• 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 CPU₀ away from thread T, another thread on CPU₁ 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?
Program C

```c
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

- 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 ...

Another great reference: /five.pnum / /four.pnum/four.pnum
Correct answers

- Program A: I don’t know
Correct answers

- Program A: I don’t know
- Program B: 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
• 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)
• 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 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 (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) int p2 (void)
{
    register int f, g;
    flag1 = 1;
    f = flag1;
    g = flag2;
    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 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 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
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
  ```

  ```
  register ← count
  register ← register - 1
  count ← register
  ```

- **Possible execution (count one less than correct):**
  
  ```
  register ← count
  register ← register + 1
  ```

  ```
  register ← count
  register ← register - 1
  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?
- 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 (;;) { /* assume i is thread number (0 or 1) */
    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
1. Memory consistency
2. The critical section problem
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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);
    }
}
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);
    }
}

Improved consumer
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
  ```
Improved producer

```c
mutex_t mutex = MUTEX_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**
  ```c
  cond_wait (...);
  ```

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

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

  *use buffer[out]... ← No items in buffer*
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**
  ```c
  while (count == BUFFER_SIZE) {
    mutex_unlock (&mutex);
    cond_wait (&nonfull);
  }
  ```

  **Consumer**
  ```c
  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 \textit{priority donation} (will be familiar concept after lab 1)
- Thread-specific global data
  - Need for things like \texttt{errno}
- Different synchronization primitives (later in lecture)
1. Memory consistency
2. The critical section problem
3. Mutexes and condition variables
4. Implementing synchronization
5. Alternate synchronization abstractions
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 */
};
```
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_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

- **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 – 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

- ldl_l – load locked
  stl_c – store conditional (reg ← 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 (c.f. mfence on x86)
  - See [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

```
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 spinlocks)

- 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?
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?
- 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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Semaphores [Dijkstra]

- 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);
    }
}

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**