CONCURRENCY: CONDITION VARIABLES

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Grading updates

Project 4 out!

TA Office hours

RECAP

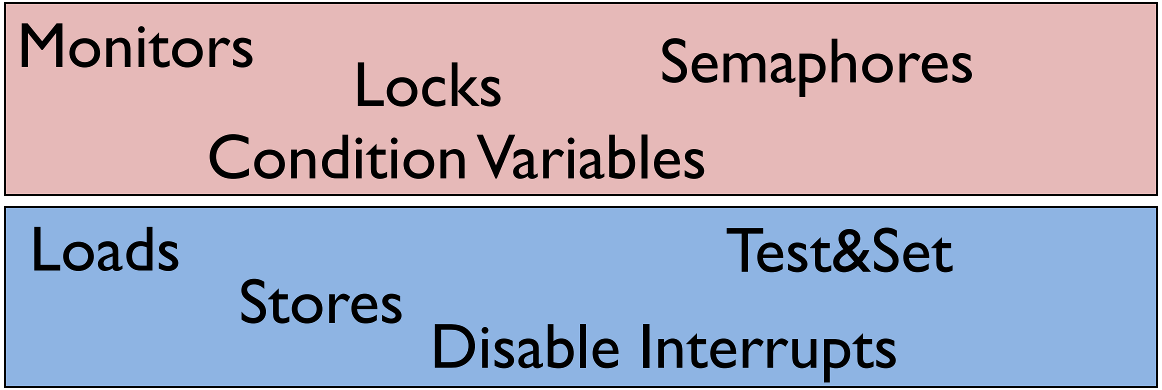
SYNCHRONIZATION

Build higher-level synchronization primitives in OS

Operations that ensure correct ordering of instructions across threads

Use help from hardware

Motivation: Build them once and get them right



CONCURRENCY OBJECTIVES

Mutual exclusion (e.g., A and B don't run at same time)

- solved with *locks*

Ordering (e.g., B runs after A does something)

- solved with *condition variables* and *semaphores*

ORDERING EXAMPLE: JOIN

```
pthread_t p1, p2;
Pthread_create(&p1, NULL, mythread, "A");
Pthread_create(&p2, NULL, mythread, "B");
// join waits for the threads to finish
Pthread_join(p1, NULL);
Pthread_join(p2, NULL);
printf("main: done\n [balance: %d]\n [should: %d]\n",
    balance, max*2);
return 0;
```

how to implement join()?

CONDITION VARIABLES

Condition Variable: queue of waiting threads

B waits for a signal on CV before running

- wait(CV, …)

A sends signal to CV when time for ***B*** to run

- signal(CV, …)

CONDITION VARIABLES

wait(cond_t *cv, mutex_t *lock)

- assumes the lock is held when wait() is called
- puts caller to sleep + releases the lock (atomically)
- when awoken, reacquires lock before returning

signal(cond_t *cv)

- wake a single waiting thread (if >= 1 thread is waiting)
- if there is no waiting thread, just return, doing nothing

JOIN IMPLEMENTATION: ATTEMPT 1

Parent:

```
void thread_join() {
        Mutex_lock(&m);      // x
        Cond_wait(&c, &m);   // y
        Mutex_unlock(&m);    // z
}
```

Child:

```
void thread_exit() {
        Mutex_lock(&m);      // a
        Cond_signal(&c);     // b
        Mutex_unlock(&m);    // c
}
```

Example schedule:

Parent:	x	y				z
Child:			a	b	c	

JOIN IMPLEMENTATION: ATTEMPT 1

Parent:

```
void thread_join() {
        Mutex_lock(&m);     // x
        Cond_wait(&c, &m);  // y
        Mutex_unlock(&m);   // z
}
```

Child:

```
void thread_exit() {
        Mutex_lock(&m);     // a
        Cond_signal(&c);    // b
        Mutex_unlock(&m);   // c
}
```

Example broken schedule:

Parent:				x	y
Child:	a	b	c		

RULE OF THUMB 1

Keep state in addition to CV's!

CV's are used to signal threads when state changes

If state is already as needed, thread doesn't wait for a signal!

JOIN IMPLEMENTATION: ATTEMPT 2

Parent:

```
void thread_join() {
        Mutex_lock(&m);          // w
        if (done == 0)           // x
            Cond_wait(&c, &m); // y
        Mutex_unlock(&m);        // z
}
```

Child:

```
void thread_exit() {
        done = 1;          // a
        Cond_signal(&c); // b
}
```

Parent:			w	x	y	z
Child:	a	b				

JOIN IMPLEMENTATION: ATTEMPT 2

Parent:

```
void thread_join() {
        Mutex_lock(&m);            // w
        if (done == 0)             // x
            Cond_wait(&c, &m); // y
        Mutex_unlock(&m);          // z
}
```

Child:

```
void thread_exit() {
        done = 1;          // a
        Cond_signal(&c); // b
}
```

Parent:	w	x			y
Child:			a	b	

JOIN IMPLEMENTATION: CORRECT

Parent:

```
void thread_join() {
        Mutex_lock(&m);         // w
        if (done == 0)          // x
            Cond_wait(&c, &m); // y
        Mutex_unlock(&m);        // z
}
```

Child:

```
void thread_exit() {
        Mutex_lock(&m);        // a
        done = 1;              // b
        Cond_signal(&c);       // c
        Mutex_unlock(&m);      // d
}
```

Parent:	w	x	y				z
Child:				a	b	c	

Use mutex to ensure no race between interacting with state and wait/signal

QUIZ 11

https://tinyurl.com/cs537-fa24-q11

Assume a list L originally contains three nodes with keys 3, 4, and 5. Assume thread T calls List_Insert(L,2) and thread S calls List_Insert(L,6). Assume malloc() does not fail.

```
typedef struct __node_t {
    int key;
    struct __node_t *next;
} node_t;
Typedef struct __list_t {
    node_t *head;
} list_t;
Void List_Insert(list_t *L,  int key) {
    node_t *new = malloc(sizeof(node_t));
    new->key = key;
    new->next = L->head;
    L->head = new;
}
```

TTTTSSSS

SSTTTTSS

```
void add (int *val, int amt) {
    mutex_lock(&m);
    *val += amt;
    mutex_unlock(&m);
}
```

```
int CAS(int *addr, int ex, int n) {
  int actual = *addr;
  if (actual == ex)
    *addr = n;
  return actual;
}
```

```
void add (int *val, int amt) {
   do {
      int old = *val;
   } while (CompareAndSwap(<Q1>, <Q2>, <Q3>) != <Q4>);
}
```

Q1

Q2

Q3

Q4

PRODUCER/CONSUMER PROBLEM

EXAMPLE: UNIX PIPES

A pipe may have many writers and readers

Internally, there is a finite-sized buffer

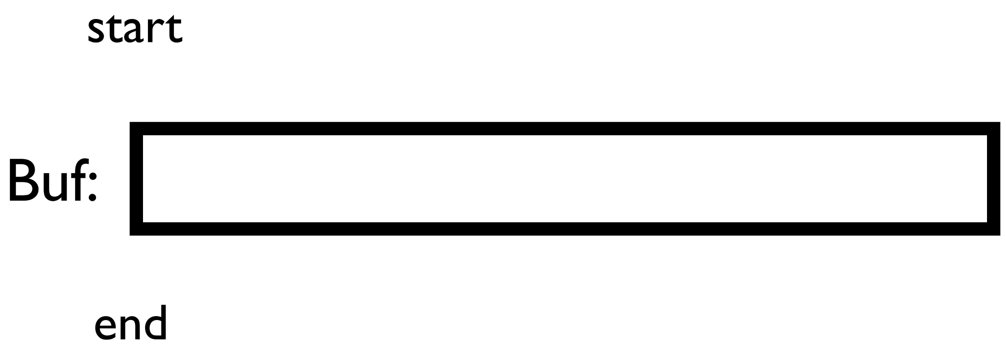
Writers add data to the buffer

- Writers have to wait if buffer is full

Readers remove data from the buffer

- Readers have to wait if buffer is empty

EXAMPLE: UNIX PIPES



EXAMPLE: UNIX PIPES

Implementation:

- reads/writes to buffer require locking
- when buffers are full, writers must wait
- when buffers are empty, readers must wait

PRODUCER/CONSUMER PROBLEM

Producers generate data (like pipe writers)

Consumers grab data and process it (like pipe readers)

Producer/consumer problems are frequent in systems (e.g. web servers)

General strategy use condition variables to:

- make producers wait when buffers are full
- make consumers wait when there is nothing to consume

PRODUCE/CONSUMER EXAMPLE

Start with easy case:

- 1 producer thread
- 1 consumer thread
- 1 shared buffer to fill/consume (max = 1)

Numfull = number of buffers currently filled

numfull

Thread 1 state:

```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m);
        if(numfull == max)
            Cond_wait(&cond, &m);
        do_fill(i);
        Cond_signal(&cond);
        Mutex_unlock(&m);
    }
}
```

Thread 2 state:

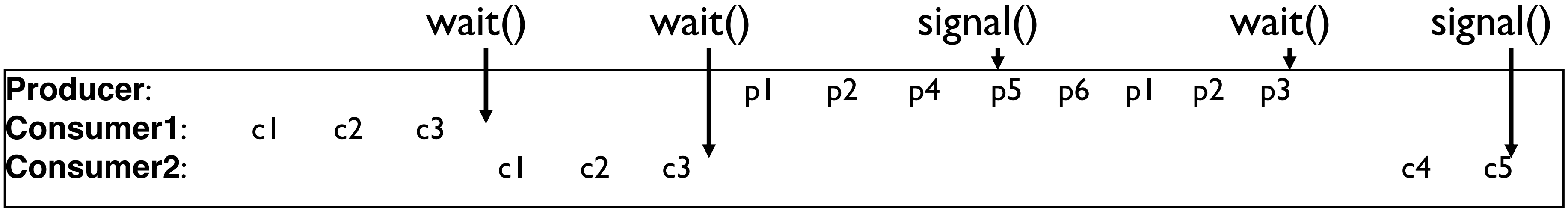
```
void *consumer(void *arg) {
    while(1) {
        Mutex_lock(&m);
        if(numfull == 0)
            Cond_wait(&cond, &m);
        int tmp = do_get();
        Cond_signal(&cond);
        Mutex_unlock(&m);
        printf(“%d\n”, tmp);
    }
}
```

WHAT ABOUT 2 CONSUMERS?

Can you find a problematic timeline with 2 consumers (still 1 producer)?

```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m); // p1
        if(numfull == max) //p2
            Cond_wait(&cond, &m); //p3
        do_fill(i); // p4
        Cond_signal(&cond); //p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while(1) {
        Mutex_lock(&m);  // c1
        if(numfull == 0) // c2
            Cond_wait(&cond, &m); // c3
        int tmp = do_get(); // c4
        Cond_signal(&cond); // c5
        Mutex_unlock(&m); // c6
        printf("%d\n", tmp); // c7
    }
}
```



HOW TO WAKE THE RIGHT THREAD?

Wake all the threads!?

Better solution (usually): use two condition variables

PRODUCER/CONSUMER: TWO CVS

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        if (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i);  // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m);
        if (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```

PRODUCER/CONSUMER: TWO CVS

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        if (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i);  // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m);
        if (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```

1. consumer1 waits because numfull == 0
2. producer increments numfull, wakes consumer1
3. before consumer1 runs, consumer2 runs, grabs entry, sets numfull=0.
4. consumer2 then reads bad data.

PRODUCER/CONSUMER: TWO CVS AND WHILE

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        while (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i);  // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m);
        while (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```

No concurrent access to shared state

Every time lock is acquired, assumptions are reevaluated

A consumer will get to run after every do_fill()

A producer will get to run after every do_get()

GOOD RULE OF THUMB 3

Whenever a lock is acquired, recheck assumptions about state!

Another thread could grab lock in between signal and wakeup from wait

Note that some libraries also have "spurious wakeups" (may wake multiple waiting threads at signal or at any time)

SUMMARY: RULES OF THUMB FOR CVS

1. Keep state in addition to CV's

2. Always do wait/signal with lock held

3. Whenever thread wakes from waiting, recheck state

NEXT STEPS

Next class: Semaphores