Sistemi Operativi

Corso di Laurea in Informatica

a.a. 2019-2020

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SAPIENZA UNIVERSITÀ DI ROMA

Recap from Last Lecture: Synchronization

- Concurrent accesses to shared resources by multiple cooperating processes/threads can lead to unexpected or erroneous behavior
- Process/Thread cooperation must guarantee consistency of any shared data/resource, regardless of CPU scheduling
- Maintaining shared data consistency requires mechanisms to ensure synchronized execution of critical sections by processes/threads
- Critical sections are specific pieces of code which contain shared resources that need to be "protected"

Recap from Last Lecture: Locks

- Synchronization primitives ensure that only one process/thread at a time executes in a critical section (mutual exclusion)
- Locks allow protection of critical sections by atomically testing and taking/releasing the access to a critical section
- Locks can be implemented leveraging some HW support:
  - **disabling interrupts** (can miss or delay important events)
  - **atomic instructions** (busy waiting/spinlock inefficient)

Higher-Level Synchronization Primitives

- More general synchronization mechanisms
  - Not only for safely accessing critical sections

Higher-Level Synchronization Primitives

- More general synchronization mechanisms
  - Not only for safely accessing critical sections
- **2** common high-level synchronization primitives:
  - **Semaphores:** binary (mutex) and counting
  - **Monitors:** mutex and condition variables

Semaphores: Overview

- Another data structure that provides mutual exclusion to critical sections

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- Another data structure that provides mutual exclusion to critical sections
- Can also play the role of an atomic counter
- Generalization of locks invented by Dijkstra in 1965
- Special type of (integer) variable that supports **2 atomic operations**
  - `wait()` (also `P()`): decrement, block until semaphore is open
  - `signal()` (also `V()`): increment, allow another thread to enter

Blocking in Semaphores

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- Then `signal()` opens the semaphore:
  - If a thread is waiting on the queue the thread is unblocked, whilst if no threads are waiting on the queue, the signal is remembered for the next thread
- In other words, `signal()` is stateful and has "history"

Semaphores: Types

- **Binary Semaphore** a.k.a. Mutex (same as a Lock)
  - Guarantees mutually exclusive access to a resource (i.e., only one process/thread executes in a critical section)
  - Its associated integer variable can only take 2 values: 0 or 1
  - Initialized to open (e.g., `value = 1`)

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  - Its associated integer variable can only take 2 values: 0 or 1
  - Initialized to open (e.g., `value = 1`)
- **Counting Semaphore**
  - To manage multiple shared resources
  - The initial value of the semaphore is usually the number of resources
  - A process can access to a resource as long as at least one is available

Semaphores: Key Ideas

```
// Semaphore S

S.wait(); // wait until S is available

<critical section>

S.signal(); notify other processes that S is open
```

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Each semaphore supports a queue of processes that are waiting to access the critical section (e.g., to buy milk)

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If a process executes `S.wait()` and semaphore `S` is open (non-zero), it continues executing, otherwise the OS puts the process on the wait queue

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If a process executes `S.wait()` and semaphore `S` is open (non-zero), it continues executing, otherwise the OS puts the process on the wait queue

A `S.Signal()` unblocks one process on semaphore `S`'s wait queue

Binary Semaphore: Example

"Too Much Milk" Using Lock

```
# Thread Bob

Lock.acquire()

if (!milk):
    buy_milk()

Lock.release()
```

```
# Thread Carl

Lock.acquire()

if (!milk):
    buy_milk()

Lock.release()
```

"Too Much Milk" Using Semaphore

```
# Thread Bob

S.wait()

if (!milk):
    buy_milk()

S.signal()
```

```
# Thread Carl

S.wait()

if (!milk):
    buy_milk()

S.signal()
```

Semaphore: Implementation

```
Class Semaphore {
  public void wait(Thread t);
  public void signal();
  private int value;
  private int guard;
  private Queue q;

  Semaphore(int val) {
    // initialize semaphore
    // with val and empty queue
    this.value = val;
    this.q = null;
  }
}
```

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}
```

```
public void wait(Thread t) {
  while(test&set(this.guard) == 1) {
    // while busy do nothing
  }
  this.value -= 1;
  if(this.value < 0) {
    q.push(t);
    t.sleep();
  }
  this.guard = 0;
}
```

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  this.value -= 1;
  if(this.value < 0) {
    q.push(t);
    t.sleep();
  }
  this.guard = 0;
}
```

```
public void signal() {
  while(test&set(this.guard) == 1) {
    // while busy do nothing
  }
  this.value += 1;
  if(!q.isEmpty()) {
    t = q.pop();
    push_onto_ready_queue(t);
  }
  this.guard = 0;
}
```

Semaphore: Implementation

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Class Semaphore {
  public void wait(Thread t);
  public void signal();
  private int value;
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    t = q.pop();
    push_onto_ready_queue(t);
  }
  this.guard = 0;
}
```

`wait()` and **`signal()`** are of course atomic!

either interrupts must be disabled or **`test&set`** used

Semaphore: Example

```
S = 2
```

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
```

Semaphore: Example

`S = 2`

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
```

A possible execution flow

S (`value`)	**Queue**	**A**	**B**
2	∅	ready to exec	ready to exec

Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
```

A possible execution flow

	S (`value`)	Queue	A	B
	2	∅	ready to exec	ready to exec
A: `S.wait()`				

Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
```

A possible execution flow

	S (`value`)	**Queue**	**A**	**B**
	2	∅	ready to exec	ready to exec
A: `S.wait()`	1	∅	ready to exec	ready to exec

Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
```

A possible execution flow

	S (`value`)	**Queue**	**A**	**B**
	2	Ø	ready to exec	ready to exec
A: `S.wait()`	1	Ø	ready to exec	ready to exec
B: `S.wait()`				

Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
```

A possible execution flow

	S (`value`)	Queue	A	B
	2	∅	ready to exec	ready to exec
A: `S.wait()`	1	∅	ready to exec	ready to exec
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Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
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S.signal()
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A possible execution flow

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	2	∅	ready to exec	ready to exec
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A: `S.wait()`				

Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
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S.signal()
```

A possible execution flow

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	2	∅	ready to exec	ready to exec
A: `S.wait()`	1	∅	ready to exec	ready to exec
B: `S.wait()`	0	∅	ready to exec	ready to exec
A: `S.wait()`	-1	A	blocked	ready to exec

Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
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A possible execution flow

	S (`value`)	Queue	A	B
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B: `S.signal()`				

Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
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A possible execution flow

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Semaphore: Example

A

```
S.wait()
S.wait()
S.signal()
S.signal()
```

B

```
S.wait()
S.signal()
```

A possible execution flow

	S (`value`)	**Queue**	**A**	**B**
	2	∅	ready to exec	ready to exec
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A: `S.wait()`	-1	A	blocked	ready to exec
B: `S.signal()`	0	∅	ready to exec	ready to exec
A: `S.signal()`	1	∅	ready to exec	ready to exec
A: `S.signal()`	2	∅	ready to exec	ready to exec

Semaphores: Purposes

- **Mutual Exclusion:** used to guard critical sections
  - The initial value of the semaphore is set to 1
  - Call **`wait()`** before the critical section, **`signal()`** after the critical section

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- **Scheduling Constraints:** used to enforce threads to wait
  - The initial value of the semaphore is set to 0
  - Example → `join()` or `waitpid()`

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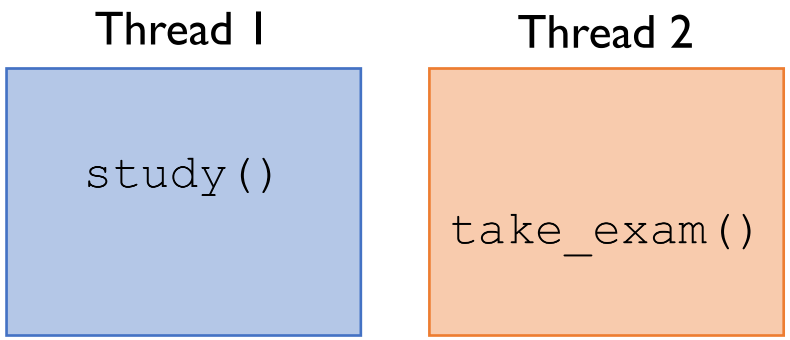

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  - Call **`wait()`** before the critical section, **`signal()`** after the critical section
- **Scheduling Constraints:** used to enforce threads to wait
  - The initial value of the semaphore is set to 0
  - Example → **`join()`** or **`waitpid()`**

```
S = 0
```

Thread 1

```
study()
S.signal()
```

Thread 2

```
S.wait()
take_exam()
```

Producer-Consumer

Producer Process:

```
while (true)
{
      /* produce an item in nextProduced */
      while (counter == BUFFER_SIZE)
         ; /* do nothing */
      buffer[in] = nextProduced;
      in = (in + 1) % BUFFER_SIZE;
      counter++;
}
```

Consumer Process:

```
while (true)
{
      while (counter == 0)
         ; /* do nothing */
      nextConsumed = buffer[out];
      out = (out + 1) % BUFFER_SIZE;
      counter--;
      /* consume the item in nextConsumed */
}
```

Both the producer and the consumer share a common buffer (of items)

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Both the producer and the consumer share a common buffer (of items)

`counter` keeps track of the number of items currently in the buffer

possible race condition as `counter` can be updated by the producer and consumer

Producer-Consumer: Race Condition

Producer:

$$\begin{aligned} &register_1 = \texttt{counter} \\ &register_1 = register_1 + 1 \\ &\texttt{counter} = register_1 \end{aligned}$$

Consumer:

$$\begin{aligned} &register_2 = \texttt{counter} \\ &register_2 = register_2 - 1 \\ &\texttt{counter} = register_2 \end{aligned}$$

Interleaving:

Assuming the initial value of `counter` is 5

T_0:	*producer*	execute	$register_1 = \texttt{counter}$	$\{register_1 = 5\}$
T_1:	*producer*	execute	$register_1 = register_1 + 1$	$\{register_1 = 6\}$
T_2:	*consumer*	execute	$register_2 = \texttt{counter}$	$\{register_2 = 5\}$
T_3:	*consumer*	execute	$register_2 = register_2 - 1$	$\{register_2 = 4\}$
T_4:	*producer*	execute	$\texttt{counter} = register_1$	$\{counter = 6\}$
T_5:	*consumer*	execute	$\texttt{counter} = register_2$	$\{counter = 4\}$

Producer-Consumer: Race Condition

Producer:

$$register_1 = \texttt{counter}$$
$$register_1 = register_1 + 1$$
$$\texttt{counter} = register_1$$

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Q1: What would be the resulting value of `counter` if the order of statements T4 and T5 were reversed?

Producer-Consumer: Race Condition

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T_5:	*consumer*	execute	$\texttt{counter} = register_2$	$\{counter = 4\}$

Q1: What would be the resulting value of `counter` if the order of statements T4 and T5 were reversed?

Q2: What *should* the value of `counter` be after one producer and one consumer, assuming the original value was 5?

Producer-Consumer: Desiderata

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  - Access to the shared buffer of items must be granted to a single thread at a time (either to the producer or the consumer)

Producer-Consumer: Desiderata

- **Mutual Exclusion**
  - Access to the shared buffer of items must be granted to a single thread at a time (either to the producer or the consumer)
- **Scheduling Constraints**
  - Producer can only produce a new item iff the buffer is **not full**
  - Consumer can only consume an item iff the buffer is **not empty**

Producer-Consumer: Java Example

Semaphores: Wrap Up

- Generalization of locks
- Can be used for **3 purposes**:
  - To ensure mutually exclusive execution of a critical section as locks do (binary semaphore)
  - To control access to a shared pool of resources (counting semaphore)
  - To enforce scheduling constraints so as to execute threads according to some specific order

What's wrong with Semaphores?

- Not easy to get the meaning of waiting/signaling on a semaphore
- They are essentially shared global variables
- There is no direct connection between the semaphore and the data which the semaphore controls access to
- They serve multiple purposes (e.g., mutex, scheduling constraints, etc.)
- Their correctness depends on the programmer's ability

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Solution: Use a higher level primitive called **monitors**

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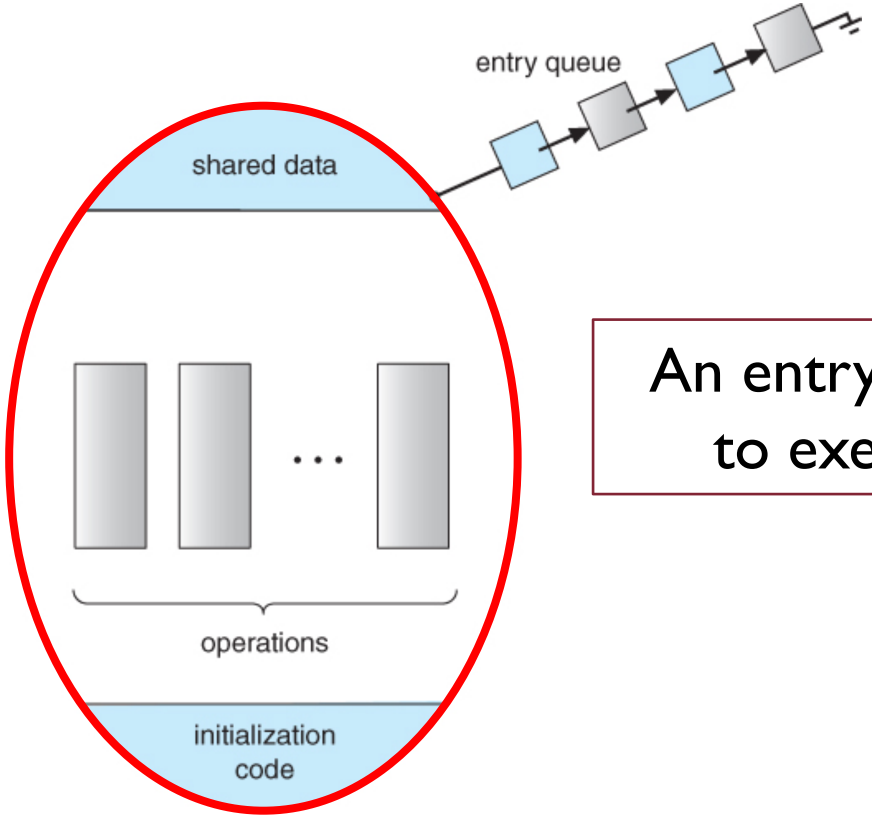
What is a Monitor?

- A monitor is a programming language construct that controls access to shared data
- Similar to a (Java/C++) class that embodies all together: **data**, **operations**, and **synchronization**
- Synchronization code added by compiler, enforced at runtime
- Unlike classes, monitors:
  - guarantee mutual exclusion, i.e., only one thread may execute a monitor's method at a time
  - require all data to be private

Monitor: A Schematic Overview



An entry queue of processes waiting their turn to execute monitor operations (methods)

Monitor: A Formal Definition

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- Defines a lock and zero or more **condition variables** for managing concurrent access to shared data
- Uses the lock to ensure that only a single thread is active within the monitor at any time
- The lock provides of course mutual exclusion for shared data

Monitor: Java Implementation Example

- It is straightforward to turn a Java class into a monitor by just:
  - Making all the data private
  - Making all methods (or non-private ones) `synchronized`

Monitor: Java Implementation Example

- It is straightforward to turn a Java class into a monitor by just:
  - Making all the data private
  - Making all methods (or non-private ones) `synchronized`
- The `synchronized` keyword indicates the method is subject to mutual exclusion

Monitor: Java Implementation Example

```
class Queue {
    …
    private ArrayList<Item> data;
    …

    public void synchronized add(Item i) {
        data.add(i);
    }

    public Item synchronized remove() {
        if (!data.isEmpty()) {
            Item i = data.remove(0);
            return i;
        }
    }
}
```

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    …
    private ArrayList<Item> data;
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    public void synchronized add(Item i) {
        data.add(i);
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        if (!data.isEmpty()) {
            Item i = data.remove(0);
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        }
    }
}
```

What happens if a thread tries to remove an element from an empty queue?

Condition Variables

- In the previous example, the **`remove()`** method should wait until something is available on the queue

Condition Variables

- In the previous example, the `remove()` method should wait until something is available on the queue
  - Intuitively, the thread should sleep inside of the critical section

Condition Variables

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  - But if the thread sleeps while still holding a lock then no other threads can access the queue, add an item to it, and eventually wake up the sleeping thread
  - **Deadlock** (more on this later…)
- Solution: **condition variables**
  - Enable a thread to sleep within a critical section
  - Any lock held by the thread is atomically released before going to sleep

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  - **`wait`** → release lock and go to sleep atomically (queue of waiters)
  - **`signal`** → wake up a waiting thread if one exists, otherwise it does nothing
  - **`broadcast`** → wake up all waiting threads
- **Rule:** thread must hold the lock when doing condition variable operations
- **Note:** condition variables are not boolean objects!

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- Use `notify()` to signal that the condition a thread is waiting on is satisfied
- Use `notifyAll()` to wake up all waiting threads
- Concretely, one condition variable per object

Monitor: Java Implementation Example

```
class Queue {
    …
    private ArrayList<Item> data;
    …

    public void synchronized add(Item i) {
        data.add(i);
        notify();
    }

    public Item synchronized remove() {
        while (data.isEmpty()) {
            wait(); // give up the lock and sleep
        }
        Item i = data.remove(0);
        return i;
        }
    }
}
```

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- Access to the monitor is controlled by a lock
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  - to call **`wait()`**, the thread has to be in the monitor (hence has lock)
  - on a semaphore, **`wait()`** just blocks the thread on the queue
- **`signal()`** causes a waiting thread to wake up
  - If there is no waiting thread, the signal is lost though!
  - on a semaphore, signal increases the counter, allowing future entry even if no thread is currently waiting

`signal()`: Mesa- vs. Hoare-style Monitors

- **Mesa-style** (Nachos, Java, and most real OSs)
  - The signaling thread places a waiter on the ready queue, but signaler continues inside monitor
  - Condition is not necessarily true when waiter runs again
  - Returning from **`wait()`** is only a hint that something changed
  - Must re-check the conditional case

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  - Condition is not necessarily true when waiter runs again
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  - Must re-check the conditional case
- **Hoare-style** (most textbooks)
  - The signaling thread immediately switches to a waiting thread
  - The condition that the waiter was anticipating is guaranteed to hold when waiter executes

Mesa vs. Hoare Monitors

- **Mesa-style**

```
while (empty) {
    wait(condition);
}
```

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while (empty) {
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Easier to use and more efficient

- **Hoare-style**

```
if (empty) {
    wait(condition);
}
```

Easier to reason about the program's behaviour

Mesa vs. Hoare

Mesa

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class Queue {
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        }
    }
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```

The waiting thread may need to wait again after it is awakened, because some other thread could grab the lock and remove the item before it gets to run

Hoare

```
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        if (data.isEmpty()) {
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```

The waiting thread runs immediately after an item is added to the queue

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  - **Readers:** read data, never modify it
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- Simplest solution:
  - Use a single lock on the data object for each operation
  - May be too restrictive!
- Each read or write of the shared data must happen within a critical section
- Guarantee mutual exclusion for writers
- Allow multiple readers to execute in the critical section at once

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  - if a reader wants access to the data, and there is not already a writer accessing it, then access is granted to the reader
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- **second readers-writers** problem (priority to the writers)
  - when a writer wants access to the data it jumps to the head of the queue
  - possible starvation of the readers, as they are all blocked as long as there are writers

(First) Readers-Writers Problem: Solution I

- Use a counter and 2 binary semaphores
  - **`numReaders`** → used by the reader processes to count the number of readers currently accessing the data
  - **`mutex`** → binary semaphore used only by the readers for controlled access to **`numReaders`**
  - **`rw_mutex`** → binary semaphore used to block and release the writers

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- The first reader to come along will block on `rw_mutex` if there is currently a writer accessing the data
- All following readers will only block on `mutex` for their turn to increment `numReaders`

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- If a writer exits and a reader goes next, then all readers that are waiting will fall through (at least one is waiting on `rw_mutex` and zero or more can be waiting on `mutex`)
- Does this solution guarantee all threads will make progress?
- Alternatively, let a writer enter its critical section first (priority to writers)

Solution II: Using Monitors

Summary

- **3 synchronization primitives**:
  - Locks → the simplest one
  - Semaphores → a generalization of locks
  - Monitors → highest-level primitives that wrap methods with mutex
- Examples of typical synchronization problems:
  - Producers-Consumers
  - Readers-Writers