Concurrency (Part I): Mutual Exclusion, Synchronization, Deadlock, and Starvation

Professor Travis Peters
CSCI 460 Operating Systems
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Some slides & figures adapted from Stallings instructor resources.

Some slides adapted from Adam Bates’s F’18 CS423 course @ UIUC
https://courses.engr.illinois.edu/cs423/sp2018/schedule.html

Goals for Today

Learning Objectives

• Dive into core topics in concurrency
• Discuss common mechanisms for achieving mutual exclusion & synchronization

Announcements

• Homework 2 (Chapters 3-4) out later today
• Coming Soon…
  • 1st Programming Assignment (Concurrency)
  • Homework 3 (Chapters 5-6)
  • Exam will be held in-class next week
Concurrency — *What is it? & Why is it?*

Concurrent operation is all about managing shared resources whilst interleaving & overlapping execution.

Recall...

**Thread** = a single (separately schedulable) execution sequence

Servers

*Multiple connections handled simultaneously*

Parallel Programs

*To achieve better performance*

Programs w/ User Interfaces

*To achieve user responsiveness while doing computation*

Network & Disk Bound Programs

*To hide network/disk latency*
Concurrency — Why is it challenging?

Concurrency is all about managing shared resources whilst interleaving & overlapping execution.

Difficult for OS to manage resources in an optimal way…
Difficult to debug programing errors (non-deterministic and hard to reproduce)…

Programmer vs. Processor View

Possible Executions

Program must anticipate all of these possible executions!

(Keep this in mind for later when we discuss scheduling)
Some Key Terminology Related to Concurrency

atomic operation—A function or action implemented as a sequence of one or more instructions that appears to be indivisible; that is, no other process can see an intermediate state or interrupt the operation. The sequence of instruction is guaranteed to execute as a group, or not execute at all, having no visible effect on system state. Atomicity guarantees isolation from concurrent processes.

critical section—A section of code within a process that requires access to shared resources and that must not be executed while another process is in a corresponding section of code.

deadlock—A situation in which two or more processes are unable to proceed because each is waiting for one of the others to do something.

livelock—A situation in which two or more processes continuously change their states in response to changes in the other process(es) without doing any useful work.

mutual exclusion—The requirement that when one process is in a critical section that accesses shared resources, no other process may be in a critical section that accesses any of those shared resources.

race condition—A situation in which multiple threads or processes read and write a shared data item and the final result depends on the relative timing of their execution.

starvation—A situation in which a runnable process is overlooked indefinitely by the scheduler; although it is able to proceed, it is never chosen.
Mutual Exclusion — What is it? & What are the requirements?

• Any facility or capability that is to provide support for mutual exclusion should meet the following requirements:
  1. Mutual exclusion must be enforced: only one process at a time is allowed into its critical section, among all processes that have critical sections for the same resource or shared object
  2. A process that halts must do so without interfering with other processes
  3. It must not be possible for a process requiring access to a critical section to be delayed indefinitely: no deadlock or starvation
  4. When no process is in a critical section, any process that request entry to its critical section must be permitted to enter without delay
  5. No assumptions are made about relative process speeds or number of processes
  6. A process remains inside its critical section for a finite time only

Solutions?
Solutions for Mutual Exclusion

To achieve correct & meaningful solutions to concurrency problems, mutual exclusion is a must!

Software Support (today)

- Assume elementary mutual exclusion at the memory access level; serialized by “memory arbiter”
- Decker’s Algorithm, Peterson’s Algorithm

Hardware Support (today-ish)

- Interrupt Disabling
  - Disadvantages: inhibits processor’s ability to interleave processes; doesn’t work across processors.
- Special Instructions
  - Compare&Swap: compare values => if values are the same, swap!
  - Exchange (XCHG): exchanges the contents of a register w/ that of a memory location
  - Advantages: simple & easy to implement; can be used on multi-processor machines
  - Disadvantages: possibly expensive busy-waiting; starvation & deadlock are still possible

Programming Language Mechanisms

- Semaphores, Mutex (Lock), Condition Variables, Monitors, …oh my!
Mutual Exclusion—*Workings towards a solution*…
Mutual Exclusion—Workings towards a solution...

Attempt 1: Dependent Turn-taking (1 flag)

- If value of `turn` == process #, process can proceed
- What if one process takes a long turn?

```c
/* PROCESS 0 */
while (turn != 0) /* do nothing */;
/* critical section*/;
turn = 1;

/* PROCESS 1 */
while (turn != 1) /* do nothing */;
/* critical section*/;
turn = 0;
```

(a) First attempt
Mutual Exclusion—Workings towards a solution...

Attempt 1: Dependent Turn-taking (1 flag)
- If value of turn == process #, process can proceed
- What if one process takes a long turn?

Attempt 2: Independent Turn-taking (2+ flags)
- Each process can proceed independently*
- What if one process fails in critical section?

*while other process is not in the critical section
Mutual Exclusion—Workings towards a solution...

Attempt 1: Dependent Turn-taking (1 flag)
- If value of turn == process #, process can proceed
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Attempt 2: Independent Turn-taking (2+ flags)
- Each process can proceed independently*
- What if one process fails in critical section?
- => Also, possibly incorrect! Mutual exclusion broken! (TOCTOU)

Problematic Sequence...
- P0 executes the while statement and finds flag[1] set to false
- P1 executes the while statement and finds flag[0] set to false
- P0 sets flag[0] to true and enters its critical section
- P1 sets flag[1] to true and enters its critical section

*while other process is not in the critical section
Mutual Exclusion—Workings towards a solution...

**Attempt 1: Dependent Turn-taking (1 flag)**
- If value of `turn ==` process #, process can proceed
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- Each process can proceed independently*
- What if one process fails in critical section?
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**Attempt 3: Set THEN check**
- Mutual exclusion fixed...
- What if both processes set flags to `true`?

---

Problematic Sequence...

| P0 executes the `while` statement and finds `flag[1]` set to false |
| P1 executes the `while` statement and finds `flag[0]` set to false |
| P0 sets `flag[0]` to true and enters its critical section |
| P1 sets `flag[1]` to true and enters its critical section |

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<td>/* critical section*/;</td>
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<td>turn = 1;</td>
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| /* |}

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<th>(b) Second attempt</th>
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<td>flag[0] = false;</td>
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<tr>
<td>/* delay */</td>
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*while other process is not in the critical section
Mutual Exclusion—Workings towards a solution…

Attempt 1: Dependent Turn-taking (1 flag)
  • If value of turn == process #, process can proceed
  • What if one process takes a long turn?

Attempt 2: Independent Turn-taking (2+ flags)
  • Each process can proceed independently*
  • What if one process fails in critical section?
  • => Also, possibly incorrect! Mutual exclusion broken! (TOCTOU)

Attempt 3: Set THEN check
  • Mutual exclusion fixed…
  • What if both processes set flags to true?
  • => Deadlock is now possible!

Problematic Sequence...
- P0 executes the while statement and finds flag[1] set to false
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- P0 sets flag[0] to true and enters its critical section
- P1 sets flag[1] to true and enters its critical section

**Attempt 4: Set THEN check (THEN back-off?)**
- Processes will “back-off”
- What if both processes alternate in deferring to the other?
Mutual Exclusion—Workings towards a solution...

Attempt 1: Dependent Turn-taking (1 flag)
- If value of `turn` == process #, process can proceed
- What if one process takes a long turn?

Attempt 2: Independent Turn-taking (2+ flags)
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- What if one process fails in critical section?
  => Also, possibly incorrect! Mutual exclusion broken! (TOCTOU)

Attempt 3: Set THEN check
- Mutual exclusion fixed...
- What if both processes set flags to `true`?
  => **Deadlock is now possible!**

Attempt 4: Set THEN check (THEN back-off?)
- Processes will “back-off”
- What if both processes alternate in deferring to the other?
  => **Livelock is now possible!**

Problematic Sequence...
- Process 0 sets flag[0] to true and enters its critical section
- Process 1 sets flag[1] to true and enters its critical section
- Process 0 executes the while statement and finds flag[1] set to false
- Process 1 executes the while statement and finds flag[0] set to false
- Process 0 sets flag[0] to true and enters its critical section
- Process 1 sets flag[1] to true and enters its critical section

Problematic Sequence...
- Process 0 sets flag[0] to true
- Process 1 sets flag[1] to true
- Process 0 executes the while statement and finds flag[1] set to false
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- Process 0 sets flag[0] to true
- Process 1 sets flag[1] to true

Problematic Sequence...
- Process 0 sets flag[0] to true
- Process 1 sets flag[1] to true
- Process 0 executes the while statement
- Process 1 executes the while statement
- Process 0 sets flag[0] to true
- Process 1 sets flag[1] to true

Problematic Sequence...
- Process 0 sets flag[0] to true
- Process 1 sets flag[1] to true
- Process 0 executes the while statement
- Process 1 executes the while statement
- Process 0 sets flag[0] to false
- Process 1 sets flag[1] to false
- Process 0 sets flag[0] to true
- Process 1 sets flag[1] to true
Peterson’s Algorithm for Two Processes

Generalizable to 3+ processes

```c
boolean flag [2];
int turn;
void P0()
{
    while (true) {
        flag[0] = true;
        turn = 1;
        while (flag[1] && turn == 1) /*do nothing*/;
        // critical section */;
        flag[0] = false;
        /* remainder */;
    }
}
void P1()
{
    while (true) {
        flag[1] = true;
        turn = 0;
        while (flag[0] && turn == 0) /*do nothing*/;
        // critical section */;
        flag[1] = false;
        /* remainder */;
    }
}
void main()
{
    flag[0] = false;
    flag[1] = false;
    parbegin (P0, P1);
}
```

See Also: Dekker’s Algorithm
### Synchronization Roadmap

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