Operating Systems

Semaphores, Condition Variables, and Monitors

Lecture 6
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Semaphore

- More sophisticated Synchronization mechanism
- Semaphore ***S*** – integer variable
- Can only be accessed via two indivisible (atomic) operations
  - **`wait()`** and **`signal()`**
    - Originally called **`P()`** and **`V()`**
- Definition

```
wait(S) {
     while (S <= 0)
         ; // busy wait
     S--;
}
```

- Definition

```
signal(S) {
     S++;
}
```

Do these operations *atomically*

Semaphore Usage

- **Counting semaphore** – integer value can range over an unrestricted domain
- **Binary semaphore** – integer value can range only between 0 and 1
  - Same as a **lock**
- Can solve various synchronization problems
- Consider P_1 and P_2 that require S_1 to happen before S_2

  Create a semaphore "`synch`" initialized to 0

```
P1:
    S1;
    signal(synch);
P2:
    wait(synch);
    S2;
```

- Can implement a counting semaphore S as a binary semaphore

Implementation with no Busy waiting

Each semaphore has an associated queue of threads

```
wait(semaphore *S) {
   S->value--;
   if (S->value < 0) {
      add this thread to S->list;
      block();
   }
}
signal(semaphore *S) {
   S->value++;
   if (S->value <= 0) {
      remove a thread T from S->list;
      wakeup(T);
   }
}
```

Binary semaphore usage

- From the programmer’s perspective, P and V on a binary semaphore are just like Acquire and Release on a lock

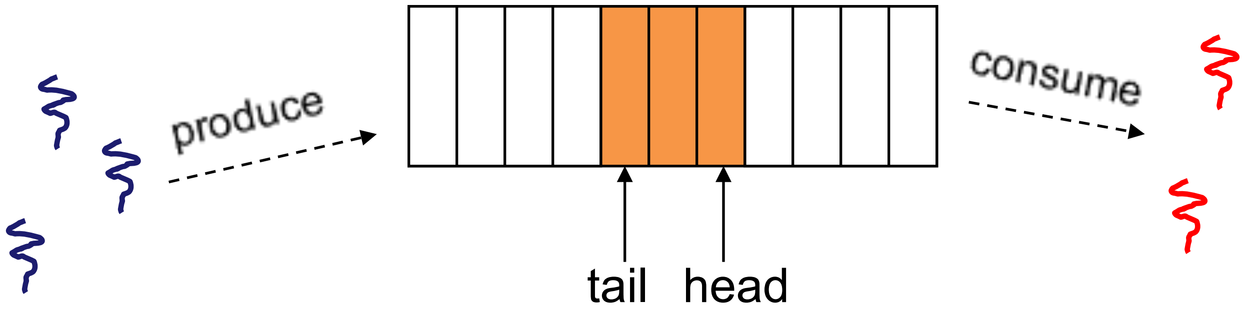
```
P(sem)
   .
   .
   .
   do whatever stuff requires mutual exclusion; could conceivably
   be a lot of code
   .
   .
   .
V(sem)
```

  - same lack of programming language support for correct usage

- Important differences in the underlying implementation, however
- No busy waiting

Example: Bounded buffer problem

- *AKA* "producer/consumer" problem
  - there is a circular buffer in memory with N entries (slots)
  - producer threads insert entries into it (one at a time)
  - consumer threads remove entries from it (one at a time)
- Threads are concurrent
  - so, we must use synchronization constructs to control access to shared variables describing buffer state



Bounded buffer using semaphores (both binary and counting)

```
var mutex: semaphore = 1        ; mutual exclusion to shared data
    empty: semaphore = n      ; count of empty slots (all empty to start)
    full: semaphore = 0       ; count of full slots (none full to start)
```

```
producer:
    P(empty)   ; block if no slots available
    P(mutex)   ; get access to pointers
      <add item to slot, adjust pointers>
    V(mutex)   ; done with pointers
    V(full)    ; note one more full slot
```

```
consumer:
    P(full)    ; wait until there’s a full slot
    P(mutex)   ; get access to pointers
      <remove item from slot, adjust pointers>
    V(mutex)   ; done with pointers
    V(empty)   ; note there’s an empty slot
      <use the item>
```

Example: Readers/Writers

- Description:
  - A single object is shared among several threads/processes
  - Sometimes a thread just reads the object
  - Sometimes a thread updates (writes) the object

  - **We can allow multiple readers at a time**
    - **Do not change state – no race condition**

  - **We can only allow one writer at a time**
    - Change state- race condition

Readers/Writers using semaphores

```
var mutex: semaphore = 1        ; controls access to readcount
      wrt: semaphore = 1    ; control entry for a writer or first reader
      readcount: integer = 0        ; number of active readers
```

```
writer:
        P(wrt)              ; any writers or readers?
                <perform write operation>
        V(wrt)              ; allow others
```

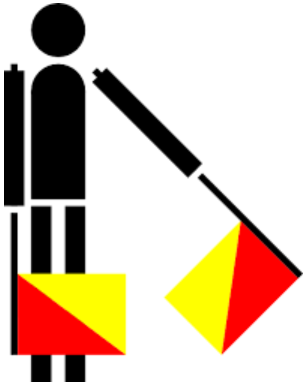
```
reader:
        P(mutex)                              ; ensure exclusion
            readcount++                       ; one more reader
            if readcount == 1 then P(wrt)       ; if we're the first, synch with writers
        V(mutex)
                <perform read operation>
        P(mutex)                              ; ensure exclusion
           readcount--                        ; one fewer reader
           if readcount == 0 then V(wrt)        ; no more readers, allow a writer
        V(mutex)
```

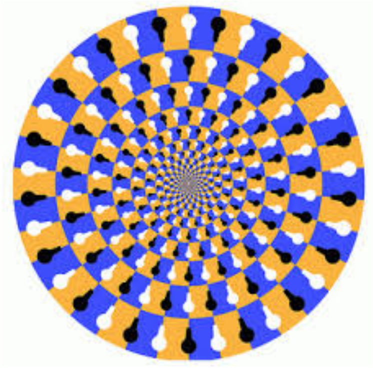
Readers/Writers notes

- Notes:
  - the first reader blocks on P(wrt) if there is a writer
    - any other readers will then block on P(mutex)
  - if a waiting writer exists, the last reader to exit signals the waiting writer
    - Can new readers get in while a writer is waiting?
  - When writer exits, if there is both a reader and writer waiting, which one goes next?

Semaphores vs. Spinlocks

- Threads that are blocked at the level of program logic (that is, by the semaphore P operation) are placed on queues, rather than busy-waiting
- Busy-waiting may be used for the "real" mutual exclusion required to implement P and V
  - but these are very short critical sections – totally independent of program logic
  - and they are not implemented by the application programmer

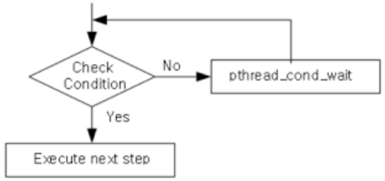




Abstract implementation

- P/wait(sem)
  - acquire "real" mutual exclusion
    - if sem is "available" (>0), decrement sem; release "real" mutual exclusion; let thread continue
    - otherwise, place thread on associated queue; release "real" mutual exclusion; run some other thread
- V/signal(sem)
  - acquire "real" mutual exclusion
    - if thread(s) are waiting on the associated queue, unblock one (place it on the ready queue)
    - if no threads are on the queue, sem is incremented
      - » the signal is "remembered" for next time P(sem) is called
  - release "real" mutual exclusion
  - the "V-ing" thread continues execution

Another approach: Condition Variables



- Basic operations
  - Wait()
    - Wait until some thread signal *and* release the associated lock, as an atomic operation
  - Signal()
    - If any threads are waiting, wake up one
    - Cannot proceed until lock re-acquired
- Signal() is not remembered
  - Signal to a condition variable that has no threads waiting is a no-op
- Qualitative use guideline
  - You wait() when you can’t proceed until some shared state changes
  - You signal() when shared state changes from “bad” to “good”

Bounded buffers with condition variables

```
var mutex: lock             ; mutual exclusion to shared data
     freeslot: condition           ; there's a free slot
     fullslot: condition           ; there's a full slot
```

```
producer:
      lock(mutex)      ; get access to pointers
      if [no slots available] wait(freeslot);
         <add item to slot, adjust pointers>
      signal(fullslot);
      unlock(mutex)
```

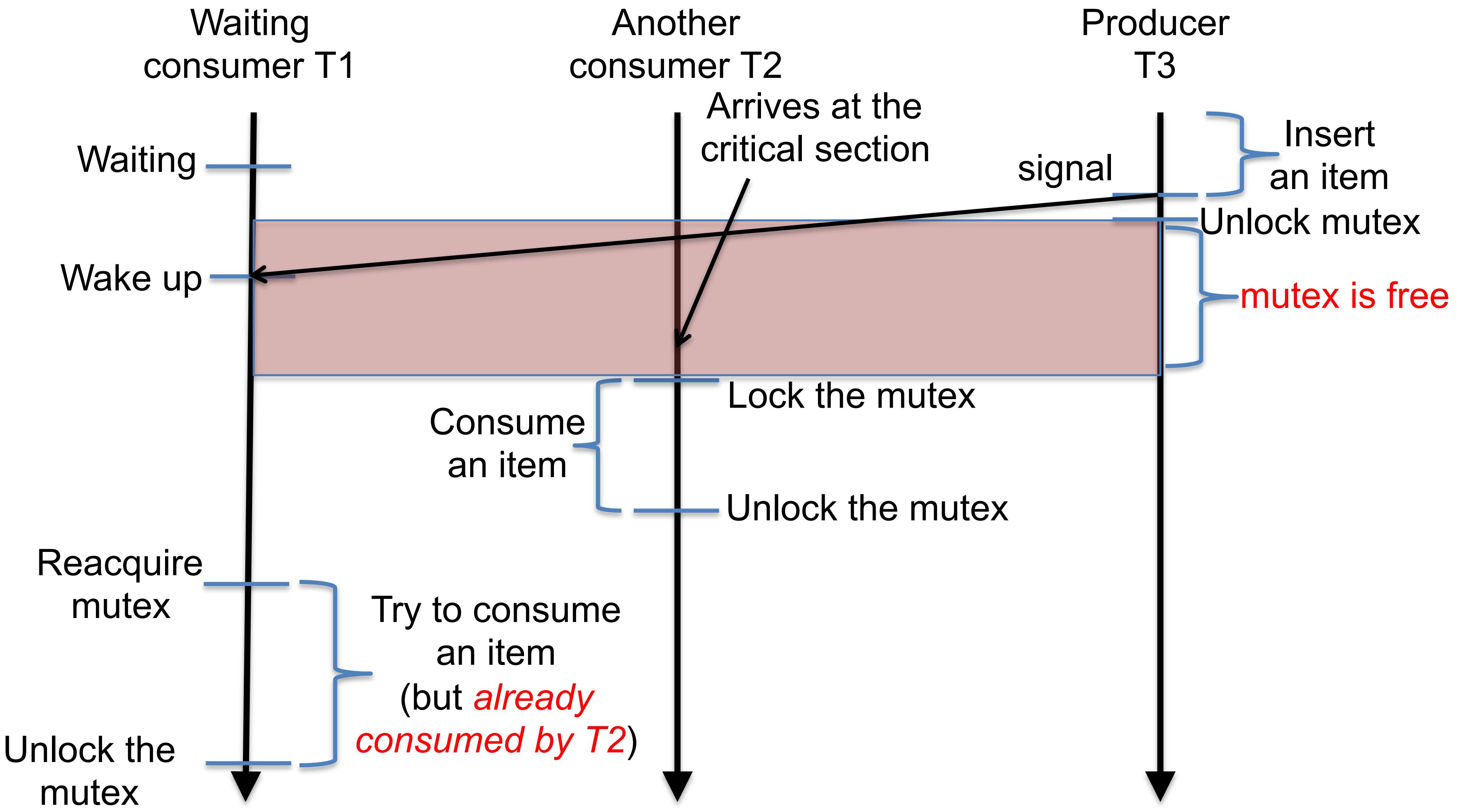
```
consumer:
      lock(mutex)      ; get access to pointers
      if [no slots have data] wait(fullslot);
         <remove item from slot, adjust pointers>
      signal(freeslot);
      unlock(mutex);
      <use the item>
```

The possible bug

- Depending on the implementation …
  - Between the time a thread is woken up by signal() and the time it re-acquires the lock, the condition it is waiting for may be false again
    - Waiting for a thread to put something in the buffer
    - A thread does, and signals
    - Now another thread comes along and consumes it
    - Then the "signalled" thread forges ahead …
- Solution
    - Not
      - if [no slots have data] wait(fullslot)
    - Instead
      - While [no slots have data] wait(fullslot)

The possible bug

Y-axis is time



Waiting consumer T1

Another consumer T2

Producer T3

Insert an item

signal

Unlock mutex

Waiting

Arrives at the critical section

Wake up

mutex is free

Lock the mutex

Consume an item

Unlock the mutex

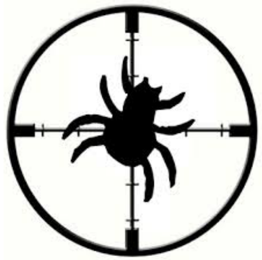
Reacquire mutex

Try to consume an item (but *already consumed by T2*)

Unlock the mutex

Problems with semaphores, locks, and condition variables

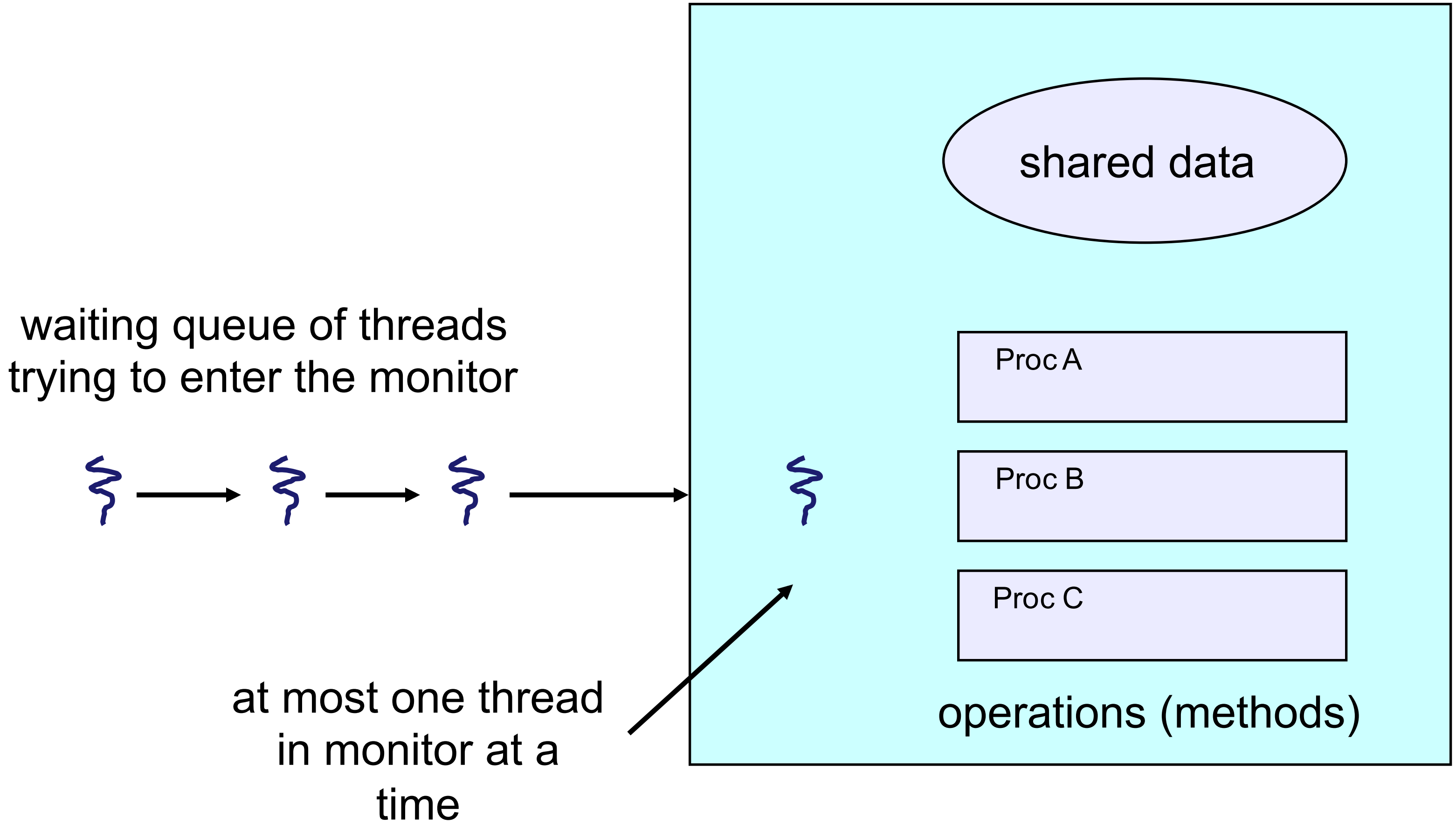
- They can be used to solve any of the traditional synchronization problems, but it’s easy to make mistakes
  - they are essentially shared global variables
    - can be accessed from anywhere (bad software engineering)
  - there is no connection between the synchronization variable and the data being controlled by it
  - No control over their use, no guarantee of proper usage
    - Condition variables: will there ever be a signal?
    - Semaphores: will there ever be a V()?
    - Locks: did you lock when necessary? Unlock at the right time? At all?
- Thus, they are prone to bugs
  - We can reduce the chance of bugs by “stylizing” the use of synchronization
  - Language help is useful for this



One More Approach: Monitors

- A <u>programming language construct</u> supports controlled shared data access
  - synchronization code is added by the compiler
- A class in which every method automatically acquires a lock on entry, and releases it on exit – it combines:
  - shared data structures (object)
  - procedures that operate on the shared data (object metnods)
  - synchronization between concurrent threads that invoke those procedures
- Data can only be accessed from within the
  - protects the data from unstructured access
  - Prevents ambiguity about what the synchronization variable protects
- Addresses the key usability issues that arise with semaphores

A monitor



waiting queue of threads
trying to enter the monitor

shared data

Proc A

Proc B

Proc C

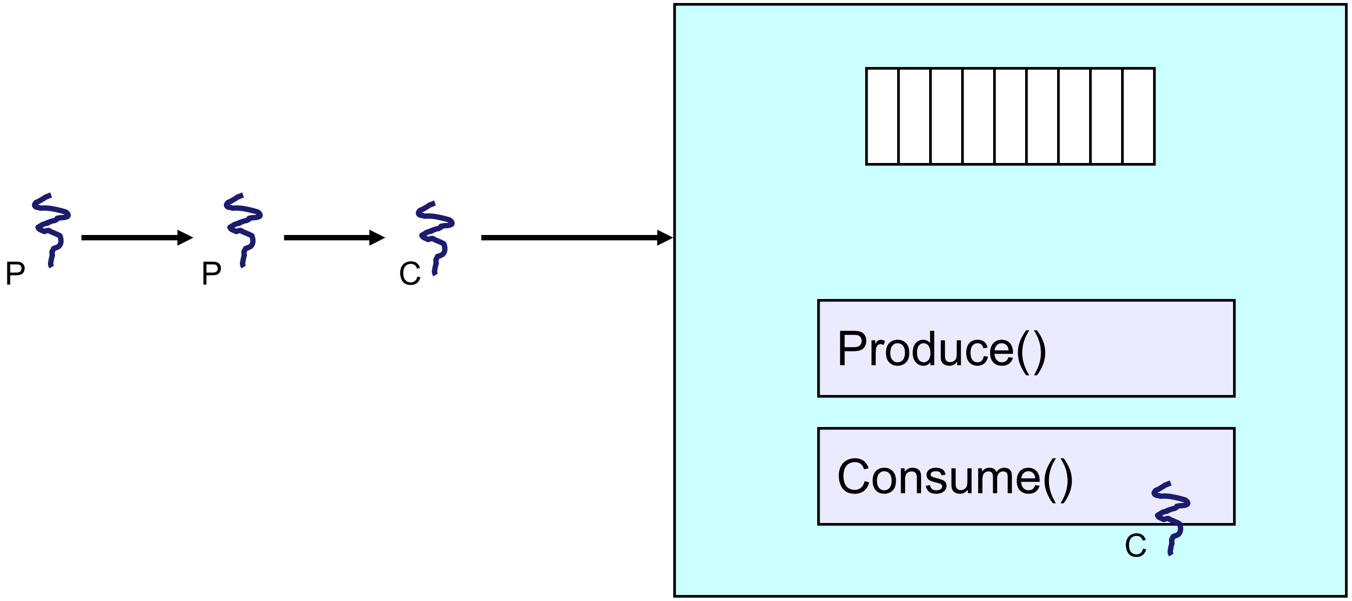
operations (methods)

at most one thread
in monitor at a
time

Monitor facilities

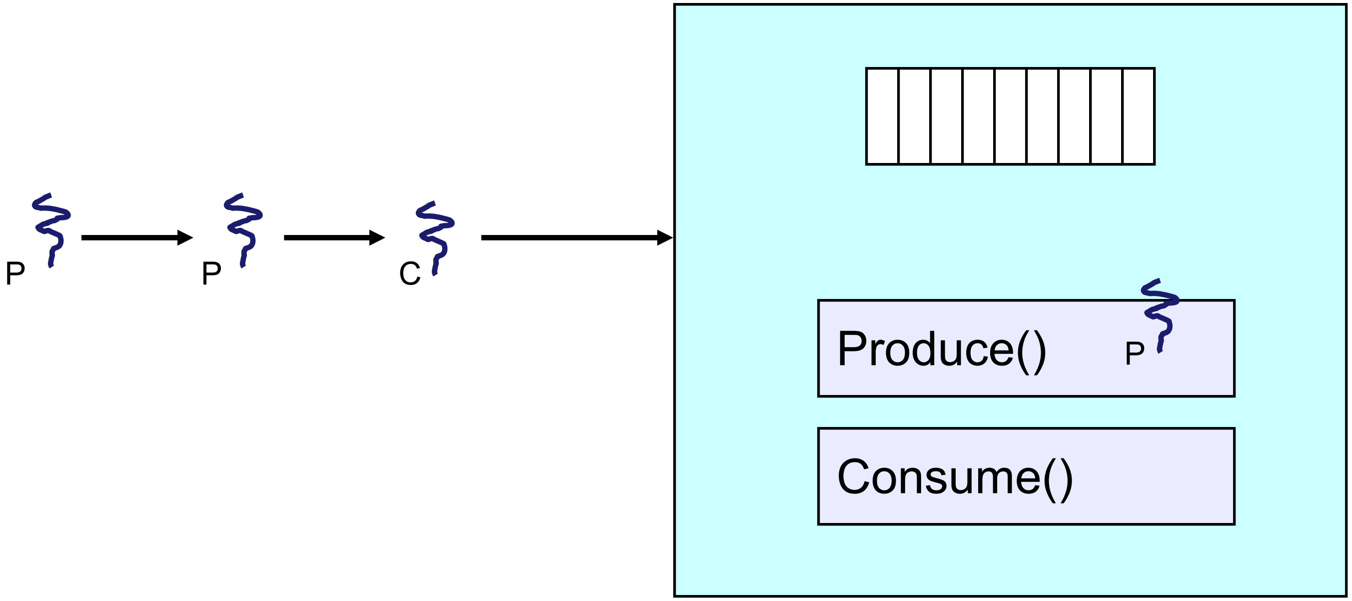
- "Automatic" mutual exclusion
  - only one thread can be executing inside at any time
    - thus, synchronization is implicitly associated with the monitor – it "comes for free"
  - if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
    - more restrictive than semaphores
    - but easier to use (most of the time)
- But, there's a problem…

Problem: Bounded Buffer Scenario



- Buffer is empty
- Now what?

Problem: Bounded Buffer Scenario



- Buffer is full
- Now what?

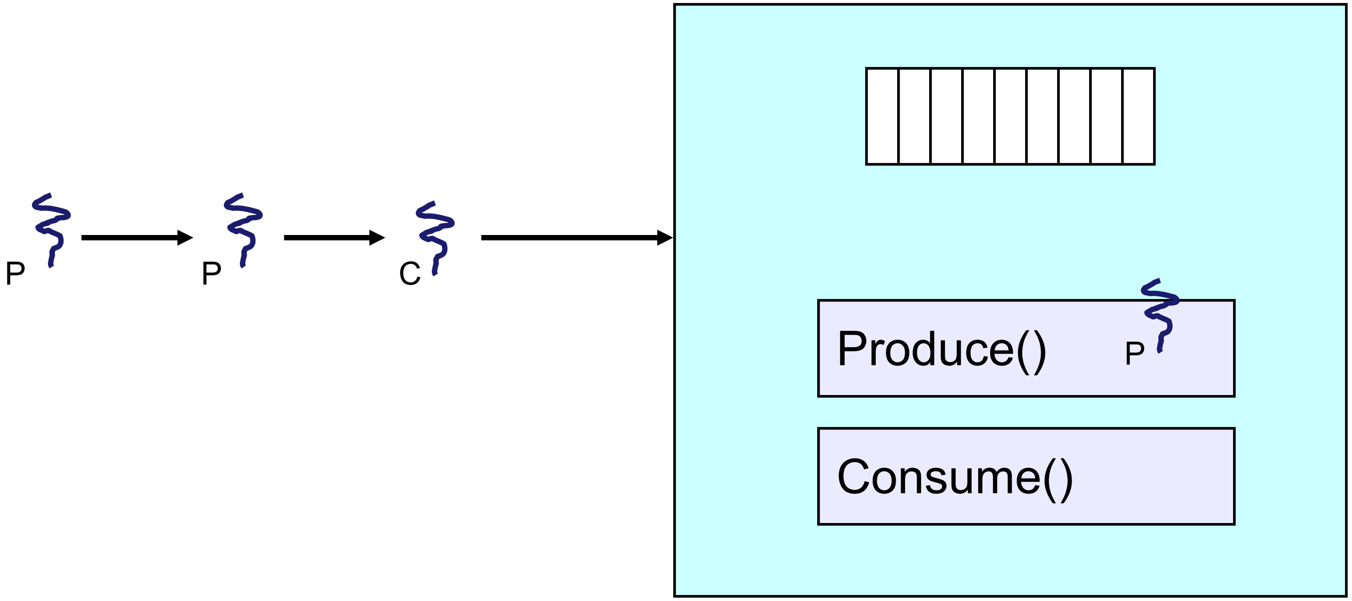
Solution?

- Monitors require condition variables
- Operations on condition variables (just as before!)
  - wait(c)
    - release monitor lock, so somebody else can get in
    - wait for somebody else to signal condition
    - thus, condition variables have associated wait queues
  - signal(c)
    - wake up at most one waiting thread
      - "Hoare" monitor: wakeup immediately, signaller steps outside
    - if no waiting threads, signal is lost
      - this is different than semaphores: no history!
  - broadcast(c)
    - wake up all waiting threads

Bounded buffer using (Hoare) monitors

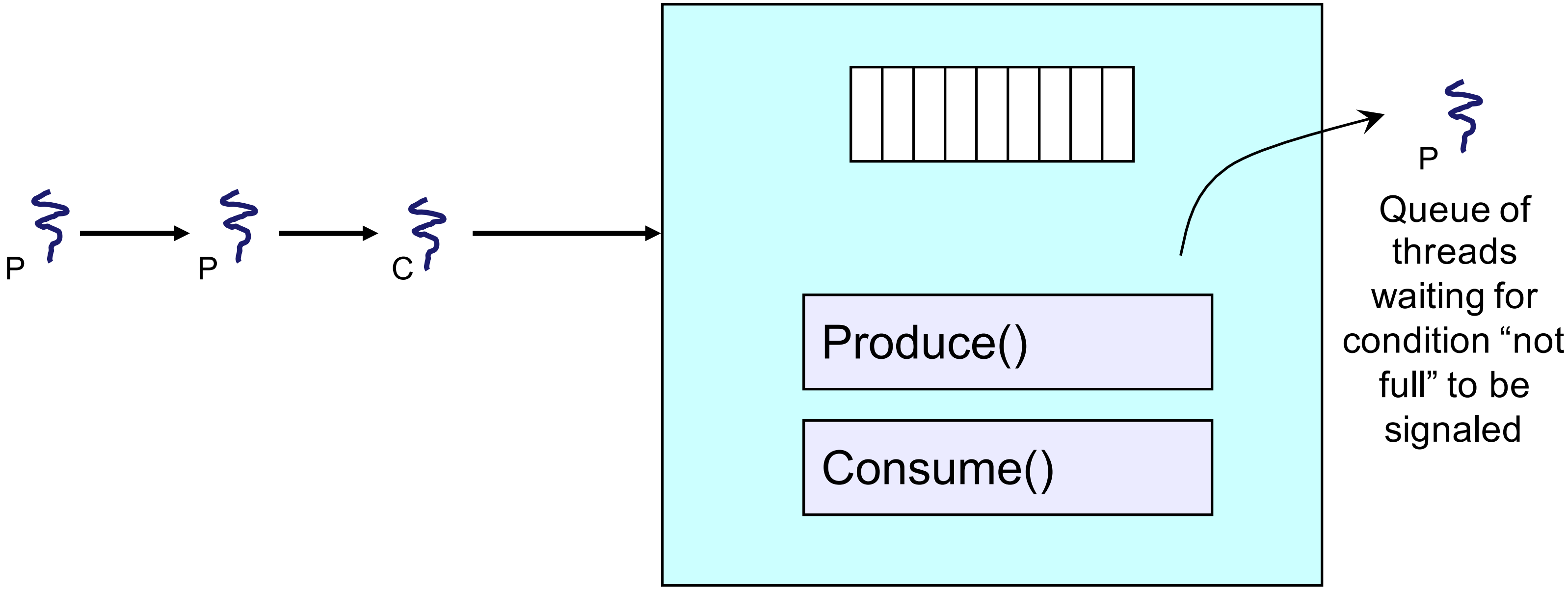
```
Monitor bounded_buffer {
  buffer resources[N];
  condition  not_full, not_empty;

produce(resource x) {
    if (array “resources” is full, determined maybe by a count)
          wait(not_full);
    insert “x” in array “resources”
    signal(not_empty);
  }

 consume(resource *x) {
    if (array “resources” is empty, determined maybe by a count)
           wait(not_empty);
    *x = get resource from array “resources”
    signal(not_full);
  }
}
```

Problem: Bounded Buffer Scenario



- Buffer is full
- Now what?

Bounded Buffer Scenario with CV's



Produce()

Consume()

Queue of threads waiting for condition "not full" to be signaled

- Buffer is full
- Now what?

Runtime system calls for (Hoare) monitors

- EnterMonitor(m) {guarantee mutual exclusion}
- ExitMonitor(m) {hit the road, letting someone else run}
- Wait(c) {step out until condition satisfied}
- Signal(c) {if someone’s waiting, step out and let him run}

- EnterMonitor and ExitMonitor are inserted automatically by the compiler.
- This guarantees mutual exclusion for code inside of the monitor.

Bounded buffer using (Hoare) monitors

```
Monitor bounded_buffer {
 buffer resources[N];
 condition not_full, not_empty;

 procedure add_entry(resource x) {                              EnterMonitor(m)
   if (array "resources" is full, determined maybe by a count)
     wait(not_full);
   insert "x" in array "resources"
   signal(not_empty);                                           ExitMonitor(m)
 }
 procedure get_entry(resource *x) {                             EnterMonitor(m)
   if (array "resources" is empty, determined maybe by a count)
     wait(not_empty);
   *x = get resource from array "resources"
   signal(not_full);                                            ExitMonitor(m)
 }
```

Monitor Summary

- Language supports monitors
- Compiler understands them
  - Compiler inserts calls to runtime routines for
    - monitor entry
    - monitor exit
  - Programmer inserts calls to runtime routines for
    - signal
    - wait
  - Language/object encapsulation ensures correctness
    - Sometimes! With conditions, you *still* need to think about synchronization
- Runtime system implements these routines
  - moves threads on and off queues
  - *ensures mutual exclusion!*