CS162
Operating Systems and Systems Programming
Lecture 7

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

September 21st, 2020

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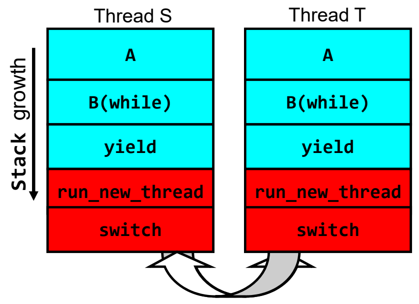
Recall: Multithreaded Stack Example

- Consider the following code blocks:

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

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

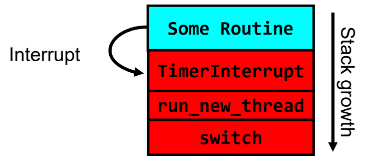
- Suppose we have 2 threads:
  – Threads S and T



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

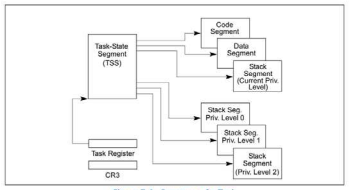
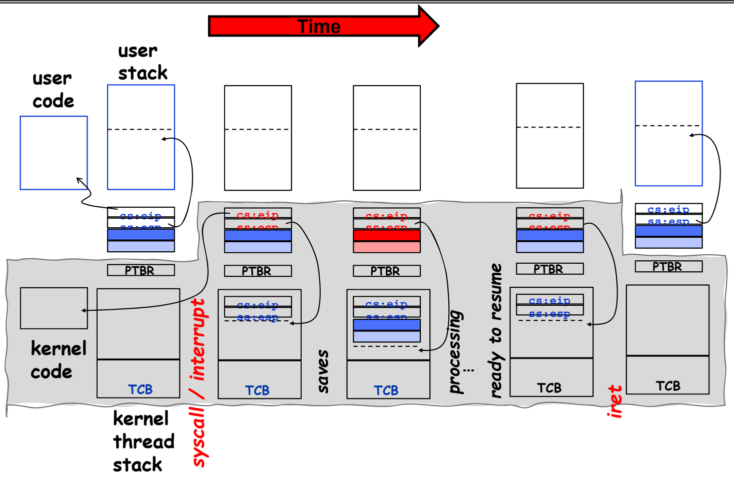


Figure 7-1. Structure of a Task

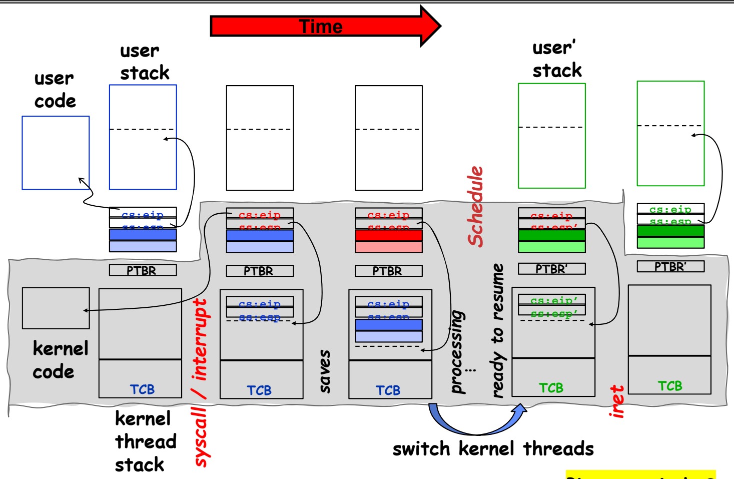
pg 2,942 of 4,922 of x86 reference manual

Pintos: tss.c, intr-stubs.S

Pintos: Kernel Crossing on Syscall or Interrupt



Pintos: Context Switch – Scheduling



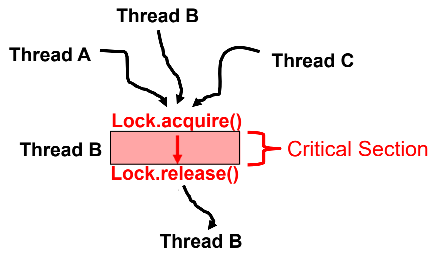
Pintos: switch.S

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

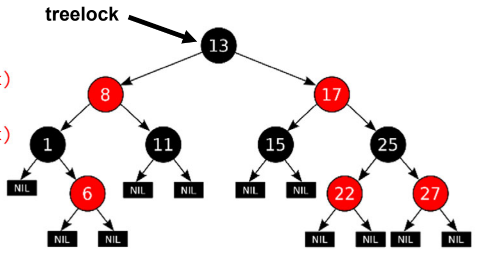


- Must use SAME lock with all of the methods (Withdraw, etc…)

Recall: Red-Black tree example

Thread A

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



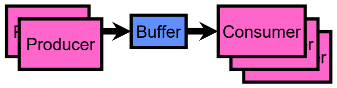
Tree-Based Set Data Structure

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…

Producer-Consumer with a Bounded Buffer

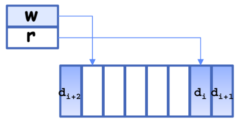


- Problem Definition
  - Producer(s) put things into a shared buffer
  - Consumer(s) take them out
  - Need synchronization to coordinate producer/consumer
- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  - Need to synchronize access to this buffer
  - 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 ?

Higher-level Primitives than Locks

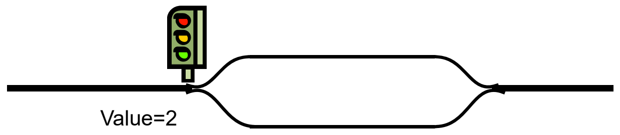
- What is right abstraction for synchronizing threads that share memory?
  - Want as high a level primitive as possible
- Good primitives and practices important!
  - Since execution is not entirely sequential, really hard to find bugs, since they happen rarely
  - UNIX is pretty stable now, but up until 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;
}
```

Administrivia

- Midterm 1: October 1st, 5-7PM (Three weeks from tomorrow!)
  - We understand that this partially conflicts with CS170, but those of you in CS170 can start that exam after 7PM (according to CS170 staff)
  - Video Proctored, No curve, Use of computer to answer questions
  - More details as we get closer to exam
- Midterm Review: Tuesday September 29th, 7-9pm
  - Details TBA

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

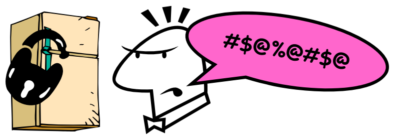
Motivating Example: “Too Much Milk”

- 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!

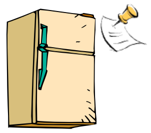
Too Much Milk: Correctness Properties

- 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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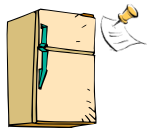
  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

```
Thread A                      Thread B
if (noMilk) {
                              if (noMilk) {
                                 if (noNote) {
   if (noNote) {
     leave Note;
     buy Milk;
     remove Note;
   }
}
                                   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):

```
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

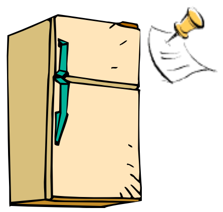
Too Much Milk Solution #2

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

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

- 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

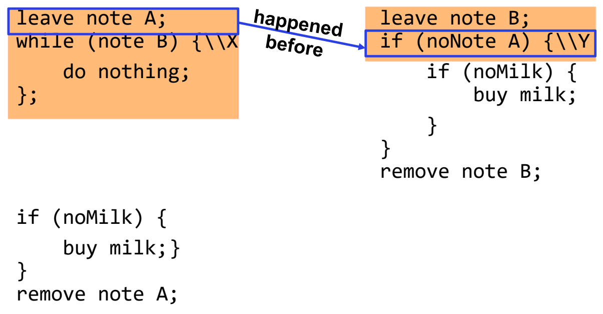
- "`leave note A`" happens before "`if (noNote A)`"

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

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

Case 1

- “`leave note A`” happens before “`if (noNote A)`”



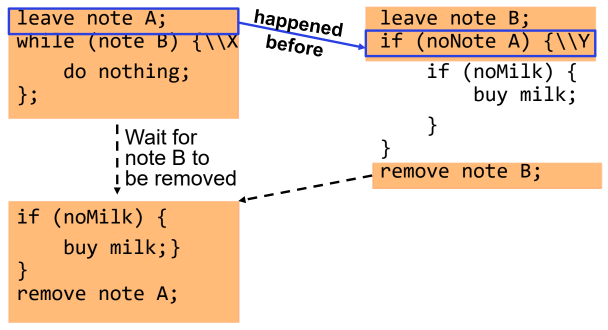
```
leave note A;
while (note B) {\\X
    do nothing;
};

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)`”



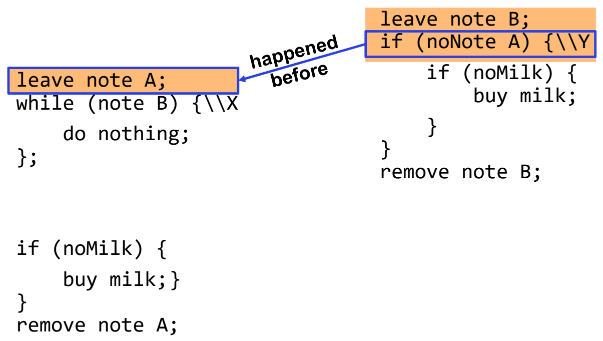
```
leave note A;
while (note B) {\\X
    do nothing;
};

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`”



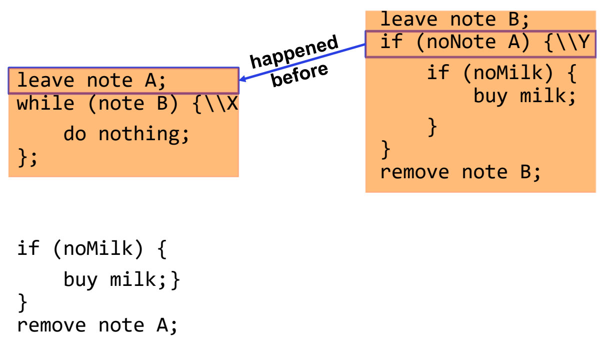
```
leave note A;
while (note B) {\\X
    do nothing;
};

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`”



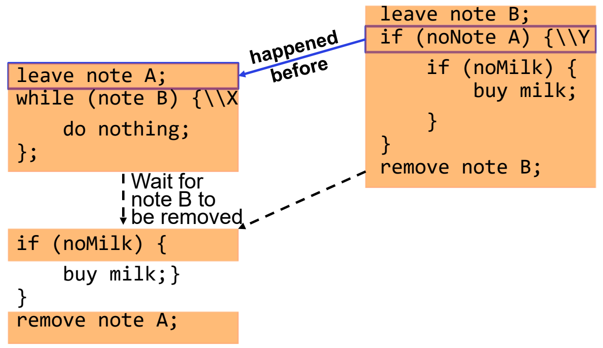
```
leave note A;
while (note B) {\\X
    do nothing;
};

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`"



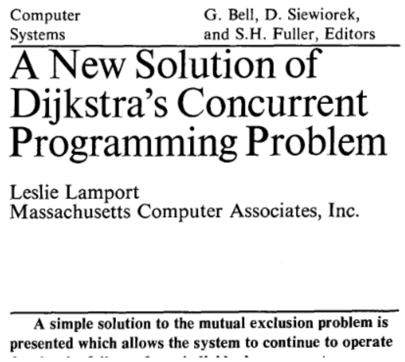
```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

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

```
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'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 got to 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's free, only one succeeds to grab the lock
- Then, our milk problem is easy:

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

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: get 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?

```
                 Acquire() {
                    disable interrupts;
                    if (value == BUSY) {
Enable Position ──→    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?

```
                 Acquire() {
                    disable interrupts;
                    if (value == BUSY) {
Enable Position ──→    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?

```
                 Acquire() {
                    disable interrupts;
                    if (value == BUSY) {
                       put thread on wait queue;
Enable Position ──→    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?

```
                     Acquire() {
                        disable interrupts;
                        if (value == BUSY) {
Enable Position ────────→  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

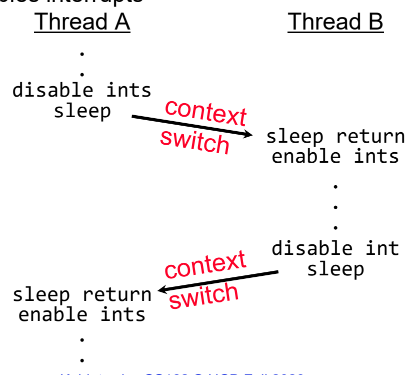
- What about re-enabling ints when going to sleep?

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

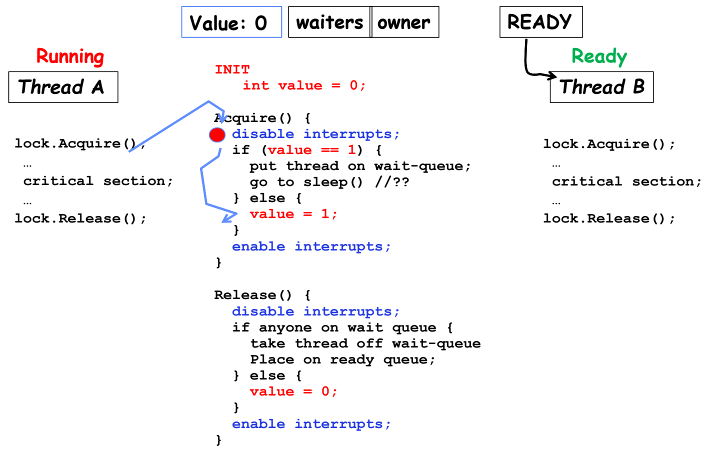
- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  – Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  – Misses wakeup and still holds lock (deadlock!)
- Want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



In-Kernel Lock: Simulation



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

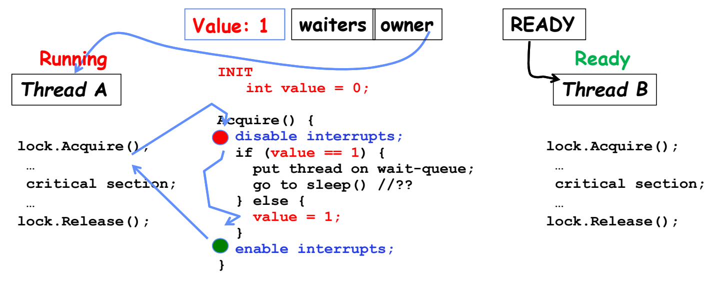
```
INIT
   int value = 0;

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;
}
```

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

In-Kernel Lock: Simulation



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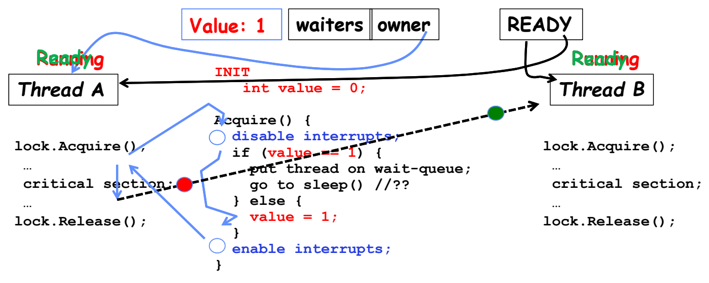

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

In-Kernel Lock: Simulation

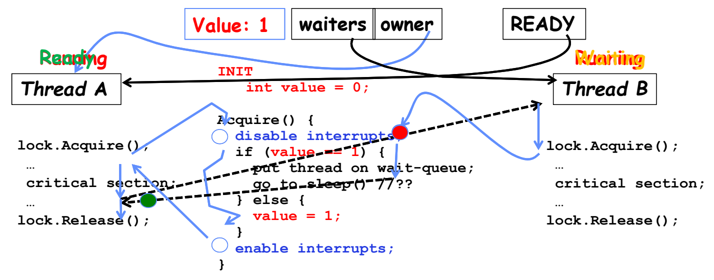


```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
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;
}
```

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

In-Kernel Lock: Simulation

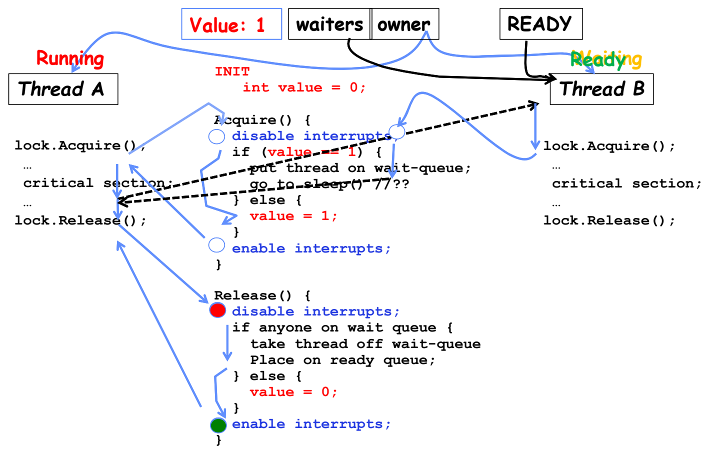


```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
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;
}
```

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

In-Kernel Lock: Simulation

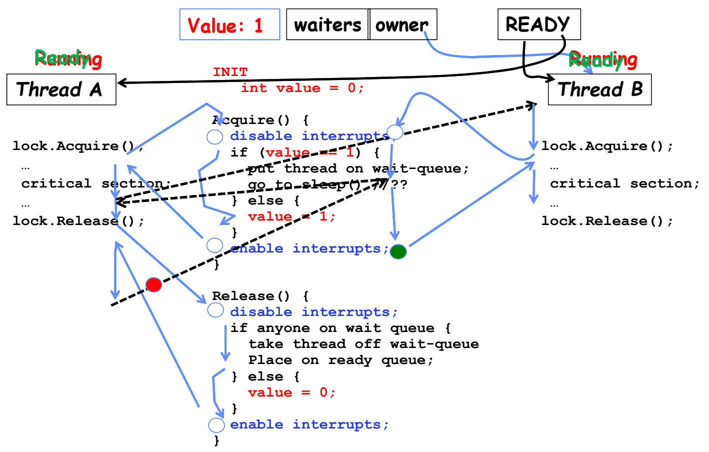


```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
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;
}
```

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

In-Kernel Lock: Simulation



```
int value = 0;
```

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

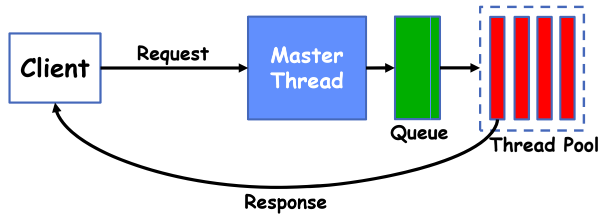
```
Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}
```

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

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

Recall: Multithreaded Server

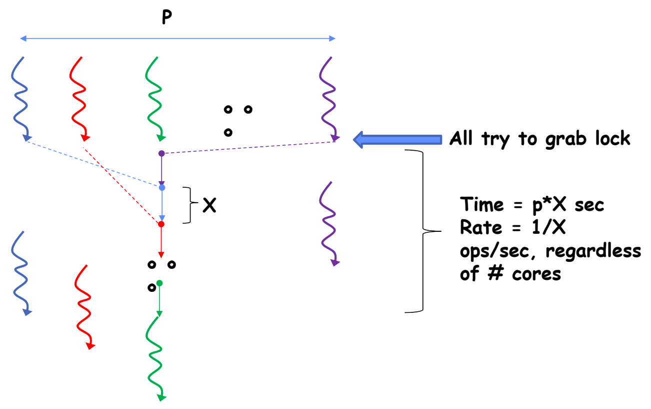
- **Bounded** pool of worker threads
  - Allocated in **advance:** no thread creation overhead
  - **Queue** of pending requests



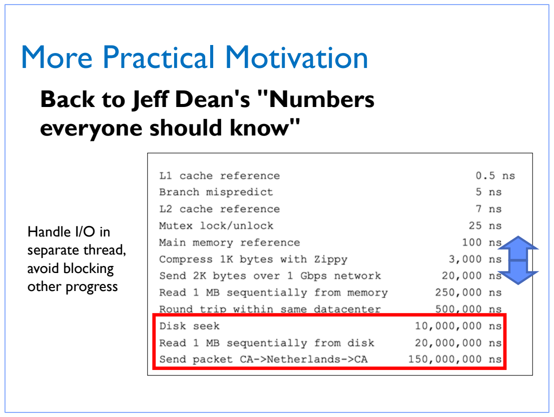
Simple Performance Model

- 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

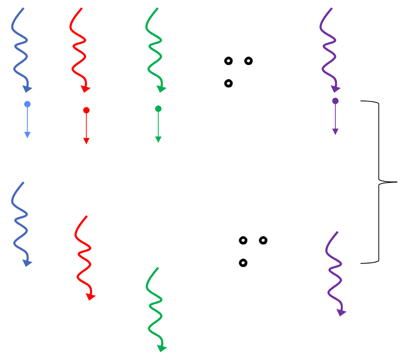
Back to Jeff Dean's "Numbers everyone should know"

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 = `1`ms => `1,000` ops/sec

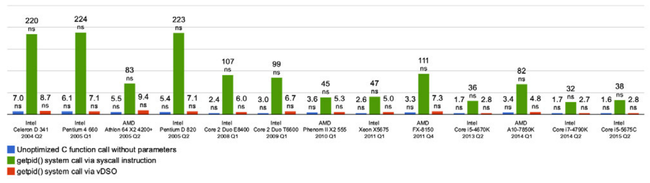
Uncontended Many-Lock Case



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)

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

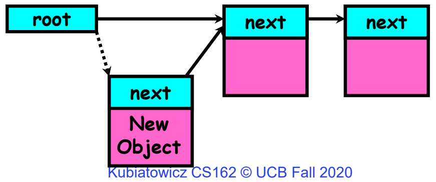
```
• test&set (&address) {          /* most architectures */
      result = M[address];        // return result from "address" and
      M[address] = 1;             // set value at "address" to 1
      return result;
  }
• swap (&address, register) {    /* x86 */
      temp = M[address];          // 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 */
      loop:
           ll r1, M[address];
           movi r2, 1;              // Can do arbitrary computation
           sc r2, M[address];
           beqz r2, loop;
  }
```

Using of Compare&Swap for queues

```
• compare&swap (&address, reg1, reg2) { /* 68000 */
      if (reg1 == M[address]) {
          M[address] = reg2;
          return success;
      } else {
          return failure;
      }
  }
```

Here is an atomic add to linked-list function:

```
addToQueue(&object) {
    do {                   // repeat until no conflict
        ld r1, M[root]     // Get ptr to current head
        st r1, M[object]  // Save link in new object
    } until (compare&swap(&root,r1,object));
}
```



Implementing Locks with test&set

- Another flawed, but simple solution:

```
int value = 0; // Free
Acquire() {
   while (test&set(value)); // while busy
}
Release() {
   value = 0;
}
```

- Simple explanation:
  - If lock is free, test&set reads 0 and sets value=1, so lock is now busy. It returns 0 so while exits.
  - If lock is busy, test&set reads 1 and sets value=1 (no change) It returns 1, so while loop continues.
  - When we set value = 0, someone else can get lock.
- Busy-Waiting: thread consumes cycles while waiting
  - For multiprocessors: every test&set() is a write, which makes value ping-pong around in cache (using lots of network BW)

Problem: Busy-Waiting for Lock

- Positives for this solution
  - Machine can receive interrupts
  - User code can use this lock
  - Works on a multiprocessor
- Negatives
  - This is very inefficient as thread will consume cycles waiting
  - Waiting thread may take cycles away from thread holding lock (no one wins!)
  - Priority Inversion: If busy-waiting thread has higher priority than thread holding lock ⇒ no progress!
- Priority Inversion problem with original Martian rover
- For semaphores and monitors, waiting thread may wait for an arbitrary long time!
  - Thus even if busy-waiting was OK for locks, definitely not ok for other primitives
  - Homework/exam solutions should avoid busy-waiting!

Multiprocessor Spin Locks: test&test&set

- A better solution for multiprocessors:

```
int mylock = 0; // Free
Acquire() {
   do {
      while(mylock);   // Wait until might be free
   } while(test&set(&mylock)); // exit if get lock
}

Release() {
   mylock = 0;
}
```

- Simple explanation:
  - Wait until lock might be free (only reading – stays in cache)
  - Then, try to grab lock with test&set
  - Repeat if fail to actually get lock
- Issues with this solution:
  - Busy-Waiting: thread still consumes cycles while waiting
    - » However, it does not impact other processors!

Better Locks using test&set

- Can we build test&set locks without busy-waiting?
  - Can't entirely, but can minimize!
  - Idea: only busy-wait to atomically check lock value

```
int guard = 0;
int value = FREE;

Acquire() {
   // Short busy-wait time
   while (test&set(guard));
   if (value == BUSY) {
      put thread on wait queue;
      go to sleep() & guard = 0;
   } else {
      value = BUSY;
      guard = 0;
   }
}

Release() {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   guard = 0;
```

- Note: sleep has to be sure to reset the guard variable
  - Why can't we do it just before or just after the sleep?

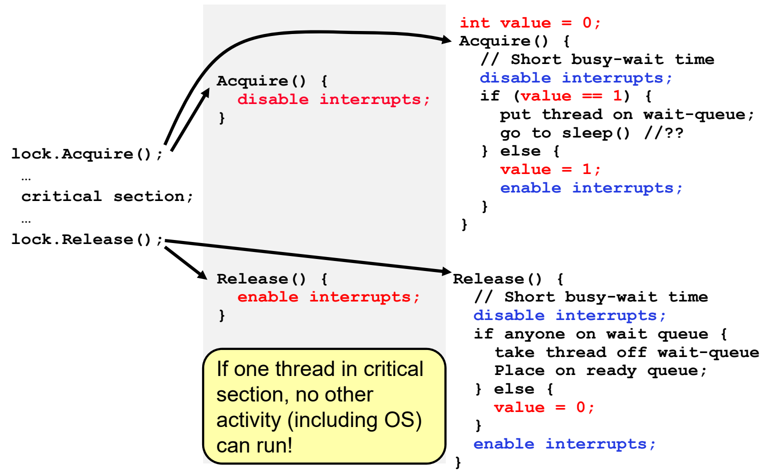
Recall: Locks using Interrupts vs. test&set

Compare to "disable interrupt" solution

```
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;
}
```

Basically we replaced:
- `disable interrupts` → `while (test&set(guard));`
- `enable interrupts` → `guard = 0;`

Recap: Locks using interrupts



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

```
Acquire() {
   disable interrupts;
}

Release() {
   enable interrupts;
}
```

If one thread in critical section, no other activity (including OS) can run!

```
int value = 0;
Acquire() {
   // Short busy-wait time
   disable interrupts;
   if (value == 1) {
      put thread on wait-queue;
      go to sleep() //??
   } else {
      value = 1;
      enable interrupts;
   }
}

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

Recap: Locks using test & set

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

```
int value = 0;
Acquire() {
  while(test&set(value));
}

Release() {
  value = 0;
}
```

Threads waiting to enter critical section busy-wait

```
int guard = 0;
int value = 0;
Acquire() {
  // Short busy-wait time
  while(test&set(guard));
  if (value == 1) {
    put thread on wait-queue;
    go to sleep()& guard = 0;
  } else {
    value = 1;
    guard = 0;
  }
}

Release() {
  // Short busy-wait time
  while (test&set(guard));
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  guard = 0;
}
```

Linux `futex`: Fast Userspace Mutex

```
#include <linux/futex.h>
#include <sys/time.h>

int futex(int *uaddr, int futex_op, int val,
          const struct timespec *timeout );
```

- `uaddr` points to a 32-bit value in user space
- `futex_op`
  - `FUTEX_WAIT` – if `val == *uaddr` sleep till `FUTEX_WAIT`
    - » ***Atomic*** check that condition still holds
  - `FUTEX_WAKE` – wake up at most `val` waiting threads
  - `FUTEX_FD`, `FUTEX_WAKE_OP`, `FUTEX_CMP_REQUEUE`
- `timeout`
  - ptr to a *timespec* structure that specifies a timeout for the op

Linux futex: Fast Userspace Mutex

- Idea: Userspace lock is *syscall-free* in the uncontended case
- Lock has three states
  - Free (no syscall when acquiring lock)
  - Busy, no waiters (no syscall when releasing lock)
  - Busy, possibly with some waiters
- `futex` is not exposed in libc; it is used within the implementation of pthreads

Example: Userspace Locks with `futex`

```
int value = 0; // free
bool maybe_waiters = false;

Acquire() {
  while (test&set(value)) {
    maybe_waiters = true;
    futex(&value, FUTEX_WAIT, 1);
    // futex: sleep if lock is acquired
    maybe_waiters = true;
  }
}

Release() {
  value = 0;
  if (maybe_waiters) {
    maybe_waiters = false;
    futex(&value, FUTEX_WAKE, 1);
    // futex: wake up a sleeping thread
  }
}
```

- This is syscall-free in the uncontended case
  - Temporarily falls back to syscalls if multiple waiters, or concurrent acquire/release
- But it can be considerably optimized!
  - See "Futexes are Tricky" by Ulrich Drepper

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-locked & 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