

Part III

Synchronization

Critical Section and Mutual Exclusion

*The question of whether computers can think is just like
the question of whether submarines can swim*

Process Synchronization Topics

- **Why is synchronization needed?**
- **Race Conditions**
- **Critical Sections**
- **Pure Software Solutions**
- **Hardware Support**
- **Semaphores**
- **Race Conditions, Revisited**
- **Monitors**

Synchronization Needed! 1/6

```
int a[3] = { 3, 4, 5};
```

Process 1

```
a[1] = a[0] + a[1];
```

Process 2

```
a[2] = a[1] + a[2];
```

```
a[3] = { 3, ?, ? }
```

Statement level execution interleaving

Synchronization Needed! 2/6

```
int a[3] = { 3, 4, 5};
```

Process 1

```
a[1] = a[0] + a[1];
```

Process 2

```
a[2] = a[1] + a[2];
```

- If process 1 updates $a[1]$ first, $a[1]$ is 7, and $a[] = \{3, 7, 5\}$
- Then, process 2 uses the new $a[1]$ to compute $a[2]$, and $a[] = \{3, 7, 12\}$
- If process 2 uses $a[1]$ first, now $a[2]$ is 9, and $a[] = \{3, 4, 9\}$
- Then, process 1 computes $a[1]$, and $a[] = \{3, 7, 9\}$

Results are non-deterministic!

Synchronization Needed! 3/6

```
int Count = 10;
```

Process 1

Process 2



Higher-level language statements are **not** atomic

Count = 9, 10 or 11?

Synchronization Needed! 4/6

```
int Count = 10;
```

Process 1

```
  ⋮  
LOAD  Reg, Count  
ADD   #1  
STORE Reg, Count  
  ⋮
```

Process 2

```
  ⋮  
LOAD  Reg, Count  
SUB   #1  
STORE Reg, Count  
  ⋮
```

The problem is that the execution flow may be switched in the middle. **Results become non-deterministic!**

instruction level execution interleaving

Synchronization Needed! 5/6

Process 1			Process 2		
Inst	Reg	Memory	Inst	Reg	Memory
LOAD	10	10			
			LOAD	10	10
			SUB	9	10
ADD	11	10			
STORE	11	11			
			STORE	9	9

overwrites the previous value 11

Always use instruction level interleaving to show race conditions⁷

Synchronization Needed! 6/6

Process 1			Process 2		
Inst	Reg	Memory	Inst	Reg	Memory
LOAD	10	10			
ADD	11	10			
			LOAD	10	10
			SUB	9	10
			STORE	9	9
STORE	11	11			

overwrites the previous value 9

Always use instruction level interleaving to show race conditions⁸

Race Conditions

- A ***Race Condition*** occurs, if
 - ❖ **two or more** processes/threads manipulate a **shared** resource **concurrently**, and
 - ❖ the outcome of the execution **depends on the particular order** in which the access takes place.
- ***Synchronization*** is needed to prevent race conditions from happening.
- ***Synchronization is a difficult topic. Don't miss classes; otherwise, you will miss a lot of things.***

Execution Sequence Notes: 1/3

- ***You must always use instruction level interleaving to demonstrate the existence of race conditions***, because
 - a) higher-level language statements are not atomic and can be switched in the middle of execution
 - b) instruction level interleaving can show clearly the “sharing” of a resource among processes and threads.
 - c) ***two*** execution sequences are needed to show the answer depends on order of execution.

Execution Sequence Notes: 2/3

```
int a[3] = { 3, 4, 5};
```

Process 1

```
a[1] = a[0] + a[1];
```

Process 2

```
a[2] = a[1] + a[2];
```

Execution Sequence 1

Process 1	Process 2	Array a[]
<code>a[1]=a[0]+a[1]</code>		{ 3, 7, 5 }
	<code>a[2]=a[1]+a[2]</code>	{ 3, 7, 12 }

There is no concurrent sharing, not a valid example for a race condition.

Execution Sequence 2

Process 1	Process 2	Array a[]
	<code>a[2]=a[1]+a[2]</code>	{ 3, 4, 9 }
<code>a[1]=a[0]+a[1]</code>		{ 3, 7, 9 }

Execution Sequence Notes: 3/3

```
int Count = 10;
```

Process 1

```
LOAD Reg, Count  
ADD #1  
STORE Reg, Count
```

Process 2

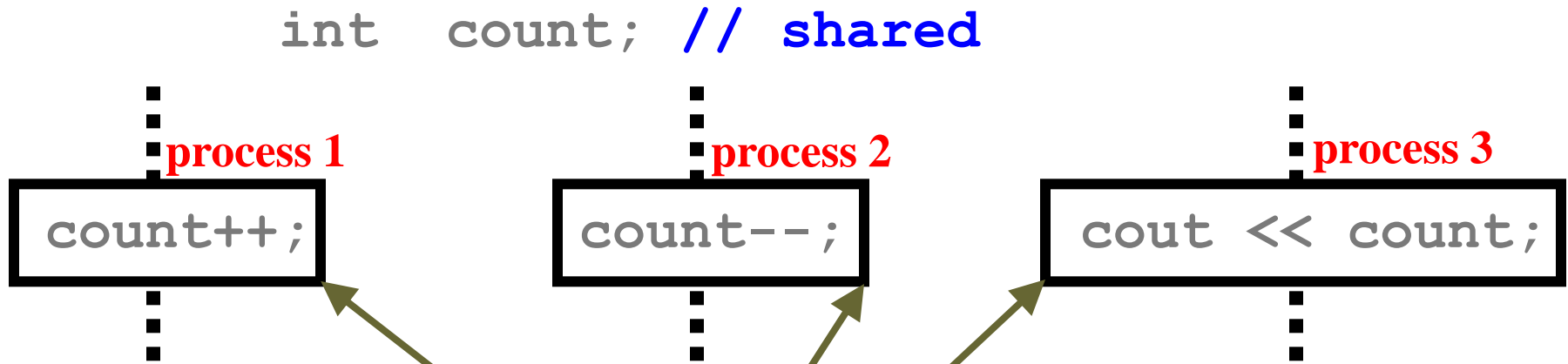
```
LOAD Reg, Count  
SUB #1  
STORE Reg, Count
```

Process 1	Process 2	Memory
LOAD Reg, Count		10
	LOAD Reg, Count	10
	SUB #1	10
ADD #1		10
STORE Reg, Count		11
	STORE Reg, Count	9

variable
count is
shared
concurrently
here

Critical Section

- A **critical section**, **CS**, is a section of code in which a process accesses shared resources.

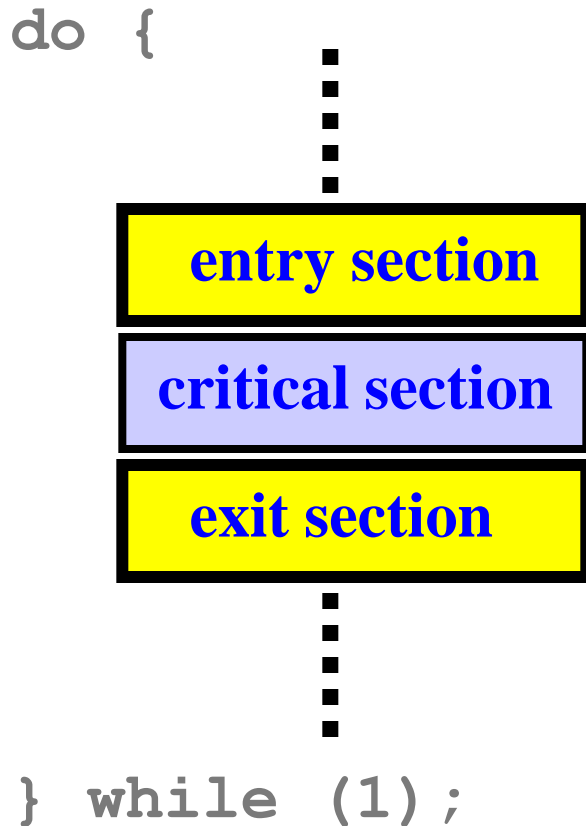


These are critical sections since `count` is a shared resource

Mutual Exclusion

- To avoid race conditions, the execution of critical sections must be ***mutually exclusive*** (e.g., at most one process can be in its critical section at any time).
- The ***critical-section problem*** is to design a protocol with which processes can use to cooperate and ensure mutual exclusion.

The Critical Section Protocol



- A **critical section protocol** consists of **two** parts: an *entry section* and an *exit section*.
- Between them is the critical section that must run in a **mutually exclusive** way.

Good Solutions to the CS Problem

- A good solution to the critical section problem must satisfy the following three conditions:
 - ❖ **Mutual Exclusion**
 - ❖ **Progress**
 - ❖ **Bounded Waiting**
- Moreover, the solution cannot depend on CPU's **relative speed, timing, scheduling policy** and other external factors.

Mutual Exclusion

- If a process **P** is executing in its critical section, ***no*** other processes can be executing in their corresponding critical sections.
- The **entry protocol** should be able to block processes that wish to enter but should not.
- When the process that is executing in its critical section exits, the **entry protocol** must be able to know this fact and allows a waiting process to enter.

Progress

- If ***no*** process is executing in its critical section and some processes want to enter their corresponding critical sections, then
 1. Only those processes that are waiting to enter can participate in the competition (to enter their critical sections) and no other processes can influence this decision.
 2. This decision cannot be postponed indefinitely (i.e., finite decision time). Thus, one of the waiting processes can enter its critical section.

Bounded Waiting

- **After** a process made a request to enter its critical section and **before** it is granted the permission to enter, there exists a ***bound*** on the **number of turns** that other processes are allowed to enter.
- ***Finite is not the same as bounded.***
The former means any value you can write down (e.g., billion, trillion, etc) while the latter means this value has to be no larger than a particular one (i.e., the bound).

Progress vs. Bounded Waiting

- ***Progress*** does not imply ***Bounded Waiting***:
Progress says a process can enter within a finite decision time. It does not say which process can enter, and there is no guarantee for bounded waiting.
- ***Bounded Waiting*** does not imply ***Progress***:
Even through we have a bound, all processes may be locked up in the enter section (i.e., infinite decision time).
- Therefore, ***Progress*** and ***Bounded Waiting*** are independent of each other.

A Few Related Terms: 1/7

- ***Deadlock-Freedom***: If two or more processes are trying to enter their critical sections, one of them will eventually enter. This is ***Progress*** without the “outsiders having no influence” condition.
- Since the enter section is able to select a process to enter, the decision time is certainly finite.

A Few Related Terms: 2/7

- ***r-Bounded Waiting***: There exists a fixed value r such that after a process made a request to enter its critical section and before it is granted the permission to enter, no more than r other processes are allowed to enter.
- Therefore, bounded waiting means there is a r such that the waiting is r -bounded.

A Few Related Terms: 3/7

- ***FIFO***: No process that is about to enter its critical section can pass an already waiting process. ***FIFO*** is usually referred to as ***0-bounded***.
- ***Linear-Waiting (1-Bounded Waiting)***: No process can enter its critical section twice while there is a process waiting.

A Few Related Terms: 4/7

- ***Starvation-Freedom***: If a process is trying to enter its critical section, it will eventually enter.
- ***Questions***:
 1. Does starvation-freedom imply deadlock-freedom?
 2. Does starvation-freedom imply bounded-waiting?
 3. Does bounded-waiting imply starvation-freedom?
 4. Does bounded-waiting ***AND*** deadlock-freedom imply starvation-freedom?

A Few Related Terms: 5/7

- ***Question (1):*** Does starvation-freedom imply deadlock-freedom?
- ***Yes!*** If every process can eventually enter its critical section, although waiting time may vary, it means the decision time of selecting a process is finite. Otherwise, all processes would wait in the enter section.

A Few Related Terms: 6/7

- ***Question (2):*** Does starvation-freedom imply bounded-waiting?
- ***No!*** This is because the waiting time may not be bounded even though each process can enter its critical section.

A Few Related Terms: 7/7

- ***Question (3)***: Does bounded-waiting imply starvation-freedom?
- ***No.*** Bounded-Waiting does not say if a process can actually enter. It only says there is a bound. For example, all processes are locked up in the enter section (i.e., failure of ***Progress***).
- We need ***Progress + Bounded-Waiting*** to imply ***Starvation-Freedom*** (***Question (4)***). In fact, ***Progress + Bounded-Waiting*** is stronger than ***Starvation-Freedom***. ***Why?***

The End