# COS 318: Operating Systems

# Semaphores, Monitors and Condition Variables

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

# Today's Topics

- Producer-consumer problem
- Semaphores
- 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 );
```

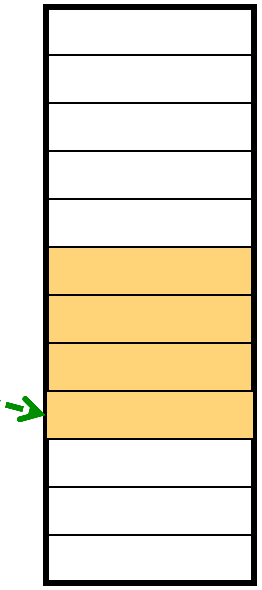
- Are mutex primitives adequate to solve all problems?

# Producer-Consumer (Bounded Buffer) Problem

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

    Insert item in buffer

    count++;
}
```



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

    count--;

    consume an item
  }
```

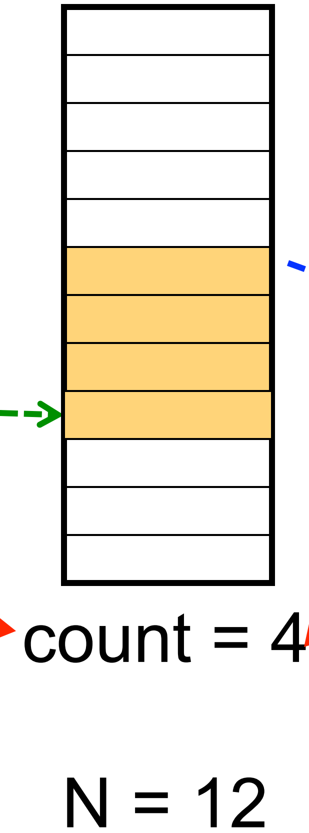
count = 4

N = 12

- 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);
  }
```

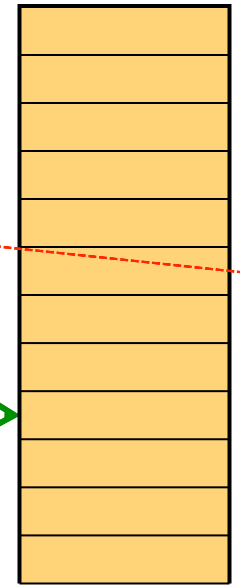



```
Consumer:
  while (1) {
    if (!count)
       Block();
    remove an item from buffer
    Acquire(lock);
    count--;
    Release(lock);
    if (count == N-1)
       Unblock(Producer);
    consume an item
  }
```

- 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);
  }
```



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

# Semaphores (Dijkstra, 1965)

- Initialization
  - Initialize to an integer value
- Never access the value directly after that, only through P(), V()
  - The operations P() and V() are atomic operations
  - System implements the atomicity
- 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 "Probeer") definition
  - Atomic operation
  - Decrement value, and if less than zero block
  - Or: 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) definition
  - Atomic operation
  - Increment semaphore
  - Or increment semaphore, and if non-positive (which means at least one thread is blocked waiting on the sempahore) then unblock a thread

```
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
  }
```

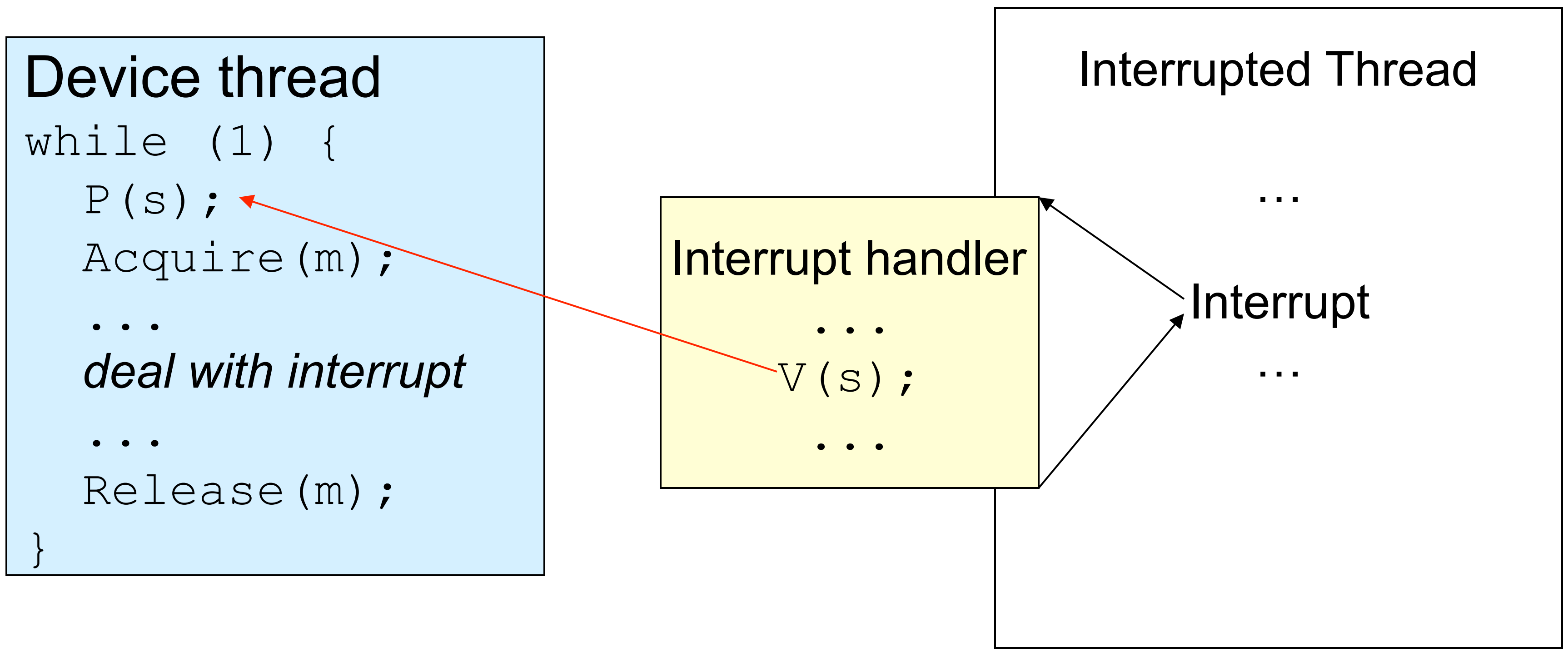
- Initialization: emptyCount = N; fullCount = 0
- Are **`P(mutex)`** and **`V(mutex)`** necessary?

# Uses of Semaphores in this Example

- 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

# 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);
  }
}
```

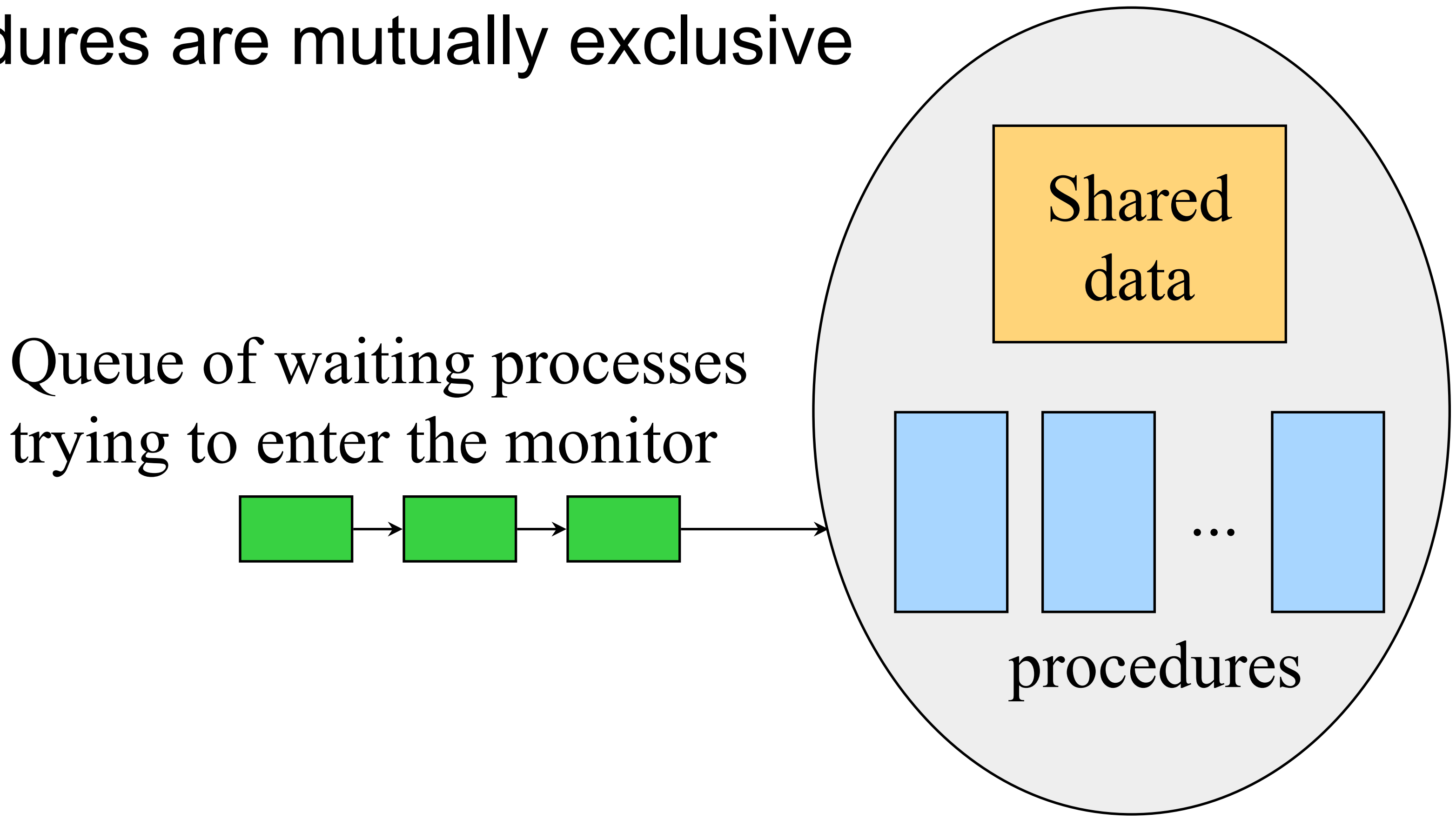
```
consumer() {
  while (1) {
    P(fullCount);

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

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

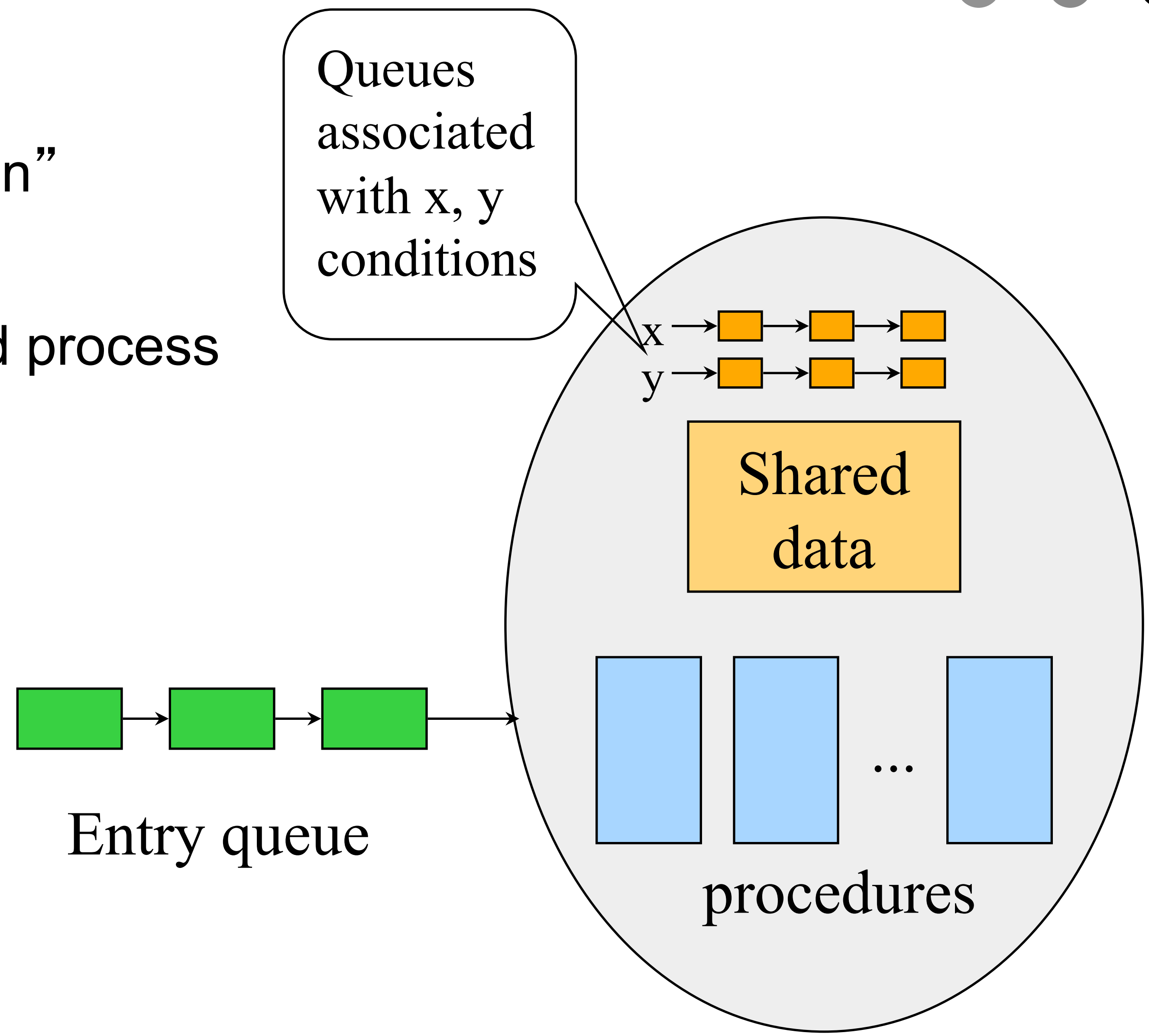
# Monitor: Hide Mutual Exclusion

- 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!

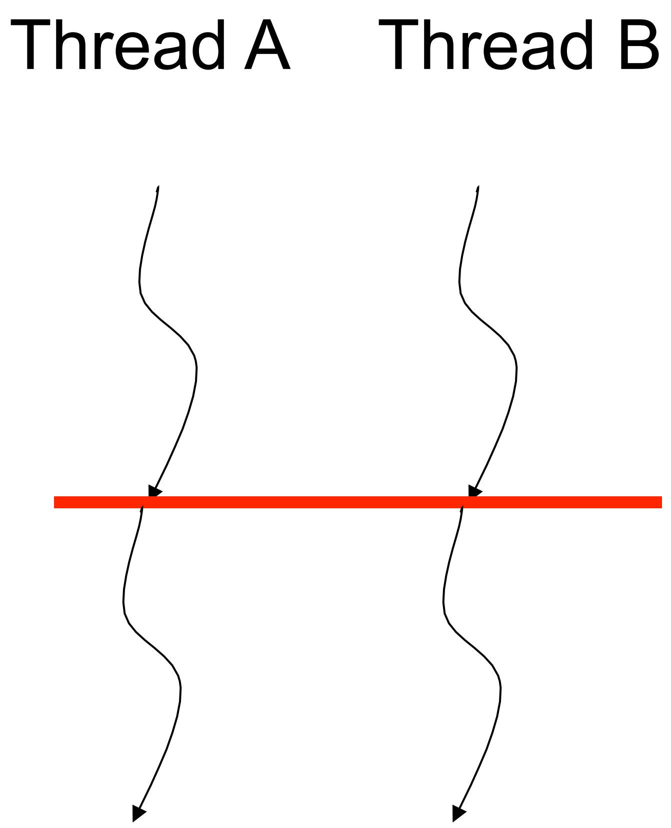
- Issues?

# 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

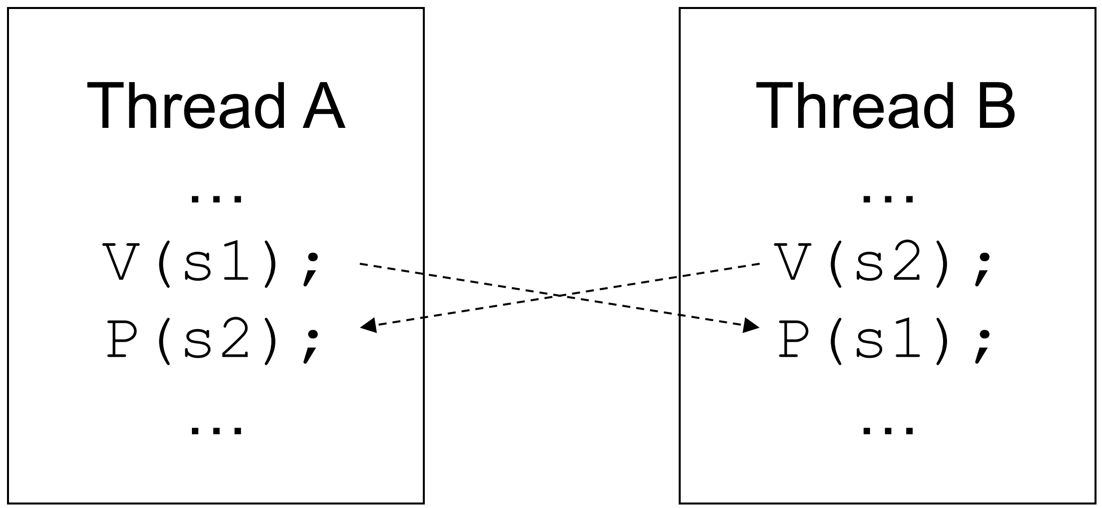
- Thread A and Thread B want to meet at a particular point
- The one toget there first waits for the other one to reach that point before proceeding
- Then both go forward



# Using Semaphores as A Barrier

- Use two semaphores?

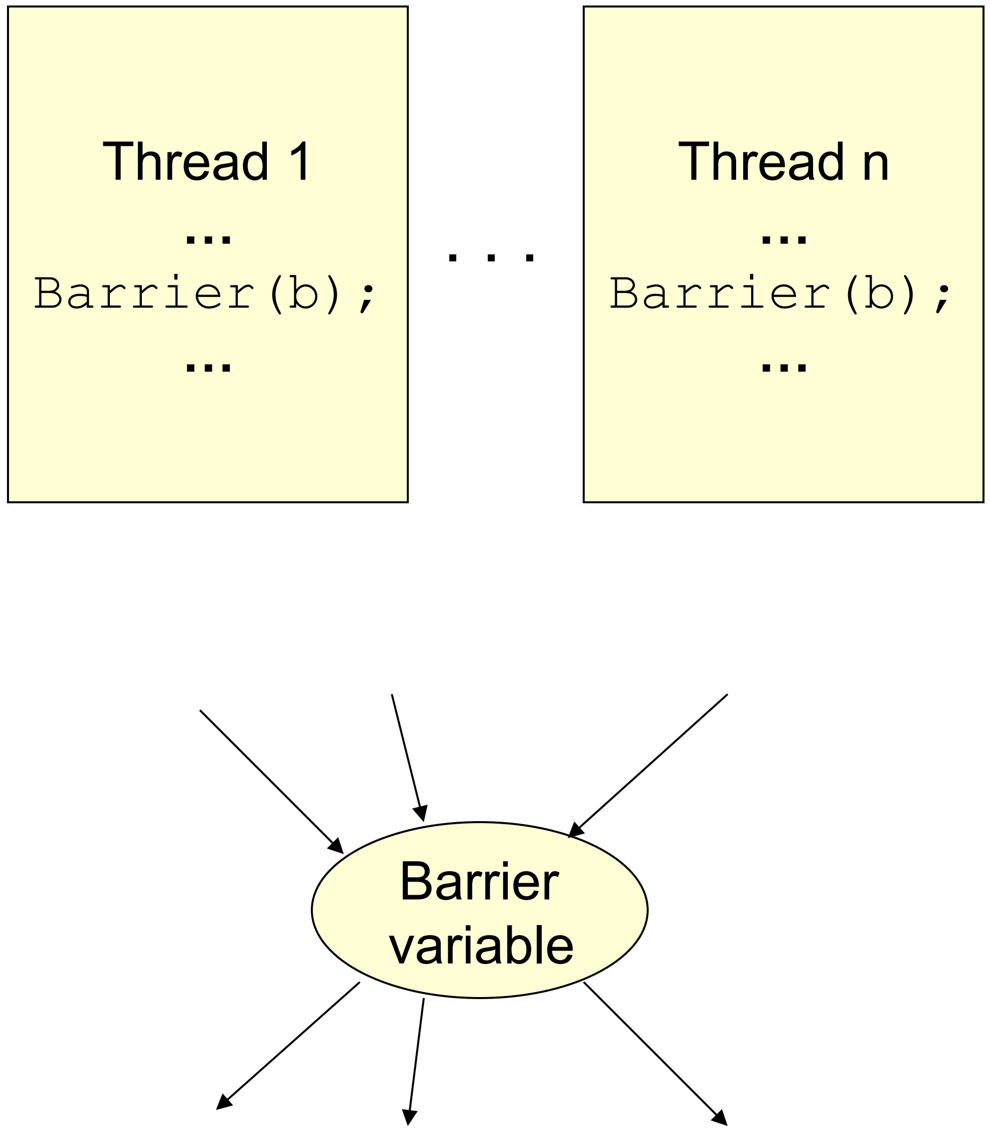
```
init(s1, 0);
init(s2, 0);
```




- 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
- Monitors
  - Good for scheduling and mutex
  - Maybe 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