THE UNIVERSITY of EDINBURGH
informatics

Operating Systems (INFR10079)

2023/2024 Semester 2

Semaphores and Monitors

abarbala@inf.ed.ac.uk

Chapter 6 (6.6 – 6.7)

What About Busy Waiting Solutions?

- Disadvantages
  - Waste CPU time waiting
  - High priority jobs may hinder progress of low priority jobs (scheduling)
  - Protect a single resource

```
while (TRUE) {
  enter_region:
    TAS REGISTER,LOCK_ADDR
    CMP REGISTER,#0
    JNE enter_region
  critical_region(); /* work */
  leave_region:
    MOV LOCK_ADDR,#0
  noncritical_region();
}
```

Process A and Process B

a) Process A enters its critical region
b) Process A descheduled, Process B scheduled (high priority)
c) Process B busy waits for the critical region (depends on A)
d) Process B will busy wait until Process A is scheduled back
e) A is scheduled back and exits its critical section

sleep() and wakeup()

- Instead of busy wait, let the process sleep
- Introduce new **Operating System** functions
- `sleep()`
  - Caller gives up the CPU for some duration of time
  - Until a thread/process wakes it up
- `wakeup()`
  - Caller wakes up some sleeping thread/process

- In practice
  - To `sleep()` a thread/process may call `yield()` syscall
  - A thread/process may be woken with a signal
  - Each has also a kernel-level implementation

Semaphore

- E.W. Dijkstra, 1965
  - Semaphore variable ***value***

```
int value=N; /* protected resource */
```

function ENTER_CRITICAL

```
– Proberen (value) /* P, Wait */
    value--;
    if (value < 0)
      sleep(); /* sleep without completing wait */
```

function EXIT_CRITICAL

```
– Verhogen (value) /* V, Signal */
    value++;
    if (value <= 0)
      wakeup(); /* wakeup one sleeper with a policy */
```

Each function **executes atomically**

Semaphore Implementation

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

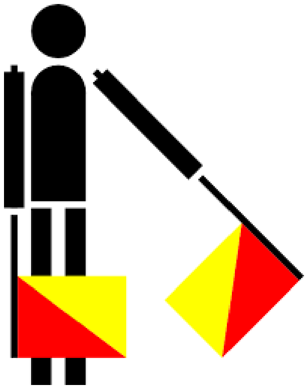
- A list of TCBs
- The list kept in any **order** (e.g. FIFO)
- User- or kernel-level TCBs
- Each function should be atomic

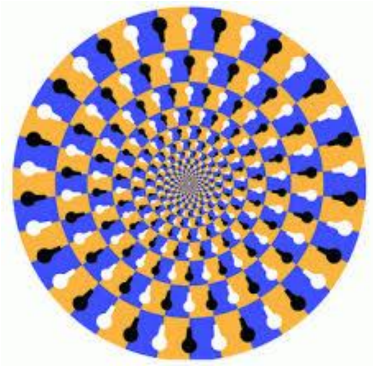
How to Provide Atomicity?
Need a spinlock! (“real” mutual exclusion lock)

- P/wait(sem)
  - acquire “real” mutual exclusion lock
    - if sem is “available” (>0), decrement sem; release “real” mutual exclusion lock; let thread continue
    - otherwise, place thread on associated queue; release “real” mutual exclusion lock; run some other thread
- V/signal(sem)
  - acquire “real” mutual exclusion lock
    - 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 lock
  - the “V-ing” thread continues execution

Semaphores vs Spinlocks

- **With Semaphores**
- Threads/processes are blocked at the level of **program logic**
  - By the semaphore P/wait operation
  - Placed on queues, rather than busy-waiting
    - The scheduler is **aware** about thread/process **waiting**
    - **Other tasks** can execute
- Busy-waiting may be used for the “real” mutual exclusion lock
  - To implement P/wait and V/signal
  - These are very short critical sections – **independent of program logic**
  - They are not implemented by the application programmer



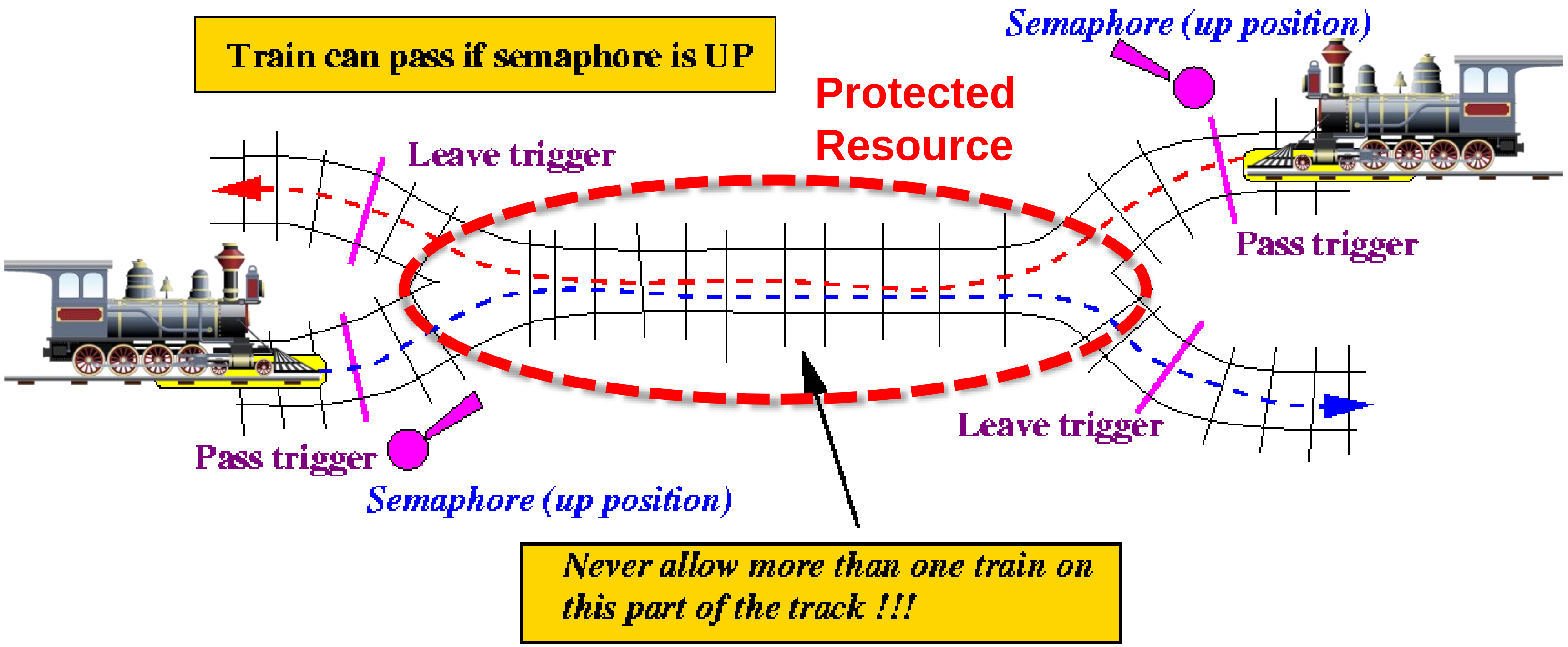


Semaphore Usage

- **Binary semaphore**
- Integer ***value*** **initialized and capped** to 1
  - 0 means **lock is held**
  - Same as a lock, but no busy waiting
    - `wait()` is `acquire()`
    - `signal()` is `release()`
- **Counting semaphore**
- Integer ***value*** **initialized and capped** to the # of protected resources
  - **Positive** value means still resource available
  - **Negative or zero** value, how many waiting for resources, no resources available
- **Sychronization semaphore**
- Integer ***value*** **initialized** to 0
  - **0** means no events pending
  - **Positive** value means there are events pending

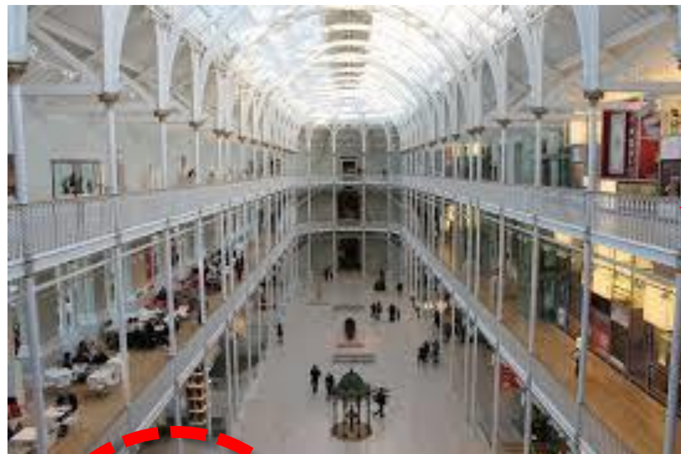
Binary Semaphores in Real-life

A Semaphore with **one** resource



Counting Semaphores in Real-life

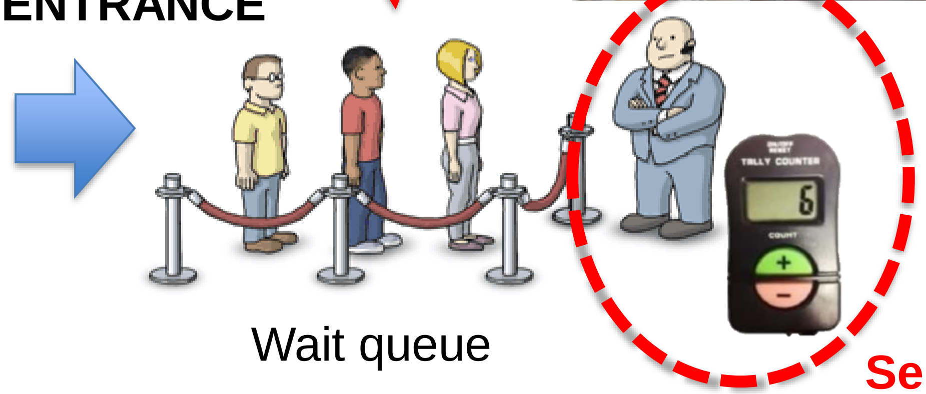
MAX PEOPLE IN MUSEUM = **N**



Threads
Processes

Protected
Resource

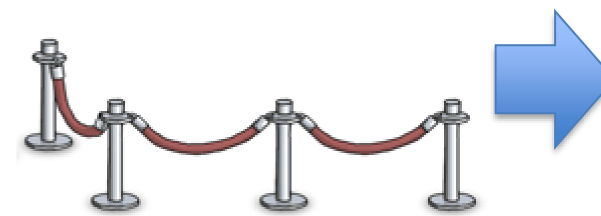
MUSEUM
ENTRANCE



Wait queue

Semaphore

MUSEUM
EXIT



Signal queue

Synchronization Semaphore

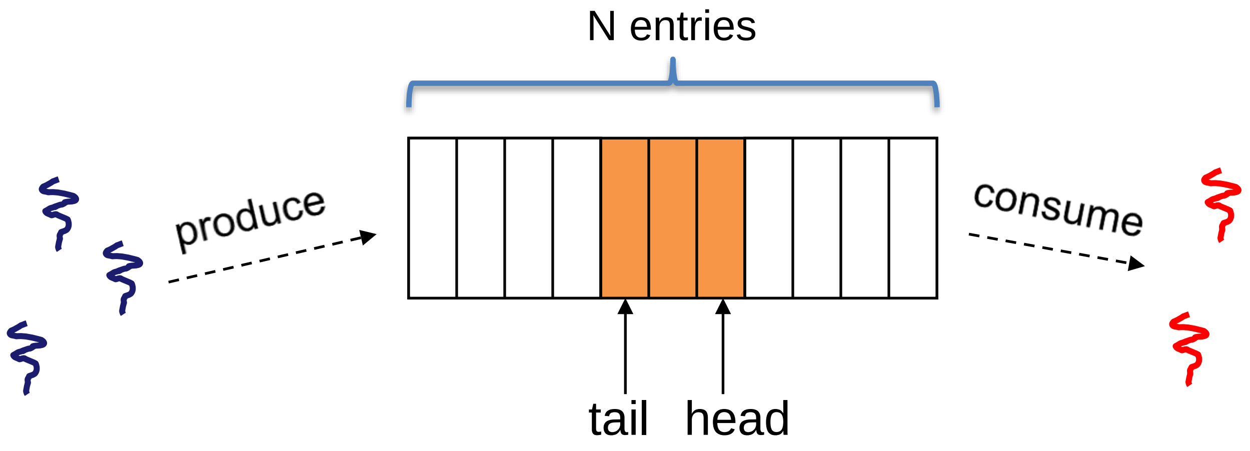
- ***P_1*** and ***P_2*** that require ***S_1*** to happen before ***S_2***

Create a semaphore "**`synch`**" initialized to 0

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

Producer-consumer Problem

- *AKA* "**Bounded-buffer**"
  - 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/process are concurrent/parallel
  - Must use synchronization constructs to control access to shared variables describing buffer state



Example: Producer-consumer Problem Counting Semaphores (1)

```
Shared variables
const int N=100;
int count=0;
```

Previous code

```
Shared variables
const int N=100;
semaphore full=N, empty=0;
```

New code

- In producer-consumer problem ***count*** controls two conditions
  - Buffer empty
    - count == 1 or count == 0
  - Buffer full
    - count == N or count == N-1
- A semaphore controls a single condition on ***value***
  - Two semaphores are needed

Producer-consumer Problem Counting Semaphores (2)

Previous code:

```
Shared variables
const int N=100;
int count=0;

Producer
while (1){
  produce an item A;
  if(count==N) sleep();
  insert item;
  count++;
  if(count==1) wakeup(consumer);
}

Consumer
while (1){
  if(count==0) sleep();
  remove item;
  count--;
  if(count==N-1) wakeup(producer);
  consume an item;
}
```

Full?

Empty ?

Previous code

New code:

```
Shared variables
const int N=100;
semaphore full=N, empty=0;

Producer
while (1){
  produce an item A;
  wait(full);
  insert item;
  signal(empty);
}

Consumer
while (1){
  wait(empty);
  remove item;
  signal(full);
  consume an item;
}
```

New code

Example: Producer-consumer Problem Counting and Binary Semaphores (1)

```
Shared variables
const int N=100;
int count=0;
```

Previous code

```
Shared variables
const int N=100;
semaphore empty=N, full=0;
semaphore mux=1;
```

New code

- Multiple threads/process trying to add/remove different items in the buffer
  - Operations on the buffer are critical operation
- Mutex to protect buffer operations
  - Avoid races

Producer-consumer Problem
Counting and Binary Semaphores (2)

```
Shared variables
const int N=100;
int count=0;

Producer
while (1){
  produce an item A;
  if(count==N) sleep();
  insert item;
  count++;
  if(count==1) wakeup(consumer);
}

Consumer
while (1){
  if(count==0) sleep();
  remove item;
  count--;
  if(count==N-1) wakeup(producer);
  consume an item;
}
```

sleep()&wakeup() code

```
Shared variables
const int N=100;
semaphore full=N, empty=0;
semaphore mux=1;
Producer
while (1){
  produce an item A;
  wait(full);
  wait(mux); // acquire(mux)
  insert item;
  signal(mux); // release(mux)
  signal(empty);
}
Consumer
while (1){
  wait(empty);
  wait(mux); // acquire(mux)
  remove item;
  signal(mux); // release(mux)
  signal(full);
  consume an item;
}
```

New code

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
```

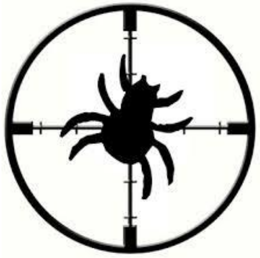
```
reader:
    P(mutex)                              ; ensure exclusion
      readcount++                         ; one more reader
      if readcount == 1 then P(wrt)       ; if we're the first, synch with writers
    V(mutex)
        <perform read operation>
    P(mutex)                              ; 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 reader 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?

Problems with Semaphores and Locks

- Solve any of the **traditional synchronization problems**
- But it is easy to make mistakes
  - Like shared global variables
    - Can be accessed from anywhere (bad software engineering)
  - No connection between the synchronization variable, and the data being controlled
  - 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?
- Prone to bugs
  - We can reduce the chance of bugs by "stylizing" the use of synchronization
  - Language help is useful for this



Problem Example

- The sequence of wait and signal operations
  - Producer – wait(full), wait(mux), signal(mux), signal(empty)
  - Consumer – wait(empty), wait(mux), signal(mux), signal(full)
- **Is order of *wait/signal* important?**

Starts with full=N, empty=0, mux=1

```
Producer
while (1){                 4
  produce an item A;       5
  wait(full);          6
  wait(mux);              7  Blocked!
  insert item;
  signal(mux);
  signal(empty);
}
```

```
Consumer
while (1){        1
  wait(mux);        2
  wait(empty);        3  Blocked!
  remove item;
  signal(mux);
  signal(full);
  consume an item;
}
```

Both may block forever!

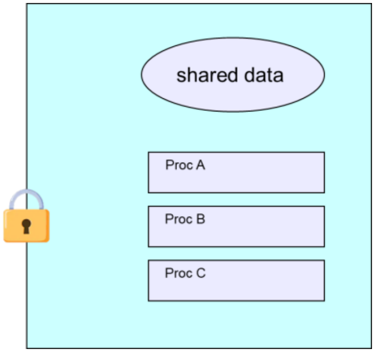
Semaphore Summary

- Solve lock problems
  - No busy-waiting
  - Waiting is controlled by the scheduler
    - Improved scheduling
      - No wasted CPU time
      - Respect task priorities
  - Control multiple resources
- Different usages
  - Binary
  - Counting
  - Synchronization
- Easy to introduce bugs

Monitors

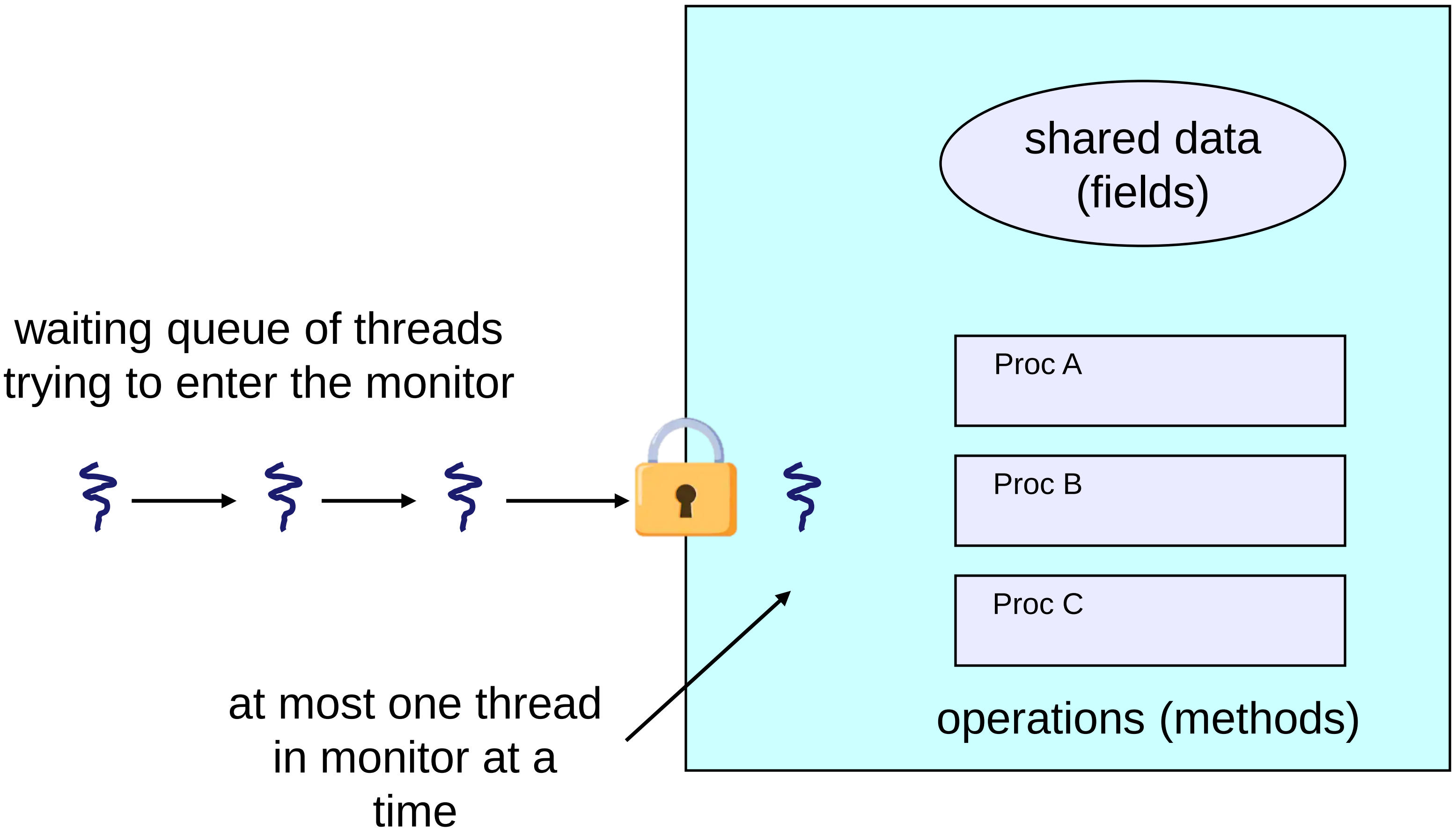
Monitors

- Address the key usability issues with semaphores
- A **programming language construct** to support **controlled shared data access**
  - Synchronization code is added by the compiler/language VM
- An **abstract data type/class** in which every method **automatically**
  - acquires a lock on entry
  - releases the lock on exit



- Includes
  - **shared data** structures (object fields)
  - **procedures** that operate on the shared data (object methods)
  - **synchronization** between concurrent execution flows that invoke those procedures
- Data can only be accessed **from within**
  - Protects the data from unstructured access
  - Prevents ambiguity about synchronization

A monitor



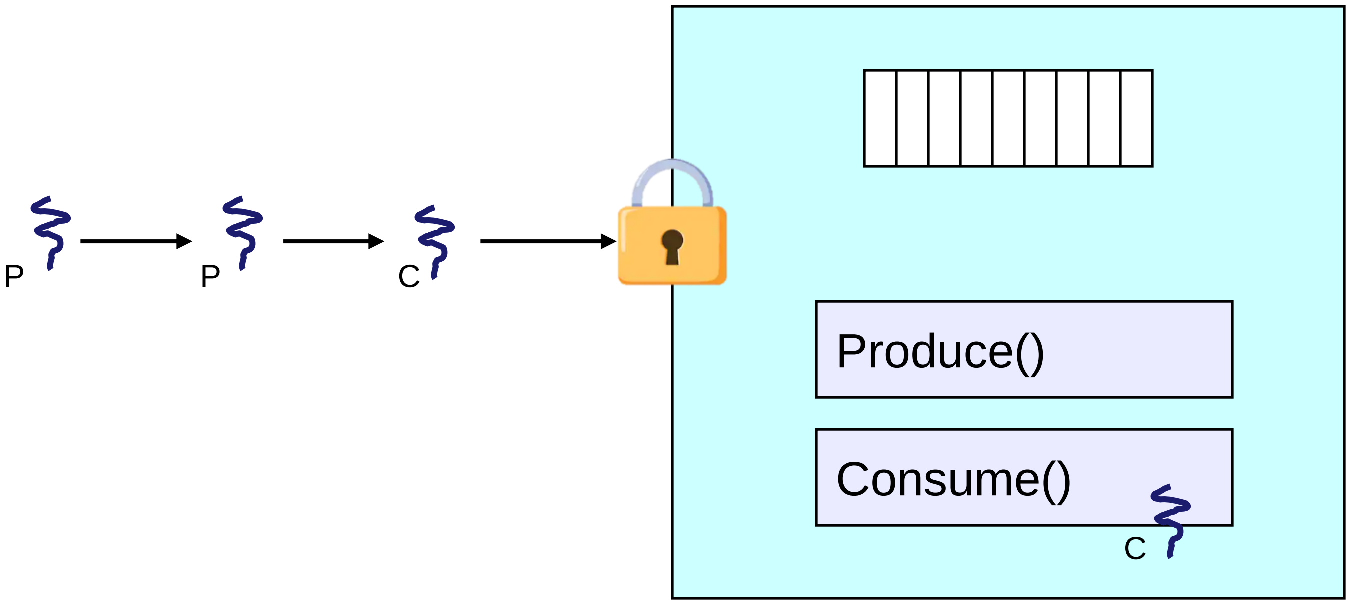
waiting queue of threads
trying to enter the monitor
shared data
(fields)
Proc A
Proc B
Proc C
operations (methods)
at most one thread
in monitor at a
time

Monitor facilities

- **Automatic** mutual exclusion
  - Only **one thread** can be executing inside at any time
    - 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
    - Easier to use (most of the time)

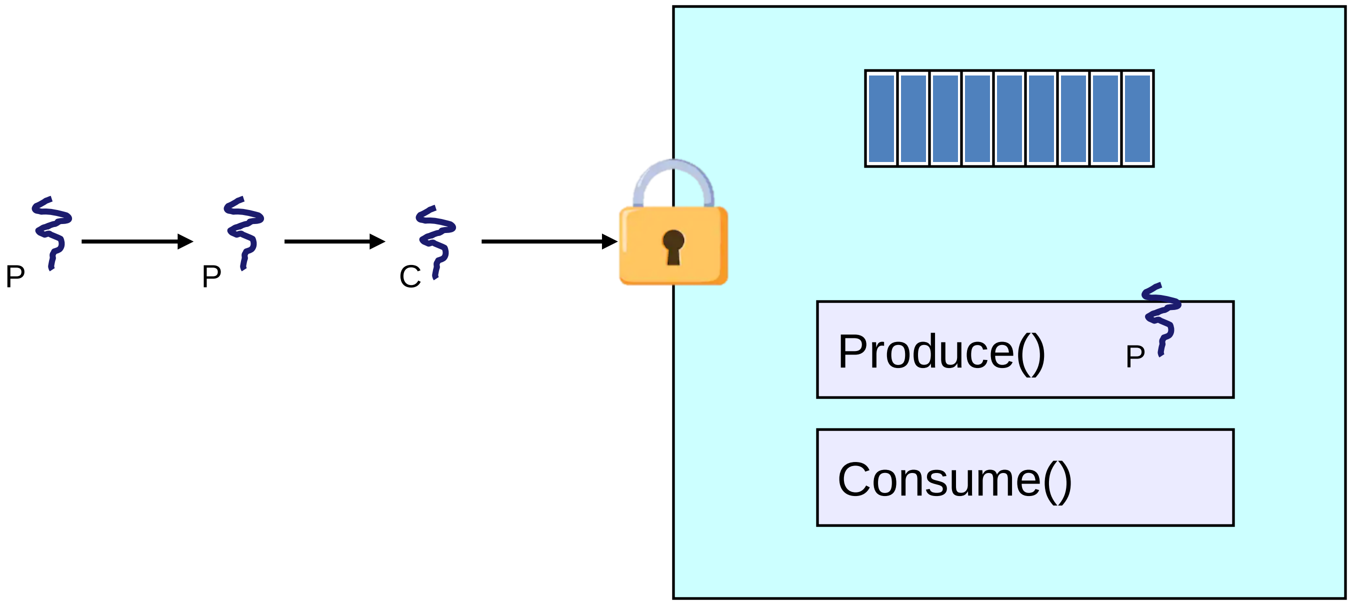
- However, there's a problem…

Problem: Producer-consumer Scenario



- Buffer is **empty**
- Now what?

Problem: Producer-consumer Scenario



- Buffer is **full**
- Now what?

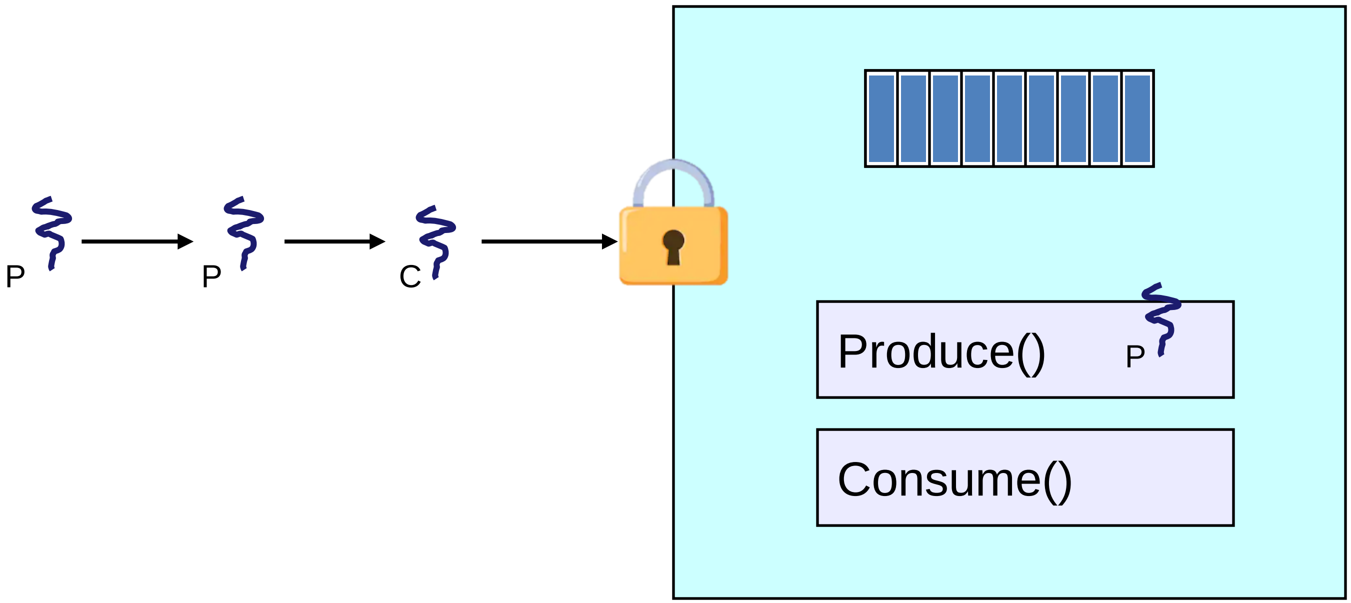
Solution?

- **Condition variables**
- Operations on condition variables
  - **cond_wait(c)**
    - Release monitor lock, so somebody else can get in
    - Wait for somebody else to signal condition
    - Condition variables have associated wait queues
  - **cond_signal(c)**
    - Wake up at most one waiting thread
      - "Hoare" monitor: wakeup immediately, signaler steps outside
    - If no waiting threads, signal is lost
      - this is different than semaphores: no history!
  - **cond_broadcast(c)**
    - Wake up all waiting threads

Producer-consumer using (Hoare) monitors

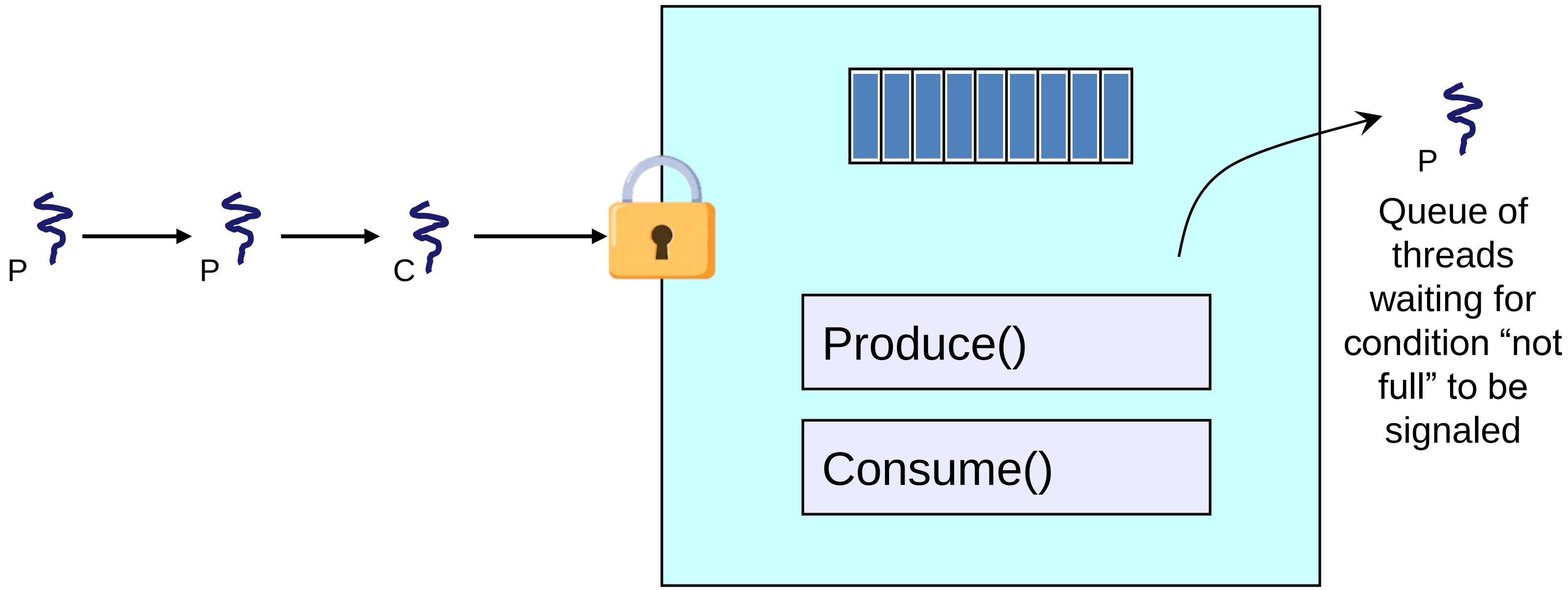
```
Monitor producer_consumer {
  buffer resources[N];
  condition not_full, not_empty;

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

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

Problem: Producer-consumer Scenario



- Buffer is **full**
- Now what?

Producer-consumer Scenario with Conditional Variable



- Buffer is **full**
- Now what?

Runtime Functions for (Hoare) Monitors

- EnterMonitor(m)
  - guarantee mutual exclusion
- ExitMonitor(m)
  - hit the road, letting someone else run
- CondWait(c)
  - step out until condition satisfied
- CondSignal(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

Producer-consumer Using (Hoare) Monitors

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

produce(resource x) {                                              EnterMonitor(m)
    if (array "resources" is full, determined maybe by a count)
          cond_wait(not_full);
    insert "x" in array "resources"
    cond_signal(not_empty);                                        ExitMonitor(m)
  }

 consume(resource *x) {                                            EnterMonitor(m)
    if (array "resources" is empty, determined maybe by a count)
           cond_wait(not_empty);
    *x = get resource from array "resources"
    cond_signal(not_full);                                         ExitMonitor(m)
  }
}
```

Monitor Summary

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