Administrivia

- **The Google group is up and running**
  - Join here:
    http://groups.google.com/group/cs140-11wi/subscribe
  - Or email `cs140-11wi+subscribe@googlegroups.com`
- **Please ask questions on Google group**
  - We keep answering the same question to staff over and over
  - As of now, we will just answer "please ask on google groups"
  - We don't want to be rude, but if you re-send to google groups and answer there, will help more people
- **x86 manuals linked on reference materials page**
  - Several people were curious for more info on architecture

Review: Thread package API

- `tid thread_create (void (*fn) (void *), void *arg);`
  - Create a new thread that calls `fn` with `arg`
- `void thread_exit ();`
- `void thread_join (tid thread);`
- **The execution of multiple threads is interleaved**
- **Can have *non-preemptive threads*:**
  - One thread executes exclusively until it makes a blocking call.
- **Or *preemptive threads*:**
  - May switch to another thread between any two instructions.
- **Using multiple CPUs is inherently preemptive**
  - Even if you don't take CPU_0 away from thread T, another thread on CPU_1 can execute between any two instructions of T.

Program A

```
int flag1 = 0, flag2 = 0;

void p1 (void *ignored) {
  flag1 = 1;
  if (!flag2) { critical_section_1 (); }
}

void p2 (void *ignored) {
  flag2 = 1;
  if (!flag1) { critical_section_2 (); }
}

int main () {
  tid id = thread_create (p1, NULL);
  p2 (); thread_join (id);
}
```

- **Can both critical sections run?**

Program B

```
int data = 0, ready = 0;

void p1 (void *ignored) {
  data = 2000;
  ready = 1;
}

void p2 (void *ignored) {
  while (!ready)
    ;
  use (data);
}

int main () { ... }
```

- **Can** `use` **be called with value 0?**

Program C

```
int a = 0, b = 0;

void p1 (void *ignored) { a = 1; }

void p2 (void *ignored) {
  if (a == 1)
    b = 1;
}

void p3 (void *ignored) {
  if (b == 1)
    use (a);
}

int main () { ... }
```

- **Can** `use` **be called with value 0?**

Correct answers

- **Program A: I don't know**
- **Program B: I don't know**
- **Program C: I don't know**
- **Why?**
  - It depends on your hardware
  - If it provides *sequential consistency*, then answers all No
  - But not all hardware provides sequential consistency
- **Note: Examples and other slide content from [Adve & Gharachorloo]**

Sequential Consistency

- *Sequential consistency*: The result of execution is as if all operations were executed in some sequential order, and the operations of each processor occurred in the order specified by the program. [Lamport]
- Boils down to two requirements:
  1. Maintaining *program order* on individual processors
  2. Ensuring *write atomicity*
- **Without SC, multiple CPUs can be "worse" than preemptive threads**
  - May see results that cannot occur with any interleaving on 1 CPU
- **Why doesn't all hardware support sequential consistency?**

SC thwarts hardware optimizations

- **Complicates write buffers**
  - E.g., read flag$n$ before flag$(2-n)$ written through in Program A
- **Can't re-order overlapping write operations**
  - Concurrent writes to different memory modules
  - Coalescing writes to same cache line
- **Complicates non-blocking reads**
  - E.g., speculatively prefetch `data` in Program B
- **Makes cache coherence more expensive**
  - Must delay write completion until invalidation/update (Program B)
  - Can't allow overlapping updates if no globally visible order (Program C)

SC thwarts compiler optimizations

- **Code motion**
- **Caching value in register**
  - E.g., `ready` flag in Program B
- **Common subexpression elimination**
  - Could cause memory location to be read fewer times
- **Loop blocking**
  - Re-arrange loops for better cache performance
- **Software pipelining**
  - Move instructions across iterations of a loop to overlap instruction latency with branch cost

x86 consistency [intel 3a, §8.2]

- **x86 supports multiple consistency/caching models**
  - Memory Type Range Registers (MTRR) specify consistency for ranges of physical memory (e.g., frame buffer)
  - Page Attribute Table (PAT) allows control for each 4K page
- **Choices include:**
  - **WB**: Write-back caching (the default)
  - **WT**: Write-through caching (all writes go to memory)
  - **UC**: Uncacheable (for device memory)
  - **WC**: Write-combining – weak consistency & no caching
- **Some instructions have weaker consistency**
  - String instructions (written cache-lines can be re-ordered)
  - Special "non-temporal" instructions that bypass cache

x86 WB consistency

- **Old x86s (e.g, 486, Pentium 1) had almost SC**
  - Exception: A read could finish before an earlier write to a different location
  - Which of Programs A, B, C might be affected?
- **Newer x86s also let a CPU read its own writes early**

x86 WB consistency

- **Old x86s (e.g, 486, Pentium 1) had almost SC**
  - Exception: A read could finish before an earlier write to a different location
  - Which of Programs A, B, C might be affected? *Just A*
- **Newer x86s also let a CPU read its own writes early**
  - E.g., *both* `p1` and `p2` can return 2:

```
int flag1 = 0, flag2 = 0;

int p1 (void *ignored)           int p2 (void *ignored)
{                                {
  register int f, g;               register int f, g;
  flag1 = 1;                       flag2 = 1;
  f = flag1;                       f = flag2;
  g = flag2;                       g = flag1;
  return 2*f + g;                  return 2*f + g;
}                                }
```

  - Older CPUs would wait at "`f = ...`" until store complete

x86 atomicity

- `lock` **prefix makes a memory instruction atomic**
  - Usually locks bus for duration of instruction (expensive!)
  - Can avoid locking if memory already exclusively cached
  - All lock instructions totally ordered
  - Other memory instructions cannot be re-ordered w. locked ones
- `xchg` **instruction is always locked (even w/o prefix)**
- **Special fence instructions can prevent re-ordering**
  - `LFENCE` – can't be reordered w. reads (or later writes)
  - `SFENCE` – can't be reordered w. writes
  - `MFENCE` – can't be reordered w. reads or writes

Assuming sequential consistency

- **Important point: Known your memory model**
  - Particularly as OSes typically have their own synchronization
- **Most application code should avoid depending on memory model**
  - Obey certain rules, and behavior should be identical to S.C.
- **Let's for now say we have sequential consistency**
- **Example concurrent code: Producer/Consumer**
  - `buffer` stores `BUFFER_SIZE` items
  - `count` is number of used slots
  - `out` is next empty buffer slot to fill (if any)
  - `in` is oldest filled slot to consume (if any)

```c
void producer (void *ignored) {
    for (;;) {
        /* produce an item and put in nextProduced */
        while (count == BUFFER_SIZE)
            ; // do nothing
        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        count++;
    }
}

void consumer (void *ignored) {
    for (;;) {
        while (count == 0)
            ; // do nothing
        nextConsumed =  buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        count--;
        /*  consume the item in nextConsumed */
    }
}
```

- **What can go wrong here?**

Data races

- `count` **may have wrong value**
- **Possible implementation of** `count++` **and** `count--`

register←count	register←count
register←register $+ 1$	register←register $- 1$
count←register	count←register

- **Possible execution (count one less than correct):**

register←count
register←register $+ 1$
register←count
register←register $- 1$
count←register
count←register

Data races (continued)

- **What about a single-instruction add?**
  - E.g., i386 allows single instruction `addl $1,_count`
  - So implement `count++/--` with one instruction
  - Now are we safe?

Data races (continued)

- **What about a single-instruction add?**
  - E.g., i386 allows single instruction `addl $1,_count`
  - So implement `count++/--` with one instruction
  - Now are we safe?
- **Not atomic on multiprocessor!**
  - Will experience exact same race condition
  - Can potentially make atomic with `lock` prefix
  - But `lock` very expensive
  - Compiler won't generate it, assumes you don't want penalty
- **Need solution to *critical section* problem**
  - Place `count++` and `count--` in critical section
  - Protect critical sections from concurrent execution

Desired solution

- ***Mutual Exclusion***
  - Only one thread can be in critical section at a time
- ***Progress***
  - Say no process currently in critical section (C.S.)
  - One of the processes trying to enter will eventually get in
- ***Bounded waiting***
  - Once a thread T starts trying to enter the critical section, there is a bound on the number of times other threads get in
- **Note progress vs. bounded waiting**
  - If no thread can enter C.S., don't have progress
  - If thread A waiting to enter C.S. while B repeatedly leaves and re-enters C.S. *ad infinitum*, don't have bounded waiting

Peterson's solution

- **Still assuming sequential consistency**
- **Assume two threads,** T_0 **and** T_1
- **Variables**
  - `int not_turn;` – not this thread's turn to enter C.S.
  - `bool wants[2];` – `wants[i]` indicates if T_i wants to enter C.S.
- **Code:**

```
for (;;) { /* code in thread i */
  wants[i] = true;
  not_turn = i;
  while (wants[1-i] && not_turn == i)
    /* other thread wants in and not our turn, so loop */;
  Critical_section ();
  wants[i] = false;
  Remainder_section ();
}
```

Does Peterson's solution work?

```
for (;;) { /* code in thread i */
  wants[i] = true;
  not_turn = i;
  while (wants[1-i] && not_turn == i)
    /* other thread wants in and not our turn, so loop */;
  Critical_section ();
  wants[i] = false;
  Remainder_section ();
}
```

- **Mutual exclusion – can't both be in C.S.**
  - Would mean `wants[0] == wants[1] == true`, so `not_turn` would have blocked one thread from C.S.
- **Progress – If T_{1-i} not in C.S., can't block T_i**
  - Means `wants[1-i] == false`, so T_1 won't loop
- **Bounded waiting – similar argument to progress**
  - If T_i wants lock and T_{1-i} tries to re-enter, T_{1-i} will set `not_turn = 1 - i`, allowing T_i in

Mutexes

- **Peterson expensive, only works for 2 processes**
  - Can generalize to n, but for some fixed n
- **Want to insulate programmer from implementing synchronization primitives**
- **Thread packages typically provide *mutexes*:**

```
void mutex_init (mutex_t *m, ...);
void mutex_lock (mutex_t *m);
int mutex_trylock (mutex_t *m);
void mutex_unlock (mutex_t *m);
```

  - Only one thread acuires `m` at a time, others wait

Thread API contract

- **All global data should be protected by a mutex!**
  - Global = accessed by more than one thread, at least one write
  - Exception is initialization, before exposed to other threads
  - This is the responsibility of the application writer
- **If you use mutexes properly, behavior should be indistinguishable from Sequential Consistency**
  - This is the responsibility of the threads package (& compiler)
  - Mutex is broken if you use properly and don't see S.C.
- **OS kernels also need synchronization**
  - May or may not look like mutexes

Same concept, many names

- **Most popular application-level thread API: *pthreads***
  - Function names in this lecture all based on *pthreads*
  - Just add `pthread_` prefix
  - E.g., `pthread_mutex_t`, `pthread_mutex_lock`, ...
- **Same abstraction in Pintos under different name**
  - Data structure is `struct lock`
  - `void lock_init (struct lock *);`
  - `void lock_acquire (struct lock *);`
  - `bool lock_try_acquire (struct lock *);`
  - `void lock_release (struct lock *);`
- **Extra Pintos feature:**
  - Release checks lock was acquired by same thread
  - `bool lock_held_by_current_thread (struct lock *lock);`

Improved producer

```
mutex_t mutex = MUTEX_INITIALIZER;

void producer (void *ignored) {
    for (;;) {
        /* produce an item and put in nextProduced */

        mutex_lock (&mutex);
        while (count == BUFFER_SIZE) {
          mutex_unlock (&mutex);  // <--- Why?
          thread_yield ();
          mutex_lock (&mutex);
        }

        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        count++;
        mutex_unlock (&mutex);
    }
}
```

Improved consumer

```
void consumer (void *ignored) {
    for (;;) {
        mutex_lock (&mutex);
        while (count == 0) {
          mutex_unlock (&mutex);
          thread_yield ();
          mutex_lock (&mutex);
        }

        nextConsumed =  buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        count--;
        mutex_unlock (&mutex);

        /*  consume the item in nextConsumed */
    }
}
```

Condition variables

- **Busy-waiting in application is a bad idea**
  - Thread consumes CPU even when can't make progress
  - Unnecessarily slows other threads and processes
- **Better to inform scheduler of which threads can run**
- **Typically done with condition variables**
- `void cond_init (cond_t *, ...);`
  - Initialize
- `void cond_wait (cond_t *c, mutex_t *m);`
  - Atomically unlock `m` and sleep until `c` signaled
  - Then re-acquire `m` and resume executing
- `void cond_signal (cond_t *c);`
  `void cond_broadcast (cond_t *c);`
  - Wake one/all threads waiting on `c`

Improved producer

```
mutex_t mutex = MUTEX_INITIALIZER;
cond_t nonempty = COND_INITIALIZER;
cond_t nonfull = COND_INITIALIZER;

void producer (void *ignored) {
    for (;;) {
        /* produce an item and put in nextProduced */

        mutex_lock (&mutex);
        while (count == BUFFER_SIZE)
          cond_wait (&nonfull, &mutex);

        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        count++;
        cond_signal (&nonempty);
        mutex_unlock (&mutex);
    }
}
```

Improved consumer

```
void consumer (void *ignored) {
    for (;;) {
        mutex_lock (&mutex);
        while (count == 0)
          cond_wait (&nonempty, &mutex);

        nextConsumed =  buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        count--;
        cond_signal (&nonfull);
        mutex_unlock (&mutex);

        /*  consume the item in nextConsumed */
    }
}
```

Re-check conditions

- **Always re-check condition on wake-up:**
  - `while (count == 0)      // not if`
    `  cond_wait (&nonempty, &mutex);`
  - Otherwise, breaks with two consumers:

C_1	C_2	P
`cond_wait (...);`		
		`count++;`
		`cond_signal (...);`
		⋮
		`mutex_unlock (...);`
	`if (count)`	
	⋮	
	`count--;`	
	`mutex_unlock (...);`	
`count--;`		

Condition variables (continued)

- **Why must** `cond_wait` **both release mutex & sleep?**
- **Why not separate mutexes and condition variables?**

```
while (count == BUFFER_SIZE) {
  mutex_unlock (&mutex);
  cond_wait (&nonfull);
  mutex_lock (&mutex);
}
```

Condition variables (continued)

- **Why must `cond_wait` both release mutex & sleep?**
- **Why not separate mutexes and condition variables?**

```
while (count == BUFFER_SIZE) {
  mutex_unlock (&mutex);
  cond_wait (&nonfull);
  mutex_lock (&mutex);
}
```

- **Can end up stuck waiting when bad interleaving**

```
PRODUCER                                CONSUMER
while (count == BUFFER_SIZE);
mutex_unlock (&mutex);
                                        mutex_lock (&mutex);
                                        ...
                                        count--;
                                        cond_signal (&nonfull);
cond_wait (&nonfull);
```

Other thread package features

- **Alerts – cause exception in a thread**
- **Timedwait – timeout on condition variable**
- **Shared locks – concurrent read accesses to data**
- **Thread priorities – control scheduling policy**
  - Mutex attributes allow various forms of *priority donation* (will be familiar concept after lab 1)
- **Thread-specific global data**
- **Different synchronization primitives (in a few slides)**
  - Monitors
  - Semaphores

Implementing synchronization

- **User-visible mutex is straight-forward data structure**

```
typedef struct mutex {
  bool is_locked;          /* true if locked */
  thread_id_t owner;       /* thread holding lock, if locked */
  thread_list_t waiters; /* threads waiting for lock */

  lower_level_lock_t lk; /* Protect above fields */
};
```

- **Need lower-level lock `lk` for mutual exclusion**
  - Internally, `mutex_*` functions bracket code with `lock(mutex->lk)` ... `unlock(mutex->lk)`
  - Otherwise, data races! (E.g., two threads manipulating `waiters`)
- **How to implement `lower_level_lock_t`?**
  - Could use Peterson's algorithm, but typically a bad idea (too slow and don't know maximum number of threads)

Approach #1: Disable interrupts

- **Only for apps with** $n : 1$ **threads (1 kthread)**
  - Cannot take advantage of multiprocessors
  - But sometimes most efficient solution for uniprocessors
- **Have per-thread "do not interrupt" (DNI) bit**
- `lock (lk)`**: sets thread's DNI bit**
- **If timer interrupt arrives**
  - Check interrupted thread's DNI bit
  - If DNI clear, preempt current thread
  - If DNI set, set "interrupted" (I) bit & resume current thread
- `unlock (lk)`**: clears DNI bit *and* checks I bit**
  - If I bit is set, immediately yields the CPU

Approach #2: Spinlocks

- **Most CPUs support atomic read-[modify-]write**
- **Example:** `int test_and_set (int *lockp);`
  - Atomically sets `*lockp = 1` and returns old value
  - Special instruction – can't be implemented in portable C
- **Use this instruction to implement *spinlocks*:**

```
#define lock(lockp)    while (test_and_set (lockp))
#define trylock(lockp) (test_and_set (lockp) == 0)
#define unlock(lockp)  *lockp = 0
```

- **Spinlocks implement mutex's** `lower_level_lock_t`
- **Can you use spinlocks instead of mutexes?**
  - Wastes CPU, especially if thread holding lock not running
  - Mutex functions have short C.S., less likely to be preempted
  - On multiprocessor, sometimes good to spin for a bit, then yield

Synchronization on x86

- **Test-and-set only one possible atomic instruction**
- **x86 `xchg` instruction, exchanges reg with mem**
  - Can use to implement test-and-set

```
_test_and_set:
        movl    8(%esp), %edx    # %edx = lockp
        movl    $1, %eax         # %eax = 1
        xchgl   %eax, (%edx)     # swap (%eax, *lockp)
        ret
```

- **CPU locks memory system around read and write**
  - Recall `xchgl` always acts like it has `lock` prefix
  - Prevents other uses of the bus (e.g., DMA)
- **Usually runs at memory bus speed, not CPU speed**
  - Much slower than cached read/buffered write

Synchronization on alpha

- `ldl_l` – **load locked**

  `stl_c` – **store but sets reg to 0 if not atomic w.** `ldl_l`

```
_test_and_set:
        ldq_l   v0, 0(a0)          # v0 = *lockp (LOCKED)
        bne     v0, 1f             # if (v0) return
        addq    zero, 1, v0        # v0 = 1
        stq_c   v0, 0(a0)          # *lockp = v0 (CONDITIONAL)
        beq     v0, _test_and_set  # if (failed) try again
        mb
        addq    zero, zero, v0     # return 0
1:
        ret     zero, (ra), 1
```

- **Note: Alpha memory consistency weaker than x86**
  - Want all CPUs to think memory accesses in C.S. happened after acquiring lock, before releasing
  - *Memory barrier* instruction, `mb`, ensures this, like `MFENCE`

Kernel Synchronization

- **Should kernel use locks or disable interrupts?**
- **Old UNIX had non-preemptive threads, no mutexes**
  - Interface designed for single CPU, so `count++` etc. not data race
  - … *Unless* memory shared with an interrupt handler

```
int x = splhigh ();  // Disable interrupts
// Touch data shared with interrupt handler
splx (x);            // Restore previous state
```

  - C.f., Pintos `intr_disable` / `intr_set_level`
- **Used arbitrary pointers like condition variables**
  - `int [t]sleep (void *ident, int priority, ...);`
    put thread to sleep; will wake up at `priority` (∼`cond_wait`)
  - `int wakeup (void *ident);`
    wake up all threads sleeping on `ident` (∼`cond_broadcast`)

Kernel locks

- **Nowadays, should design for multiprocessors**
  - Even if first version of OS is for uniprocessor
  - Someday may want multiple CPUs and need *preemptive* threads
  - That's why Pintos uses locks
- **Multiprocessor performance needs fine-grained locks**
  - Want to be able to call into the kernel on multiple CPUs
- **If kernel has locks, should it ever disable interrupts?**

Kernel locks

- **Nowadays, should design for multiprocessors**
  - Even if first version of OS is for uniprocessor
  - Someday may want multiple CPUs and need *preemptive* threads
  - That's why Pintos uses locks
- **Multiprocessor performance needs fine-grained locks**
  - Want to be able to call into the kernel on multiple CPUs
- **If kernel has locks, should it ever disable interrupts?**
  - Yes! Can't sleep in interrupt handler, so can't wait for lock
  - So even modern OSes have support for disabling interrupts
  - Often uses DNI trick, which is cheaper than masking interrupts in hardware

Monitors [BH][Hoar]

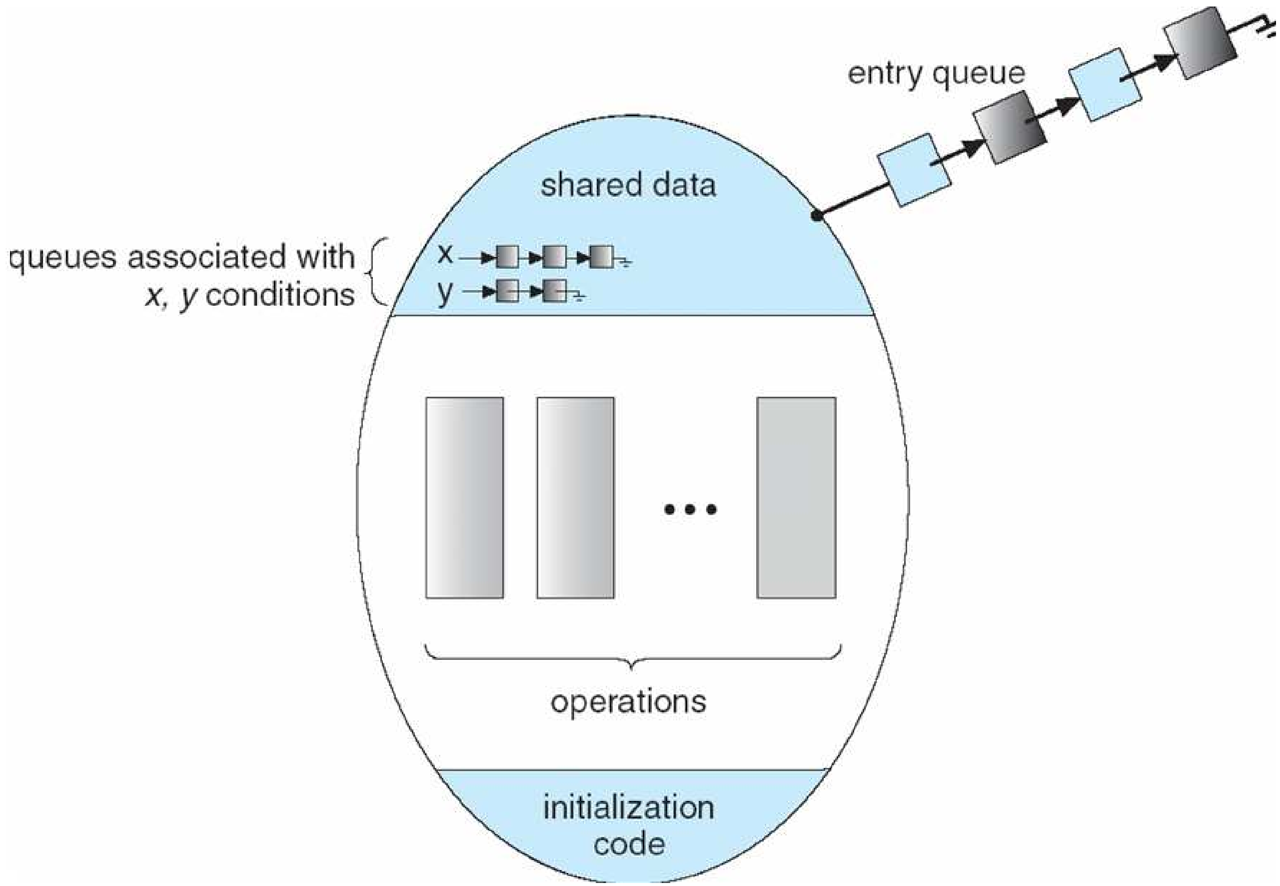
- **Programming language construct**
  - Possibly less error prone than raw mutexes, but less flexible too
  - Basically a class where only one procedure executes at a time

```
monitor monitor-name
{
  // shared variable declarations
  procedure P1 (...) { ... }
  ...
  procedure Pn (...) { ... }

  Initialization code (..) { ... }
}
```

- **Can implement mutex w. monitor or vice versa**
  - But monitor alone doesn't give you condition variables
  - Need some other way to interact w. scheduler
  - Use *conditions*, which are essentially condition variables

Monitor implementation



- **Queue of threads waiting to get in**
  - Might be protected by spinlock
- **Queues associated with conditions**

Semaphores [Dijkstra]

- **A *Semaphore* is initialized with an integer N**
- **Provides two functions:**
  - `sem_wait (S)` (originally called P, called *down* in Pintos)
  - `sem_signal (S)` (originally called V, called *up* in Pintos)
- **Guarantees `sem_wait` will return only N more times than `sem_signal` called**
  - Example: If $N == 1$, then semaphore is a mutex with `sem_wait` as lock and `sem_signal` as unlock
- **Semaphores give elegant solutions to some problems**
- **Linux primarily uses semaphores for sleeping locks**
  - `sema_init`, `down_interruptible`, `up`, ...
  - Also weird reader-writer semaphores, `rw_semaphore` [Love]
  - But evidence might favor mutexes [Molnar]

Semaphore producer/consumer

- **Can re-write producer/consumer to use three semaphores**
- **Semaphore** `mutex` **initialized to 1**
  - Used as mutex, protects buffer, in, out…
- **Semaphore** `full` **initialized to 0**
  - To block consumer when buffer empty
- **Semaphore** `empty` **initialized to N**
  - To block producer when queue full

```
void producer (void *ignored) {
    for (;;) {
        /* produce an item and put in nextProduced */
        sem_wait (&empty);
        sem_wait (&mutex);
        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        sem_signal (&mutex);
        sem_signal (&full);
    }
}

void consumer (void *ignored) {
    for (;;) {
        sem_wait (&full);
        sem_wait (&mutex);
        nextConsumed =  buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        sem_signal (&mutex);
        sem_signal (&empty);
        /*  consume the item in nextConsumed */
    }
}
```