CS 422/522  Design & Implementation
of Operating Systems

Lectures 8-9: Implementing
Synchronization

Zhong Shao
Dept. of Computer Science
Yale University

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The big picture

Concurrent Applications

Shared Objects

Bounded Buffer  Barrier

Synchronization Variables

Semaphores  Locks  Condition Variables

Atomic Instructions

Interrupt Disable  Test-and-Set

Hardware

Multiple Processors  Hardware Interrupts
Semaphores (Dijkstra 1965)

- Semaphores are a kind of generalized lock.
  * They are the main synchronization primitives used in the earlier Unix.
- 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. none-negative values; (2) only allow P&V --- can't read/write value except to set it initially; (3) operations must be atomic: two P's that occur together can't decrement the value below zero. Similarly, 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)

```cpp
class Semaphore {
    int value = initialValue;

    Semaphore::P() {
        Disable interrupts;
        while (value == 0) {
            Put on queue of threads waiting for this semaphore;
            Go to sleep;
        }
        value = value - 1;
        Enable interrupts
    }

    Semaphore::V() {
        Disable interrupts;
        if anyone on wait queue {
            Take a waiting thread off wait queue and put it on the ready queue;
        }
        value = value + 1;
        Enable interrupts
    }
};
```
Binary semaphores

Like a lock; also known as “mutex”; can only have value 0 or 1 (unlike the previous “counting semaphore” which can be any non-negative integers)

```cpp
class Semaphore { int value = 0 or 1; }
Semaphore::P() {  
  Disable interrupts;  
  while (value == 0) {  
    Put on queue of threads waiting  
    for this semaphore;  
    Go to sleep;  
  }  
  value = 0;  
  Enable interrupts  
}
Semaphore::V() {  
  Disable interrupts;  
  if anyone on wait queue {  
    Take a waiting thread off wait  
    queue and put it on the ready  
    queue;  
  }  
  value = 1;  
  Enable interrupts  
}
```

◆ 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.

```cpp
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

How to use semaphores
Scheduling constraints

- Something must happen after one another

  Initial value of semaphore = 0;
  Fork a child thread
  Thread::Join calls P  // will wait until something
  // makes the semaphore positive
                          // makes the semaphore positive
                          // and wakes up the thread
                          // waiting in Join

Scheduling with semaphores

- In general, scheduling dependencies between threads $T_1$, $T_2$, ..., $T_n$ can be enforced with n-1 semaphores, $S_1$, $S_2$, ..., $S_{n-1}$ used as follows:
  - $T_1$ runs and signals $V(S_1)$ when done.
  - $T_m$ waits on $S_{m-1}$ (using P) and signals $V(S_m)$ when done.
- (contrived) example: schedule print(f(x,y))

```c
float x, y, z;
sem Sx = 0, Sy = 0, Sz = 0;

T1:           T2:           T3:
  x = ...;    p(Sx);      p(Sz);  
  V(Sx):      p(Sy);  print(z); 
  y = ...;    z = f(x,y);  ...    
  V(Sy):      V(Sz);  
  ...         ...     
```
Producer-consumer with semaphores (1)

- **Correctness constraints**
  * consumer must wait for producer to fill buffers, if all empty (scheduling constraints)
  * producer must wait for consumer to empty buffers, if all full (scheduling constraints)
  * Only one thread can manipulate buffer queue at a time (mutual exclusion)

- **General rule of thumb: use a separate semaphore for each constraint**
  
<table>
<thead>
<tr>
<th>Semaphore</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>fullBuffers;</td>
<td>consumer's constraint</td>
</tr>
<tr>
<td>emptyBuffers;</td>
<td>producer's constraint</td>
</tr>
<tr>
<td>mutex;</td>
<td>mutual exclusion</td>
</tr>
</tbody>
</table>

Producer-consumer with semaphores (2)

```
Producer() {
    emptyBuffers.P(); // check if there is space
    mutex.P();        // make sure no one else is using machine
    put 1 Coke in machine;
    mutex.V();        // ok for others to use machine
}
```

```
Consumer() {
    fullBuffers.P(); // check if there is a coke in the machine
    mutex.P();       // make sure no one else is using machine
    take 1 Coke out;
    mutex.V();       // next person's turn
    emptyBuffers.V(); // tell producer we need more
}
```

What if we have 2 producers and 2 consumers?
Order of P&Vs --- what can go wrong

Semaphore fullBuffers = 0; // initially no coke
Semaphore emptyBuffers = numBuffers;
   // initially, # of empty slots semaphore used to
   // count how many resources there are
Semaphore mutex = 1; // no one using the machine

Producer() {
    mutex.P(); // make sure no one else
    // is using machine
    emptyBuffers.P(); // check if there is space
    // for more coke
    put 1 Coke in machine;
    fullBuffers.V(); // tell consumers there is now
    // a coke in the machine
    mutex.V(); // ok for others to use machine
}

Consumer() {
    mutex.P(); // make sure no one
    // else is using machine
    fullBuffers.P(); // check if there is
    // a coke in the machine
    take 1 Coke out;
    emptyBuffers.V(); // tell producer
    // we need more
    mutex.V(); // next person's turn
}

Deadlock---two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes.

Implementing synchronization

Concurrent Applications

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Synchronization Variables

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<th>Condition Variables</th>
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Atomic Instructions

<table>
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<th>Interrupt Disable</th>
<th>Test-and-Set</th>
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Hardware

| Multiple Processors | Hardware Interrupts |
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 }
```

Take 3: queueing locks

No point on running the threads waiting for locks

---

Lock 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();
}
```

```
class Lock {
    private int value = FREE;
    private Queue waiting;
    public void acquire();
    public void release();
}
```

---
## 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

```c
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 lock
  - One spinlock for the scheduler ready list
    - Per-core ready list: one spinlock per core

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, multiprocessor

```cpp
class Lock {
    private:
        int value = FREE;
        SpinLock spinLock;
        Queue waiting;
    
    Lock::acquire() {
        disableInterrupts();
        spinLock.acquire();
        if (value == BUSY) {
            waiting.add(myTCB);
            scheduler->suspend(&spinlock);
        } else {
            value = BUSY;
            spinLock.release();
        }
        enableInterrupts();
    }

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

Lock implementation, multiprocessor (cont’d)

```cpp
class Scheduler {
    private:
        Queue readyList;
        SpinLock schedulerSpinLock;
    public:
        void suspend(SpinLock *lock);
        void makeReady(Thread *thread);
    }

    void Scheduler::suspend(SpinLock *lock) {
        disableInterrupts();
        schedulerSpinLock.acquire();
        lock->release();
        runningThread->state = WAITING;
        chosenTCB = readyList.getNextThread();
        thread_switch(runningThread, chosenTCB);
        runningThread->state = RUNNING;
        schedulerSpinLock.release();
        enableInterrupts();
    }

    void Scheduler::makeReady(TCB *thread) {
        disableInterrupts();
        schedulerSpinLock.acquire();
        readyList.add(thread);
        thread->state = READY;
        schedulerSpinLock.release();
        enableInterrupts();
    }
```
Condition variable implementation, multiprocessor

```java
class CV {
    private Queue waiting;
    public void wait(Lock *lock);  
    public void signal();
    public void broadcast();
}
```

```java
// Monitor lock held by current thread.
void CV::wait(Lock *lock) {
    assert(lock.isHeld());
    waiting.add(myTCB);
    // Switch to new thread & release lock.
    scheduler.suspend(&lock);
    lock->acquire();
}

// Monitor lock held by current thread.
void CV::signal() {
    if (waiting.notEmpty()) {
        thread = waiting.remove();
        scheduler.makeReady(thread);
    }
}

void CV::broadcast() {
    while (waiting.notEmpty()) {
        thread = waiting.remove();
        scheduler.makeReady(thread);
    }
}
```

Semaphore implementation, a comparison

```java
Semaphore::P() {  
    disableInterrupts();
    spinLock.acquire();
    if (value == 0) {  
        waiting.add(myTCB);
        suspend(&spinlock);
    } else {
        value--;
    }
    spinLock.release();
    enableInterrupts();
}
```

```java
Semaphore::V() {  
    disableInterrupts();
    spinLock.acquire();
    if (!waiting.Empty) {  
        next = waiting.remove();
        scheduler->makeReady(next);
    } else {
        value++;
    }
    spinLock.release();
    enableInterrupts();
}
```
“Semaphores considered harmful!”

- Using separate lock and condition variable classes makes code more self-documenting and easier to read
  - The code is clearer when the role of each synchronization variable is made clear through explicit typing

- A stateless condition variable bound to a lock is a better abstraction for generalized waiting than a semaphore
  - Semaphores rely on the programmer to carefully map the object's state to the semaphore's value ...

- Nevertheless, semaphores are used for synchronizing communication between an I/O device and threads waiting for I/O completion.

Implementing Condition Variables using Semaphores (Take 1)

```
wait(lock) {
    lock.release();
    semaphore.P();
    lock.acquire();
}
signal() {
    semaphore.V();
}
```
Implementing Condition Variables using Semaphores (Take 2)

```java
wait(lock) {
    lock.release();
    semaphore.P();
    lock.acquire();
}

signal() {
    if (semaphore queue is not empty)
        semaphore.V();
}
```

Implementing Condition Variables using Semaphores (Take 3)

```java
wait(lock) {
    semaphore = new Semaphore;
    queue.Append(semaphore);  // queue of waiting threads
    lock.release();
    semaphore.P();
    lock.acquire();
}

signal() {
    if (!queue.Empty()) {
        semaphore = queue.Remove();
        semaphore.V();  // wake up waiter
    }
}
```
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

```
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 1f  // jump if not signed
     // (if value is now 0)
call slowpath_acquire
1:
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!

Example: Bounded Buffer

```go
get() {
    lock.acquire();
    while (front == tail) {
        empty.wait(lock);
    }
    item = buf[front % MAX];
    front++;
    full.signal(lock);
    lock.release();
    return item;
}

put(item) {
    lock.acquire();
    while ((tail - front) == MAX) {
        full.wait(lock);
    }
    buf[tail % MAX] = item;
    tail++;
    empty.signal(lock);
    lock.release();
}
```

Initially: front = tail = 0; MAX is buffer capacity
empty/full are condition variables
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
Remember the rules

- 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()