Sistemi Operativi I

Corso di Laurea in Informatica

2024-2025

Gabriele Tolomei
Dipartimento di Informatica
Sapienza Università di Roma
tolomei@di.uniroma1.it

SAPIENZA
UNIVERSITÀ DI ROMA

Process/Thread Synchronization

- We already mentioned that processes/threads can cooperate with each other in order to achieve a common task

Process/Thread Synchronization

- We already mentioned that processes/threads can cooperate with each other in order to achieve a common task
- However, cooperation may require synchronization between threads due to the presence of so-called critical sections (critical regions)

Process/Thread Synchronization

- We already mentioned that processes/threads can cooperate with each other in order to achieve a common task
- However, cooperation may require synchronization between threads due to the presence of so-called critical sections (critical regions)
- Synchronization primitives are required to ensure that only one thread at a time executes a critical section

Process/Thread Synchronization

- We already mentioned that processes/threads can cooperate with each other in order to achieve a common task
- However, cooperation may require synchronization between threads due to the presence of so-called critical sections (critical regions)
- 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

Part III:
Process Synchronization

The Need for Synchronization

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

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	
5:10pm	Leaves home for the grocery	

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	
5:10pm	Leaves home for the grocery	
5:20pm		Gets home

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	
5:10pm	Leaves home for the grocery	
5:20pm		Gets home
5:25pm	Gets at the grocery	Looks in the fridge → No milk!

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	
5:10pm	Leaves home for the grocery	
5:20pm		Gets home
5:25pm	Gets at the grocery	Looks in the fridge → No milk!
5:30pm	Buys milk	Leaves home for the grocery

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	
5:10pm	Leaves home for the grocery	
5:20pm		Gets home
5:25pm	Gets at the grocery	Looks in the fridge → No milk!
5:30pm	Buys milk	Leaves home for the grocery
5:45pm	Gets home, puts the milk in the fridge	Gets at the grocery

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	
5:10pm	Leaves home for the grocery	
5:20pm		Gets home
5:25pm	Gets at the grocery	Looks in the fridge → No milk!
5:30pm	Buys milk	Leaves home for the grocery
5:45pm	Gets home, puts the milk in the fridge	Gets at the grocery
5:50pm		Buys milk

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	
5:10pm	Leaves home for the grocery	
5:20pm		Gets home
5:25pm	Gets at the grocery	Looks in the fridge → No milk!
5:30pm	Buys milk	Leaves home for the grocery
5:45pm	Gets home, puts the milk in the fridge	Gets at the grocery
5:50pm		Buys milk
6:05pm		Gets home, puts the milk in the fridge

The Need for Synchronization

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

Time	Bob	Carla
5:00pm	Gets home	
5:05pm	Looks in the fridge → No milk!	
5:10pm	Leaves home for the grocery	
5:20pm		Gets home
5:25pm	Gets at the grocery	Looks in the fridge → No milk!
5:30pm	Buys milk	Leaves home for the grocery
5:45pm	Gets home, puts the milk in the fridge	Gets at the grocery
5:50pm		Buys milk
6:05pm		Gets home, puts the milk in the fridge
6:05pm	Oh f*%#k!	Oh f*%#k!

The Need for Synchronization:

- In the example, Bob and Carla represents 2 processes/threads

The Need for Synchronization:

- In the example, Bob and Carla represents 2 processes/threads
- Theoretically, they should cooperate to achieve a common task (e.g., buying some milk)

The Need for Synchronization:

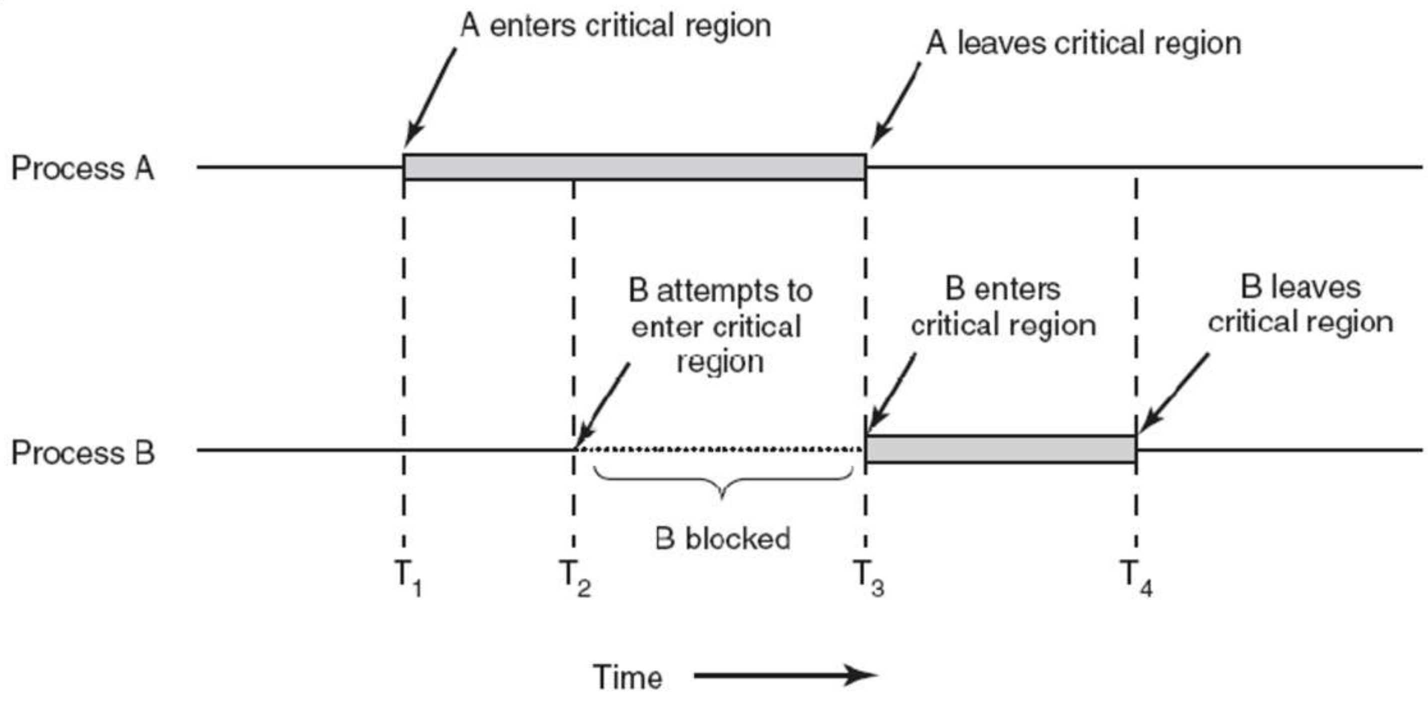
- In the example, Bob and Carla represents 2 processes/threads
- Theoretically, they should cooperate to achieve a common task (e.g., buying some milk)
- In practice, though, they might incur in unpleasant situations (e.g., buying too much milk!)

The Need for Synchronization:

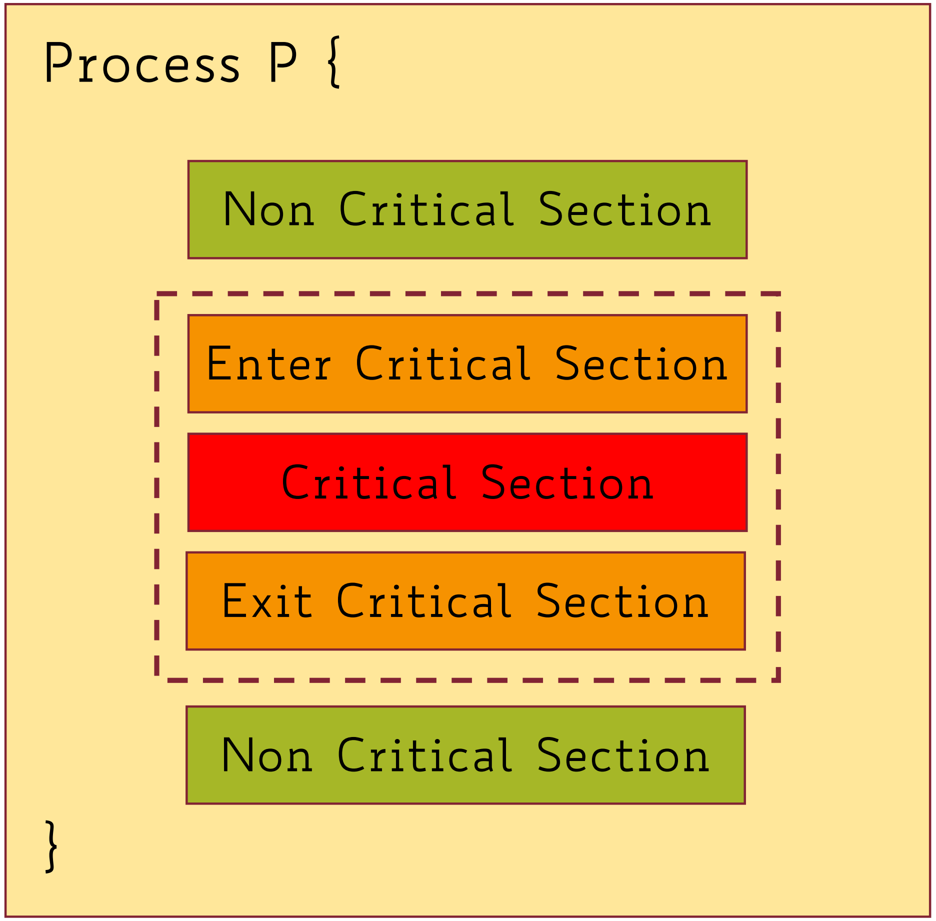
- In the example, Bob and Carla represents 2 processes/threads
- Theoretically, they should cooperate to achieve a common task (e.g., buying some milk)
- In practice, though, they might incur in unpleasant situations (e.g., buying too much milk!)

What mechanism do we need to get independent yet cooperating processes to communicate with each other
and have a consistent view of the "world" (i.e., computational state)?

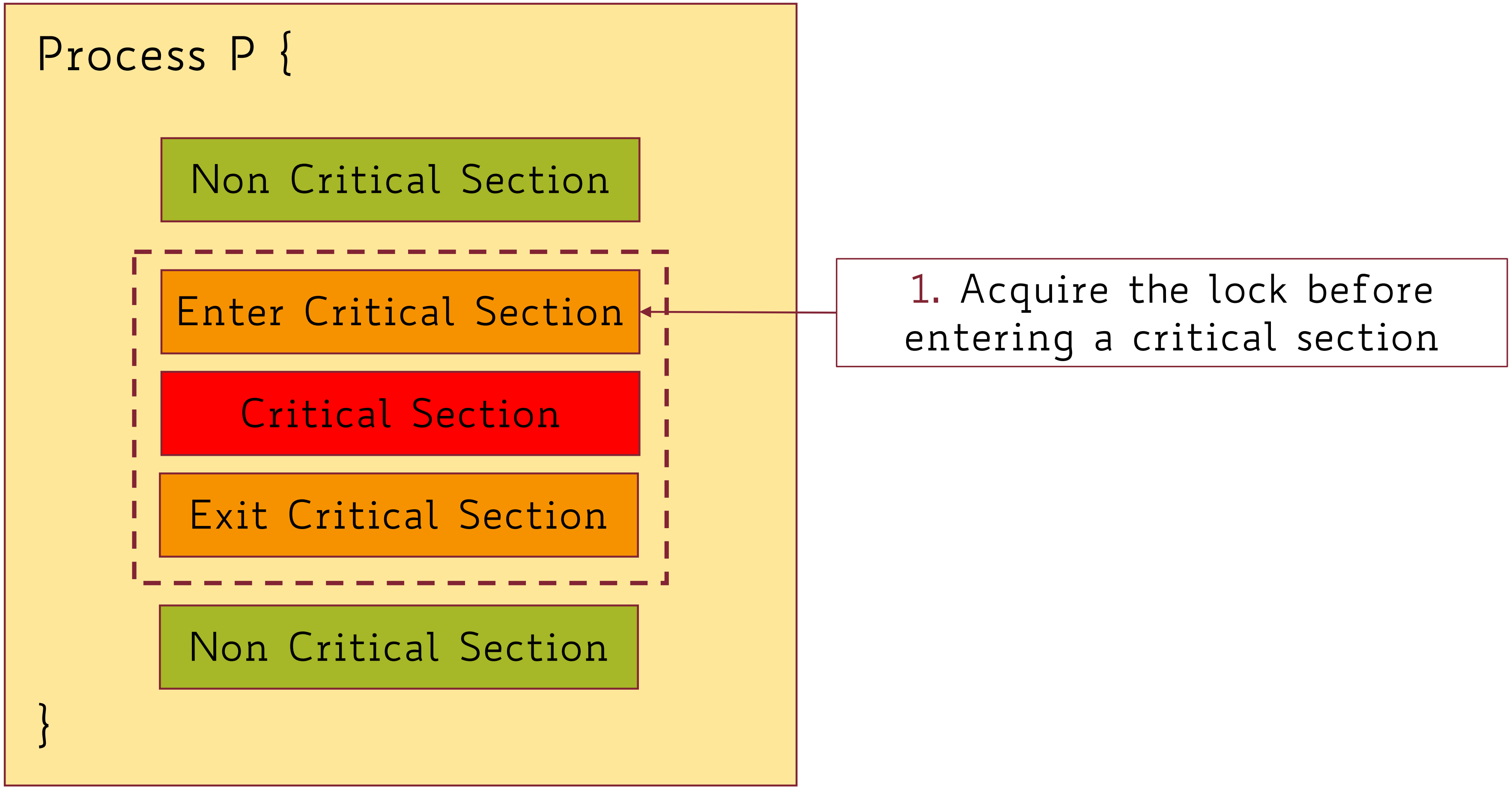
The Critical Section Problem



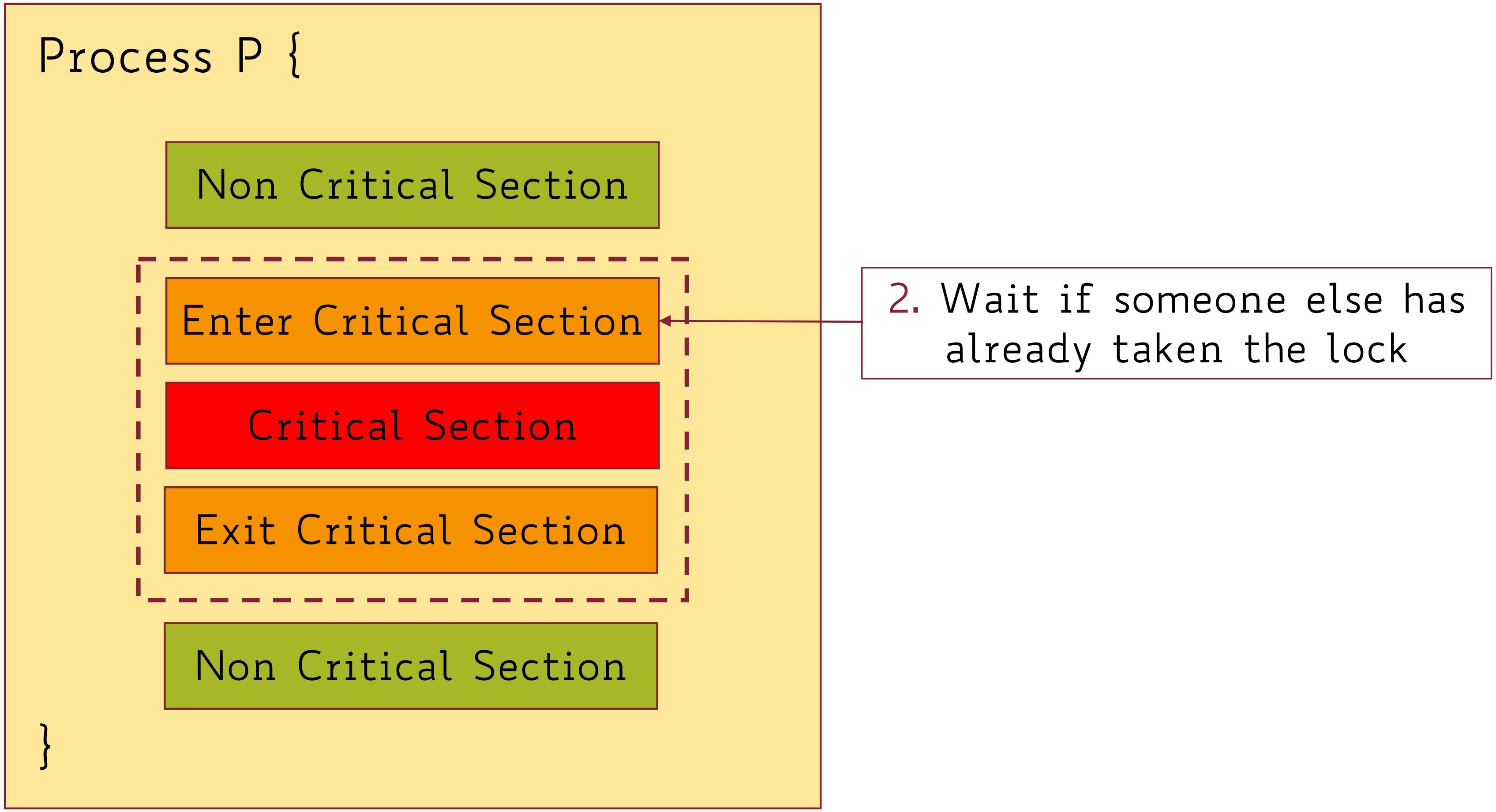
The Anatomy of a Critical Section



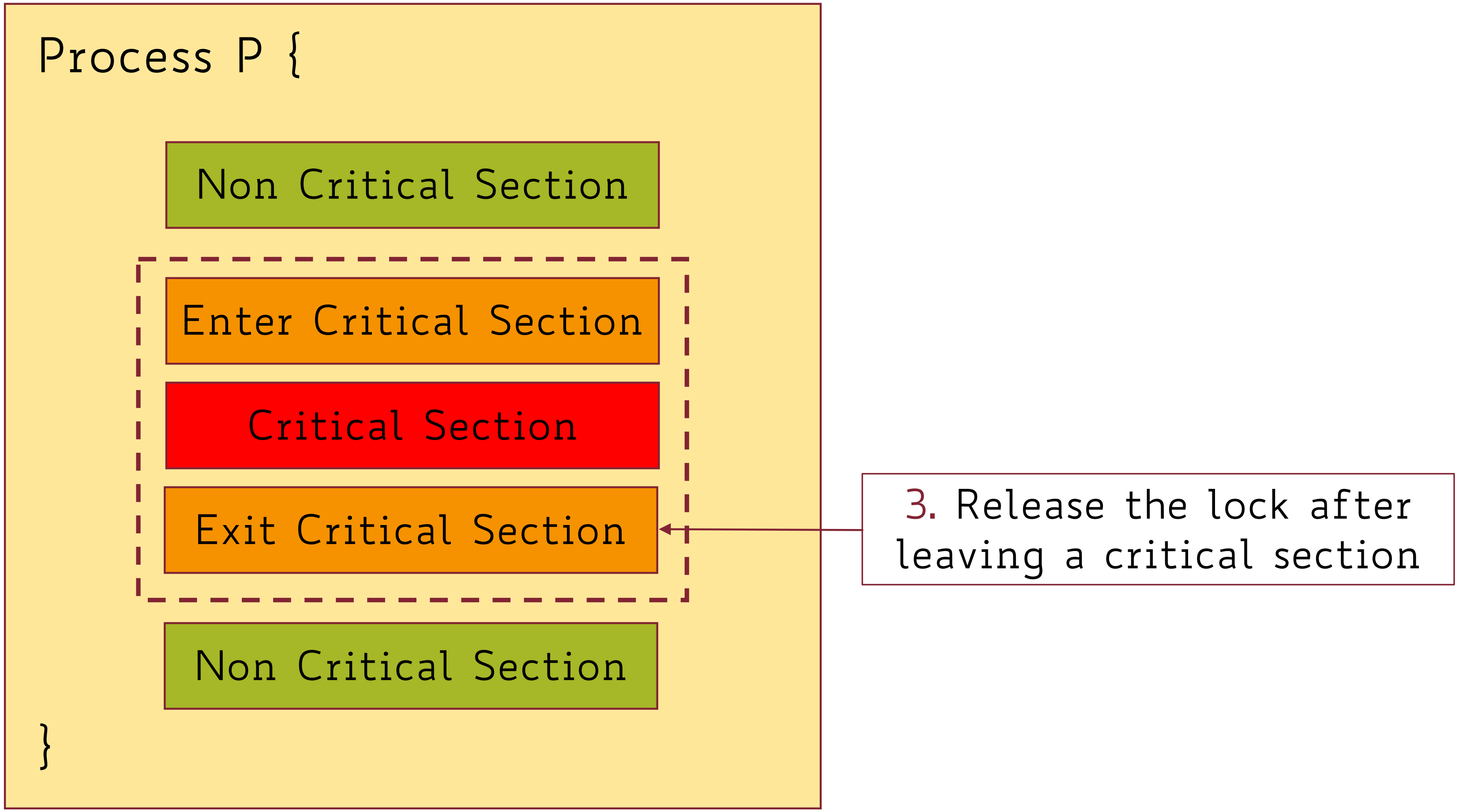
Locking Critical Section



Locking Critical Section



Locking Critical Section



Locking Critical Section

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:

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!

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

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 Carla will buy milk if needed)

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)
  - 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)

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)
  - 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()
```

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()
```

Does this solution work?

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()
```

Does this solution work regardless of the scheduling?

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()
```

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

remove_note()
```

```
# Thread Carla

leave_note(Carla)

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

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

remove_note()
```

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

remove_note()
```

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Y:

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

Y:

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Y:

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

```
# Thread Carla

leave_note(Carla)

if (!note(Bob)):      <- Y:
    if (!milk):
        buy_milk()

remove_note()
```

Case 1: no note from Bob

Thread Bob must be executing different code

Carla will buy milk only if needed

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Y:

Case 2: Bob has left a note

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

Y: →

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Case 2: Bob has left a note

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

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

Y:

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

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)):      <- X:
    do_nothing()
if (!milk):
    buy_milk()

remove_note()
```

Case 1: no note from Carla

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

X:

Case 1: no note from Carla

Thread Carla must be executing different code

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

X:

Case 1: no note from Carla

Thread Carla must be executing different code

Bob will buy milk only if needed

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

X:

Case 2: Carla has left a note

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

X:

Case 2: Carla has left a note

Bob will wait doing nothing until Carla removes her note

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Too Much Milk: Solution 3

```
# Thread Bob

leave_note(Bob)

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

remove_note()
```

X:

Case 2: Carla has left a note

Bob will wait doing nothing until Carla removes her note

Carla will buy milk only if needed

```
# Thread Carla

leave_note(Carla)

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

remove_note()
```

Is Solution 3 Good?

$\boxed{\text{Not exactly!}}$

Is Solution 3 Good?

Not exactly!

- 3 main reasons why this solution is not viable:

Is Solution 3 Good?

Not exactly!

- 3 main reasons why this solution is not viable:
  - too complicated → it is quite hard to see that it actually works

Is Solution 3 Good?

$\boxed{\text{Not exactly!}}$

- 3 main reasons why this solution is not viable:
  - too complicated → it is quite hard to see that it actually works
  - asymmetrical → thread Bob and Carla are different (adding more threads will mess up things even more!)

Is Solution 3 Good?

Not exactly!

- 3 main reasons why this solution is not viable:
  - too complicated → it is quite hard to see that it actually works
  - 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

Is Solution 3 Good?

Not exactly!

- 3 main reasons why this solution is not viable:
  - too complicated → it is quite hard to see that it actually works
  - 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)

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

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

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

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

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

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

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()

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

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()
```

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

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

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

HW Support for Synchronization

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

HW Support for Synchronization

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

High-level atomic operations (SW)	lock, monitor, semaphore, send/receive

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)

Summary

- Communication among threads is usually done via shared variables

Summary

- Communication among threads is usually done via shared variables
- Access or modification to those shared variable often identifies critical sections

Summary

- Communication among threads is usually done via shared variables
- Access or modification to those shared variable often identifies critical sections
- A critical section is a piece of code that cannot be executed in parallel or concurrently by multiple threads

Summary

- Communication among threads is usually done via shared variables
- Access or modification to those shared variable often identifies critical sections
- A critical section is a piece of code that cannot be executed in parallel or concurrently by multiple threads
- Synchronization primitives ensure only one thread at a time executes a critical section (mutual exculsion), e.g., locks