Review: Thread package API

- `tid create (void (*fn) (void *), void *arg);`
  - Create a new thread, run `fn` with `arg`
- `void exit ();`
- `void join (tid thread);`
- **Threads may run simultaneously**
  - E.g., `create (p1, NULL); create (p2, NULL);`
  - `p1` and `p2` run interleaved or concurrently
- **Threads have same address space**
  - Usually share some memory locations between threads
  - Otherwise, could just have used processes
- **Sharing + Concurrency can lead to unexpected results**

Program A

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

void p1 (void *ignored) {
  flag1 = 1;
  if (!flag2) { /* critical section */ }
}

void p2 (void *ignored) {
  flag2 = 1;
  if (!flag1) { /* critical section */ }
}
```

- **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);
}
```

- **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);
}
```

- **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
- **[BTW, examples and some other slide content from excellent Tech Report by 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*
- **Why doesn't all hardware support sequential consistency?**

S.C. thwarts hardware optimizations

- **Write buffers**
  - E.g., read flag$n$ before flag$(2-n)$ written through in Program A
- **Overlapping write operations can be reordered**
  - Concurrent writes to different memory modules
  - Coalescing writes to same cache line
- **Non-blocking reads**
  - E.g., speculatively prefetch `data` in Program B
- **Cache coherence**
  - Write completion only after invalidation/update (Program B)
  - Can't have overlapping updates (Program C)

S.C. thwarts compiler optimizations

- **Code motion**
- **Caching value in register**
  - E.g., ready flag in Program B
- **Common subexpression elimination**
- **Loop blocking**
- **Software pipelining**

Assuming sequential consistency

- **Let’s for now say we have sequential consistency**
  - Apologies for starting out with trick questions
  - Just don’t forget to check the memory model in real life
- **Later will see alpha which doesn’t have S.C.**
- **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 (;;) {
        /* 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
- **Note that without S.C., even reads can be dangerous**
- **Need solution to *critical section* problem**
  - Place `count++` and `count--` in critical section

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.)
  - Threads trying to enter C.S. can’t be blocked by those not trying
  - One of the processes trying to enter will eventually get in
- ***Bounded waiting***
  - After thread *T* starts trying to enter critical section
  - Bound on # times other threads get in

Peterson's solution

- **Still assuming sequential consistency**
- **Assume two threads,** T_0 **and** T_1
- **Variables**
  - `int turn` – whose turn to enter C.S.
  - `bool flag[2]` – `flag[i]` means T_i ready to enter C.S.
- **Code:**

```
for (;;) { /* code in thread i */
  flag[i] = true;
  turn = 1 - i;
  while (flag[1-i] && turn == 1-i)
    ;
  /* Critical Section */
  flag[i] = false;
  /* Remainder Section */
}
```

Does Peterson's solution work?

```
for (;;) { /* code in thread i */
  flag[i] = true;
  turn = 1 - i;
  while (flag[1-i] && turn == 1-i)
    ;
  /* Critical Section */
  flag[i] = false;
  /* Remainder Section */
}
```

- **Mutual exclusion – can't both be in C.S.**
  - Would mean `flag[0] == flag[1] == true`,
    so `turn` would have allowed only one thread into C.S.
- **Progress – If T_0 not in C.S., can't block T_1**
  - Means `flag[0] == false`, so T_1 won't loop
  - Similarly, if T_1 not in C.S. can't block T_0
- **Bounded waiting – similar argument to progress**

Mutexes

- **Peterson expensive, only works for 2 processes**
  - Can generalize to n, but for some fixed n
- **Typically want to insulate programmer from implementing synchronization primitives**
- **Thread packages typically provide mutexes:**
- `void lock (mutex_t m);`
  `void unlock (mutex_t m);`
  - Only one thread acuires `m` at a time, others wait
  - All global data must be protected by a mutex!
- **OS kernels also need some synchronization**
  - May or may not look like mutexes

Improved producer

```
mutex_t mutex;

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

        lock (mutex);
        while (count == BUFFER_SIZE) {
          unlock (mutex);  // <--- Why?
          yield ();
          lock (mutex);
        }

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

Improved consumer

```
void consumer (void *ignored) {
    for (;;) {
        lock (mutex);
        while (count == 0) {
          unlock (mutex);
          yield ();
          lock (mutex);
        }

        nextConsumed =  buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        count--;
        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 even processes
- **Better to inform scheduler of which threads can run**
- **Typically done with condition variables**
- `void wait (mutex_t m, cond_t c);`
  - Atomically unlock `m` and sleep until `c` signaled
  - Then reacquire `m` and resume executing
- `void signal (cond_t c);`
  `void broadcast (cond_t c);`
  - Wake one/all users waiting on `c`

Improved producer

```
mutex_t mutex;
cond_t nonempty, nonfull;

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

        lock (mutex);
        while (count == BUFFER_SIZE)
          wait (mutex, nonfull);

        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        count++;
        signal (nonempty);
        unlock (mutex);
    }
}
```

Improved consumer

```
void consumer (void *ignored) {
    for (;;) {
        lock (mutex);
        while (count == 0)
          wait (mutex, nonempty);

        nextConsumed =  buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        count--;
        signal (nonfull);
        unlock (mutex);

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

Condition variables (continued)

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

```
while (count == BUFFER_SIZE) {
  unlock (mutex);
  wait (nonfull);
  lock (mutex);
}
```

Condition variables (continued)

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

```
while (count == BUFFER_SIZE) {
  unlock (mutex);
  wait (nonfull);
  lock (mutex);
}
```

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

```
PRODUCER                       CONSUMER
while (count == BUFFER\_SIZE);
unlock (mutex);
                               lock (mutex);
                               ...
                               count--;
                               signal (nonfull);
wait (nonfull);
```

Implementing synchronization

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

```
struct mutex_t {
  bool is_locked;            /* true if locked */
  thread_id_t owner;         /* thread holding lock if locked */
  thread_list_t waiters;     /* threads waiting to lock */

  lower_level_lock_t lk;
};
```

- **Need lower-level lock `lk` for mutual exclusion**
  - Otherwise, would have data races on `mutex_t` itself
  - E.g., two threads manipulating `waiters` list corrupt list
- **How to implement `lower_level_lock_t`?**
  - Could use Peterson's algorithm, but typically not
  - Instead, use hardware support for synchronization

One approach: Disable interrupts

- **Does not work on multiprocessors**
  - But often most efficient solution for uniprocessors
- **For user-level threads, can use one kernel thread**
  - Context switch on timer interrupts (setitimer)
  - In critical section: Set “do not interrupt” (DNI) bit
  - If timer interrupt arrives, set “interrupted” bit
  - Manipulate protected low-level data structure
  - Clear DNI bit
  - If interrupted bit set, yield
- **In kernel, can do what old UNIX kernels did**
  - Non-preemptive threads, so `count++` etc. not data race
  - *Except* memory touched in both top-half thread & interrupt

UNIX Synchronization 1

- **Interface designed before multiprocessors common**
- **Top half kernel procedures can mask interrupts**

```
int x = splhigh ();
/* ... */
splx (x);
```

- **splhigh disables all interrupts, but also splnet, splbio, splsoftnet, …**
  - C.f., Pintos `intr_disable` / `intr_set_level`
- **Masking interrupts in hardware can be expensive**
  - Optimistic implementation – set mask flag on splhigh, check interrupted flag on splx

UNIX Synchronization 2

- **Need to relinquish CPU when waiting for events**
  - Disk read, network packet arrival, pipe write, signal, etc.
- `int tsleep(void *ident, int priority, ...);`
  - Switches to another process
  - `ident` is arbitrary pointer—e.g., buffer address
  - `priority` is priority at which to run when woken up
  - PCATCH, if ORed into `priority`, means wake up on signal
  - Returns 0 if awakened, or ERESTART/EINTR on signal
- `int wakeup(void *ident);`
  - Awakens all processes sleeping on `ident`
  - Restores SPL to value when they went to sleep
    (so fine to sleep at splhigh)

For MP, need hardware support

- **Need atomic read-write or read-modify-write:**
- **Example:** `int test_and_set (int *lockp);`
  - Sets `*lockp = 1` and returns old value
- **Now can implement *spinlocks*:**

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

- **Spinlocks used at low level to implement mutexes**
  - Using spinlocks directly would waste CPU time, especially if thread holding lock doesn't have a CPU
  - Critical section in mutex implementation very short, so OK
- **But gratuitous context switch has cost**
  - On MP, sometimes good to spin for a bit, then yield

Synchronization on x86

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

```
_test_and_set:
        movl    8(%esp), %edx
        movl    $1, %eax
        xchg    %eax, (%edx)
        ret
```

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

Synchronization on alpha

- **Another approach: load locked, store conditional**
- `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)
        bne     v0, 1f
        addq    zero, 1, v0
        stq_c   v0, 0(a0)
        beq     v0, _test_and_set
        mb
        addq    zero, zero, v0
1:
        ret     zero, (ra), 1
```

- **Note: Alpha does not have sequential consistency**
  - Yet want all processors to think that memory accesses happened after acquiring lock, before releasing
  - `mb`, *memory barrier* instruction, ensures this

Other thread package features

- **Alerts – cause exception in a thread**
- **Trylock – don't block if can't acquire mutex**
- **Timedwait – timeout on condition variable**
- **Shared locks – concurrent read accesses to data**
- **Thread priorities – control scheduling policy**
- **Thread-specific global data**
- **Different synchronization primitives**
    - Monitors
    - Semaphores
    - Reader/writer (shared) locks

Monitors

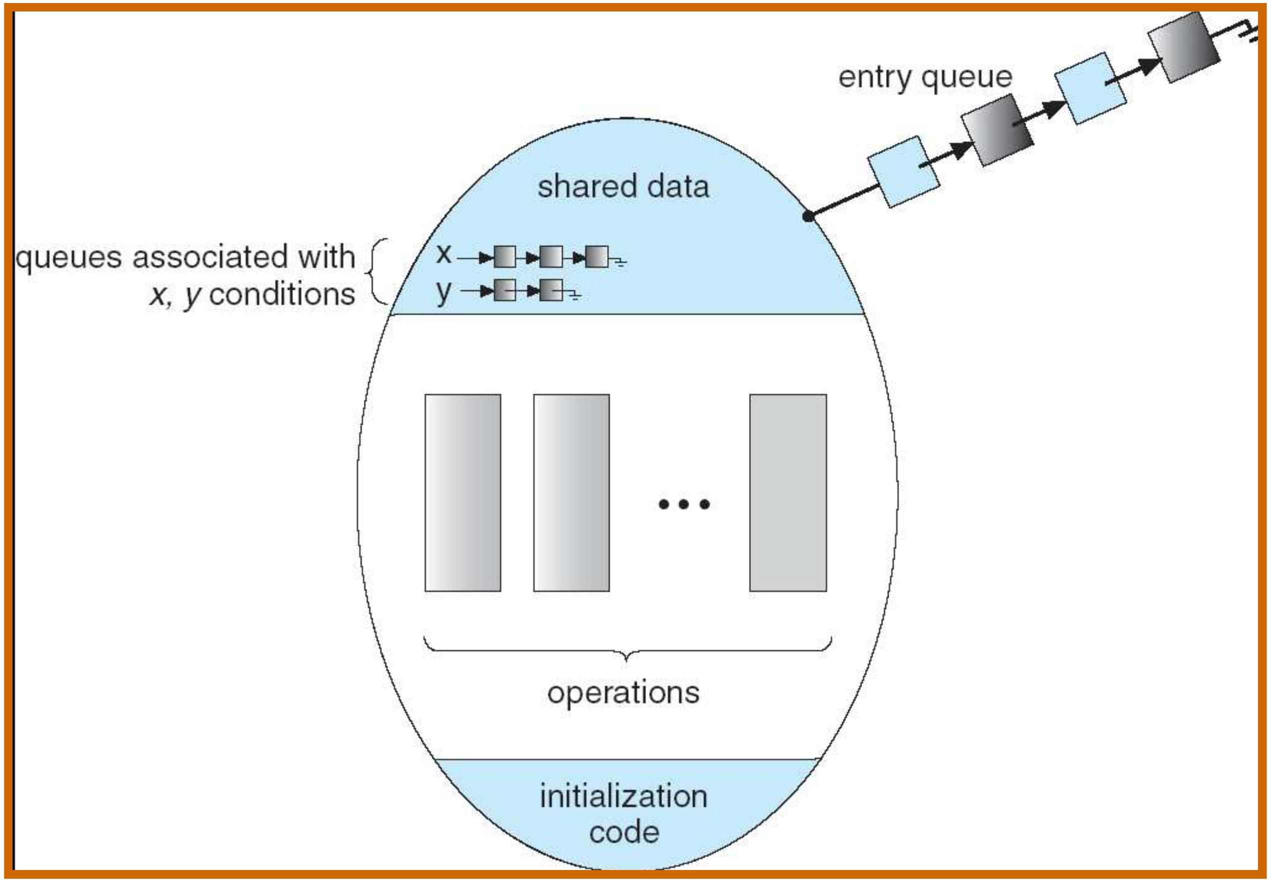
- **Programming language construct**
  - Possibly less error prone than raw mutexes, but less flexible too
  - Basically a class where only one procedure executes at a time

```
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* kind of like condition variables

Monitor implementation



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

Semaphores

- **A *Semaphore* is initialized with an integer** N
- **Provides two functions:**
  - `wait (S)` (originally called P)
  - `signal (S)` (originally called V)
- **Guarantees `wait` will return only** N **more times than `signal` called**
  - Example: If $N == 1$, then semaphore is a mutex
- **Semaphores allow elegant solutions to some problems**

Semaphore producer/consumer

- **Semaphore `mutex` initialized to 1**
  - To protect 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 */
        wait (empty);
        wait (mutex);
        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        signal (mutex);
        signal (full);
    }
}

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

Readers-Writers Problem

- **Multiple threads may access data**
    - *Readers* – will only observe, not modify data
    - *Writers* – will change the data
- **Goal: allow multiple readers or one single writer**
    - Thus, lock can be *shared* amongst concurrent readers
- **Can implement with other primitives**
    - Keep integer `i` – # or readers or -1 if held by writer

Implementing shared locks

```
struct sharedlk {
  int i;
  mutex_t m;
  cond_t c;
};

void AcquireExclusive (sharedlk *sl) {
  lock (sl->m);
  while (sl->i) { wait (sl->m, sl->c); }
  sl->i = -1;
  unlock (sl->m);
}

void AcquireShared (sharedlk *sl) {
  lock (sl->m);
  while (sl->i < 0) { wait (sl->m, sl->c); }
  sl->i++;
  unlock (sl->m);
}
```

shared locks (continued)

```
void ReleaseShared (sharedlk *sl) {
  lock (sl->m);
  if (!--sl->i) signal (sl->c);
  unlock (sl->m);
}

void ReleaseExclusive (sharedlk *sl) {
  lock (sl->m);
  sl->i = 0;
  broadcast (sl->c);
  unlock (sl->m);
}
```

- **Note: Must deal with starvation**