

Sistemi Operativi

Corso di Laurea in Informatica

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Process/Thread Synchronization

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- Synchronization primitives are required to ensure that only one thread at a time executes a critical section

Synchronization as a solution to the critical section problem

The Need for Synchronization: Example

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

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5:00pm	Arrive home	

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Time	Bob	Carl
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5:05pm	Look in the fridge → No milk!	

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5:20pm		Arrive home

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Time	Bob	Carl
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5:10pm	Leave home for the grocery	
5:20pm		Arrive home
5:25pm	Arrive at the grocery	Look in the fridge → No milk!

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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

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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

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

Time	Bob	Carl
5:00pm	Arrive home	
5:05pm	Look in the fridge → No milk!	
5:10pm	Leave home for the grocery	
5:20pm		Arrive home
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!

The Need for Synchronization: Example

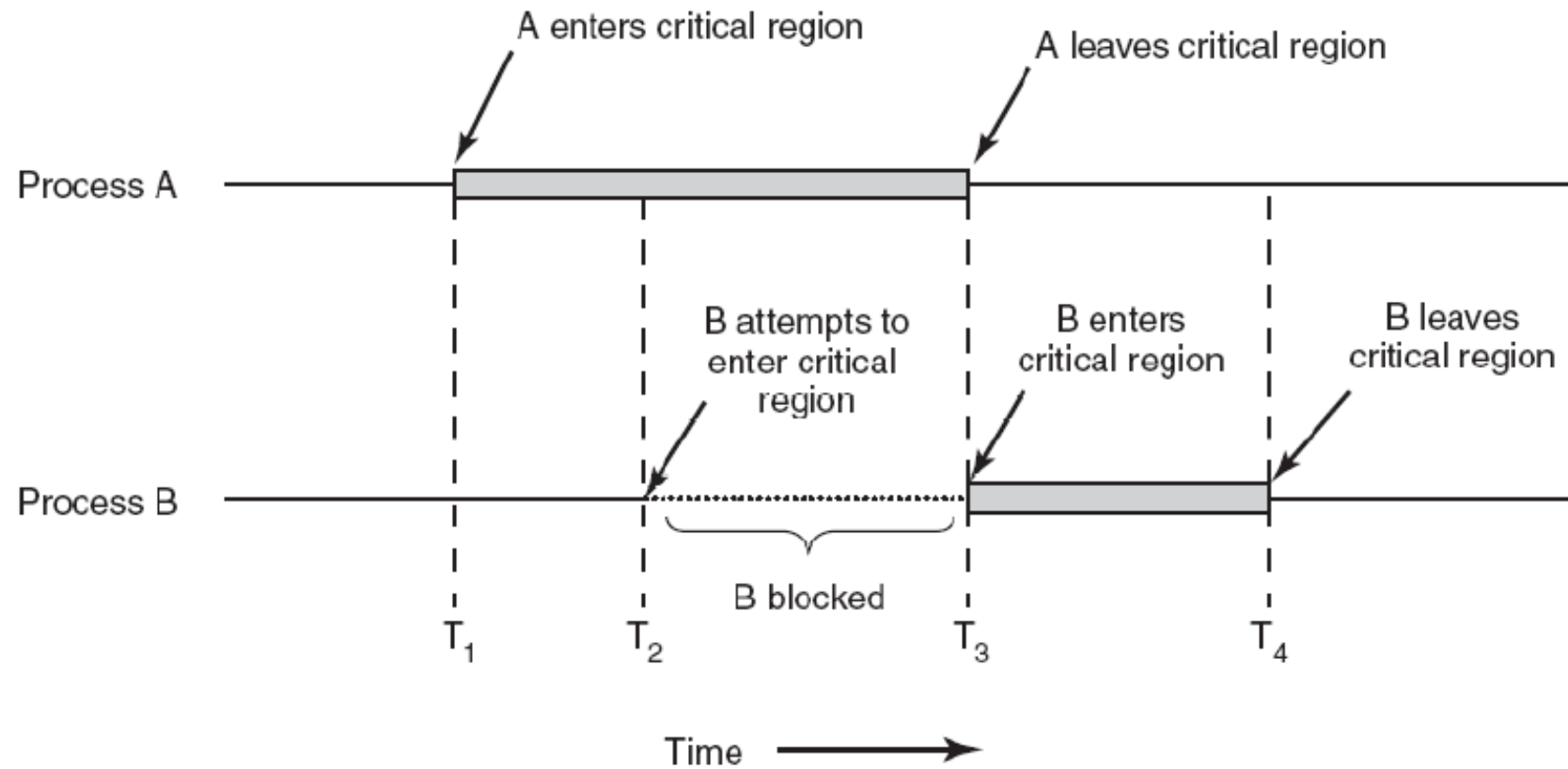
- In the example **Bob** and **Carl** represents 2 processes/threads
- Theoretically, they should cooperate to achieve a common task (e.g., buying some milk)
- In practice, though, they might incur in unpleasant situations (e.g., buying too much milk!)

The Need for Synchronization: Example

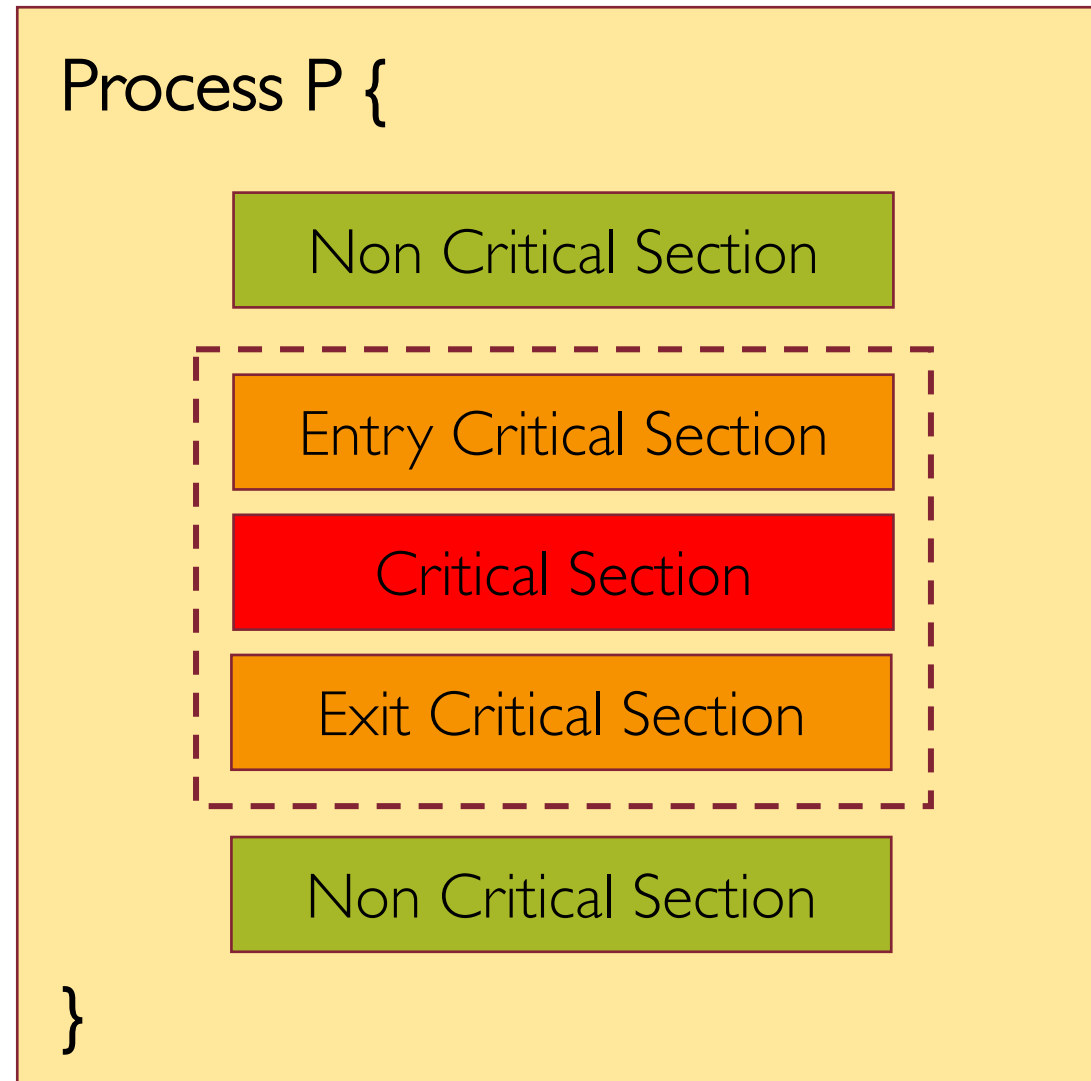
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- Theoretically, they should cooperate to achieve a common task (e.g., buying some milk)
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What kind of mechanisms do we need in order to get independent yet cooperating processes to communicate and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

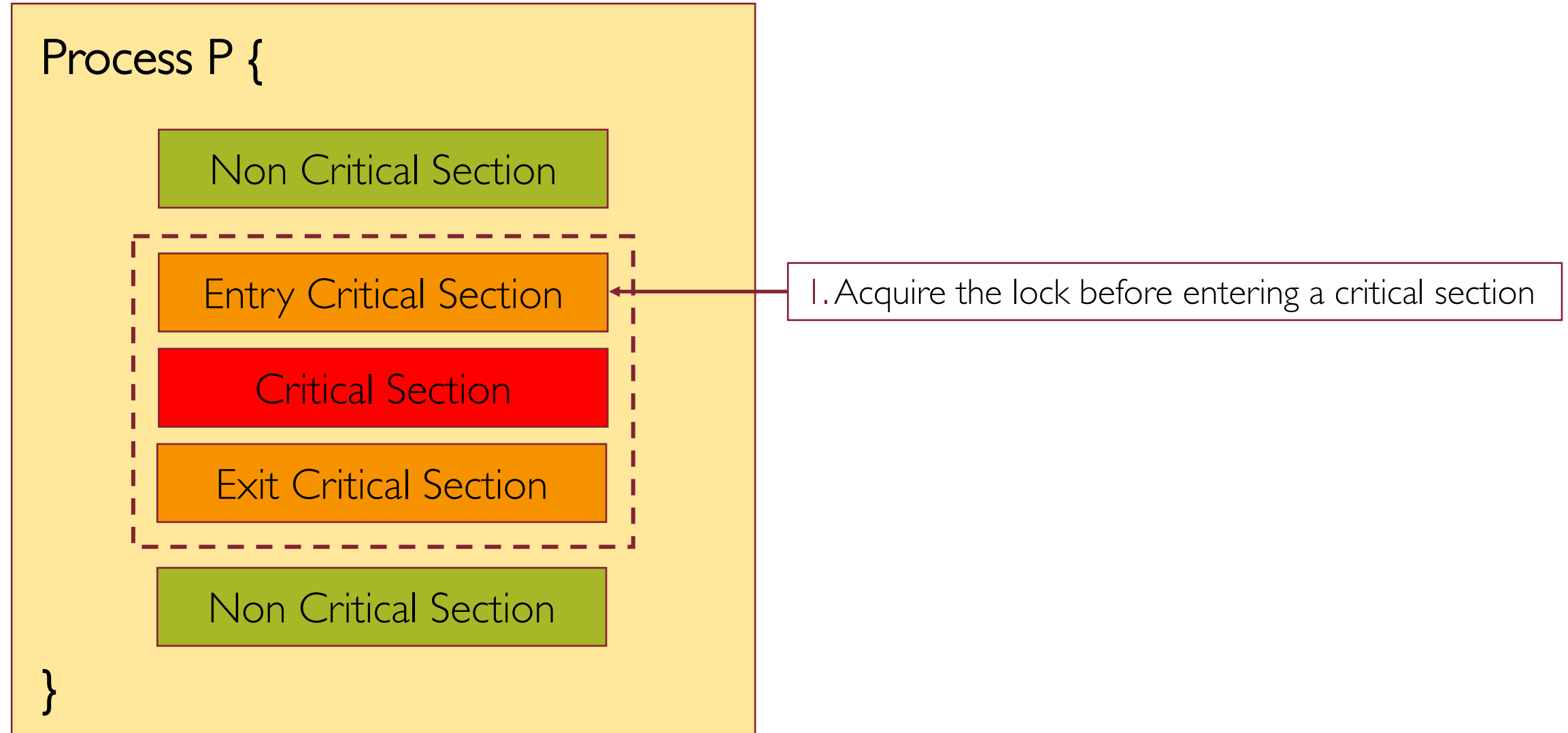
The Critical Section Problem



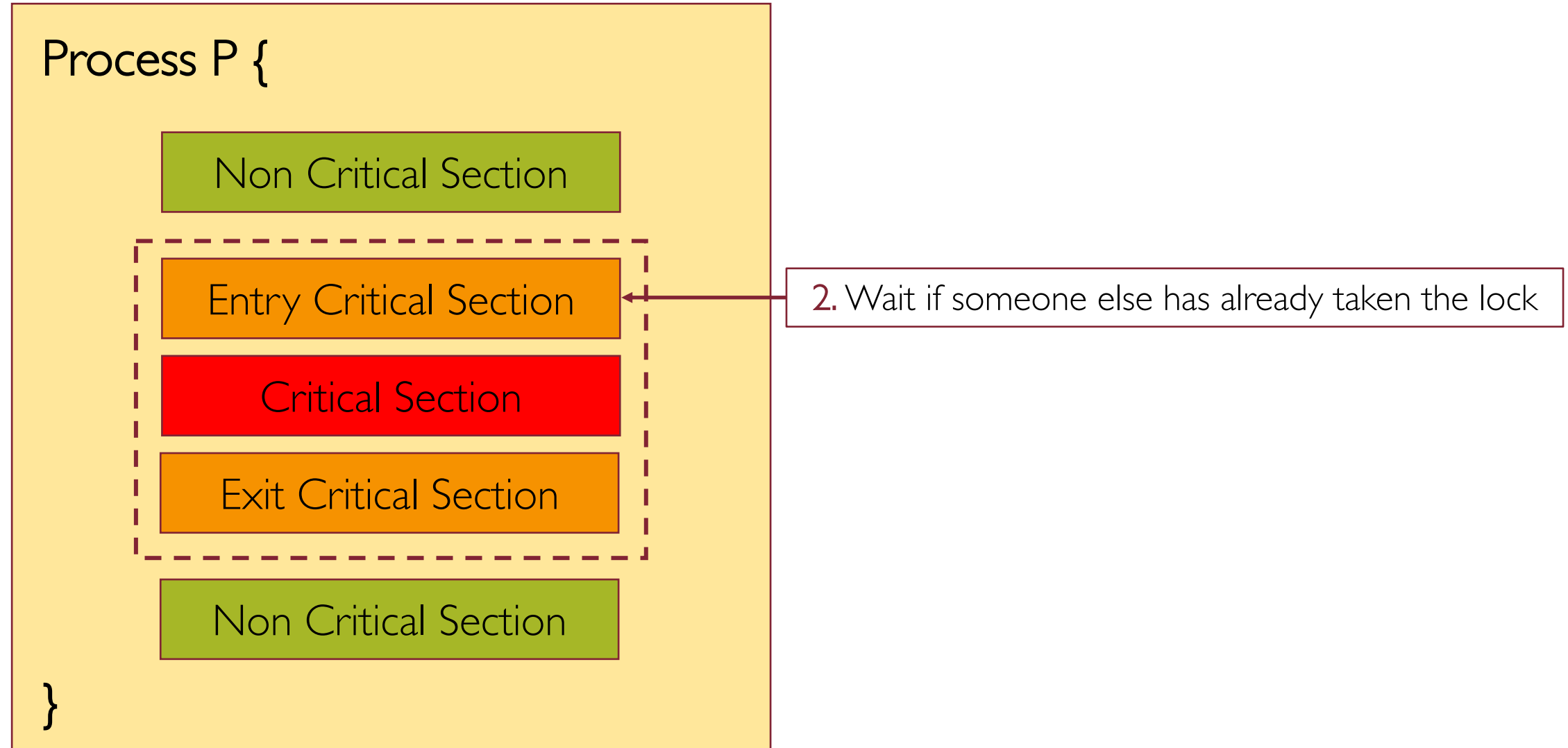
The Anatomy of a Critical Section



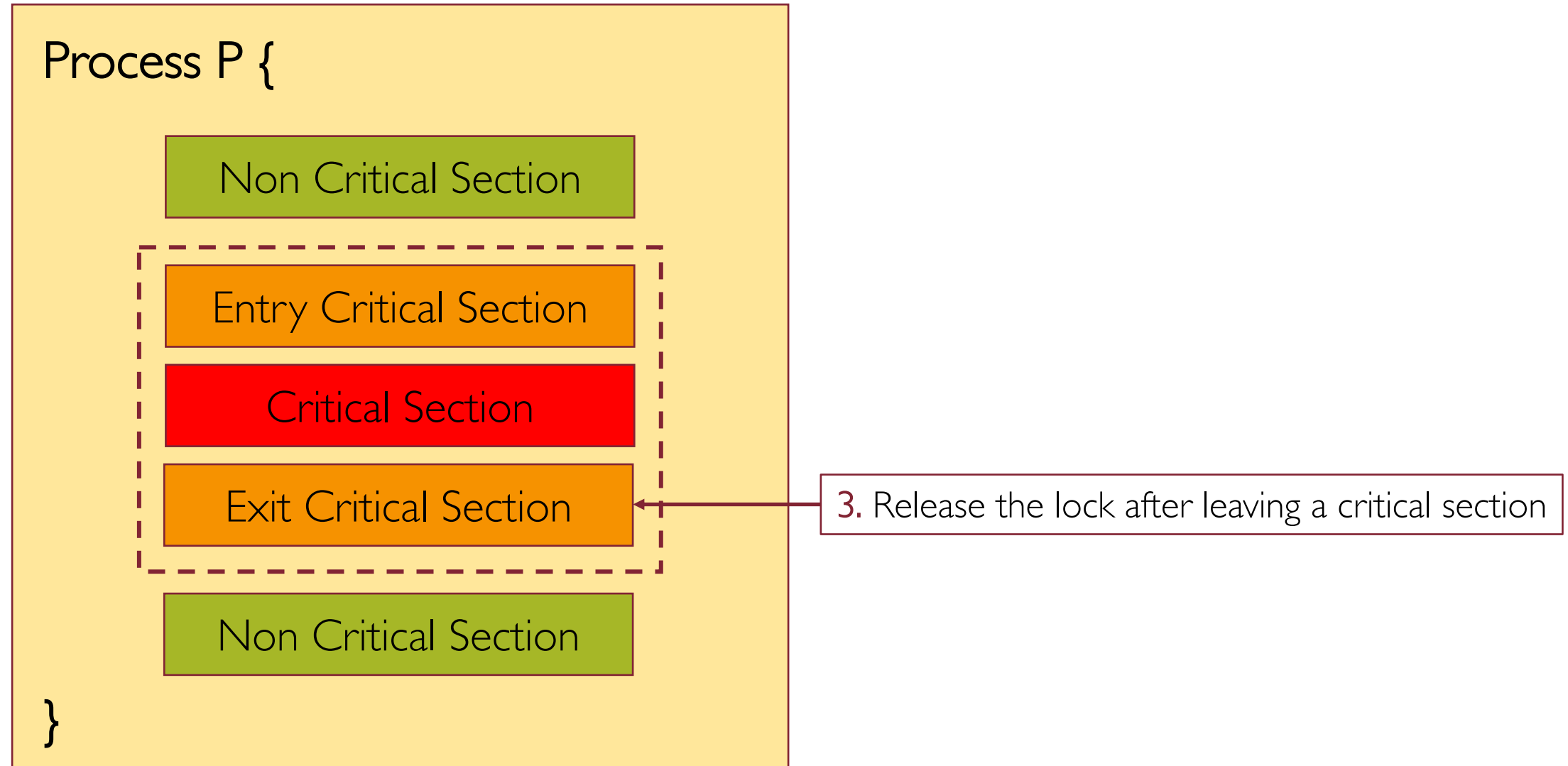
Locking Critical Section



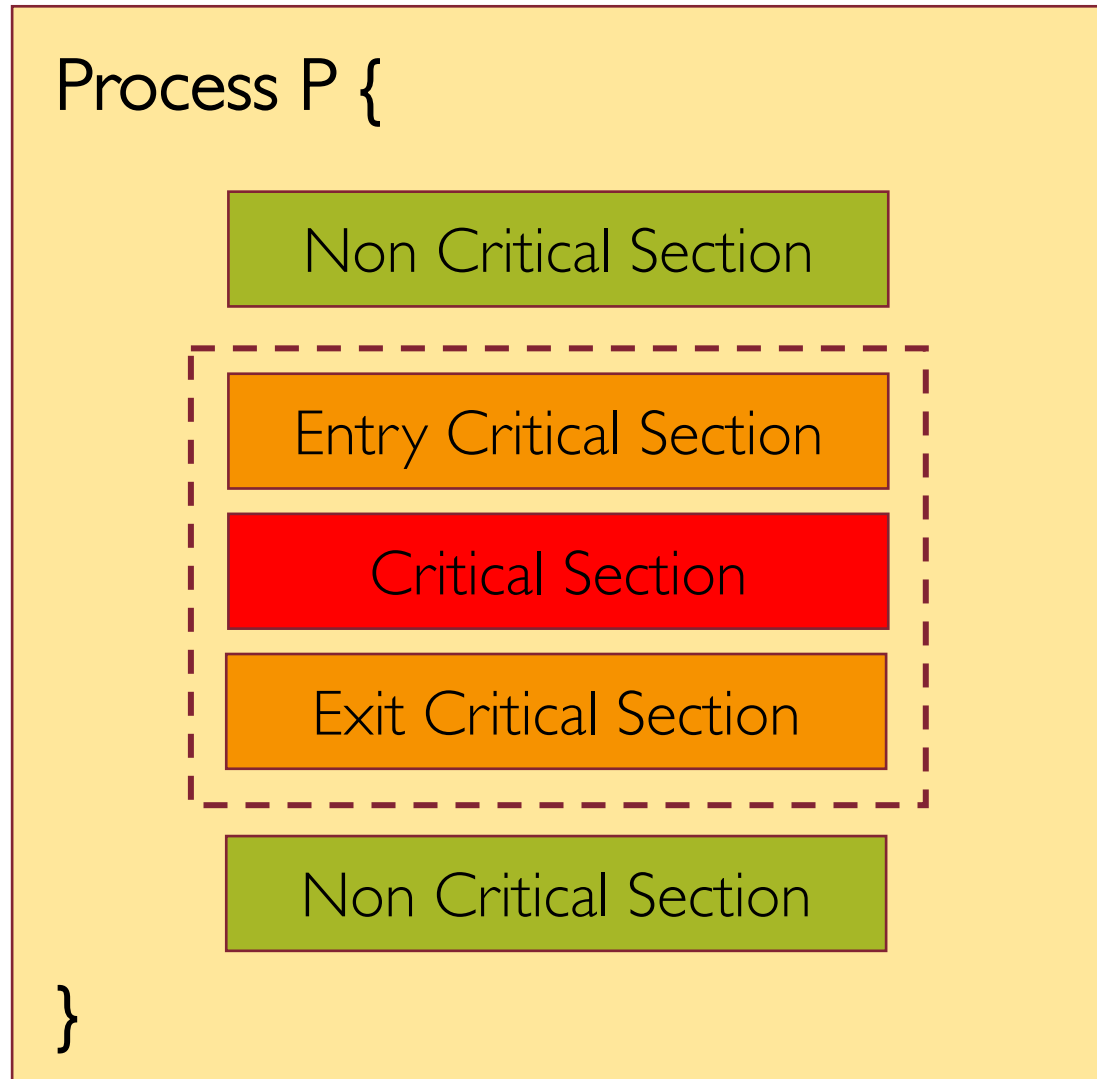
Locking Critical Section



Locking Critical Section



Locking 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

- 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!
 - **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 **Carl** will buy milk if needed)

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Synchronization: Goals

- In the milk example:
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 - Ensuring **liveness** means that someone should buy some milk (i.e., the option where both **Bob** and **Carl** do not do anything is surely safe but undesirable)
 - Ensuring **bounding waiting** means that eventually **Bob** and **Carl** will enter their critical section

Too Much Milk: Solution I

Use a **note**

```
# Thread Bob

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

```
# Thread Carl

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


Too Much Milk: Solution I

Use a **note**

```
# Thread Bob

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```

```
# Thread Carl

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

Does this solution work?

Too Much Milk: Solution I

Use a **note**

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# Thread Bob

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

```
# Thread Carl

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

Does this solution work **regardless of the scheduling?**

Too Much Milk: Solution I

Use a **note**

```
# Thread Bob

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

```
# Thread Carl

if (!milk and !note):
    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(Carl)) :
    if (!milk):
        buy_milk()

remove_note()
```

```
# Thread Carl

leave_note(Carl)

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(Carl)) :
    if (!milk):
        buy_milk()

remove_note()
```

```
# Thread Carl

leave_note(Carl)

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

remove_note()
```

Does this solution work regardless of the scheduling?

Too Much Milk: Solution 2

Use 2 (labeled) notes

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

```
# Thread Carl

leave_note(Carl)

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

remove_note()
```

Does this solution work **regardless of the scheduling?**

No! Liveness property can be violated

Too Much Milk: Solution 3

Use **2** (labeled) notes... more cleverly

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

```
# Thread Carl

leave_note(Carl)

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

remove_note()
```

Too Much Milk: Solution 3

Use **2** (labeled) notes... more cleverly

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

```
# Thread Carl

leave_note(Carl)

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

remove_note()
```

Does this solution work **regardless of the scheduling?**

Too Much Milk: Solution 3

Use **2** (labeled) notes... more cleverly

```
# Thread Bob

leave_note(Bob)

while (note(Carl)) :
    do_nothing()
if (!milk):
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```
# Thread Carl

leave_note(Carl)

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

remove_note()
```

Y: →

```
# Thread Carl

leave_note(Carl)

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

remove_note()
```

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

Y: →

```
# Thread Carl

leave_note(Carl)

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

remove_note()
```

Case 1: no note from Bob

Too Much Milk: Solution 3

```
# Thread Bob  
  
leave_note(Bob)  
  
while (note(Carl)) :  
    do_nothing()  
if (!milk):  
    buy_milk()  
  
remove_note()
```

Y: →

```
# Thread Carl  
  
leave_note(Carl)  
  
if (!note(Bob)) :  
    if (!milk):  
        buy_milk()  
  
remove_note()
```

Case 1: no note from Bob



Thread Bob must be
executing different code

Too Much Milk: Solution 3

```
# Thread Bob  
  
leave_note(Bob)  
  
while (note(Carl)) :  
    do_nothing()  
if (!milk):  
    buy_milk()  
  
remove_note()
```

Y: →

```
# Thread Carl  
  
leave_note(Carl)  
  
if (!note(Bob)) :  
    if (!milk):  
        buy_milk()  
  
remove_note()
```

Case 1: no note from Bob



Thread Bob must be
executing different code



Carl will buy milk only if
needed

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

Y: →

```
# Thread Carl

leave_note(Carl)

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

remove_note()
```

Case 2: Bob has left a note

Too Much Milk: Solution 3

```
# Thread Bob  
  
leave_note(Bob)  
  
while (note(Carl)) :  
    do_nothing()  
if (!milk):  
    buy_milk()  
  
remove_note()
```

Y: →

```
# Thread Carl  
  
leave_note(Carl)  
  
if (!note(Bob)) :  
    if (!milk):  
        buy_milk()  
  
remove_note()
```

Case 2: Bob has left a note



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

Too Much Milk: Solution 3

```
# Thread Bob  
  
leave_note(Bob)  
  
while (note(Carl)) :  
    do_nothing()  
if (!milk):  
    buy_milk()  
  
remove_note()
```

Y: →

```
# Thread Carl  
  
leave_note(Carl)  
  
if (!note(Bob)) :  
    if (!milk):  
        buy_milk()  
  
remove_note()
```

Case 2: Bob has left a note



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



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

Too Much Milk: Solution 3

X: →

```
# Thread Bob  
leave_note(Bob)  
  
while (note(Carl)) :  
    do_nothing()  
if (!milk) :  
    buy_milk()  
  
remove_note()
```

Case 1: no note from Carl

```
# Thread Carl  
leave_note(Carl)  
  
if (!note(Bob)) :  
    if (!milk) :  
        buy_milk()  
  
remove_note()
```

Too Much Milk: Solution 3

X: →

```
# Thread Bob
leave_note(Bob)
while (note(Carl)) :
    do_nothing()
if (!milk):
    buy_milk()
remove_note()
```

Case 1: no note from Carl



Thread Carl must be
executing different code

```
# Thread Carl
leave_note(Carl)

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

Too Much Milk: Solution 3

X: →

```
# Thread Bob  
leave_note(Bob)  
  
while (note(Carl)) :  
    do_nothing()  
if (!milk) :  
    buy_milk()  
  
remove_note()
```

Case 1: no note from Carl

Thread Carl must be
executing different code

Bob will buy milk only if
needed

```
# Thread Carl  
leave_note(Carl)  
  
if (!note(Bob)) :  
    if (!milk) :  
        buy_milk()  
  
remove_note()
```

Too Much Milk: Solution 3

X: →

```
# Thread Bob  
leave_note(Bob)  
  
while (note(Carl)) :  
    do_nothing()  
if (!milk) :  
    buy_milk()  
  
remove_note()
```

Case 2: Carl has left a note

```
# Thread Carl  
leave_note(Carl)  
  
if (!note(Bob)) :  
    if (!milk) :  
        buy_milk()  
  
remove_note()
```

Too Much Milk: Solution 3

X: →

```
# Thread Bob  
leave_note(Bob)  
  
while (note(Carl)) :  
    do_nothing()  
if (!milk):  
    buy_milk()  
  
remove_note()
```

Case 2: Carl has left a note



Bob will wait doing nothing
until Carl removes his note

```
# Thread Carl  
leave_note(Carl)  
  
if (!note(Bob)) :  
    if (!milk):  
        buy_milk()  
  
remove_note()
```

Too Much Milk: Solution 3

X: →

```
# Thread Bob
leave_note(Bob)

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

Case 2: Carl has left a note



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Carl will buy milk only if
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```
# Thread Carl
leave_note(Carl)

if (!note(Bob)) :
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 - **busy waiting** → thread **Bob** is consuming CPU cycles doing nothing

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

So? How Do We Implement Synchronization?

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

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So? How Do We Implement Synchronization?

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- **Semaphores** → A generalization of locks

So? How Do We Implement Synchronization?

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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

So? How Do We Implement Synchronization?

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:

Locks

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 - **Lock.acquire()** → wait until the lock is free, then grab it

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Locks

- Provide **mutual exclusion** to shared data using **2** atomic primitives:
 - **Lock.acquire()** → wait until the lock is free, then grab it
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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**

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 Carl  
  
Lock.acquire()  
  
if (!milk):  
    buy_milk()  
  
Lock.release()
```

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This solution is clean and symmetric

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Lock.acquire()  
  
if (!milk):  
    buy_milk()  
  
Lock.release()
```

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

HW Support for Synchronization

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High-level atomic operations
(SW)

lock, monitor, semaphore, send/receive

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

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 interrupt , atomic instructions (test&set)

Implementing Locks: Disabling Interrupts

- If we think about it, the reason why we care about synchronization is because context switches may occur unexpectedly

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- If we think about it, the reason why we care about synchronization is because context switches may occur unexpectedly
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Implementing Locks: Disabling Interrupts

- If we think about it, the reason why we care about synchronization is because context switches may occur unexpectedly
- The CPU scheduler takes control due to 2 possible situations:
 - **internal events** → the current thread voluntarily relinquishes control of the CPU (e.g., via an I/O system call)
 - **external events** → interrupts (e.g., time slice) cause the scheduler to take over the currently running thread

Implementing Locks: Disabling Interrupts

- If we think about it, the reason why we care about synchronization is because context switches may occur unexpectedly
- The CPU scheduler takes control due to **2** possible situations:
 - **internal events** → the current thread voluntarily relinquishes control of the CPU (e.g., via an I/O system call)
 - **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:
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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() {  
        // lock is initially FREE  
        this.value = 0;  
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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;
    }
    enable_interrupts();
}
```

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```
public void release() {  
    disable_interrupts() ;  
    if(!q.is_empty()) {  
        t = q.pop(); // extract a waiting thread from q  
        push_onto_ready_queue(t); // put t on ready queue  
    }  
    else {  
        this.value = 0;  
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We need both **acquire** and **release** being implemented as system calls

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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 interrupt, 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 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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Class Lock {  
    public void acquire();  
    public void release();  
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```
public void acquire() {  
    while(test&set(this.value) == 1) {  
        // while busy do nothing  
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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

Implementing Locks: `test&set`

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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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    public void acquire();  
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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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```

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

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) {  
        // while busy do nothing  
    }  
}
```

- 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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- 2 main problems with disabling interrupts:
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- 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

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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