CSC 369

Operating Systems

Lecture 3:

Synchronization: Semaphores & Locks

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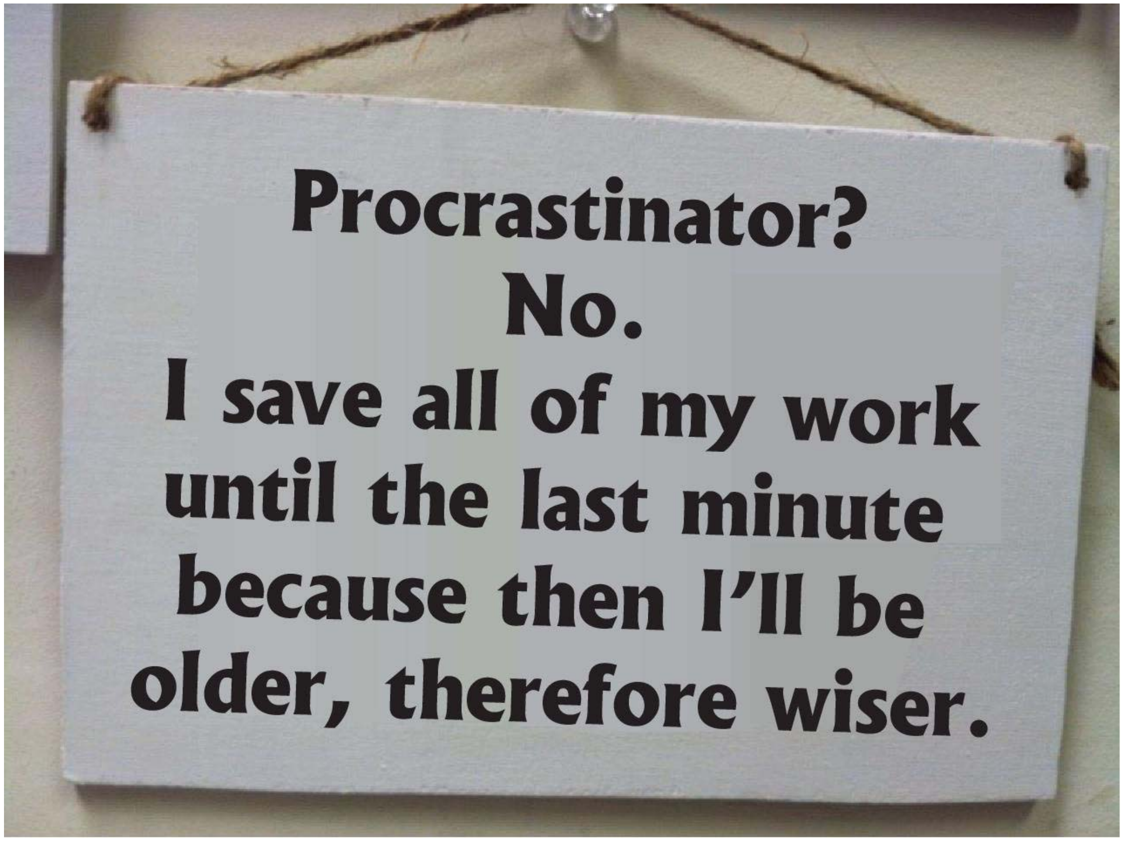
Assignment 1

- Remember: start early!



This Week

- Critical Section Problem
- Synchronization Primitives
  - Semaphores
    - Basic but flexible, Easy to understand
    - Can be hard to program with
  - Synchronization Hardware
  - Spinlocks
    - Very primitive, minimal semantics

Brief preview of scheduling

We have:

- Multiple threads/processes ready to run
- Some mechanism for switching between them
  - *Context switches*
- Some policy for choosing the next process to run
  - This policy may be *pre-emptive*
  - Meaning thread/process can't anticipate when it may be forced to yield the CPU
  - By design, it is not easy to detect it has happened (only the timing changes)

Synchronization

- Processes (and threads) interact in a multiprogrammed system
  - To share resources (such as shared data)
  - To coordinate their execution
- Arbitrary interleaving of thread executions can have unexpected consequences
  - We need a way to restrict the possible interleavings of executions
  - Scheduling is invisible to the application
- Synchronization is the mechanism that gives us this control

Flavours of Synchronization

- Two main uses:
  1. Enforce single use of a shared resource
     - Called the critical section problem
     - E.g. using a lock to ensure only one thread can print output to console at a time
       - T1: printf("Hello"); T2: printf("Goodbye");
       - Result should be "HelloGoodbye" OR "GoodbyeHello", but never "HeGooldbloye" or some other mixture
  2. Control order of thread execution
     - E.g. parent waits for child to finish
       - Ensure menu prints prompt *after* all output from thread running program

Motivating Example

- Suppose we write functions to handle withdrawals and deposits to bank account:

```
Withdraw(acct, amt) {
    balance = get_balance(acct);
    balance = balance - amt;
    put_balance(acct,balance);
    return balance;
}
```

```
Deposit(acct, amt) {
    balance = get_balance(acct);
    balance = balance + amt;
    put_balance(acct,balance);
    return balance;
}
```

- Now suppose you share this account with someone and the balance is $1000
- You each go to separate ATM machines - you withdraw $100 and your co-account holder deposits $100

Example Continued

- We can represent this situation by creating separate threads for each action, which may run at the bank's central server:

```
Withdraw(acct, amt) {
    balance = get_balance(acct);
    balance = balance - amt;
    put_balance(acct,balance);
    return balance;
}
```

```
Deposit(account, amount) {
    balance = get_balance(acct);
    balance = balance + amt;
    put_balance(acct,balance);
    return balance;
}
```

- What's wrong with this implementation?
  - Think about potential schedules for these two threads

Interleaved Schedules

- The problem is that the execution of the two processes can be interleaved:

Schedule A

```
balance = get_balance(acct);
balance = balance - amt;
```

```
balance = get_balance(acct);
balance = balance + amt;
put_balance(acct, balance);
```

```
put_balance(acct, balance);
```

Context switch

Schedule B

```
balance = get_balance(acct);
balance = balance - amt;
```

```
balance = get_balance(acct);
balance = balance + amt;
```

```
put_balance(acct, balance);
```

```
put_balance(acct, balance);
```

- What is the account balance now?
- Is the bank happy with our implementation?
  - Are you?

What Went Wrong?

- Two concurrent threads manipulated a *shared resource* (the account) without any synchronization
  - Outcome depends on the order in which accesses take place
    - Aka a *race condition*
- We need to ensure that only one thread at a time can manipulate the shared resource
  - So that we can reason about program behavior

➔ We need *synchronization*

Caution!

- Bank account problem can occur even with a simple shared variable, even on a uniprocessor:
  - T_1 and T_2 share variable X
  - T_1 increments X (X := X+1)
  - T_2 decrements X (X := X-1)
  - But at the machine level, we have:

```
T1:   LOAD X
      INCR
      STORE X
```

```
T2:   LOAD X
      DECR
      STORE X
```

- => Same problem of interleaving can occur!

Aside: What program data is shared?

That is, by threads in the same address space…

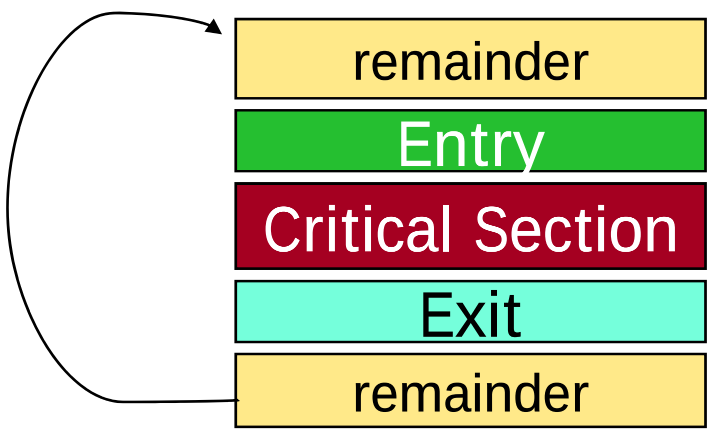
- Local variables are not shared (*private*)
  - Each thread has its own stack
  - Local vars are allocated on this private stack
  - Never pass/share/store a pointer to a local variable on another thread's stack!
- Global variables and static objects are *shared*
  - Stored in the static data segment, accessible by any thread
- Dynamic objects and other heap objs are *shared*
  - Allocated from heap with malloc/free (or new/delete, etc.)

Mutual Exclusion

- Given:
  - A set of *n* threads, $T_0, T_1, \ldots, T_{n-1}$
  - A set of resources shared between threads
  - A segment of code which accesses the shared resources, called the *critical section, CS*
- We want to ensure that:
  - Only one thread at a time can execute in the critical section
  - All other threads are forced to wait on entry
  - When a thread leaves the CS, another can enter

The Critical Section Problem

- Design a protocol that threads can use to cooperate
  - Each thread must request permission to enter its CS, in its *entry* section
  - CS may be followed by an *exit* section
  - Remaining code is the *remainder* section



- Each thread is executing at non-zero speed
  - no assumptions about relative speed

Critical Section Requirements

1) Mutual Exclusion
   - If one thread is in the CS, then no other is
2) Progress
   - Only threads not in the “remainder” section can influence the choice of which thread enters next, and choice cannot be postponed indefinitely
   - In other words: If no thread is in the CS, and some threads want to enter CS, they should be able to, unrestricted by threads in the “remainder”
3) Bounded waiting (no starvation)
   - If some thread T is waiting on the CS, then there is a limit on the number of times other threads can enter CS before this thread is granted access

- Performance
  - The overhead of entering and exiting the CS is small with respect to the work being done within it

Some Assumptions & Notation

- Assume **no special hardware instructions** (no H/W support)
- Assume no restrictions on the # of processors (for now)
- Assume that basic machine language instructions (LOAD, STORE, etc.) are ***atomic:***
  - If two such instructions are executed concurrently, the result is equivalent to their sequential execution in some unknown order
  - On modern architectures, this assumption may be false
- Let's consider a simple scenario: only 2 threads, numbered T_0 and T_1
  - Use T_i to refer to one thread, T_j for the other (j=1-i) when the exact numbering doesn't matter
- Let's look at one solution… [Exercise]

2-Thread Solutions: Take 1

- Let the threads share an integer variable *turn* initialized to 0 (or 1)
- If *turn=i* , thread T_i is allowed into its CS

```
My_work(id_t id) {  /* id_t can be 0 or 1 */
        ...
        while (turn != id) ;/* entry section */
        /* critical section, access protected resource */
        turn = 1 - id;       /* exit section */
        ...                  /* remainder section */
}
```

✓ Only one thread at a time can be in its CS

✗ Progress is not satisfied

- Requires strict alternation of threads in their CS: if *turn=0*, T_1 may not enter, even if T_0 is in the remainder section

2-Thread Solutions: Take 2

- First attempt does not have enough info about state of each process. It only remembers which process is allowed to enter its CS
- Replace turn with a shared flag for each thread
  - **`boolean`** `flag[2] = {false, false}`
  - Each thread may update its own flag, and read the other thread's flag
  - If `flag[i]` is true, T_i is ready to enter its CS
- Exercise ..

A Closer Look at 2nd Attempt

```
My_work(id_t id) {  /* id can be 0 or 1 */
        ...
        while (flag[1-id]) ;/* entry section */
        flag[id] = true;    /* indicate entering CS */
        /* critical section, access protected resource */
        flag[id] = false;   /* exit section */
        ...                 /* remainder section */
}
```

- Progress guaranteed?
- Starvation?
- Mutual exclusion is not guaranteed
    - Each thread executes *while* statement, finds *flag* set to false
    - Each thread sets own *flag* to *true* and enters CS

Example Execution Sequence

- Thread0 (id = 0)
- Thread1 (id = 1)

Time

```
while (flag[1]);
  /*false*/
                     switch
                                  while (flag[0]);
                                    /*false*/

  flag[id] = true;
  /* in crit. sect. */
                                   flag[id] = true;
                                   /* in crit. sect. */

  flag[id] = false;
                                   flag[id] = false;
```

Can't fix this by changing order of testing and setting *flag* variables (leads to *deadlock*)

2-Thread Solutions: Take 3

- Combine key ideas of first two attempts for a correct solution
- The threads share the variables *turn* and *flag* (where *flag* is an array, as before)
- Basic idea:
  - Set own flag (indicate interest) and set turn to self
  - Spin waiting while turn is self AND other has flag set (is interested)
  - If both threads try to enter their CS at the same time, *turn* will be set to both 0 and 1 at roughly the same time. Only one of these assignments will last. The final value of *turn* decides which of the two threads is allowed to enter its CS first.
- This is the basis of *Dekker's Algorithm* (1965) and *Peterson's Algorithm* (1981) - Modern OS book, 4th Ed. (A. Tanenbaum) – Fig 2.24, p 125

Peterson's Algorithm

```
int turn;
int flags[2];  /* Shows "interest" in the CS,
                  Are both initially 0, aka false. */

My_work(id_t id) {  /* id can be 0 or 1 */
      ...
      flag[id] = true;
      turn = id;
      while (turn == id && flag[1-id]) ;
      /* critical section, access protected resource */
      flag[id] = false;   /* exit section */
      ...                 /* remainder section */
}
```

- Convince yourself that this works…

Multiple-Thread Solutions

- Peterson's Algorithm can be extended to N threads
- Another approach is Lamport's *Bakery Algorithm*
  - Upon entering each customer (thread) gets a #
  - The customer with the lowest number is served next
  - No guarantee that 2 threads do not get same #
    - In case of a tie, thread with the lowest id is served first
    - Thread ids are unique and totally ordered
  - Mutual exclusion? Progress guaranteed? Starvation?

How multithreaded programming feels like ...

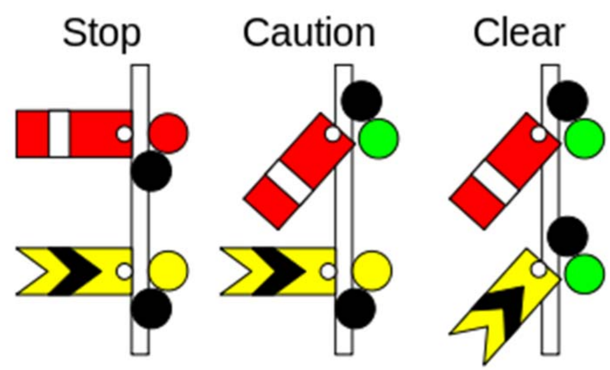
Source: 9gag.com

Next: Higher-level Abstractions for CS's

- Semaphores
  - Basic, easy to understand, hard to program with
- Locks
  - Very primitive, minimal semantics
- Condition variables
  - Stronger semantics, easier for diverse conditions
- Monitors
  - High-level, ideally has language support (Java)

Semaphores

- Semaphores are abstract data types that provide synchronization.



Source: wikipedia.org

- They include:
  - An integer counter variable, accessed only through 2 atomic operations
  - The atomic operation *wait* (also called *P* or *decrement*) - decrement the variable and block until semaphore is free
  - The atomic operation *signal* (also called *V* or *increment*) - increment the variable, unblock a waiting thread if there are any
  - A queue of waiting threads

Types of Semaphores

- Mutex (or Binary) Semaphore (count = 0/1)
  - Single access to a resource
  - Mutual exclusion to a critical section

Source: muppethub.com

- Counting semaphore
  - A resource with many units available, or a resource that allows certain kinds of unsynchronized concurrent access (e.g., reading)
  - Multiple threads can pass the semaphore
  - Max number of threads is determined by semaphore's initial value, *count*
    - Mutex has *count = 1*, counting has *count = N*

Using Binary Semaphores

Have semaphore, S, associated with acct

- Consider its initial value is 1

```
typedef struct account {
    double balance;
    semaphore S;
} account_t;

Withdraw(account_t *acct, amt){
    double bal;
    wait(acct->S);
    bal = acct->balance;
    bal = bal - amt;
    acct->balance = bal;
    signal(acct->S);
    return bal;
}
```

Three threads execute Withdraw()

```
wait(acct->S);
bal = acct->balance;
bal = bal - amt;
```

```
wait(acct->S);
```

```
wait(acct->S);
```

```
acct->balance = bal;
signal(acct->S);
```

```
...
signal(acct->S);
```

```
...
signal(acct->S);
```

It is **undefined** which thread runs after a **signal**

Atomicity of wait() and signal()

- We must ensure that two threads cannot execute *wait* and *signal* at the same time
- This is another critical section problem!
  - Use lower-level primitives to implement wait and signal
  - Uniprocessor: disable interrupts
  - Multiprocessor: use hardware instructions
    - Examples later in this lecture…

Locks vs. Semaphores

- A binary semaphore (with initial value 1) can be used just like a lock
- Why bother with both abstractions?
    - Semantic difference – logically, a lock has an “owner” and can only be released by its owner
        - Permits some error checking
        - Helps reason about the correct behavior
- Let’s look at a synchronization problem…

Producer / Consumer

- Classic synchronization problem
- Think how you would implement a pipe

```
Producer() {
     while(1) {

          write();

     }
}
```

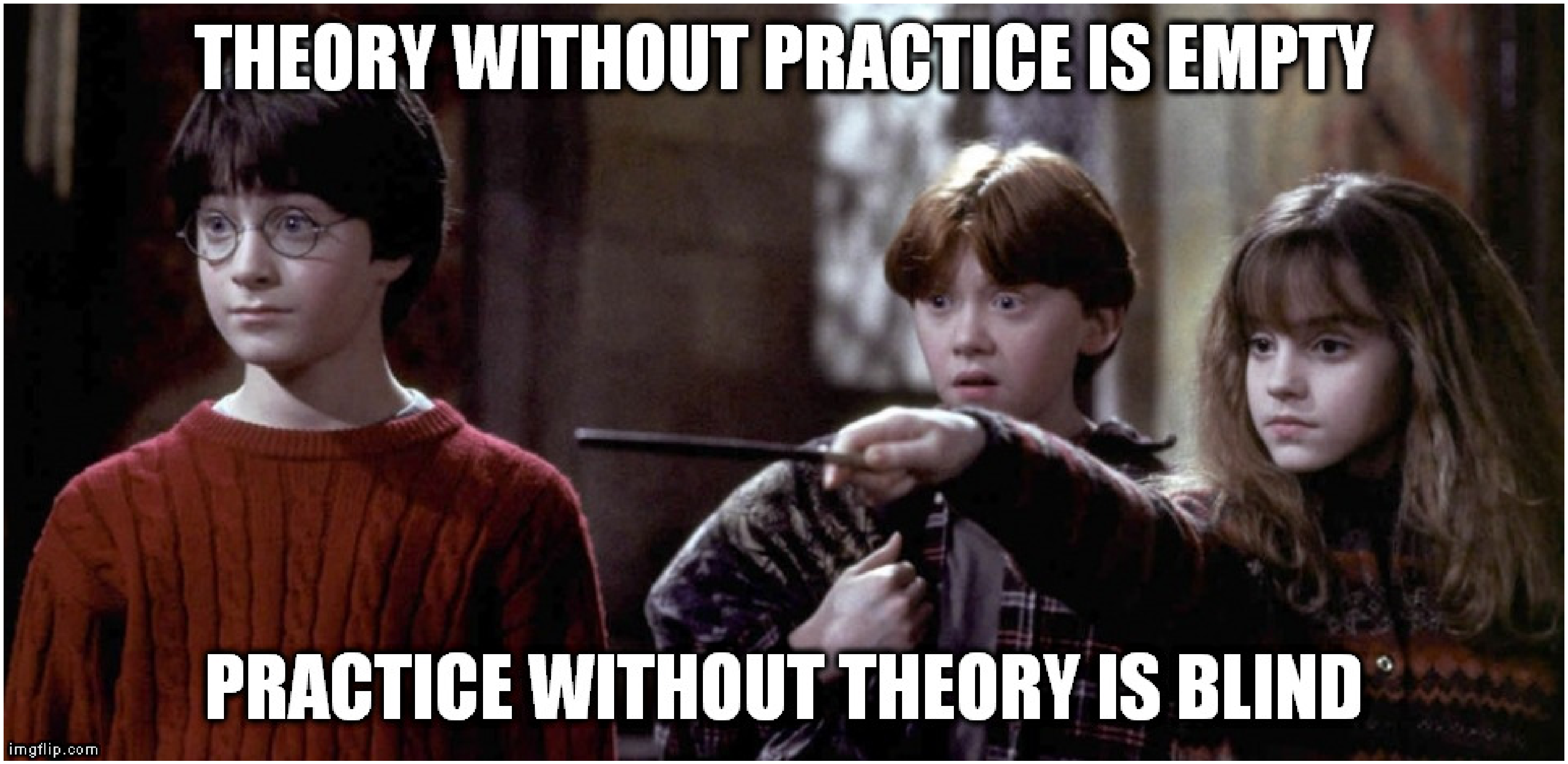
```
Consumer() {
     while(1) {

          read();

     }
}
```

- To be continued later ..

Posix Semaphores API

```
#include <semaphore.h>
sem_t mysem;
sem_init(&mysem, 0, VALUE);
sem_wait(&mysem);    → s.wait or P()
sem_post(&mysem);    → s.signal or V()
```

Example: semaphores and locks (pthread_mutex)



And now ...

- Semaphore exercise (use wait/signal)…

s1(0) s2(0)

Thread A	Thread B
a1	b1
s1.signal()	s1.wait()
s2.wait()	s2.signal()
a2	b2

Synchronization Hardware

- To build these higher-level abstractions, it is useful to have some help from the hardware
- On a uniprocessor, in the OS:
  - disable interrupts before entering critical section (prevents context switches)

```
oldspl = splhigh();
CRITICAL SECTION CODE
splx(oldspl);
```

- Disabling interrupts is insufficient on a multiprocessor. Why?
- Need some special atomic instructions

Atomic Instructions: Test-and-Set

- The semantics of test-and-set are:
  - Record the old value of the variable
  - Set the variable to some non-zero value
  - Return the old value
- Hardware executes this atomically!
- Can be used to implement simple lock variables

```
boolean test_and_set(boolean *lock) {
      boolean old = *lock;
      *lock = True;
      return old;
}
```

Alternate Defn of Test-and-Set

- We'll use "TAS" in the code example for "test-and-set"

```
boolean TAS(boolean *lock) {
        boolean old = *lock;
        *lock = True;
        return old;
}
```

```
boolean TAS(boolean *lock) {
    if(*lock == False) {
        *lock = True;
        return False;
    } else
        return True;
}
```

- *lock* is always *True* on exit from test-and-set
  - Either it was *True* (locked) already, and nothing changed, or it was *False* (available), but the caller now holds it
- Return value is either *True* if it was locked already, or *False* if it was previously available

A Lock Implementation

- There are two operations on locks: *acquire()* and *release()*

```
boolean lock;

void acquire(boolean *lock) {
        while(test_and_set(lock));
}

void release(boolean *lock) {
        *lock = false;
}
```

When false, we know that we've acquired it

To release, simply turn it to false.

- This is a *spinlock*
  - Uses *busy waiting* - thread continually executes *while* loop in *acquire()* , consumes CPU cycles

Using Locks

Function Definitions

```
Withdraw(acct, amt) {
    acquire(lock);
    balance = get_balance(acct);
    balance = balance - amt;
    put_balance(acct,balance);
    release(lock);
    return balance;
}
```

```
Deposit(account, amount) {
    acquire(lock);
    balance = get_balance(acct);
    balance = balance + amt;
    put_balance(acct,balance);
    release(lock);
    return balance;
}
```

Possible schedule

```
acquire(lock);
balance = get_balance(acct);
balance = balance - amt;
```

```
acquire(lock);
```

```
put_balance(acct, balance);
release(lock);
```

```
balance = get_balance(acct);
balance = balance + amt;
put_balance(acct, balance);
release(lock);
```

More Special Instructions

- *Swap* (or *Exchange*) instruction
  - Operates on two words atomically
  - Can also be used to solve critical section problem
  - Swap(boolean *varA, boolean *varB)

```
boolean lock = false; // shared by all processes
...

// in each thread
boolean key = true;  // local to each thread
while(key)  Swap(&lock, &key); // ENTRY

// Critical section

Swap(&lock, &key);  // EXIT
```

Other considerations

- Spinlocks are built on machine instructions
- Machine instructions have three problems:
  - Busy waiting
  - Starvation is possible
    - when a thread leaves its CS, the next one to enter depends on scheduling
    - a waiting thread could be denied entry indefinitely
  - Deadlock is possible through *priority inversion*
    - *More on that later, with scheduling…*

Sleep Locks

- Instead of spinning, put thread to sleep (into "blocked" state) while waiting to acquire a lock
- Requires a queue for waiting threads
  - Linux: wait queues

Source: http://joyreactor.com

```
wait_event(queue, condition)
wake_up(wait_queue_head_t *queue);
```