CS 370: OPERATING SYSTEMS
[PROCESS SYNCHRONIZATION]

Shrideep Pallickara
Computer Science
Colorado State University

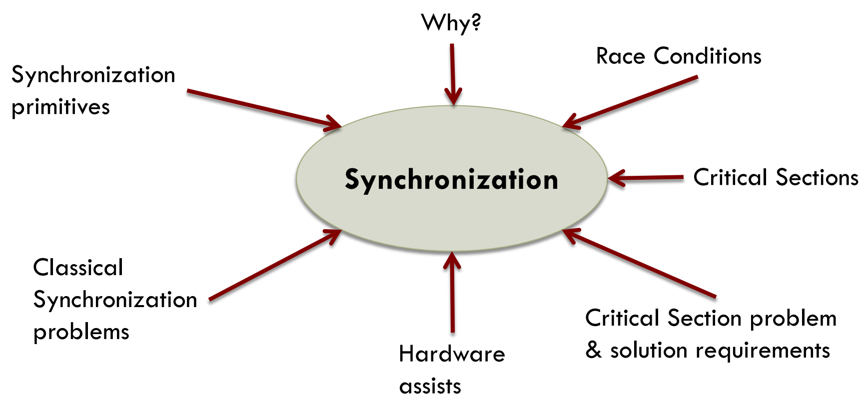
1

Frequently asked questions from the previous class survey

- What is "thread-safe"?
- Some confusion between `start()` and `run()` in Java threads
- Say, thread A performs a `join()` on a thread B
  - Is thread A now running?
  - Is thread B now running?

2

Synchronization: What we will look at



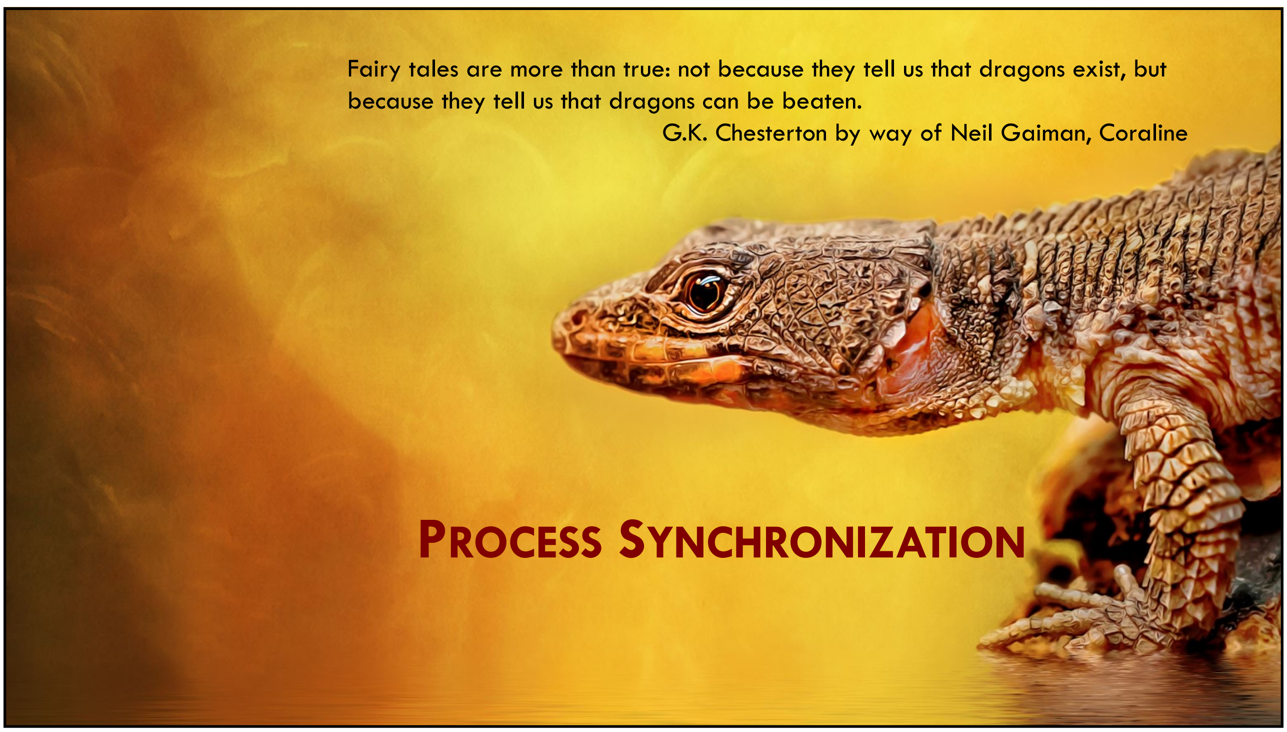
Topics covered in the lecture

- Critical section
- Critical section problem
- Peterson's solution
- Hardware assists

Reasoning about interleaved access to shared state: Too much milk!

	Roommate 1's actions	Roommate 2's actions
3:00	Look in fridge; out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in fridge; out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home; put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home; put milk away
		Oh no!

5



6

Process synchronization

- How can processes **pass information** to one another?
- Make sure two or more processes **do not get in each other's way**
  - E.g., 2 processes in an airline reservation system, each trying to grab the last seat for a different passenger
- Ensure proper **sequencing** when dependencies are present

Applicability to threads

- Passing information between threads is easy
  - They share the same address space of the parent process
- Other two aspects of process synchronization are applicable to threads
  - Keeping out of each other's hair
  - Proper sequencing

A look at the producer consumer problem

```
while (true) {
  while (counter == BUFFER_SIZE) {
     ; /*do nothing */
   }
   buffer[in] = nextProduced
   in = (in +1)%BUFFER_SIZE;
   counter++;
}
```

Producer

? Operators?

```
while (true) {
  while (counter == 0) {
     ; /*do nothing */
   }
   nextConsumed = buffer[out]
   out = (out +1)% BUFFER_SIZE;
   counter--;
}
```

Consumer

9

Implementation of ++/-- in machine language

```
counter++
  register1 = counter
  register1 = register1 + 1
  counter   = register1
```

```
counter--
  register2 = counter
  register2 = register2 - 1
  counter   = register2
```


10

Lower-level statements may be interleaved in any order

```
Producer execute:   register1 = counter
Producer execute:   register1 = register1 + 1
Producer execute:   counter = register1

Consumer execute:   register2 = counter
Consumer execute:   register2 = register2 - 1
Consumer execute:   counter = register2
```

? Correctness?

Lower-level statements may be interleaved in any order

```
Producer execute:   register1 = counter
Consumer execute:   register2 = counter
Producer execute:   register1 = register1 + 1
Consumer execute:   register2 = register2 - 1
Producer execute:   counter = register1
Consumer execute:   counter = register2
```

The **order** of statements *within* each high-level statement is **preserved**

Lower-level statements may be interleaved in any order (counter = 5)

`Producer execute: register1 = counter`	{register1 = 5}
`Producer execute: register1 = register1 + 1`	{register1 = 6}
`Consumer execute: register2 = counter`	{register2 = 5}
`Consumer execute: register2 = register2 - 1`	{register2 = 4}
`Producer execute: counter = register1`	{counter = 6}
`Consumer execute: counter = register2`	{counter = 4}

Counter has ***incorrect*** state of 4

COLORADO STATE UNIVERSITY Professor: SHRIDEEP PALLICKARA COMPUTER SCIENCE DEPARTMENT INTER-PROCESS SYNCHRONIZATION L9.13

13

Lower-level statements may be interleaved in any order (counter = 5)

`Producer execute: register1 = counter`	{register1 = 5}
`Producer execute: register1 = register1 + 1`	{register1 = 6}
`Consumer execute: register2 = counter`	{register2 = 5}
`Consumer execute: register2 = register2 - 1`	{register2 = 4}
`Consumer execute: counter = register2`	{counter = 4}
`Producer execute: counter = register1`	{counter = 6}

Counter has ***incorrect*** state of 6

COLORADO STATE UNIVERSITY Professor: SHRIDEEP PALLICKARA COMPUTER SCIENCE DEPARTMENT INTER-PROCESS SYNCHRONIZATION L9.14

14

15

Race condition

- Several processes access and manipulate data **concurrently**
- **Outcome** of execution *depends* on
  - Particular **order** in which accesses takes place
- Debugging programs with race conditions?
  - Painful!
  - Program runs fine most of the time, but once in a rare while something weird and unexpected happens

COLORADO STATE UNIVERSITY Professor: SHRIDEEP PALLICKARA COMPUTER SCIENCE DEPARTMENT INTER-PROCESS SYNCHRONIZATION L9.16

16

Race condition: Example [1/3]

- When process wants to print file, adds file to a special **spooler directory**
- Printer daemon periodically checks to see if there are files to be printed
  - If there are, print them
- In our example, spooler directory has a large number of slots
- Two variables
  - `in`: Next free slot in directory
  - `out`: Next file to be printed

Race condition: Example [2/3]

- In jurisdictions where Murphy's Law hold …
- Process A reads `in`, and stores the value `7`, in local variable `next_free_slot`
- Context switch occurs
- Process B also reads `in`, and stores the value `7`, in local variable `next_free_slot`
  - Stores name of the file in slot `7`
- Process A context switches again, and stores the name of the file it wants to print in slot `7`

Race condition: Example [3/3]

- Spooler directory is internally consistent
- But process B will never receive any output
  - User B loiters around printer room for years, wistfully hoping for an output that will never come …

The kernel is subject to several possible race conditions

- E.g.: Kernel maintains list of all open files
  - 2 processes open files simultaneously
  - Separate updates to kernel list may result in a race condition
- Other kernel data structures
  - Memory allocation
  - Process lists
  - Interrupt handling

Segment of code where processes change common variables

CRITICAL SECTION

21

Critical Section

- ***Concurrent accesses*** to shared resources can lead to unexpected or erroneous behavior
- Parts of the program where the shared resource is accessed thus need to be protected
  - This protected section is the **critical section**

22

Critical-Section

- System of *n* processes {P_0, P_1, …, P_{n-1}}
- Each process has a segment of code (**critical section**) where it:
  - **Changes common variables**, updates a table, etc
- No two processes can execute in *their* critical sections at the same time

The Critical-Section problem

- Design a **protocol** that processes can use to cooperate
- Each process must **request permission** to enter its critical section
  - The **entry** section

General structure of a participating process

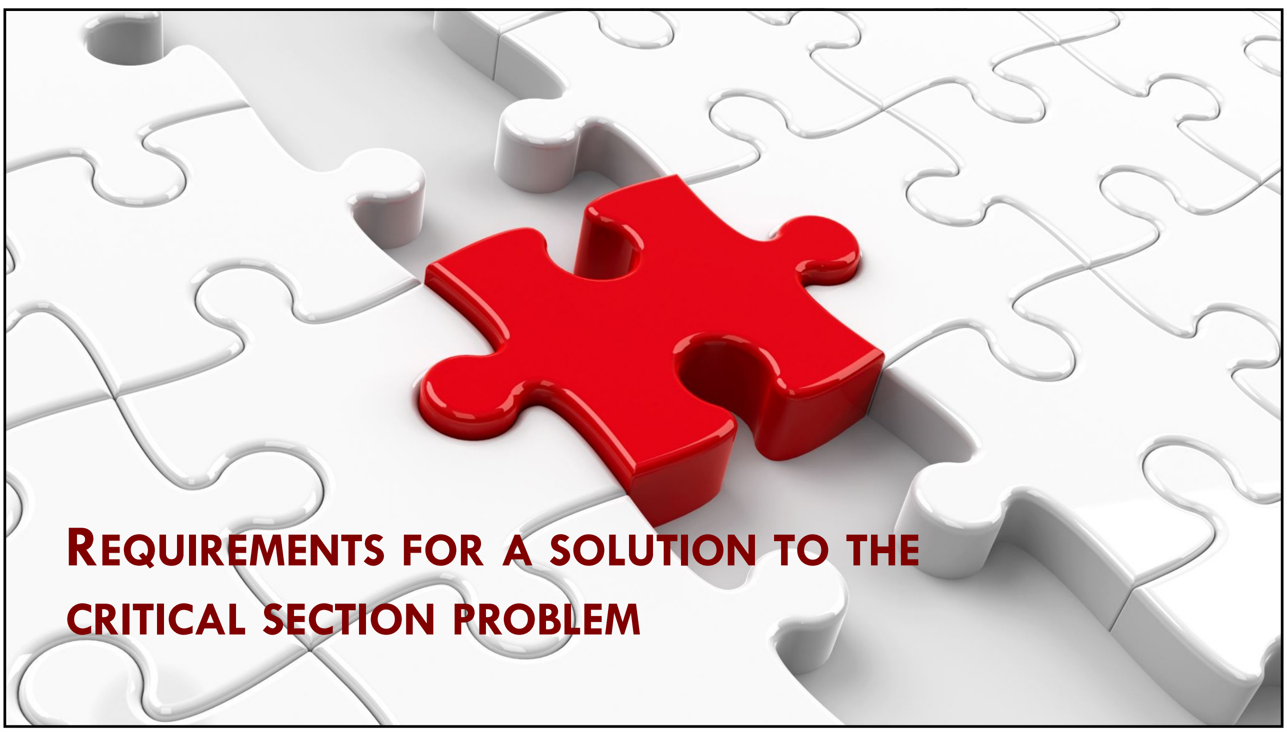
```
do {

        entry section

        critical section

        exit section

        remainder section

} while (TRUE);
```

entry section ← Request permission to enter

exit section ← Housekeeping to let other processes enter

COLORADO STATE UNIVERSITY | Professor: SHRIDEEP PALLICKARA, COMPUTER SCIENCE DEPARTMENT | INTER-PROCESS SYNCHRONIZATION | L9.25

25



26

Requirements for a solution to the critical section problem

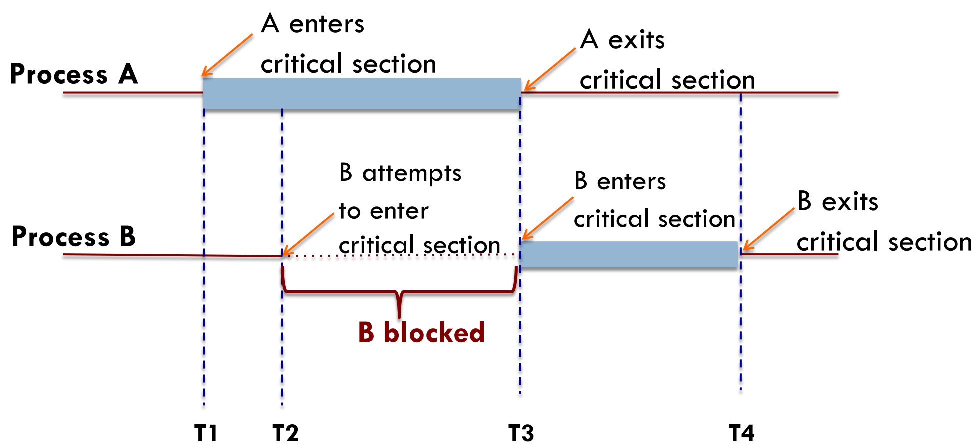
1. Mutual exclusion
2. Progress
3. Bounded wait

- PROCESS SPEED
  - Each process operates at *non-zero* speed
  - Make no assumption about the ***relative speed*** of the *n* processes

Mutual Exclusion

- Only **one** process can execute in its critical section
- When a process executes in its critical section
  - **No other process** is allowed to execute in *its* critical section

Mutual Exclusion: Depiction



COLORADO STATE UNIVERSITY
Professor: Shrideep Pallickara
Computer Science Department
Inter-Process Synchronization
L9.29

29

Progress

- **{C1}** If *No* process is executing in its critical section, and …
- **{C2}** *Some* processes wish to enter their critical sections

- **Decision** on who gets to enter the critical section
  - Is made by processes that are NOT executing in their remainder section
  - Selection **cannot be postponed indefinitely**

COLORADO STATE UNIVERSITY
Professor: Shrideep Pallickara
Computer Science Department
Inter-Process Synchronization
L9.30

30

Bounded waiting

- *After* a process has made a **request** to enter its critical section
  - AND *before* this request is granted
- **Limit number** of times other processes are allowed to enter their critical sections

Approaches to handling critical sections in the OS

- Nonpreemptive kernel
  - If a process runs in kernel mode: no preemption
  - **Free** from race conditions on kernel data structures
- Preemptive kernels
  - Must ensure shared kernel data is free from race conditions
  - <u>Difficult</u> on SMP (Symmetric Multi Processor) architectures
    - 2 processes may run simultaneously on different processors

Kernels: Why preempt?

- Suitable for real-time
  - A real-time process may preempt a kernel process
- More **responsive**
  - *Less risk* that kernel mode process will run arbitrarily long

33

34

Peterson's Solution

- **Software solution** to the critical section problem
  - Restricted to two processes
- No guarantees on modern architectures
  - Machine language instructions such as `load` and `store` implemented differently
- Good algorithmic description
  - Shows how to address the 3 requirements

Peterson's Solution: The components

- Restricted to two processes
  - P_i and P_j where `j = 1-i`
- **Share** two data items
  - `int turn`
    - Indicates whose *turn* it is to enter the critical section
  - `boolean flag[2]`
    - Whether process *is ready* to enter the critical section

Peterson's solution: Structure of process P_i

```
do {
        flag[i] = TRUE;
        turn = j;
        while (flag[j] && turn==j) {;}

        critical section

        flag[i] = FALSE;

        remainder section

} while (TRUE);
```


Peterson's solution: Mutual exclusion

```
while (flag[j] && turn==j) {;}
```

- P_i enters critical section only if
  `flag[j] == false OR turn == i`
- If both processes execute in critical section at the same time
  - `flag[0] == flag[1] == true`
  - **But** `turn` can be `0 or 1`, not BOTH
- If P_j entered critical section
  - `flag[j] == true AND turn == j`
  - Will persist as long as P_j is in the critical section

Peterson's Solution: Progress and Bounded wait

- P_i can be stuck only if `flag[j]==true AND turn==j`
  - If P_j is *not ready*: `flag[j] == false`, and P_i can enter
  - Once P_j *exits*: it resets `flag[j]` to `false`

- If P_j resets `flag[j]` to `true`
  - Must set `turn = i;`

- P_i **will enter** critical section (*progress*) after <u>at most one</u> entry by P_j (*bounded wait*)

39

SYNCHRONIZATION HARDWARE

40

41

Solving the critical section problem using locks

```
do {
        acquire lock
        critical section
        release lock
        remainder section

} while (TRUE);
```


42

Possible assists for solving critical section problem [1/2]

- Uniprocessor environment
  - **Prevent interrupts** from occurring when shared variable is being modified
    - *No unexpected modifications*!
- Multiprocessor environment
  - Disabling interrupts is *time consuming*
    - Message passed to ALL processors

Possible assists for solving critical section problem [2/2]

- Special **atomic** hardware instructions
  - Swap content of two words
  - Modify word

Swap()

```
void Swap(boolean *a, boolean *b ) {

     boolean temp = *a;
     *a = *b;
     *b = temp;
}
```


Swap: Shared variable LOCK is initialized to false

```
do {
        key = TRUE;
        while (key == TRUE) {
           Swap(&lock, &key)
        }

        critical section

        lock = FALSE;

        remainder section

} while (TRUE);
```

Cannot enter critical section UNLESS `lock == FALSE`

`lock` is a SHARED variable
`key` is a LOCAL variable

If two `Swap()` are executed *simultaneously*, they will be executed *sequentially* in some arbitrary order

`TestAndSet()`

```
boolean TestAndSet(boolean *target ) {

     boolean rv = *target;
     *target = TRUE;
     return rv;
}
```

Sets `target` to `true` and returns old value of `target`

`TestAndSet`: Shared boolean variable `lock` initialized to `false`

```
do {

        while (TestAndSet(&lock)) {;}

        critical section

        lock = FALSE;


        remainder section


} while (TRUE);
```

To break out:
Return value of `TestAndSet` should be `FALSE`

If two `TestAndSet()` are executed *simultaneously*, they will be executed *sequentially* in some arbitrary order

Entering and leaving critical regions using TestAndSet and Swap (Exchange)

```
enter_region:
    TSL REGISTER, LOCK
    CMP REGISTER, #0
    JNE enter_region
    RET

leave_region:
   MOVE LOCK, #0
   RET
```

```
enter_region:
    MOVE REGISTER, #1
    XCHNG REGISTER,LOCK
    CMP REGISTER, #0
    JNE enter_region
    RET

leave_region:
    MOVE LOCK, #0
    RET
```

All Intel x86 CPUs have the `XCHG` instruction for low-level synchronization

The contents of this slide set are based on the following references

- *Avi Silberschatz, Peter Galvin, Greg Gagne. Operating Systems Concepts, 9th edition. John Wiley & Sons, Inc. ISBN-13: 978-1118063330.* [Chapter 5]
- *Andrew S Tanenbaum and Herbert Bos. Modern Operating Systems. 4th Edition, 2014. Prentice Hall. ISBN: 013359162X/ 978-0133591620.* [Chapter 2]
- *Thomas Anderson and Michael Dahlin. Operating Systems Principles and Practice. 2nd Edition. ISBN: 978-0985673529.* [Chapter 5]
- https://en.wikipedia.org/wiki/Critical_section