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
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


Statement level execution interleaving
Synchronization Needed! 2/6

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

<table>
<thead>
<tr>
<th>Process 1</th>
<th>Process 2</th>
</tr>
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</table>

- 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!
Situation can be much worse.
Synchronization Needed! 3/6

```c
int Count = 10;

Process 1  Process 2

Count++; Count--;

Count = 9, 10 or 11?
```

Higher-level language statements are *not* atomic.
Synchronization Needed! 4/6

```c
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**

<table>
<thead>
<tr>
<th>Inst</th>
<th>Reg</th>
<th>Memory</th>
<th>Inst</th>
<th>Reg</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOAD</td>
<td>10</td>
<td>10</td>
<td>LOAD</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>SUB</td>
<td>9</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD</td>
<td>11</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STORE</td>
<td>11</td>
<td>11</td>
<td>STORE</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

Overwrites the previous value 11

Always use instruction level interleaving to show race conditions
### Synchronization Needed! 6/6

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<tbody>
<tr>
<td><strong>Inst</strong></td>
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</tr>
<tr>
<td><strong>Reg</strong></td>
<td><strong>Reg</strong></td>
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<tr>
<td><strong>Memory</strong></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LOAD</th>
<th>10</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>STORE</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

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

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**Execution Sequence Notes:**

**Execution Sequence 1**

<table>
<thead>
<tr>
<th>Process 1</th>
<th>Process 2</th>
<th>Array a[ ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a[1] = a[0] + a[1]</td>
<td></td>
<td>{3, 7, 5}</td>
</tr>
</tbody>
</table>

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

**Execution Sequence 2**

<table>
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<tr>
<th>Process 1</th>
<th>Process 2</th>
<th>Array a[ ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a[1] = a[0] + a[1]</td>
<td></td>
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Execution Sequence Notes: 3/3

```c
int Count = 10;
```

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</tr>
<tr>
<td>ADD #1</td>
<td>SUB #1</td>
<td>10</td>
</tr>
<tr>
<td>STORE Reg, Count</td>
<td>STORE Reg, Count</td>
<td>11</td>
</tr>
</tbody>
</table>

variable count is shared concurrently here
Critical Section

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

```c
int count; // shared

process 1
count++;

process 2
count--;

process 3
cout << count;
```

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.
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 though 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.
**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?**