Lecture 7: Semaphores and Monitors
Administrivia

Next Tuesday is project hacking day

- No class, work on lab 1
- I will hold office hours in Malone 231 at the lecture time
Higher-Level Synchronization

We looked at using locks to provide mutual exclusion

Locks work, but they have limited semantics
- Just provide mutual exclusion

Instead, we want synchronization mechanisms that
- Block waiters, leave interrupts enabled in critical sections
- Provide semantics beyond mutual exclusion

Look at two common high-level mechanisms
- **Semaphores**: binary (mutex) and counting
- **Monitors**: mutexes and condition variables
Semaphores

An abstract data type to provide synchronization
- Described by Dijkstra in the “THE” system in 1968

Semaphores are “integers” that support two operations:
- Semaphore::P() decrements, blocks until semaphore is open, a.k.a wait()
  • after the Dutch word “Proberen” (to try)
- Semaphore::V() increments, allows another thread to enter, a.k.a signal()
  • after the Dutch word “Verhogen” (increment)
- That's it! No other operations – not even just reading its value

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

When $P(\ )$ is called by a thread:
- If semaphore is open, thread continues
- If semaphore is closed, thread blocks on queue

Then $V(\ )$ 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
  - In other words, $V(\ )$ has “history” (c.f., condition vars later)
  - This “history” is a counter
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)**
- Represents a resource with many units available, or a resource that allows certain kinds of unsynchronized concurrent access (e.g., reading)
- Multiple threads can pass the semaphore
- Number of threads determined by the semaphore “count”
  - mutex has count = 1, counting has count = N
Using Semaphores

Use is similar to our locks, but semantics are different

```c
struct Semaphore {
    int value;
    Queue q;
} S;
withdraw (account, amount) {
    P(S);
    balance = get_balance(account);
    balance = balance - amount;
    put_balance(account, balance);
    v(S);
    return balance;
}
```

Threads block critical section

It is undefined which thread runs after a signal

P(S);
balance = get_balance(account);
balance = balance - amount;

P(S);
put_balance(account, balance);
v(S);

P(S);

v(S);

... v(S);

... v(S);
Semaphore Questions

Are there any problems that can be solved with counting semaphores that cannot be solved with mutex semaphores?

- If a system only gives you mutex semaphore, can you use it to implement counting semaphores?

Does it matter which thread is unblocked by a signal operation?
Semaphore Implementation in Pintos

```c
void sema_down(struct semaphore *sema) {
    enum intr_level old_level;
    old_level = intr_disable();
    while (sema->value == 0) {
        list_push_back(&sema->waiters,
                        &thread_current()->elem);
        thread_block();
    }
    sema->value--;
    intr_set_level(old_level);
}

void sema_up(struct semaphore *sema) {
    enum intr_level old_level;
    old_level = intr_disable();
    if (!list_empty(&sema->waiters))
        thread_unblock(list_entry(
                             list_pop_front(&sema->waiters),
                             struct thread, elem));
    sema->value++;
    intr_set_level(old_level);
}
```

To reference current thread: `thread_current()`

`thread_block()` puts the current thread to sleep

Lab 1 note:
- leverage semaphore instead of directly using `thread_block()`
Implementation of thread_block()

thread_block() assumes the interrupts are disabled

This means we will have the thread sleep with interrupts disabled

Isn’t this bad?
- Shouldn’t we only disable interrupts when entering/leaving critical sections but keep interrupts enabled during critical section?
Interrupts Re-enabled Right After Ctxt Switch

```
thread_yield() {
    Disable interrupts;
    add current thread to ready_list;
    schedule(); // context switch
    Enable interrupts;
}

sema_down() {
    Disable interrupts;
    while(value == 0) {
        add current thread to waiters;
        thread_block();
    }
    value--;
    Enable interrupts;
}
```

### Diagram

```
    Thread 1
    [thread_yield]
    Disable interrupts;
    add current thread to ready_list;
    schedule();
    (Returns from schedule())
    Enable interrupts;

    Thread 2
    [thread_yield]
    (Returns from schedule())
    Enable interrupts;

    Thread 2
    [sema_down]
    Disable interrupts;
    while(value == 0) {
        add current thread to waiters;
        thread_block();
    }

    Thread 1
    [thread_yield]
    (Returns from schedule())
    Enable interrupts;
```

Thread 1
Thread 2
Thread 2
Thread 1
...
Semaphore Summary

Semaphores can be used to solve any traditional sync. problems

However, they have some drawbacks
- They are essentially shared global variables
  - Can potentially be accessed anywhere in program
- No connection between the semaphore and the data controlled by the semaphore
- Used both for critical sections (mutual exclusion) and coordination (scheduling)
  - Note that I had to use comments in the code to distinguish
- No control or guarantee of proper usage

Sometimes hard to use and prone to bugs
- Another approach: Use programming language support
Monitors

A programming language construct that controls access to shared data
- Synchronization code added by compiler, enforced at runtime
- Why is this an advantage?

A monitor is a module that encapsulates
- Shared data structures
- Procedures that operate on the shared data structures
- Synchronization between concurrent threads that invoke the procedures

A monitor protects its data from unstructured access

It guarantees that threads accessing its data through its procedures interact only in legitimate ways
Monitor Semantics

A monitor guarantees **mutual exclusion**
- Only one thread can execute any monitor procedure at any time
  - the thread is “in the monitor”
- If a second thread invokes a monitor procedure when a first thread is already executing one, it blocks
  - So the monitor has to have a wait queue…
- If a thread within a monitor blocks, another one can enter

What are the implications in terms of parallelism in a monitor?

A **monitor invariant** is a **safety property** associated with the monitor
- It’s expressed over the monitored variables.
- It holds whenever a thread enters or exits the monitor.
Account Example

Monitor `account` {
    double balance;

    double withdraw(amount) {
        balance = balance - amount;
        return balance;
    }
}

Hey, that was easy!

Monitor invariant: `balance ≥ 0`
Condition Variables

But what if a thread wants to wait for sth inside the monitor?

- If we busy wait, it’s bad
- Even worse, no one can get in the monitor to make changes now!

A condition variable is associated with a condition needed for a thread to make progress once it is in the monitor.

Monitor M {
    ... monitored variables
    Condition c;

    void enterMonitor (...) {
        if (extra property not true) wait(c);  // waits outside of the monitor's mutex
        do what you have to do
        if (extra property true) signal(c);   // brings in one thread waiting on condition
    }
}
Condition Variables

Condition variables support three operations:

- **Wait** – release monitor lock, wait for C/V to be signaled
  
  - So condition variables have wait queues, too
- **Signal** – wakeup one waiting thread
- **Broadcast** – wakeup all waiting threads

Condition variables are not boolean objects

- **if (condition_variable) then ... does not make sense**
  
  - An example later will make this more clear
- **if (num_resources == 0) then wait(resources_available) does**
Condition Vars != Semaphores

Condition variables != semaphores
- Although their operations have the same names, they have entirely different semantics (such is life, worse yet to come)
- However, they each can be used to implement the other

Access to the monitor is controlled by a lock
- wait() blocks the calling thread, and gives up the lock
  • To call wait, the thread has to be in the monitor (hence has lock)
  • Semaphore::wait just blocks the thread on the queue
- signal() causes a waiting thread to wake up
  • If there is no waiting thread, the signal is lost
  • Semaphore::signal increases the semaphore count, allowing future entry even if no thread is waiting
  • Condition variables have no history
Signal Semantics

Two flavors of monitors that differ in the scheduling semantics of `signal()`

- **Hoare** monitors (original)
  - `signal()` immediately switches from the caller to a waiting thread
  - The condition that the waiter was anticipating is guaranteed to hold when waiter executes
  - Signaler must restore monitor invariants before signaling

- **Mesa** monitors (Mesa, Java)
  - `signal()` places a waiter on the ready queue, but signaler continues inside monitor
  - Condition is not necessarily true when waiter runs again
    - Returning from `wait()` is only a *hint* that something changed
    - Must recheck conditional case
Hoare vs. Mesa Monitors

Hoare

```c
if (!condition)
    wait(cond_var);
```

Mesa

```c
while (!condition)
    wait(cond_var);
    wait(cond_var);
```

Tradeoffs

- Mesa monitors easier to use, more efficient
  - Fewer context switches, easy to support broadcast
- Hoare monitors leave less to chance
  - Easier to reason about the program
More on Condition Variable and Monitor
C/Vs are also used without monitors in conjunction with locks

- `void cond_init (cond_t *, ...);`
- `void cond_wait (cond_t *c, mutex_t *m);`
  - Atomically unlock `m` and sleep until `c` signaled
  - Then re-acquire `m` and resume executing
- `void cond_signal (cond_t *c);`
- `void cond_broadcast (cond_t *c);`
  - Wake one/all threads waiting on `c`
Condition Vars & Locks

C/Vs are also used without monitors in conjunction with locks

A monitor \(\approx\) a module whose state includes a C/V and a lock
- Difference is syntactic; with monitors, compiler adds the code

It is “just as if” each procedure in the module calls acquire() on entry and release() on exit
- But can be done anywhere in procedure, at finer granularity

With condition variables, the module methods may wait and signal on independent conditions
Condition Vars & Locks

Why must `cond_wait` both release `mutex_t` & sleep?

- void cond_wait(cond_t *c, mutex_t *m);

Why not separate mutexes and condition variables?

```c
while (count == BUFFER_SIZE) {
    mutex_unlock(&mutex);
    cond_wait(&not_full);
    mutex_lock(&mutex);
}
```
Why must \texttt{cond\_wait} both release \texttt{mutex\_t} \& sleep?

- \texttt{void cond\_wait(cond\_t *c, mutex\_t *m)};

Why not separate mutexes and condition variables?

```
while (count == BUFFER_SIZE) {
    mutex_unlock(&mutex);
    cond_wait(&not_full);
    mutex_lock(&mutex);
}
```

Producer

```
mutex_lock(&mutex);
... count--;
cond_signal(&not_full);
mutex_unlock(&mutex);
```

Consumer
Using Cond Vars & Locks

Alternation of two threads (ping-pong)

Each executes the following:

```c
Lock lock;
Condition cond;
void ping_pong () {
    acquire(lock);
    while (1) {
        printf("ping or pong\n");
        signal(cond);
        wait(cond, lock);
    }
    release(lock);
}
```

Must acquire lock before you can wait (similar to needing interrupts disabled to call thread_block in Pintos)

Wait atomically releases lock and blocks until signal()

Wait atomically acquires lock before it returns
Monitors and Java

A lock and condition variable are in every Java object
- No explicit classes for locks or condition variables

Every object is/has a monitor
- At most one thread can be inside an object’s monitor
- A thread enters an object’s monitor by
  - Executing a method declared "synchronized"
  - Executing the body of a "synchronized" statement
- The compiler generates code to acquire the object’s lock at the start of the method and release it just before returning
  - The lock itself is implicit, programmers do not worry about it
Monitors and Java

Every object can be treated as a condition variable
- Half of Object’s methods are for synchronization!

Take a look at the Java Object class:
- Object.wait(*) is Condition::wait()
- Object.notify() is Condition::signal()
- Object.notifyAll() is Condition::broadcast()
Summary

Semaphores
- `wait()`/`signal()` implement blocking mutual exclusion
- Also used as atomic counters (counting semaphores)
- Can be inconvenient to use

Monitors
- Synchronizes execution within procedures that manipulate encapsulated data shared among procedures
  - Only one thread can execute within a monitor at a time
- Relies upon high-level language support

Condition variables
- Used by threads as a synchronization point to wait for events
- Inside monitors, or outside with locks
Next Time...

Read Chapter 32