COS 318: Operating Systems

Semaphores, Monitors and Condition Variables

Kai Li and Andy Bavier
Computer Science Department
Princeton University

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

Today's Topics

- Consumer-producer problem
- Semaphores
- Monitors
- Mesa-style monitor and its idioms
- Barriers

Revisit Mutex

- Mutex can solve the critical section problem

  Acquire(lock);

    Critical section

  Release(lock);

- Always use Mutex primitives when you access shared data structures

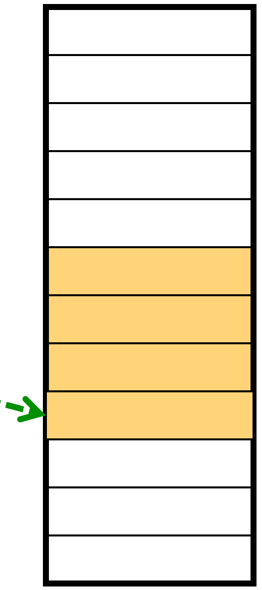
  E.g. shared "count" variable

  ```
  Acquire( lock );
  count++;
  Release( lock );
  ```

- Are mutex primitives adequate to solve all problems?

Producer-Consumer (Bounded Buffer) Problem

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

     Insert item in buffer

     count++;
}
```



count = 4

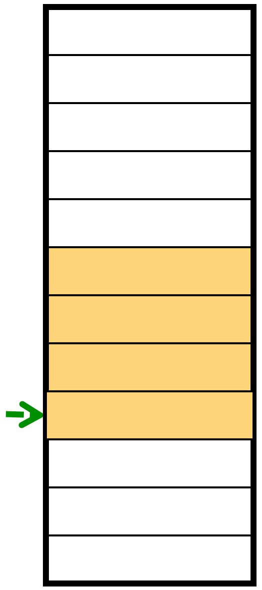
N = 12

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

     count--;

     consume an item
  }
```

- Can we solve this problem with Mutex primitives?

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);
  }
```



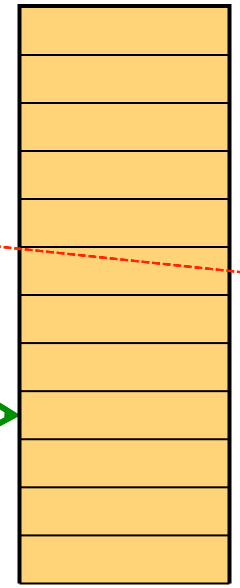
count = 4

N = 12

```
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 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
  }
```

- Race condition!
- Any way to make this work?
- These primitives are not enough

Semaphores (Dijkstra, 1965)

- Initialization
  - Initialize a semaphore s
- P (or Down or Wait or “Probeer”) definition
  - Atomic operation
  - Wait for semaphore to become positive and then decrement

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

- V (or Up or Signal or “Verhoog”) definition
  - Atomic operation
  - Increment semaphore by 1

```
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?

Example: Interrupt Handler

Device thread

```
...
Acquire(m);
...

Release(m);
...
```

Interrupt handler

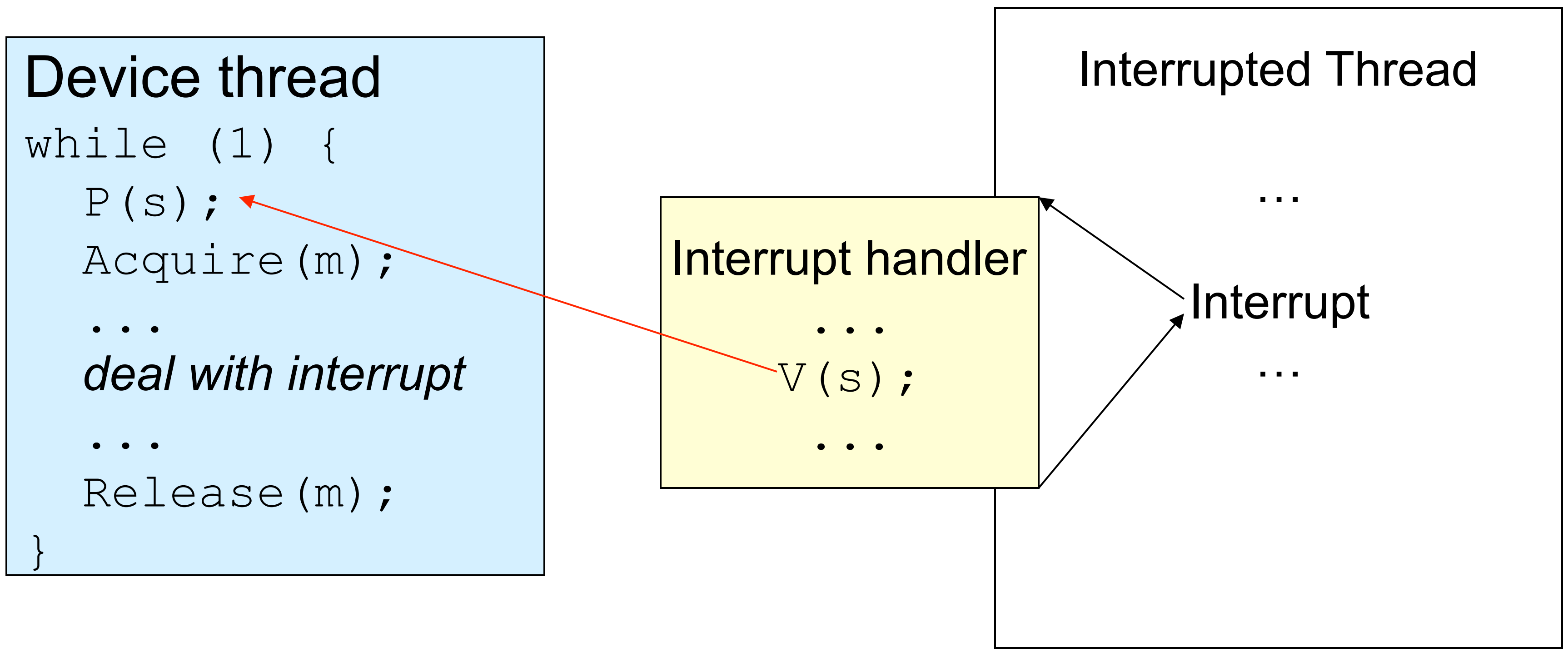
```
...
Acquire(m);
...

Release(m);
...
```

?

- A device thread works with an interrupt handler
- What to do with shared data?
- What if “m” is held by another thread or by itself?

Use Semaphore

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



Semaphores Are Not Always Convenient

- A shared queue with Enqueue and Dequeue:

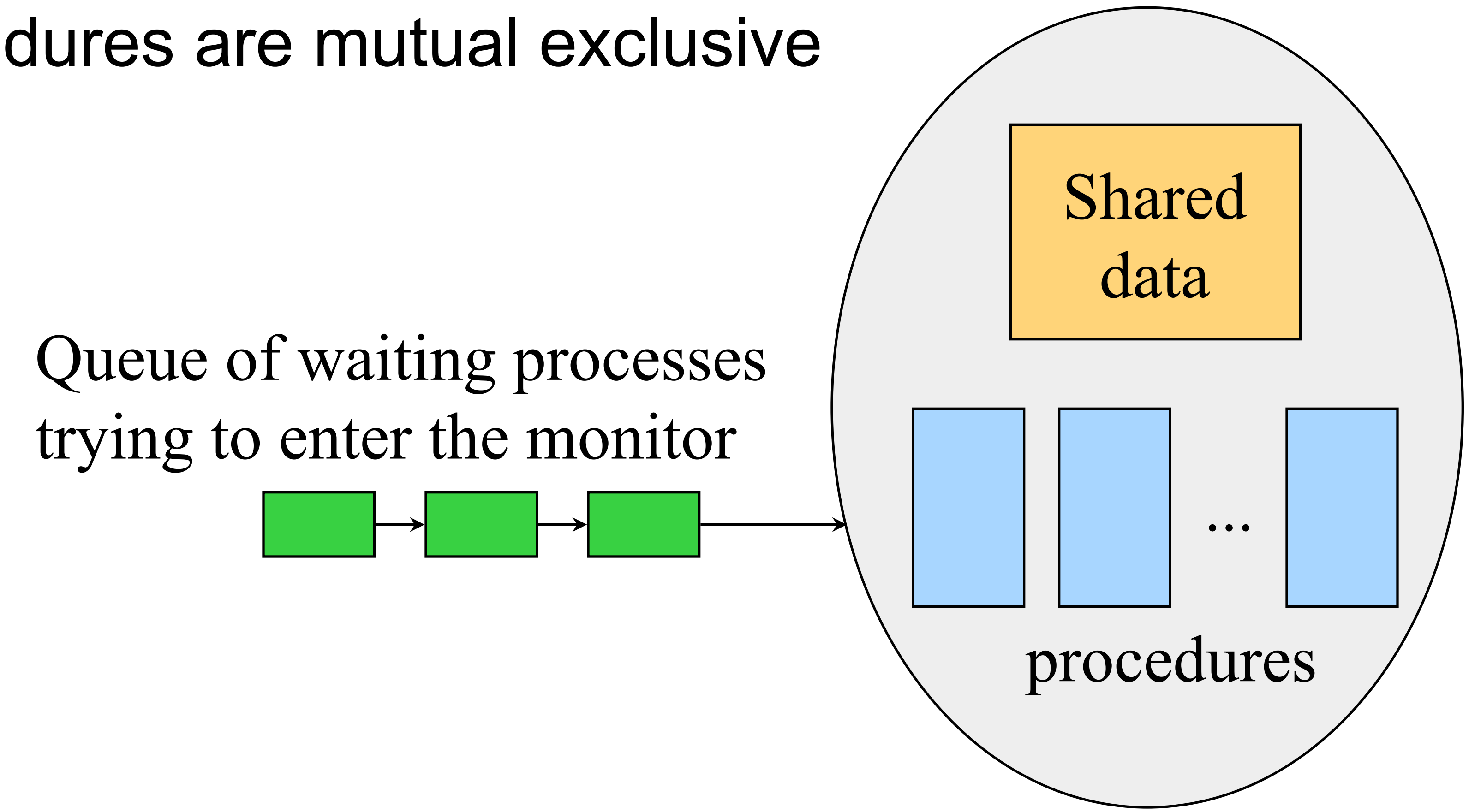
```
Enqueue(q, item)
{
  Acquire(mutex);
  put item into q;
  Release(mutex);
}
```

```
Dequeue(q)
{
  Acquire(mutex);
  take an item from q;
  Release(mutex);
  return item;
}
```

- What if we want **`Dequeue(q)`** to block until **`q`** is not empty?
  - It is a consumer and producer problem
- Semaphores are difficult to use
  - Orders are important

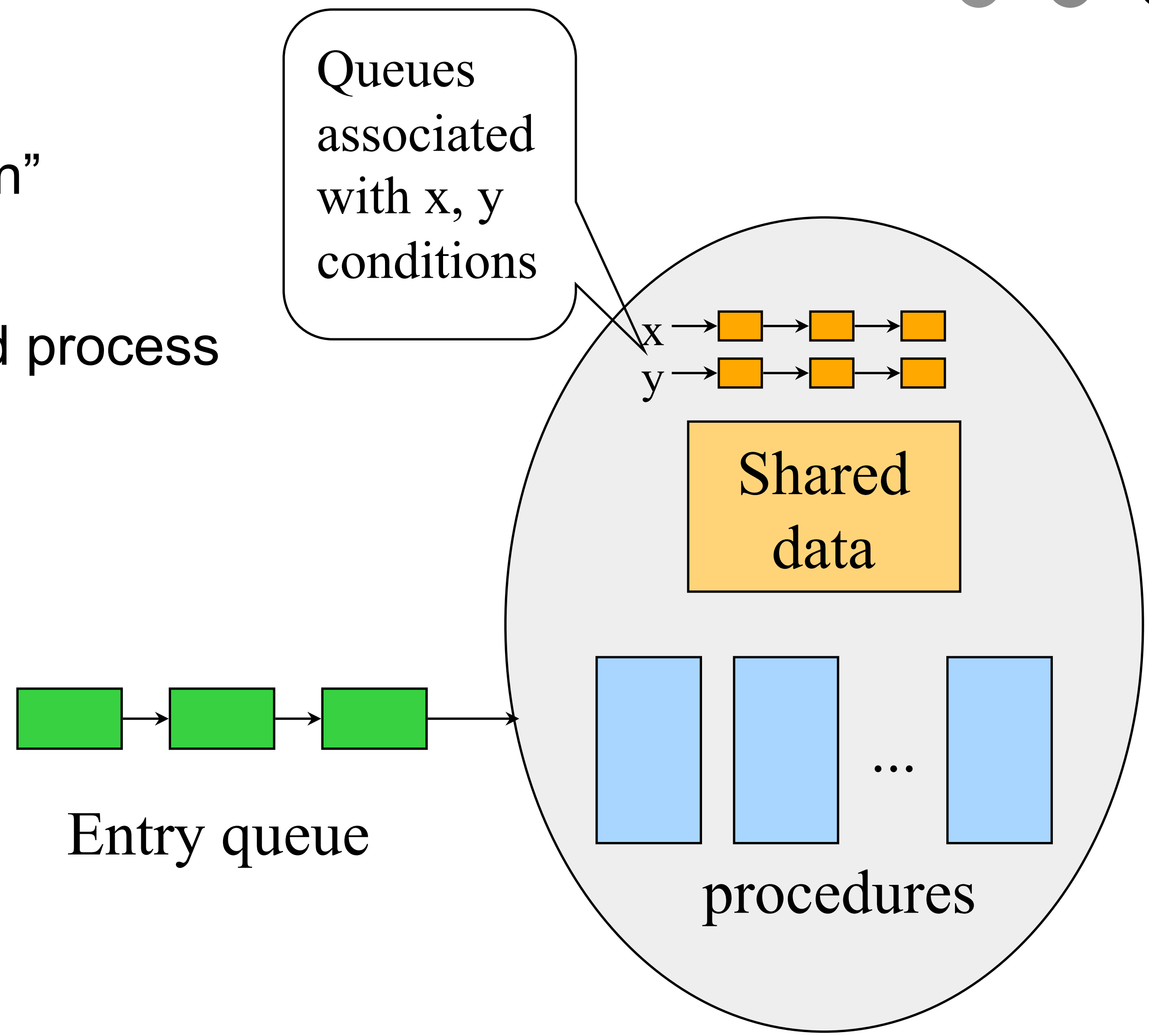
Monitor: Hide Mutual Exclusion

- Brinch-Hansen (73), Hoare (74)
- Procedures are mutual 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?

Mesa Style "Monitor" (Birrell's Paper)

- Associate a condition variable with a mutex
- Wait(mutex, condition)
  - Atomically unlock the mutex and enqueued on the condition variable (block the thread)
  - Re-lock the lock when it is awaken
- Signal(condition)
  - No-op if there is no thread blocked on the condition variable
  - Wake up at least one if there are threads blocked
- Broadcast(condition)
  - Wake up all waiting threads

Consumer-Producer with Mesa-Style Monitor

```
static count = 0;
static Cond full, empty;
static Mutex lock;

Enter(Item item) {
   Acquire(lock);
   if (count==N)
      Wait(lock, full);
   insert item into buffer
   count++;
   if (count==1)
      Signal(empty);
   Release(lock);
}

Remove(Item item) {
   Acquire(lock);
   if (!count)
      Wait(lock, empty);
   remove item from buffer
   count--;
   if (count==N-1)
      Signal(full);
   Release(lock);
}
```

Any issues with this?

Consumer-Producer with Mesa-Style Monitor

```
static count = 0;
static Cond full, empty;
static Mutex lock;

Enter(Item item) {
  Acquire(lock);
  while (count==N)
    Wait(lock, full);
  insert item into buffer
  count++;
  if (count==1)
    Signal(empty);
  Release(lock);
}
```

```
Remove(Item item) {
  Acquire(lock);
  while (!count)
    Wait(lock, empty);
  remove item from buffer
  count--;
  if (count==N-1)
    Signal(full);
  Release(lock);
}
```

The Programming Idiom

- Waiting for a resource

```
Acquire( mutex );
while ( no resource )
  wait( mutex, cond );
...
(use the resource)
...
Release( mutex);
```

- Make a resource available

```
Acquire( mutex );
...
(make resource available)
...
Signal( cond );
/* or Broadcast( cond );
Release( mutex);
```

Revisit the Motivation Example

```
Enqueue(Queue q,
        Item item) {

  Acquire(lock);

  insert an item to q;

  Signal(Empty);
  Release(lock);
}
```

```
Item GetItem(Queue q) {
  Item item;

  Acquire( lock );
  while ( q is empty )
    Wait( lock, Empty);

    remove an item;

  Release( lock );
  return item;
}
```

- Does this work?

Condition Variables Primitives

- Wait(mutex, cond)
  - Enter the critical section (min busy wait)
  - Release mutex
  - Put my TCB to cond's queue
  - Call scheduler
  - Exit the critical section
    . . . (blocked)
  - Waking up:
    - Acquire mutex
    - Resume

- Signal(cond)
  - Enter the critical section (min busy wait)
  - Wake up a TCB in cond's queue
  - Exit the critical section

More on Mesa-Style Monitor

- Signaler continues execution
- Waiters simply put on ready queue
  - Must reevaluate the condition
- No constraints on when the waiting thread must run
- No constrains on signaler
  - Can execute after signal call (Hansen's cannot)
  - Do not need to relinquish control to awaken thread/process

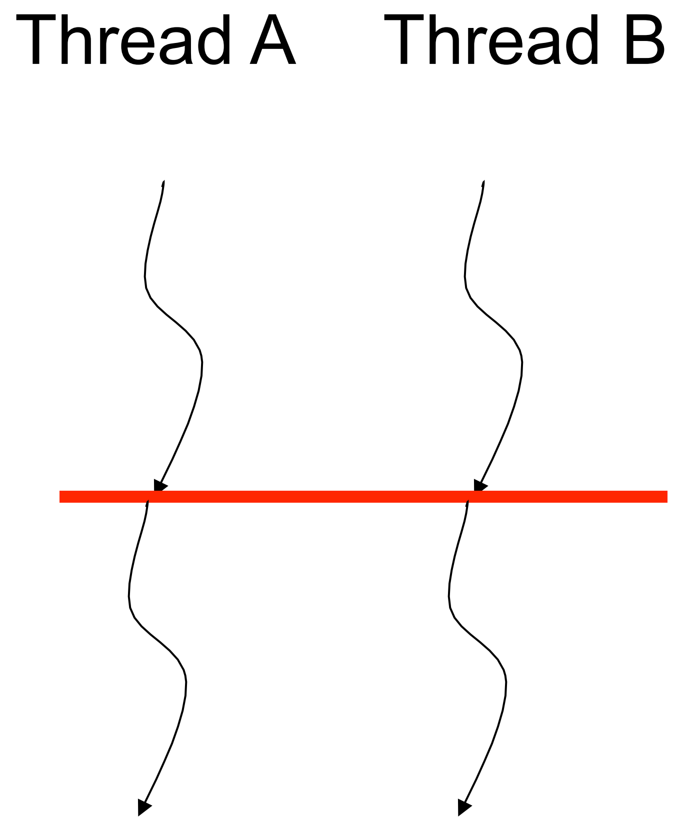
Evolution of Monitors

- 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

Example: A Simple Barrier

- Thread A and Thread B want to meet at a particular point
- Then both go forward

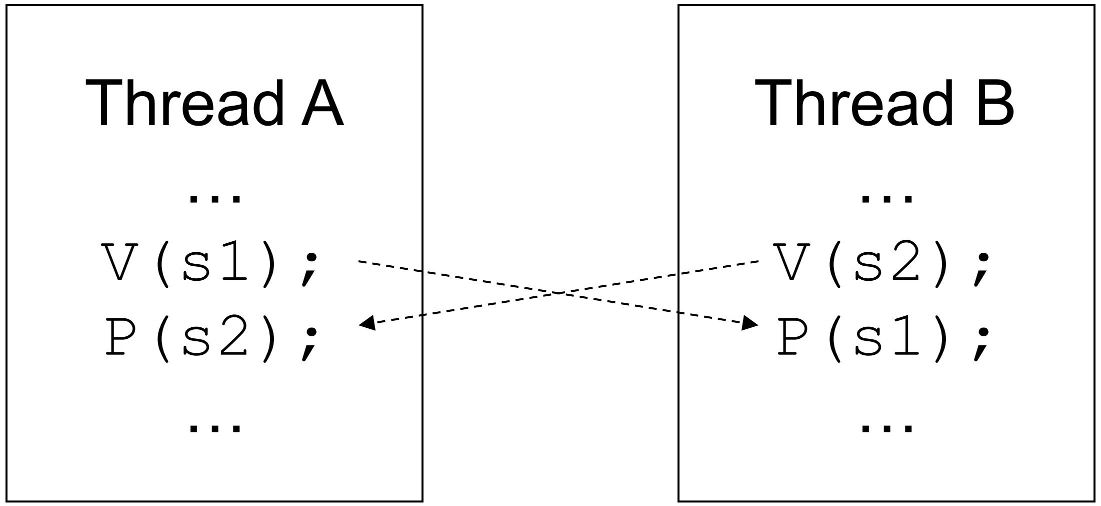
- How would you program this with a monitor?



Using Semaphores as A Barrier

- Use two semaphore?

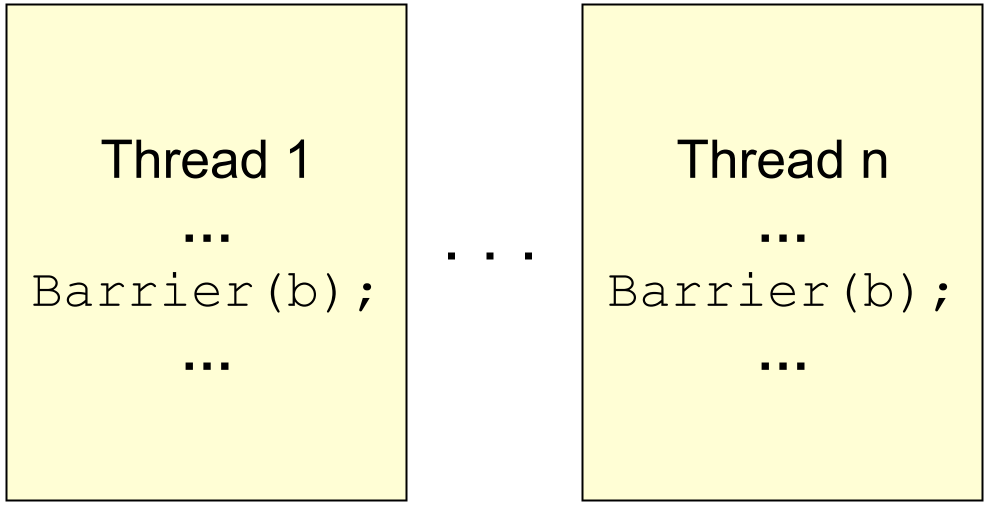
```
init(s1, 0);
init(s2, 0);
```



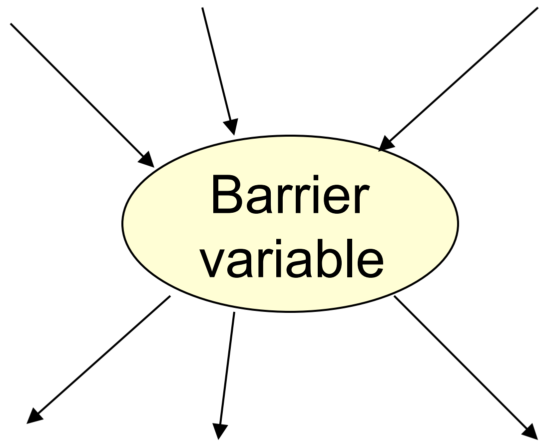
- What about more than two threads?

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
  - Not good for mutex because it is easy to introduce a bug
- Monitors
  - Good for scheduling and mutex
  - Maybe costly for a 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