Sistemi Operativi I

Corso di Laurea in Informatica

2023-2024

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SAPIENZA UNIVERSITÀ DI ROMA

Recap from Last Lecture

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- Concurrent accesses to shared resources by multiple cooperating processes/threads can lead to unexpected 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

We need to have appropriate "tools" (i.e., primitive constructs)
provided by programming languages
used as atomic building blocks for synchronization

- **Locks** → At each time, only one process holds a lock, executes its critical section, and finally releases the lock
- **Semaphores** → A generalization of locks
- **Monitors** → To connect shared data to synchronization primitives

Require some HW support and waiting

Locks

- Provide **mutual exclusion** to shared data using **2** atomic primitives:

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- Rules for using a lock:
  - Always acquire the lock **before** accessing shared data
  - Always release the lock **after** finishing with shared data
  - Lock must be **initially free**

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- Rules for using a lock:
  - Always acquire the lock **before** accessing shared data
  - Always release the lock **after** finishing with shared data
  - Lock must be **initially free**
- Only one process/thread can acquire the lock, others will wait!

Too Much Milk: Solution Using Locks

Use lock primitives

```
# Thread Bob

Lock.acquire()

if (!milk):
    buy_milk()

Lock.release()
```

```
# Thread Carla

Lock.acquire()

if (!milk):
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Lock.release()
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This solution is clean and symmetric

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Q: How do we make acquire() and release() atomic?

HW Support for Synchronization

Implementing high-level synchronization primitives requires low-level hardware support

High-level atomic operations (SW)	lock, monitor, semaphore, send/receive
Low-level atomic operations (HW)	disabling interrupts, atomic instructions (test&set)

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We want to prevent the CPU scheduler to take control **while** an acquire() operation is ongoing

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> We cover all the possible cases where the current thread might loose control of the CPU, either voluntarily (due to internal events) or involuntarily (due to external events)

Implementing Locks: Disabling Interrupts

```
Class Lock {
  public void acquire(Thread t);
  public void release();
  private int value; // 0=FREE, 1=BUSY
  private Queue q;

  Lock() {
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public void acquire(Thread t) {
  disable_interrupts();
  if(this.value) { // lock is held by someone
    q.push(t); // add t to waiting queue
    t.sleep(); // put t to sleep
  }
  else {
    this.value = 1;
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public void release() {
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  if(!q.is_empty()) {
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Implementing Locks: Atomic Instructions

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  - On a **uniprocessor** → straightforward to implement adding a new instruction
  - On a **multiprocessor** → the processor issuing the instruction must also be able to invalidate any copies of the value other processes may have in their cache

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public void acquire() {
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Case 1: if lock is free (value = 0) test&set(value) will read 0, set it to 1 and return 0

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The lock is now busy, the boolean expression in the while guard is false and acquire terminates

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Case 2: if lock is busy (value = 1) test&set(value) will read 1, set it to 1 and return 1

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Case 2: if lock is busy (value = 1) test&set(value) will read 1, set it to 1 and return 1

The lock is still busy, the boolean expression in the while guard is true and acquire continues to loop until release executes

Atomic Instructions: Any Issue?

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- What's wrong with the above implementation?

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who is going to take the lock once released?

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Disabling Interrupts vs. Atomic Instructions

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  - **overhead** as it requires invoking the kernel
  - **unfeasible** with mulitprocessor architectures
- 2 main problems with atomic instructions:
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  - **unfairness** as there is no queue where threads wait for the lock to be released

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No, but we can minimize busy-waiting time by atomically checking the lock value and giving up the CPU if the lock is busy

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We can't totally get rid of busy-waiting but we can make it independent on how long is the critical section delimited by acquire and release

Locks: Wrap Up

- 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)

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- 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

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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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- 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: 0/1
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- **Counting Semaphore**
  - To manage multiple shared resources
  - The semaphore is initially set to 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)

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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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 Carla

Lock.acquire()

if (!milk):
    buy_milk()

Lock.release()
```

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"Too Much Milk" Using **Semaphore**

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S.signal()
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# Thread Carla
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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    // initialize semaphore
    // with val and empty queue
    this.value = val;
    this.q = null;
  }
}
```

```
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_and_reset_guard_to_0();
  }
  else {
    this.guard = 0;
  }
}
```

Semaphore: Implementation

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    q.push(t);
    t.sleep_and_reset_guard_to_0();
  }
  else {
    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);
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    t.sleep_and_reset_guard_to_0();
  }
  else {
    this.guard = 0;
  }
}
```

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

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```
public void signal() {
  while(test&set(this.guard) == 1) {
    // while busy do nothing
  }
  this.value += 1;
  if(!q.isEmpty()) {        // this.value <= 0
    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	∅	ready to exec	ready to exec
A: S.wait()	1	∅	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
B: S.wait()	0	∅	ready to exec	ready to exec

Semaphore: Example

A

```
S.wait()
S.wait()
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S.signal()
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S.signal()
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	S (value)	Queue	A	B
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Semaphore: Example

A

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

B

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

A possible execution flow

	S (value)	Queue	A	B
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A: S.wait()	1	∅	ready to exec	ready to exec
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A: S.wait()	-1	A	blocked	ready to exec

Semaphore: Example

A

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

B

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

	S (value)	Queue	A	B
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Semaphore: Example

A

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

B

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

	S (value)	Queue	A	B
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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	Ø	ready to exec	ready to exec
A: S.wait()	1	Ø	ready to exec	ready to exec
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B: S.signal()	0	Ø	ready to exec	ready to exec
A: S.signal()	1	Ø	ready to exec	ready to exec
A: S.signal()	2	Ø	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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  - Example → join() or waitpid()

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Thread 1	Thread 2
study()	take_exam()

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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()

	Thread 1	Thread 2
S = 0	study() S.signal()	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)

Producer-Consumer

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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:

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

Consumer:

$$register_2 = \texttt{counter}$$
$$register_2 = register_2 - 1$$
$$\texttt{counter} = register_2$$

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	$\texttt{counter} = register_2$	$\{counter = 4\}$

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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	$\texttt{counter} = register_2$	$\{counter = 4\}$

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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$$register_1 = register_1 + 1$$
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Q2: What should the value of counter be after one producer and one consumer, assuming the original value was 5?

Producer-Consumer: Desiderata

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

Producer-Consumer in Java

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

What is a Monitor?

- A monitor is a programming language construct that controls access to shared data

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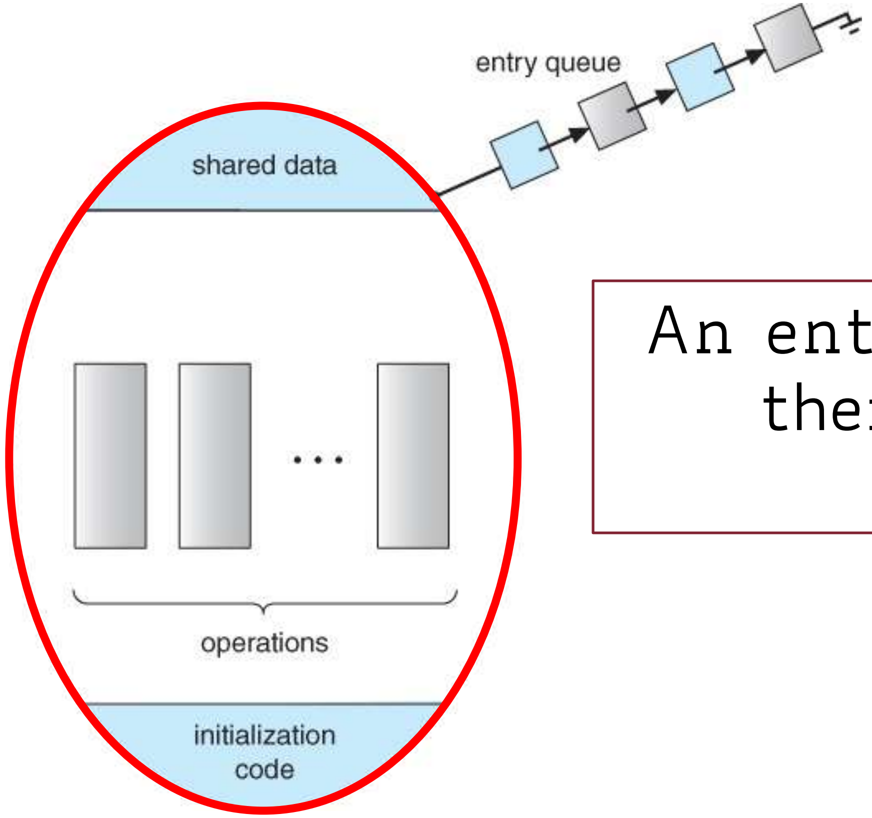
- A monitor is a programming language construct that controls access to shared data
- Similar to a (Java/C++) class that embodies all together: **data**, **operations**, and **synchronization**
- Synchronization code added by compiler, enforced at runtime

What is a Monitor?

- 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

- Defines a lock and zero or more **condition variables** for managing concurrent access to shared data

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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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```

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

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

Condition Variables

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  - Intuitively, the thread should sleep inside of the critical section
  - 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…)

Condition Variables

- Solution: `condition variables`

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Condition Variables

- Solution: **condition variables**
  - Conceptually a queue of threads, associated with a lock, on which a thread may wait for some condition to become true
  - Enable a thread to sleep **within** a critical section
  - Any lock held by the thread is **atomically** released before going to sleep

Condition Variables: Operations

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  - 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!

Condition Variables in Java

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Condition Variables in Java

- Use wait() to give up the lock
- 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;
        }
    }
}
```

Condition Variables != Semaphores

- Same operations yet entirely different semantics

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- wait() blocks the calling thread, and gives up the lock
  - to call wait(), the thread has to be in the monitor (hence, it has the lock!)
  - on a semaphore, wait() just blocks the thread on the queue

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- Access to the monitor is controlled by a lock
- wait() blocks the calling thread, and gives up the lock
  - to call wait(), the thread has to be in the monitor (hence, it has the 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

- **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

signal(): Mesa- vs. Hoare-style

- 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);
}
```

Mesa vs. Hoare Monitors

- Mesa-style

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

- Hoare-style

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

Mesa vs. Hoare Monitors

- Mesa-style

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

Easier to use and more efficient

- Hoare-style

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

Easier to reason about the program's behaviour

Mesa vs. Hoare

Mesa

```
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;
        }
    }
}
```

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

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

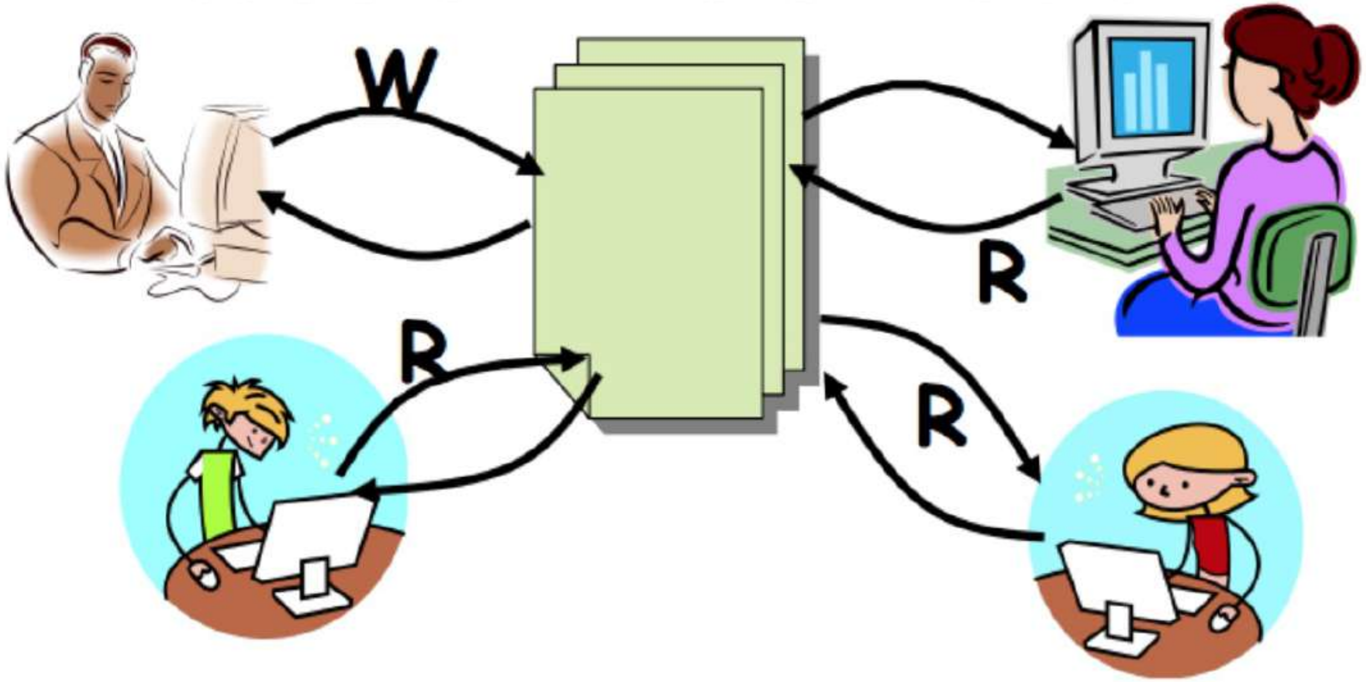
    public void synchronized add(Item i) {
        data.add(i);
        notify();
    }

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

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

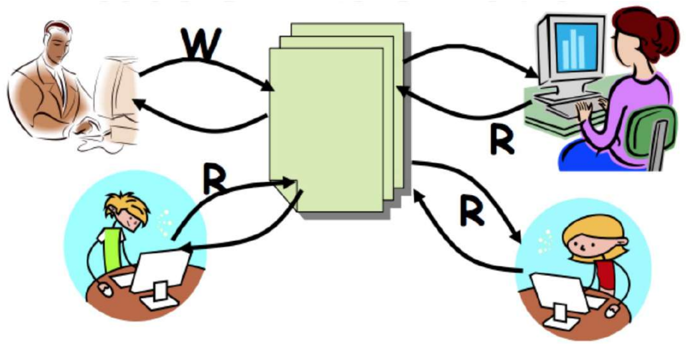
Readers-Writers Problem

Motivation: Consider a shared database system
(more generally, any shared resource)



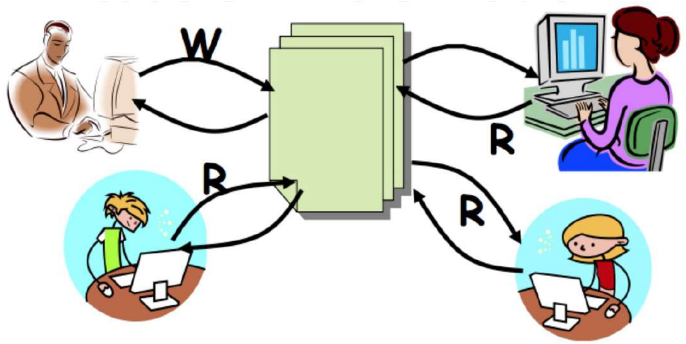
Readers-Writers Problem

Two classes of users:
- **Readers** → never modify the DB



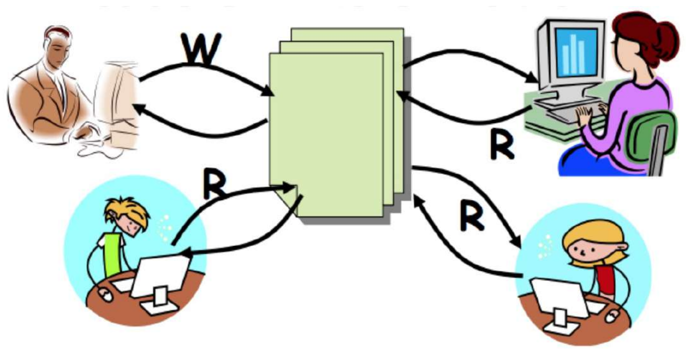
Readers-Writers Problem

Two classes of users:
- **Readers** → never modify the DB
- **Writers** → read and modify the DB



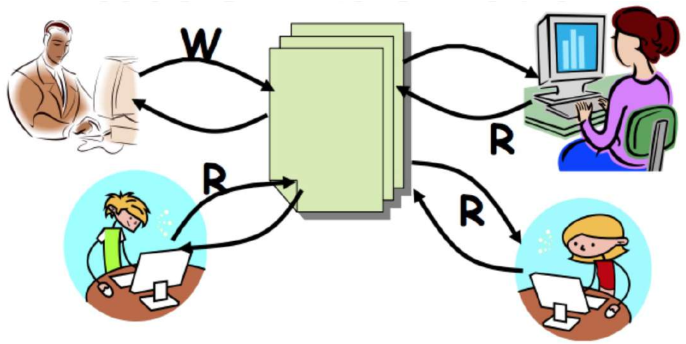
Readers-Writers Problem

Simplest solution:
- Use a single lock on the data object for each operation



Readers-Writers Problem

Simplest solution:
- Use a single lock on the data object for each operation
- May be too restrictive!



Readers-Writers Problem

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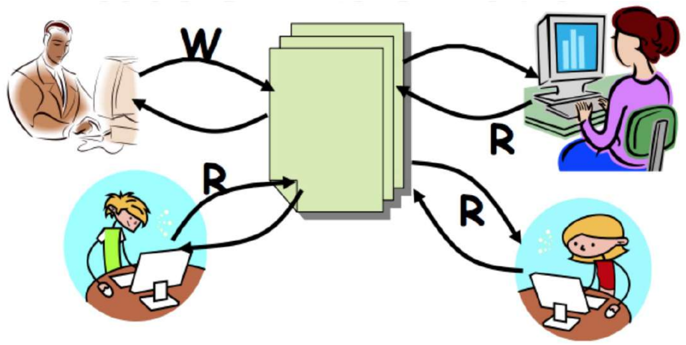
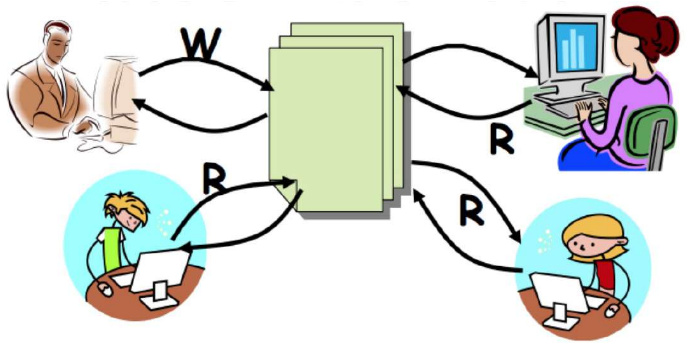


Only one writer at a time but, possibly, multiple readers

Readers-Writers Problem

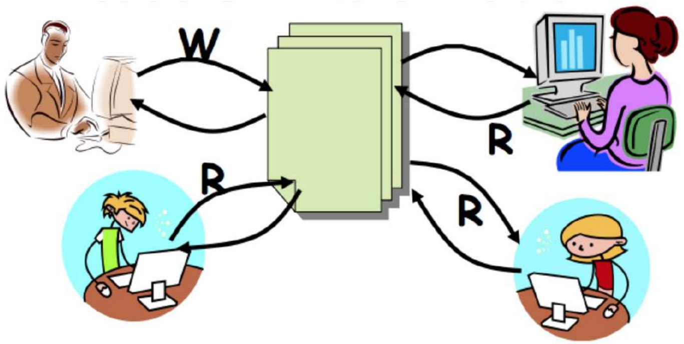
Constraints:

- Readers can access DB when no writers



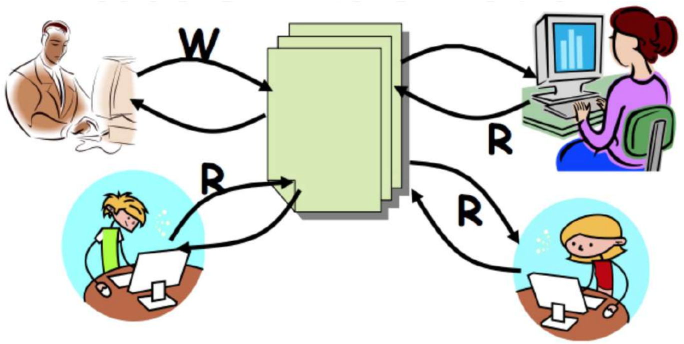
Readers-Writers Problem

<u>Constraints:</u>
- Readers can access DB when no writers
- Writers can access DB when no readers or writers



Readers-Writers Problem

<u>Constraints:</u>
- Readers can access DB when no writers
- Writers can access DB when no readers or writers
- Only one thread manipulates state variables at a time



Readers-Writers Problem

- **2 variations** of the problem depending on whether priority is on readers or writers:

Readers-Writers Problem

- **2 variations** of the problem depending on whether priority is on readers or writers:
  - **first readers-writers** problem (priority to the readers)

Readers-Writers Problem

- 2 variations of the problem depending on whether priority is on readers or writers:
  - first readers-writers problem (priority to the readers)
  - second readers-writers problem (priority to the writers)

First Readers-Writers Problem

- Priority to the readers
- If a reader wants access to the data, and there is not already a writer accessing it, then access is granted to the reader
- Possible starvation of the writers, as there could always be more readers coming along to access the data

Second Readers-Writers Problem

- Piority 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

Readers-Writers in Java Using Lock

Readers-Writers in Java Using Monitors

Summary

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  - Readers-Writers