COS 318: Operating Systems

Synchronization: Semaphores, Monitors and Condition Variables

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 );
```

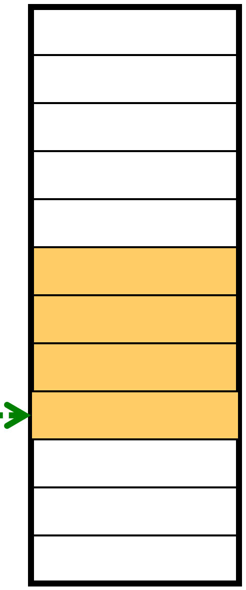
- Are mutex primitives adequate to solve all synchronization problems?

Producer-Consumer (Bounded Buffer) Problem

```
Producer:
  while (1) {
    produce an item

    Insert item in buffer

    count++;
}
```



count = 4

N = 12

```
Consumer:
  while (1) {
    remove an item from buffer

    count--;

    consume an item
  }
```

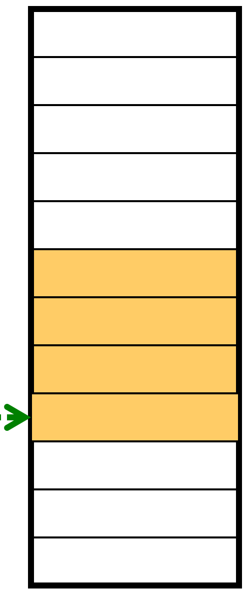
- Can we solve this problem with Mutex primitives?

Producer-Consumer (Bounded Buffer) Problem

```
Producer:
  while (1) {
    produce an item

    Acquire(lock);
    Insert item in buffer
    count++;
    Release(lock);

}
```



count = 4

N = 12

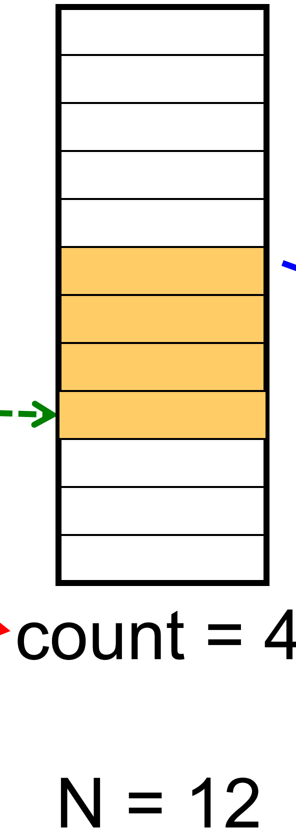
```
Consumer:
  while (1) {
   Acquire(lock);
   remove an item from buffer
    count--;
    Release(lock);

    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);
  }
```

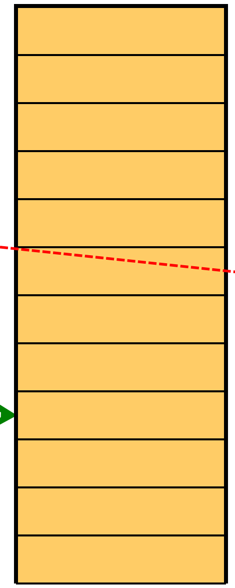



```
Consumer:
  while (1) {
    if (!count)
      Block();
    remove an item from buffer
    Acquire(lock);
    count--;
    Release(lock);
    if (count == N-1)
      Unblock(Producer);
    consume an item
  }
```

- Use block/unblock for ordering
- 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);
  }
```



count = 12

N = 12

```
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
  }
```

- 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 (aka event synchronization)
  - 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 some way of counting or remembering number or events

- 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
    - P(), (or down() or wait()); P for Proberen
    - V() (or up() or signal()); V for Verhogen
- 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

- Provides ordering and counting (of ‘surplus’ events/resources)

Semaphores (Dijkstra, 1965)

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

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

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

```
V(s){
    s++;
}
```

Bounded Buffer with Semaphores

```
Producer:
  while (1) {
    produce an item
    P(emptyCount);

    P(mutex);
    put item in buffer
    V(mutex);

    V(fullCount);
  }
```

```
Consumer:
  while (1) {
    P(fullCount);

    P(mutex);
    take an item from buffer
    V(mutex);

    V(emptyCount);
    consume item
  }
```

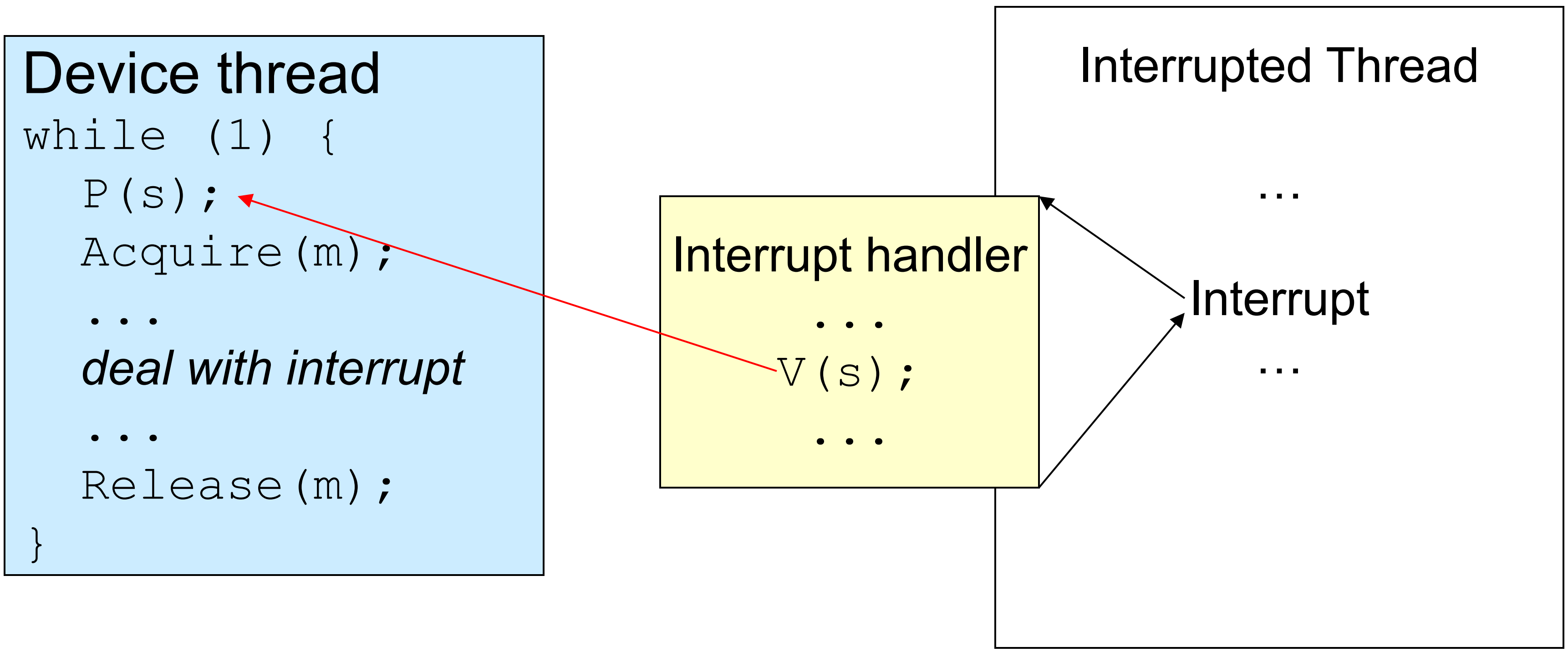
- Initialization: emptyCount = N; fullCount = 0
- Are `P(mutex)` and `V(mutex)` necessary?

Uses of Semaphores in this Example

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

Example: Interrupt Handler

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



Bounded Buffer with Semaphores (again)

```
producer() {
  while (1) {
    produce an item
    P(emptyCount);

    P(mutex);
    put the item in buffer
    V(mutex);

    V(fullCount);
  }
}
```

```
consumer() {
  while (1) {
    P(fullCount);

    P(mutex);
    take an item from buffer
    V(mutex);

    V(emptyCount);
    consume the item
  }
}
```

Does Order Matter?

```
producer() {
  while (1) {
    produce an item

    P(mutex);
    P(emptyCount);
    put the item in buffer
    V(mutex);

    V(fullCount);
  }
}
```

```
consumer() {
  while (1) {
    P(fullCount);

    P(mutex);
    take an item from buffer
    V(mutex);

    V(emptyCount);
    consume the item
  }
}
```

- Q: What problem can happen if the order of P(mutex) and P(emptycount) are reversed as here?

Different Example: Waiting in Critical Section

- 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

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

    // Read/write shared state

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

    // Read/write shared state

    lock.release();
}
```

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

    // Read/write shared state

    while (!testSharedState()) {
        cv.wait(&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

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 for something inside critical section
  - while(needToWait()) { condition.Wait(lock); }
- If do something that should 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

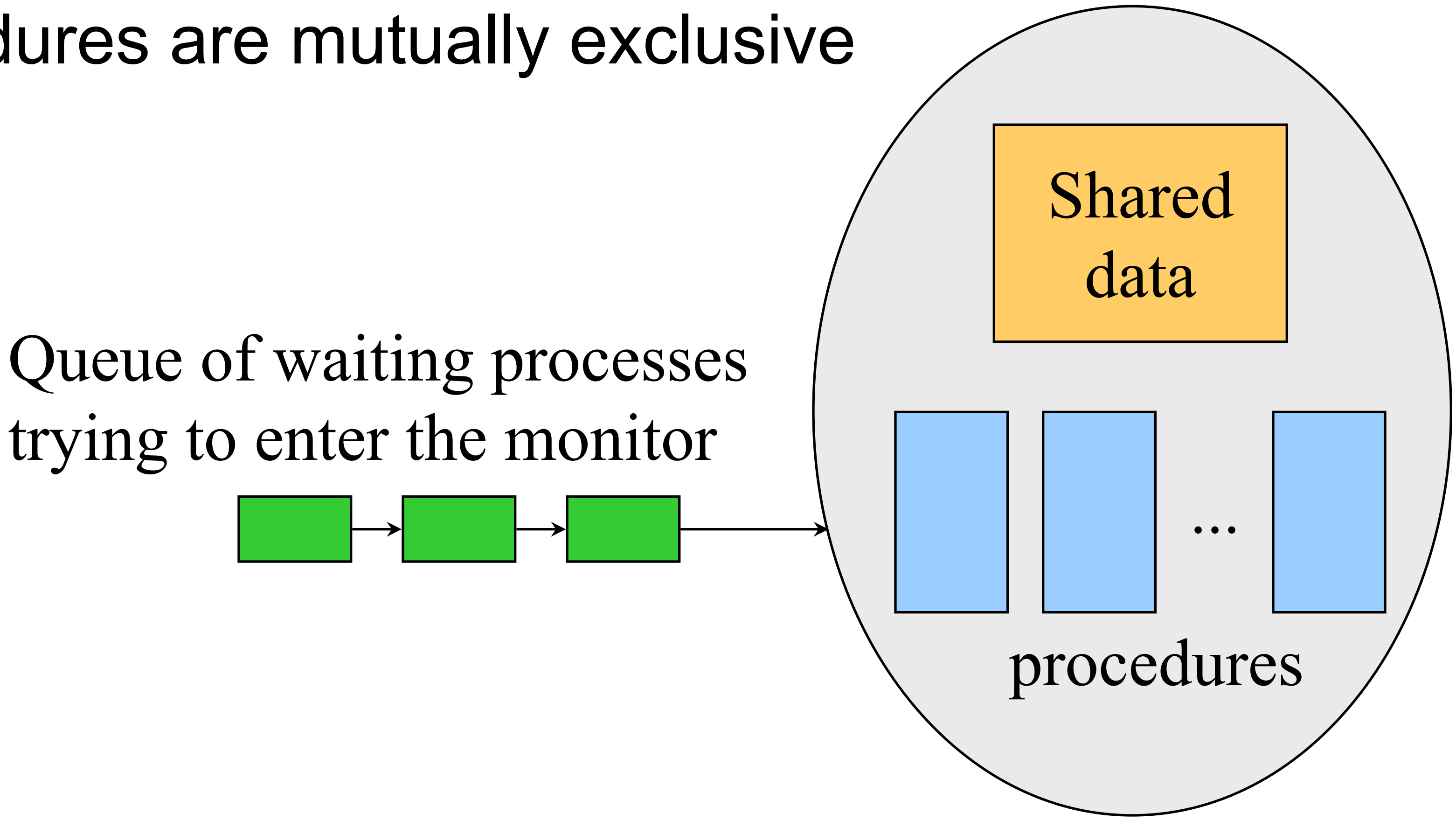
- High-level data abstraction that unifies handling of:
  - Shared data, operations on it, synchronization and scheduling
    - All operations on data structure have single (implicit) lock
    - An operation can relinquish control and wait on a condition

```
// 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)

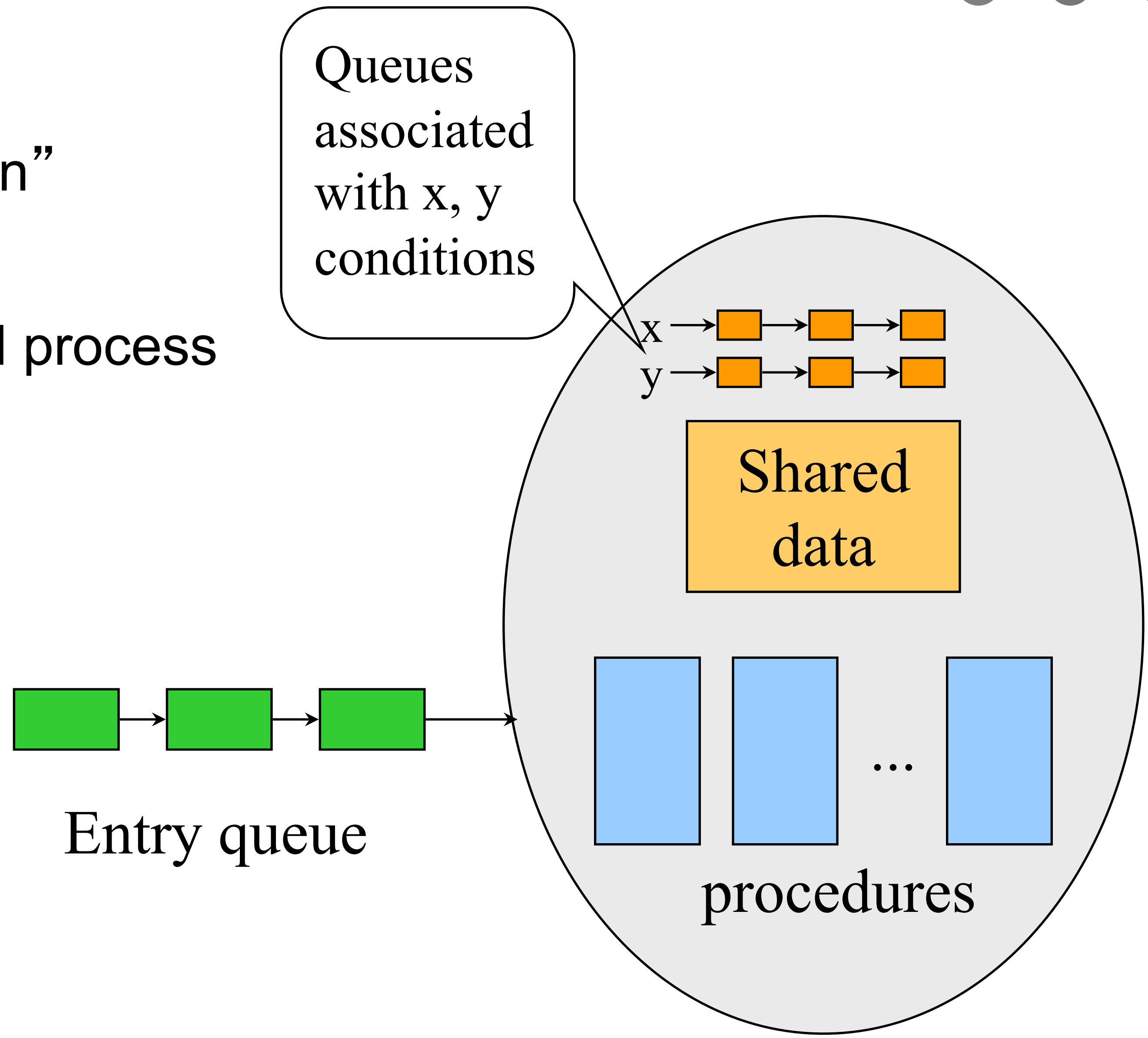
Monitor: Hide Mutual Exclusion

- 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.Add();
  end;
end;

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

```
monitor ProdCons
  condition full, empty;

  procedure Add;
  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;
```

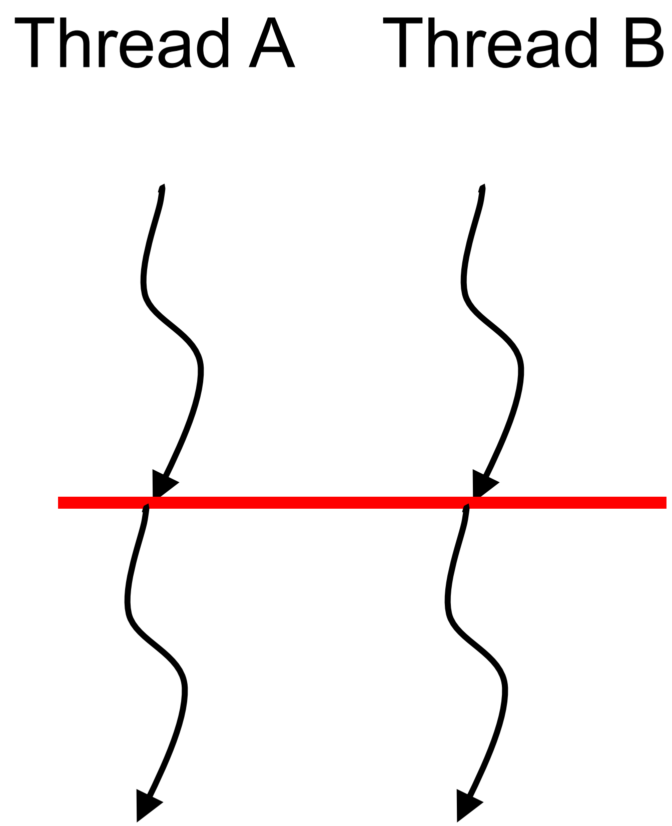
  - B. W. Lampson and D. D. Redell, "Experience with Processes and Monitors in Mesa," Communiction of the ACM, 23(2):105-117. 1980.
- This is easy to implement!
- Issues?

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 waiting signaled thread (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

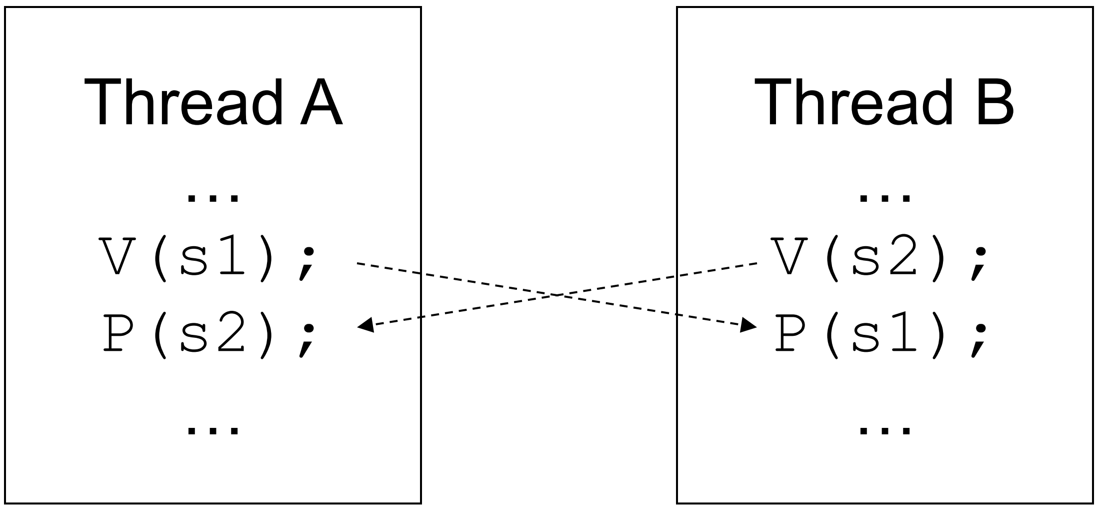
- Thread A and Thread B want to meet at a particular point
- The one to get there first waits for the other one to reach that point before proceeding
- Then both go forward



Using Semaphores as A Barrier

- Use two semaphores?

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



- What about more than two threads?

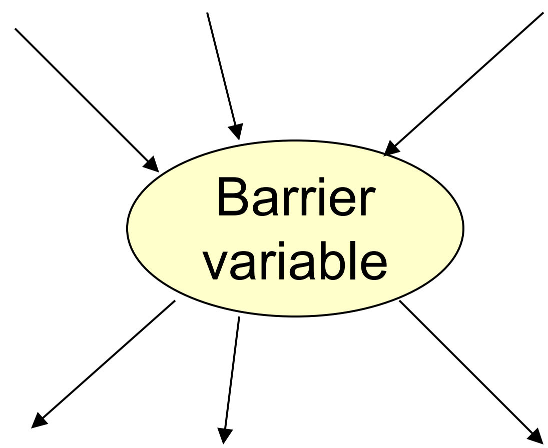
Barrier Primitive

- 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

Thread 1
```
...
Barrier(b);
...
```

. . .

Thread n
```
...
Barrier(b);
...
```



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	

Summary

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