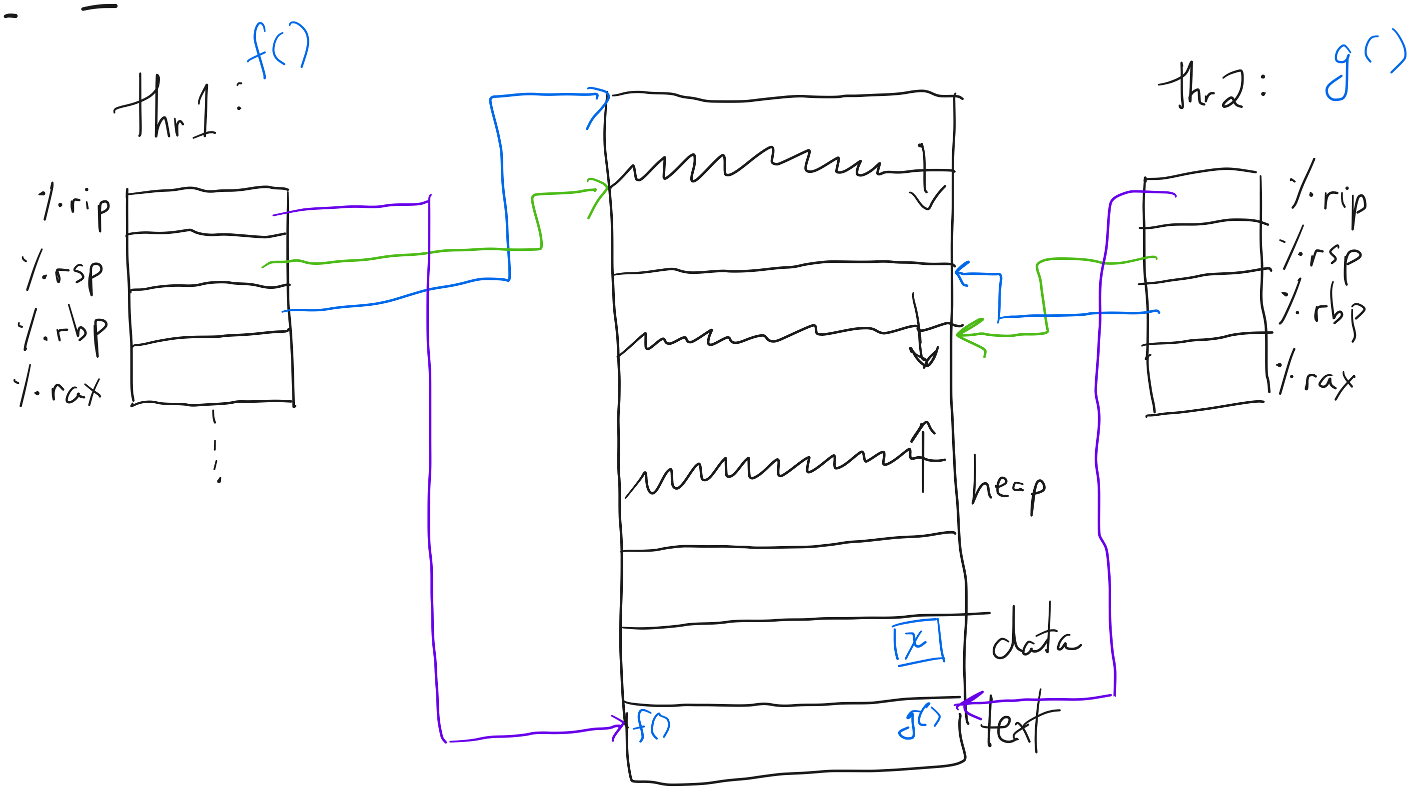
- [x] 1. Last time
- [x] 2. Intro to concurrency, continued
- [x] 3. Managing concurrency
- [x] 4. Mutexes
- [ ] 5. Condition variables
- [ ] 6. Semaphores

---

2. Intro to concurrency

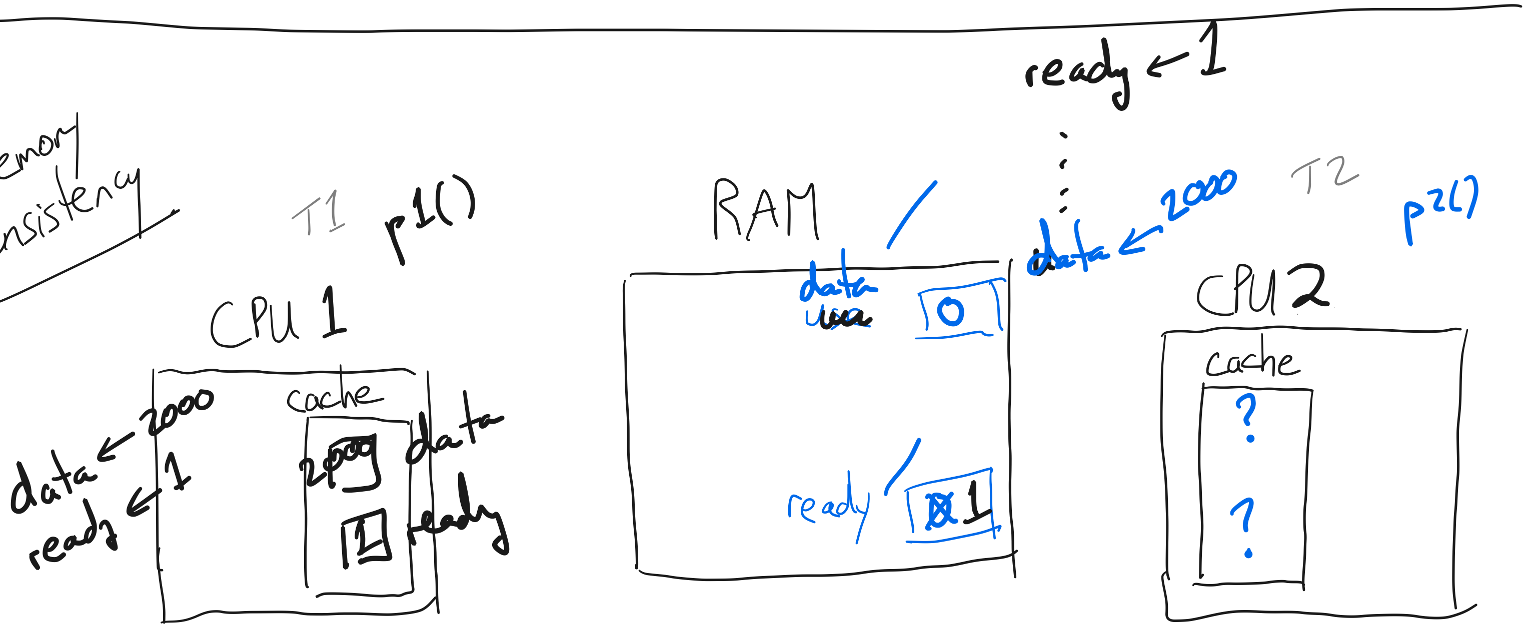
- panels 1-3 on handout03: all examples of "race conditions" (uncontrolled access to shared memory)
- hardware makes the problem harder (see panel 4)



Threads share memory, but they have their own "execution context" (registers and stack).

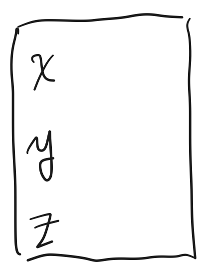
To the programmer, it "feels like" multiple things are happening at once in the program.

memory consistency



3. Managing concurrency

a. Critical sections: the concept: "protect from concurrent execution".



i. mutual exclusion

ii. progress

iii. bounded waiting

b. Protecting critical sections

lock() / unlock()

enter() / leave()

acquire() / release()

l.acquire()

l.release()

Implementing critical sections

c. Implementing critical sections

(i) single-CPU machine: enter() → disable interrupts

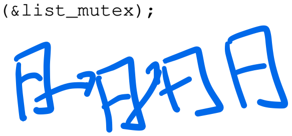
leave() → enable interrupts

---

4. Mutexes

5. Condition variables

```
CS 202, Fall 2021
Handout 4 (Class 5)

The handout from the last class gave examples of race conditions. The following
panels demonstrate the use of concurrency primitives (mutexes, etc.). We are
using concurrency primitives to eliminate race conditions (see items 1
and 2a) and improve scheduling (see item 2b).

1. Protecting the linked list......

        Mutex list_mutex;

        insert(int data) {
            List_elem* l = new List_elem;
            l->data = data;

            acquire(&list_mutex);

            l->next = head;
            head = l;

            release(&list_mutex);
        }
```




```
2.  Producer/consumer revisited [also known as bounded buffer]

   2a. Producer/consumer [bounded buffer] with mutexes

     Mutex mutex;

     void producer (void *ignored) {
         for (;;) {
             /* next line produces an item and puts it in nextProduced */
             nextProduced = means_of_production();

             acquire(&mutex);
             while (count == BUFFER_SIZE) {
                release(&mutex);
                yield(); /* or schedule() */
                acquire(&mutex);
             }

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

     void consumer (void *ignored) {
         for (;;) {

             acquire(&mutex);
             while (count == 0) {
                release(&mutex);
                yield(); /* or schedule() */
                acquire(&mutex);
             }

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

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

```
2b. Producer/consumer [bounded buffer] with mutexes and condition variables

     Mutex mutex;
     Cond nonempty;
     Cond nonfull;

     void producer (void *ignored) {
         for (;;) {
             /* next line produces an item and puts it in nextProduced */
             nextProduced = means_of_production();

             acquire(&mutex);
             while (count == BUFFER_SIZE)
                cond_wait(&nonfull, &mutex);

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

     void consumer (void *ignored) {
         for (;;) {

             acquire(&mutex);
             while (count == 0)
                cond_wait(&nonempty, &mutex);

             nextConsumed = buffer[out];
             out = (out + 1) % BUFFER_SIZE;
             count--;
             cond_signal(&nonfull, &mutex);
             release(&mutex);

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

Question: why does cond_wait need to both release the mutex and sleep? Why not:

```
        while (count == BUFFER_SIZE)  {
            release(&mutex);
            cond_wait(&nonfull);
            acquire(&mutex);
        }
```



```
2c.  Producer/consumer [bounded buffer] with semaphores

    Semaphore mutex(1);            /* mutex initialized to 1 */
    Semaphore empty(BUFFER_SIZE);  /* start with BUFFER_SIZE empty slots */
    Semaphore full(0);             /* 0 full slots */

    void producer (void *ignored) {
         for (;;) {
             /* next line produces an item and puts it in nextProduced */
             nextProduced = means_of_production();

            /*
             * next line diminishes the count of empty slots and
             * waits if there are no empty slots
             */
             sem_down(&empty);
             sem_down(&mutex);  /* get exclusive access */

             buffer [in] = nextProduced;
             in = (in + 1) % BUFFER_SIZE;

             sem_up(&mutex);
             sem_up(&full);   /* we just increased the # of full slots */
         }
     }

     void consumer (void *ignored) {
         for (;;) {

             /*
              * next line diminishes the count of full slots and
              * waits if there are no full slots
              */
             sem_down(&full);
             sem_down(&mutex);

             nextConsumed = buffer[out];
             out = (out + 1) % BUFFER_SIZE;

             sem_up(&mutex);
             sem_up(&empty);   /* one further empty slot */

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

Semaphores *can* (not always) lead to elegant solutions (notice that the code above is fewer lines than 2b) but they are much harder to use.

The fundamental issue is that semaphores make implicit (counts, conditions, etc.) what is probably best left explicit. Moreover, they *also* implement mutual exclusion.

For this reason, you should not use semaphores. This example is here mainly for completeness and so you know what a semaphore is. But do not code with them. Solutions that use semaphores in this course will receive no credit.

```
CS 202, Fall 2021
Handout 3 (Class 4)

1. Example to illustrate interleavings: say that thread A executes f()
and thread B executes g(). (Here, we are using the term "thread"
abstractly. This example applies to any of the approaches that fall
under the word "thread".)

    a. [this is pseudocode]

        int x;

        int main(int argc, char** argv) {

            tid tid1 = thread_create(f, NULL);
            tid tid2 = thread_create(g, NULL);

            thread_join(tid1);
            thread_join(tid2);

            printf("%d\n", x);
        }

        void f()
        {
            x = 1;
            thread_exit();
        }

        void g()
        {
            x = 2;
            thread_exit();
        }


        What are possible values of x after A has executed f() and B has
        executed g()? In other words, what are possible outputs of the
        program above?



    b.  Same question as above, but f() and g() are now defined as
    follows:

        int y = 12;

        f() { x = y + 1; }
        g() { y = y * 2; }

        What are the possible values of x?



    c. Same question as above, but f() and g() are now defined as
    follows:

        int x = 0;
        f() { x = x + 1; }
        g() { x = x + 2; }

        What are the possible values of x?
```

13 12 24 24

25

13

ALU

x=1
x=2
x=3

assume: x lives at 0x5000

x ← x+1
x ← x+2
x==3

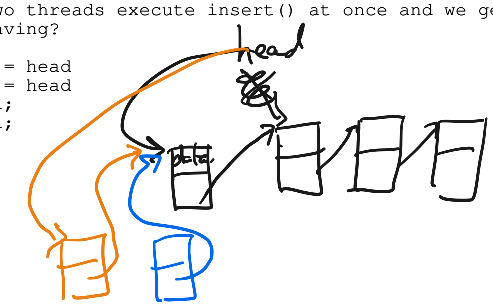
x = x+1:
(1) movq 0x5000, %rax
(2) addq 1, %rax
(3) movq %rax, 0x5000

x ← x+2
(4) movq 0x5000, %rax
(5) addq 2, %rax
(6) movq %rax, 0x5000


```
2. Linked list example

    struct List_elem {
        int data;
        struct List_elem* next;
    };

    List_elem* head = 0;

    insert(int data) {
        List_elem* l = new List_elem;
        l->data = data;
        l->next = head;
        head = l;
    }

    What happens if two threads execute insert() at once and we get the
    following interleaving?

    thread 1: l->next = head
    thread 2: l->next = head
    thread 2: head = l;
    thread 1: head = l;
```

T1: insert()

T2: insert()



```
3. Producer/consumer example:

    /*
    "buffer" stores BUFFER_SIZE items
    "count" is number of used slots. a variable that lives in memory
    "out" is next empty buffer slot to fill (if any)
    "in" is oldest filled slot to consume (if any)
    */

     void producer (void *ignored) {
         for (;;) {
             /* next line produces an item and puts it in nextProduced */
             nextProduced = means_of_production();
             while (count == BUFFER_SIZE)
                 ; // do nothing
             buffer [in] = nextProduced;
             in = (in + 1) % BUFFER_SIZE;
             count++;  => count = count + 1
         }
     }

     void consumer (void *ignored) {
         for (;;) {
             while (count == 0)
                ; // do nothing
             nextConsumed = buffer[out];
             out = (out + 1) % BUFFER_SIZE;
             count--;  count = count - 1
             /* next line abstractly consumes the item */
             consume_item(nextConsumed);
         }
     }

    /*
       what count++ probably compiles to:
        reg1 <-- count      # load
        reg1 <-- reg1 + 1   # increment register
        count <-- reg1      # store

       what count-- could compile to:
        reg2 <-- count      # load
        reg2 <-- reg2 - 1   # decrement register
        count <-- reg2      # store
    */

    What happens if we get the following interleaving?

  %rax  reg1 <-- count          1 -> 6
        reg1 <-- reg1 + 1
  %rax  reg2 <-- count
        reg2 <-- reg2 - 1
        count <-- reg1
        count <-- reg2
```



```
4. Some other examples. What is the point of these?

    [From S.V. Adve and K. Gharachorloo, IEEE Computer, December 1996,
    66-76. http://rsim.cs.uiuc.edu/~sadve/Publications/computer96.pdf]

    a. Can both "critical sections" run?

        int flag1 = 0, flag2 = 0;

        int main () {
            tid id = thread_create (p1, NULL);
            p2 (); thread_join (id);
        }

        void p1 (void *ignored) {
     (1)    flag1 = 1;
     (2)    if (!flag2) {
                critical_section_1 ();
            }
        }

        void p2 (void *ignored) {
     (3)    flag2 = 1;
     (4)    if (!flag1) {
                critical_section_2 ();
            }
        }

        1 3 2 4        1 2 3 4

    b. Can use() be called with value 0, if p2 and p1 run concurrently?

        int data = 0, ready = 0;

        void p1 () {
            data = 2000;
            ready = 1;
        }
        int p2 () {
            while (!ready) {}
            use(data);   ?
        }        0

    c. Can use() be called with value 0?

        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);
        }
```