CS162
Operating Systems and Systems Programming
Lecture 7

Synchronization 2: Semaphores (Con't)
Lock Implementation, Atomic Instructions

February 9th, 2021

Profs. Natacha Crooks and Anthony D. Joseph

http://cs162.eecs.Berkeley.edu

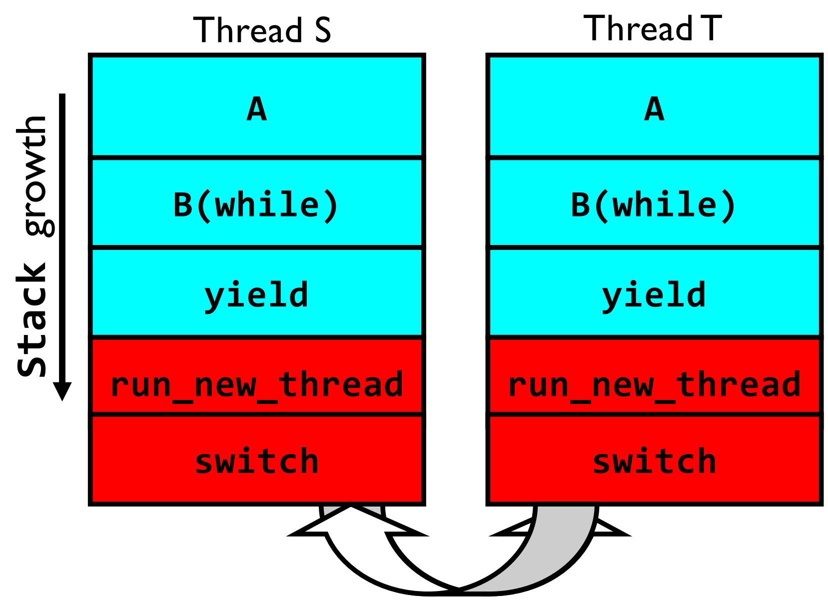
Recall: Multithreaded Stack Example

- Consider the following code blocks:

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

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

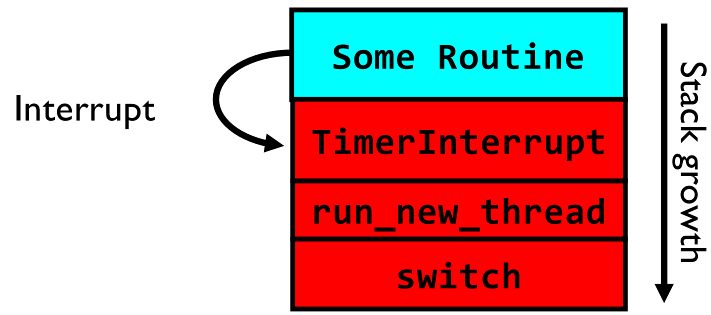
- Suppose we have 2 threads:
  - Threads S and T



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

Recall: 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();
}
```

Hardware Context Switch Support in x86

- Syscall/Intr (U → K)
  - PL 3 → 0;
  - TSS ← EFLAGS, CS:EIP;
  - SS:ESP ← k-thread stack (TSS PL 0);
  - push (old) SS:ESP onto (new) k-stack
  - push (old) eflags, cs:eip, <err>
  - CS:EIP ← <k target handler>
- Then
  - *Handler then saves other regs, etc*
  - *Does all its works, possibly choosing other threads, changing PTBR (CR3)*
  - kernel thread has set up user GPRs
- iret (K → U)
  - PL 0 → 3;
  - Eflags, CS:EIP ← popped off k-stack
  - SS:ESP ← popped off k-stack

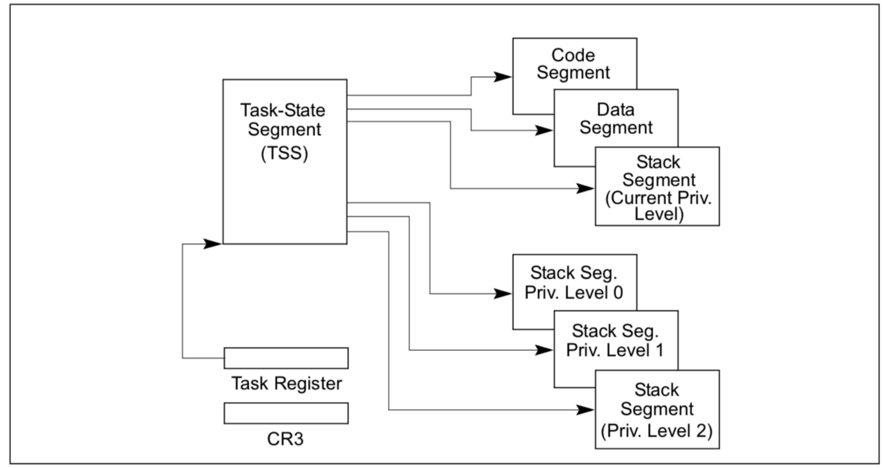
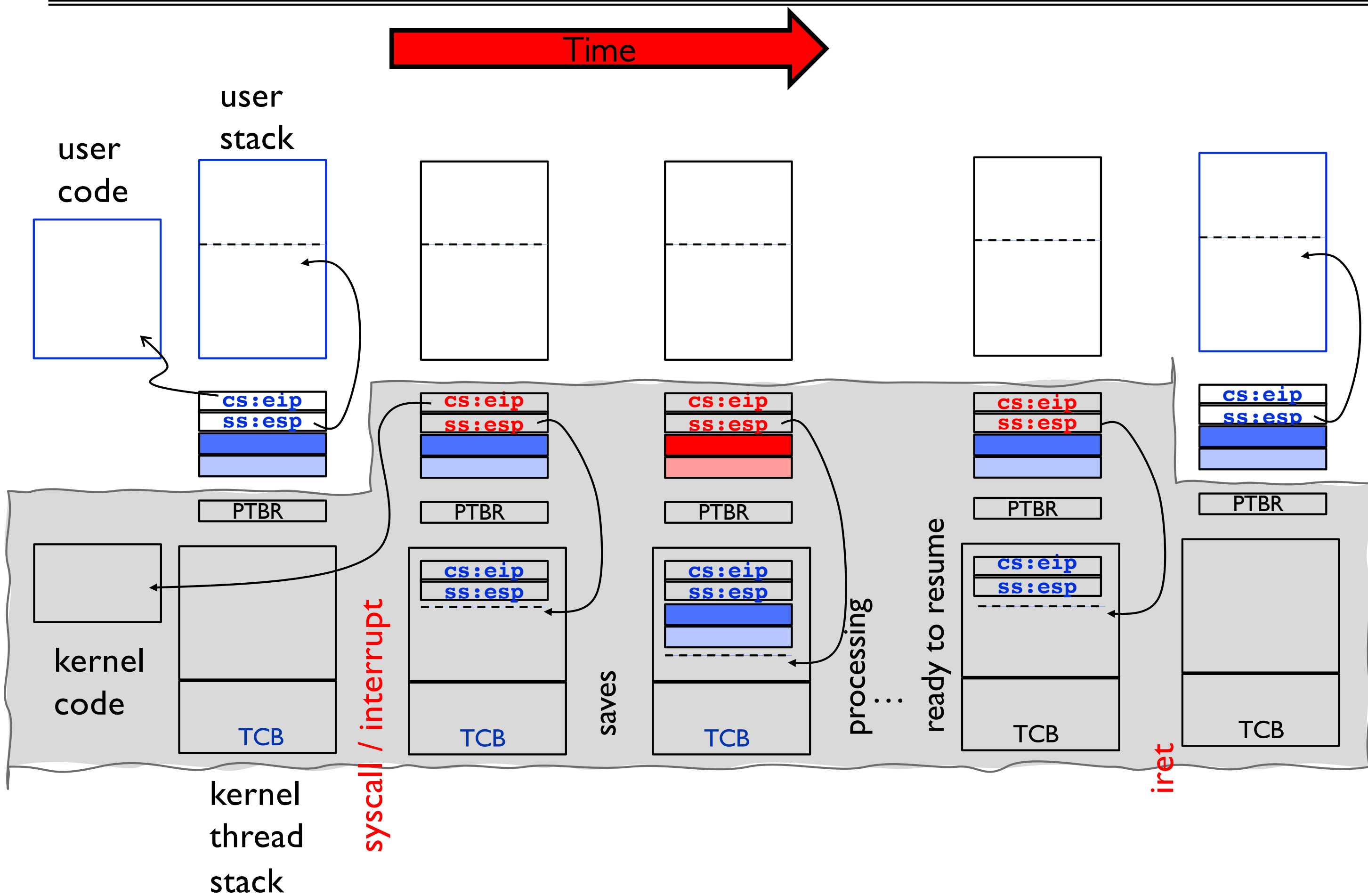


Figure 7-1. Structure of a Task

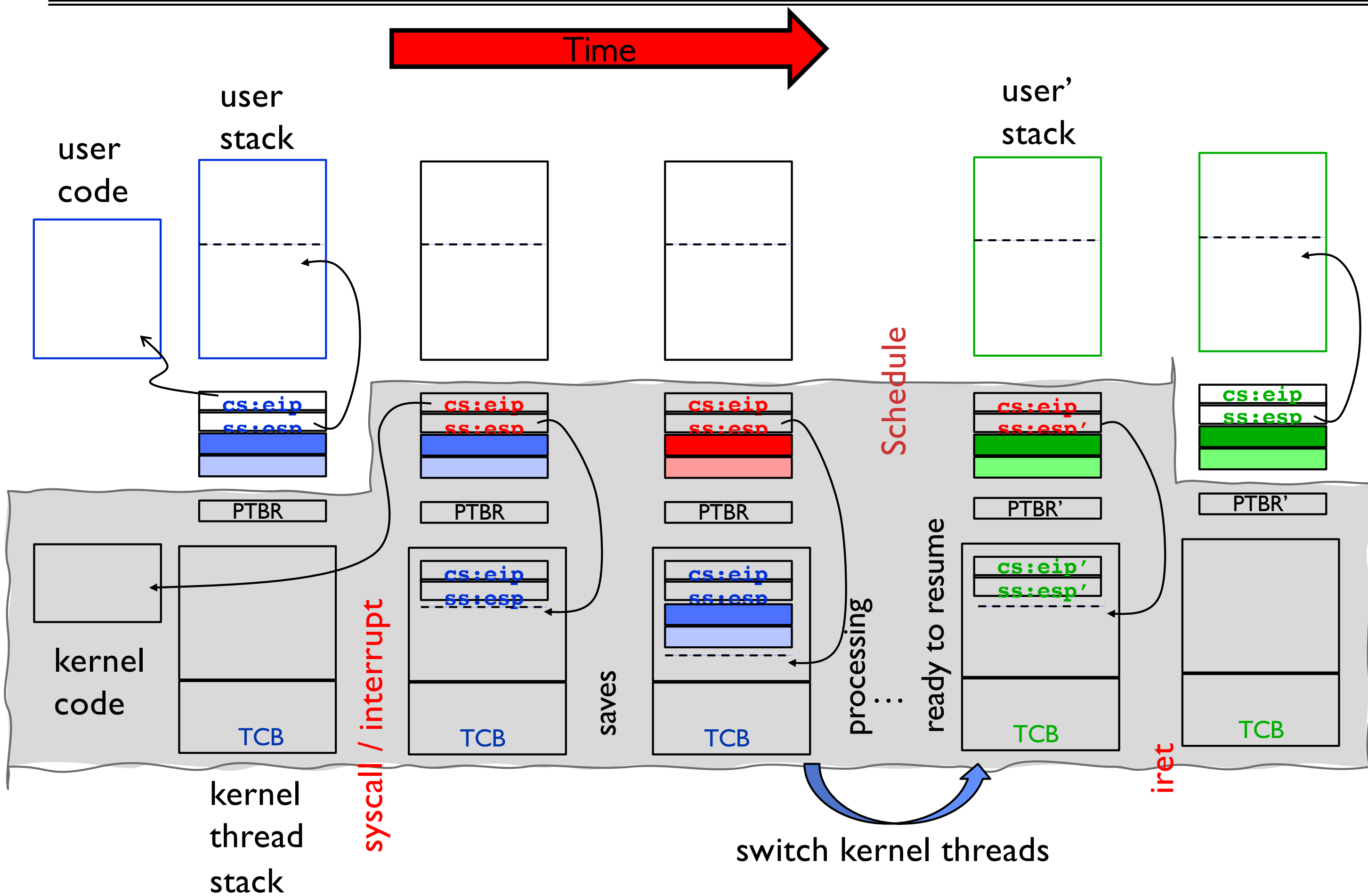
pg 2,942 of 4,922 of x86 reference manual

Pintos: tss.c, intr-stubs.S

Pintos: Kernel Crossing on Syscall or Interrupt



Pintos: Context Switch – Scheduling



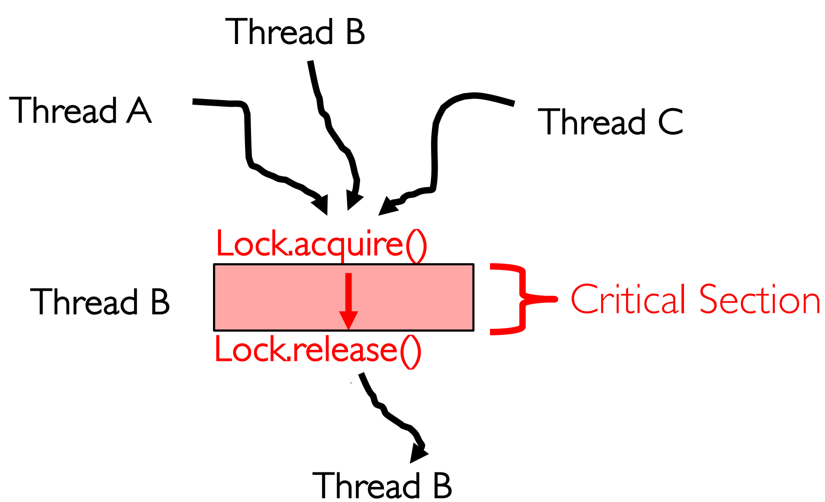
Pintos: switch.S

Recall: Fix banking problem with Locks!

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

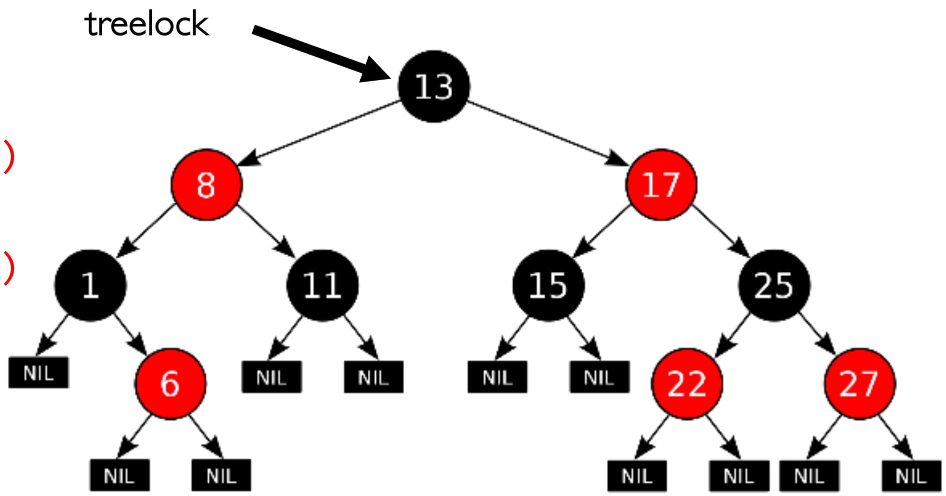
```
Deposit(acctId, amount) {
  Lock.acquire()   // Wait if someone else in critical section!
  acct = GetAccount(actId);
  acct->balance += amount;
  StoreAccount(acct);
  Lock.release()   // Release someone into critical section
}
```

Critical Section



- Must use SAME lock with all of the methods (Withdraw, etc…)

Recall: Red-Black tree example



Tree-Based Set Data Structure

Thread A

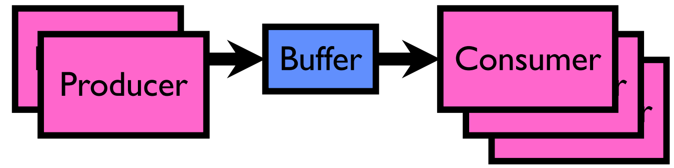
```
Insert(3) {
  acquire(&treelock)
  Tree.Insert(3)
  release(&treelock)
}
```

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…

Producer-Consumer with a Bounded Buffer

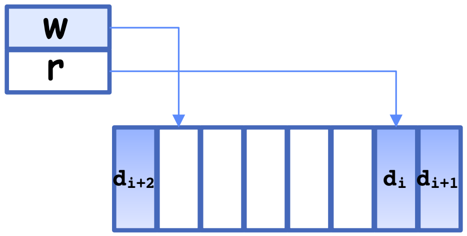


- Problem Definition
  - Producer(s) put things into a shared buffer
  - Consumer(s) take them out
  - Need synchronization to coordinate producer/consumer

- 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);
}

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

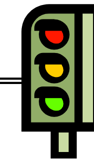
What happens when one is waiting for the other?
- Multiple cores ?
- Single core ?

[redacted]

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 some ways of structuring sharing

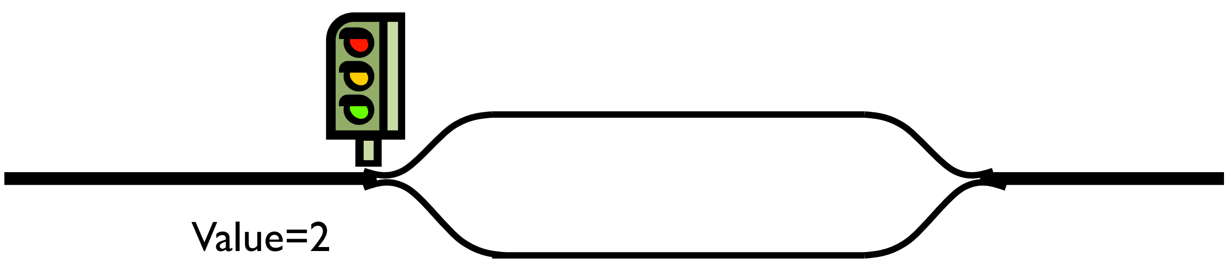
Recall: Semaphores



- 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;
}
```

Critical sections using mutex protect integrity of the queue

`fullSlots` signals coke

`emptySlots` signals space

Discussion about Solution

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

    Decrease # of empty slots

    Increase # of occupied slots
  - Consumer does: **semaP(&fullBuffer), semaV(&emptyBuffer)**

    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;
}
```

[redacted]

Administrivia

- Midterm 1: Thu February 18th, 5-6:30PM (9 days from today!)
  - Video Proctored, Use of computer to answer questions
  - More details as we get closer to exam
- Midterm topics:
  - Everything up to lecture 9 – lecture will be released early
  - Homework 1 and Project 1 (high-level design) are fair game
- Midterm Review: Tuesday February 16th, 5-7pm
  - Details TBA

[redacted]

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

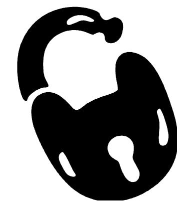
- We are going to implement various higher-level synchronization primitives using atomic operations
  - Everything is pretty painful if only atomic primitives are load and store
  - Need to provide primitives useful at user-level

Motivating Example: "Too Much Milk"

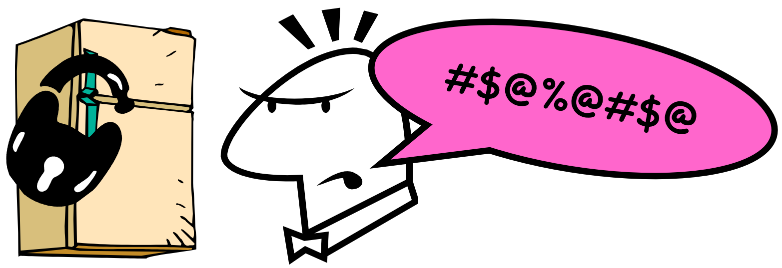
- Great thing about OS's – analogy between problems in OS and problems in real life
  - Help you understand real life problems better
  - But, computers are much stupider than people
- Example: People need to coordinate:

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

Recall: What is a lock?



- 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
  - Let's see if we can answer this question!

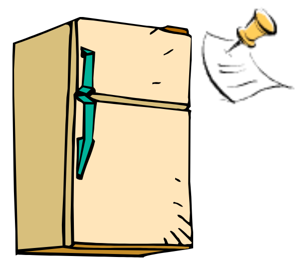
Too Much Milk: Correctness Properties

- 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
- First attempt: 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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  - Don't buy if note (wait)
- 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")
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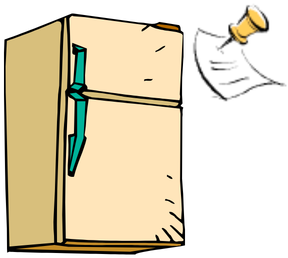
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

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



- 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

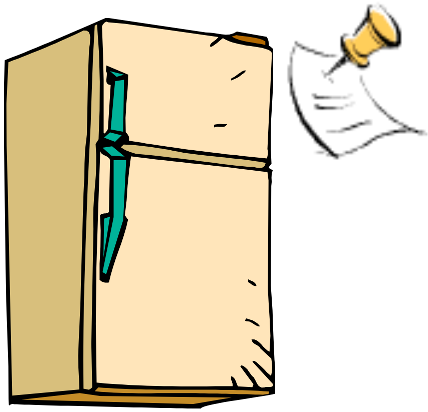
```
leave note A;
if (noNote B) {
   if (noMilk) {
      buy Milk;
   }
}
remove note A;
```

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'm* not getting milk, *You're* getting milk
- This kind of lockup is called "starvation!"

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

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

happened before

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)`"

```
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;
```

Wait for note B to be removed

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

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

happened before

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

Wait for note B to be removed

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

This Generalizes to n Threads…

- Leslie Lamport's "Bakery Algorithm" (1974)

Computer Systems

G. Bell, D. Siewiorek, and S.H. Fuller, Editors

A New Solution of Dijkstra's Concurrent Programming Problem

Leslie Lamport
Massachusetts Computer Associates, Inc.

A simple solution to the mutual exclusion problem is presented which allows the system to continue to operate

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 is 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 must be 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?

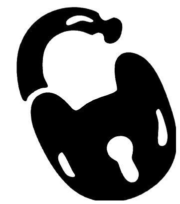
- Recall our target lock interface:
  - `acquire(&milklock)` – wait until lock is free, then grab
  - `release(&milklock)` – Unlock, waking up anyone waiting
  - These must be atomic operations – if two threads are waiting for the lock and both see it is free, only one succeeds to grab the lock
- Then, our milk problem is easy:

```
acquire(&milklock);
if (nomilk)
   buy milk;
release(&milklock);
```

[redacted]

Back to: How to Implement 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
    - » Should *sleep* if waiting for a long time



- Atomic Load/Store: yields a solution like Milk #3
  - Pretty complex and error prone
- Hardware Lock instruction
  - Is this a good idea?
  - What about putting a task to sleep?
    - » What is the interface between the hardware and scheduler?
  - Complexity?
    - » Done in the Intel 432
    - » Each feature makes HW more complex and slow

Naïve use of Interrupt Enable/Disable

- How can we build multi-instruction atomic operations?
  - Recall: dispatcher gets control in two ways.
    - » Internal: Thread does something to relinquish the CPU
    - » External: Interrupts cause dispatcher to take CPU
  - On a uniprocessor, can avoid context-switching by:
    - » Avoiding internal events (although virtual memory tricky)
    - » Preventing external events by disabling interrupts
- Consequently, naïve Implementation of locks:

```
LockAcquire { disable Ints; }
LockRelease { enable Ints; }
```

- Problems with this approach:
  - Can't let user do this! Consider following:

```
LockAcquire();
While(TRUE) {;}
```

  - Real-Time system—no guarantees on timing!
    - » Critical Sections might be arbitrarily long
  - What happens with I/O or other important events?
    - » "Reactor about to meltdown. Help?"

Better Implementation of Locks by Disabling Interrupts

- Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```
int value = FREE;
```

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

```
Release() {
   disable interrupts;
   if (anyone on wait queue) {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

New Lock Implementation: Discussion

- Why do we need to disable interrupts at all?
  - Avoid interruption between checking and setting lock value
  - Otherwise two threads could think that they both have lock

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

Critical Section

- Note: unlike previous solution, the critical section (inside `Acquire()`) is very short
  - User of lock can take as long as they like in their own critical section: doesn't impact global machine behavior
  - Critical interrupts taken in time!

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

- Before Putting thread on the wait queue?

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

- Before Putting thread on the wait queue?
  - Release can check the queue and not wake up thread
- After putting the thread on the wait queue

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  – Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  – Misses wakeup and still holds lock (deadlock!)

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  – Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  – Misses wakeup and still holds lock (deadlock!)
- Want to put it after `sleep()`. But – how?

How to Re-enable After Sleep()?

- In scheduler, since interrupts are disabled when you call sleep:
  – Responsibility of the next thread to re-enable ints
  – When the sleeping thread wakes up, returns to acquire and re-enables interrupts

Thread A		Thread B
.		
.		
disable ints		
sleep		
	context switch →	sleep return
		enable ints
		.
		.
		.
		disable int
		sleep
sleep return	← context switch	
enable ints		
.		
.		

In-Kernel Lock: Simulation

Value: 0	waiters	owner

READY

Running

Thread A

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
INIT
   int value = 0;

Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
  disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Ready

Thread B

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

In-Kernel Lock: Simulation

Value: 1 | waiters | owner

READY

Running

Thread A

Ready

Thread B

```
INIT
   int value = 0;

Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
  disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Thread A:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

Thread B:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running / Ready — Thread A

Running / Ready — Thread B

INIT
```
int value = 0;
```

Thread A:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
  disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Thread B:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Ready Running — Thread A

Running Waiting — Thread B

INIT
```
int value = 0;
```

Thread A:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
  disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Thread B:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running
Thread A

Ready
Thread B

```
INIT
   int value = 0;
```

Thread A:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

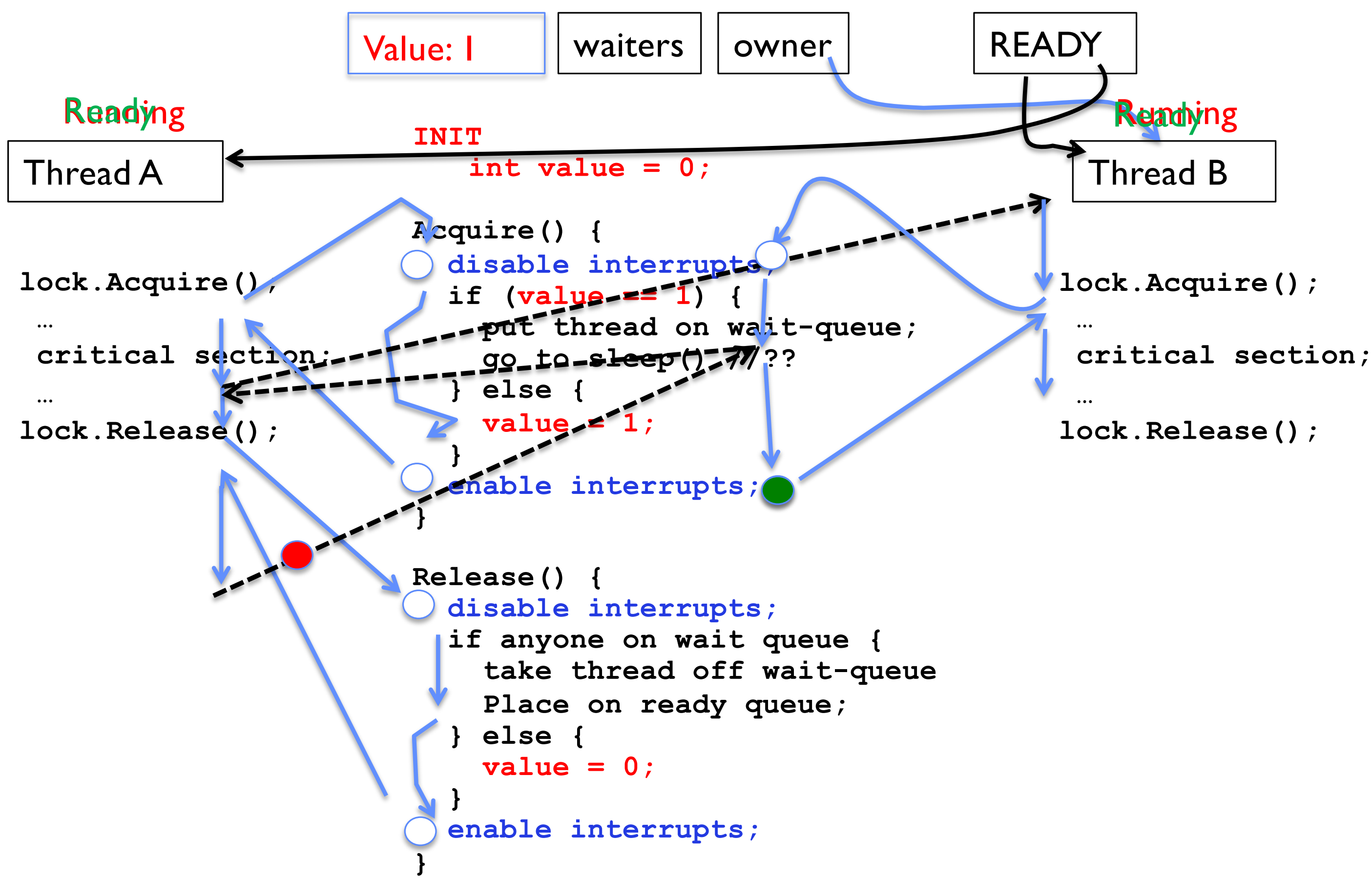
```
Acquire() {
  disable interrupts;
  if (value == 1) {
     put thread on wait-queue;
     go to sleep() //??
  } else {
     value = 1;
  }
  enable interrupts;
}
```

```
Release() {
  disable interrupts;
  if anyone on wait queue {
     take thread off wait-queue
     Place on ready queue;
  } else {
     value = 0;
  }
  enable interrupts;
}
```

Thread B:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

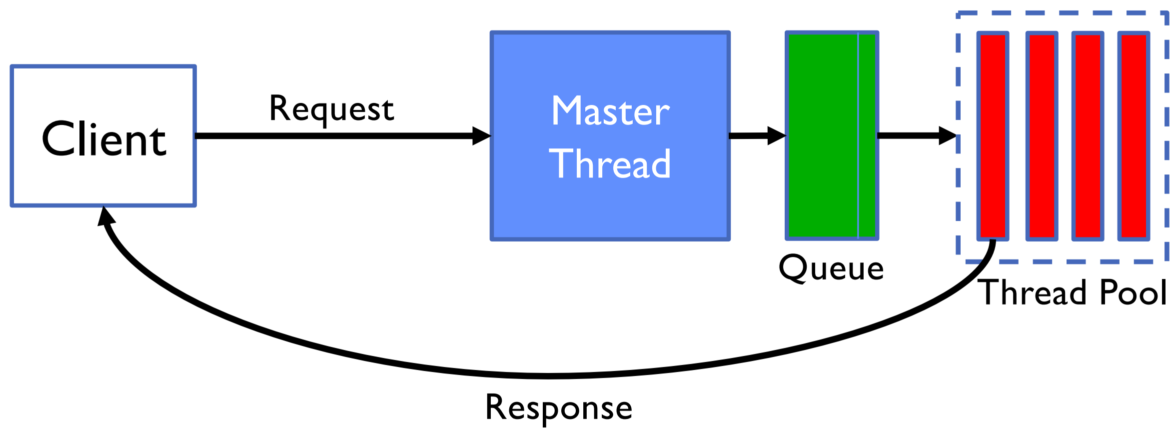
In-Kernel Lock: Simulation



[redacted]

Recall: Multithreaded Server

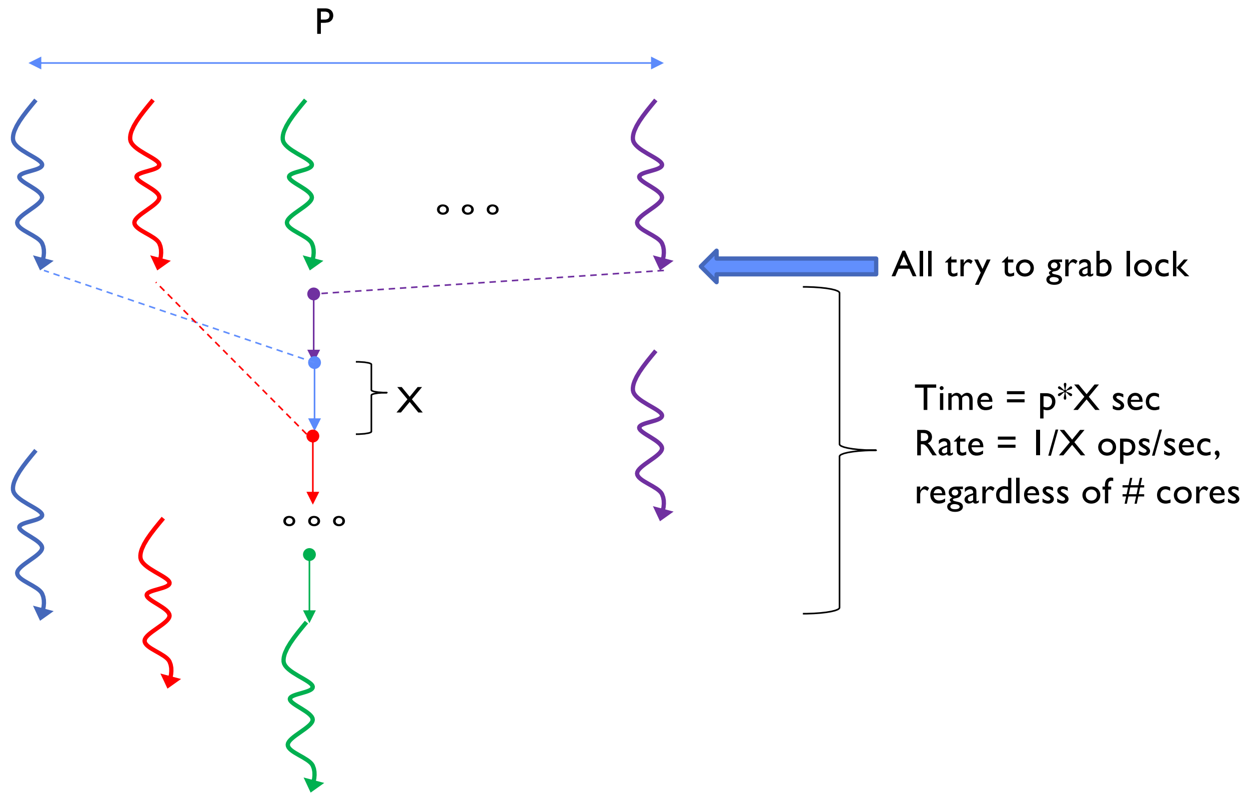
- **Bounded** pool of worker threads
  - Allocated in **advance:** no thread creation overhead
  - **Queue** of pending requests



Simple Performance Model

- Given that the overhead of a critical section is X
  - User->Kernel Context Switch
  - Acquire Lock
  - Kernel->User Context Switch
  - <perform exclusive work>
  - User->Kernel Context Switch
  - Release Lock
  - Kernel->User Context Switch
- Even if everything else is infinitely fast, with any number of threads and cores
- What is the maximum rate of operations that involve this overhead?

Highly Contended Case – in a picture



Back to system performance

More Practical Motivation

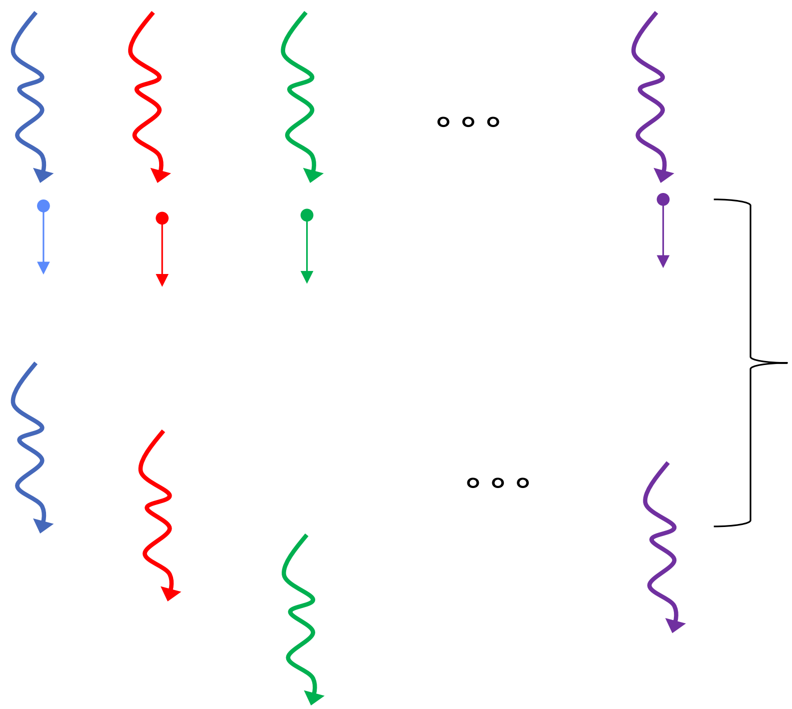
Back to Jeff Dean's "Numbers everyone should know"

Handle I/O in separate thread, avoid blocking other progress

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

- X = 1ms => 1,000 ops/sec

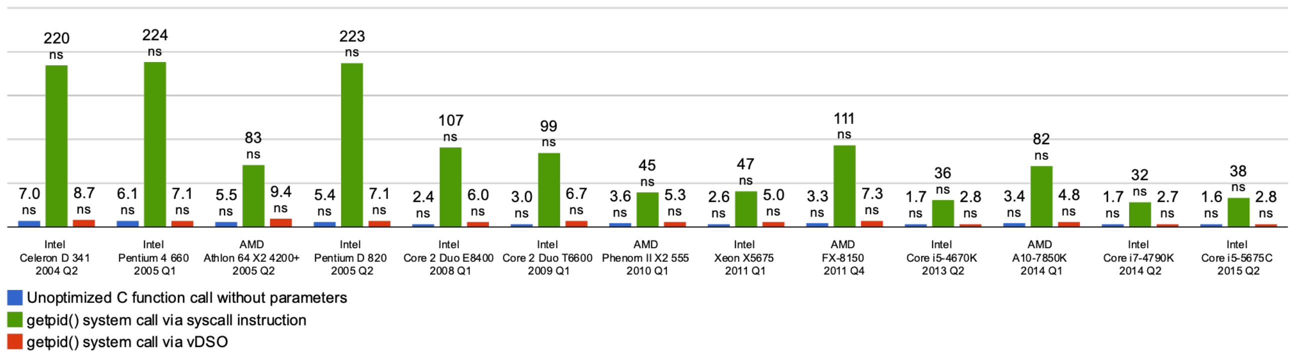
Uncontended Many-Lock Case



What if sys overhead is Y, even when the lock is free?

What if the OS can only handle one lock operation at a time?

Recall: Basic cost of a system call



- Min System call ~ 25x cost of function call
- Scheduling could be many times more
- Streamline system processing as much as possible
- Other optimizations seek to process as much of the call in user space as possible (eg, Linux vDSO)

[redacted]

Atomic Read-Modify-Write Instructions

- Problems with previous solution:
  – Can't give lock implementation to users
  – Doesn't work well on multiprocessor
    » Disabling interrupts on all processors requires messages and would be very time consuming
- Alternative: atomic instruction sequences
  – These instructions read a value and write a new value atomically
  – Hardware is responsible for implementing this correctly
    » on both uniprocessors (not too hard)
    » and multiprocessors (requires help from cache coherence protocol)
  – Unlike disabling interrupts, can be used on both uniprocessors and multiprocessors

Examples of Read-Modify-Write

- ```
  test&set (&address) {           /* most architectures */
      result = M[address];        // return result from "address" and
      M[address] = 1;             // set value at "address" to 1
      return result;
  }
  ```
- ```
  swap (&address, register) {     /* x86 */
      temp = M[address];          // swap register's value to
      M[address] = register;      // value at "address"
      register = temp;
  }
  ```
- ```
  compare&swap (&address, reg1, reg2) { /* 68000 */
      if (reg1 == M[address]) {   // If memory still == reg1,
          M[address] = reg2;      // then  put reg2 => memory
          return success;
      } else {                    // Otherwise do not change memory
          return failure;
      }
  }
  ```
- ```
  load-linked&store-conditional(&address) { /* R4000, alpha, ARM, RISC-V */
      loop:
           ll r1, M[address];
           movi r2, 1;             // Can do arbitrary computation
           sc r2, M[address];
           beqz r2, loop;
  }
  ```

Conclusion

- 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
- Talked about hardware atomicity primitives:
  - Disabling of Interrupts, test&set, swap, compare&swap, load-linked & store-conditional
- Showed several constructions of Locks
  - Must be very careful not to waste/tie up machine resources
    - » Shouldn't disable interrupts for long
    - » Shouldn't spin wait for long
  - Key idea: Separate lock variable, use hardware mechanisms to protect modifications of that variable