# **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

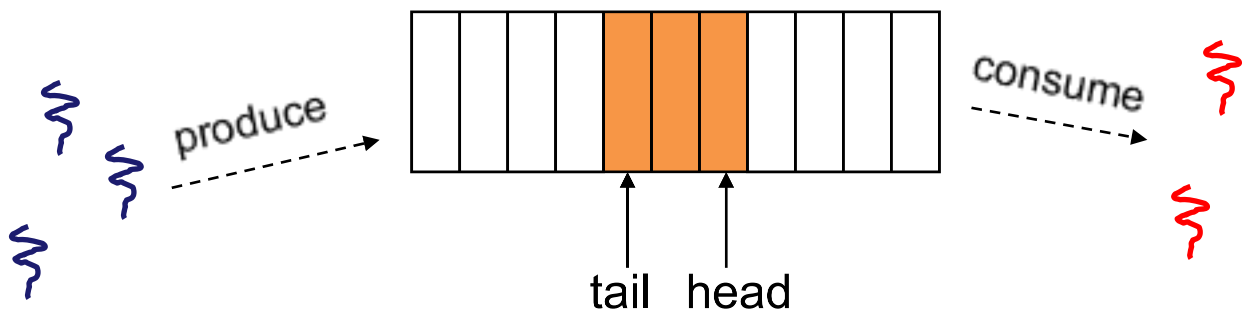
```
P(sem)
    .
    .
    .
    do whatever stuff requires mutual exclusion; could conceivably
    be a lot of code
    .
    .
    .
V(sem)
```

  – 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
```

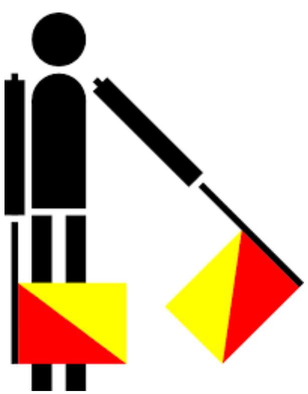
```
reader:
    P(mutex)                        ; ensure exclusion
      readcount++                   ; one more reader
      if readcount == 1 then P(wrt)     ; if we're the first, synch with writers
    V(mutex)
        <perform read operation>
    P(mutex)                        ; ensure exclusion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

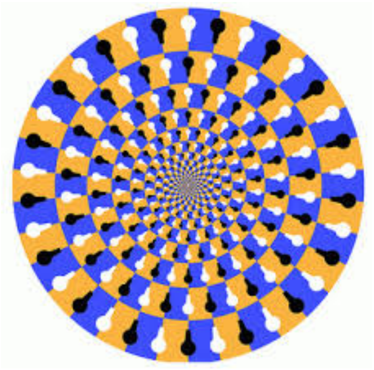
# Readers/Writers notes

- 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
    - A new reader cannot 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

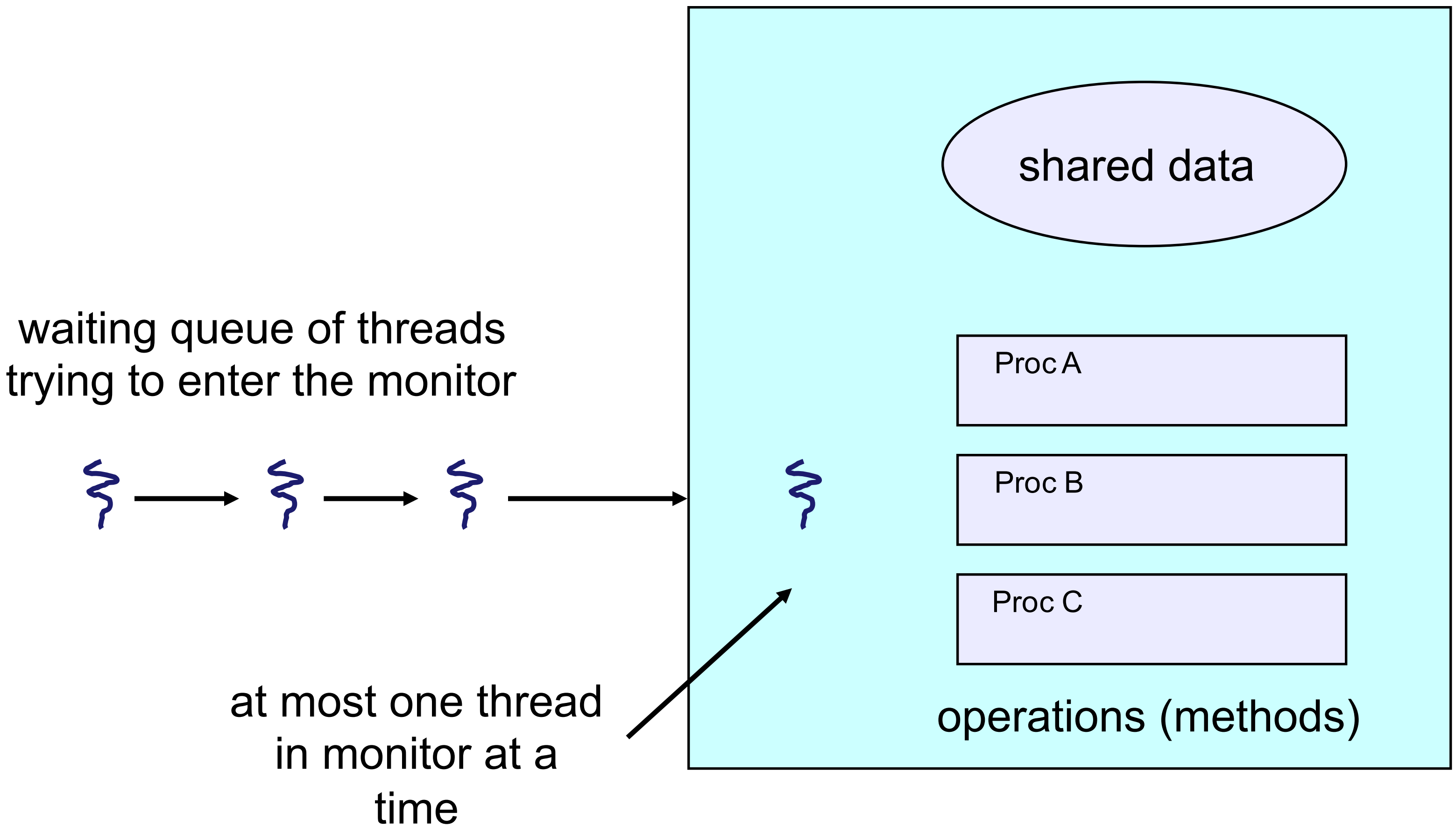
# Problems with semaphores, locks

- 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
    - 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 programming language construct 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

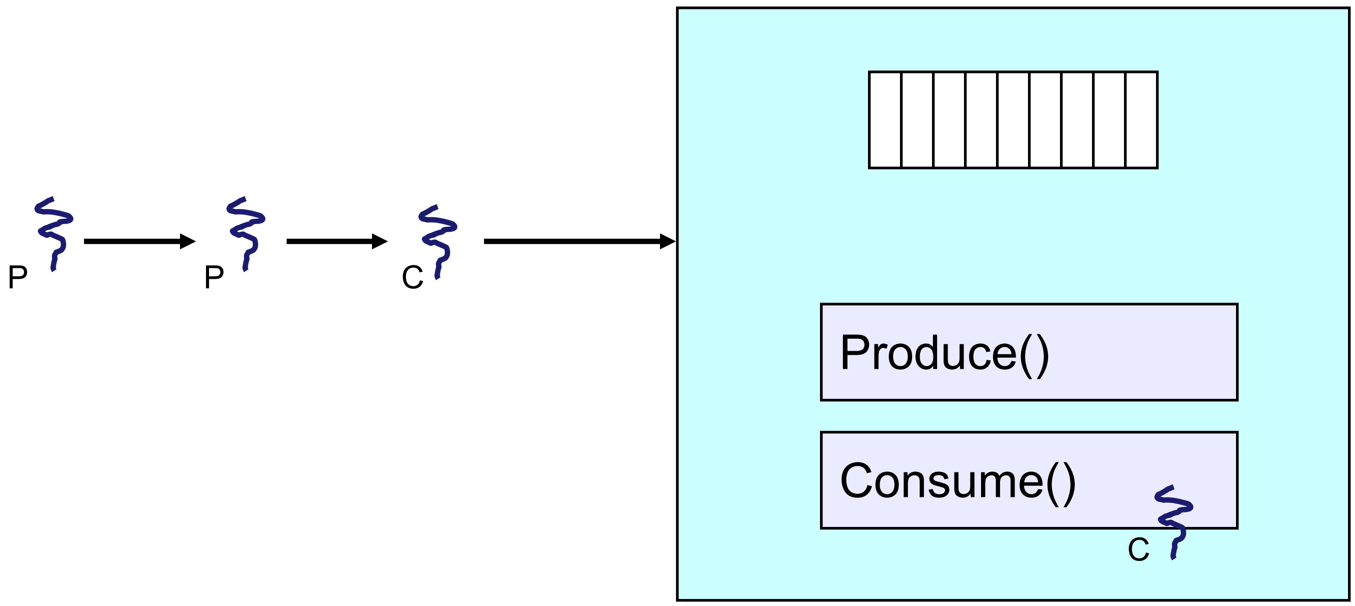
# A monitor


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

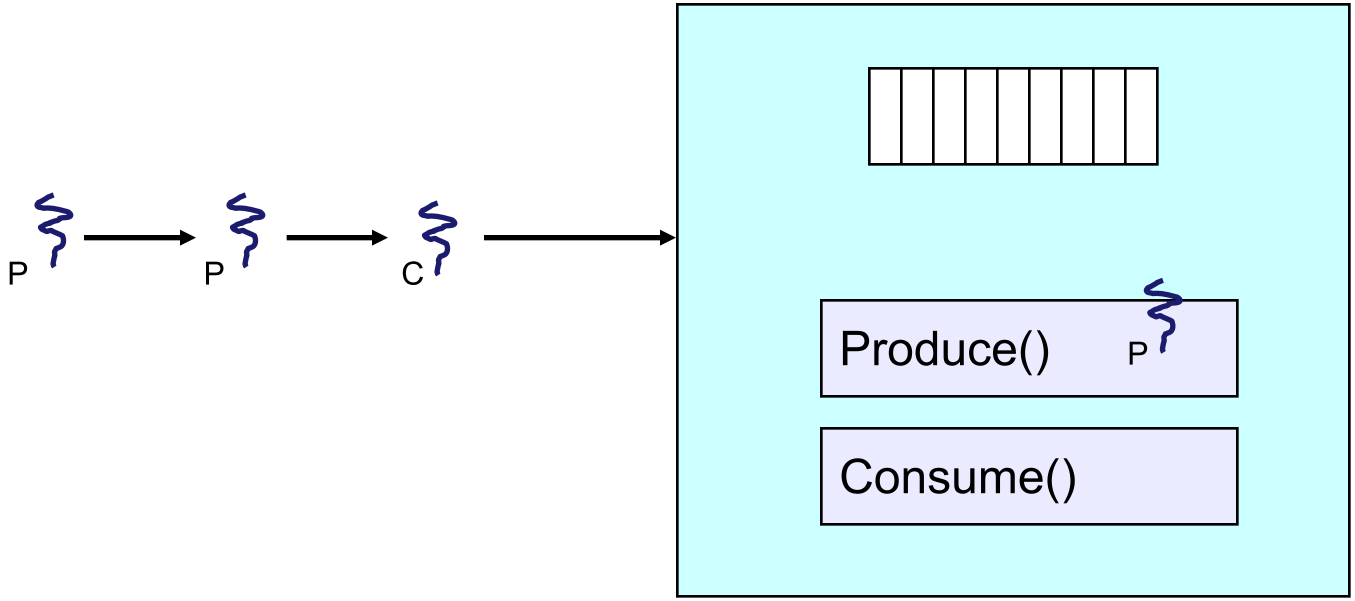
- “Automatic” mutual exclusion
  - only one thread can be executing inside at any time
    - thus, synchronization is implicitly associated with the monitor – it “comes for free”
  - if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
    - more restrictive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

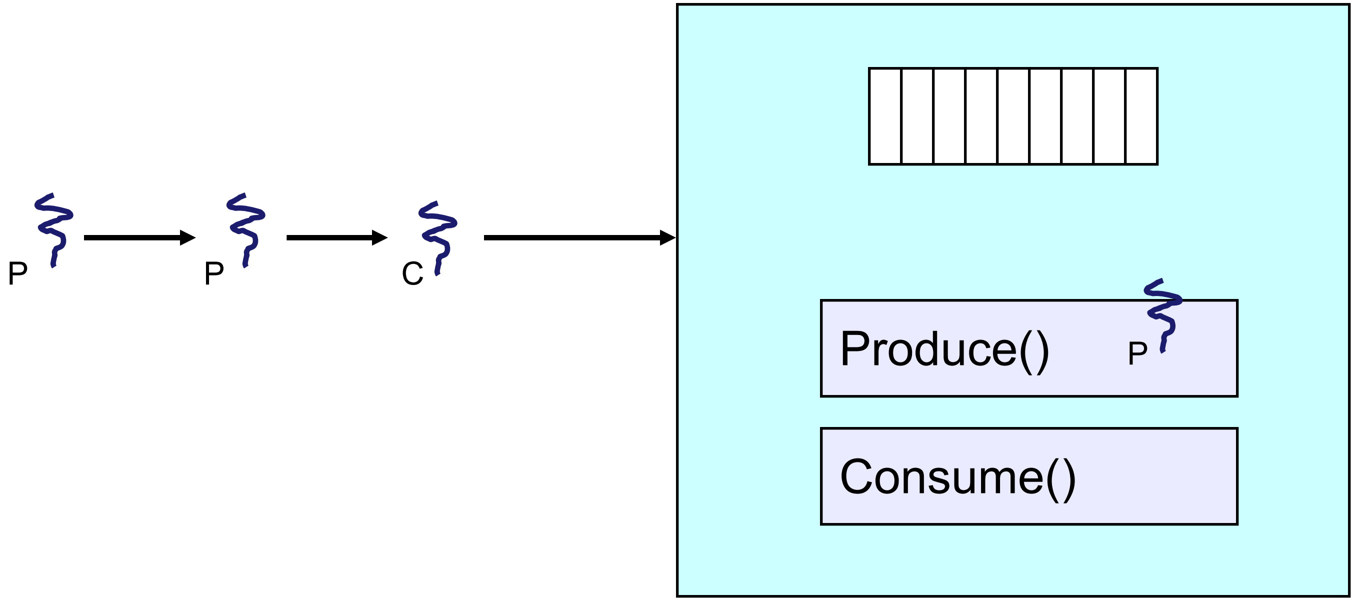
# Solution?

- Monitors require condition variables
- Operations on condition variables
  - 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

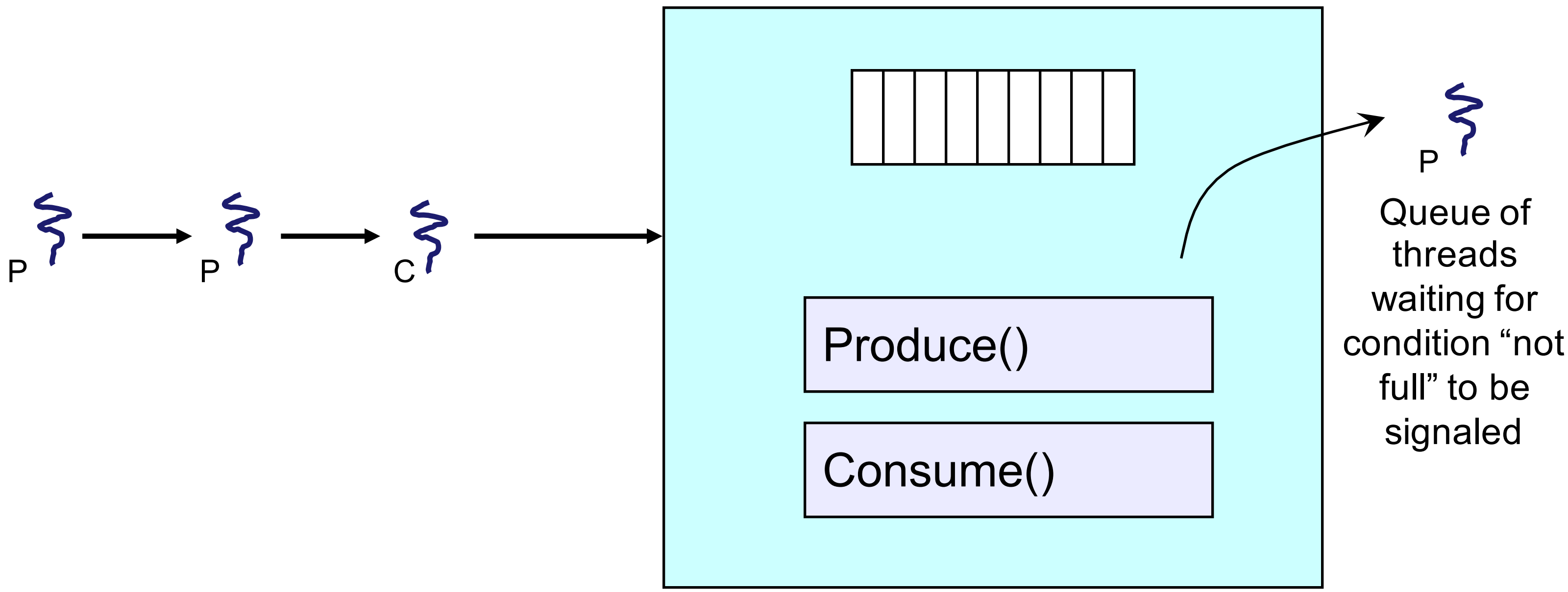
```
Monitor bounded_buffer {
  buffer resources[N];
  condition not_full, not_empty;

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 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!*