermittently
  - Makes it really hard to debug…
  - Must work despite what the dispatcher does!

Too Much Milk: Solution #1½

- Clearly the Note is not quite blocking enough
  – Let's try to fix this by placing note first
- Another try at previous solution:

```
leave Note;
if (noMilk) {
   if (noNote) {
      buy milk;
   }
}
remove Note;
```

- What happens here?
  – Well, with human, probably nothing bad
  – With computer: no one ever buys milk

Too Much Milk Solution #2

- How about labeled notes?
  – Now we can leave note before checking
- Algorithm looks like this:

Thread A

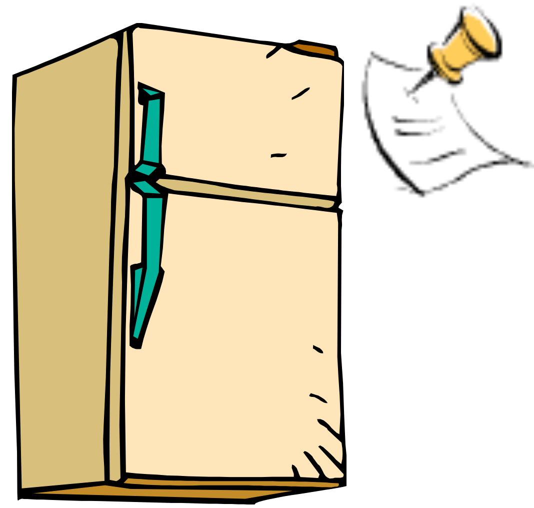
```
leave note A;
if (noNote B) {
   if (noMilk) {
      buy Milk;
   }
}
remove note A;
```

Thread B

```
leave note B;
if (noNoteA) {
   if (noMilk) {
      buy Milk;
   }
}
remove note B;
```

- Does this work?
- Possible for neither thread to buy milk
  – Context switches at exactly the wrong times can lead each to think that the other is going to buy
- Really insidious:
  – Extremely unlikely this would happen, but will at worse possible time
  – Probably something like this in UNIX

Too Much Milk Solution #2: problem!



- I thought *you* had the milk! But I thought *you* had the milk!
- This kind of lockup is called "starvation!"

Review: Too Much Milk Solution #3

- Here is a possible two-note solution:

Thread A

```
leave note A;
while (note B) {\\X
   do nothing;
}
if (noMilk) {
   buy milk;
}
remove note A;
```

Thread B

```
leave note B;
if (noNote A) {\\Y
   if (noMilk) {
      buy milk;
   }
}
remove note B;
```

- Does this work? Yes. Both can guarantee that:
  - It is safe to buy, or
  - Other will buy, ok to quit
- At **X**:
  - If no note B, safe for A to buy,
  - Otherwise wait to find out what will happen
- At **Y**:
  - If no note A, safe for B to buy
  - Otherwise, A is either buying or waiting for B to quit

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

```
if (noMilk) {
    buy milk;}
}
remove note A;
```

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

happened before

```
leave note A;
while (note B) {\\X
    do nothing;
};

if (noMilk) {
    buy milk;}
}
remove note A;
```

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
```

Wait for note B to be remove

```
remove note B;
```

```
if (noMilk) {
    buy milk;}
}
remove note A;
```

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

happened before

```
leave note A;
while (note B) {\\X
    do nothing;
};


if (noMilk) {
    buy milk;}
}
remove note A;
```

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

happened before

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

```
if (noMilk) {
    buy milk;}
}
remove note A;
```

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

Wait for note B to be remove

```
if (noMilk) {
    buy milk;}
}
remove note A;
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

Review: Solution #3 discussion

- Our solution protects a single "Critical-Section" piece of code for each thread:

```
if (noMilk) {
   buy milk;
}
```

- Solution #3 works, but it's really unsatisfactory
  – Really complex – even for this simple an example
    » Hard to convince yourself that this really works
  – A's code is different from B's – what if lots of threads?
    » Code would have to be slightly different for each thread
  – While A is waiting, it is consuming CPU time
    » This is called "busy-waiting"
- There's a better way
  – Have hardware provide higher-level primitives than atomic load & store
  – Build even higher-level programming abstractions on this hardware support

Too Much Milk: Solution #4

- Suppose we have some sort of implementation of a lock
  - `lock.Acquire()` – wait until lock is free, then grab
  - `lock.Release()` – Unlock, waking up anyone waiting
  - These must be atomic operations – if two threads are waiting for the lock and both see it's free, only one succeeds to grab the lock
- Then, our milk problem is easy:

```
milklock.Acquire();
if (nomilk)
   buy milk;
milklock.Release();
```

- Once again, section of code between **`Acquire()`** and **`Release()`** called a "Critical Section"
- Of course, you can make this even simpler: suppose you are out of ice cream instead of milk
  - Skip the test since you always need more ice cream ;-)

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

Summary

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