CS 153
Design of Operating Systems

Winter 2016

Lecture 9: Semaphores and Monitors

Some slides from Matt Welsh

Summarize Where We Are

- Goal: Use mutual exclusion to protect critical sections of code that access shared resources
- Method: Use locks (spinlocks or disable interrupts)
- Problem: Critical sections can be long

Spinlocks:

- Threads waiting to acquire lock spin in test-and-set loop
- Wastes CPU cycles
- Longer the CS, the longer the spin
- Greater the chance for lock holder to be interrupted

```
acquire(lock)
…
Critical section
…
release(lock)
```

Disabling Interrupts:

- Should not disable interrupts for long periods of time
- Can miss or delay important events (e.g., timer, I/O)

Implementing Locks (4) -- (no spin)

```
struct lock {
    int held = 0;
}
void acquire (lock) {
    while (test-and-set(&lock->held))
            thread_yield();
}
void release (lock) {
    lock->held = 0;
}
```

Implementing Locks (4) -- (no spin)

- mutex_lock:
- TSL REGISTER, MUTEX |copy mutex to register, set mutex to 1
- CMP REGISTER, #0 |was mutex zero?
- JNE ok |if zero, mutex was unlocked, so return
- CALL thread_yield |mutex busy, schedule another thread
- JMP mutex_lock |try again later
- ok: RET |return to caller; CR entered

- mutex_unlock:
- MOVE MUTEX, #0 |store a 0 in mutex
- RET |return to caller

Implementing Locks (5) -- Mutex (true blocking)

System-wide

```
struct lock {
    int held = 0;
}
void acquire (lock) {
    if(test-and-set(&lock->held))
        //  block the thread;
        //  send it to a waiting queue
}
void release (lock) {
    lock->held = 0;
    // move on thread from the waiting
    // queue to ready queue
}
```

Higher-level synchronization primitives

- We have looked at one synchronization primitive: locks
- Locks are useful, but may not satisfy all program needs
- Examples? Reader/Writer problem
  - Say we had a shared variable where we wanted any number of threads to read the variable, but only one thread to write it.
  - How would you do this with locks? What's wrong with this code?

```
Reader() {
   lock.acquire();
   local_copy = shared_var;
   lock.release();
   return local_copy;
}
```

```
Writer() {
   lock.acquire();
   shared_var = NEW_VALUE;
   lock.release();
}
```

Semaphores

- Semaphores are an abstract data type that provide mutual exclusion to critical sections
  - Block waiters, interrupts enabled within critical section
  - Described by Dijkstra in THE system in 1968
- Semaphores are integers that support two operations:
  - wait(semaphore): decrement, block until semaphore is open
    - Also P(), after the Dutch word for test, or down()
  - signal(semaphore): increment, allow another thread to enter
    - Also V() after the Dutch word for increment, or up()
  - That's it! No other operations – not even just reading its value – exist
- Semaphore safety property: the semaphore value is always greater than or equal to 0

Blocking in Semaphores

- Associated with each semaphore is a queue of waiting threads/processes
- When wait() is called by a thread:
  - If semaphore is open, thread continues
  - If semaphore is closed, thread blocks on queue
- Then signal() opens the semaphore:
  - If a thread is waiting on the queue, the thread is unblocked
  - If no threads are waiting on the queue, the signal is remembered for the next thread

Semaphore Types

- Semaphores come in two types
- Mutex semaphore (or binary semaphore)
  - Represents single access to a resource
  - Guarantees mutual exclusion to a critical section

- Counting semaphore (or general semaphore)
  - Multiple threads pass the semaphore determined by count
    - » mutex has count = 1, counting has count = N
  - Represents a resource with many units available
  - or a resource allowing some unsynchronized concurrent access (e.g., reading)

Using Semaphores

- Use is similar to our locks, but semantics are different

```
struct Semaphore {
    int value;
    Queue q;
} S;
withdraw (account, amount) {
    wait(S);
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    signal(S);
    return balance;
}
```

critical section

Threads block

```
wait(S);
balance =
get_balance(account);
balance = balance – amount;
```

```
wait(S);
```

```
wait(S);
```

```
put_balance(account,
balance);
signal(S);
```

```
…
signal(S);
```

```
…
signal(S);
```

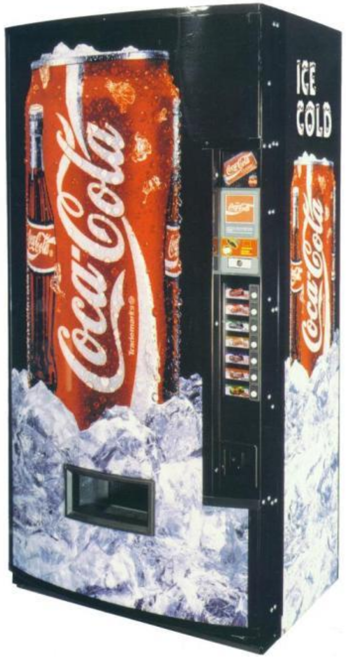
It is undefined which thread runs after a signal

Using Semaphores

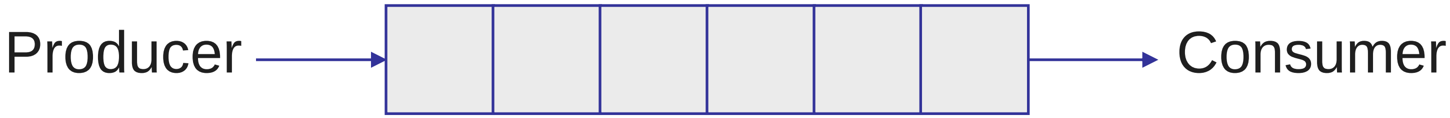
- We've looked at a simple example for using synchronization
  - Mutual exclusion while accessing a bank account
- Now we're going to use semaphores to look at more interesting examples
  - Producer consumer with bounded buffers
  - Readers/Writers

Producer-Consumer Problem / Bounded Buffer

- Problem:
  - Producer puts things into a shared buffer
  - Consumer takes them out
  - Need synchronization for coordinating producer and consumer
- Example
  - Coke machine



Bounded Buffer



- Problem: There is a set of resource buffers shared by producer and consumer threads
  - Producer inserts resources into the buffer set
    - » Output, disk blocks, memory pages, processes, etc
- Buffer between producer and consumer allows them to
  - operate somewhat independently (execute at different rates)
- Otherwise must operate in lockstep
  - producer puts 1 thing in buffer, then consumer takes it out
  - then producer adds another, then consumer takes it out, etc
- **What is desired safety property?**
  - **Sequence of consumed values is prefix of sequence of produced values**
  - **If *nc* is number consumed, *np* number produced, and N the size of the buffer, then $0 \le np - nc \le N$**

First Try: Sleep and Wakeup

```
#define N 100        //# of slots in the buffer
int count=0;         //# of items in the buffer
```

```
producer {
  while(TRUE) {
    // produce new item
    if (count==N) sleep(inf); // wait for buffer
    // insert item
    count=count+1;
    if(count==1)  // just filled an empty buffer
      wakeup(consumer);
  }
}
```

```
consumer {
  while(TRUE) {
    if (count==0) sleep(inf);  // no more item
    // remove item
    count=count-1;
    if(count==N-1) // have spaces now
      wakeup(producer);
    // consume resource;
  }
}
```

What are the problems?

- Producer-consumer problem with fatal race condition
  - Access to “count” is a race condition
  - Access to “buffer” is a race condition
  - Wakeup call could get lost
- count = count + 1; count = count – 1;

```
mov  eax, count
inc  eax
mov  count, eax
```

```
mov  eax, count
dec  eax
mov  count, eax
```

- Obviously, we need synchronization!

Second Try: Mutual Exclusion

```
#define N 100          //# of slots in the buffer
int count=0;           //# of items in the buffer
Semaphore mutex = 1;   // mutual exclusion
```

```
producer {
  while(TRUE) {
    // produce new item
    wait(mutex); // lock for shared data access
    if (count==N) sleep(inf); // wait for buffer
    // insert item
    count=count+1;
    if(count==1)  // just filled an empty buffer
      wakeup(consumer);
    signal(mutex); // unlock
  }
}
```

```
consumer {
  while(TRUE) {
    wait(mutex); // lock for shared data access
    if (count==0) sleep(inf);  // no more item
    // remove item
    count=count-1;
    if(count==N-1) // have spaces now
      wakeup(producer);
    signal(mutex); // unlock
    // consume resource;
  }
}
```

Bounded Buffer (2)

- $0 \le np - nc \le N$
- Use three semaphores:
  - filled – count of filled buffers
    - » Counting semaphore
    - » filled = ?
      - $(np - nc)$
  - empty – count of empty buffers
    - » Counting semaphore
    - » empty = ?
      - $N - (np - nc)$
  - mutex – mutual exclusion to shared set of buffers
    - » Binary semaphore

Last Try: Semaphores

```
Semaphore mutex = 1;   // mutual exclusion to shared buffer
Semaphore empty = N;  // count of empty buffer slots (all empty to start)
Semaphore filled = 0;       // count of filled buffer slots (none to start)
```

```
producer {
  while (1) {
    Produce new resource;
    wait(empty); // wait for empty slot
    wait(mutex); // lock buffer list
    Add resource to an empty slot;
    signal(mutex); // unlock buffer list
    signal(filled);      // note a filled slot
  }
}
```

```
consumer {
  while (1) {
    wait(filled);      // wait for a filled slot
    wait(mutex);     // lock buffer list
    Remove resource from a filled slot;
    signal(mutex); // unlock buffer list
    signal(empty); // note an empty slot
    Consume resource;
  }
}
```

Bounded Buffer (4)

- Why need the mutex at all?

- The pattern of signal/wait on full/empty is a common construct often called an interlock

- Producer-Consumer and Bounded Buffer are classic examples of synchronization problems

Next time...

- Scheduling
  - Read Chapter 6