Synchronization
Module 6

Implementing Synchronization

Concurrent Applications

Semaphores | Locks | Condition Variables

Interrupt Disable | Atomic Read/Modify/Write Instructions

Multiple Processors | Hardware Interrupts

Synchronization Variable Interfaces

- (spin) lock
  - acquire() / release() [lock()/unlock()]

- (blocking) lock [mutex]
  - acquire() / release() [lock()/unlock()]

- Semaphore(int n)
  - P – if value <= 0 then wait; decrement value
  - V – increment value; if there is a waiter, wake one up

- Condition variable(lock)
  - wait() - suspend this thread and release lock
  - signal() - wake up one waiting thread, if there is one, and regain its lock
  - broadcast() - wake up all waiting threads, if any, and let them battle for lock

Question: Can this panic?

Thread 1

```
p = someComputation();
pInitialized = true;
```

Thread 2

```
while (!pInitialized)
    ;
q = someFunction(p);
if (q != someFunction(p))
    panic
```

Will this code work?

```
if (p == NULL) {
    lock.acquire();
    if (p == NULL) {
        p = newP();
    }
    lock.release();
}
use p->field1
```

```
newP() {
    p = malloc(sizeof(p));
    p->field1 = …
    p->field2 = …
    return p;
}
```

Why Reordering?

- Why do compilers reorder instructions?
  - Efficient code generation requires analyzing control/data dependency
  - If variables can spontaneously change, most compiler optimizations become impossible
- Why do CPUs reorder instructions?
  - Write buffering: allow next instruction to execute while write is being completed

Fix: **memory barrier**

- Instruction to compiler/CPU
- All ops before barrier complete before barrier returns
- No op after barrier starts until barrier returns

Implementing Synchronization

Take 1: using memory load/store

- See too much milk solution/Peterson’s algorithm

Take 2:

```
Lock::acquire()
    { disable interrupts }
Lock::release()
    { enable interrupts }
```

Spinlock Implementation in xk

```
void acquire(struct spinlock *lk) {
  pushcli(); // disable interrupts to avoid deadlock.
  if (holding(lk))
    panic("acquire");

  // The xchg is atomic.
  while (xchg(&lk->locked, 1) != 0)
    ;

  // Tell the C compiler and the processor to not move loads or stores
  // past this point, to ensure that the critical section's memory
  // references happen after the lock is acquired.
  __sync_synchronize();

  // Record info about lock acquisition for debugging.
  lk->cpu = mycpu();
  getcallerpcs(&lk, lk->pcs);
}
```

Spinlock Implementation in xk

```
void release(struct spinlock *lk) {
  if (!holding(lk))
    panic("release");

  lk->pcs[0] = 0;
  lk->cpu = 0;

  __sync_synchronize();

  // Release the lock, equivalent to lk->locked = 0.
  // This code can't use a C assignment, since it might
  // not be atomic. A real OS would use C atomics here.
  asm volatile("movl $0, %0" : "+m"(lk->locked) :);

  popcli();
}
```

Multiprocessor

- Read-modify-write instructions
  - Atomically read a value from memory, operate on it, and then write it back to memory
  - Intervening instructions prevented in hardware
- Examples
  - Test and set
  - Intel: xchgb, lock prefix
  - Compare and swap
- Any of these can be used for implementing locks and condition variables!

Spinlocks

A spinlock is a lock where the processor waits in a loop for the lock to become free

- Assumes lock will be held for a short time
- Used to protect the CPU scheduler and to implement locks

```
Spinlock::acquire() {
   while (testAndSet(&lockValue) == BUSY)
      ;
}
Spinlock::release() {
   lockValue = FREE;
  memorybarrier();
}
```

How many spinlocks?

- Various data structures
  - Queue of waiting threads on lock X
  - Queue of waiting threads on lock Y
  - List of threads ready to run
- One spinlock per kernel?
  - Bottleneck!
- Instead:
  - One spinlock per blocking lock
  - One spinlock for the scheduler ready list
    - Per-core ready list: one spinlock per core

Mutex Implementation, Uniprocessor

```
Lock::acquire() {
    disableInterrupts();
    if (value == BUSY) {
        waiting.add(myTCB);
        myTCB->state = WAITING;
        next = readyList.remove();
        switch(myTCB, next);
        myTCB->state = RUNNING;
    } else {
        value = BUSY;
    }
    enableInterrupts();
}
```

```
Lock::release() {
    disableInterrupts();
    if (!waiting.Empty()) {
        next = waiting.remove();
        next->state = READY;
        readyList.add(next);
    } else {
        value = FREE;
    }
    enableInterrupts();
}
```

Lock Implementation, Multiprocessor

```
Lock::acquire() {
    disableInterrupts();
    spinLock.acquire();
    if (value == BUSY) {
        waiting.add(myTCB);
        suspend(&spinlock);
    } else {
        value = BUSY;
    }
    spinLock.release();
   enableInterrupts();
}
```

```
Lock::release() {
    disableInterrupts();
    spinLock.acquire();
    if (!waiting.Empty()) {
        next = waiting.remove();
        scheduler->makeReady(next);
    } else {
        value = FREE;
    }
    spinLock.release();
    enableInterrupts();
}
```

What thread is currently running?

- Thread scheduler needs to find the TCB of the currently running thread
  - To suspend and switch to a new thread
  - To check if the current thread holds a lock before acquiring or releasing it
- On a uniprocessor, easy: just use a global
- On a multiprocessor, various methods:
  - Compiler dedicates a register (e.g., r31 points to TCB running on the this CPU; each CPU has its own r31)
  - If hardware has a special per-processor register, use it
  - Fixed-size stacks: put a pointer to the TCB at the bottom of its stack
    - Find it by masking the current stack pointer

Lock Implementation, Linux

- Most locks are free most of the time
  - Why?
  - Linux implementation takes advantage of this fact
- Fast path
  - If lock is FREE, and no one is waiting, two instructions to acquire the lock
  - If no one is waiting, two instructions to release the lock
- Slow path
  - If lock is BUSY or someone is waiting, use multiproc impl.

- User-level locks
  - Fast path: acquire lock using test&set
  - Slow path: system call to kernel, use kernel lock

Lock Implementation, Linux

```
struct mutex {
 /∗ 1: unlocked ; 0: locked;
    negative : locked,
    possible waiters ∗/
 atomic_t count;
 spinlock_t wait_lock;
 struct list_head wait_list;
};
```

```
// atomic decrement
// %eax is pointer to count
lock decl (%eax)
jns 1 // jump if not signed
          // (if value is now 0)
call slowpath_acquire
1:
```

Semaphores

- Semaphore has a non-negative integer value
  - P() atomically waits for value to become > 0, then decrements
  - V() atomically increments value (waking up waiter if needed)
- Semaphores are like integers except:
  - Only operations are P and V
  - Operations are atomic
    - If value is 1, two P’s will result in value 0 and one waiter

Semaphore Bounded Buffer

```
get() {
    fullSlots.P();
    mutex.P();
    item = buf[front % MAX];
    front++;
    mutex.V();
    emptySlots.V();
    return item;
}
```

```
put(item) {
    emptySlots.P();
    mutex.P();
    buf[last % MAX] = item;
    last++;
    mutex.V();
    fullSlots.V();
}
```

Initially: front = last = 0; MAX is buffer capacity
mutex = 1; emptySlots = MAX; fullSlots = 0;

Communicating Sequential Processes (CSP/Google Go)

- A thread per shared object
  - Only thread allowed to touch object's data
  - To call a method on the object, send thread a message with method name, arguments
  - Thread waits in a loop, get msg, do operation
- No memory races (in user code)!

Bounded Buffer (CSP)

```
while (cmd = getNext()) {
   if (cmd == GET) {
    if (front < tail) {
         // do get
         // send reply
         // if pending put, do it
        // and send reply
    } else
        // queue get operation
    }
} else { // cmd == PUT
    if ((tail – front) < MAX) {
       // do put
      // send reply
      // if pending get, do it
     // and send reply
    } else
     // queue put operation
}
```

Locks/CVs vs. CSP

- Create a lock on shared data

  = create a single thread to operate on data
- Call a method on a shared object

  = send a message/wait for reply
- Wait for a condition

  = queue an operation that can't be completed just yet
- Signal a condition

  = perform a queued operation, now enabled

“Rules” for Using Synchronization

- Use consistent structure
- Always use locks and condition variables
- Always acquire lock at beginning of procedure, release at end
- Always hold lock when using a condition variable
- Always wait in while loop
- Never spin in sleep()