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

Edsger W. Dijkstra

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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	Process 2
`a[1] = a[0] + a[1];`	`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	Process 2
`a[1] = a[0] + a[1];`	`a[2] = a[1] + a[2];`

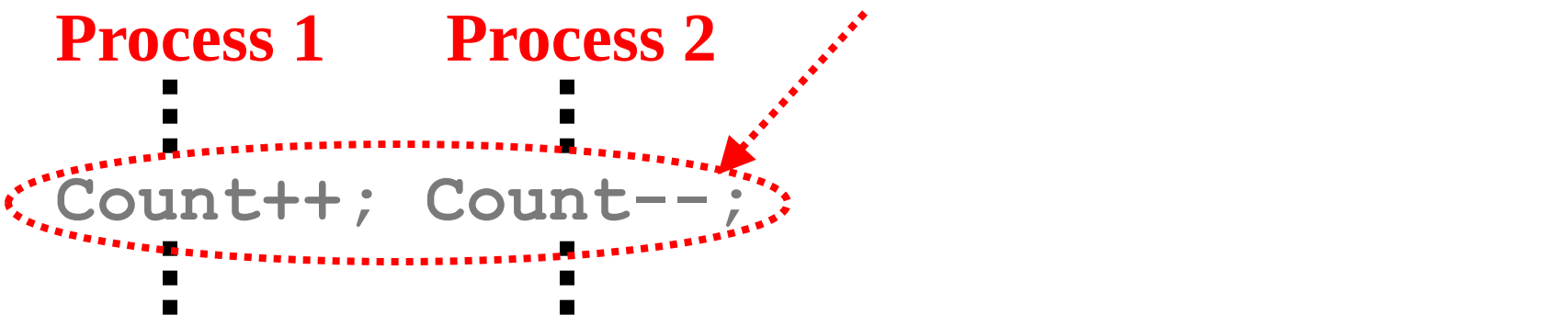
- If process 1 updates `a[1]` first, `a[1]` is 7, and `a[ ]={3,7,5}`
- Then, process 2 uses the new `a[1]` to computes `a[2]`, and `a[ ]={3,7,12}`

- 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;
```



`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 conditions

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 conditions

Race Conditions

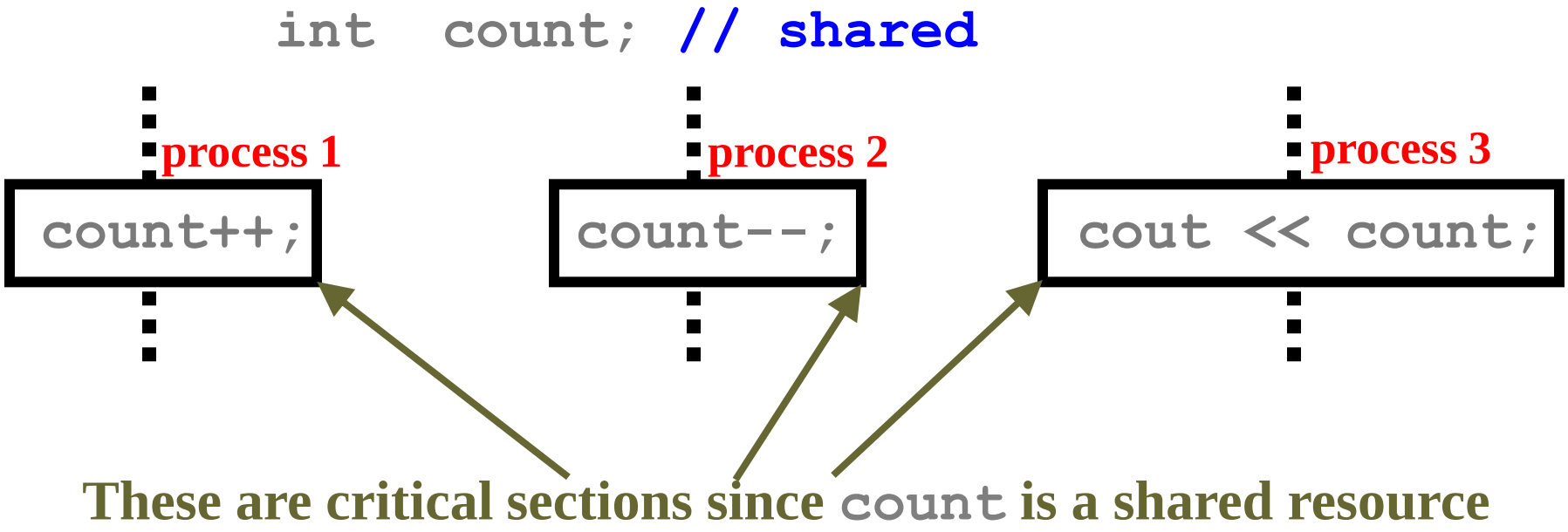
- A ***Race Condition*** occurs, if
  - ❖ two or more processes/threads manipulate a shared resource concurrently, and
  - ❖ the outcome of the execution depends on the particular order in which the access takes place.
- *Synchronization* is needed to prevent race conditions from happening.
- Synchronization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

Execution Sequence Notes

- ***You should 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.**

Critical Section

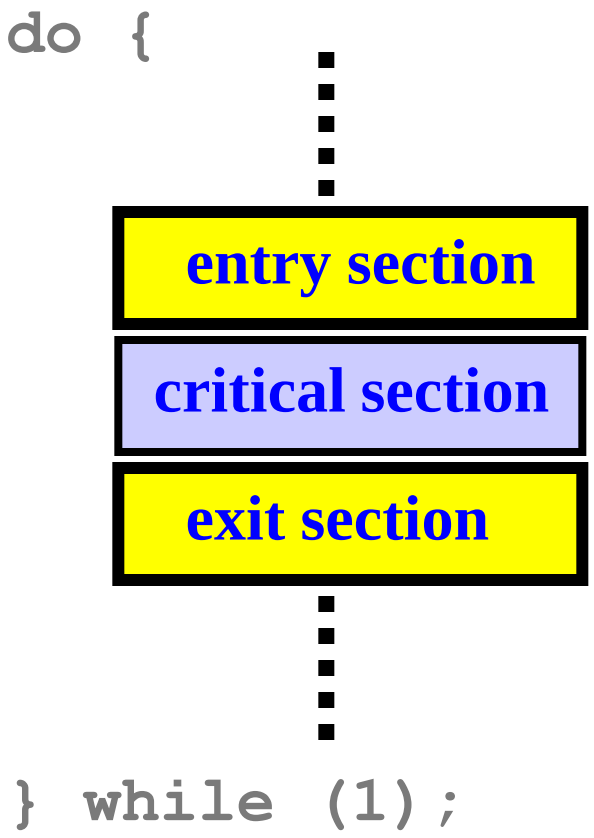
- **A *critical section*, *CS*, is a section of code in which a process accesses shared resources.**



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 cannot.**
- **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 with 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., failure of** ***Progress*****).**
- **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