CS 370: OPERATING SYSTEMS
[PROCESS SYNCHRONIZATION]

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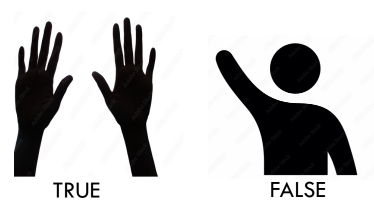
Frequently asked questions from the previous class survey

- Can the way statements within a processes interleave be different each time they execute?
- Is `++counter` (i.e., the prefix increment operator) atomic?
- Critical sections
  - What happens if a process never leaves the critical section?
  - Do all critical sections block all other critical sections or is it just those that access the same resource?

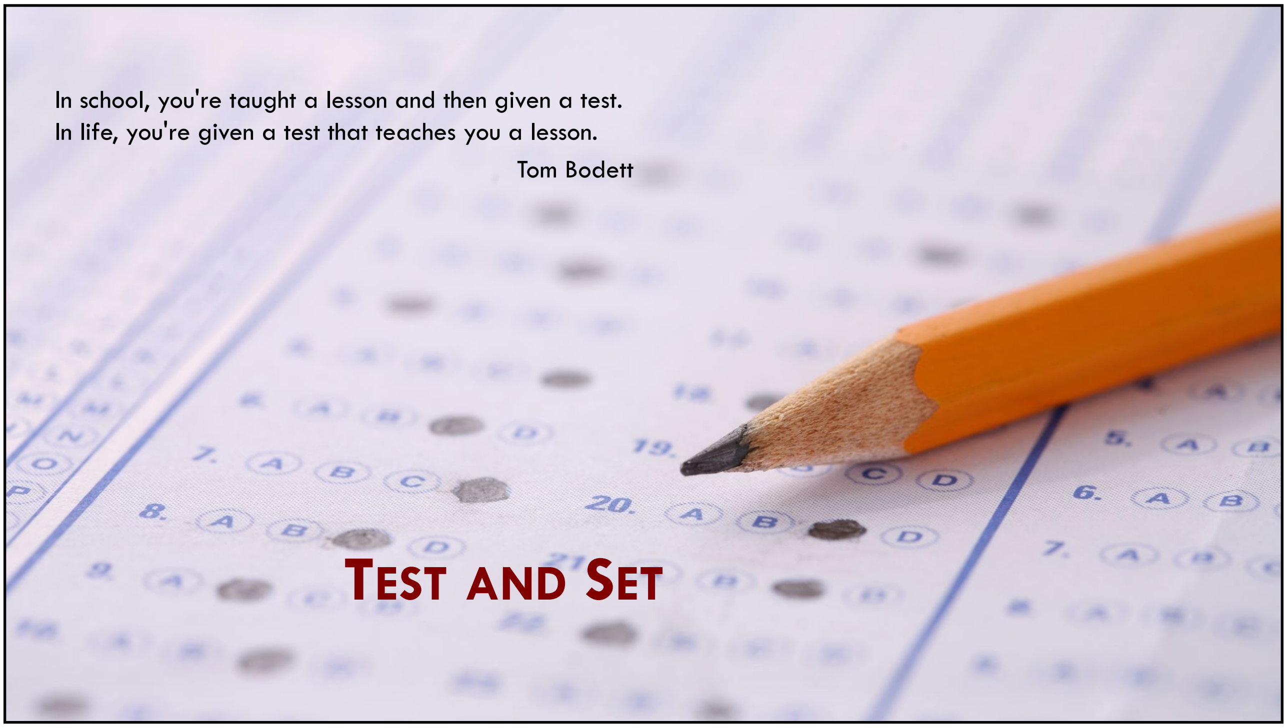
Topics covered in the lecture

- TestAndSet
- Using `TestAndSet` to satisfy critical section requirements
- Semaphores
- Classical process synchronization problems

Critical Section: Quick Review



- There can be only one critical section in a process
- There are no limits to the number of processes that are *trying to access* a shared resource
- All processes that access the same shared resource must have similar entry and exit sections
- It is OK to miss the exit section in one of the processes
- If there are N processes accessing a shared resource it is OK for <u>one process</u> to access that resource directly (i.e., without using the entry/exit bookends)



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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`

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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 returned by `TestAndSet` should be `FALSE`

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

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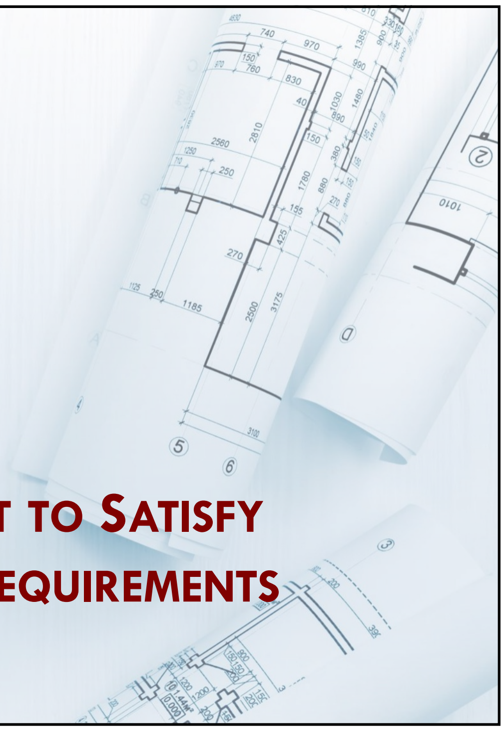

USING TEST-AND-SET TO SATISFY CRITICAL SECTION REQUIREMENTS

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Using `TestAndSet` to satisfy all critical section requirements

- N processes
- Data structures initialized to FALSE
  - `boolean waiting[n];`
  - `boolean lock;`

These data structures are maintained in shared memory.

The entry section for process i

```
waiting[i] = TRUE;
key = TRUE;

while (waiting[i] && key) {
   key = TestAndSet(&lock);
}

waiting[i] = FALSE;
```

Will break out only if `waiting[i]==FALSE` OR `key==FALSE`

First process to execute `TestAndSet` will find `key == false;`
ENTER critical section
EVERYONE else must wait

The exit section: Part I
Finding a suitable waiting process

If a process is not waiting move to the next one

```
j = (i + 1)%n;

while ( (j != i ) && !waiting[j] ) {
    j = (j+1)%n
}
```

Will break out at `j==i` if there are no waiting processes

If a process **is** waiting:
break out of loop

The exit section: Part II
Finding a suitable waiting process

Could NOT find a suitable waiting process

```
if (j==i) {
   lock = FALSE;
} else {
   waiting[j] = FALSE;
}
```

Found a suitable waiting process

Mutual exclusion

- The variable `waiting[i]` can become `false` ONLY if another process leaves its critical section
  - **Only one** `waiting[i]` is set to `FALSE`

Progress

- A process exiting the critical section
  1. Sets `lock` to `FALSE`
     OR
  2. `waiting[j]` to `FALSE`
- Allows a process that is *waiting* to proceed

Bounded waiting requirement

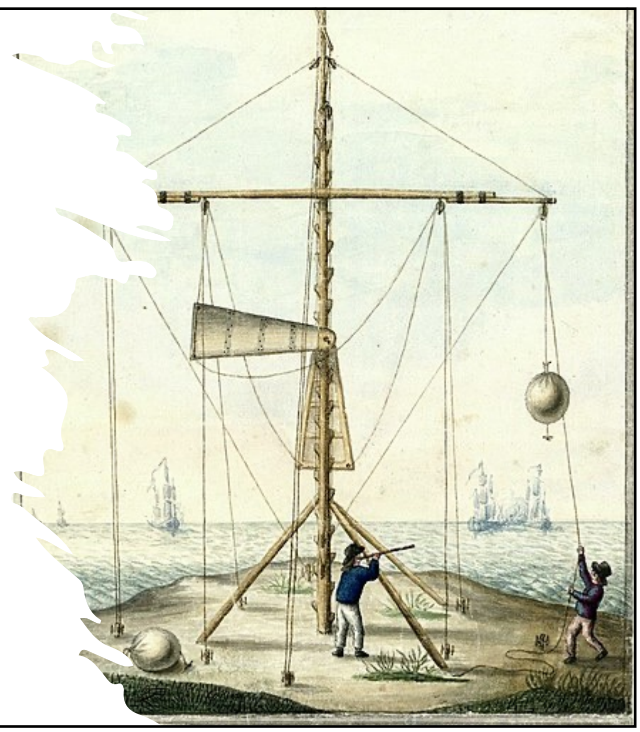
```
j = (i + 1)%n;

while ( (j != i ) && !waiting[j] ) {
   j = (j+1)%n
}
```

- **Scans** `waiting[]` in the ***cyclic*** ordering
  (`i+1, i+2, …n, 0, …, i-1`)

- ANY waiting process trying to enter critical section will do so in **`(n-1)`** turns

Semaphore: apparatus for signaling
from Ancient Greek σῆμα (**sêma**) 'sign, token',
and Greek -φόρος (**-phóros**) 'bearer, carrier'

SEMAPHORES



Semaphores

- Semaphore **S** is an integer variable
- Once *initialized*, accessed through **atomic** operations
  - `wait()`
  - `signal()`

Modifications to the integer value of semaphore execute indivisibly

```
wait(S) {
   while (S<=0) {
     ; //no operation
   }
   S--;
}
```

```
signal(S) {
  S++;
}
```

Types of semaphores

- Binary semaphores
  - The value of **S** can be 0 or 1
    - Also known as **mutex locks**
- Counting semaphores
  - Value of **S** can range over an *unrestricted* domain

Using the Binary semaphore to deal with the critical section problem

mutex is initialized to 1

```
do {

    wait(mutex);

    critical section

    signal(mutex);

    remainder section

} while (TRUE);
```

Suppose we require S2 to execute only after S1 has executed

Semaphore **synch** is initialized to **0**

Wait for **synch** to be > 0

PROCESS **P1**

```
S1;
signal(synch);
```

Set **synch** to 1

PROCESS **P2**

```
wait(synch);
S2;
```


The counting semaphore

- Controls access to a **finite** set of resource instances
- INITIALIZED to the <u>number of resources</u> available
- Resource Usage
  - `wait()`: To *use* a resource
  - `signal()`: To *release* a resource
- When all resources are being used: **S**==0
  - Block until **S** > 0 to use the resource

Problems with the basic semaphore implementation

- **{C1}** If there is a process in the critical section
- **{C2}** If another process tries to enter its critical section
  - Must loop continuously in entry code
  - **Busy waiting!**
    - Some other process could have used this more productively!
  - Sometimes these locks are called **spinlocks**
    - One advantage: No context switch needed when process must wait on a lock

Overcoming the need to busy wait

- During `wait` if **S**==0
  - Instead of *busy waiting*, the process **block**s itself
  - Place process in waiting queue for **S**
  - Process state switched to **waiting**
  - CPU scheduler picks *another* process to execute
- **Restart** process when another process does `signal`
  - Restarted using `wakeup()`
  - Changes process state from *waiting* to **ready**

Defining the semaphore

```
typedef struct {
   int value;
   struct process *list;
} semaphore;
```

list of processes

The `wait()` operation to eliminate busy waiting

```
wait(semaphore *S){
    S→value--;

    if (S→value <0) {
      add process to S→list;
      block();
    }

}
```

If value < 0 abs(value) is the number of waiting processes

`block()` suspends the process that invokes it

The `signal()` operation to eliminate busy waiting

```
signal(semaphore *S) {
     S→value++;

     if (S→value <= 0) {
        remove a process P from S→list;
        wakeup(P);
     }

}
```

`wakeup(P)` resumes the execution of process `P`

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Deadlocks and Starvation: Implementation of semaphore with a waiting queue

PROCESS P0	PROCESS P1

`wait(S);`
`wait(Q);`
 	
`signal(S);`
`signal(Q);`
	`wait(Q);`
	`wait(S);`
	
	`signal(Q);`
	`signal(S);`

Say: P0 executes `wait(S)` and *then* **P1** executes `wait(Q)`

P0 must wait till **P1** executes `signal(Q)`
P1 must wait till **P0** executes `signal(S)`

Cannot be executed so deadlock

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Semaphores and atomic operations

- Once a semaphore action has started
  - **No other process** can access the semaphore UNTIL
    - Operation has *completed* or *process has blocked*
- Atomic operations
  - Group of related operations
  - Performed without interruptions
    - Or not at all

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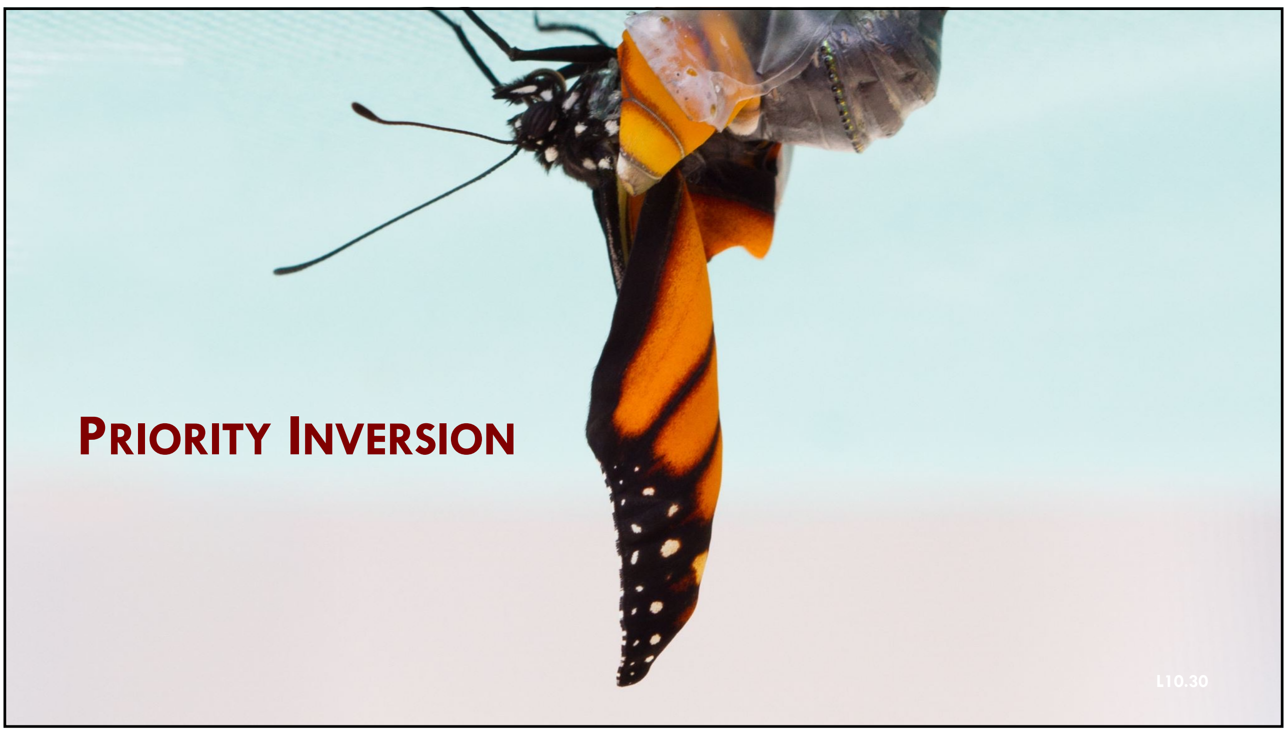

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Priority inversion

- Processes **L, M, H** (priority of **L** < **M** < **H)**
- Process **H** requires
  - Resource R being accessed by process **L**
  - Typically, **H** will wait for **L** to finish resource use
- **M** becomes runnable and preempts **L**
  - Process (**M**) with lower priority affects *how long* process **H** has to wait for **L** to release R

Priority inheritance protocol

- Process accessing resource needed by higher priority process
  - ***Inherits*** higher priority till it finishes resource use
  - Once done, process **reverts** to lower priority

Now you and me go parallel together and apart
And you keep your perfect distance and it's tearing at my heart
Did you never feel the distance?
You never tried to cross no line
Hand in Hand, Mark Knopfler, Dire Straits

Classic Problems of Synchronization

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The bounded buffer problem

- Binary semaphore (`mutex`)
  - Provides mutual exclusion for accesses to buffer pool
  - Initialized to 1
- Counting semaphores
  - `empty`: Number of empty slots available to produce
    - Initialized to ***n***
  - `full`: Number of filled slots available to consume
    - Initialized to **0**

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Some other things to bear in mind

- Producer and consumer must be **ready** before they **attempt to enter** critical section
- Producer readiness?
  - When a slot is available **to add** produced item
    - `wait(empty)`: `empty` is initialized to **n**
- Consumer readiness?
  - When a **producer has added** new item to the buffer
    - `wait(full)` : `full` initialized to **0**

Interpreting these variables:
How many slots are empty?
How many slots are full?

? Initializing Values

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The Producer

```
do {
        produce item nextp
        wait(empty);
        wait(mutex);

        add nextp to buffer

        signal(mutex);
        signal(full);

        remainder section

} while (TRUE);
```

`wait` till slot available

Only producer **OR** consumer can be in critical section

Allow producer **OR** consumer to (re)enter critical section

`signal` consumer that a slot is available

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The Consumer

```
do {

        wait(full);
        wait(mutex);

      remove item from buffer
         (nextc)

        signal(mutex);
        signal(empty);

        consume nextc

} while (TRUE);
```

- `wait(full);` — `wait` till slot available for consumption
- `wait(mutex);` — Only producer **OR** consumer can be in critical section
- `signal(mutex);` — Allow producer **OR** consumer to (re)enter critical section
- `signal(empty);` — `signal` producer that a slot is available to add

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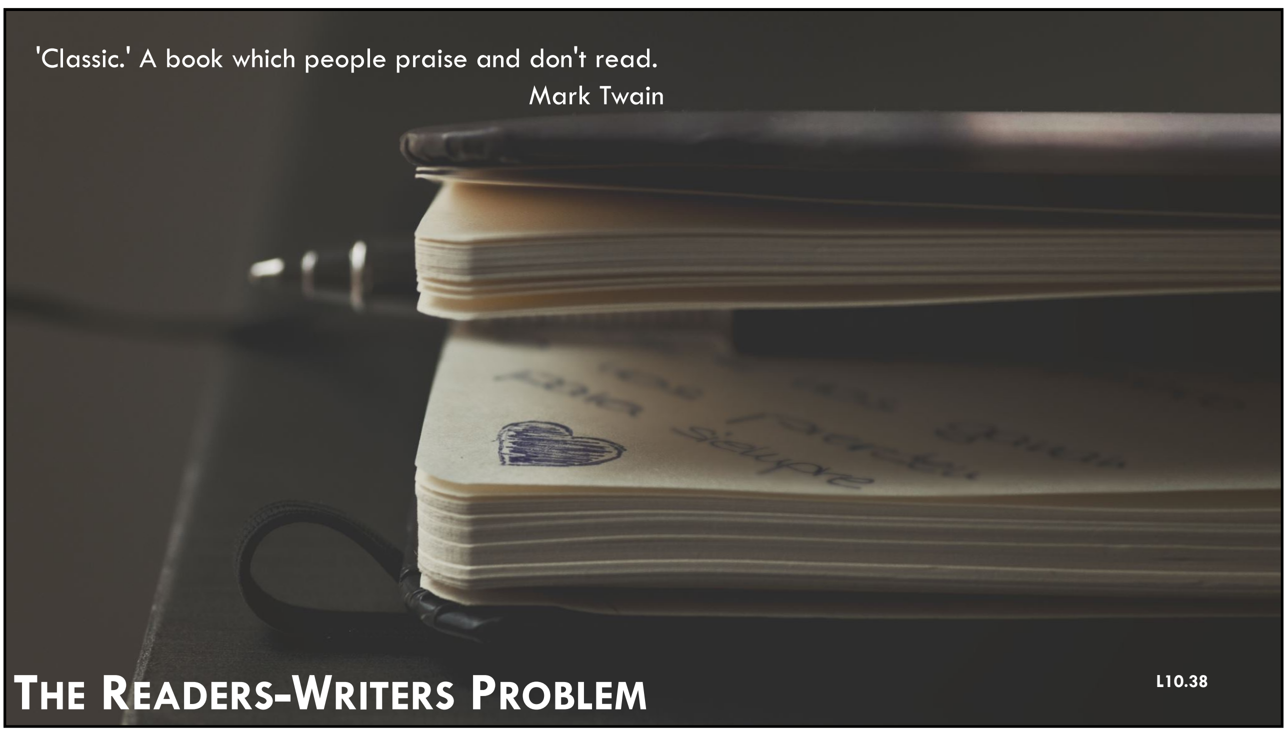

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The Readers-Writers problem

- A database is **shared** among several concurrent processes
- Two types of processes
  - Readers
  - Writers

Readers-Writers: Potential for adverse effects

- If *two readers* access shared data simultaneously?
  - No problems
- If a *writer and some other reader* (or writer) access shared data simultaneously?
  - Chaos

Writers must have exclusive access to shared database while writing

- FIRST readers-writers problem:
  - No reader should wait for other readers to finish; simply because a writer is waiting
    - Writers may starve
- SECOND readers-writers problem:
  - If a writer is ready it performs its write ASAP
    - Readers may starve

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Solution to the FIRST readers-writers problem

- Variable `int readcount`
  - Tracks how many readers are reading object
- Semaphore **`mutex`** **{1}**
  - Ensure mutual exclusion when `readcount` is accessed
- Semaphore **`wrt`** **{1}**
  1. Mutual exclusion for the writers
  2. First (last) reader that enters (exits) critical section
     - Not used by readers, when **other** readers **are in** their critical section

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The Writer: When a writer signals either a waiting writer or the readers resume

```
do {

        wait(wrt);

        writing is performed

        signal(wrt);

} while (TRUE);
```

When:
writer in critical section
and if n readers waiting

1 reader is queued on **wrt**
(n-1) readers queued on **mutex**

The Reader process

```
do {
        wait(mutex);
        readcount++;
        if (readcount ==1) {
          wait(wrt);
        }
        signal(mutex);

        reading is performed

        wait(mutex);
        readcount--;
        if (readcount ==0) {
          signal(wrt);
        }
        signal(mutex);
} while (TRUE);
```

mutex for mutual exclusion to `readcount`

When:
writer in critical section
and if n readers waiting

1 is queued on **wrt**
(n-1) queued on **mutex**

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. Modern Operating Systems. 4th Edition, 2014. Prentice Hall. ISBN: 013359162X/ 978-0133591620.* [Chapter 2]