- [✓] 1. Last time
- [✓] 2. Advice
- [✓] 3. Practice w/ concurrent programming
- [✓] 4. Implementation of spinlocks, mutexes
- [ ] 5. Deadlock (intro)

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2. Advice

1. Getting started
   - 1a. identify units of concurrency
   - 1b. identify chunks of state
   - 1c. write down high-level main loop of each thread

   separate threads from objects

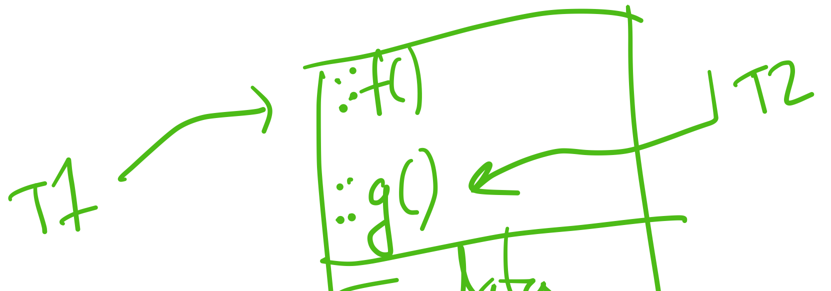
2. write down the synchronization constraints, and the kind (mutual exclusion or scheduling)

   m.e — one thread at a time on shared state
   sched1 = producer waits til non-full
   sched2 — consumer waits til non-empty

   cv1
   cv2

3. Create a lock or CV for each constraint

4. Write the methods, using the locks + CVs



3. Practice

Example

- workers interact w/ a database

- readers never modify
- writers read and modify
- single mutex would be too restrictive
- instead, want:
    - many readers at once OR
    - only one writer (and no readers)

Let's follow the advice:

a. units of concurrency? readers, writers

b. shared chunks of state? database

c. what does main function look like?

```
read()
    checkin .. wait until no writers
    access_DB()
```

check out... wake waiting writers, if any

write()
    checkin ... wait until no one else
    access_DB()
    check out... wake up waiting readers or writers.

2. and 3: synch. constraints and synch. objects

- reader can access the DB iff there are no active writers
  okToRead

- writer can access the DB iff there are no other active readers or writers
  okToWrite

- shared variables should be modified by only one thread at a time

4. write the methods

```
int AR = 0;  // active readers
int AW = 0;
int AW
int WR = 0; // waiting readers
int WW = 0; // waiting writers
```

---

4. Implementation of mutexes

Assume sequential consistency for now

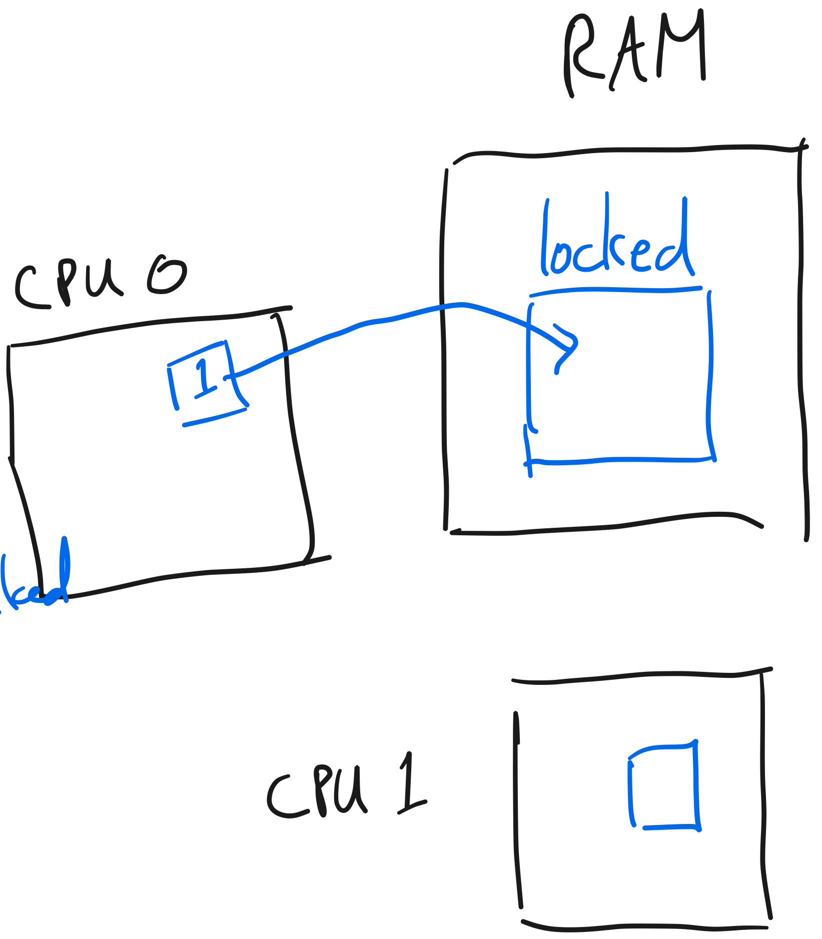
lock()/unlock()?

(a) Peterson $\longrightarrow$ busy waiting, static bound

(b) disable interrupts

(c) spinlocks

```
lock():
while(1) {
    read "locked"
    if (0) {
        write 1 to locked
        break;
    }
}
```



(d) mutexes: spinlock + a queue
- textbook has an implementation
- handout has another

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5. Deadlock

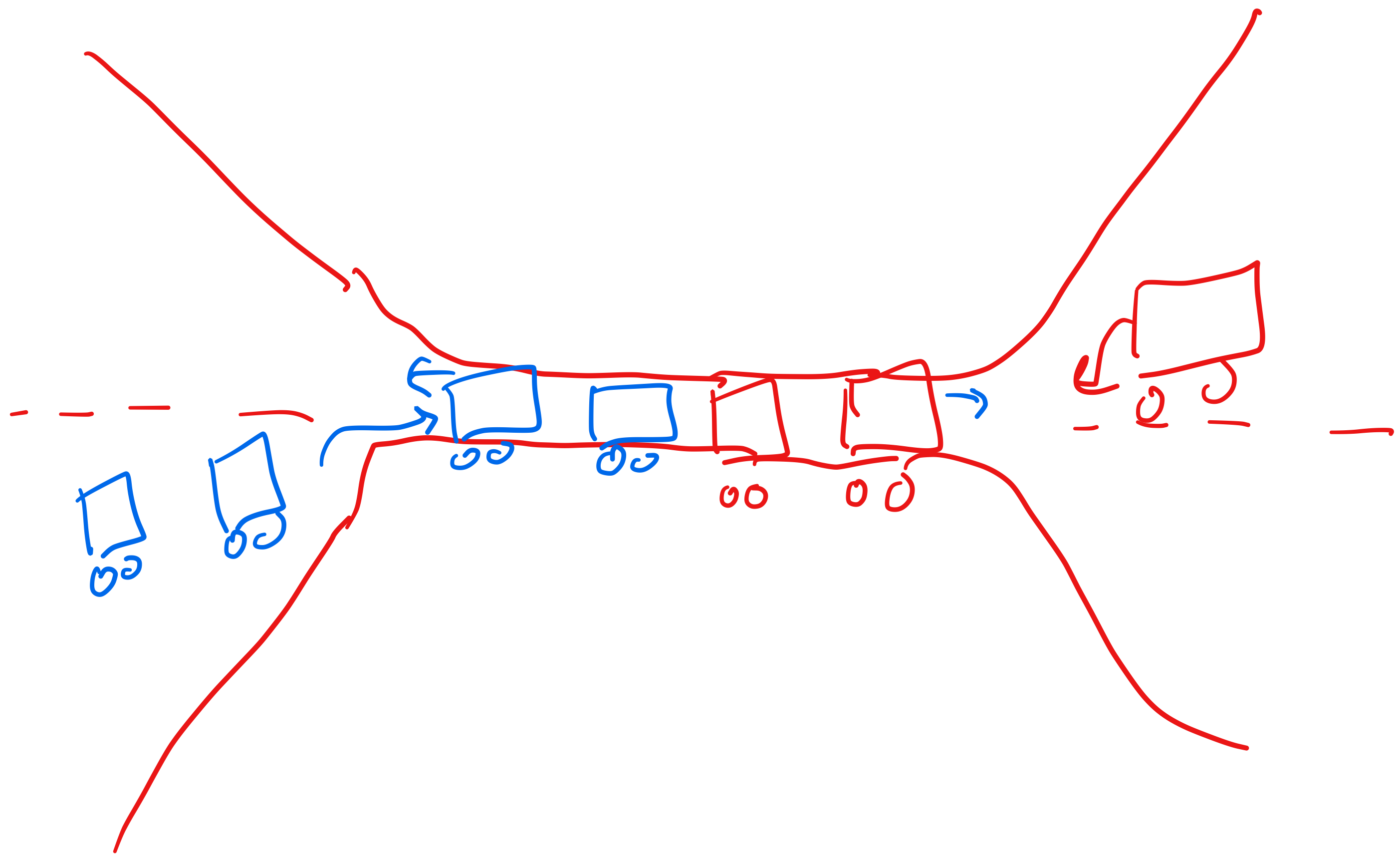
mutex A
mutex B

T1:

```
acquire(&A);
acquire(&B);
   .
   .
   .
release(&B);
release(&A);
```

T2:

```
acquire(&B);
acquire(&A);
   .
   .
   .
release(&A);
release(&B);
```



CS 202, Fall 2021
Handout 5 (Class ~~6~~ 7)

The previous handout demonstrated the use of mutexes and condition variables. This handout demonstrates the use of monitors (which combine mutexes and condition variables).

1. The bounded buffer as a monitor

```
    // This is pseudocode that is inspired by C++.
    // Don't take it literally.

    class MyBuffer {
      public:
        MyBuffer();
        ~MyBuffer();
        void Enqueue(Item);
        Item = Dequeue();
      private:
        int count;
        int in;
        int out;
        Item buffer[BUFFER_SIZE];
        Mutex* mutex;
        Cond* nonempty;
        Cond* nonfull;
    }

    void
    MyBuffer::MyBuffer()
    {
        in = out = count = 0;
        mutex = new Mutex;
        nonempty = new Cond;
        nonfull = new Cond;
    }

    void
    MyBuffer::Enqueue(Item item)
    {
        mutex.acquire();
        while (count == BUFFER_SIZE)
            cond_wait(&nonfull, &mutex);

        buffer[in] = item;
        in = (in + 1) % BUFFER_SIZE;
        ++count;
        cond_signal(&nonempty, &mutex);
        mutex.release();
    }

    Item
    MyBuffer::Dequeue()
    {
        mutex.acquire();
        while (count == 0)
            cond_wait(&nonempty, &mutex);

        Item ret = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        --count;
        cond_signal(&nonfull, &mutex);
        mutex.release();
        return ret;
    }
```

```
    int main(int, char**)
    {
        MyBuffer buf;
        int dummy;
        tid1 = thread_create(producer, &buf);
        tid2 = thread_create(consumer, &buf);

        // never reach this point
        thread_join(tid1);
        thread_join(tid2);
        return -1;
    }

    void producer(void* buf)
    {
        MyBuffer* sharedbuf = reinterpret_cast<MyBuffer*>(buf);
 while(1)
        for (;;) {
            /* next line produces an item and puts it in nextProduced */
            Item nextProduced = means_of_production();
            sharedbuf->Enqueue(nextProduced);
        }
    }

    void consumer(void* buf)
    {
        MyBuffer* sharedbuf = reinterpret_cast<MyBuffer*>(buf);
        for (;;) {
            Item nextConsumed = sharedbuf->Dequeue();

            /* next line abstractly consumes the item */
            consume_item(nextConsumed);
        }
    }
```

Key point: *Threads* (the producer and consumer) are separate from *shared object* (MyBuffer). The synchronization happens in the shared object.

```
2. This monitor is a model of a database with multiple readers and
writers. The high-level goal here is (a) to give a writer exclusive
access (a single active writer means there should be no other writers
and no readers) while (b) allowing multiple readers. Like the previous
example, this one is expressed in pseudocode.

    // assume that these variables are initialized in a constructor
    state variables:
        AR = 0;  // # active readers
        AW = 0;  // # active writers
        WR = 0;  // # waiting readers
        WW = 0;  // # waiting writers

        Condition okToRead = NIL;
        Condition okToWrite = NIL;
        Mutex mutex = FREE;

    Database::read() {
        startRead();  // first, check self into the system
        Access Data
        doneRead();   // check self out of system
    }

    Database::startRead() {
        acquire(&mutex);
        while((AW + WW) > 0){
            WR++;
            wait(&okToRead, &mutex);
            WR--;
        }
        AR++;
        release(&mutex);
    }

   Database::doneRead() {
        acquire(&mutex);
        AR--;
        if (AR == 0 && WW > 0) { // if no other readers still
          signal(&okToWrite, &mutex);   // active, wake up writer
        }
        release(&mutex);
    }

    Database::write(){  // symmetrical
        startWrite();  // check in
        Access Data
        doneWrite();  // check out
    }

    Database::startWrite() {
        acquire(&mutex);
        while ((AW + AR) > 0) { // check if safe to write.
                                // if any readers or writers, wait
            WW++;
            wait(&okToWrite, &mutex);
            WW--;
        }
        AW++;
        release(&mutex);
    }

    Database::doneWrite() {
        acquire(&mutex);
        AW--;
        if (WW > 0) {
            signal(&okToWrite, &mutex); // give priority to writers
        } else if (WR > 0) {
            broadcast(&okToRead, &mutex);
        }
        release(&mutex);
    }

    NOTE: what is the starvation problem here?
```

```

3. Shared locks

    struct sharedlock {
      int i;
      Mutex mutex;
      Cond c;
    };

    void AcquireExclusive (sharedlock *sl) {
      acquire(&sl->mutex);
      while (sl->i) {
        wait (&sl->c, &sl->mutex);
      }
      sl->i = -1;
      release(&sl->mutex);
    }

    void AcquireShared (sharedlock *sl) {
      acquire(&sl->mutex);
      while (sl->i < 0) {
        wait (&sl->c, &sl->mutex);
      }
      sl->i++;
      release(&sl->mutex);
    }

    void ReleaseShared (sharedlock *sl) {
      acquire(&sl->mutex);
      if (!--sl->i)
        signal (&sl->c, &sl->mutex);
      release(&sl->mutex);
    }

    void ReleaseExclusive (sharedlock *sl) {
      acquire(&sl->mutex);
      sl->i = 0;
      broadcast (&sl->c, &sl->mutex);
      release(&sl->mutex);
    }

    QUESTIONS:
    A. There is a starvation problem here. What is it? (Readers can keep
       writers out if there is a steady stream of readers.)
    B. How could you use these shared locks to write a cleaner version
       of the code in the prior item? (Though note that the starvation
       properties would be different.)
```

Implementation of spinlocks and mutexes

1. Here is a BROKEN spinlock implementation:

```
        struct Spinlock {
          int locked;
        }

        void acquire(Spinlock *lock) {
          while (1) {
            if (lock->locked == 0) { // A
              lock->locked = 1;       // B
              break;
            }
          }
        }

        void release (Spinlock *lock) {
          lock->locked = 0;
        }
```

What's the problem? Two acquire()s on the same lock on different CPUs might both execute line A, and then both execute B. Then both will think they have acquired the lock. Both will proceed. That doesn't provide mutual exclusion.

2. Correct spinlock implementation

Relies on atomic hardware instruction. For example, on the x86-64, doing

```
            "xchg addr, %rax"
```

locked

does the following:

```
    (i)   freeze all CPUs' memory activity for address addr
    (ii)  temp <-- *addr
    (iii) *addr <-- %rax
    (iv)  %rax <-- temp
    (v)   un-freeze memory activity
```

$\boxed{\text{xchg}}$

```
    /* pseudocode */
    int xchg_val(addr, value) {
        %rax = value;
        xchg (*addr), %rax
    }

    /* bare-bones version of acquire */
    void acquire (Spinlock *lock) {
      pushcli();    /* what does this do? */
      while (1) {
        if (xchg_val(&lock->locked, 1) == 0)
          break;
      }
    }
```

cmpxchg

```
    void release(Spinlock *lock){
        xchg_val(&lock->locked, 0);
        ~~popcli~~();    /* what does this do? */
    }
```

$\cancel{\boxed{\text{lock}\rightarrow\text{locked} = 0}}$

```
    /* optimization in acquire; call xchg_val() less frequently */
    void acquire(Spinlock* lock) {
        pushcli();
        while (xchg_val(&lock->locked, 1) == 1) {
            while (lock->locked) ;
        }
    }
```

The above is called a *spinlock* because acquire() spins. The bare-bones version is called a "test-and-set (TAS) spinlock"; the other is called a "test-and-test-and-set spinlock".

The spinlock above is great for some things, not so great for others. The main problem is that it *busy waits*: it spins, chewing up CPU cycles. Sometimes this is what we want (e.g., if the cost of going to sleep is greater than the cost of spinning for a few cycles waiting for another thread or process to relinquish the spinlock). But sometimes this is not at all what we want (e.g., if the lock would be held for a while: in those cases, the CPU waiting for the lock would waste cycles spinning instead of running some other thread or process).

NOTE: the spinlocks presented here can introduce performance issues when there is a lot of contention. (This happens even if the programmer is using spinlocks correctly.) The performance issues result from cross-talk among CPUs (which undermines caching and generates traffic on the memory bus). If we have time later, we will study a remediation of this issue (search the Web for "MCS locks").

ANOTHER NOTE: In everyday application-level programming, spinlocks will not be something you use (use mutexes instead). But you should know what these are for technical literacy, and to see where the mutual exclusion is truly enforced on modern hardware.

```
3. Mutex implementation

    The intent of a mutex is to avoid busy waiting: if the lock is not
    available, the locking thread is put to sleep, and tracked by a
    queue in the mutex. The next page has an implementation.
```

mutex:
- spinlock +
- queue +
- id of curr owner

```c
#include <sys/queue.h>

typedef struct thread {
    // ... Entries elided.
    STAILQ_ENTRY(thread_t) qlink; // Tail queue entry.
} thread_t;

struct Mutex {
    // Current owner, or 0 when mutex is not held.
    thread_t *owner;

    // List of threads waiting on mutex
    STAILQ(thread_t) waiters;

    // A lock protecting the internals of the mutex.
    Spinlock splock;   // as in item 1, above
};

void mutex_acquire(struct Mutex *m) {

    acquire(&m->splock);

    // Check if the mutex is held; if not, current thread gets mutex and returns
    if (m->owner == 0) {
        m->owner = id_of_this_thread;
        release(&m->splock);
    } else {
        // Add thread to waiters.
        STAILQ_INSERT_TAIL(&m->waiters, id_of_this_thread, qlink);

        // Tell the scheduler to add current thread to the list
        // of blocked threads. The scheduler needs to be careful
        // when a corresponding sched_wakeup call is executed to
        // make sure that it treats running threads correctly.
        sched_mark_blocked(&id_of_this_thread);

        // Unlock spinlock.
        release(&m->splock);

        // Stop executing until woken.
        sched_swtch();

        // When we get to this line, we are guaranteed to hold the mutex. This
        // is because we can get here only if context-switched-TO, which itself
        // can happen only if this thread is removed from the waiting queue,
        // marked "unblocked",/ and set to be the owner (in mutex_release()
        // below). However, we might actually have held the mutex in lines 39-42

        // (if we were context-switched out after the spinlock release(),
        // followed by being run as a result of another thread's release of the
        // mutex). But if that happens, it just means that we are
        // context-switched out an "extra" time before proceeding.
    }
}

void mutex_release(struct Mutex *m) {
    // Acquire the spinlock in order to make changes.
    acquire(&m->splock);

    // Assert that the current thread actually owns the mutex
    assert(m->owner == id_of_this_thread);

    // Check if anyone is waiting.
    m->owner = STAILQ_GET_HEAD(&m->waiters);

    // If so, wake them up.
    if (m->owner) {
        sched_wakeone(&m->owner);
        STAILQ_REMOVE_HEAD(&m->waiters, qlink);
    }

    // Release the internal spinlock
    release(&m->splock);
}
```