

Systems and Networking I

Applied Computer Science and Artificial Intelligence
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Recap from Last Lecture

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- Maintaining shared data consistency requires mechanisms to ensure synchronized execution of critical sections by processes/threads

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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:
 - **lock.acquire()** → wait until the lock is free, then grab it
 - **lock.release()** → unlock and wake up any thread waiting in **acquire()**
- 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):  
    buy_milk()  
  
lock.release()
```

This solution is clean and symmetric

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# Thread Carla  
  
lock.acquire()  
  
if (!milk):  
    buy_milk()  
  
lock.release()
```

This solution is clean and symmetric

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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Low-level atomic operations (HW)	<code>disabling interrupts</code> , atomic instructions (<code>test&set</code>)

Implementing Locks: Disabling Interrupts

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- The CPU scheduler takes control due to **2** possible situations:
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 - **external events** → interrupts (e.g., time slice) cause the scheduler to take over the currently running thread

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

Implementing Locks: Disabling Interrupts

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 - **internal events** → discouraging threads from requesting any I/O operation within a critical section
 - **external event** → disabling interrupts (i.e., telling the HW to delay the handling of any external event until the current thread is done with the critical section)

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

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Class Lock {  
    public void acquire(Thread t);  
    public void release();  
  
    Lock() {}  
}
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Implementing Locks: Disabling Interrupts

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```
public void acquire(Thread t) {  
    disable_interrupts();  
}
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Implementing Locks: Disabling Interrupts

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Class Lock {  
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Implementing Locks: Disabling Interrupts

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Class Lock {  
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We need both **acquire** and **release** being implemented as **system calls**

```
public void acquire(Thread t) {  
    disable_interrupts();  
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public void release() {  
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Implementing Locks: Disabling Interrupts

```
Class Lock {  
    public void acquire(Thread t);  
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We need both **acquire** and **release** being implemented as system calls

Why?

```
public void acquire(Thread t) {  
    disable_interrupts();  
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public void release() {  
    enable_interrupts();  
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Implementing Locks: Disabling Interrupts

- PROs:
 - Very simple!

Implementing Locks: Disabling Interrupts

- **PROs:**
 - Very simple!
- **CONs:**
 - Privileged instructions
 - Trust no one abuses this capability, e.g.:
 - A greedy program that gets the lock and hogs the CPU
 - A malicious program that gets the lock and goes into an infinite loop
 - Does not work on multiprocessors!
 - May lose relevant interrupts
 - Masking/Unmasking interrupts is inefficient

Implementing Locks: A First Attempt

```
Class Lock {  
    public void acquire(Thread t);  
    public void release();  
    private int flag; // 0=free; 1=busy  
  
    Lock() {  
        this.flag = 0; // initially free  
    }  
}
```

Implementing Locks: A First Attempt

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    public void acquire(Thread t);  
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    Lock() {  
        this.flag = 0; // initially free  
    }  
}
```

```
public void acquire(Thread t) {  
    while(this.flag == 1) { // test flag  
        // do nothing (spin-wait)  
    }  
    this.flag = 1; // set the flag to busy  
}
```

```
public void release() {  
    this.flag = 0; // set the flag to free  
}
```

Does this solution work?

Implementing Locks: A First Attempt

An unlucky (yet plausible) trace

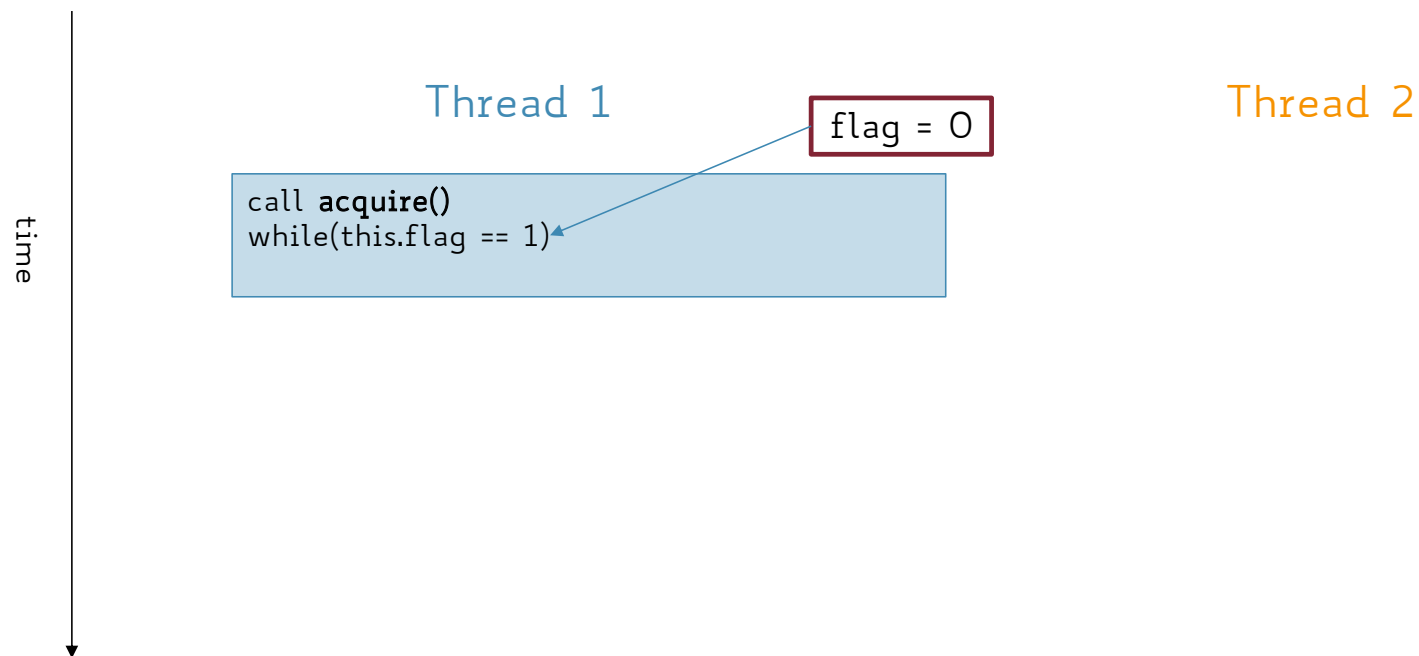
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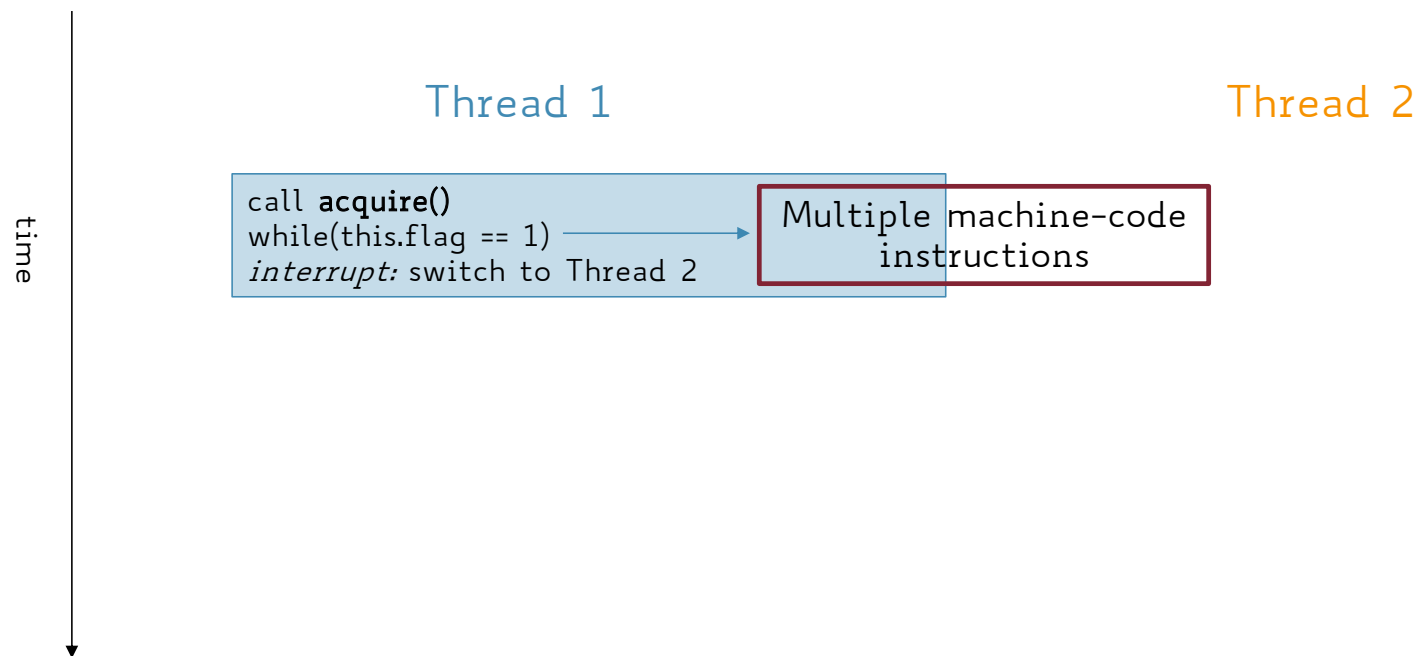
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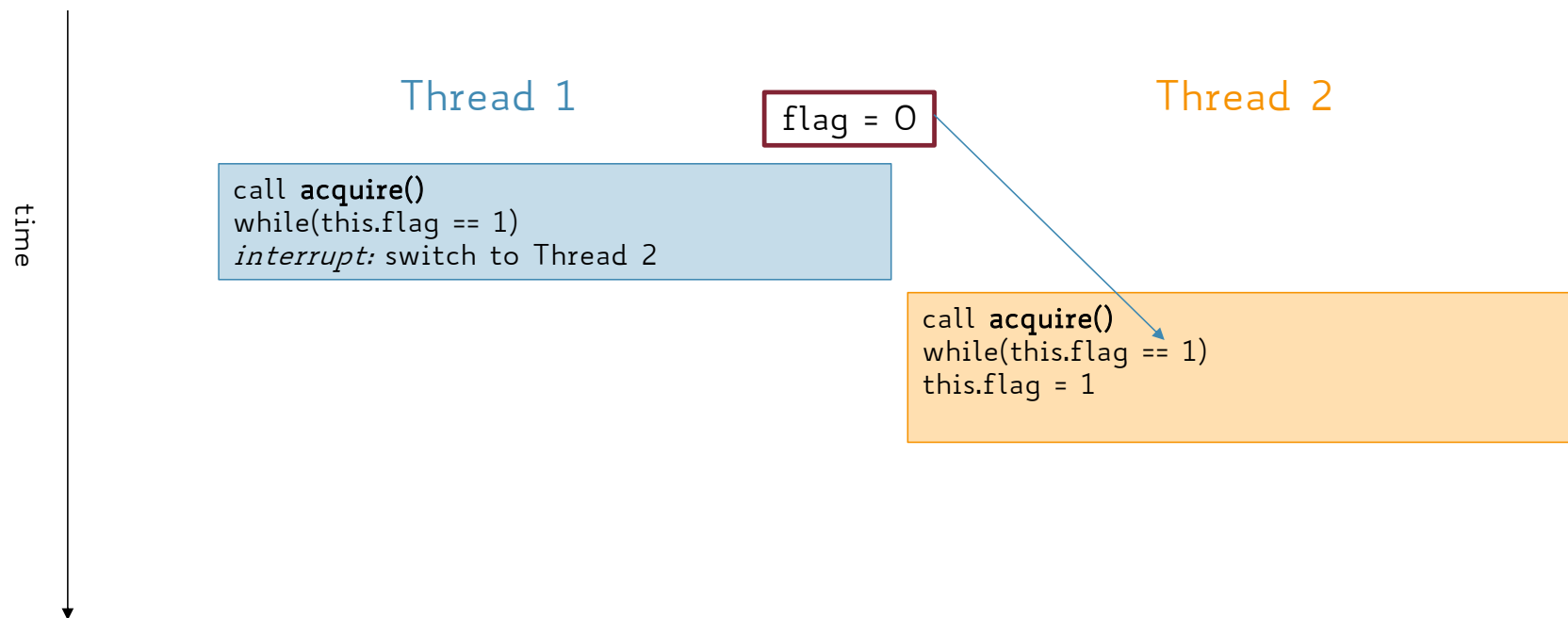
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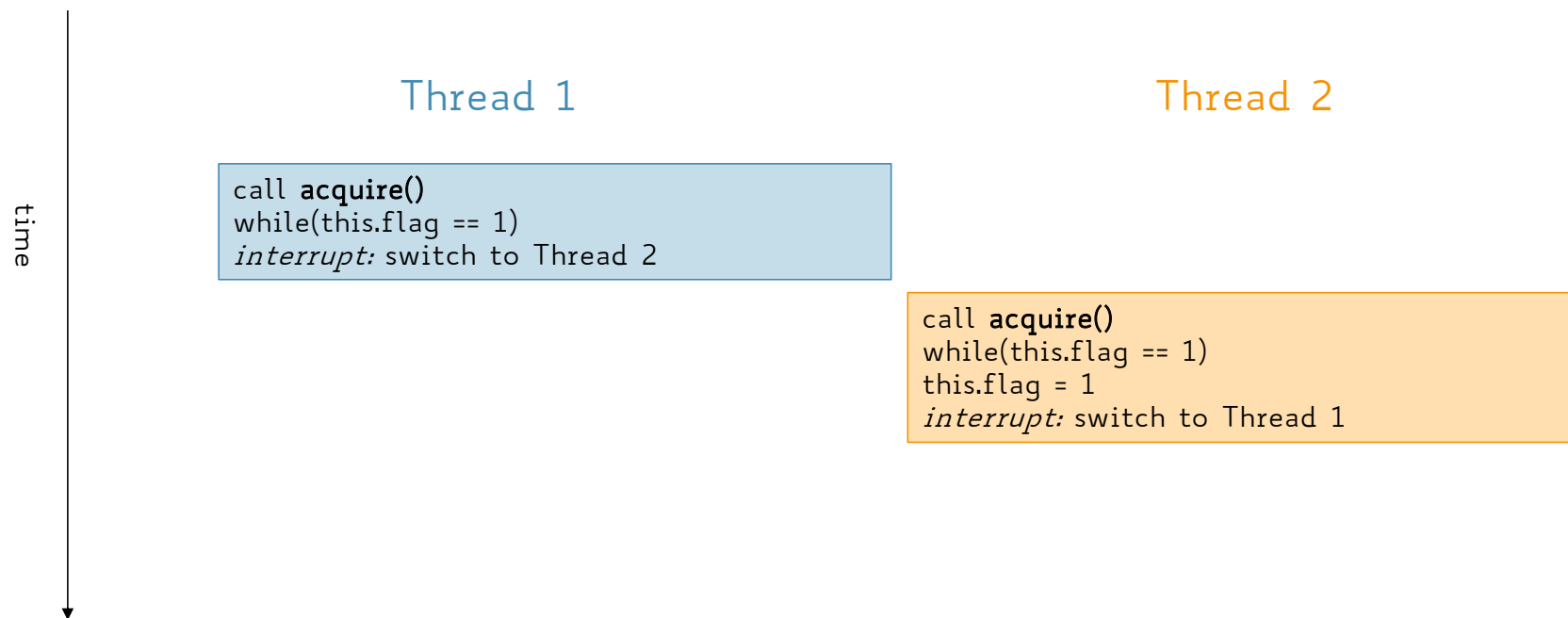
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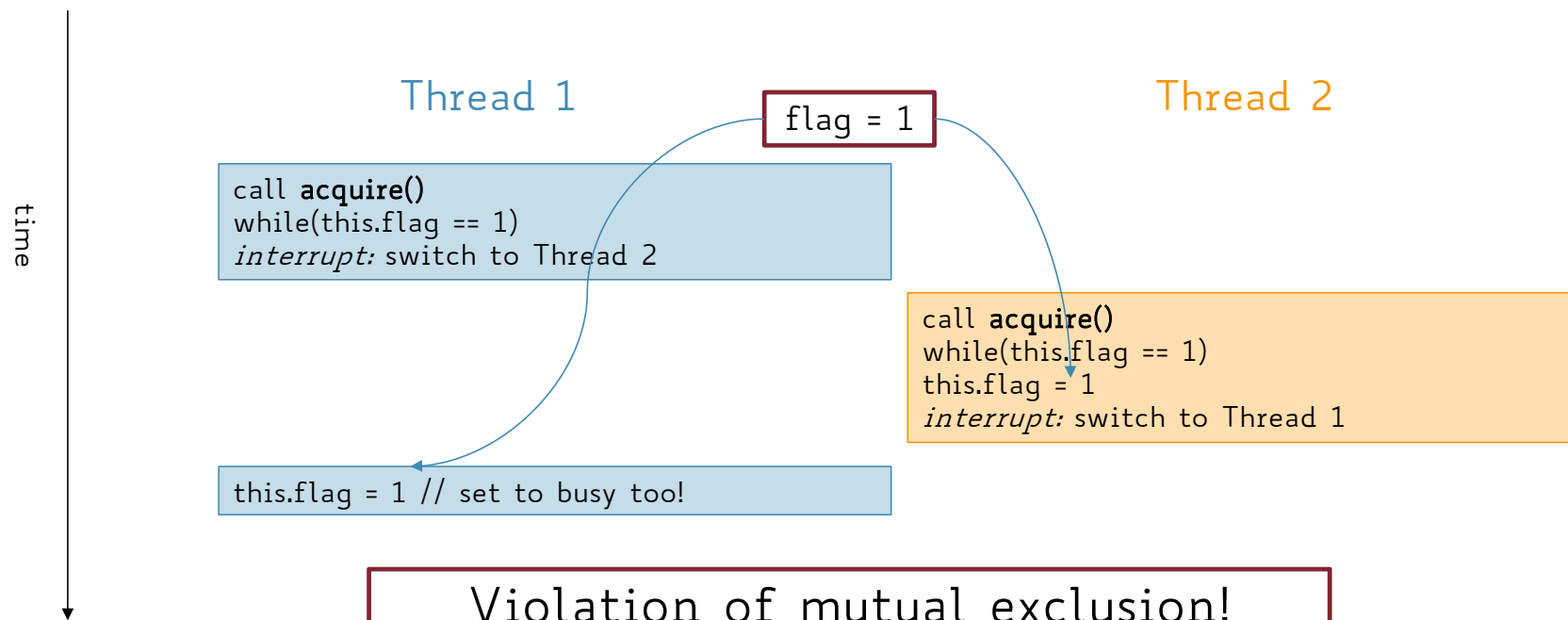
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Implementing Locks: A First Attempt

- Testing and setting a variable with MOV-like instructions does not work
- Spin-Waiting is bad!
 - The waiter thread will waste CPU cycles doing nothing
 - On uniprocessors such a waste could be even worse
 - The only thread holding the lock must take its turn on the CPU, otherwise the other(s) spin-waiting will never take it!
- What if the we have a single CPU with a non-preemptive scheduler?

HW Support for Synchronization

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

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

Implementing Locks: Atomic Instructions

- An atomic `read-modify-write` instruction reads a value from memory into a register and writes a new value in one shot!

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- An atomic `read-modify-write` instruction reads a value from memory into a register and writes a new value in one shot!
 - 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

Implementing Locks: Atomic Instructions

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 - `test&set` → writes (sets) 1 to a memory location and returns its old value

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 - `test&set` → writes (sets) 1 to a memory location and returns its old value
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Implementing Locks: test&set

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Class Lock {  
    public void acquire();  
    public void release();  
    private int flag;  
  
    Lock() {  
        // lock is initially free  
        this.flag = 0;  
    }  
}
```

Implementing Locks: test&set

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        this.flag = 0;  
    }  
}
```

```
public void acquire() {  
    while(test&set(this.flag) == 1) {  
        // while busy do nothing  
    }  
}
```


Implementing Locks: test&set

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Case 1: if lock is free (flag = 0) test&set(flag) will read 0, set it to 1 and return 0

Implementing Locks: test&set

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Case 1: if lock is free (flag = 0) test&set(flag) will read 0, set it to 1 and return 0

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

Implementing Locks: test&set

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

Implementing Locks: test&set

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Class Lock {  
    public void acquire();  
    public void release();  
    private int flag;  
  
    Lock() {  
        // lock is initially free  
        this.flag = 0;  
    }  
}
```

```
public void acquire() {  
    while(test&set(this.flag) == 1) {  
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```
public void release() {  
    this.flag = 0;  
}
```

Case 2: if lock is busy (flag = 1) test&set(flag) 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?

```
public void acquire() {  
    while(test&set(this.value) == 1) {  
        // while busy do nothing  
    }  
}
```

- What's (still) bad with the above implementation?

Atomic Instructions: Any Issue?

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public void acquire() {  
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 - What is the CPU doing?

Atomic Instructions: Any Issue?

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busy waiting
(*spin-lock*)

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 - What could happen to threads with different priorities waiting for the lock?

Atomic Instructions: Any Issue?

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public void acquire() {  
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        // while busy do nothing  
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who is going to
take the
lock once released?

- What's (still) bad with the above implementation?
 - What is the CPU doing?
 - What could happen to threads with different priorities waiting for the lock?

Masking Interrupts vs. Atomic Instructions

- 3 main problems with disabling interrupts:
 - **overhead** as it requires kernel privileges
 - **trusted code** (only OS kernel code can use this mechanism)
 - **unfeasible** with multiprocessor architectures

Masking Interrupts vs. Atomic Instructions

- 3 main problems with disabling interrupts:
 - **overhead** as it requires kernel privileges
 - **trusted code** (only OS kernel code can use this mechanism)
 - **unfeasible** with multiprocessor architectures
- 3 main problems with atomic instructions:
 - **busy waiting** (*spin-lock*)
 - **unfairness** as there is no queue where threads wait for the lock to be released
 - **performance** as N-1 waiter threads may spin for one round each before the thread holding the lock gets its turn on the CPU

Reduce Busy-Waiting: Yield!

```
Class Lock {  
    public void acquire();  
    public void release();  
    private int flag;  
  
    Lock() {  
        // lock is initially free  
        this.flag = 0;  
    }  
}
```

```
public void acquire() {  
    while(test&set(this.flag) == 1) {  
        yield(); // give up the CPU  
    }  
}
```

```
public void release() {  
    this.flag = 0;  
}
```

An OS primitive (**yield**) that allows threads to give up the CPU

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In this way, the waiter thread releases the CPU immediately

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```

An OS primitive (**yield**) that allows threads to give up the CPU

In this way, the waiter thread releases the CPU immediately

Still, some threads may starve in an endlessly yielding!

Reduce Busy-Waiting and Improve Fairness: Sleeping + Queues

```
Class Lock {  
    public void acquire(Thread t);  
    public void release();  
    private int flag;  
    private int guard;  
    private Queue q;  
  
    Lock() {  
        // lock is initially free  
        this.flag = 0;  
        this.guard = 0;  
        this.q = new Queue();  
    }  
}
```

```
public void acquire(Thread t) {  
    while(test&set(this.guard) == 1) {  
        // while busy do nothing  
    }  
    if(this.flag == 0) {  
        this.flag = 1; // lock is taken  
        this.guard = 0;  
    }  
    else {  
        this.q.push(t);  
        this.guard = 0;  
        park(); // Solaris primitive  
    }  
}
```

```
public void release() {  
    while(test&set(this.guard) == 1) {  
        // while busy do nothing  
    }  
    if(q.is_empty()) {  
        this.flag = 0; // lock is free  
    }  
    else {  
        t = q.pop();  
        unpark(t); // Solaris primitive  
    }  
    this.guard = 0;  
}
```

park → Put the caller thread to sleep if it tries to acquire a busy lock

unpark → Wake up the waiter when the lock is free

Reduce Busy-Waiting and Improve Fairness: Sleeping + Queues

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Class Lock {  
    public void acquire(Thread t);  
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    private int guard;  
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    else {  
        t = q.pop();  
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    }  
    this.guard = 0;  
}
```

NOTE: The flag is not set to 0 when another thread is woken up

The thread releasing the lock passes it directly to the next thread

Reduce Busy-Waiting and Improve Fairness: Sleeping + Queues

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    }  
    this.guard = 0;  
}
```

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**

Reduce Busy-Waiting and Improve Fairness: Sleeping + Queues

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}
```

What would happen if an unlucky thread switch happens right before calling park() and the incoming thread releases the lock?

Reduce Busy-Waiting and Improve Fairness: Sleeping + Queues

```
Class Lock {
    public void acquire(Thread t);
    public void release();
    private int flag;
    private int guard;
    private Queue q;

    Lock() {
        // lock is initially free
        this.flag = 0;
        this.guard = 0;
        this.q = new Queue();
    }
}
```

```
public void acquire(Thread t) {
    while(test&set(this.guard) == 1) {
        // while busy do nothing
    }
    if(this.flag == 0) {
        this.flag = 1; // lock is taken
        this.guard = 0;
    }
    else {
        this.q.push(t);
        setpark(); // Solaris primitive
        this.guard = 0;
        park(); // Solaris primitive
    }
}
```

```
public void release() {
    while(test&set(this.guard) == 1) {
        // while busy do nothing
    }
    if(q.is_empty()) {
        this.flag = 0; // lock is free
    }
    else {
        t = q.pop();
        unpark(t); // Solaris primitive
    }
    this.guard = 0;
}
```

Solution:

Use another system call to tell the OS the thread is *about* to park

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/spin-lock inefficient)

Higher-Level Synchronization Primitives

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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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Semaphores: Overview

- 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

- Associated with each semaphore is a queue of waiting processes/threads

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 - 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: 0/1
 - Initialized to open (e.g., value = 1)

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 - 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
 - Initialized to open (e.g., value = 1)
- **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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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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# Thread Bob  
S.wait()  
  
if (!milk):  
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S.signal()
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lock.acquire()	lock.acquire()
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"Too Much Milk" Using
Semaphore

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S.wait()	S.wait()
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S.signal()	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 = new Queue();  
    }  
}
```

```
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);  
        park();  
    }  
    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();  
        unpark(t);  
    }  
    this.guard = 0;  
}
```

Semaphore: Implementation

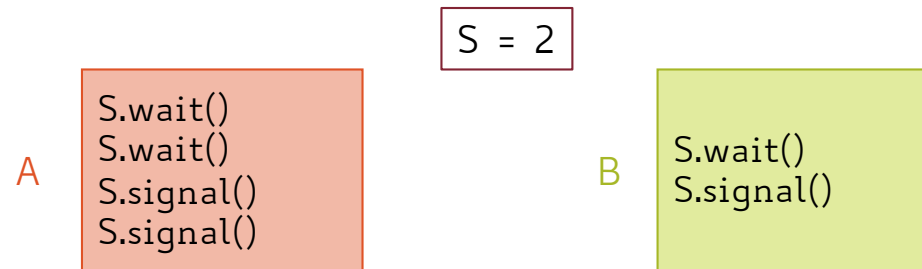
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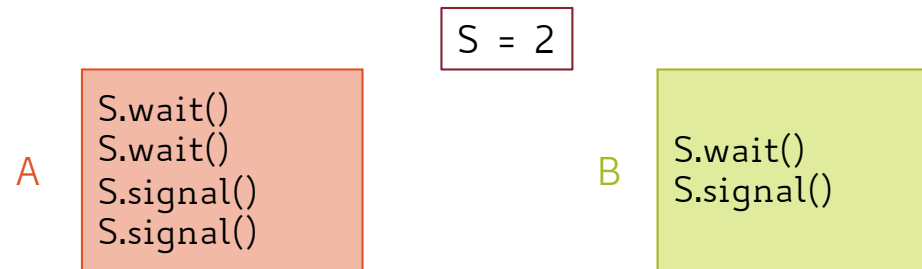
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    }  
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    if(!q.isEmpty()) { // this.value < 0  
        t = q.pop();  
        unpark(t);  
    }  
    this.guard = 0;  
}
```

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

Semaphore: Example



Semaphore: Example



A possible execution flow

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

Semaphore: Example



A possible execution flow

A: S.wait()

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Semaphore: Example



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Semaphore: Example



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Semaphore: Example



A possible execution flow

A: S.wait()
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Semaphore: Example



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Semaphores: Purposes

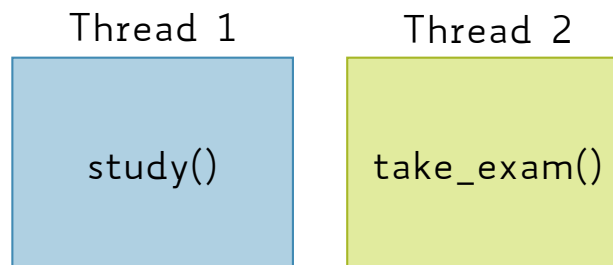
- **Mutual Exclusion:** used to guard critical sections
 - The initial value of the semaphore is set to 1
 - Call `wait()` before the critical section, `signal()` after the critical section

Semaphores: Purposes

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 - The initial value of the semaphore is set to 0
 - Example → `join()` or `waitpid()`

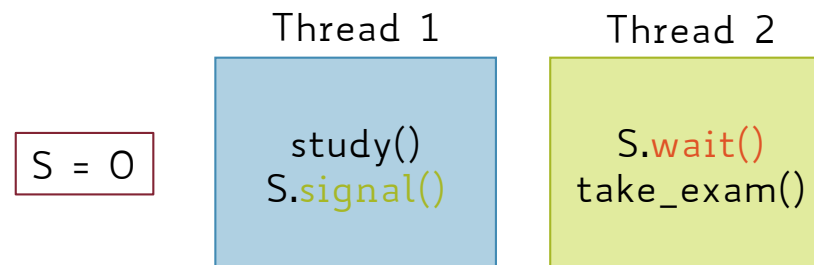
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 - The initial value of the semaphore is set to 0
 - Example → `join()` or `waitpid()`



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:

```
register1 = counter  
register1 = register1 + 1  
counter = register1
```

Consumer:

```
register2 = counter  
register2 = register2 - 1  
counter = register2
```

Interleaving:

Assuming the initial value of counter is 5

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

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T_4 :	producer	execute	$counter = register_1$	{ $counter = 6$ }
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Q1: What would be the resulting value of counter if the order of statements T_4 and T_5 were reversed?

Producer-Consumer: Race Condition

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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

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 - 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**

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

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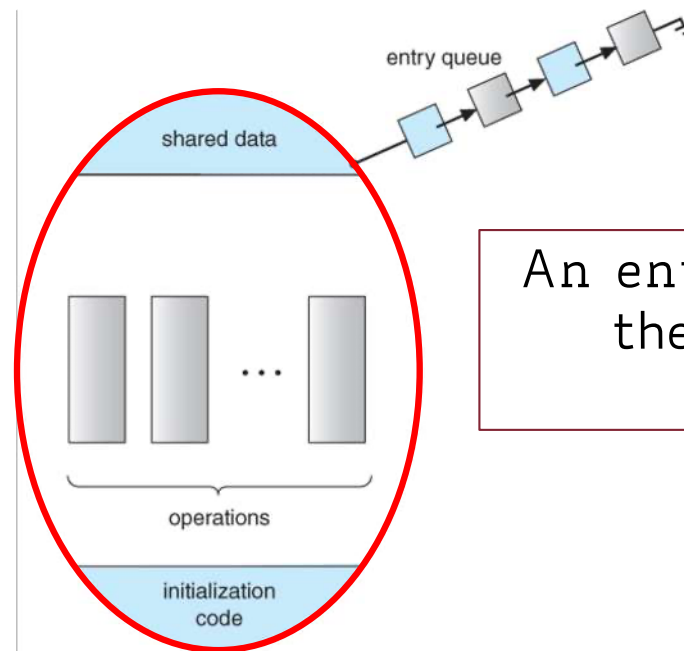
What is a Monitor?

- 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

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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- Uses the lock to ensure that only a single thread is active within the monitor at any time

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- 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;  
        }  
    }  
}
```

Condition Variables

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 - Intuitively, the thread should sleep inside 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...)

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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

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- Each condition variable supports 3 operations:

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 - `broadcast` → wake up all waiting threads

Condition Variables: Operations

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 - **wait** → release lock and go to sleep atomically (queue of waiters)
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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

- Use `wait()` to give up the lock *and* sleep atomically

Condition Variables in Java

- Use `wait()` to give up the lock *and* sleep **atomically**
- Use `notify()` to signal that the condition a thread is waiting on is satisfied

Condition Variables in Java

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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

Condition Variables in Java

- Use `wait()` to give up the lock *and* sleep **atomically**
- 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

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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, 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;  
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        }  
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        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

28/10/2025

Hoare

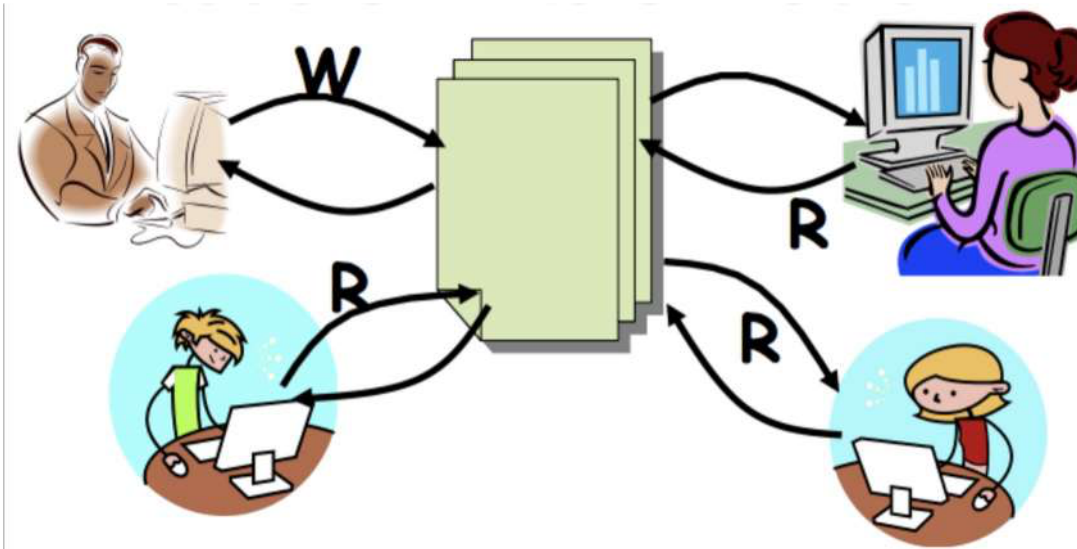
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```

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

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Readers-Writers Problem

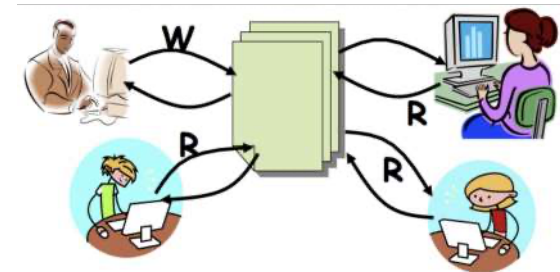
Motivation: Consider a shared database system
(more generally, any shared resource)



Readers-Writers Problem

Two classes of users:

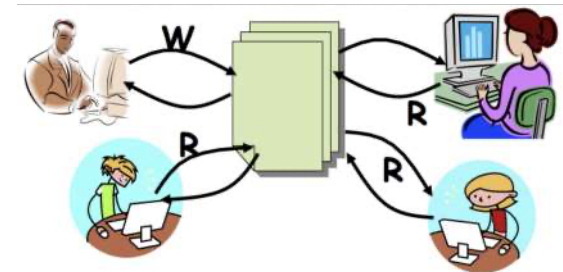
- **Readers** → never modify the DB



Readers-Writers Problem

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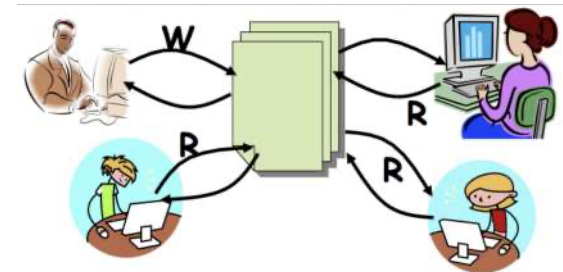
- **Readers** → never modify the DB
- **Writers** → read and modify the DB



Readers-Writers Problem

Simplest solution:

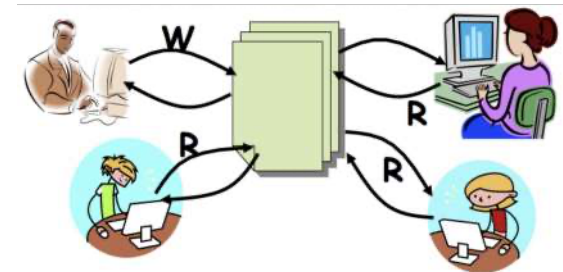
- Use a single lock on the data object for each operation



Readers-Writers Problem

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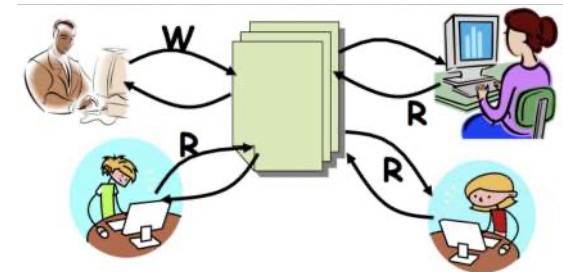
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Readers-Writers Problem

Simplest solution:

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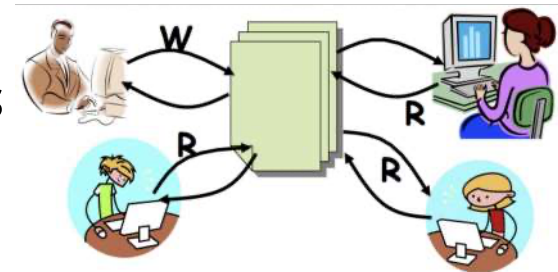


Only one writer at a time but, possibly, multiple readers

Readers-Writers Problem

Constraints:

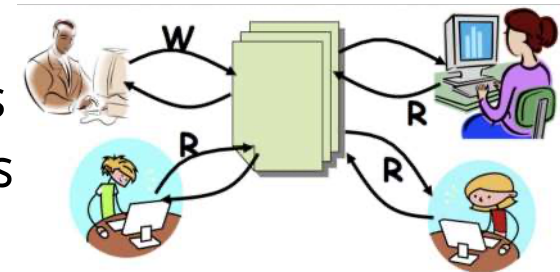
- Readers can access DB when no writers



Readers-Writers Problem

Constraints:

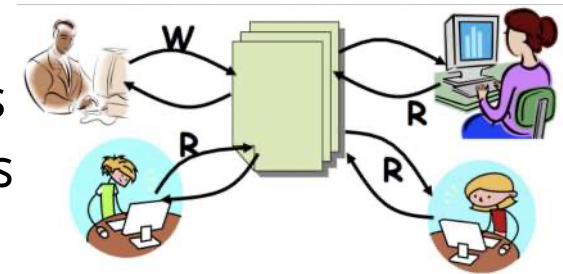
- Readers can access DB when no writers
- Writers can access DB when no readers or writers



Readers-Writers Problem

Constraints:

- 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

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Readers-Writers Problem

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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

- 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

Readers-Writers in Java Using Lock

Readers-Writers in Java Using Monitors

Summary

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