CSCE 313-200
Introduction to Computer Systems
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Synchronization III

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Chapter 5: Roadmap

5.1 Concurrency

5.2 Hardware mutex

5.3 Semaphores

5.4 Monitors

5.5 Messages

5.6 Reader-Writer

Hardware Mutex

- Without CPU support, mutual exclusion is impossible
- One seemingly good approach is to disable interrupts
  - Assembly instructions cli (clear interrupts) and sti (set interrupts)

```
__asm { cli }
// critical section
__asm { sti }
```

- May work fine on single-CPU hardware, but is unsuitable as a general solution
  - Privileged instruction, only the kernel can use
  - Masked interrupts on one CPU do not affect others
  - Cache coherency issues not resolved

Hardware Mutex

- A more powerful approach is to employ instructions that lock the memory bus and synchronize caches
  - CPU has to support this
- Now mutex v4.0

```
taken = 0
Mutex.Lock () {
    while (AtomicSwap (&taken, 1) == 1)
        ;
    // owns mutex
}
Mutex.Unlock ()
    taken = 0;
```

```
int AtomicSwap (int *ptr, int val) {
    __asm {
            mov     eax, val
            xchg    eax, [ptr]
            ret     eax
    }
}
```

xchg is always locked

- Another low-level primitive is Compare & Swap (CAS)
  - Compares the target to some constant, *swaps if equal*
  - Maps to assembly instruction CMPXCHG

Hardware Mutex

- Mutex v4.1 using CAS:
- Usually slower than AtomicSwap
  - Why use it then?
- Example where AtomicSwap doesn't work
  - Suppose `taken` can be 0-2
  - If 0, set it to 1
  - If 1, set to 2; if 2, set to 0
- Windows APIs
  - Several versions: 32-bit, 64-bit, and pointers

```
taken = 0
Mutex.Lock () {
    want = 0; newValue = 1
    // CAS returns the old value
    while (CAS (&taken, newValue, want) != want)
          ;
    // owns mutex
}
Mutex.Unlock ()
    taken = 0;
```

```
InterlockedExchange = AtomicSwap
InterlockedCompareExchange = CAS
InterlockedIncrement = a++
InterlockedDecrement = a--
InterlockedAdd = a + constant
InterlockedXor = a ^ constant
InterlockedAnd = a & constant
InterlockedOr  = a | constant
InterlockedBitTestAndSet = set bit to 1
InterlockedBitTestAndReset = set bit to 0
```

all of these use 32-bit destinations

Hardware Mutex

- Mutexes 4.0-4.1 are called spinlocks
- Internally, OS uses them to mutex against itself
  - Tiny critical sections make this acceptable
- At user level, spinlocks are used rarely
  - Mostly to achieve extreme levels of performance
  - We'll have benchmarks later in this chapter
- More common is to call a kernel-level mutex
  - User thread is blocked until its event is signaled
  - Useful for large critical sections and I/O operations
- As the event is signaled
  - Threads are unblocked in FIFO order (unless priorities dictate otherwise)
  - Specific APIs will be discussed next week

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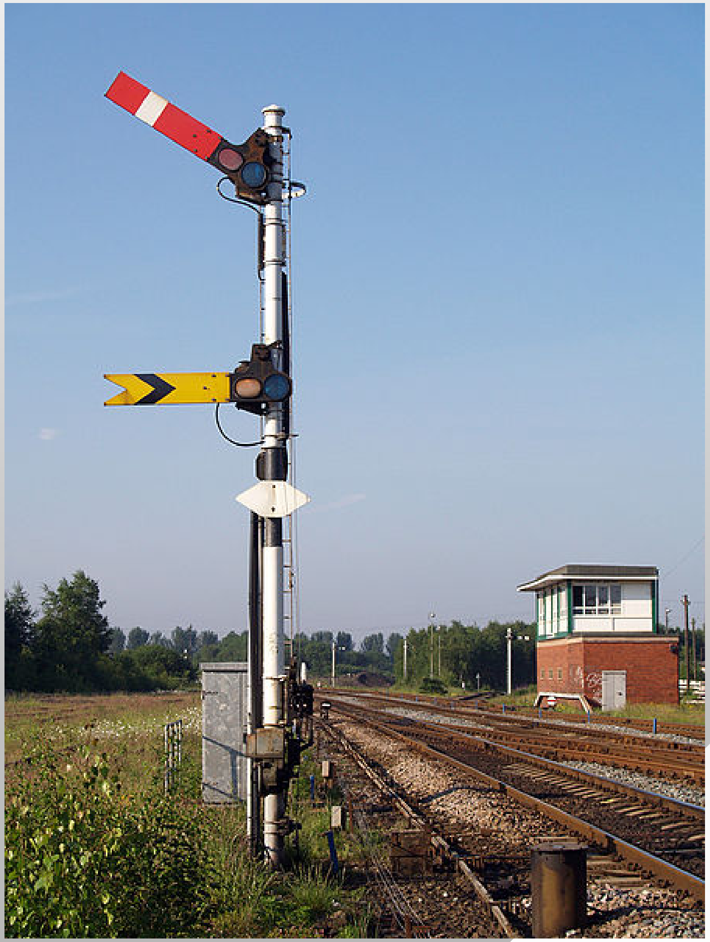

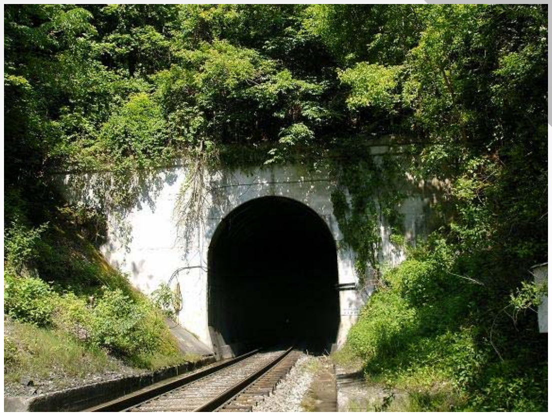

Semaphore

```
class Semaphore1 {
        int      s;       // current state
        P();     V();     // operations
}
```

- Perhaps one of the most useful synchronization constructs was invented by Dijkstra in 1965
- Definition: semaphore v1.0 is a class shared between threads/processes that admits two atomic operations:

```
Semaphore1::P() {
    s--
    if (s < 0)
        // block current thread
}
```

also called Lock or Wait

```
Semaphore1::V() {
    s++
    if (s <= 0)
        // unblock one waiting thread
}
```

also called Unlock or Release

- This version allows the state to be negative
  - Does not set any limits on its maximum or minimum value
  - Potential overflow issues

Semaphore

```
class Semaphore2 {
        int      s;          // current state
        int      max;        // max value
        List     blocked;    // pending threads
        P();     V();     // operations
}
```

- Semaphore v2.0 avoids incrementing s when there are pending threads and adds an upper bound on s

```
Semaphore2::P() { // inside kernel
    if (s > 0)
        s--;
    else
        t = GetCurrentThread()
        blocked.add (t)
        // block thread t
}
```

```
Semaphore2::V() { // inside kernel
    if (blocked.size() > 0)
        t = blocked.remove()
        // unblock thread t
    else
        s = min (s+1, max);
}
```

- Dijkstra defined semaphore 1.0 (abstract concept)
- Windows semaphores are 2.0 (kernel-mode)
  - Unless specified otherwise, assume this type
  - Initial state and max are set during creation

Semaphore

```
class Semaphore3 {
        Mutex    m;
        int      s;       // current state
        P();     V();     // operations
}
```

- POSIX semaphore v3.0 does not ensure that both operations P() and V() are atomic
  - Instead, it uses an internal mutex

```
Semaphore3::P() {
    m.Lock()
    while (s <= 0)
        m.Unlock()
        sleep
        m.Lock();
    s--
    m.Unlock()
}
```

```
Semaphore3::V() {
    m.Lock ()
    s++;
    m.Unlock()
}
```

- Semaphore 3.0 does not enforce any order in which competing threads acquire semaphore
  - Potential for starvation/unfairness
- Inefficient due to sleep-spinning?

Semaphore

- Examples:

```
Semaphore semaX = {15, 15}; // (s,max)
Thread () {
        semaX.Wait();    // P
        // critical section
        semaX.Release(); // V
}
```

allows up to 15 concurrent threads in some section

```
Semaphore semaX = {0, 1}; // (s,max)
Thread1 () {
        semaX.Wait();    // P
}
```

```
Semaphore semaX = {0, 1}; // (s,max)
Thread2 () {
        // initialize stuff
        semaX.Release(); // V
}
```

thread1 waits for thread2 to finish initialization

```
Semaphore semaX = {0, 1}; // (s,max)
Semaphore semaY = {0, 1}; // (s,max)
Thread1 () {
        // initialize stuff
        semaX.Wait();    // P
        semaY.Release(); // V
}
```

```
Semaphore semaX = {0, 1}; // (s,max)
Semaphore semaY = {0, 1}; // (s,max)
Thread2 () {
        // initialize stuff
        semaY.Wait();    // P
        semaX.Release(); // V
}
```

deadlock

Semaphore

- Examples (cont'd):

```
Semaphore semaX = {0, 1}; // (s,max)
Semaphore semaY = {0, 1}; // (s,max)
Thread1 () {
        // initialize stuff
        semaY.Release(); // V
        semaX.Wait();    // P
}
```

```
Semaphore semaX = {0, 1}; // (s,max)
Semaphore semaY = {0, 1}; // (s,max)
Thread2 () {
        // initialize stuff
        semaX.Release(); // V
        semaY.Wait();    // P
}
```

both threads wait for
the other to initialize

- Most common use of semaphores: allow entry of $\leq$ s concurrent threads into some section of the code
- Definition: a semaphore is called binary if max = 1 and counting (general) otherwise

Wrap-up

- Definition: a semaphore is called strong if it unblocks threads in FIFO order and weak otherwise
- Semaphore v1.0
  - Not detailed enough to determine
- Semaphore v2.0:
  - If internal data structure `List` is a FIFO queue, then it is strong
- Some kernels (e.g., Windows) run semaphore queues through the CPU scheduler
  - This makes them weak, but only to the extent of yielding to higher-priority threads
  - Thus, if user threads all have the same priority, their unblocking order relative to each other is approx FIFO
- Semaphore v3.0
  - Weak