Systems and Networking – Unit I

B.Sc. in Applied Computer Science and Artificial Intelligence

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Gabriele Tolomei

Department of Computer Science

Sapienza Università di Roma

tolomei@di.uniroma1.it

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Process/Thread Synchronization

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Synchronization as a solution to the critical section problem

Part III: Process Synchronization

The Need for Synchronization: Example

Consider the following real-world scenario, involving 2 roommates: Bob and Carla

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5:20pm		Arrive home

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5:20pm		Arrive home
5:25pm	Arrive at the grocery	Look in the fridge → No milk!

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5:45pm	Arrive home, put the milk in the fridge	Arrive at the grocery

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5:50pm		Buy milk

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5:45pm	Arrive home, put the milk in the fridge	Arrive at the grocery
5:50pm		Buy milk
6:05pm		Arrive home, put the milk in the fridge

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5:25pm	Arrive at the grocery	Look in the fridge → No milk!
5:30pm	Buy milk	Leave home for the grocery
5:45pm	Arrive home, put the milk in the fridge	Arrive at the grocery
5:50pm		Buy milk
6:05pm		Arrive home, put the milk in the fridge
6:05pm	Oh f*%#k!	Oh f*%#k!

The Need for Synchronization: Example

- In the example, Bob and Carla represents 2 processes/threads
- Theoretically, they should cooperate to achieve a common task (e.g., buying some milk)
- In practice, though, they might incur in unpleasant situations (e.g., buying too much milk!)

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- Theoretically, they should cooperate to achieve a common task (e.g., buying some milk)
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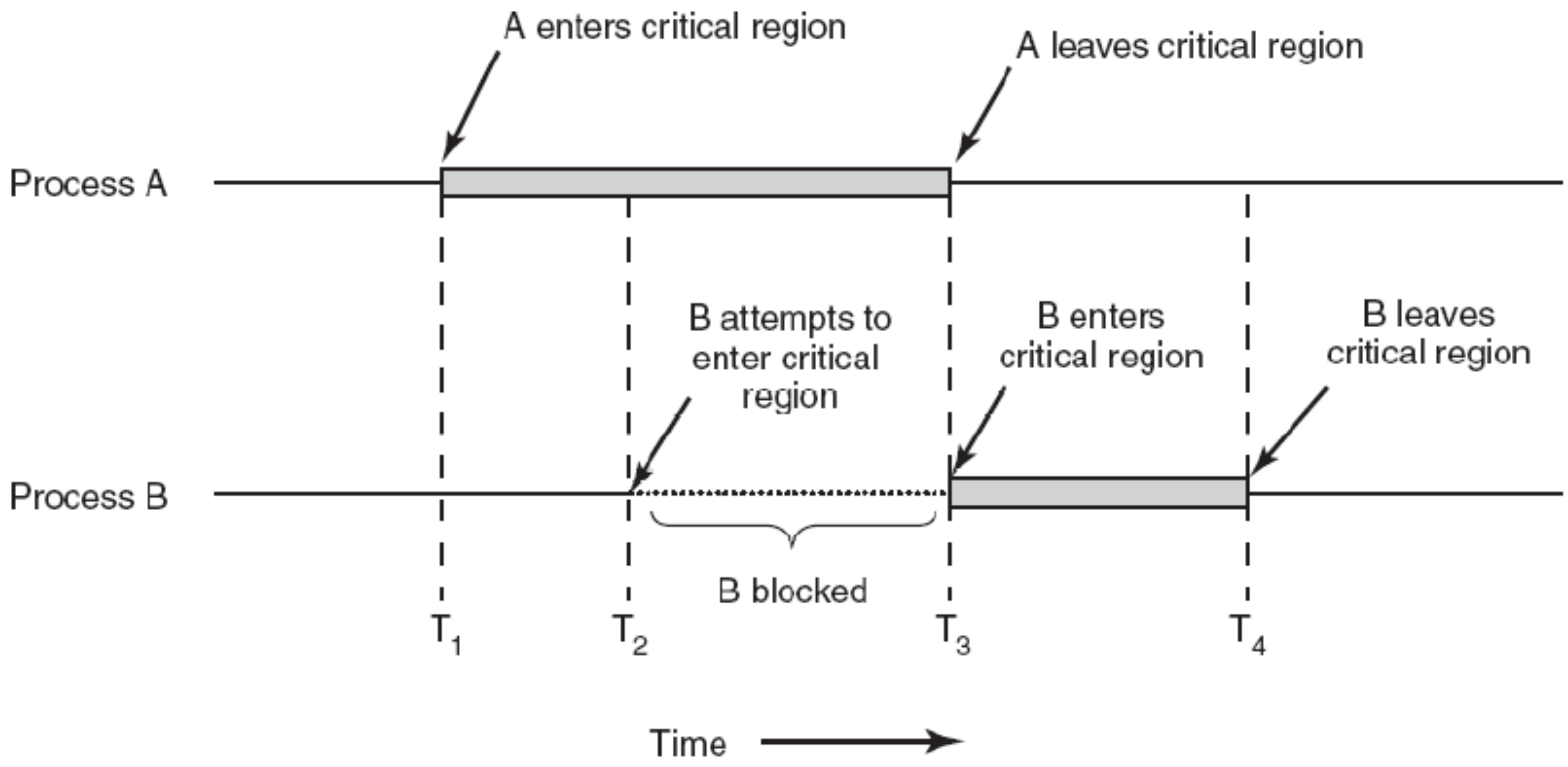
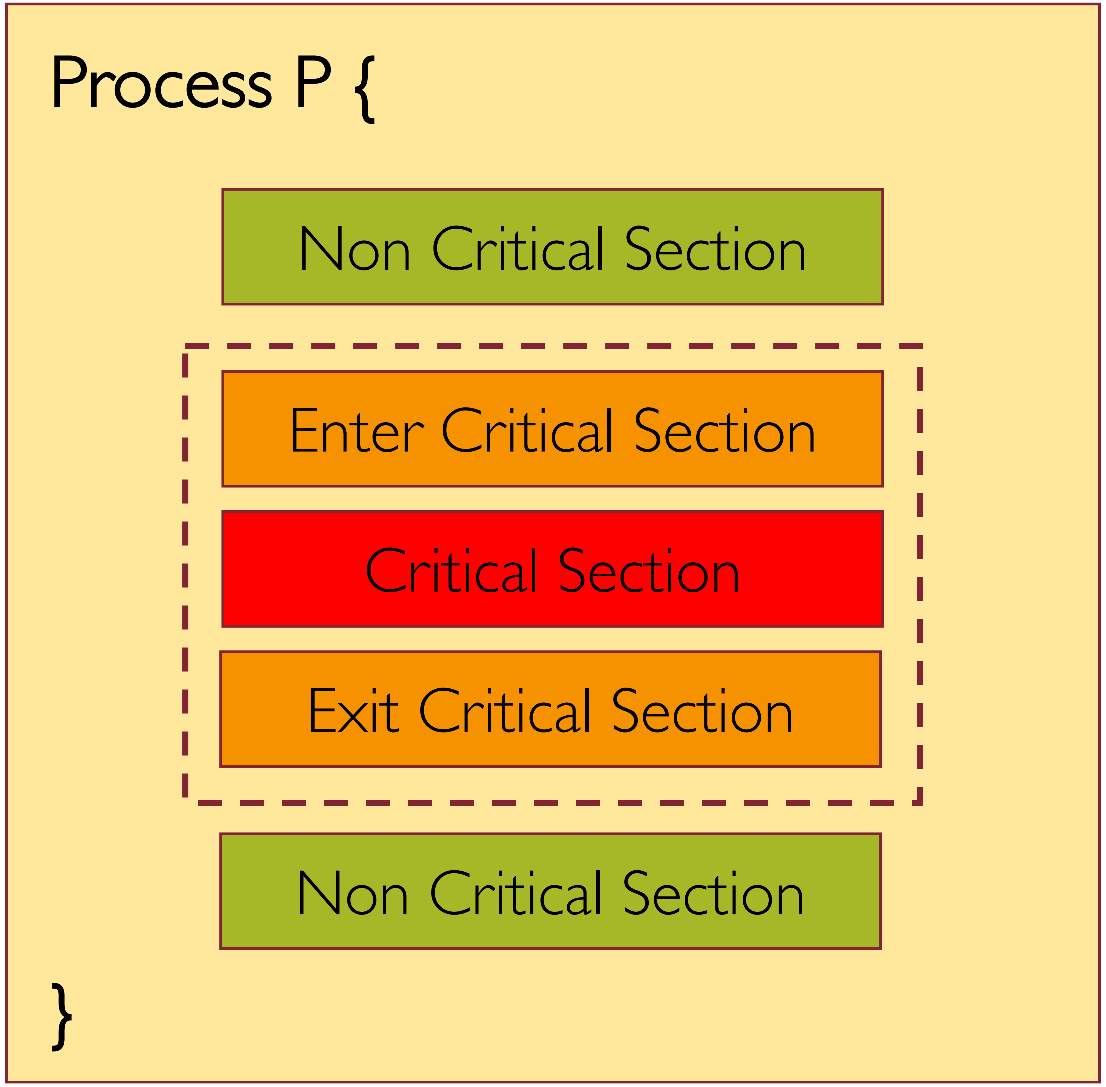
What kind of mechanisms do we need in order to get independent yet cooperating processes to communicate
and have a consistent view of the "world" (i.e., computational state)?

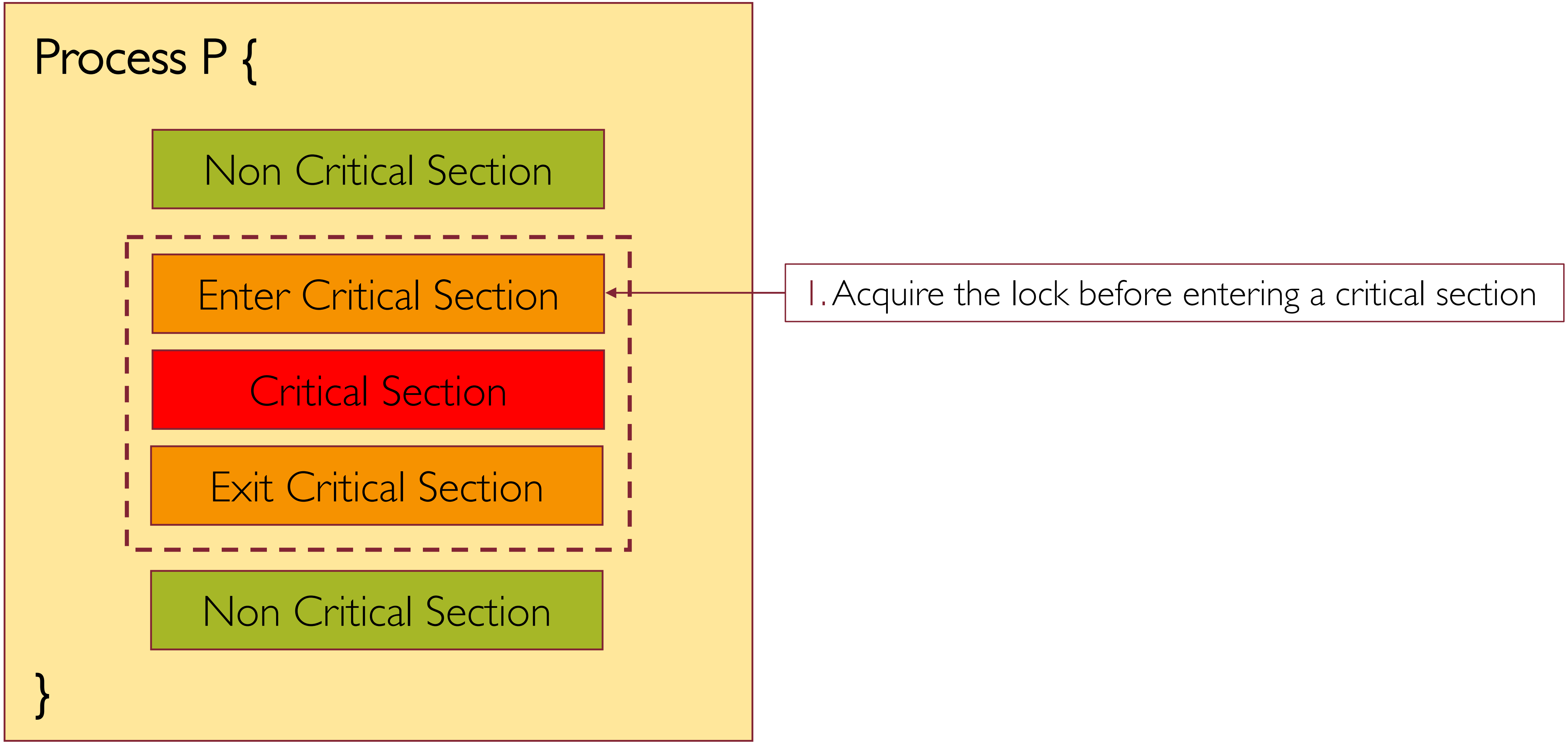
The Critical Section Problem



The Anatomy of a Critical Section



Locking Critical Section



Locking Critical Section

Process P {

Non Critical Section

Enter Critical Section

Critical Section

Exit Critical Section

Non Critical Section

}

2. Wait if someone else has already taken the lock

Locking Critical Section

Process P {

Non Critical Section

Enter Critical Section

Critical Section

Exit Critical Section

Non Critical Section

}

3. Release the lock after leaving a critical section

Locking Critical Section

Process P {

Non Critical Section

Enter Critical Section

Critical Section

Exit Critical Section

Non Critical Section

}

All synchronization involves waiting!

Synchronization: Goals

- Any synchronization solution to the critical section problem must satisfy 3 properties:
  - Mutual Exclusion → only one process/thread can be in its critical section at a time!

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Synchronization: Goals

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  - Mutual Exclusion → only one process/thread can be in its critical section at a time!
  - Liveness → If no process is in its critical section, and one or more want to execute it then any one of these must be able to get into its critical section
  - Bounded Waiting → A process requesting entry into its critical section will get a turn eventually, and there is a limit on how many others get to go first

Synchronization: Goals

- In the milk example:
  - Ensuring mutual exclusion means no more milk than what is needed will be bought (i.e., only one between Bob and Carla will buy milk if needed)

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  - Ensuring mutual exclusion means no more milk than what is needed will be bought (i.e., only one between Bob and Carla will buy milk if needed)
  - Ensuring liveness means that someone should buy some milk (i.e., the option where both Bob and Carla do not do anything is surely safe but undesirable)
  - Ensuring bounding waiting means that eventually Bob and Carla will enter their critical section

Too Much Milk: Solution 1

Use a **note**

```
# Thread Bob

if (!milk and !note):
    leave_note()
    buy_milk()
    remove_note()
```

```
# Thread Carla

if (!milk and !note):
    leave_note()
    buy_milk()
    remove_note()
```

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Does this solution work?

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Does this solution work regardless of the scheduling?

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```
# Thread Carla

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    leave_note()
    buy_milk()
    remove_note()
```

Does this solution work regardless of the scheduling?

No! mutual exclusion can be violated

Too Much Milk: Solution 2

Use 2 (labeled) notes

```
# Thread Bob

leave_note(Bob)

if (!note(Carla)):
    if (!milk):
        buy_milk()

remove_note()
```

```
# Thread Carla

leave_note(Carla)

if (!note(Bob)):
    if (!milk):
        buy_milk()

remove_note()
```

Too Much Milk: Solution 2

Use 2 (labeled) notes

```
# Thread Bob

leave_note(Bob)

if (!note(Carla)):
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remove_note()
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# Thread Carla

leave_note(Carla)

if (!note(Bob)):
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remove_note()
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Does this solution work regardless of the scheduling?

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Use 2 (labeled) notes

```
# Thread Bob

leave_note(Bob)

if (!note(Carla)):
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remove_note()
```

```
# Thread Carla

leave_note(Carla)

if (!note(Bob)):
    if (!milk):
        buy_milk()

remove_note()
```

Does this solution work regardless of the scheduling?

No! Liveness propery can be violated

Too Much Milk: Solution 3

Use 2 (labeled) notes… more cleverly

```
# Thread Bob

leave_note(Bob)

while (note(Carla)):
    do_nothing()
if (!milk):
    buy_milk()

remove_note()
```

```
# Thread Carla

leave_note(Carla)

if (!note(Bob)):
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        buy_milk()

remove_note()
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Too Much Milk: Solution 3

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```
# Thread Bob

leave_note(Bob)

while (note(Carla)):
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Does this solution work regardless of the scheduling?

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if (!note(Bob)):
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        buy_milk()

remove_note()
```

Does this solution work regardless of the scheduling?

Yes!

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

while (note(Carla)):
    do_nothing()
if (!milk):
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remove_note()
```

Y:

```
# Thread Carla

leave_note(Carla)

if (!note(Bob)):
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remove_note()
```

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# Thread Bob

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Case 1: no note from Bob

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Case 1: no note from Bob

Thread Bob must be executing different code

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Thread Bob must be executing different code

Carla will buy milk only if needed

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remove_note()
```

Case 2: Bob has left a note

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Case 2: Bob has left a note

So has Carla, therefore Bob will be waiting (loop)

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Case 2: Bob has left a note

So has Carla, therefore Bob will be waiting (loop)

Carla will remove his note and Bob will buy milk if needed

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

while (note(Carla)):
    do_nothing()
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X:

Case 1: no note from Carla

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# Thread Carla

leave_note(Carla)

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Too Much Milk: Solution 3

Case 2: Carla has left a note

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remove_note()
```

Case 2: Carla has left a note

Bob will wait doing nothing until Carla removes her note

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  - busy waiting → thread Bob is consuming CPU cycles doing nothing

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  - asymmetrical → thread Bob and Carla are different (adding more threads will mess up things even more!)
  - busy waiting → thread Bob is consuming CPU cycles doing nothing

This solution assumes loads and stores being atomic (i.e., non-interruptable)

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We need to have appropriate "tools" (i.e., primitive constructs)
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- 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

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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):
    buy_milk()

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

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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

- On single-CPU systems, we can prevent the scheduler to take over by:
  - internal events → enforcing threads not to request any I/O operation during a critical section

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  - internal events → enforcing threads not to request any I/O operation during 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

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

  Lock() {
    // lock is initially FREE
    this.value = 0;
    this.q = null;
  }
}
```

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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  }
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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
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    this.value = 1;
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Implementing Locks: Disabling Interrupts

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public void release() {
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We need both **acquire** and **release** being implemented as system calls

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Why?

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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)

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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  - 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
- Examples:
  - **`test&set`** (most architectures) → reads a value, writes **`1`** back to memory
  - **`exchange`** (x86) → swaps values between register and memory

Implementing Locks: `test&set`

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Implementing Locks: **`test&set`**

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  while(test&set(this.value) == 1) {
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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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Case 1: if lock is free (`value = 0`) `test&set(value)` 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 (`value = 1`) `test&set(value)` will read `1`, set it to `1` and return `1`

Implementing Locks: `test&set`

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public void acquire() {
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```
public void release() {
  this.value = 0;
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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?

```
public void acquire() {
  while(test&set(this.value) == 1) {
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}
```

- What's wrong with the above implementation?

Atomic Instructions: Any Issue?

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Atomic Instructions: Any Issue?

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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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- 2 main problems with disabling interrupts:
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  - unfeasible with mulitprocessor architectures
- 2 main problems with atomic instructions:
  - busy waiting
  - unfairness as there is no queue where threads wait for the lock to be released

Improving `test&set` To Reduce Busy Waiting

Can we implement locks with `test&set` without any busy-waiting?

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    t.sleep_and_reset_guard_to_0();
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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`**

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