CSE 120
Principles of Operating Systems

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Lecture 6: Semaphores and Monitors

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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
- Use them to solve common synchronization problems

Semaphores

- Semaphores are an abstract data type that provide mutual exclusion to critical sections
  - Described by Dijkstra in the “THE” system in 1968
- Semaphores can also be used as atomic counters
  - More later
- Semaphores are “integers” that support two operations:
  - Semaphore::Wait(): decrement, block until semaphore is open
    - » Also P(), after the Dutch word for “try to reduce” (also test, down)
  - Semaphore::Signal: increment, allow another thread to enter
    - » Also V() after the Dutch word for increment, up
  - 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 processes
- When wait() is called by a thread:
  - If semaphore is open, thread continues
  - If semaphore is closed, thread blocks on queue
- Then signal() 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, signal() 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

```
struct Semaphore {
    int value;
    Queue q;
} S;
withdraw (account, amount) {
    wait(S);
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    signal(S);
    return balance;
}
```

critical section

```
wait(S);
balance = get_balance(account);
balance = balance – amount;
```

```
wait(S);
```

```
wait(S);
```

Threads block

```
put_balance(account, balance);
signal(S);
```

```
…
signal(S);
```

```
…
signal(S);
```

It is undefined which thread runs after a signal

Semaphores in Nachos

```
P () {  // wait
  Disable interrupts;
  if (value == 0) {
    add currentThread to waitQueue;
    KThread.sleep(); // currentThread
  }
  value = value – 1;
  Enable interrupts;
}
```

```
V () {  // signal
  Disable interrupts;
  thread = get next on waitQueue;
  thread.ready();
  value = value + 1;
  Enable interrupts;
}
```

- To reference current thread: KThread.currentThread()
- KThread.sleep() assumes interrupts are disabled
  - Note that interrupts are disabled only to enter/leave critical section
  - How can it sleep with interrupts disabled?

Interrupts Disabled During Context Switch

```
KThread.yield () {
  Disable interrupts;
  currentThread.ready(); // add to Q
  runNextThread(); // context switch
  Enable interrupts;
}
```

```
Semaphore.P () {  // wait
  Disable interrupts;
  if (value == 0) {
    add currentThread to waitQueue;
    KThread.sleep(); // currentThread
  }
  value = value – 1;
  Enable interrupts;
}
```

[KThread.yield]
Disable interrupts;
currentThread.ready();
runNextThread();

[KThread.yield]
(Returns from runNextThread)
Enable interrupts;

[Semaphore.P]
Disable interrupts;
if (value == 0) {
  add currentThread to waitQueue;
  Kthread.sleep();

[KThread.yield]
(Returns from runNextThread)
Enable interrupts;

Using Semaphores

- We’ve looked at a simple example for using synchronization
  - Mutual exclusion while accessing a bank account
- Now we’re going to use semaphores to look at more interesting examples
  - Readers/Writers
  - Bounded Buffers

Readers/Writers Problem

- Readers/Writers Problem:
  - An object is shared among several threads
  - Some threads only read the object, others only write it
  - We can allow multiple readers but only one writer
    - » Let #r be the number of readers, #w be the number of writers
    - » Safety: $(\#r \geq 0) \wedge (0 \leq \#w \leq 1) \wedge ((\#r > 0) \Rightarrow (\#w = 0))$
- How can we use semaphores to control access to the object to implement this protocol?
- Use three variables
  - int readcount – number of threads reading object
  - Semaphore mutex – control access to readcount
  - Semaphore w_or_r – exclusive writing or reading

Readers/Writers

```
// number of readers
int readcount = 0;
// mutual exclusion to readcount
Semaphore mutex = 1;
// exclusive writer or reader
Semaphore w_or_r = 1;

writer {
    wait(w_or_r); // lock out readers
    Write;
    signal(w_or_r); // up for grabs
}
```

```
reader {
    wait(mutex);       // lock readcount
    readcount += 1; // one more reader
    if (readcount == 1)
        wait(w_or_r); // synch w/ writers
    signal(mutex);   // unlock readcount
    Read;
    wait(mutex);      // lock readcount
    readcount -= 1; // one fewer reader
    if (readcount == 0)
        signal(w_or_r); // up for grabs
    signal(mutex);   // unlock readcount
}
```

Readers/Writers Notes

- w_or_r provides mutex between readers and writers
  - writer wait/signal, reader wait/signal when readcount goes from 0 to 1 or from 1 to 0.
- If a writer is writing, where will readers be waiting?
- Once a writer exits, all readers can fall through
  - Which reader gets to go first?
  - Is it guaranteed that all readers will fall through?
- If readers and writers are waiting, and a writer exits, who goes first?
- Why do readers use mutex?
- Why don't writers use mutex?
- What if the signal is above “if (readcount == 1)”?

Bounded Buffer

- Problem: There is a set of resource buffers shared by producer and consumer threads
  - Producer inserts resources into the buffer set
    - Output, disk blocks, memory pages, processes, etc.
  - Consumer removes resources from the buffer set
    - Whatever is generated by the producer
- Producer and consumer execute at different rates
  - No serialization of one behind the other
  - Tasks are independent (easier to think about)
  - The buffer set allows each to run without explicit handoff
- Safety:
  - Sequence of consumed values is prefix of sequence of produced values
  - If *nc* is number consumed, *np* number produced, and N the size of the buffer, then $0 \leq np - nc \leq N$

Bounded Buffer (2)

- $0 \le np - nc \le N$ and $0 \le (nc - np) + N \le N$
- Use three semaphores:
  - empty – count of empty buffers
    - » Counting semaphore
    - » empty = $(nc - np) + N$
  - full – count of full buffers
    - » Counting semaphore
    - » $np - nc$ = full
  - mutex – mutual exclusion to shared set of buffers
    - » Binary semaphore

Bounded Buffer (3)

```
Semaphore mutex = 1;   // mutual exclusion to shared set of buffers
Semaphore empty = N;   // count of empty buffers (all empty to start)
Semaphore full = 0;    // count of full buffers (none full to start)
```

```
producer {
  while (1) {
    Produce new resource;
    wait(empty);  // wait for empty buffer
    wait(mutex);  // lock buffer list
    Add resource to an empty buffer;
    signal(mutex); // unlock buffer list
    signal(full);  // note a full buffer
  }
}
```

```
consumer {
  while (1) {
    wait(full);    // wait for a full buffer
    wait(mutex);   // lock buffer list
    Remove resource from a full buffer;
    signal(mutex); // unlock buffer list
    signal(empty); // note an empty buffer
    Consume resource;
  }
}
```

Bounded Buffer (4)

- Why need the mutex at all?
- Where are the critical sections?
- What happens if operations on mutex and full/empty are switched around?
  - The pattern of signal/wait on full/empty is a common construct often called an interlock
- Producer-Consumer and Bounded Buffer are classic examples of synchronization problems

Semaphore Questions

- Are there any problems that can be solved with counting semaphores that cannot be solved with mutex semaphores?
- Does it matter which thread is unblocked by a signal operation?
  - Hint: consider the following three processes sharing a semaphore mutex that is initially 1:

```
while (1) {
    wait(mutex);
    // in critical section
    signal(mutex);
}
```

```
while (1) {
    wait(mutex);
    // in critical section
    signal(mutex);
}
```

```
while (1) }
    wait(mutex);
    // in critical section
    signal(mutex);
}
```

Semaphore Summary

- Semaphores can be used to solve any of the traditional synchronization 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 being 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 monitor is 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

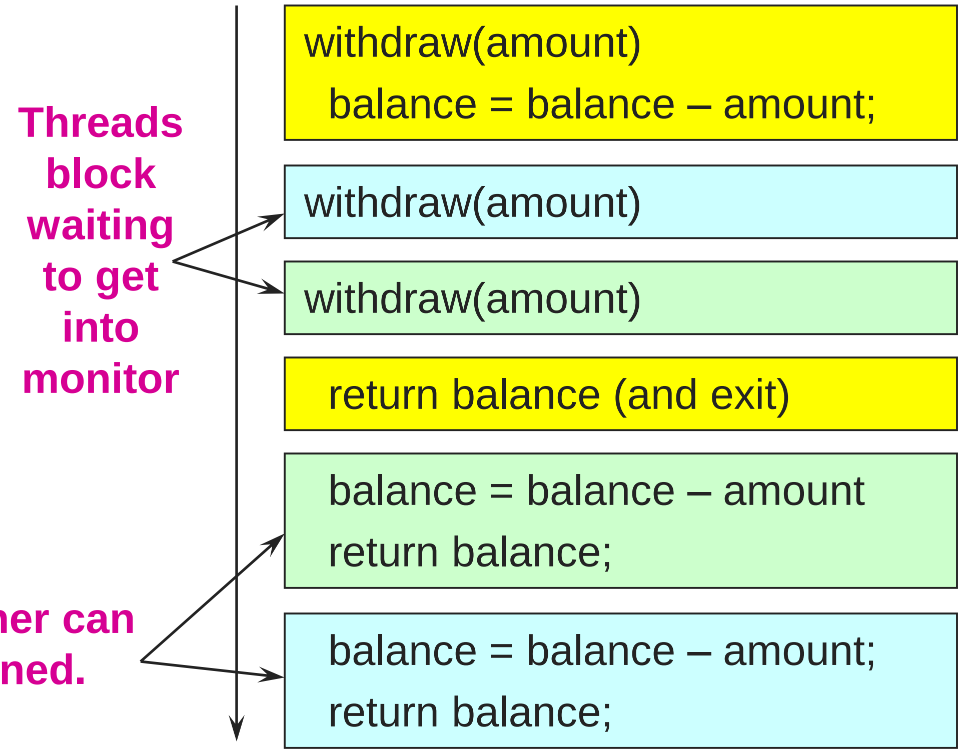
Monitor Semantics

- 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?

Account Example

```
Monitor account {
  double balance;

  double withdraw(amount) {
    balance = balance – amount;
    return balance;
  }
}
```



When first thread exits, another can enter. Which one is undefined.

- Hey, that was easy!
- But what if a thread wants to wait inside the monitor?
  - » Such as “mutex(empty)” by reader in bounded buffer?

Monitors, Monitor Invariants and Condition Variables

- A monitor invariant is a safety property associated with the monitor, expressed over the monitored variables. It holds whenever a thread enters or exits the monitor.
- 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
    - Also called wait (Java, C++), sleep (Nachos, C#)
  - Signal – wakeup one waiting thread
    - Also called wake (Nachos, C#), notify (Java), notify_one (C++)
  - Broadcast – wakeup all waiting threads
    - Also called wakeAll (Nachos, C#), notifyAll (Java), notify_all (C++)
- Condition variables are not boolean objects
  - "if (condition_variable) then" … does not make sense
  - "if (num_resources == 0) then wait(resources_available)" does
  - An example will make this more clear

Monitor Bounded Buffer

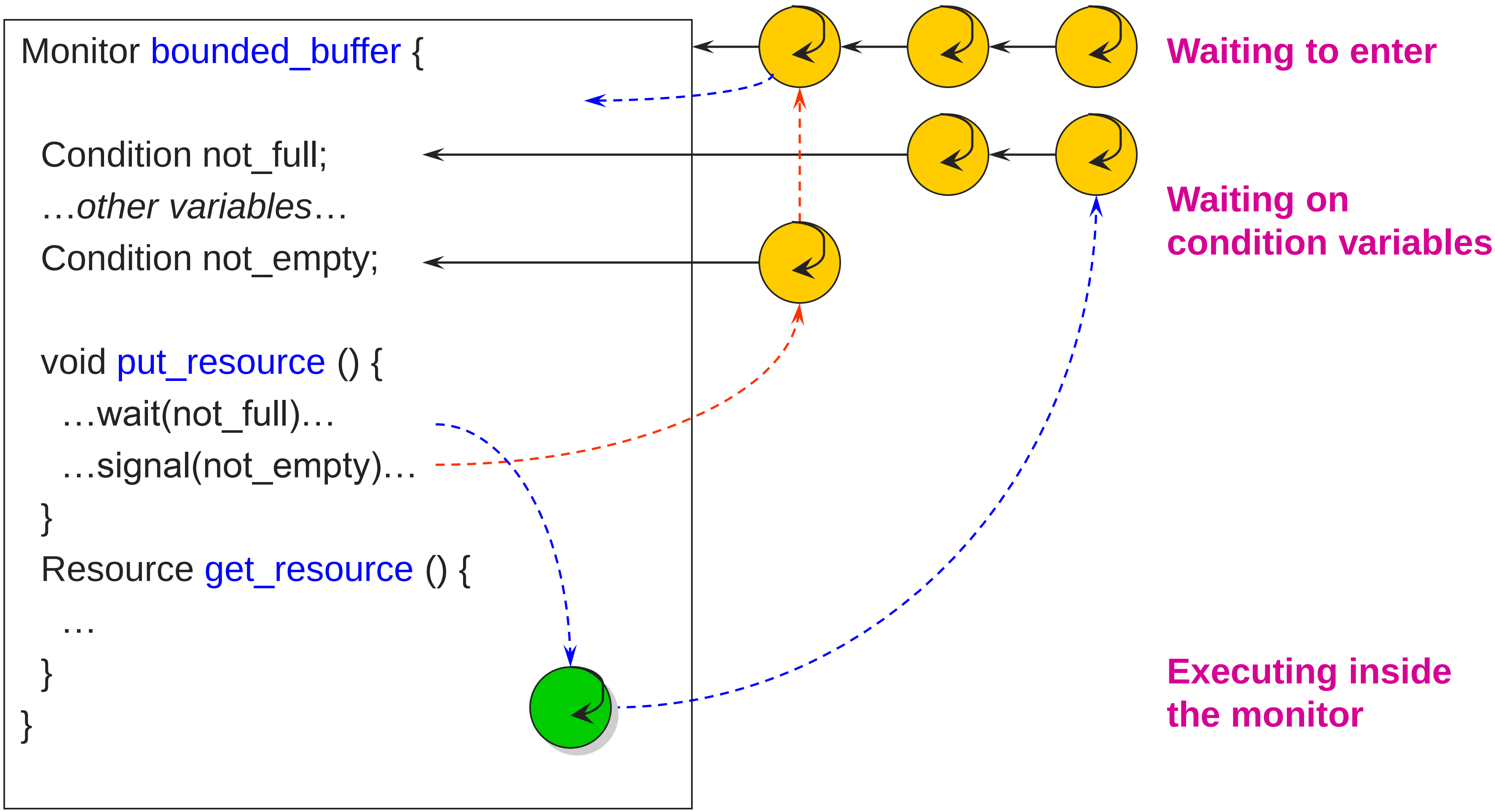
```
Monitor bounded_buffer {
  Resource buffer[N];
  // Variables for indexing buffer
  // monitor invariant involves these vars
  Condition not_full; // space in buffer
  Condition not_empty; // value in buffer

  void put_resource (Resource R) {
    while (buffer array is full)
        wait(not_full);
    Add R to buffer array;
    signal(not_empty);
  }
```

```
  Resource get_resource() {
    while (buffer array is empty)
        wait(not_empty);
    Get resource R from buffer array;
    signal(not_full);
    return R;
  }
} // end monitor
```

- What happens if no threads are waiting when signal is called?

Monitor Queues



Condition Vars != Semaphores

- Condition variables != semaphores
  - Although their operations can have the same names, they have entirely different semantics
  - 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

- signal() places a waiter on the ready queue, but signaler continues inside monitor
  - Known as “Mesa” semantics
- Conditional not necessarily true when waiter runs again
  - Returning from wait() is only a hint that something changed
  - Must recheck conditional case

Monitor Readers and Writers

Using Mesa monitor semantics.

- Will have four methods: StartRead, StartWrite, EndRead and EndWrite
- Monitored data: nr (number of readers) and nw (number of writers) with the monitor invariant

$$(nr \geq 0) \wedge (0 \leq nw \leq 1) \wedge ((nr > 0) \Rightarrow (nw = 0))$$

- Two conditions:
  - canRead: $nw = 0$
  - canWrite: $(nr = 0) \wedge (nw = 0)$

Monitor Readers and Writers

- Write with just wait()
  - Will be safe, maybe not live – why?

```
Monitor RW {
 int nr = 0, nw = 0;
 Condition canRead, canWrite;

 void StartRead () {
  while (nw != 0) do wait(canRead);
  nr++;
 }

 void EndRead () {
  nr--;
 }
```

```
 void StartWrite {
  while (nr != 0 || nw != 0) do wait(canWrite);
  nw++;
 }

 void EndWrite () {
  nw--;
 }
} // end monitor
```

Monitor Readers and Writers

- add signal() and broadcast()

```
Monitor RW {
  int nr = 0, nw = 0;
  Condition canRead, canWrite;

  void StartRead () {
    while (nw != 0) do wait(canRead);
    nr++;
  }              can we put a signal here?

  void EndRead () {
    nr--;
    if (nr == 0) signal(canWrite);
  }
```

```
  void StartWrite () {
    while (nr != 0 || nw != 0) do wait(canWrite);
    nw++;
  }              can we put a signal here?

  void EndWrite () {
    nw--;
    broadcast(canRead);
    signal(canWrite);
  }
} // end monitor
```

Monitor Readers and Writers

- Is there any priority between readers and writers?
- What if you wanted to ensure that a waiting writer would have priority over new readers?

Condition Vars & Locks

- Condition variables are also used without monitors in conjunction with blocking locks
  - This is what you are implementing in Project 1
- A monitor is “just like” a module whose state includes a condition variable 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

Using Cond Vars & Locks

- Alternation of two threads (ping-pong)
- Each executes the following:

```
Lock lock;
Condition cond;

void ping_pong () {
  acquire(lock);
  while (1) {
     printf(“ping or pong\n”);
     signal(cond, lock);
     wait(cond, lock);
  }
  release(lock);
}
```

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

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"
      - Can mix synchronized/unsynchronized methods in same class
    - Executing the body of a "synchronized" statement
      - Supports finer-grained locking than an entire method
      - Identical to the Modula-2 "LOCK (m) DO" construct
  - 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 wait (Condition.sleep in Nachos)
  - Object.notify() is signal (Condition.wake)
  - Object.notifyAll() is broadcast (Condition.wakeAll)

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 Chapters 7, 8, 32

Race Conditions

```
int x = 0;
int i, j;

void AddToX() {
  for (i = 0; i < 100; i++) x++;
}

void SubFromX() {
  for (j = 0; j < 100; j++) x--;
}
```

- What is the range of possible values for x? Why?

Signal

```
lock.acquire();
…
while (flag != 1) {
   cv.wait();
}
…
lock.release();
```

```
lock.acquire();
…
flag = 1;
cv.signal();
…
lock.release();
```

```
lock.acquire();
…
cv.signal();
flag = 1;
…
lock.release();
```

- Does the order of setting the flag and calling signal change the correctness? (Mesa semantics)

Common Pitfall (actual bug in Linux device driver)

```
void mptctl_simplified(unsigned long arg) {
  mpt_ioctl_header khdr, __user *uhdr = (void __user *) arg;
  MPT_ADAPTER *iocp = NULL;

  // first fetch
  if (copy_from_user(&khdr, uhdr, sizeof(khdr)))
    return -EFAULT;

  // dependency lookup
  if (mpt_verify_adapter(khdr.iocnum, &iocp) < 0 || iocp == NULL)
    return -EFAULT;

  // dependency usage
  mutex_lock(&iocp->ioctl_cmds.mutex);
  struct mpt_fw_xfer kfwdl, __user *ufwdl = (void __user *) arg;

  // second fetch
  if (copy_from_user(&kfwdl, ufwdl, sizeof(struct mpt_fw_xfer)))
    return -EFAULT;


  mptctl_do_fw_download(kfwdl.iocnum, ......);
  mutex_unlock(&iocp->ioctl_cmds.mutex);
}
```

Critical Section

Fig. 1: A dependency lookup *double-fetch bug*, adapted from `__mptctl_ioctl` in file `drivers/message/fusion/mptctl.c`

Synchronization

```
Class Event {
   …
   void Signal () {
      …
   }
   void Wait () {
      …
   }
}
```

- Event synchronization (e.g., Win32)
- Event::Wait blocks if and only if Event is unsignaled
- Event::Signal makes Event signaled, wakes up blocked threads
- Once signalled, an Event remains signaled until deleted
- Use locks and condition variables (e.g., as in Nachos)