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** (what we usually mean in this class):
  - 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`
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);
}

Q: Can both critical sections run?
int data = 0;
int ready = 0;

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

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

int main () { ... }

Q: Can use be called with value 0?
int a = 0;
int 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);
}

Q: If p1–3 run concurrently, can use be called with value 0?
Correct answers

[git push slides to web site now]
Correct answers

- Program A: I don’t know

Why don’t we know?

- It depends on what machine you use
- If a system provides sequential consistency, then answers all No
- But not all hardware provides sequential consistency

Note: Examples, other content from

Another great reference:
Correct answers

- Program A: I don’t know
- Program B: I don’t know
Correct answers

• Program A: I don’t know
• Program B: I don’t know
• Program C: I don’t know
• Why don’t we know?
  - It depends on what machine you use
  - If a system provides sequential consistency, then answers all No
  - But not all hardware provides sequential consistency

• Note: Examples, other content from [Adve & Gharachorloo]
• Another great reference: Why Memory Barriers
Sequential Consistency

Definition

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 on loads and stores:
  1. Maintaining program order of on individual processors
  2. Ensuring write atomicity

- Without SC (Sequential Consistency), multiple CPUs can be “worse”—i.e., less intuitive—than preemptive threads
  - Result may not correspond to any instruction 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\((3 - n)\) 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**
  - Collapse multiple loads/stores of same address into one operation
- **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 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 (used for frame buffers, when sending a lot of data to GPU)

• **Some instructions have weaker consistency**
  - String instructions (written cache-lines can be re-ordered)
  - Special “non-temporal” store instructions (movnt*) that bypass cache and can be re-ordered with respect to other writes
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?
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

```c
volatile int flag1;
volatile int flag2;

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

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

- E.g., both p1 and p2 can return 2:
- Older CPUs would wait at “f = . . .” until store complete
x86 atomicity

- **lock prefix makes a memory instruction atomic**
  - Historically locked bus for duration of instruction (expensive!)
  - Now requires exclusively caching memory, synchronizing with other memory operations
  - All lock instructions totally ordered
  - Other memory instructions cannot be re-ordered with locked ones

- **xchg instruction is always locked (even without prefix)**

- **Special barrier (or “fence”) instructions can prevent re-ordering**
  - **lfence** – can’t be reordered with reads (or later writes)
  - **sfence** – can’t be reordered with writes
    (e.g., use after non-temporal stores, before setting a *ready* flag)
  - **mfence** – can’t be reordered with reads or writes
Outline

1. Memory consistency
2. The critical section problem
3. Mutexes and condition variables
4. Implementing synchronization
5. Alternate synchronization abstractions
Assuming sequential consistency

- Often we reason about concurrent code assuming SC
- But for low-level code, **know your memory model!**
  - May need to sprinkle barrier/fence instructions into your source
  - Or may need compiler barriers to restrict optimization
- For most code, avoid depending on memory model
  - Idea: If you obey certain rules (**discussed later**) … system behavior should be indistinguishable from SC
- 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)
void producer (void *ignored) {
    for (;;) {
        item *nextProduced = produce_item ();
        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 */;
        item *nextConsumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        count--;
        consume_item (nextConsumed);
    }
}

Q: What can go wrong in above threads (even with SC)?
Data races

- count may have wrong value
- Possible implementation of `count++` and `count--`
  ```
  register ← count  
  register ← register + 1  
  count ← register
  ```

- Possible execution (count one less than correct):
  ```
  register ← count  
  register ← register + 1
  ```
• 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?
• 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 on multiprocessors!

• A single instruction may encode a load and a store operation
  - S.C. doesn’t make such *read-modify-write* instructions atomic
  - So on multiprocessor, suffer same race as 3-instruction version

• Can make x86 instruction atomic with `{lock}` prefix
  - But `{lock}` potentially very expensive
  - Compiler assumes you don’t want penalty, doesn’t emit it

• Need solution to *critical section* problem
  - Place `count++` and `count--` in critical section
  - Protect critical sections from concurrent execution
Desired properties of 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:

```c
for (;;) {
    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?

```c
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** – given demand, one thread can always enter C.S.
  - If $T_{1-i}$ doesn’t want C.S., wants[1-i] == false, so $T_i$ won’t loop
  - If both threads want in, one thread is not the not_turn thread

- **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
Outline

1 Memory consistency
2 The critical section problem
3 Mutexes and condition variables
4 Implementing synchronization
5 Alternate synchronization abstractions
Mutexes

- Peterson expensive, only works for 2 processes
  - Can generalize to $n$, but for some fixed $n$
- Must adapt to machine memory model if not SC
  - If you need machine-specific barriers anyway, might as well take advantage of other instructions helpful for synchronization
- Want to insulate programmer from implementing synchronization primitives
- Thread packages typically provide **mutexes**:
  
  ```c
  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 acquires $m$ 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 SC

• OS kernels also need synchronization
  - Some mechanisms look like mutexes
  - But interrupts complicate things (incompatible w. 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, ...

- C11 uses mtx_ instead of mutex_, C++11 uses methods on mutex

- Pintos uses struct lock for mutexes:
  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 that lock was acquired by same thread
  - bool lock_held_by_current_thread (struct lock *lock);
mutex_t mutex = MUTEX_INITIALIZER;

void producer (void *ignored) {
    for (;;) {
        item *nextProduced = produce_item ();

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

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

        consume_item (nextConsumed);
    }
}
Condition variables

- **Busy-waiting in application is a bad idea**
  - Consumes CPU even when a thread can’t make progress
  - Unnecessarily slows other threads/processes or wastes power

- **Better to inform scheduler of which threads can run**

- **Typically done with condition variables**

  - `struct cond_t;` (pthread_cond_t or condition in Pintos)
  - `void cond_init (cond_t *, ...);`
  - `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
mutex_t mutex = MUXTEX_INITIALIZER;
cond_t nonempty = COND_INITIALIZER;
cond_t nonfull = COND_INITIALIZER;

void producer (void *ignored) {
    for (;;) {
        item *nextProduced = produce_item ();

        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);
    }
}
void consumer (void *ignored) {
    for (;;) {
        mutex_lock (&mutex);
        while (count == 0)
            cond_wait (&nonempty, &mutex);
        item *nextConsumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        count--;
        cond_signal (&nonfull);
        mutex_unlock (&mutex);
        consume_item (nextConsumed);
    }
}
Re-check conditions

- Always re-check condition on wake-up
  ```c
  while (count == 0) /* not if */
  cond_wait (&nonempty, &mutex);
  ```

- Otherwise, breaks with spurious wakeup or two consumers
  - Start where Consumer 1 has mutex but buffer empty, then:

  **Consumer 1**
  ```
  cond_wait (...);
  ```

  **Consumer 2**
  ```
  mutex_lock (...);
  if (count == 0)
  ...
  use buffer[out] ...
  count--;
  mutex_unlock (...);
  ```

  **Producer**
  ```
  mutex_lock (...);
  ...
  count++;
  cond_signal (...);
  mutex_unlock (...);
  ```

  *use buffer[out] ... ← No items in buffer*
Condition variables (continued)

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

```c
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?
  ```c
  while (count == BUFFER_SIZE) {
    mutex_unlock (&mutex);
    cond_wait (&nonfull);
    mutex_lock (&mutex);
  }
  ```
- Can end up stuck waiting when bad interleaving

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

Consumer
```
mutex_lock (&mutex);
...
count--;
cond_signal (&nonfull);
```

- **Problem:** `cond_wait` & `cond_signal` do not commute
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
  - Need for things like `errno`
- Different synchronization primitives (later in lecture)
1 Memory consistency
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Implementing synchronization

- Implement mutex as straight-forward data structure?

```c
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 */
};
```

- Fine, so long as we avoid data races on the mutex itself
- 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)
Implementing synchronization

• Implement mutex as straight-forward data structure?

```c
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 */
};
```

- Fine, so long as we avoid data races on the mutex itself

• 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 `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

- Typical setup: periodic timer signal caught by thread scheduler

- Have per-thread “do not interrupt” (DNI) bit

- **lock** (lk): sets thread’s DNI bit

- **unlock** (lk): clears DNI bit and checks I 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

- 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 – no way to implement in portable C99 (C11 supports with explicit `atomic_flag_test_and_set` function)

- 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 4(%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 `xchg` always acts like it has implicit `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

- \texttt{ldl}_l – \textbf{load locked}
  - \texttt{stl}_c – \textbf{store conditional} (reg$\leftarrow$0 if not atomic w. \texttt{ldl}_l)

\_test\_and\_set:

- \texttt{ldq}_l \ v0, 0(a0) # v0 = *lockp (LOCKED)
- \texttt{bne} \ v0, 1f # if (v0) return
- \texttt{addq} \ zero, 1, v0 # v0 = 1
- \texttt{stq}_c \ v0, 0(a0) # *lockp = v0 (CONDITIONAL)
- \texttt{beq} \ v0, \_test\_and\_set # if (failed) try again
- \texttt{mb}
- \texttt{addq} \ zero, zero, v0 # return 0

1:
- \texttt{ret} \ zero, (ra), 1

- \textbf{Note: Alpha memory consistency weaker than x86}
  - Want all CPUs to think memory accesses in C.S. happened after acquiring lock, before releasing
  - \textit{Memory barrier} instruction \texttt{mb} ensures this (c.f. \texttt{mfence} on x86)
  - See \textbf{Why Memory Barriers} for why alpha still worth understanding
Kernel Synchronization

- Should kernel use locks or disable interrupts?

- Old UNIX had 1 CPU, non-preemptive threads, no mutexes
  - Interface designed for single CPU, so `count++` etc. not data race
  - ... *Unless* memory shared with an interrupt handler

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

- C.f., `intr_disable/intr_set_level` in Pintos, and `preempt_disable/preempt_enable` in Linux

- 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 sleeping locks
    (*sleeping* locks means mutexes, as opposed to *spin*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
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    (*sleeping* locks means mutexes, as opposed to *spin*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 when cheaper than masking interrupts in hardware
1. Memory consistency
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A Semaphore is initialized with an integer $N$

Provides two functions:
- `sem_wait(S)` (originally called $P$, called `sema_down` in Pintos)
- `sem_signal(S)` (originally called $V$, called `sema_up` in Pintos)

Guarantees `sem_wait` will return only $N$ more times than `sem_signal` called
- Example: If $N == 1$, then semaphore acts as a mutex with `sem_wait` as lock and `sem_signal` as unlock

Semaphores give elegant solutions to some problems
- Unlike condition variables, wait & signal commute

Linux primarily uses semaphores for sleeping locks
- `sema_init`, `down_interruptible`, `up`, ...
- Also weird reader-writer semaphores, `rw_semaphore` [Love]
Semaphore producer/consumer

- **Initialize full to 0** (block consumer when buffer empty)
- **Initialize empty to N** (block producer when queue full)

```c
void producer (void *ignored) {
    for (;;) {
        item *nextProduced = produce_item ()
        sem_wait (&empty);
        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        sem_signal (&full);
    }
}
```

```c
void consumer (void *ignored) {
    for (;;) {
        sem_wait (&full);
        item *nextConsumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        sem_signal (&empty);
        consume_item (nextConsumed);
    }
}
```
Various synchronization mechanisms

• Other more esoteric primitives you might encounter
  - Plan 9 used a rendezvous mechanism
  - Haskell uses MVars (like channels of depth 1)

• Many synchronization mechanisms equally expressive
  - Pintos implements locks, condition vars using semaphores
  - Could have been vice versa
  - Can even implement condition variables in terms of mutexes

• Why base everything around semaphore implementation?
  - High-level answer: no particularly good reason
  - If you want only one mechanism, can’t be condition variables (interface fundamentally requires mutexes)
  - Because `sem_wait` and `sem_signal` commute, eliminates problem of condition variables w/o mutexes