Hello!

CONCURRENCY: CONDITION VARIABLES

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Grading updates → P2, P3 grades out

Regrade forms on Piazza | Midterm in progress

Project 4 out!

→ Discussion

TA Office hours

↳

RECAP

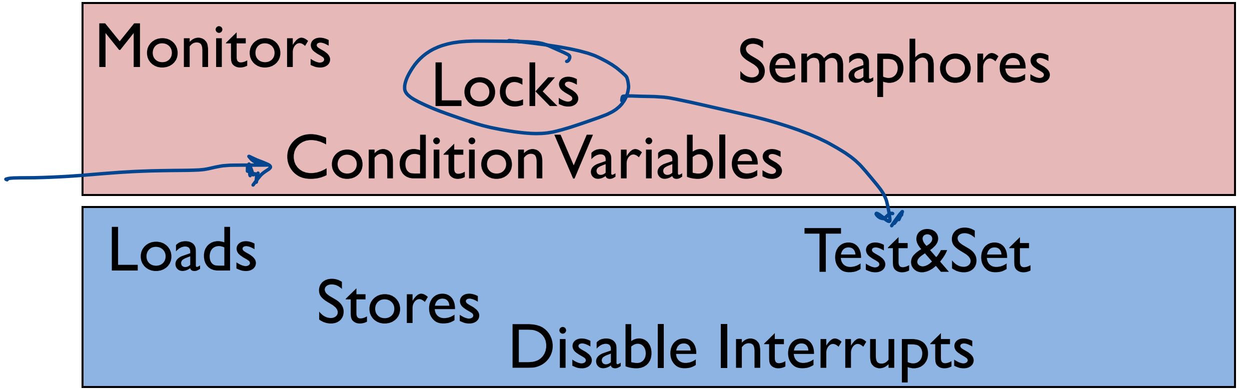
SYNCHRONIZATION

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



Monitors

Locks

Semaphores

Condition Variables

Loads

Test&Set

Stores

Disable Interrupts

CONCURRENCY OBJECTIVES

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

- solved with *locks*

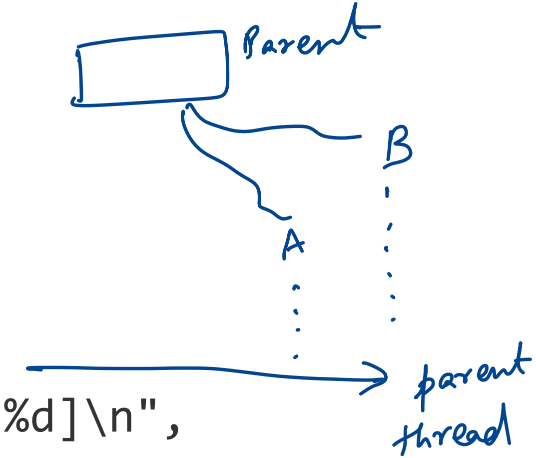
Ordering (e.g., B runs after A does something)

- 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;
```

thread name A



Desire some ordering of execution Thread A & Thread B will run before parent Printf

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, …)

parent
}
wait until child thread has run

child thread
↓
signal to notify that child is done

CONDITION VARIABLES

if multiple threads are calling wait

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

holds the lock after 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

sleep, block until you get a signal

wake up parent

Parent:

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

wakes up holds the lock

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	

time

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		

go to sleep
never woken up!

RULE OF THUMB 1

Keep state in addition to CV's!

variable to indicate if parent thread is waiting

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

int done = 0;

done = 1 ⇒ thread exit has finished !

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
}
```

lock ??

Parent:			w	x	~~y~~	z
Child:	a	b				

done is not zero

done = 1

JOIN IMPLEMENTATION: ATTEMPT 2

atomically

Parent:

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

hold the lock when updating shared state

Child:

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

get stuck

Parent: w x y

Child: a b

JOIN IMPLEMENTATION: CORRECT

① Keep shared state

② Hold the lock to access state

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
}
```

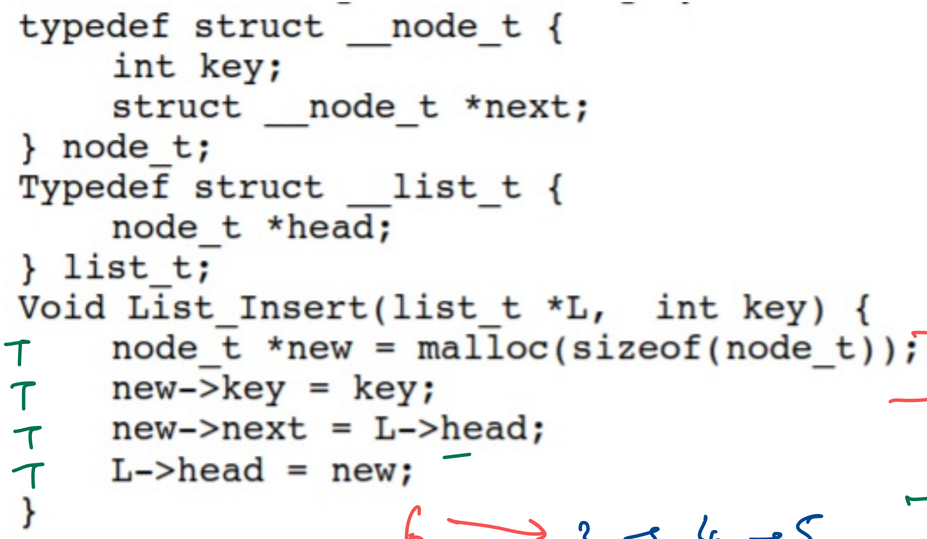
Parent:	w	x	y				z
Child:				a	b	c	

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;
}
```

S T
S T
S T
S T

6 → 3 → 4 → 5

head → 2 → 3

TTTTSSSS

6 → 2 → 3 → 4 → 5

SSTTTTSS

6 → 2 → 3 → 4 → 5

TTT SSSS T

??

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

→ not performant

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

5

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

55

if it is still 55 → set it to 60

existing

new

Q1 val

Q2 old

Q3 old + amt

Q4 old

PRODUCER/CONSUMER PROBLEM

EXAMPLE: UNIX PIPES

A pipe may have many writers and readers

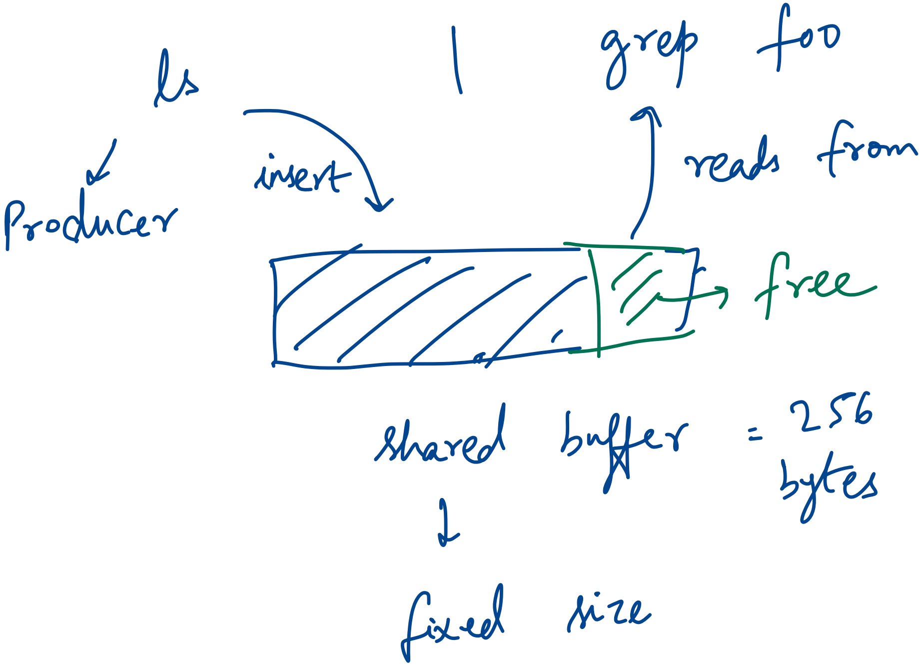
Internally, there is a finite-sized buffer

Writers add data to the buffer

- Writers have to wait if buffer is full

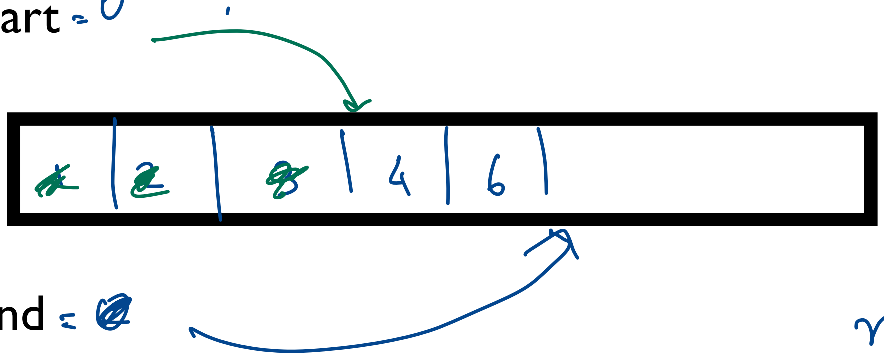
Readers remove data from the buffer

- Readers have to wait if buffer is empty



EXAMPLE: UNIX PIPES

start = 0



Buf:

end = ~~2~~

read

insert

EXAMPLE: UNIX PIPES

Implementation:

- reads/writes to buffer require locking
- when buffers are full, writers must wait → or block until there is free space
- when buffers are empty, readers must wait

until there are items available

PRODUCER/CONSUMER PROBLEM

Producers generate data (like pipe writers)

Consumers grab data and process it (like pipe readers)

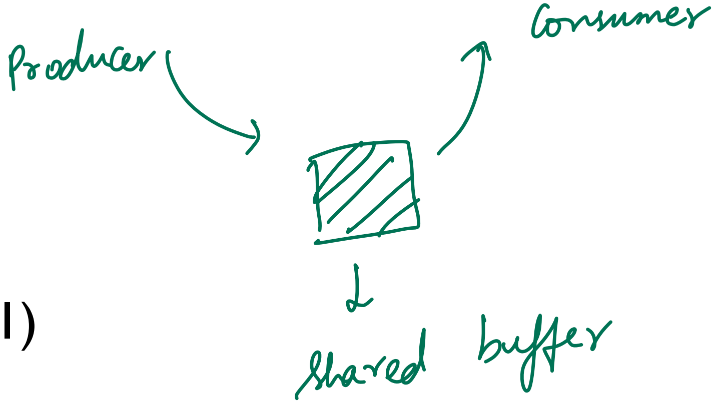
Producer/consumer problems are frequent in systems (e.g. web servers)

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

shared state or shared variable

numfull

numfull = number of entries in buffer

Thread 1 state:

Thread 2 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);
    }
}
```

some space available

wake up consumer

```
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);
    }
}
```

empty

wake up producer

WHAT ABOUT 2 CONSUMERS?

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

if Consumer1 woken up buffer empty

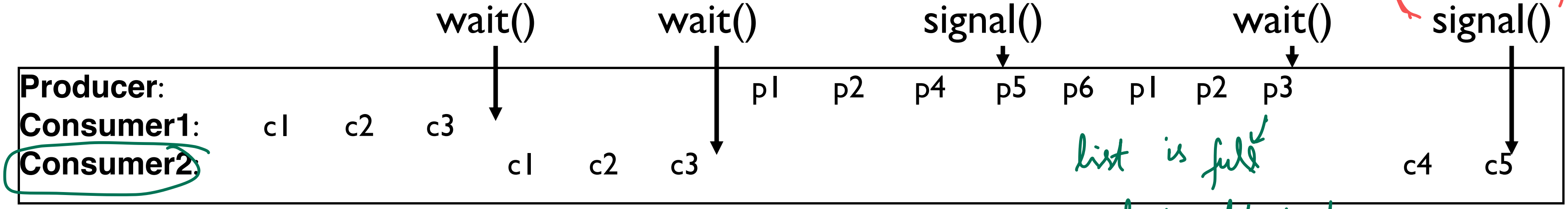
```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m); // p1
        if(numfull == max) //p2
            Cond_wait(&cond, &m); //p3
        do_fill(i); // p4
        Cond_signal(&cond); //p5
        Mutex_unlock(&m); //p6
    }
}
```

```
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
    }
}
```

buffer empty
2 consumer threads blocked

wakes up a thread waiting on cond

unclear who to wake up



wait() wait() signal() wait() signal()

Producer: p1 p2 p4 p5 p6 p1 p2 p3

Consumer1: c1 c2 c3

Consumer2: c1 c2 c3 c4 c5

list is full

Prod is blocked

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);
    }
}
```

Two cond vars

1. Producer waits on empty. Consumers signal when
   make space

2. Consumer waits on fill

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) {
c1      Mutex_lock(&m);
c2      if (numfull == 0)
c3          Cond_wait(&fill, &m);
c4      int tmp = do_get();
c5      Cond_signal(&empty);
c6      Mutex_unlock(&m);
    }
}
```

C1 : c1 c2 c3

P : P1 P2 P4 P5 P6

C2 :

c1 c2 c4 c5 c6

C4

numfull can change between signal thread run

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);
    }
}
```

check numfull →

woken up ←

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