CSE 451: Operating Systems
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Module 8
Semaphores, Condition Variables, and Monitors

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Semaphores

- Semaphore = a synchronization primitive
  - higher level of abstraction than locks
  - invented by Dijkstra in 1968, as part of the THE operating system
- A semaphore is:
  - a variable that is manipulated through two operations, P and V (Dutch for "wait" and "signal")
    - **P(sem)** (wait)
      - block until sem > 0, then subtract 1 from sem and proceed
    - **V(sem)** (signal)
      - add 1 to sem
- Do these operations *atomically*

Blocking in semaphores

- Each semaphore has an associated queue of threads
  - when P (sem) is called by a thread,
    - if sem was “available” (>0), decrement sem and let thread continue
    - if sem was “unavailable” (0), place thread on associated queue; run some other thread
  - when V (sem) is called by a thread
    - if thread(s) are waiting on the associated queue, unblock one
      - place it on the ready queue
      - might as well let the “V-ing” thread continue execution
    - otherwise (when no threads are waiting on the sem), increment sem
      - the signal is “remembered” for next time P(sem) is called

Two types of semaphores

- Binary semaphore (aka mutex semaphore)
  - sem is initialized to 1
  - guarantees mutually exclusive access to resource (e.g., a critical section of code)
  - only one thread/process allowed entry at a time
  - Logically equivalent to a lock with blocking rather than spinning
- Counting semaphore
  - Allow up to N threads continue (we'll see why in a bit …)
  - sem is initialized to N
    - N = number of units available
  - represents resources with many (identical) units available
  - allows threads to enter as long as more units are available

Binary semaphore usage

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

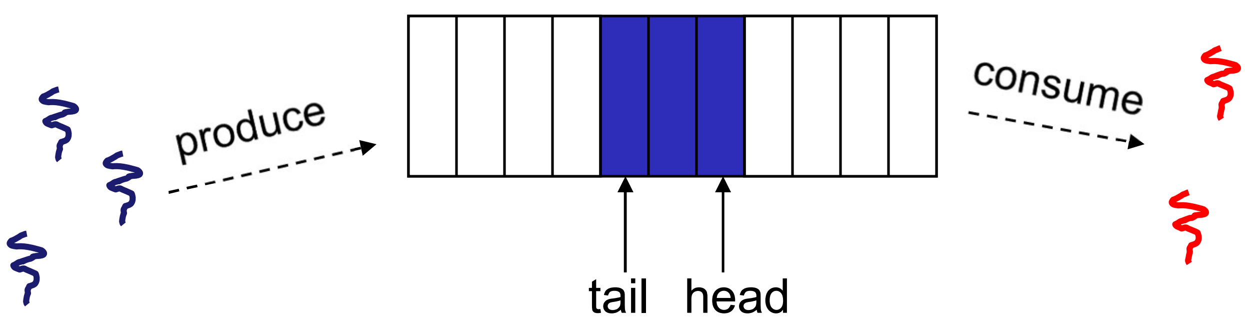
```
P(sem)
    .
    .
    .
    do whatever stuff requires mutual exclusion; could conceivably
    be a lot of code
    .
    .
    .
V(sem)
```

  - same lack of programming language support for correct usage

- Important differences in the underlying implementation, however

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>
```

Note:
I have elided all the code concerning which is the first full slot, which is the last full slot, etc.

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**
    - why?
  - **We can only allow one writer at a time**
    - why?

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?
    - so?
  - 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, or may be preempted]

Pressing questions

- How do you acquire “real” mutual exclusion?
- Why is this any better than using a spinlock (test-and-set) or disabling interrupts (assuming you’re in the kernel) in lieu of a semaphore?
- What if someone issues an extra V?
- What if someone forgets to P before manipulating shared state?

Quick roadmap

- The synchronization landscape using locks
- The academic “textbook” view of the world
  - Spinlocks – rudimentary
  - Semphores – add yielding on top of spinlocks
  - Condition Variables – similar to Semaphores but without history
  - Monitors - add programing structure to make using locks less error prone
- Locks that we actually used in Windows. That’s another story

Condition Variables

- Basic operations
  - Wait()
    - Wait until some thread does a 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
  - A 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>
```

Note 1:
Do you see why wait() must release the associated lock?

Note 2:
How is the associated lock re-acquired?

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 available] wait(fullslot)
    - Instead
      - While [no slots available] wait(fullslot)
  - Could the scheduler also solve this problem?

Bounded buffers comparison

Condition Variable

```
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)
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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>
```

Semaphores

```
var mutex: semaphore = 1       ; mutual exclusion to shared data
    empty: semaphore = n       ; count of empty slots (all empty to start)
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```

```
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>
```

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

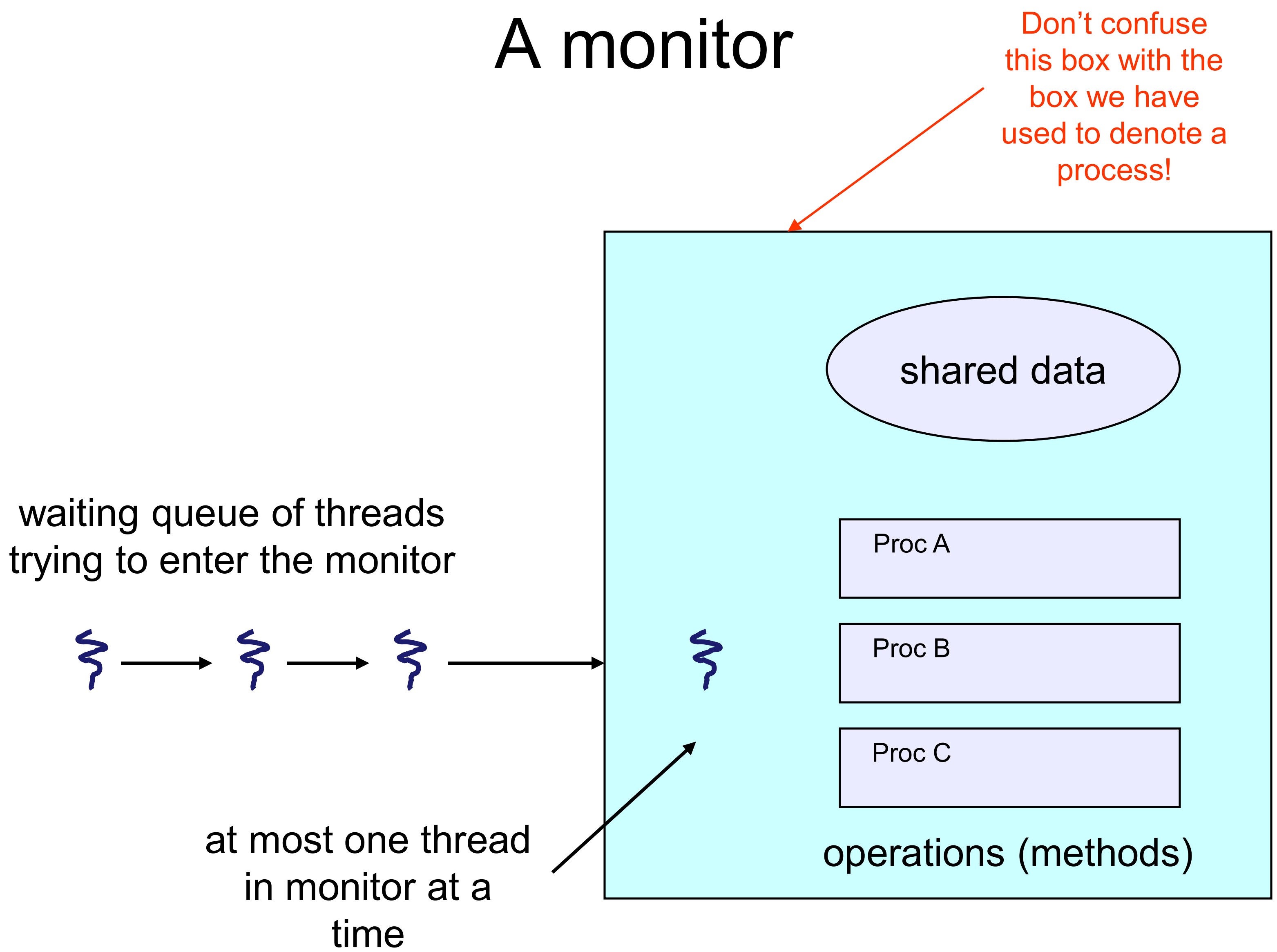
- A *monitor* is a programming language construct that supports controlled access to shared data
  - synchronization code is added by the compiler
    - why does this help?

- A monitor is (essentially) 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 monitor, using the provided procedures
  - protects the data from unstructured access
  - Prevents ambiguity about what the synchronization variable protects

- Addresses the key usability issues that arise with semaphores

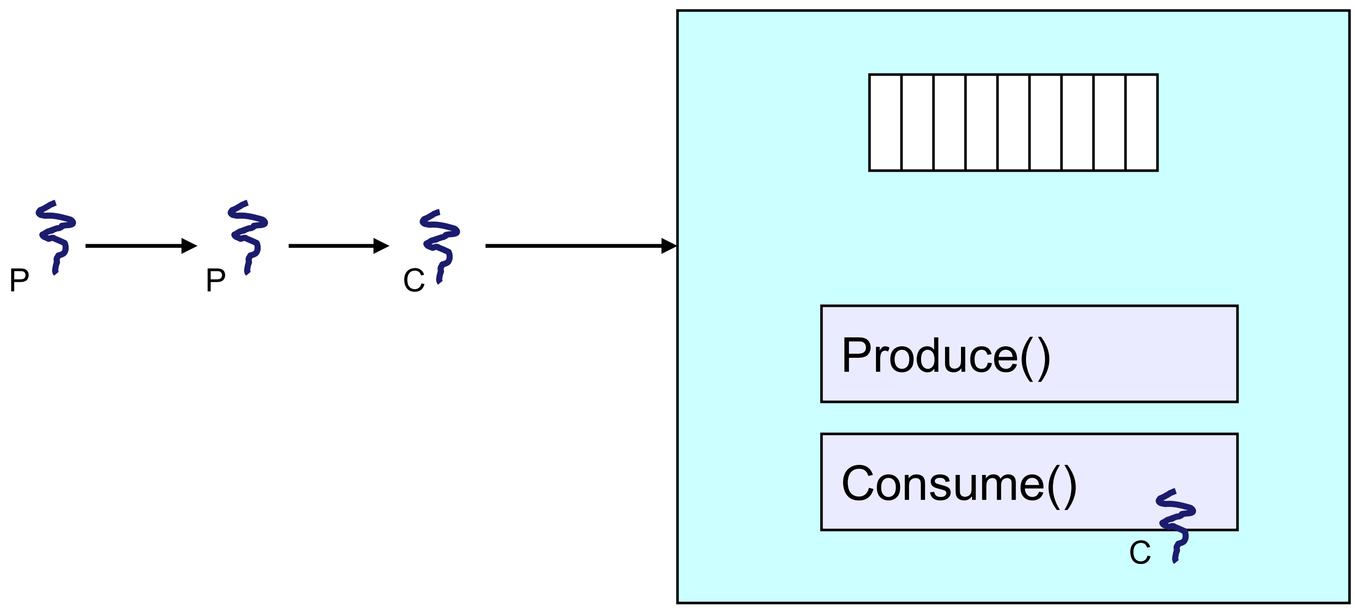
A monitor


Don't confuse this box with the box we have used to denote a process!
shared data
Proc A
Proc B
Proc C
operations (methods)
waiting queue of threads trying to enter the monitor
at most one thread in monitor at a time

Monitor facilities

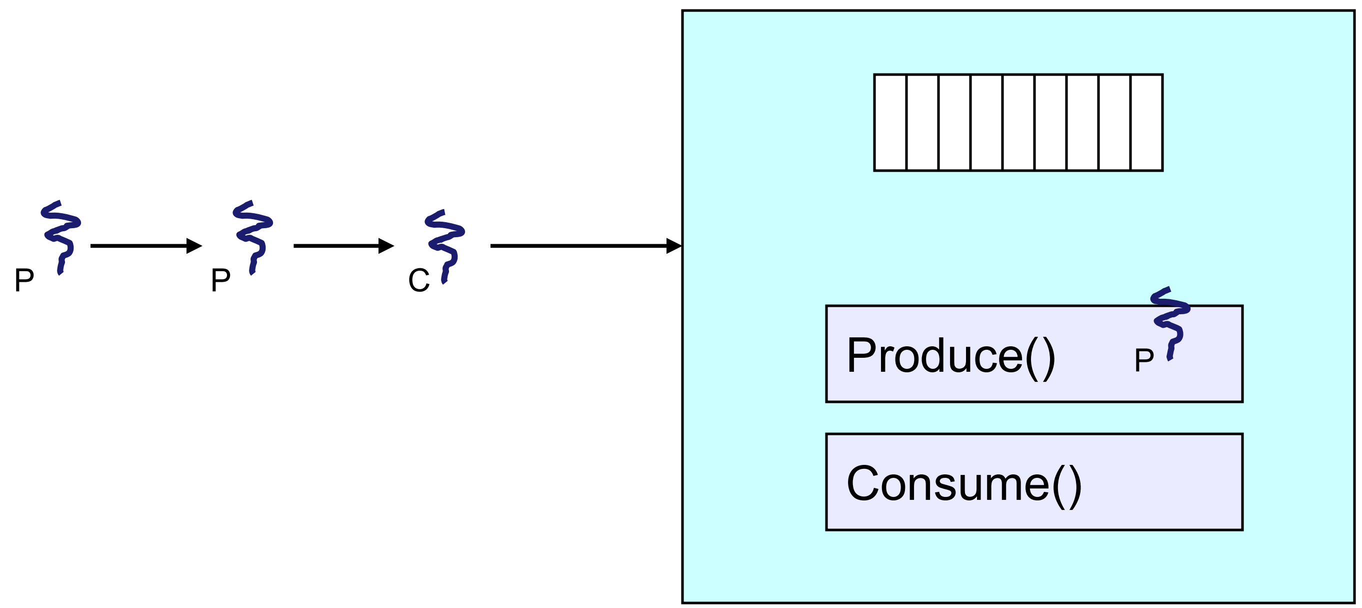
- “Automatic” mutual exclusion
  - only one thread can be executing inside at any time
    - thus, synchronization is implicitly associated with the monitor – it “comes for free”
  - if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
    - more restrictive 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?

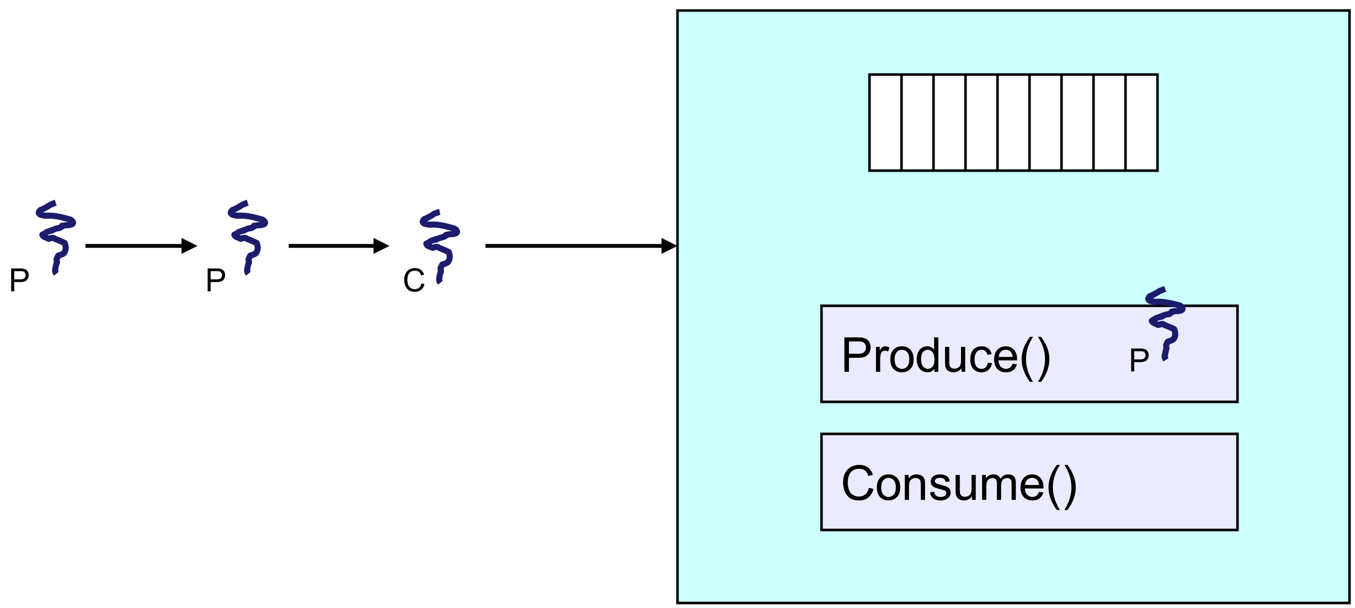
Solution?

- 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

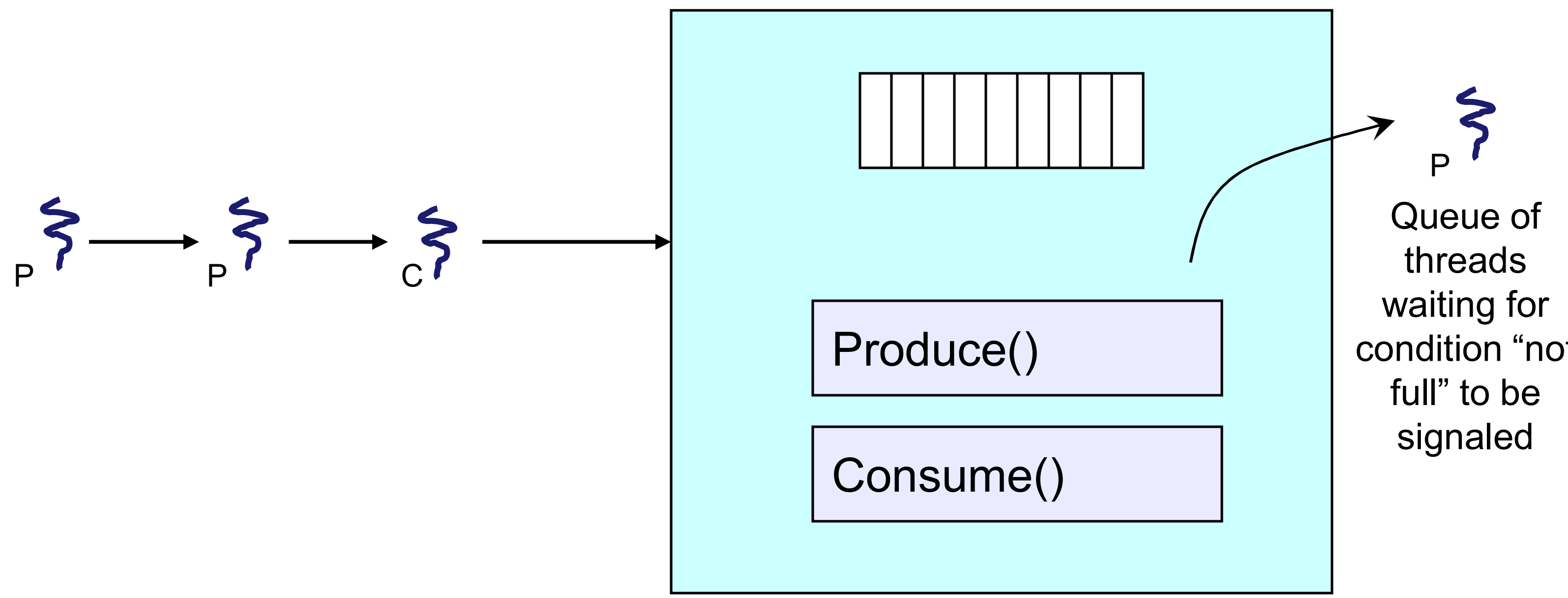
```
Monitor bounded_buffer {
  buffer resources[N];
  condition not_full, not_empty;

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



- 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 them 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)
 }
```

There is a subtle issue with that code…

- Who runs when the signal() is done and there is a thread waiting on the condition variable?

- **Hoare monitors**: signal(c) means
  - run waiter immediately
  - signaller blocks immediately
    - condition guaranteed to hold when waiter runs
    - but, signaller must restore monitor invariants before signalling!
      - cannot leave a mess for the waiter, who will run immediately!

- **Mesa monitors**: signal(c) means
  - waiter is made ready, but the signaller continues
    - waiter runs when signaller leaves monitor (or waits)
  - signaller need not restore invariant until it leaves the monitor
  - being woken up is only a hint that something has changed
    - signalled condition may no longer hold
    - must recheck conditional case

Hoare vs. Mesa Monitors

- Hoare monitors: `if (notReady) wait(c)`
- Mesa monitors: `while (notReady) wait(c)`
- Mesa monitors easier to use
  - more efficient
  - fewer context switches
  - directly supports broadcast
- Hoare monitors leave less to chance
  - when wake up, condition guaranteed to be what you expect

Runtime system calls for Hoare monitors

- EnterMonitor(m) {guarantee mutual exclusion}
  - if m occupied, insert caller into queue m
  - else mark as occupied, insert caller into ready queue
  - choose somebody to run
- ExitMonitor(m) {hit the road, letting someone else run}
  - if queue m is empty, then mark m as unoccupied
  - else move a thread from queue m to the ready queue
  - insert caller in ready queue
  - choose someone to run

- Wait(c) {step out until condition satisfied}
  - if queue m is empty, then mark m as unoccupied
  - else move a thread from queue m to the ready queue
  - put the caller on queue c
  - choose someone to run
- Signal(c) {if someone's waiting, step out and let him run}
  - if queue c is empty then put the caller on the ready queue
  - else move a thread from queue c to the ready queue, and put the caller into queue m
  - choose someone to run

Runtime system calls for Mesa 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, give them a shot after I'm done}
  - if queue c is occupied, move one thread from queue c to queue m
  - return to caller

- Broadcast(c) {food fight!}
  - move all threads on queue c onto queue m
  - return to caller

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!*

Basic Lock tools

- Spinlocks
- Semaphores (aka: sleep locks, mutex)
  - Binary and Counting
- Condition Variables (Monitors)
  - Hoare and Mesa

Other approaches

We can optimize locks even further when there is significant lock contention

- MCS Locks
- RCU Locks

We can enrich the lock semantics

- Reader/Writer (Shared/Exclusive) Locks

What are we really locking?

- Code Centric locks. Classic critical sections where only one thread is allowed to execute a section of code at a time.

- Data Centric locks. The data is really locked meaning only one thread can one own the data at one time. So multiple threads can be executing the same code but on different data sets.

- The advantages of one over the other.

- Orthogonal to this how much to lock. One big lock or many little locks.