CS 370: OPERATING SYSTEMS
[PROCESS SYNCHRONIZATION]

The Critical Section
Concurrent accesses
Adding to your woes

Looking for this to abate?
a critical section to regulate
protect shared resources, before it's too late

A simple segment, a coded gate
A shared space
where processes wait and take their turn

With rules tight
Keeping chaos locked up right
No races running wild

Accesses now mutually exclusive
When one steps in, the rest postpone

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Frequently asked questions from the previous class survey

- How different is the actual code for user vs kernel threads?
- Do we decide when to use kernel vs user threads?
- Are threads ever launched without the user ever knowing them?
- Is there a process-level distinction for the main thread vs. other threads?
- When a join is called by a thread, does the number of program counters reduce by one?
- Does every class that needs be a Java Thread need to implement Runnable?
  - Why is the first statement that is executed in a Java thread in the run() method?
- Can only the main-thread join()?
- Say, thread A performs a `join()` on a thread B
  - Is thread A now running?
  - Is thread B now running?
- What is a thread pool?

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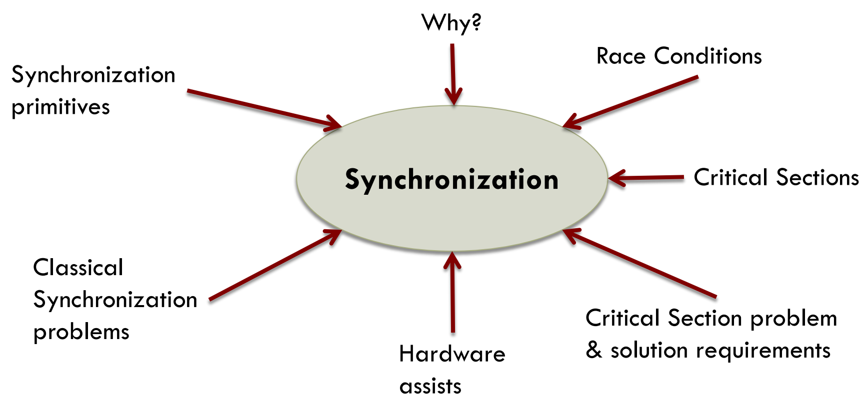
Synchronization: What we will look at



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Topics covered in the lecture

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

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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!

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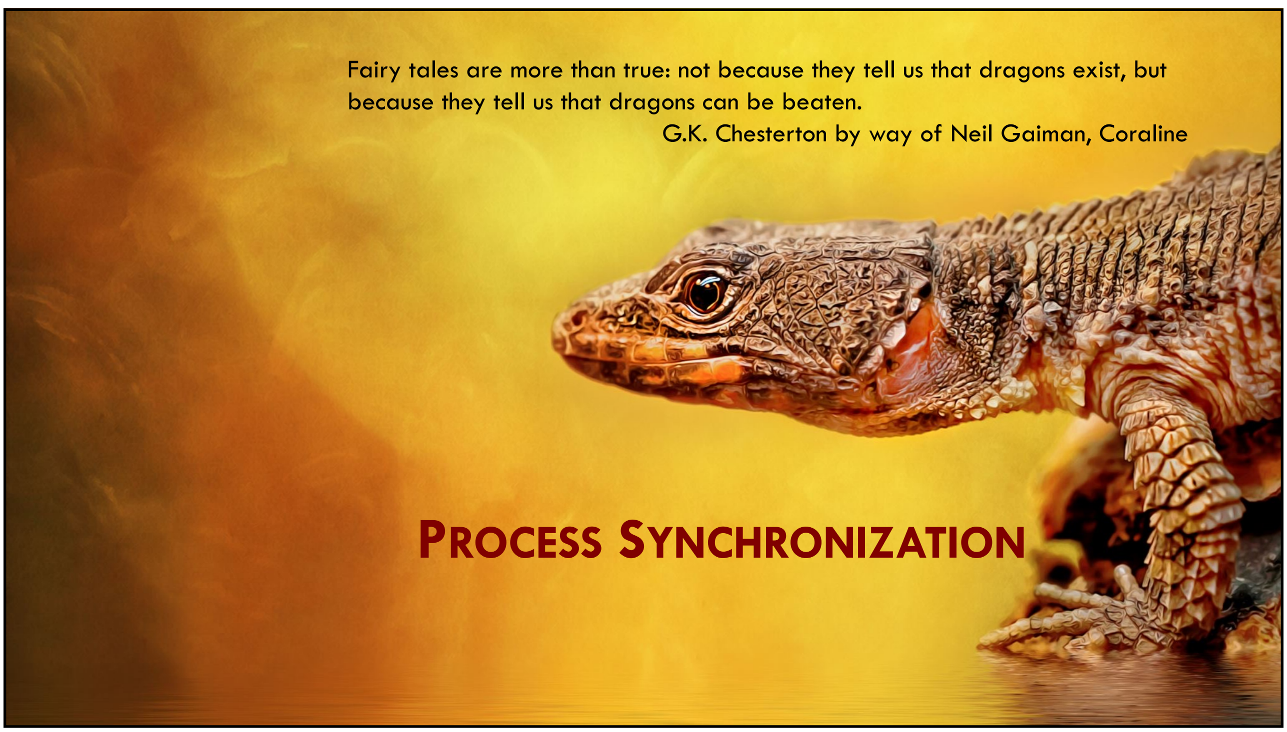

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Process synchronization

- 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

Implementation of ++/-- in machine language

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

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

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

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

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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

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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

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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**

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Critical-Section

- System of *n* processes $\{P_0, P_1, \ldots, P_{n-1}\}$
- 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

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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

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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

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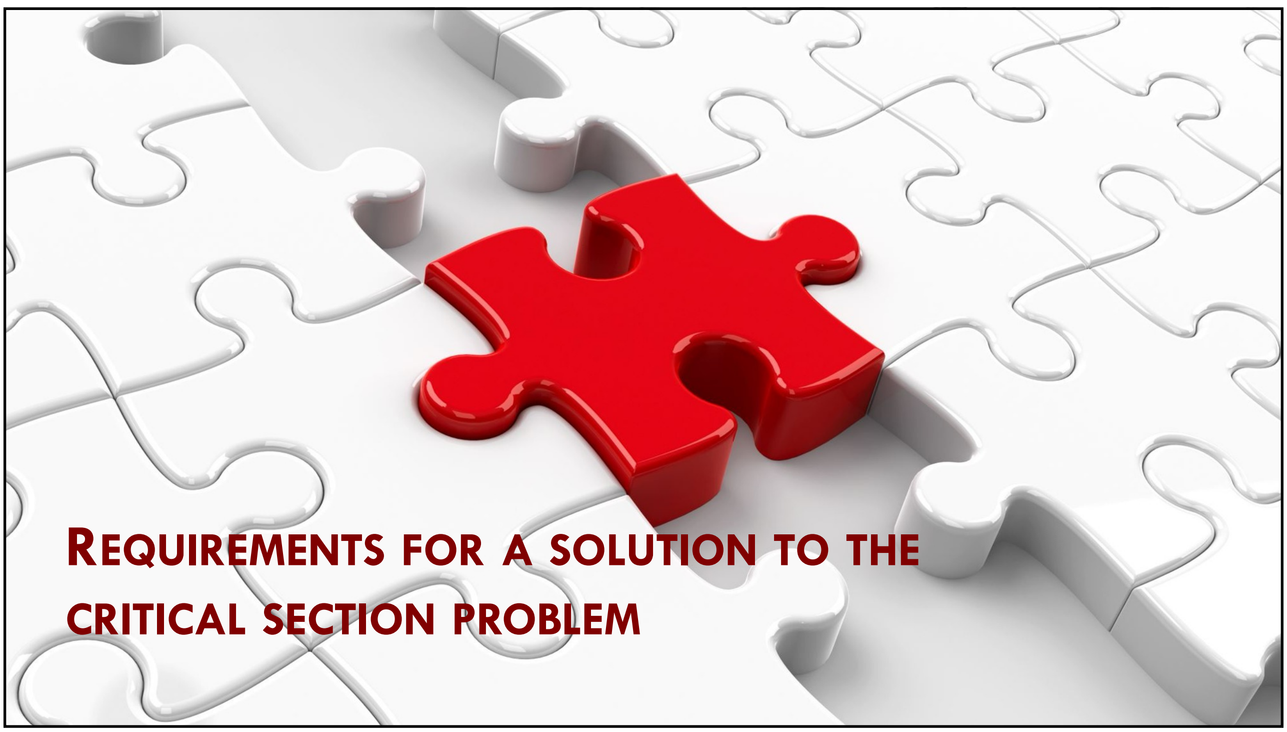

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Requirements for a solution to the critical section problem

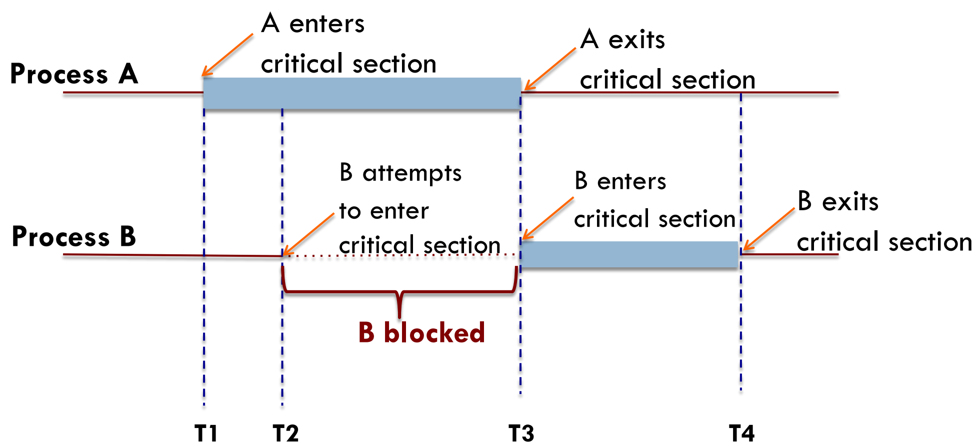
1. Mutual exclusion
2. Progress
3. Bounded wait

- 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



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**

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

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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*)

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Synchronization Hardware

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Solving the critical section problem using locks

```
do {
        acquire lock

        critical section

        release lock

        remainder section

} while (TRUE);
```


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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;
}
```


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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

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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