UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

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LOCKS AND CONDITION VARIABLES

Questions answered in this lecture:

How can threads **block** instead of **spin-waiting** while waiting for a lock?

When should a waiting thread block and when should it spin?

How can threads enforce **ordering** across operations (**condition variables**)?

How can **thread_join()** be implemented?

How can **condition** variables be used to support **producer/consumer** apps?

ANNOUNCEMENTS

Exam 2 solutions posted
- Look in your handin directory for **midterm1.pdf** details

Project 2: Due Sunday midnight

Project 3: Shared Memory Segments – Available Monday
- New project partner if desired; your own or matched
- Linux: Using shmget() and shmat()
  - with partner
- Xv6: Implementing shmget() and shmat()
  - Alone
- Due Wednesday 11/02

Today's Reading: Chapter 30

Ticket Lock Implementation

```
typedef struct __lock_t {
    int ticket;
    int turn;
}

void lock_init(lock_t *lock) {
    lock->ticket = 0;
    lock->turn = 0;
}
```

```
void acquire(lock_t *lock) {
    int myturn = FAA(&lock->ticket);
    while(lock->turn != myturn);  // spin
}

void release (lock_t *lock) {
    lock->turn++;
}
```

FAA() used in textbook → conservative
Try this modification in Homework simulations

Lock Evaluation

How to tell if a lock implementation is good?

Fairness:

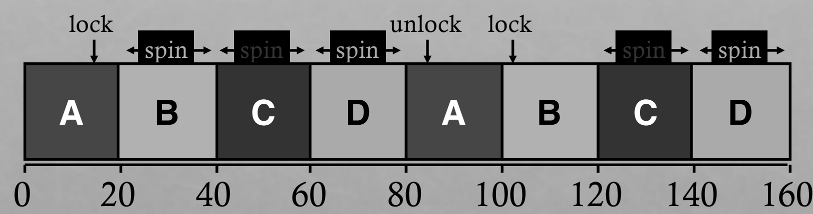
- Do processes acquire lock in same order as requested?

Performance

Two scenarios:

- \- low contention (fewer threads, lock usually available)
- \- high contention (many threads per CPU, each contending)

CPU Scheduler is Ignorant



CPU scheduler may run **B** instead of **A**
even though **B** is waiting for **A**

Ticket Lock Implementation

```
typedef struct __lock_t {
    int ticket;
    int turn;
}

void lock_init(lock_t *lock) {
    lock->ticket = 0;
    lock->turn = 0;
}
```

```
void acquire(lock_t *lock) {
    int myturn = FAA(&lock->ticket);
    while(lock->turn != myturn); // spin
}

void release (lock_t *lock) {
    lock->turn++;
}
```

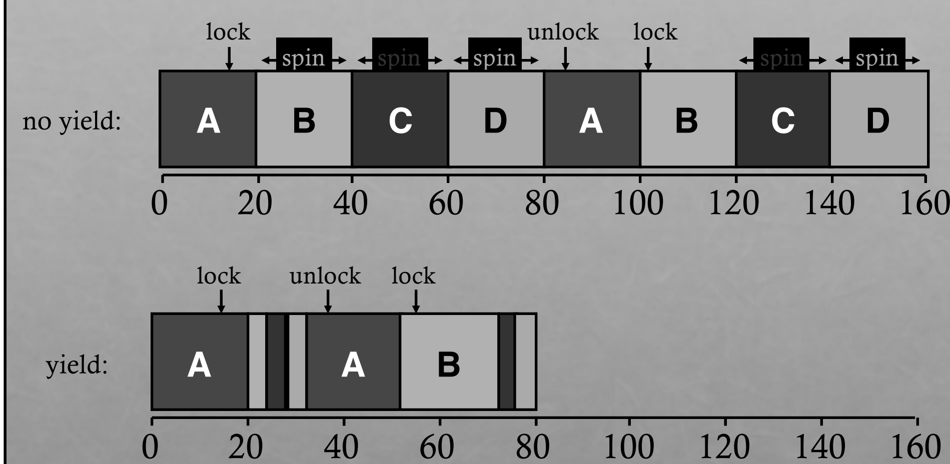
Trivial modification to improve?

Ticket Lock with yield()

```
typedef struct __lock_t {
        int ticket;
        int turn;
}

void lock_init(lock_t *lock) {
        lock->ticket = 0;
        lock->turn = 0;
}

void acquire(lock_t *lock) {
        int myturn = FAA(&lock->ticket);
        while(lock->turn != myturn)
                yield();
}

void release (lock_t *lock) {
        FAA(&lock->turn);
}
```

Remember: yield() voluntarily relinquishes CPU for remainder of timeslice, but process remains READY

Yield Instead of Spin



Spinlock Performance

Waste…

Without yield: O(threads * **time_slice**)

With yield: O(threads * **context_switch**)

So even with yield, spinning is slow with high thread contention

Next improvement:
Block and put thread on waiting queue instead of spinning

Lock Implementation: Block when Waiting

Lock implementation removes waiting threads from scheduler ready queue (e.g., park() and unpark())

Scheduler runs any thread that is **ready**

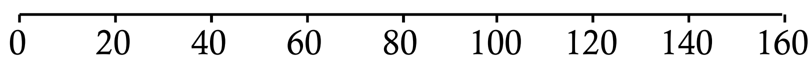
Good separation of concerns

RUNNABLE: A, B, C, D

RUNNING: <empty>

WAITING: <empty>

Same as BLOCKED

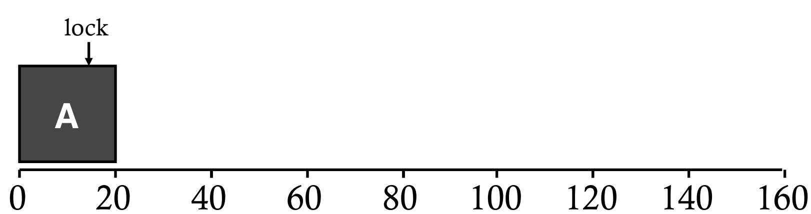


RUNNABLE: B, C, D

RUNNING: A

WAITING: <empty>

Same as BLOCKED

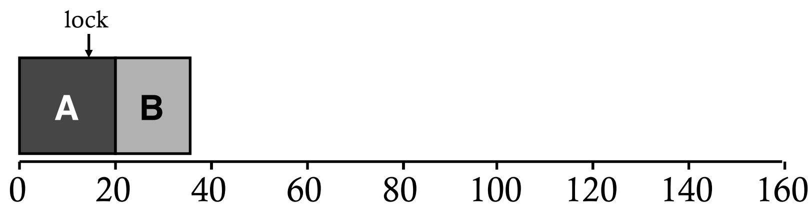


RUNNABLE: C, D, A

RUNNING: B

WAITING: <empty>

Same as BLOCKED

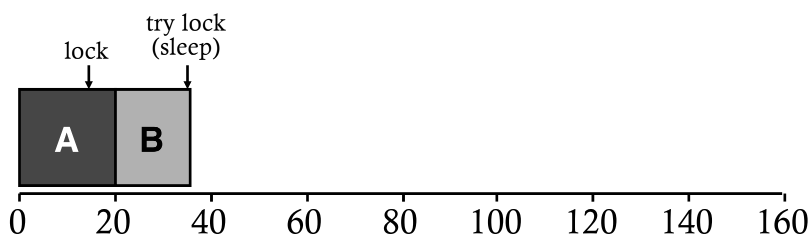


RUNNABLE: C, D, A

RUNNING:

WAITING: B

Same as BLOCKED

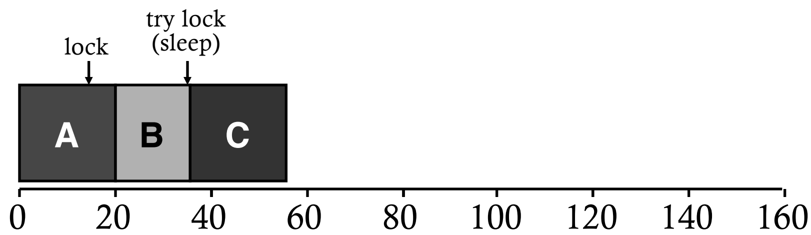


RUNNABLE: D, A

RUNNING: C

WAITING: B

Same as BLOCKED

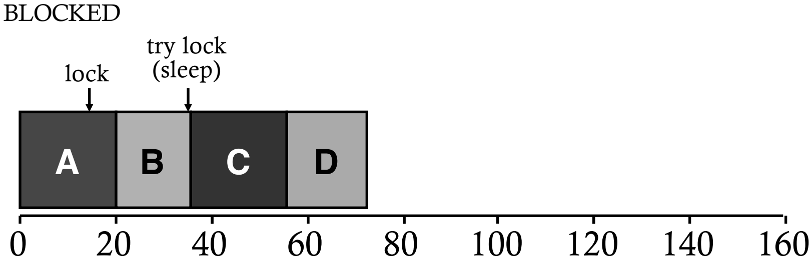


RUNNABLE: A, C

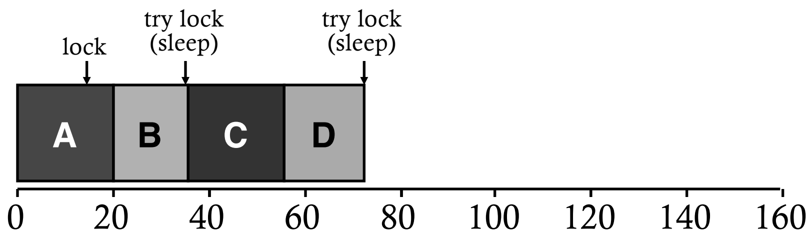
RUNNING: D

WAITING: B

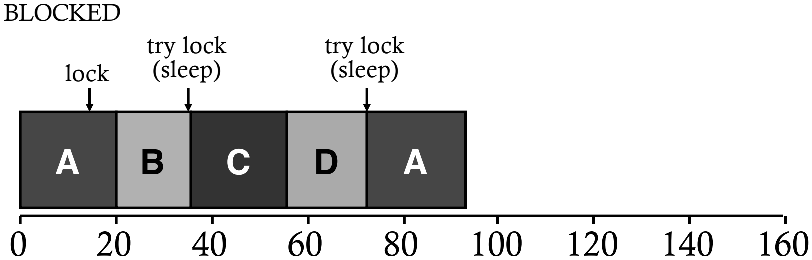
Same as BLOCKED



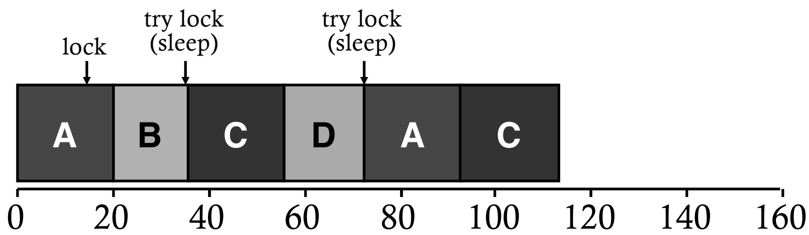
RUNNABLE: A, C
RUNNING:
WAITING: B, D
Same as BLOCKED



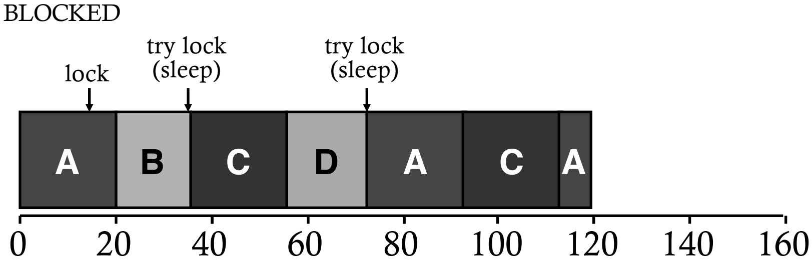
RUNNABLE: C
RUNNING: A
WAITING: B, D
Same as BLOCKED



RUNNABLE: A
RUNNING: C
WAITING: B, D
Same as BLOCKED



RUNNABLE: C
RUNNING: A
WAITING: B, D
Same as BLOCKED

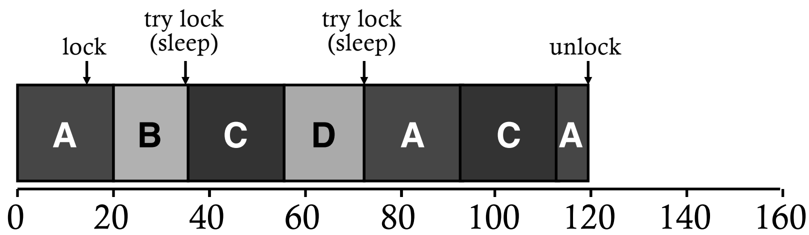


RUNNABLE: B, C

RUNNING: A

WAITING: D

Same as BLOCKED

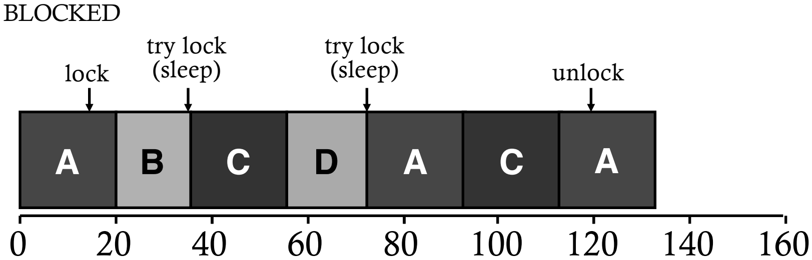


RUNNABLE: B, C

RUNNING: A

WAITING: D

Same as BLOCKED

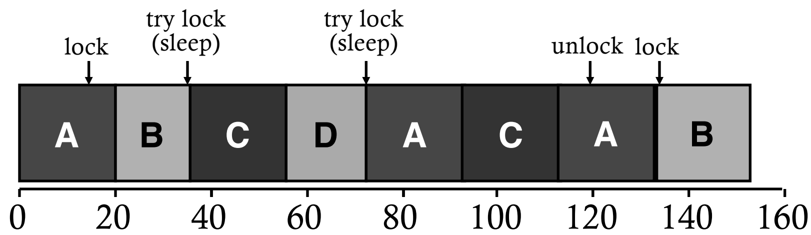


RUNNABLE: C, A

RUNNING: B

WAITING: D

Same as BLOCKED



LOCK IMPLEMENTATION: BLOCK WHEN WAITING

```
typedef struct {

  bool lock = false;

  bool guard = false;

  queue_t q;

} LockT;
```

(a) Why is **guard** used?
(b) Why okay to **spin** on guard?
(c) In release(), why not set lock=false when unpark?
(d) What is the race condition?

```
void acquire(LockT *l) {
   while (TAS(&l->guard, true));
   if (l->lock) {
       qadd(l->q, tid);
       l->guard = false;
       park();     // blocked
   } else {
       l->lock = true;
       l->guard = false;
   }
}

void release(LockT *l) {
   while (TAS(&l->guard, true));
   if (qempty(l->q)) l-
   >lock=false;
   else unpark(qremove(l->q));
   l->guard = false;
}
```

Race Condition

Thread 1 (in acquire)

```
if (l->lock) {
      qadd(l->q, tid);
      l->guard = false;
```

Thread 2 (in release)

```
while (TAS(&l->guard, true));
if (qempty(l->q)) // false!!
else unpark(qremove(l->q));
l->guard = false;
```

```
      park();    // block
```

Problem: Guard not held when call park()
Unlocking thread may unpark() before other park()

Block when Waiting: Final Correct Lock

```
Typedef struct {

  bool lock = false;

  bool guard = false;

  queue_t q;

} LockT;
```

setpark() fixes race condition

Park() does not block if unpark() occurred after setpark()

```
void acquire(LockT *l) {
   while (TAS(&l->guard, true));
   if (l->lock) {
       qadd(l->q, tid);
       setpark(); // notify of plan
       l->guard = false;
       park(); // unless unpark()
   } else {
       l->lock = true;
       l->guard = false;
   }
}

void release(LockT *l) {
   while (TAS(&l->guard, true));
   if (qempty(l->q)) l->lock=false;
   else unpark(qremove(l->q));
   l->guard = false;
}
```

Spin-Waiting vs Blocking

Each approach is better under different circumstances

Uniprocessor

- Waiting process is scheduled --> Process holding lock isn't
- Waiting process should always relinquish processor
- Associate queue of waiters with each lock (as in previous implementation)

Multiprocessor

- Waiting process is scheduled --> Process holding lock might be
- Spin or block depends on how long, t, before lock is released
  - Lock released quickly --> Spin-wait
  - Lock released slowly --> Block
  - Quick and slow are relative to context-switch cost, C

When to Spin-Wait? When to Block?

If know how long, **t,** before lock released, can determine optimal behavior

How much CPU time is wasted when spin-waiting?

t

How much wasted when block?

C

What is the best action when t<C?

spin-wait

When t>C?

block

Problem:

Requires knowledge of future; too much overhead to do any special prediction

Two-Phase Waiting

Theory: Bound worst-case performance; ratio of actual/optimal

When does worst-possible performance occur?

Spin for very long time t >> C

Ratio: t/C (unbounded)

Algorithm: Spin-wait for C then block --> Factor of 2 of optimal

Two cases:

- t < C: optimal spin-waits for t; we spin-wait t too
- t > C: optimal blocks immediately (cost of C); we pay spin C then block (cost of 2 C); 2C / C → 2-competitive algorithm

Example of competitive analysis

Implementing Synchronization

Build higher-level synchronization primitives in OS

- Operations that ensure correct ordering of instructions across threads

Motivation: Build them once and get them right

Monitors Locks Semaphores
Condition Variables

Loads Stores Test&Set
Disable Interrupts

Condition Variables

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() {
        Cond_signal(&c);        // a
}
```

Example schedule:

Parent:	x	y		z
Child:			a	

Works!

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() {
        Cond_signal(&c);        // a
}
```

Can you construct ordering that does not work?

Example broken schedule:

Parent:		x	y
Child:	a		

Parent waits forever!

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
}
```

Fixes previous broken ordering:

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
}
```

Can you construct ordering that does not work?

Parent: w x y … sleep forever …

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
}
```

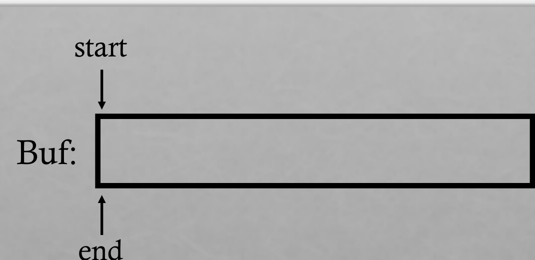
Parent:	w	x	y				z
Child:				a	b	c	

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

Producer/Consumer Problem

Example: Unix Pipes

Example: Unix Pipes



Pipe may have many writers and readers

- Implemented with finite-sized buffer

Writers add data to the buffer

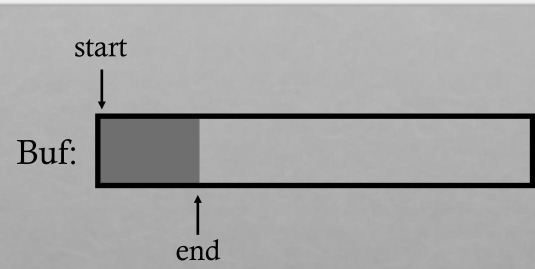
- Writers have to **wait** if buffer is full

Readers remove data from the buffer

- Readers have to wait if buffer is empty

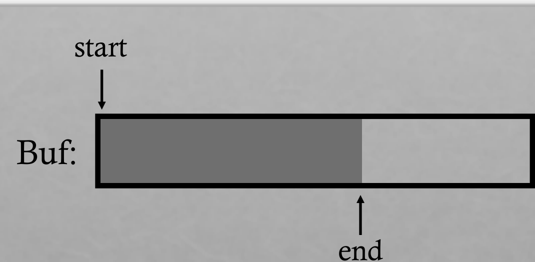
Example: Unix Pipes

write!



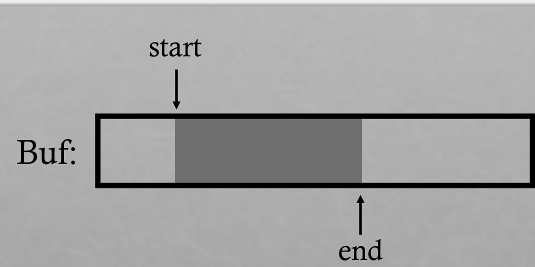
Example: Unix Pipes

write!



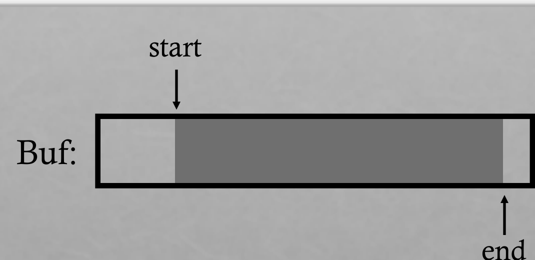
Example: Unix Pipes

read!



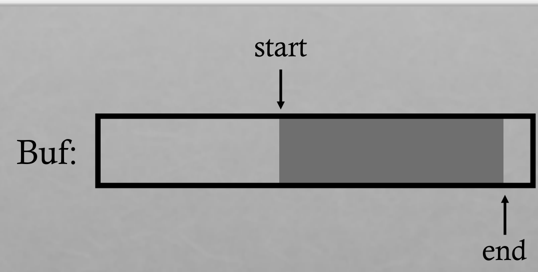
Example: Unix Pipes

write!



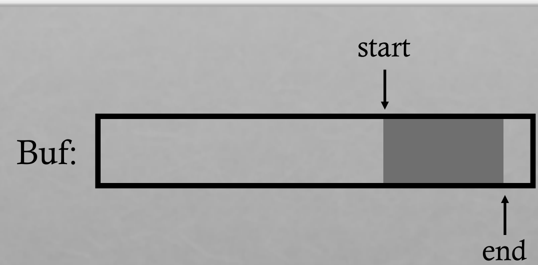
EXAMPLE: UNIX PIPES

read!



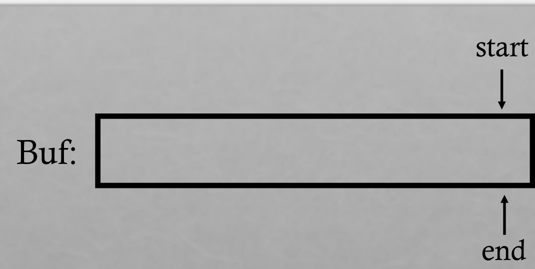
EXAMPLE: UNIX PIPES

read!



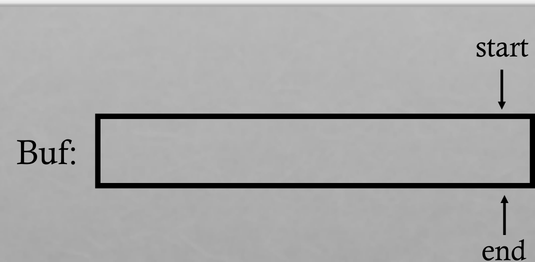
Example: Unix Pipes

read!



Example: Unix Pipes

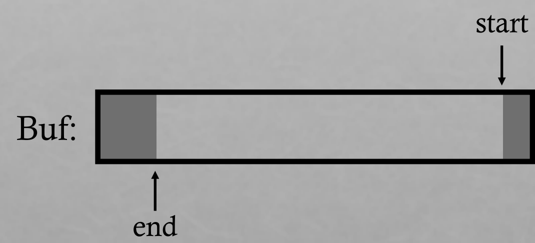
read!



note: readers must wait

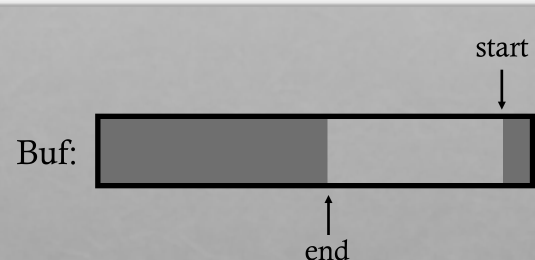
Example: Unix Pipes

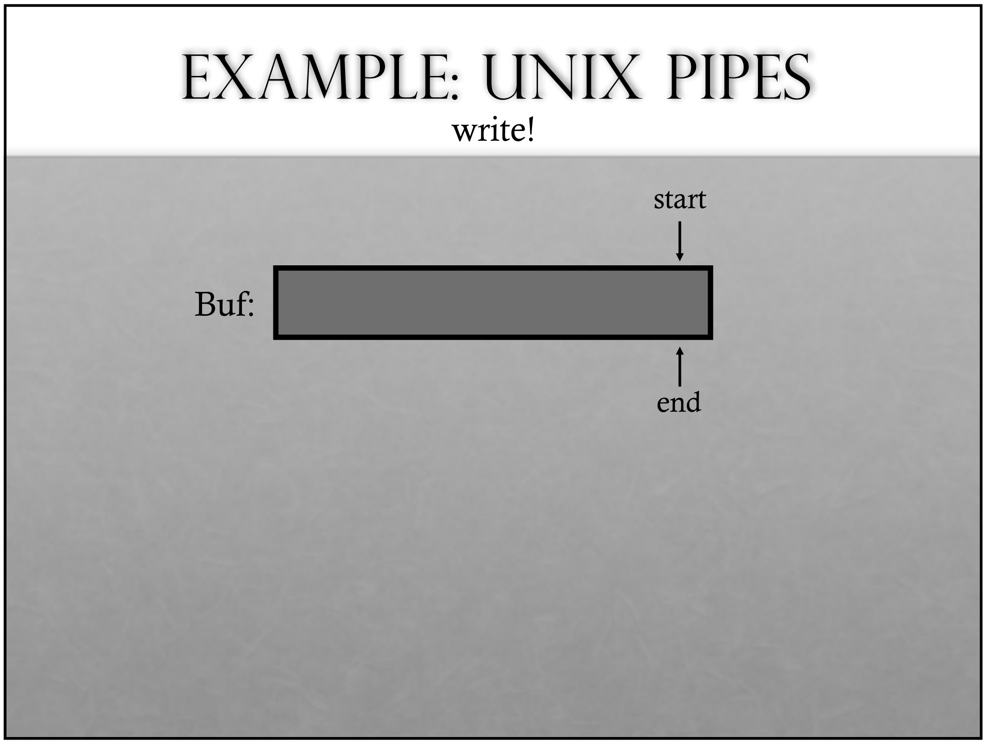
write!

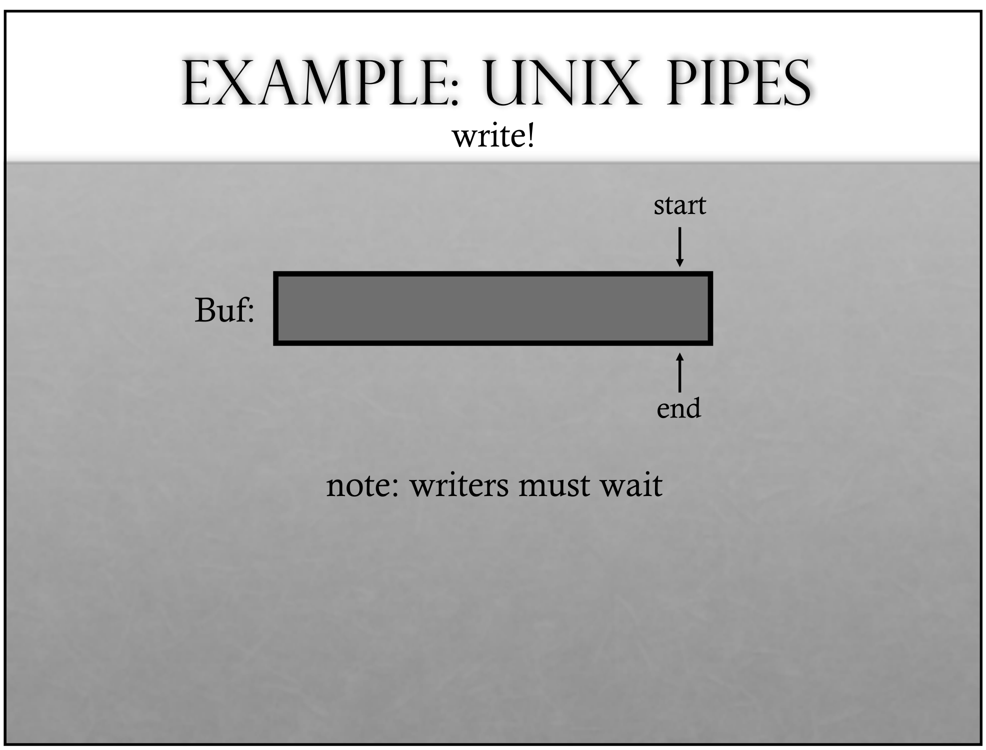


Example: Unix Pipes

write!

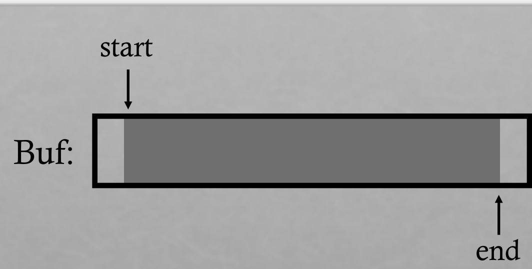



Example: Unix Pipes
write!
start
Buf:
end


Example: Unix Pipes
write!
start
Buf:
end
note: writers must wait

Example: Unix Pipes

read!



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

- 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)

Numfill = number of buffers currently filled

Examine slightly broken code to begin…

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
- Implication:
  1. BLOCKED on condition variable
  2. WAIT to acquire lock again (separate step)

signal(cond_t *cv)

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

numfull=0

[RUNNABLE]

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

[RUNNING]

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

Assume do_fill(i) increments numfull

Assume do_get() decrements numfull

numfull=0

[RUNNABLE]

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

[RUNNING]

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

numfull=0

[RUNNABLE]

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

[RUNNING]

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

numfull=0

[RUNNABLE]

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

[RUNNING]

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

numfull=0

[RUNNABLE]

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

[BLOCKED on CV]

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

Arrow shows location when run again

numfull=0

[RUNNING]

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

[BLOCKED on CV]

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

Will producer be stuck waiting for mutex_lock()?

numfull=0

[RUNNING]

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

[BLOCKED on CV]

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

No, because cond_wait() releases lock for m

numfull=0

[RUNNING]

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

[BLOCKED on CV]

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

numfull=1

[RUNNING]

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

[BLOCKED on CV]

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

What happens to consumer?

numfull=1

[RUNNING]

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

[RUNNABLE, WAIT on MUTEX]

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

numfull=1

[RUNNING]

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

[RUNNABLE, WAIT on MUTEX]

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

numfull=1

[RUNNING]

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

[RUNNABLE, WAIT on MUTEX]

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

Who acquires lock next?

- Could be either producer or consumer
- Example gives lock to producer

numfull=1

[RUNNING]

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

[RUNNABLE, WAIT on MUTEX]

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

numfull=1

[RUNNING]

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

[RUNNABLE, WAIT on MUTEX]

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

What important thing happens during cond_wait()?

numfull=1

[BLOCKED on CV]

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

[RUNNING: Acquires lock]

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

numfull=1

[BLOCKED]

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

[RUNNING]

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

Decrement numfull

numfull=0

[BLOCKED on CV]

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

[RUNNING]

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

What does signal() do?

numfull=0

[RUNNABLE: wait mutex]

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

[RUNNING]

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

numfull=0

[RUNNABLE: wait mutex]

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

[RUNNING]

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

numfull=0

[RUNNABLE: wait mutex]

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

[RUNNING]

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

numfull=0

[RUNNABLE: wait mutex]

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

[RUNNING]

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

numfull=0

[RUNNABLE: wait mutex]

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

[RUNNING]

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

numfull=0

[RUNNABLE: wait mutex]

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

[RUNNING]

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

What does wait() do?

numfull=0

[RUNNABLE: wait on mutex]

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

[BLOCKED on CV]

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

numfull=0

[RUNNING]

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

[BLOCKED]

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

numfull=0

[RUNNING]

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

[BLOCKED]

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

numfull=1

[RUNNING]

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

[BLOCKED]

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

numfull=1

[RUNNING]

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

[RUNNABLE: wait mutex]

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

All fine with 1 producer, 1 consumer, 1 buffer

What about 2 consumers?

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

Two Consumers: Problems

```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m); // p1
        while(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
        while(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
    }
}
```

```
                           wait()     wait()        signal()       wait()    signal()
Producer:                                     p1 p2 p4 p5 p6 p1 p2 p3
Consumer1:   c1 c2 c3
Consumer2:             c1 c2 c3                   unblocked                c2 c4 c5
```

does last signal wake producer or consumer1?

Two Consumers: Problems

```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m); // p1
        while(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
        while(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
    }
}
```

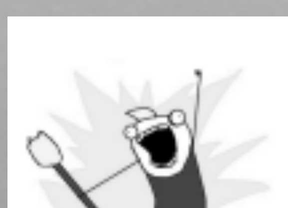
```
                       wait()     wait()        signal()         wait()    signal()
Producer:                                  p1 p2 p4 p5 p6 p1 p2 p3
Consumer1:   c1 c2 c3
Consumer2:                      c1 c2 c3          unblocked                 c2 c4 c5
```

Want consumer2 signal() to wake producer since numbufs = 0, but could wake consumer1

How to wake the right thread?

One solution:

- wake all the threads!



Waking All Waiting Threads

- **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

- **broadcast**(cond_t *cv)
- - wake **all** waiting threads (if >= 1 thread is waiting)
- - if there are no waiting thread, just return, doing nothing

any disadvantage?

Example Need for Broadcast

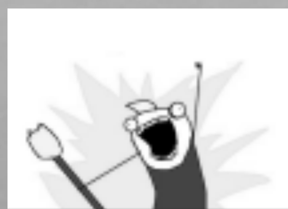
```
void *allocate(int size) {
   mutex_lock(&m);
   while (bytesLeft < size)
         cond_wait(&c);
   …
}
```

```
void free(void *ptr, int size) {
   …
   cond_broadcast(&c)
   …
}
```

HOW TO WAKE THE RIGHT THREAD?

One solution:

wake all the threads!



Better solution (usually): use separate 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);
    }
}
```

Is this correct? Can you find a bad schedule?

1. consumer1 waits because numfull == 0
2. producer increments numfull, wakes consumer1 from CV (must still get mutex!)
3. before consumer1 runs, consumer2 runs, gets lock, grabs entry, sets numfull=0.
4. consumer2 runs, gets lock, then reads bad data ☹

Good Rule of Thumb 3

Whenever a lock is acquired, recheck assumptions about state!

Possible for thread B to grab lock in between signal and thread A returning from wait (before thread A gets lock)

Some implementations have "spurious wakeups"

- May wake multiple waiting threads at signal or at any time
- May treat signal() as broadcast()

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);
    }
}
```

Is this correct? Can you find a bad schedule?

Correct!
- 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()`

Summary: Rules of Thumb for CVs

Keep state in addition to CV's

Always do wait/signal with lock held

Whenever thread wakes from waiting, recheck state