Lectures 8-9: Implementing Synchronization

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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

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

Scheduling with semaphores

◆ In general, scheduling dependencies between threads T₁, T₂, ..., Tₙ can be enforced with n-1 semaphores, S₁, S₂, ..., Sₙ₋₁ used as follows:
- 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))

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

T₁: 
   x = ...;
   P(Sx);
   V(Sx);

T₂: 
   y = ...;
   z = f(x,y);
   V(Sy);

T₃: 
   P(Sz);
   print(z);
   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

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

Producer-consumer with semaphores (2)

```
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() {
    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
    fullBuffers.V(); // tell consumers there is now
        // a Coke in the 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

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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

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

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();
}
```
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()

```cpp
while (testAndSet(&lockValue) == BUSY)
```

Spinlock::release()

```cpp
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();
        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::makeReady(TCB *thread) {
    disableInterrupts();
    schedulerSpinLock.acquire();
    readyList.add(thread);
    thread->state = READY;
    schedulerSpinLock.release();
    enableInterrupts();
}

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

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

// 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();
}

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)

```c
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

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)

```java
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()