Semaphores and Monitors:
High-level Synchronization Constructs

Synchronization Constructs

- Synchronization
  - Coordinating execution of multiple threads that share data structures
- Past few lectures:
  - Locks: provide mutual exclusion
  - Condition variables: provide conditional synchronization
- Today: Historical perspective
  - Semaphores
    - Introduced by Dijkstra in 1960s
    - Main synchronization primitives in early operating systems
  - Monitors
    - Alternate high-level language constructs
    - Proposed by independently Hoare and Hansen in the 1970s

Semaphores

- Study these for history and compatibility
  - Don't use semaphores in new code
- A non-negative integer variable with two atomic and isolated operations

Semaphore→P() (*Passeren*; wait)
    If *sem* > 0, then decrement *sem* by 1
    Otherwise "wait" until *sem* > 0 and then decrement

Semaphore→V() (*Vrijgeven*; signal)
    Increment *sem* by 1
    Wake up a thread waiting in P()

- We assume that a semaphore is *fair*
  - No thread t that is blocked on a P() operation remains blocked if the V() operation on the semaphore is invoked infinitely often
  - In practice, FIFO is mostly used, transforming the set into a queue.

Key idea of Semaphores vs. Locks

- Locks: Mutual exclusion only (1-exclusion)
- Semaphores: k-exclusion
  - k == 1, equivalent to a lock
    - Sometimes called a mutex, or binary semaphore
  - k == 2+, up to k threads at a time

- Many semaphore implementations use “up” and “down”, rather than Dutch names (P and V, respectively)
  - ‘cause how many programmers speak Dutch?
- Semaphore starts at k
  - Acquire with down(), which decrements the count
    - Blocks if count is 0
  - Release with up(), which increments the count and never blocks

Important properties of Semaphores

- Semaphores are *non-negative* integers
- The *only* operations you can use to change the value of a semaphore are P()/down() and V()/up() (except for the initial setup)
  - P()/down() can block, but V()/up() never blocks
- Semaphores are used both for
  - *Mutual exclusion, and*
  - *Conditional synchronization*
- Two types of semaphores
  - Binary semaphores: Can either be 0 or 1
  - General/Counting semaphores: Can take any non-negative value
  - Binary semaphores are as expressive as general semaphores (given one can implement the other)

- How many possible values can a binary semaphore take?
  - A. 0
  - B. 1
  - C. 2
  - D. 3
  - E. 4

Using Semaphores for Mutual Exclusion

- Use a *binary semaphore* for mutual exclusion

```
Semaphore = new Semaphore(1);
```

```
Semaphore→P();
    Critical Section;
Semaphore→V();
```

- Using Semaphores for producer-consumer with bounded buffer

```
int count;
Semaphore mutex;
Semaphore fullBuffers;
Semaphore emptyBuffers;
```

Use a separate semaphore for each constraint

Coke Machine Example

- Coke machine as a shared buffer
- Two types of users
  - Producer: Restocks the coke machine
  - Consumer: Removes coke from the machine
- Requirements
  - Only a single person can access the machine at any time
  - If the machine is out of coke, wait until coke is restocked
  - If machine is full, wait for consumers to drink coke prior to restocking
- How will we implement this?
  - How many lock and condition variables do we need?
    - A. 1 B. 2 C. 3 D. 4 E. 5

Revisiting Coke Machine Example

```
Class CokeMachine{
    …
    int count;
    Semaphore new mutex(1);
    Semaphores new fullBuffers(0);
    Semaphores new emptyBuffers(numBuffers);
}
```

```
CokeMachine::Deposit(){
    emptyBuffers→P();
    mutex→P();
    Add coke to the machine;
    count++;
    mutex→V();
    fullBuffers→V();
}
```

```
CokeMachine::Remove(){
    fullBuffers→P();
    mutex→P();
    Remove coke from to the machine;
    count--;
    mutex→V();
    emptyBuffers→V();
}
```

Does the order of P matter?

Order of V matter?

Implementing Semaphores

```
Semaphore::P() {
    if (value == 0) {
        Put TCB on wait queue for semaphore;
        Switch();  // dispatch a ready thread
        }
    else {value--;}
}
```

Does this work?

```
Semaphore::V() {
    if wait queue is not empty {
        Move a waiting thread to ready queue;
    } else
      value++;
    }
}
```

Implementing Semaphores

```
Semaphore::P() {
    while (value == 0) {
        Put TCB on wait queue for semaphore;
        Switch();  // dispatch a ready thread
        }
    value--;
}
```

```
Semaphore::V() {
    if wait queue is not empty {
        Move a waiting thread to ready queue;
    }
    value++;
}
```

The Problem with Semaphores

- Semaphores are used for dual purpose
  - Mutual exclusion
  - Conditional synchronization
- Difficult to read/develop code
- Waiting for condition is independent of mutual exclusion
  - Programmer needs to be clever about using semaphores

```
CokeMachine::Deposit(){
    emptyBuffers→P();
    mutex→P();
    Add coke to the machine;
    count++;
    mutex→V();
    fullBuffers→V();
}
```

```
CokeMachine::Remove(){
    fullBuffers→P();
    mutex→P();
    Remove coke from to the machine;
    count--;
    mutex→V();
    emptyBuffers→V();
}
```

Introducing Monitors

- Separate the concerns of mutual exclusion and conditional synchronization
- What is a monitor?
  - One lock, and
  - Zero or more condition variables for managing concurrent access to shared data
- General approach:
  - Collect related shared data into an object/module
  - Define methods for accessing the shared data
- Monitors first introduced as programming language construct
  - Calling a method defined in the monitor automatically acquires the lock
  - Examples: Mesa, Java (synchronized methods)
- Monitors also define a programming convention
  - Can be used in any language (C, C++, …)

Critical Section: Monitors

- Basic idea:
  - Restrict programming model
  - Permit access to shared variables only within a critical section
- General program structure
  - Entry section
    - "Lock" before entering critical section
    - Wait if already locked, or invariant doesn't hold
    - Key point: synchronization may involve wait
  - Critical section code
  - Exit section
    - "Unlock" when leaving the critical section
- Object-oriented programming style
  - Associate a lock with each shared object
  - Methods that access shared object are critical sections
  - Acquire/release locks when entering/exiting a method that defines a critical section

Remember Condition Variables

- Locks
  - Provide mutual exclusion
  - Support two methods
    - Lock::Acquire() – wait until lock is free, then grab it
    - Lock::Release() – release the lock, waking up a waiter, if any
- Condition variables
  - Support conditional synchronization
  - Three operations
    - Wait(): Release lock; wait for the condition to become true; reacquire lock upon return (Java wait())
    - Signal(): Wake up a waiter, if any (Java notify())
    - Broadcast(): Wake up all the waiters (Java notifyAll())
  - Two semantics for implementation of wait() and signal()
    - Hoare monitor semantics
    - Hansen (Mesa) monitor semantics

So what is the big idea?

- (Editorial) Integrate idea of condition variable with language
  - Facilitate proof
  - Avoid error-prone boiler-plate code

Coke Machine – Example Monitor

```
Class CokeMachine{
    …
    Lock lock;
    int count = 0;
    Condition notFull, notEmpty;
}
```

Does the order of aquire/while(){wait} matter?

Order of release/signal matter?

```
CokeMachine::Deposit(){
    lock→acquire();
    while (count == n) {
            notFull.wait(&lock); }
    Add coke to the machine;
    count++;
    notEmpty.signal();
    lock→release();
}
```

```
CokeMachine::Remove(){
    lock→acquire();
    while (count == 0) {
            notEmpty.wait(&lock); }
    Remove coke from to the machine;
    count--;
    notFull.signal();
    lock→release();
}
```

Monitors: Recap

- Lock acquire and release: often incorporated into method definitions on object
  - E.g., Java's synchronized methods
  - Programmer may not have to explicitly acquire/release
- But, methods on a monitor object do execute under mutual exclusion
- Introduce idea of condition variable

- Every monitor function should start with what?
  - A. wait
  - B. signal
  - C. lock acquire
  - D. lock release
  - E. signalAll

Hoare Monitors: Semantics

- Hoare monitor semantics:
  - Assume thread *T1* is waiting on condition *x*
  - Assume thread *T2* is in the monitor
  - Assume thread *T2* calls *x*.signal
  - *T2* gives up monitor, *T2* blocks!
  - *T1* takes over monitor, runs
  - *T1* gives up monitor
  - *T2* takes over monitor, resumes
- Example

T1		*T2*
*fn*1(…)		
…		
x.wait // T1 blocks	→	*fn*4(…)
		…
// T1 resumes	←	*x*.signal // T2 blocks
Lock→release();		
	→	T2 resumes

Hansen (Mesa) Monitors: Semantics

- Hansen monitor semantics:
  - Assume thread *T1* waiting on condition *x*
  - Assume thread *T2* is in the monitor
  - Assume thread *T2* calls *x*.signal; wake up T1
  - *T2* continues, finishes
  - When T1 get a chance to run, *T1* takes over monitor, runs
  - *T1* finishes, gives up monitor
- Example:

```
fn1(…)
…
x.wait      // T1 blocks   ------>  fn4(…)
                                    …
                                    x.signal   // T2 continues
                          <------   // T2 finishes
// T1 resumes
// T1 finishes
```

Tradeoff

Hoare

- Claims:
  - Cleaner, good for proofs
  - When a condition variable is signaled, it does not change
  - Used in most textbooks
- ...but
  - Inefficient implementation
  - Not modular – correctness depends on correct use and implementation of signal

```
CokeMachine::Deposit(){
   lock→acquire();
   if (count == n) {
            notFull.wait(&lock); }
   Add coke to the machine;
   count++;
   notEmpty.signal();
   lock→release();
}
```

Hansen

- Signal is only a hint that the condition may be true
  - Need to check condition again before proceeding
  - Can lead to synchronization bugs
- Used by most systems (e.g., Java)
- Benefits:
  - Efficient implementation
  - Condition guaranteed to be true once you are out of while !

```
CokeMachine::Deposit(){
   lock→acquire();
   while (count == n) {
            notFull.wait(&lock); }
   Add coke to the machine;
   count++;
   notEmpty.signal();
   lock→release();
}
```

Problems with Monitors

Nested Monitor Calls

- What happens when one monitor calls into another?
  - What happens to CokeMachine::lock if thread sleeps in CokeTruck::Unload?
  - What happens if truck unloader wants a coke?

```
CokeMachine::Deposit(){
    lock→acquire();
    while (count == n) {
            notFull.wait(&lock); }
    truck->unload();
    Add coke to the machine;
    count++;
    notEmpty.signal();
    lock→release();
}
```

```
CokeTruck::Unload(){
    lock→acquire();
    while (soda.atDoor() != coke) {
            cokeAvailable.wait(&lock);}
    Unload soda closest to door;
    soda.pop();
    Signal availability for soda.atDoor();
    lock→release();
}
```

More Monitor Headaches

The *priority inversion* problem

- Three processes (P1, P2, P3), and P1 & P3 communicate using a monitor *M.* P3 is the highest priority process, followed by P2 and P1.
- 1. P1 enters M.
- 2. P1 is preempted by P2.
- 3. P2 is preempted by P3.
- 4. P3 tries to enter the monitor, and waits for the lock.
- 5. P2 runs again, preventing P3 from running, subverting the priority system.
- A simple way to avoid this situation is to associate with each monitor the priority of the highest priority process which ever enters that monitor.

Comparing Semaphores and Monitors

```
CokeMachine::Deposit(){
    emptyBuffers→P();
    mutex→P();
    Add coke to the machine;
    count++;
    mutex→V();
    fullBuffers→V();
}
```

```
CokeMachine::Remove(){
    fullBuffers→P();
    mutex→P();
    Remove coke from to the machine;
    count--;
    mutex→V();
    emptyBuffers→V();
}
```

```
CokeMachine::Deposit(){
    lock→acquire();
    while (count == n) {
            notFull.wait(&lock); }
    Add coke to the machine;
    count++;
    notEmpty.notify();
    lock→release();
}
```

```
CokeMachine::Remove(){
    lock→acquire();
    while (count == 0) {
            notEmpty.wait(&lock); }
    Remove coke from to the machine;
    count--;
    notFull.notify();
    lock→release();
}
```

Which is better?
A. Semaphore
B. Monitors

Other Interesting Topics

- Exception handling
  - What if a process waiting in a monitor needs to time out?
- Naked notify
  - How do we synchronize with I/O devices that do not grab monitor locks, but can notify condition variables.
- Butler Lampson and David Redell, "Experience with Processes and Monitors in Mesa."

Summary

- Synchronization
  - Coordinating execution of multiple threads that share data structures
- Past lectures:
  - Locks → provide mutual exclusion
  - Condition variables → provide conditional synchronization
- Today:
  - Semaphores
    - Introduced by Dijkstra in 1960s
    - Two types: binary semaphores and counting semaphores
    - Supports both mutual exclusion and conditional synchronization
  - Monitors
    - Separate mutual exclusion and conditional synchronization