Synchronization 3: Lock Implementation

Sam Kumar
CS 162: Operating Systems and System Programming
Lecture 10
https://inst.eecs.berkeley.edu/~cs162/su20

Read: A&D 5.1-3, 5.7
Recall: Producer-Consumer

• Problem Definition
  • Producers puts things into a shared buffer
  • Consumers takes them out

• Don’t want producers and consumers to have to work in lockstep, so put a buffer (bounded) between them
  • Need synchronization to maintain integrity of the data structure and coordinate producers/consumers
  • Producer needs to wait if buffer is full
  • Consumer needs to wait if buffer is empty
Recall: Producer-Consumer (Semaphores)

Semaphore usedSlots = 0; // No slots used
Semaphore freeSlots = bufSize; // All slots free
Lock mutex = <initially unlocked>; // Nobody in critical sec.

Producer(item) {
    freeSlots.P();
    mutex.acquire();
    Enqueue(item);
    mutex.release();
    usedSlots.V();
}

Consumer() {
    usedSlots.P();
    mutex.acquire();
    item = Dequeue();
    mutex.release();
    freeSlots.V();
    return item;
}
Recall: Problems with Semaphores

• More powerful (and primitive) than locks

• Argument: Clearer to have separate constructs for
  • Mutual Exclusion: One thread can do something at a time
  • Waiting for a condition to become true

• Need to make sure a thread calls $P()$ for every $V()$
  • Other tools are more flexible than this
Recall: Condition Variables

• Queue of threads waiting *inside* a critical section
  • Typically, waiting until a condition on some variables becomes true
  • Variables typically are protected by a mutex

• Operations:
  • `wait(&lock)`: Atomically release lock and go to sleep until condition variable is signaled. Re-acquire the lock before returning.
  • `signal()`: Wake up one waiting thread (if there is one)
  • `broadcast()`: Wake up all waiting threads

• **Rule:** Hold lock when using a condition variable
Recall: Monitors

• A monitor consists of a lock and zero or more condition variables used for managing concurrent access to shared data

• Lock: the lock provides mutual exclusion to shared data

• Condition Variable: a queue of threads waiting for something inside a critical section
  • Key idea: make it possible to go to sleep inside critical section by atomically releasing lock at time we go to sleep
Recall: Why the while Loop?

• When a thread is woken up by `signal()`, it is simply marked as eligible to run

• It may or may not reacquire the lock immediately!
  • Another thread could be scheduled and “sneak in” make the condition it’s waiting for no longer true
  • Need a loop to re-check condition on wakeup

• This is called Mesa Scheduling (Mesa-style Monitors)
• Most operating systems use Mesa-style Monitors!
Recall: Mesa Monitors vs. Hoare Monitors

Mesa Monitor

```c
while (buffer empty) {
    cond_wait(&not_empty, &buf_lock);
}
```

Hoare Monitor

```c
if (buffer empty) {
    cond_wait(&not_empty, &buf_lock);
}
```

• In practice, almost all OSes implement Mesa monitors
Recall: Java Support for Monitors

• Along with a lock, every object has a **single** condition variable associated with it

• To wait inside a synchronized method:
  • `void wait();`
  • `void wait(long timeout);`

• To signal while in a synchronized method:
  • `void notify();`
  • `void notifyAll();`
Recall: Go Channels

• Semantics similar to pipes, with the following differences:
  • Used within a single process (not across processes)
  • Carries language objects/structs, not bytes (no marshalling/unmarshalling)

```go
var x chan int = make(chan int, 5)
x <- 162
y := <- x
fmt.Println(y) // Prints 162
```
Today: How to implement synchronization primitives?

For now, just consider *locks inside the kernel*.
Recall: Race Conditions

• What are the possible values of $x$ below?
• Initially $x == 0$

Thread A          Thread B
$x += 1;$           $x += 1;$

• 1 or 2 (non-deterministic)
Recall: Race Conditions

• What are the possible values of x below?
• Initially x == 0

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>x = 1;</td>
<td>x = 2;</td>
</tr>
</tbody>
</table>

• 1 or 2 (non-deterministic)
• Maybe even 3 for serial processors (!)
Atomic Operations

• To understand a concurrent program, we need to know what the underlying indivisible operations are!

• **Atomic Operation**: an operation that always runs to completion or not at all
  • It is *indivisible*: it cannot be stopped in the middle and state cannot be modified by someone else in the middle

• On most machines, memory references and assignments (i.e. loads and stores) of words are atomic
  • Consequently – weird example that produces “3” on previous slide can’t happen
Concurrency is Hard!

• Even for practicing engineers trying to write mission-critical, bulletproof code!
  • Threaded programs must work for all interleavings of thread instruction sequences
  • Cooperating threads inherently non-deterministic and non-reproducible
  • Really hard to debug unless carefully designed!

• Therac-25: Radiation Therapy Machine with Unintended Overdoses (reading on course site)

• Mars Pathfinder Priority Inversion ([JPL Account](#))

• Toyota Uncontrolled Acceleration ([CMU Talk](#))
  • 256.6K Lines of C Code, ~9-11K global variables
  • Inconsistent mutual exclusion on reads/writes
Motivating Example: “Too Much Milk”

• Analogy between problems in OS and problems in real life
• Example: People need to coordinate:

<table>
<thead>
<tr>
<th>Time</th>
<th>Person A</th>
<th>Person B</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:00</td>
<td>Look in Fridge. Out of milk</td>
<td></td>
</tr>
<tr>
<td>3:05</td>
<td>Leave for store</td>
<td></td>
</tr>
<tr>
<td>3:10</td>
<td>Arrive at store</td>
<td>Look in Fridge. Out of milk</td>
</tr>
<tr>
<td>3:15</td>
<td>Buy milk</td>
<td>Leave for store</td>
</tr>
<tr>
<td>3:20</td>
<td>Arrive home, put milk away</td>
<td>Arrive at store</td>
</tr>
<tr>
<td>3:25</td>
<td></td>
<td>Buy milk</td>
</tr>
<tr>
<td>3:30</td>
<td></td>
<td>Arrive home, put milk away</td>
</tr>
</tbody>
</table>
Too Much Milk: Correctness

1. Safety: At most one person buys milk.

2. Liveness: If milk is needed, at least one person buys it.
Attempt #1

• Leave a note
  • Place on fridge before buying
  • Remove after buying
  • Don’t go to store if there’s already a note

• Leaving/checking a note is atomic (word load/store)

```java
if (noMilk) {
    if (noNote) {
        leave Note;
        buy milk;
        remove Note;
    }
}
```
Attempt #1 in Action

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

Thread B
if (noMilk) {
  if (noNote) {
  }
}

Achieves liveness but not safety
Attempt #1.5

• Idea: leave note, then check for milk

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

But there’s always a note – you just left one!
Attempt #2: Use Named Notes

Thread A
leave note A
if (noMilk) {
    if (noNote B) {
        buy milk
    }
}
remove note A

Thread B
leave note B
if (noMilk) {
    if (noNote A) {
        buy milk
    }
}
remove note B
Attempt #2 in Action

Thread A
leave note A
if (noMilk) {
    if (noNote B) {
        buy milk
    }
}
remove note A

Thread B
leave note B

if (noMilk) {
    if (noNote A) {
        buy milk
    }
remove note B

Achieves safety but not liveness
Attempt #3: Wait

Thread A
leave note A
while (note B) {
    do nothing
}
if (noMilk) {
    buy milk
}
remove note A

Thread B
leave note B
if (noNote A) {
    if (noMilk) {
        buy milk
    }
}
remove note B

This is a correct solution!
This Generalizes to $n$ Threads...

- Leslie Lamport’s “Bakery Algorithm” (1974)

- Allows one to protect a critical section like:

```java
if (noMilk) {
    buy milk;
}
```
Solution #3 Discussion

• Solution #3 works, but it’s not great
  • Really complex – even for this simple an example
    • Hard to convince yourself that this really works
  • While A is waiting, it is consuming CPU time
    • This is called “busy-waiting”

• There’s a better way
  • Have hardware provide higher-level primitives than atomic load & store
  • Build even higher-level programming abstractions on this hardware support
  • Make sure the OS scheduler never allows another thread to enter the critical section
    • The other thread becomes blocked if it tries to enter
Where are we going with Synchronization?

<table>
<thead>
<tr>
<th>Programs</th>
<th>Shared Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher-level API</td>
<td>Shares Programs</td>
</tr>
<tr>
<td>Hardware</td>
<td>Load/Store Disable Ints Test&amp;Set Compare&amp;Swap</td>
</tr>
</tbody>
</table>

- Building an efficient, easy-to-use API
Announcements

• Homework 3 is released

• Project 1 design reviews are today

• Project 1 code is due on Tuesday, July 14
Implementing Locks: Single Core

• How can we make lock.Acquire() and lock.Release() appear atomic to other threads?

• Idea: A context switch can only happen (assuming threads don’t yield) if there’s an interrupt

• “Solution”: Disable interrupts while holding lock

• x86 has cli and sti instructions that only operate in system mode (PL=0)
  • Interrupts enabled bit in FLAGS register
Naïve Interrupt Enable/Disable

Acquire() {
    disable interrupts;
}

Release() {
    enable interrupts;
}

• Problem: can stall the entire system
  Lock.Acquire()
  While (1) {}}

• Problem: What if we want to do I/O?
  Lock.Acquire()
  Read from disk
  /* OS waits for (disabled) interrupt! */
Implementing Locks: Single Core

• Key idea: maintain a lock variable (value) and disable interrupts only during operations on that variable

```c
int value = FREE;

Acquire() {
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread();
        // Enable interrupts?
    } else {
        value = BUSY;
    } else {
        value = FREE;
    }
    enable interrupts;
}

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

• Unlike the naïve solution, interrupts are disabled for only a short time

Critical Section

• Disabling interrupts prevents preemption
• Locks disable interrupts to provide another critical section
Implementing Locks: Single Core

- Key idea: maintain a lock variable (value) and disable interrupts only during operations on that variable.

```c
int value = FREE;

Acquire() {
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread();
        // 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;
}
```
Re-enabling Interrupts when Waiting

Before on the queue?
  • Release might not wake up this thread!

After putting the thread on the queue?
  • Gets woken up, but immediately switches away

Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    run_new_thread()
  } else {
    value = BUSY;
  }
  enable interrupts;
}
Re-enabling Interrupts when Waiting

• Best solution: after the current thread suspends

• How?
  • run_new_thread() should do it!
  • Part of returning from switch()

Acquire() {
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread()
    } else {
        value = BUSY;
    }
    enable interrupts;
}
How to Re-enable Interrupts when Waiting

• In scheduler, since interrupts are disabled when switching threads:
  • Responsibility of the next thread to re-enable interrupts
  • When the sleeping thread wakes up, returns to acquire and re-enables interrupts

Thread A

disable ints

run_new_thread

Thread B

run_new_thread

enable ints

disable int

call run_new_thread

run_new_thread

return

enable ints
Enabling Interrupts vs. Restoring Interrupts

• 99% of the time, you want to restore interrupts, not enable them

• We used “enable interrupts” in this lecture since we were assuming interrupts are enabled when acquiring the lock

• In Pintos:
  
  ```c
  enum intr_level state = intr_disable();
  <code manipulating shared data>
  intr_set_level(state);
  ```
When does this Lock Implementation Work?

• Answer: For threads in the kernel on a single-core machine.

Roadmap for today’s lecture:
1. What about multi-core machines?
2. What about user threads?
Break
Multi-Core Machines

• How to synchronize with threads executing in parallel on other cores?
  • Disable interrupts on all cores?
  • Prevent other cores from making progress?

• Implement locks in hardware?
  • What’s the interface between hardware lock and OS scheduler?

• Solution: Use hardware support for atomic operations
Atomic Operations

• Definition: An operation runs to completion or not at all
• Foundation for synchronization primitives

• Example: Loading or storing a word (on most modern architectures)
Atomic Read-Modify-Write Instructions

• 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
• Natural extensions to user-level locking
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]; // Can do arbitrary computation
    movi r2, 1;
    sc r2, M[address];
    beqz r2, loop;
}
Implementing Locks with test&set

• Simple, but flawed, solution:

```c
int value = 0; // Free

Acquire() {
    while (test&set(value)) {}; // spin while busy
}

Release() {
    value = 0;                  // atomic store
}
```

• 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 multiprocessor cache coherence: every test&set() is a write, which makes value ping-pong around in cache (using lots of memory BW)
This is Called a Spinlock

• Spinlock implementation:

```c
int value = 0; // Free

Acquire() {
    while (test&set(value)) {} // spin while busy
}

Release() {
    value = 0;               // atomic store
}
```

• Spinlock doesn’t put the calling thread to sleep --- it just busy waits
Problem: Busy-Waiting for Lock

• Positives for this solution
  • Machine can receive interrupts
  • User code can use this lock (poorly)
  • Works on a multiprocessor

• Negatives
  • Very inefficient: thread will consume cycles waiting
  • Waiting thread takes cycles away from thread holding lock (no one wins!)
  • Priority Inversion: If busy-waiting thread has higher priority than thread holding lock ⇒ no progress!

• 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!
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

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

Acquire() {
    // Short busy-wait time
    while (test&set(guard));
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread() & 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?
Alternative View: Bootstrapping a Spinlock

SpinLock guard = FREE;
int value = FREE;

Acquire() {
    // Short busy-wait time
    guard.Acquire();
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread() & guard.Release();
    } else {
        value = BUSY;
        guard.Release();
    }
}

Release() {
    // Short busy-wait time
    guard.Acquire();
    if anyone on wait queue {
        take thread off wait queue
        Place on ready queue;
    } else {
        value = FREE;
    }
    guard.Release();
}
Comparison to Disabling Interrupts

- We changed `disable interrupts` → `spinlock.Acquire()` [while (test&set(guard))]
- We changed `enable interrupts` → `spinlock.Release()` [guard = 0]

```
int value = FREE;

Acquire() {
    // Short busy-wait time
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread();
        // scheduler enables 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;
}
```
Recap: Locks Using Interrupts

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

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;
}

Threads waiting to enter critical section
busy-wait
Recap: Locks Using test&set

```
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;
}
```

lock.Acquire();
...
critical section;
...
lock.Release();
Recall: *Spinlock*

- Spinlock implementation:

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

- Spinlock doesn’t put the calling thread to sleep—it just busy waits
  - When might this be preferable?

- For multiprocessor cache coherence: every test&set() is a write, which makes value ping-pong around in cache (using lots of memory BW)
Better Spinlock: test&test&set

• A better spinlock solution:

```c
int mylock = 0; // Free

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

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

• 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

• Busy-Waiting: no longer impacts other processors!
Locks in Userspace?

• We’ve looked at locks in the kernel
  • Uniprocessor case (disable interrupts)
  • Multiprocessor case (test&set)

• What about locks in userspace?
• Spinlocks just work
• Simple idea for non-busy-waiting lock:
  • For each userspace lock, allocate a lock in the kernel
  • Make a syscall for each acquire/release operation to acquire the lock in the kernel
**Recall: Overhead of Syscalls**

<table>
<thead>
<tr>
<th>Processor</th>
<th>Unoptimized C function call without parameters</th>
<th>getpid() system call via syscall instruction</th>
<th>getpid() system call via vDSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel Celeron D 341 2004 Q2</td>
<td>220 ns</td>
<td>224 ns</td>
<td></td>
</tr>
<tr>
<td>Intel Pentium 4 660 2001 Q1</td>
<td>6.7 ns</td>
<td>6.1 ns</td>
<td>83 ns</td>
</tr>
<tr>
<td>AMD Athlon 64 X2 4200+ 2005 Q2</td>
<td>7.1 ns</td>
<td>7.1 ns</td>
<td>5.5 ns</td>
</tr>
<tr>
<td>Intel Pentium D 820 2005 Q2</td>
<td>5.1 ns</td>
<td>5.4 ns</td>
<td>9.4 ns</td>
</tr>
<tr>
<td>Intel Core 2 Duo E8400 Core 2008 Q1</td>
<td>7.1 ns</td>
<td>6.0 ns</td>
<td>2.4 ns</td>
</tr>
<tr>
<td>Intel Core 2 Duo T6600 2008 Q1</td>
<td>6.7 ns</td>
<td>5.3 ns</td>
<td>3.3 ns</td>
</tr>
<tr>
<td>AMD Phenom II X2 555 2010 Q1</td>
<td>4.5 ns</td>
<td>5.0 ns</td>
<td>3.3 ns</td>
</tr>
<tr>
<td>Intel Xeon X5675 2011 Q1</td>
<td>47 ns</td>
<td>2.6 ns</td>
<td>3.3 ns</td>
</tr>
<tr>
<td>AMD FX-8150 2011 Q4</td>
<td>107 ns</td>
<td>45 ns</td>
<td>82 ns</td>
</tr>
<tr>
<td>Intel Core i5-4670K 2013 Q2</td>
<td>7.3 ns</td>
<td>111 ns</td>
<td>7.3 ns</td>
</tr>
<tr>
<td>AMD A10-7850K 2014 Q1</td>
<td>36 ns</td>
<td>8.2 ns</td>
<td>4.8 ns</td>
</tr>
<tr>
<td>Intel Core i7-4790K 2014 Q2</td>
<td>32 ns</td>
<td>36 ns</td>
<td>4.8 ns</td>
</tr>
<tr>
<td>Intel Core i5-5675S 2015 Q2</td>
<td>38 ns</td>
<td>38 ns</td>
<td>8.2 ns</td>
</tr>
</tbody>
</table>

- Syscalls are 25x more expensive than function calls (~100 ns)
- read/write a file byte by byte? Max throughput of ~**10MB/second**
- With `fgetc`? Keeps up with your SSD
Userspace Locks: Syscall Overhead

• Can we avoid syscall overhead when acquiring a non-busy-waiting lock in userspace?
  • No: can’t put a thread to sleep (i.e., block the thread) without entering the kernel

• What we can do: avoid system calls in the uncontended case (i.e., the case where we can acquire the lock without blocking)
  • Helps both uniprocessor case and multiprocessor case
Linux futex: Fast Userspace Mutex

```c
#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

```c
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
Bonus Slides (If Time)
Further Reducing Overhead

• Make locks less contended [how?]

• Move synchronization and scheduling into userspace
We’ve Looked At: Kernel-Supported Threads

- Threads run and block (e.g., on I/O) independently
- One process may have multiple threads waiting on different things
- Two mode switches for every context switch (expensive)
- Create threads with syscalls

- Alternative: multiplex several streams of execution (at user level) on top of a single OS thread
  - E.g., Java, Go, ... (and many many user-level threads libraries before it)
User-Mode Threads

- User program contains its own scheduler
- Several user threads per kernel thread
- User threads may be scheduled non-preemptively
  - Only switch on yield
- Context switches cheaper
  - Copy registers and jump (switch in userspace)
Thread Yield

Kernel-Supported Threads

- ComputePI
- yield (syscall)
- kernel_yield
- run_new_kernel_thread
- switch

User-Mode Threads

- ComputePI
- yield
- run_new_user_thread
- switch

Trap to OS (Expensive)

Library Function Call (Cheap)

Stack growth

Stack growth
Thread I/O

Kernel-Supported Threads

- CopyFile
  - read
  - kernel_read
  - run_new_thread
  - switch

User-Mode Threads

- CopyFile
  - read
  - kernel_read
  - run_new_thread
  - switch

- Trap to OS
- Stack growth

- Selects a new kernel thread to run
- Bypassing user-level scheduler
User-Mode Threads: Problems

• One user-level thread blocks on I/O: they all do
  • Kernel cannot adjust scheduling among threads it doesn’t know about

• Multiple Cores?

• Can’t completely avoid blocking (syscalls, page fault)

• One Solution: *Scheduler Activations*
  • Have kernel inform user-level scheduler when a thread blocks
  • Evolving the contract between OS and application

• Alternative Solution: Language Support?
  • Make the scheduler aware of the blocking operation
Go Goroutines

• Goroutines are lightweight, user-level threads
  • Scheduling not preemptive (relies on goroutines to yield)
  • Yield statements inserted by compiler

• Advantages relative to regular threads (e.g., pthreads)
  • More lightweight
  • Faster context-switch time

• Disadvantages
  • Less sophisticated scheduling at the user-level
  • OS is not aware of user-level threads
Go User-Level Scheduler

Why this approach?

• 1 OS (kernel-supported) thread per CPU core: allows go program to achieve parallelism not just concurrency
  • Fewer OS threads? Not utilizing all CPUs
  • More OS threads? No additional benefit
    • We’ll see one exception to this involving syscalls

• Keep goroutine on same OS thread: affinity, nice for caching and performance
Go User-Level Thread Scheduler

- Why not just have a single global run queue?
Dealing with Blocking Syscalls

• What if a goroutine wants to make a blocking syscall?
  • Example: File I/O
Dealing with Blocking Syscalls

• What if a goroutine wants to make a blocking syscall?
  • Example: File I/O

• While syscall is blocking, allocate new OS thread (M2)
  • M1 is blocked by kernel, M2 lets us continue using CPU
Dealing with Blocking Syscalls

- Syscall completes: Put invoking goroutine back on queue
- Keep M1 around in a spare pool
- Swap it with M2 upon next syscall, no need to pay thread creation cost