Semaphores & Monitors

Anvind Krishnamurthy
Spring 2004

Semaphores (Dijkstra 1965)

- Semaphores have a non-negative integer value, and support two operations:
  - `semaphore->P()`: an atomic operation that waits for semaphore to become positive, then decrements it by 1.
  - `semaphore->V()`: an atomic operation that increments semaphore by 1, waking up a waiting P, if any.

- Semaphores are like integers except:
  1. non-negative values;
  2. only allow P&V --- can't read/write value except to set it initially;
  3. operations must be atomic:
     -- two Ps that occur together can't decrement the value below zero.
     -- thread going to sleep in P won't miss wakeup from V, even if they both happen at about the same time.

Implementing semaphores

P means "test" (proberen in Dutch)
V means "increment" (verhogen in Dutch)

- Binary semaphores:
  - Like a lock; can only have value 0 or 1 (unlike the previous "counting semaphore" which can be any non-negative integers)

- How to implement semaphores? Standard tricks:
  - Can be built using interrupts disable/enable
  - Or using test-and-set
  - Use a queue to prevent unnecessary busy-waiting
  - Question: Can we build semaphores using just locks?

Using interrupts

```c
class Semaphore {int value = 0; }
Semaphore::P() {
    Disable interrupts;
    while (value == 0) {
        Enable interrupts;
        Disable interrupts;
    }
    value = value - 1;
    Enable interrupts;
}
Semaphore::V() {
    Disable interrupts;
    value++;
    Enable interrupts;
}
```

Using test&set

```c
class Semaphore {int value = 0; int guard = 0; }
Semaphore::P() {
    while (test&set(guard)) // short wait time
        if (value == 0) {
            Put on queue of threads waiting for lock
            Go to sleep and set guard to 0
        } else {
            value = value - 1;
            guard = 0;
        }
}
Semaphore::V() {
    while (test&set(guard))
        if anyone on wait queue {
            Take a waiting thread off wait queue and put it at the front of the ready queue;
        } else {
            value = value + 1;
        }
    guard = 0;
}
```

How to use semaphores

- Binary semaphores can be used for mutual exclusion:
  - initial value of 1; P() is called before the critical section; and V() is called after the critical section.

  ```c
  semaphore->P();
  // critical section goes here
  semaphore->V();
  ```

- Scheduling constraints
  - having one thread to wait for something to happen
    - Example: Thread::Join, which must wait for a thread to terminate. By setting the initial value to 0 instead of 1, we can implement waiting on a semaphore

- Controlling access to a finite resource

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**How to use semaphores**

- Binary semaphores can be used for mutual exclusion:
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- Controlling access to a finite resource
Scheduling constraints

- Some thread must wait for some event
- For instance, thread join can be implemented using semaphores

  Initial value of semaphore = 0.
  Fork a child thread
  Thread::Join calls P // will wait until something
  // makes the semaphore positive

  Thread finish calls V // makes the semaphore positive
  // and wakes up the thread
  // waiting in Join

- Question: Can we implement thread join with just locks and unlocks?

Scheduling with Semaphores

- In general:
  - scheduling dependencies between threads T1, T2, ..., Tn can be enforced with n-1 semaphores, S1, S2, ..., Sn-1
  - T1 runs and signals V(S1) when done.
  - Tm waits on Sm-1 (using P) and signals V(Sm) when done.
- Contrived example: schedule print(f(x,y))

  ```cpp
  float x, y, z;
  sem Sx = 0, Sy = 0, Sz = 0;
  T1: x = ...; P(Sx); P(Sz);
      V(Sx); P(Sy); print(z);
  T2: y = ...;
  T3:
      V(Sy); V(Sz);
      ... ...
  ```

Example: producer-consumer with a bounded buffer

- Example:
  - cpp file.S | as

Producer-consumer: problem definition

- Producer puts things into a shared buffer; consumer takes them out.
  - Need synchronization for coordinating producer and consumer
- Don’t want producer and consumer to have to operate 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
  - Semaphores are used for both mutex and scheduling
- Example coke vending machine:
  - Consumers are students/faculty
  - Producer is the delivery person

Producer-consumer with semaphores (1)

- Correctness constraints
  - consumer must wait for producer to fill buffers, if all empty (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)
- General rule of thumb: use a separate semaphore for each constraint

  Semaphore fullBuffers; // consumer’s constraint
  // if 0, no coke in machine
  Semaphore emptyBuffers; // producer’s constraint
  // if 0, nowhere to put more cake
  Semaphore mutex; // mutual exclusion

Announcements

- Zheng Ma’s office hours
- Design document structure and scope
- Paper review for “Scheduler Activations” paper: next Wednesday
Monitors & condition variables

- Locks provide mutual exclusion to shared data
- Semaphores help handle scheduling constraints
- Semaphore utility is overloaded:
  - dual purpose: mutual exclusion and scheduling constraints.
- Monitors make things easier:
  - "locks" for mutual exclusion
  - "condition variables" for scheduling constraints
- Monitor definition:
  - a lock and zero or more condition variables for managing concurrent access to shared data

Synchronized Lists

- With semaphores, you could maintain a counter on number of elements in the list
- Perform a semaphore-decrement on the counter before trying to obtain the lock
- What if you wanted to support a "peek" operation on the list? Multiple threads could be waiting for an element to appear; need to wake them all up
- What if a thread wants to wait for a general non-counter based program condition
- Can be done using semaphores, but would like a better high level construct

AddToQueue()

- lock.Acquire();           // lock before use
- put item on queue;     // ok to access
- lock.Release();           // unlock after done

RemoveFromQueue()

- lock.Acquire();
- if something on queue // can we wait?
- remove it;
- lock.Release();
- return item;

Condition variables

- How to make RemoveFromQueue wait until something is on the queue?
  - can't sleep while holding the lock
  - Key idea: make it possible to go to sleep inside critical section, by atomically releasing lock at same time we go to sleep.
- Condition variable: a queue of threads waiting for something inside a critical section.
- Wait() --- Release lock, go to sleep, re-acquire lock
  - release lock and going to sleep is atomic
- Signal() --- Wake up a waiter, if any
- Broadcast() --- Wake up all waiters

Synchronized queue

- Rule: must hold lock when doing condition variable operations

AddToQueue()

- lock.Acquire();
- put item on queue; condition.signal();
- lock.Release();

RemoveFromQueue()

- lock.Acquire();
- while nothing on queue condition.wait(&lock);
  // release lock; go to sleep; reacquire lock
- remove item from queue;
- lock.Release();
- return item;

Mesa-style vs. Hoare-style

- Mesa-style (Nachos, most real OS):
  - Signaler keeps lock, processor
  - Waiter simply put on ready queue, with no special priority
    (in other words, waiter may have to wait for lock again)
- Hoare-style (most theory, textbook):
  - Signaler passes lock, CPU to waiter; waiter runs immediately
  - Waiter gives lock, processor back to signaler when it exits critical section or if it waits again
- For Mesa-semantics, you always need to check the condition after wait (use "while"). For Hoare-semantics you can change it to "if".

Producer-consumer with monitors

Producer()

- lock.Acquire();
- while (numInBuffer <= MAX_BUFFER) full.wait(&lock);
- put 1 Coke in machine; numInBuffer++;
- empty.signal();
- lock.Release();

Consumer()

- lock.Acquire();
- while (numInBuffer >= 0) empty.wait(&lock);
- take 1 Coke; numInBuffer--;
- full.signal();
- lock.Release();

Producer()

- lock.Acquire();
- while (numInBuffer <= MAX_BUFFER) full.wait(&lock);
- put 1 Coke in machine; numInBuffer++;
- empty.signal();
- lock.Release();

Consumer()

- lock.Acquire();
- while (numInBuffer >= 0) empty.wait(&lock);
- take 1 Coke; numInBuffer--;
- full.signal();
- lock.Release();
Monitors Support in Languages

- High-level data abstraction that unifies handling of:
  - Shared data, operations on it, synch and scheduling
  - All operations on data structure have single (implicit) lock
  - An operation can relinquish control and wait on condition
  
  // only one process at time can update instance of Q
  
  class Q {
      int head, tail;  // shared data
      synchronized void enq(v) { locked access to Q instance }
      synchronized int deq() { locked access to Q instance }
  }

- Java from Sun; Mesa/Cedar from Xerox PARC

- Monitors easier and safer than semaphores
  - Compiler can check, lock implicit (cannot be forgotten)