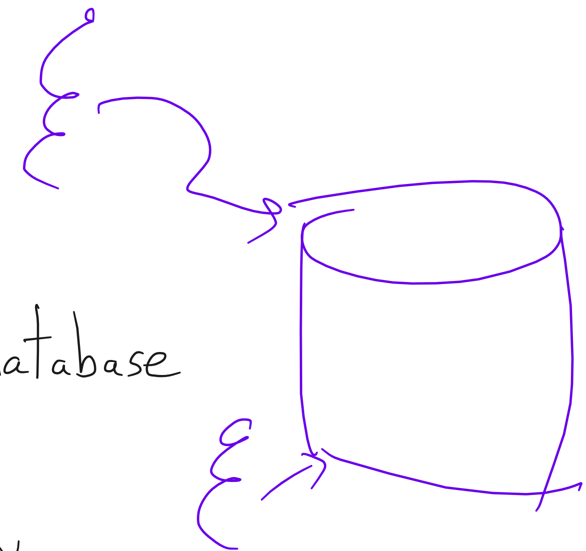
- [ ] 1. Last time

ONE HANDOUT

- [ ] 2. Practice with concurrent programming
- [ ] 3. Implementation of spinlocks, mutexes
- [ ] 4. Deadlock

## 2 Practice



Example:

- workers interact with 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? reader thrs writer thrs

b. shared chunks of state? database bookkeeping vars

c. what does main function look like?

read()

check in .... wait until no writers

access_DB()

check out ... wake waiting writers, if any write()

→ check in ... wait until no one else

→ access_DB()

→ check out ... wake up waiting readers or writers

2. and 3. synchronization constraints and synchronization objects

mutual exclusion of the state that allows us to implement checkin() / checkout().

okToWrite writer: no readers or writers. ≡ safe to proceed if no other thr.s in DB

okToRead reader: no writers ≡ safe to proceed if no active writes

4. write the methods

```
int AR = 0;   // active readers
int AW = 0;   // active writers
```

```
int WR = 0; // waiting readers
int WW = 0; // waiting writers
```

---

3. Implementation of spinlocks and mutexes

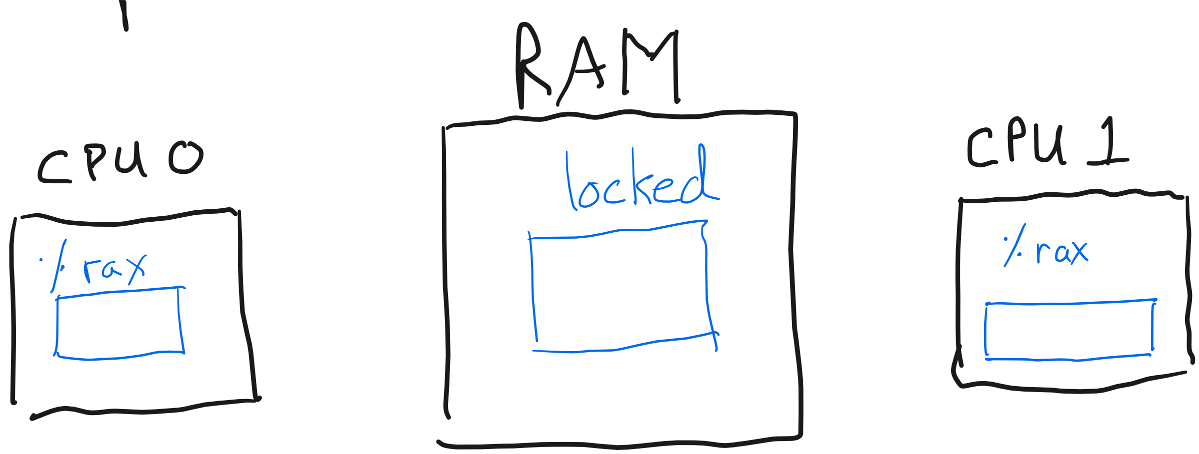
high-level interface: lock()/unlock()

how to provide?

(a) Peterson's algorithm → busy waiting, static bound

(b) disable interrupts

(c) spinlocks




(d) mutexes: spinlock + a queue

- textbook has an implementation
- handout has another

---

4. Deadlock

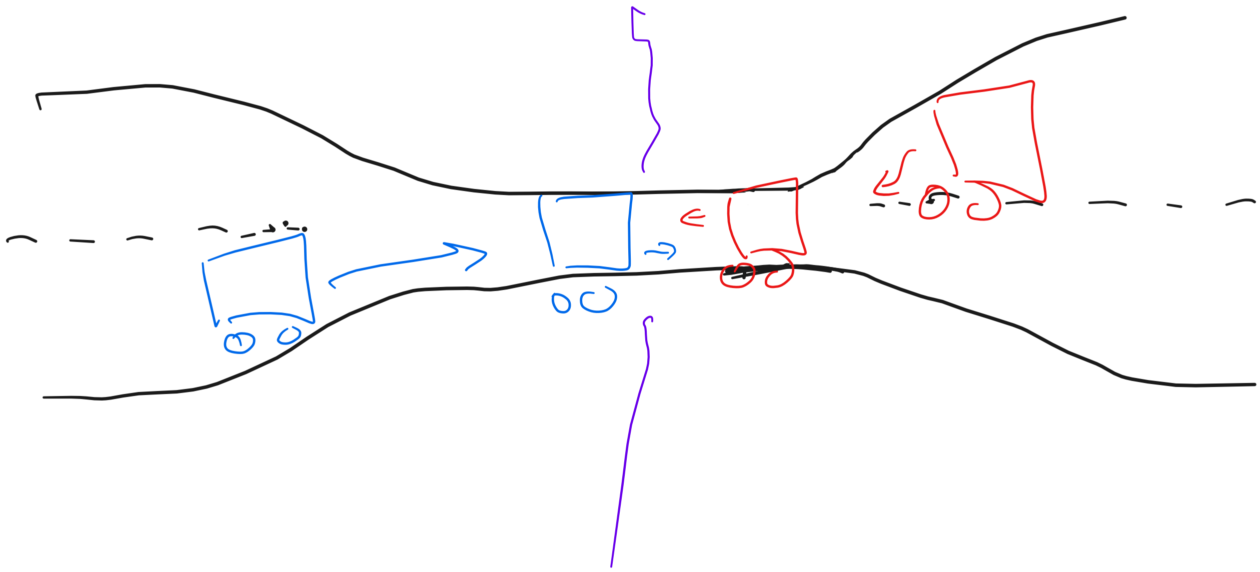
```
T1                  T2
acq(&mA);           acq(&mB);
acq(&mB);           acq(&mA);

release(&mB);
release(&mA);
```

Happens when <u>all four</u> of these conditions are present:

i. mutual exclusion
ii. hold and wait
iii. no pre-emption
iv. circular wait

What can we do about deadlock?

(a) ignore it
(b) detect & recover
(c) avoid algorithmically
(d) negate one of the 4 conditions
(e) static/dynamic detection tools



CS 202
Handout 5 (Class 6)

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);
        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"
        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

    /* 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;
      }
    }

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


    /* 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). To learn about a remediation of this
    issue, search the Web for "MCS locks".
        https://www.cs.rochester.edu/u/scott/papers/1991_TOCS_synch.pdf

    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 acq:

spinlock.acquire

critical section protected by spinlock

spinlock.rel

[either wait or continue]

critical section the mutex user is protecting

mutex release:

spinlock.acquire

critical section protected by spin lock

spinlock.release



```
1   #include <sys/queue.h>
2
3   typedef struct thread {
4       // ... Entries elided.
5       STAILQ_ENTRY(thread_t) qlink; // Tail queue entry.
6   } thread_t;
7
8   struct Mutex {
9       // Current owner, or 0 when mutex is not held.
10      thread_t *owner;
11
12      // List of threads waiting on mutex
13      STAILQ(thread_t) waiters;
14
15      // A lock protecting the internals of the mutex.
16      Spinlock splock;    // as in item 1, above
17  };
18
19  void mutex_acquire(struct Mutex *m) {
20
21      acquire(&m->splock);
22
23      // Check if the mutex is held; if not, current thread gets mutex and returns
24      if (m->owner == 0) {
25          m->owner = id_of_this_thread;
26          release(&m->splock);
27      } else {
28          // Add thread to waiters.
29          STAILQ_INSERT_TAIL(&m->waiters, id_of_this_thread, qlink);
30
31          // Tell the scheduler to add current thread to the list
32          // of blocked threads. The scheduler needs to be careful
33          // when a corresponding sched_wakeup call is executed to
34          // make sure that it treats running threads correctly.
35          sched_mark_blocked(&id_of_this_thread);
36
37          // Unlock spinlock.
38          release(&m->splock);
39
40          // Stop executing until woken.
41          sched_swtch();
42
43          // When we get to this line, we are guaranteed to hold the mutex. This
44          // is because we can get here only if context-switched-TO, which itself
45          // can happen only if this thread is removed from the waiting queue,
46          // marked "unblocked", and set to be the owner (in mutex_release()
47          // below). However, we might have held the mutex in lines 39-42
48          // (if we were context-switched out after the spinlock release(),
49          // followed by being run as a result of another thread's release of the
50          // mutex). But if that happens, it just means that we are
51          // context-switched out an "extra" time before proceeding.
52      }
53  }
54
55  void mutex_release(struct Mutex *m) {
56      // Acquire the spinlock in order to make changes.
57      acquire(&m->splock);
58
59      // Assert that the current thread actually owns the mutex
60      assert(m->owner == id_of_this_thread);
61
62      // Check if anyone is waiting.
63      m->owner = STAILQ_GET_HEAD(&m->waiters);
64
65      // If so, wake them up.
66      if (m->owner) {
67          sched_wakeone(&m->owner);
68          STAILQ_REMOVE_HEAD(&m->waiters, qlink);
69      }
70
71      // Release the internal spinlock
72      release(&m->splock);
73  }
```

```
Deadlock examples

1. Simple deadlock example

    T1:
        acquire(mutexA); 1
        acquire(mutexB);

        // do some stuff

        release(mutexB);
        release(mutexA);

    T2:
        acquire(mutexB); 2
        acquire(mutexA);

        // do some stuff

        release(mutexA);
        release(mutexB);
```



```
2. More subtle deadlock example

    Let M be a monitor (shared object with methods protected by mutex)
    Let N be another monitor

    class M {
        private:
            Mutex mutex_m;

            // instance of monitor N
            N another_monitor;

            // Assumption: no other objects in the system hold a pointer
            // to our "another_monitor"

        public:
            M();
            ~M();
            void methodA();
            void methodB();
    };

    class N {
        private:
            Mutex mutex_n;
            Cond cond_n;
            int navailable;

        public:
            N();
            ~N();
            void* alloc(int nwanted);
            void  free(void*);
    }

    int
    N::alloc(int nwanted) {
        acquire(&mutex_n);
        while (navailable < nwanted) {
            wait(&cond_n, &mutex_n);
        }

        // peel off the memory

        navailable -= nwanted;
        release(&mutex_n);
    }

    void
    N::free(void* returning_mem) {

        acquire(&mutex_n);

        // put the memory back

        navailable += returning_mem;

        broadcast(&cond_n, &mutex_n);

        release(&mutex_n);
    }
```

```
    void
    M::methodA() {

        acquire(&mutex_m);

        void* new_mem = another_monitor.alloc(int nbytes);

        // do a bunch of stuff using this nice
        // chunk of memory n allocated for us

        release(&mutex_m);
    }

    void
    M::methodB() {

        acquire(&mutex_m);

        // do a bunch of stuff

        another_monitor.free(some_pointer);

        release(&mutex_m);
    }

    QUESTION: What's the problem?
```