CS162
Operating Systems and Systems Programming
Lecture 8

Synchronization 2: Lock Implementation, Atomic Instructions, Futex, Need for Higher-Level Locking

February 8th, 2024

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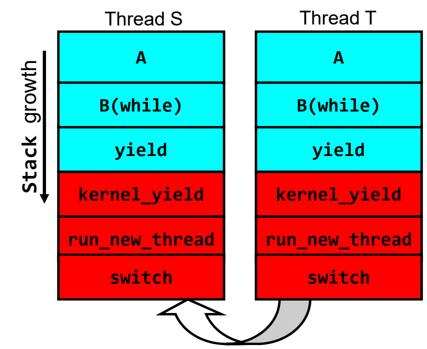
Recall: Multiple Threads on One CPU/core

- Consider the following code blocks:

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



Thread T's switch returns to Thread S
[Thread T on Ready queue, Thread S is Running]

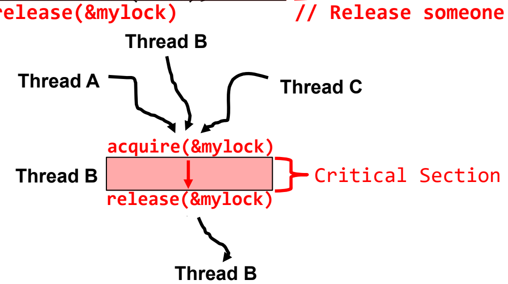
- Suppose we have 2 threads:
  – Threads S and T
- Kernel stack contains pointers to all state and can be placed on any queue:
  – Ready queue – available to run again
  – Some wait queue – won't run again until condition resolved and back on ready queue

Recall: Fix banking problem with Locks!

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

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

Critical Section



Threads serialized by lock through critical section. Only one thread at a time

- Must use SAME lock (`mylock`) with all of the methods (Withdraw, etc…)
  – Shared with all threads!

Today's Motivating Example: "Too Much Milk"

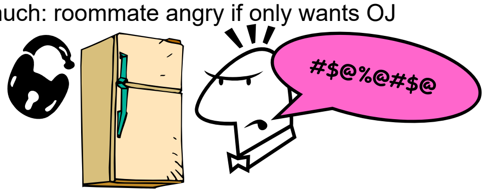
- Great thing about OS's – analogy between problems in OS and problems in real life
  – Help you understand real life problems better
  – But, computers are much stupider than people

- 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

Solve with a lock?

- Recall: Lock prevents someone from doing something
  - Lock before entering critical section
  - Unlock when leaving
  - 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!

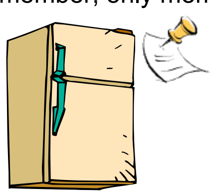
Too Much Milk: Correctness Properties

- 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;
   }
}
```



Too Much Milk: Solution #1

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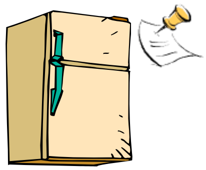
  - Leave a note before buying (kind of "lock")
  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

```
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:

<u>Thread A</u>

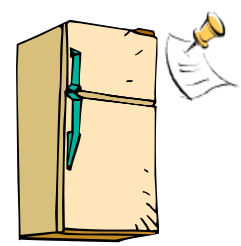
```
leave note A;
if (noNote B) {
   if (noMilk) {
      buy Milk;
   }
}
remove note A;
```

<u>Thread B</u>

```
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;
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;
```

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

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


Case 2

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

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

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

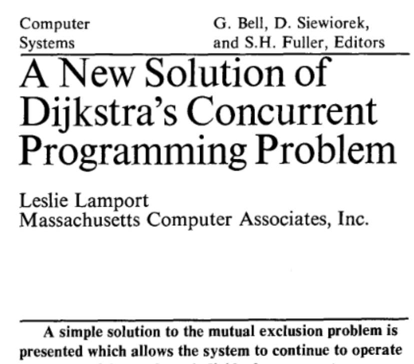

Case 2

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

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


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

Administrivia

- Midterm Next Thursday (February 15, 8-10pm)!
  - No class on day of midterm (extra office hours during class time)
  - Topics, lectures, and assignments up to an including next Tuesday
  - Closed book, one page of handwritten notes allowed
- Project 1 Design Document Due Date Saturday
- Project 1 Design reviews upcoming
  - High-level discussion of your approach
    - » What will you modify?
    - » What algorithm will you use?
    - » How will things be linked together, etc.
    - » Do not need final design (complete with all semicolons!)
  - You will be asked about testing
    - » Understand testing framework
    - » Are there things you are doing that are not tested by tests we give you?

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.
  - *Prevent switching to other thread that might be trying to acquire lock!*
  - 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;
}
```

"Meta-" Critical Section

- Note: unlike previous solution, this "meta-"critical section 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!

What about 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;
}
```


What about 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?

What about 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

What about 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

What about 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;
}
```

Enable Position?

- 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!)

What about 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;
}
```

Enable Position?

- 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
	← context switch	sleep
sleep return		
enable ints		
.		
.		

In-Kernel Lock: Simulation

Value: 0 | waiters | owner | READY

Running: Thread A

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

Ready: Thread B

```
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;
}
```

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running — Thread A

Ready — Thread B

```
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

Value: 1 | waiters | owner | READY

Ready / Running — Thread A

Ready / Running — Thread B

```
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

Value: 1 | waiters | owner | READY

Ready / Running — Thread A

Running / Waiting — Thread B

```
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

Value: 1 | waiters | owner | READY

Running — Thread A

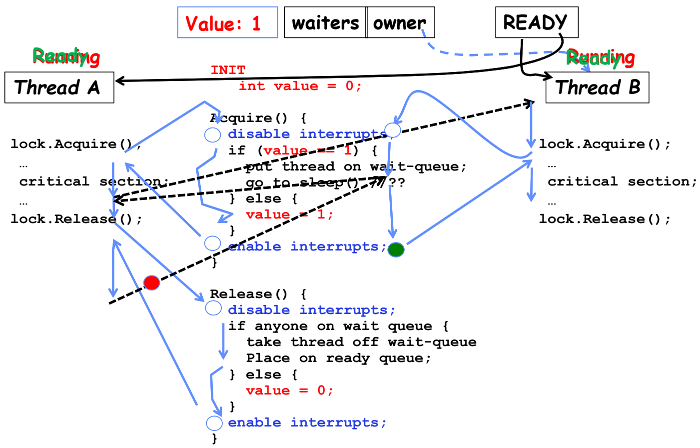
Ready / Waiting — Thread B

```
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



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

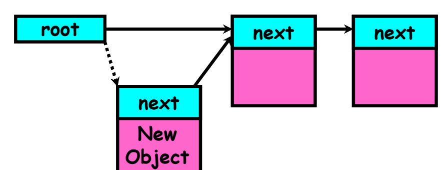
```
• test&set (&address) {          /* most architectures */
      result = M[address];       // return result from “address” and
      M[address] = 1;            // set value at “address” to 1
      return result;
  }
• swap (&address, register) {    /* x86 */
      temp = M[address];         // swap register’s value to
      M[address] = register;     // value at “address”
      register = temp;           // value from “address” put back to register
      return temp;               // value from “address” considered return from swap
  }
• compare&swap (&address, reg1, reg2) { /* x86 (returns old value), 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) { /* x86, 68000 */
      if (reg1 == M[address]) {
          M[address] = reg2;
          return success;
      } else {
          return failure;
      }
  }
```

Here is an atomic add to linkedlist 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

- Simple lock that doesn't require entry into the kernel:

```
// (Free) Can access this memory location from user space!
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);
acquire(int *thelock) {
   while (test&set(thelock)); // Atomic operation!
}
release(int *thelock) {
   *thelock = 0;              // Atomic operation!
}
```

- Simple explanation:
  – If lock is free, test&set reads 0 and sets lock=1, so lock is now busy. It returns 0 so while exits.
  – If lock is busy, test&set reads 1 and sets lock=1 (no change) It returns 1, so while loop continues.
  – When we set thelock = 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 higher-level synchronization primitives (e.g. semaphores or 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:

```
// (Free) Can access this memory location from user space!
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);
acquire(int *thelock) {
   do {
      while(*thelock);         // Wait until might be free (quick check/test!)
   } while(test&set(thelock)); // Atomic grab of lock (exit if succeeded)
}
release(int *thelock) {
   *thelock = 0;              // Atomic release of lock
}
```

- 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?
  – Mostly. Idea: only busy-wait to atomically check lock value
  –

```
int guard = 0; // Global Variable!
int mylock = FREE; // Interface: acquire(&mylock);
                   //            release(&mylock);

acquire(int *thelock) {
   // Short busy-wait time
   while (test&set(guard));
   if (*thelock == BUSY) {
      put thread on wait queue;
      go to sleep() & guard = 0;
      // guard == 0 on wakup!
   } else {
      *thelock = BUSY;
      guard = 0;
   }
}

release(int *thelock) {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      *thelock = 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?

Recap: Locks using interrupts

```
int mylock=0;

acquire(&mylock);
 …
 critical section;
 …
release(&mylock);
```

```
acquire(int *thelock) {
  disable interrupts;
}
```

```
release(int *thelock)
{
  enable interrupts;
}
```

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

Lock argument not used!

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

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


Recap: Locks using test & set

```
int mylock=0;

acquire(&mylock);
 …
 critical section;
 …
release(&mylock);
```

```
int mylock = 0;
acquire(int *thelock) {
  while(test&set(thelock));
}
```

```
release(int *thelock) {
  *thelock = 0;
}
```

Threads waiting to enter critical section busy-wait

```
int guard = 0; // global!

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

release(int *thelock) {
  // Short busy-wait time
  while (test&set(guard));
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    *thelock = 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 after we disable interrupts (in kernel!)
- `FUTEX_WAKE` – wake up at most `val` waiting threads
- `FUTEX_FD, FUTEX_WAKE_OP, FUTEX_CMP_REQUEUE: More interesting operations!`

`timeout`
- ptr to a *timespec* structure that specifies a timeout for the op

- `Interface to the kernel sleep() functionality!`
  - `Let thread put themselves to sleep – conditionally!`
- futex is not exposed in libc; it is used within the implementation of pthreads
  - Can be used to implement locks, semaphores, monitors, etc…

Example: First try: T&S and `futex`

```
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);

acquire(int *thelock) {
   while (test&set(thelock)) {
      futex(thelock, FUTEX_WAIT, 1);
   }
}

release(int *thelock) {
   *thelock = 0; // unlock
   futex(thelock, FUTEX_WAKE, 1);

}
```

- Properties:
  - Sleep interface by using futex – no busywaiting
- No overhead to acquire lock
  - Good!
- Every unlock has to call kernel to potentially wake someone up – even if none
  - Doesn't quite give us no-kernel crossings when uncontended…!

Example: Try #2: T&S and `futex`

```
bool maybe_waiters = false;
int mylock = 0; // Interface: acquire(&mylock,&maybe_waiters);
                //            release(&mylock,&maybe_waiters);

acquire(int *thelock, bool *maybe) {
   while (test&set(thelock)) {
      // Sleep, since lock busy!
      *maybe = true;
      futex(thelock, FUTEX_WAIT, 1);

      // Make sure other sleepers not stuck
      *maybe = true;
   }
}

release(int *thelock, bool *maybe) {
   *thelock = 0;
   if (*maybe) {
      *maybe = false;
      // Try to wake up someone
      futex(thelock, FUTEX_WAKE, 1);
   }
}
```

- 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

Try #3: Better, using more atomics

- Much better: Three (3) states:
  – UNLOCKED: No one has lock
  – LOCKED: One thread has lock
  – CONTESTED: Possibly more than one (with someone sleeping)
- Clean interface!
- Lock grabbed cleanly by either
  – `compare&swap()`
  – First `swap()`
- No overhead if uncontested!
- Could build semaphores in a similar way!

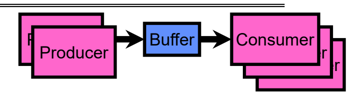
```
typedef enum { UNLOCKED,LOCKED,CONTESTED } Lock;
Lock mylock = UNLOCKED; // Interface: acquire(&mylock);
                        //            release(&mylock);

acquire(Lock *thelock) {
   // If unlocked, grab lock!
   if (compare&swap(thelock,UNLOCKED,LOCKED))
      return;

   // Keep trying to grab lock, sleep in futex
   while (swap(thelock,CONTESTED) != UNLOCKED))
      // Sleep unless someone releases here!
      futex(thelock, FUTEX_WAIT, CONTESTED);
}

release(Lock *thelock) {
   // If someone sleeping,
   if (swap(thelock,UNLOCKED) == CONTESTED)
      futex(thelock,FUTEX_WAKE,1);
}
```


Recall: 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

Producer-Consumer with a Bounded Buffer

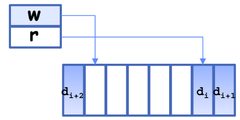


- Problem Definition
  – Producer(s) put things into a shared buffer
  – Consumer(s) take them out
  – Need synchronization to coordinate producer/consumer
- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  – Need to synchronize access to this buffer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

Bounded 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?*

Bounded 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?

Bounded 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

- Goal of last couple of lectures:
  – 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

Summary

- 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
- Showed primitive for constructing user-level locks
  - Packages up functionality of sleeping