COS 318: Operating Systems

Synchronization: Semaphores, Monitors and Condition Variables

Jaswinder Pal Singh
Computer Science Department
Princeton University

(http://www.cs.princeton.edu/courses/cos318/)

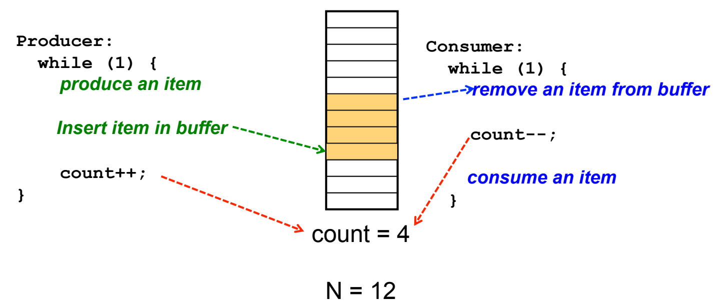
Today's Topics

- Mutex Isn't Enough
- Semaphores
- Condition Variables
- Monitors
- Barriers

Revisit Mutex

- Mutex can solve the critical section problem
  Acquire(lock);
    Critical section
  Release(lock);
- Use Mutex primitives to access shared data structures
  E.g. shared "count" variable
    Acquire(lock);
    count++;
    Release(lock);
- Are mutex primitives adequate to solve all problems?

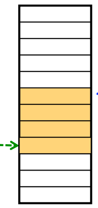
Producer-Consumer (Bounded Buffer) Problem



- Can we solve this problem with Mutex primitives?

Use Mutex, Block and Unblock

```
Producer:
  while (1) {
    produce an item
    if (count == N)
       Block();
    Insert item in buffer
    Acquire(lock);
    count++;
    Release(lock);
    if (count == 1)
       Unblock(Consumer);
  }
```

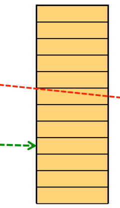



```
Consumer:
  while (1) {
    if (!count)
       Block();
    remove an item from buffer
    Acquire(lock);
    count--;
    Release(lock);
    if (count == N-1)
       Unblock(Producer);
    consume an item
  }
```

- Does this work?

Use Mutex, Block and Unblock

```
Producer:
  while (1) {
    produce an item
    if (count == N)
       Block();
    Insert item in buffer
    Acquire(lock);
    count++;
    Release(lock);
    if (count == 1)
       Unblock(Consumer);
  }
```




```
Consumer:
  while (1) {
    if (!count)
    {context switch}
       Block();
    remove an item from buffer
    Acquire(lock);
    count--;
    Release(lock);
    if (count == N-1)
       Unblock(Producer);
    consume an item
  }
```

- Race condition!
- Ultimately, both block and never wake up
- Lost the unblock; any way to "remember" them?

Limitations of Locks

- Provide mutual exclusion: only one process/thread can be in the critical section at a time
- Do not provide ordering or sequencing
  - Who gets to be in critical section first?
  - How does thread A wait for thread B (or C, D, E) to do X before A does Y?
- Need additional synchronization mechanisms
  - Semaphores
  - Condition Variables
  - Monitors
  - (Higher level constructs composed from these)

Semaphores (Dijkstra, 1965)

- A semaphore is a synchronization variable that contains an integer value
  - Cannot access the integer value directly (only via semaphore operations)
  - Initialized to some integer value
  - Supports two atomic operations other than initialization
    - down() (or wait() or P())
    - up (or signal() or V())
- If positive value, think of value as keeping track of how many 'resources' or "un-activated unblocks" are available
- If negative, tracks how many threads are waiting for a resource or unblock

Semaphores (Dijkstra, 1965)

- P (or Down or Wait or "Proberen" (to try)) definition
  - Atomic operation
  - Block version: Decrement value, and if less than zero block
  - Spin version: Wait for semaphore to become positive and then decrement

```
P(s){                              P(s){
   if (--s < 0)                      while (s <= 0)
       block(s);                          ;
                                     s--;
}                                  }
```

- V (or Up or Signal or "Verhogen" (increment)) definition
  - Atomic operation
  - Block version: increment, and if non-positive (which means at least one thread is blocked waiting on the sempahore) then unblock a thread
  - Spin version: Increment semaphore

```
V(s){                              V(s){
  if (++s <=0)                        s++;
     unblock(s);                   }
}
```

9

Bounded Buffer with Semaphores

```
Producer:                          Consumer:
  while (1) {                        while (1) {
    produce an item                    P(fullCount);
    P(emptyCount);
                                       P(mutex);
    P(mutex);                          take an item from buffer
    put item in buffer                 V(mutex);
    V(mutex);
                                       V(emptyCount);
    V(fullCount);                      consume item
  }                                  }
```

- Initialization: emptyCount = N; fullCount = 0
- Are **P(mutex)** and **V(mutex)** necessary?

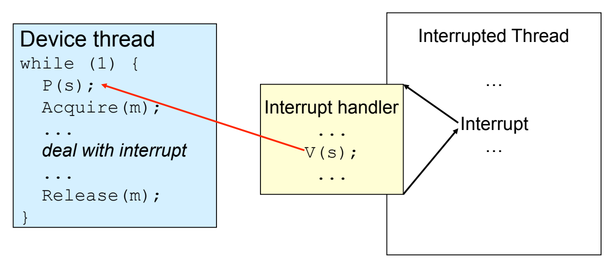
Uses of Semaphores in this Example

- Event sequencing
  - Don't consume if buffer empty, wait for something to be added
  - Don't add if buffer full, wait for something to be removed
- Mutual exclusion
  - Avoid race conditions on shared variables

11

Example: Interrupt Handler

```
Init(s,0);
```



12

Bounded Buffer with Semaphores (again)

```
producer() {                      consumer() {
  while (1) {                       while (1) {
    produce an item                   P(fullCount);
    P(emptyCount);
                                      P(mutex);
    P(mutex);                         take an item from buffer
    put the item in buffer            V(mutex);
    V(mutex);
                                      V(emptyCount);
    V(fullCount);                     consume the item
  }                                 }
}                                 }
```

Does Order Matter?

```
producer() {                      consumer() {
  while (1) {                       while (1) {
    produce an item                   P(fullCount);
    P(mutex);
    P(emptyCount);                    P(mutex);
                                      take an item from buffer
    put the item in buffer            V(mutex);
    V(mutex);
                                      V(emptyCount);
    V(fullCount);                     consume the item
  }                                 }
}                                 }
```

Another Example: Are Locks Enough?

- A lock provides mutual exclusion to the shared data
- Rules for using a lock:
  - Always acquire before accessing shared data structure
  - Always release after finishing with shared data
  - Lock is initially free.
- Simple example: a synchronized queue

```
bool tryInsert()
{
    lock.Acquire();           // lock before use
    … put item on queue;      // ok to access
    lock.Release();           // unlock after done
    return success;
}
```

```
bool tryRemove()
{   …
    lock.Acquire();
    if something on queue         // can we wait?
        remove it;
    lock->Release();
    return success;
}
```

Condition Variables

- Make tryRemove wait until something is on the queue?
  - Can't just sleep while holding the lock
  - Key idea: make it possible to go to sleep inside critical section, by atomically releasing lock at same time we go to sleep.
- **Condition variable**: *enables a **queue** of threads waiting for something inside a critical section.*
  - **Wait()** --- Release lock, go to sleep, re-acquire when woken
    - release lock and going to sleep is atomic
  - **Signal()** --- Wake up a waiter, if any
  - **Broadcast()** --- Wake up all waiters

Synchronized Queue

- **Rule:** must hold lock when doing condition variable operations

```
AddToQueue()
{
   lock.acquire();

   put item on queue;
   condition.signal();

   lock.release();
}
```

```
RemoveFromQueue()
{
   lock.acquire();

   while nothing on queue
      condition.wait(&lock);
               // release lock; got to
               // sleep; reacquire lock
               // when woken

   remove item from queue;
   lock.release();
   return item;
}
```

Condition variable design pattern

```
methodThatWaits() {
   lock.acquire();

   // Read/write shared state

   while (!testSharedState()) {
      cv.wait(&lock);
   }

   // Read/write shared state

   lock.release();
}
```

```
methodThatSignals() {
   lock.acquire();

   // Read/write shared state

   // If testSharedState is now true
   cv.signal(&lock);

   // Read/write shared state

   lock.release();
}
```

Condition variables

- ALWAYS hold lock when calling wait, signal, broadcast
  - Condition variable is synchronization FOR shared state
  - Remember: ALWAYS hold lock when accessing shared state
- Unlike semaphore, condition variable is memory-less
  - If signal when no one is waiting, no op
  - If signal after a wait is posted, a waiter wakes up
- Wait atomically releases lock

Condition variables, cont'd

- When a thread is woken up from wait, it may not run immediately
  - Signal/broadcast put thread on ready list
  - When lock is released, anyone might acquire it. Condition may change
- Wait MUST be in a loop

```
while (needToWait()) {
    condition.Wait(lock);
}
```

- Simplifies implementation
  - Of condition variables and locks
  - Of code that uses condition variables and locks

Structured synchronization

- Identify objects or data structures that can be accessed by multiple threads concurrently
- Add locks to object/module
  - Obtain lock on start to every method/procedure
  - Release lock when finished
- If need to wait
  - while(needToWait()) { condition.Wait(lock); }
  - Do not assume that when you wake up, signaler just ran
- If do something that might wake someone up
  - Signal or Broadcast
- Always leave shared state variables in a consistent state
  - When lock is released, or when waiting

Monitors

- Monitor definition:
  - *a lock and zero or more condition variables for managing concurrent access to shared data*
- Monitors make things easier:
  - “locks” for mutual exclusion
  - “condition variables” for scheduling constraints

Monitors Embedded in Languages

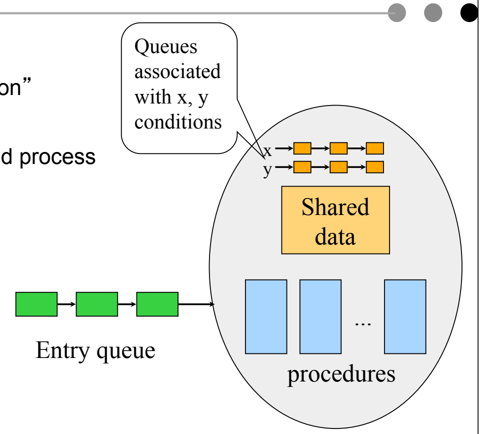
- High-level data abstraction that unifies handling of:
  - Shared data, operations on it, synchronization and scheduling
    - All operations on data structure have single (implicit) lock
    - An operation can relinquish control and wait on condition

```
// only one process at time can update instance of Q
class Q {
        int head, tail;  // shared data
        void enqueue(v) { locked access to Q instance }
        int dequeue() { locked access to Q instance }
}
```

  - Java from Sun; Mesa/Cedar from Xerox PARC
- Monitors are easy and safe
  - Compiler can check, lock is implicit (cannot be forgotten)

Condition Variables in A Monitor

- Wait(condition)
  - Block on “condition”
- Signal(condition)
  - Wakeup a blocked process on “condition”



Producer-Consumer with Monitors

```
procedure Producer
begin
  while true do
  begin
    produce an item
    ProdCons.Enter();
  end;
end;

procedure Consumer
begin
  while true do
  begin
    ProdCons.Remove();
    consume an item;
  end;
end;
```

```
monitor ProdCons
  condition full, empty;

  procedure Enter;
  begin
    if (buffer is full)
      wait(full);
    put item into buffer;
    if (only one item)
      signal(empty);
  end;

  procedure Remove;
  begin
    if (buffer is empty)
      wait(empty);
    remove an item;
    if (buffer was full)
      signal(full);
  end;
```

Hoare's Signal Implementation (MOS p137)

- Run the signaled thread immediately and suspend the current one (Hoare)
- What if the current thread has more things to do?

```
  if (only one item)
    signal(empty);
  something else
end;
```

```
monitor ProdCons
  condition full, empty;

  procedure Enter;
  begin
    if (buffer is full)
      wait(full);
    put item into buffer;
    if (only one item)
      signal(empty);
  end;

  procedure Remove;
  begin
    if (buffer is empty)
      wait(empty);
    remove an item;
    if (buffer was full)
      signal(full);
  end;
```

30

Hansen's Signal Implementation (MOS p 137)

- Signal must be the last statement of a monitor procedure
- Exit the monitor
- Any issue with this approach?

```
monitor ProdCons
  condition full, empty;

  procedure Enter;
  begin
    if (buffer is full)
      wait(full);
    put item into buffer;
    if (only one item)
      signal(empty);
  end;

  procedure Remove;
  begin
    if (buffer is empty)
      wait(empty);
    remove an item;
    if (buffer was full)
      signal(full);
  end;
```

31

Mesa Signal Implementation

- Continues its execution

```
  if (only one item)
    signal(empty);
  something else
end;
```

  - B. W. Lampson and D. D. Redell, "Experience with Processes and Monitors in Mesa," Communiction of the ACM, 23(2):105-117. 1980.
- This is easy to implement!
- Issues?

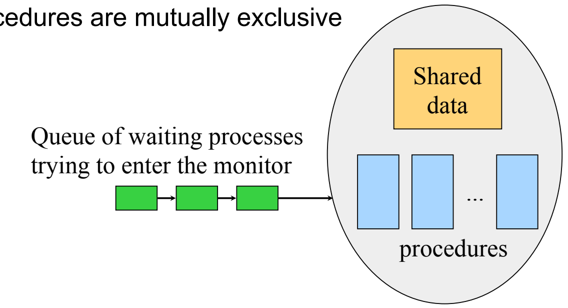
32

Evolution of Monitors

- Brinch-Hansen (73) and Hoare Monitor (74)
  - Concept, but no implementation
  - Requires Signal to be the last statement (Hansen)
  - Requires relinquishing CPU to signaler (Hoare)
- Mesa Language (77)
  - Monitor in language, but signaler keeps mutex and CPU
  - Waiter simply put on ready queue, with no special priority
- Modula-2+ (84) and Modula-3 (88)
  - Explicit LOCK primitive
  - Mesa-style monitor
- Pthreads (95)
  - Started standard effort around 1989
  - Defined by ANSI/IEEE POSIX 1003.1 Runtime library
- Java threads
  - James Gosling in early 1990s without threads
  - Use most of the Pthreads primitives

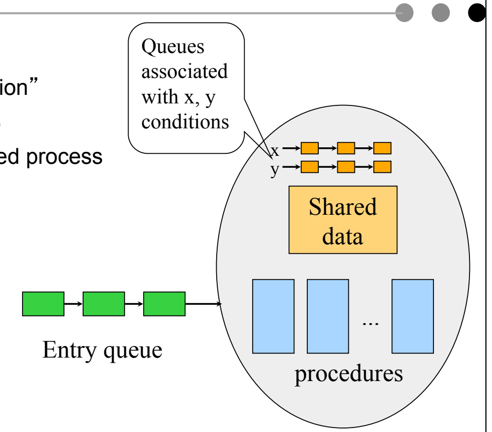
Monitor: Hide Mutual Exclusion

- Brinch-Hansen (73), Hoare (74)
- Procedures are mutually exclusive



Condition Variables in A Monitor

- Wait(condition)
  - Block on “condition”
- Signal(condition)
  - Wakeup a blocked process on “condition”



Producer-Consumer with Monitors

```
procedure Producer
begin
  while true do
  begin
    produce an item
    ProdCons.Enter();
  end;
end;

procedure Consumer
begin
  while true do
  begin
    ProdCons.Remove();
    consume an item;
  end;
end;
```

```
monitor ProdCons
  condition full, empty;

  procedure Enter;
  begin
    if (buffer is full)
      wait(full);
    put item into buffer;
    if (only one item)
      signal(empty);
  end;

  procedure Remove;
  begin
    if (buffer is empty)
      wait(empty);
    remove an item;
    if (buffer was full)
      signal(full);
  end;
```

Hoare's Signal Implementation (MOS p137)

- Run the signaled thread immediately and suspend the current one (Hoare)
- What if the current thread has more things to do?

```
if (only one item)
   signal(empty);
  something else
end;
```

```
monitor ProdCons
  condition full, empty;

  procedure Enter;
  begin
    if (buffer is full)
      wait(full);
    put item into buffer;
    if (only one item)
      signal(empty);
  end;

  procedure Remove;
  begin
    if (buffer is empty)
      wait(empty);
    remove an item;
    if (buffer was full)
      signal(full);
  end;
```


Hansen's Signal Implementation (MOS p 137)

- Signal must be the last statement of a monitor procedure
- Exit the monitor
- Any issue with this approach?

```
monitor ProdCons
  condition full, empty;

  procedure Enter;
  begin
    if (buffer is full)
      wait(full);
    put item into buffer;
    if (only one item)
      signal(empty);
  end;

  procedure Remove;
  begin
    if (buffer is empty)
      wait(empty);
    remove an item;
    if (buffer was full)
      signal(full);
  end;
```


Mesa Signal Implementation

- Continues its execution

```
if (only one item)
   signal(empty);
  something else
end;
```

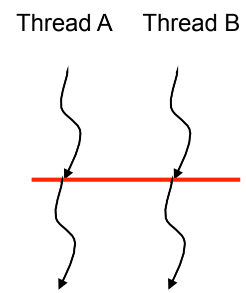
  - B. W. Lampson and D. D. Redell, "Experience with Processes and Monitors in Mesa," Communiction of the ACM, 23(2):105-117. 1980.
- This is easy to implement!
- Issues?

Evolution of Monitors

- Brinch-Hansen (73) and Hoare Monitor (74)
  - Concept, but no implementation
  - Requires Signal to be the last statement (Hansen)
  - Requires relinquishing CPU to signaler (Hoare)
- Mesa Language (77)
  - Monitor in language, but signaler keeps mutex and CPU
  - Waiter simply put on ready queue, with no special priority
- Modula-2+ (84) and Modula-3 (88)
  - Explicit LOCK primitive
  - Mesa-style monitor
- Pthreads (95)
  - Started standard effort around 1989
  - Defined by ANSI/IEEE POSIX 1003.1 Runtime library
- Java threads
  - James Gosling in early 1990s without threads
  - Use most of the Pthreads primitives

Barrier Synchronization

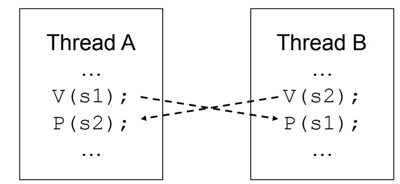
- Thread A and Thread B want to meet at a particular point
- The one to get there first waits for the other one to reach that point before proceeding
- Then both go forward



Using Semaphores as A Barrier

- Use two semaphores?

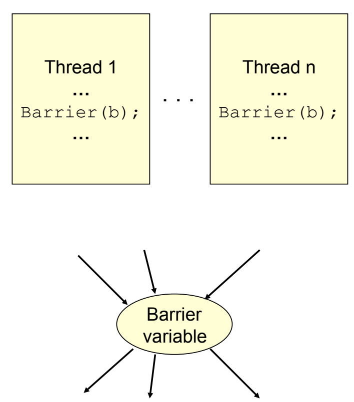
```
init(s1, 0);
init(s2, 0);
```



- What about more than two threads?

Barrier Primitive

- Functions
  - Take a barrier variable
  - Broadcast to n-1 threads
  - When barrier variable has reached n, go forward
- Hardware support on some parallel machines
  - Multicast network
  - Counting logic
  - User-level barrier variables



Equivalence

- Semaphores
  - Good for signaling and fine for simple mutex
  - Not good for mutex in general, since easy to introduce a bug with ordering against other semaphores
    - Locks are only for mutex, so clearer and less bug-prone
- Monitors
  - Good for scheduling and mutex
  - May be costly for simple signaling

The Big Picture

	OS codes and concurrent applications			
High-Level Atomic API	Mutex	Semaphores	Monitors	Barriers
Low-Level Atomic Ops	Load/store	Interrupt disable/enable	Test&Set	Other atomic instructions
	Interrupts (I/O, timer)	Multiprocessors		CPU scheduling

52

Summary

- Mutex alone are not enough
- Semaphores
- Monitors
  - Mesa-style monitor and its idiom
- Barriers

53