last time (1)

deadlock avoidance
    consistent order (usually preferred for locks)
    avoid hold and wait (one resource, abort+retry, revoke resources)

deadlock detection
    get info about what threads have what/are waiting for what
    repeatedly: eliminate threads could be immediately given all resources
    they're waiting for
    if you can't eliminate all threads: deadlock

last time (2)

producer/consumer problem
  shared queue: one+ producers (enqueue) + one+ consumer (dequeue)
  consumers wait if queue full

condition variables
  badly misnamed
  represent queue of waiting threads
  Wait(condvar, lock): unlock lock + wait + relock lock when done waiting
  Signal(condvar): stop one thread from waiting (and have it reacquire lock)
  Broadcast(convar): stop all threads from waiting

monitors = lock + shared data + condition variables

anonymous feedback (1)

"This TA has been on the same person for like 45+ minutes when there's less than an hour before the deadline and they just stand there on their phone waiting for the person to do more work and reach another question…."

> yes, I have talked to TAs about this kind of thing
>
> hopefully TAs will use strategies to switch between students
>
> (though I would hope students aren't relying on being able to get last-hour help consistently since we don't have the staff to make that happen…)

anonymous feedback (2)

"Labs for the past few weeks have been much better than earlier labs were, particularly the signals and network labs. Recent labs like the cache lab, sync games, and the pthreads lab could definitely be finished in a 75-minute time span and really helped me get some good practice with the material. Thank you for making these lab exercises more forgiving and doable in lab time."

  this is more of an accident than on purpose

  labs are mostly the way they are from pilot…

  (and I think for pthreads needs to have more — probably provide some base code for extra approach 2 + have people start it)

anonymous feedback (3)

"I was thinking about the class with a friend of mine and we just realized we are very grateful for how much effort you have put into the class, and your willingness to adjust things. I imagine it is hard to have to change things and update them in response to the weird things one of us 200something students come up with (I know I have contributed my fair share of these), so I really appreciate how willing you have been to listen to us. Thank you very much and I am sorry some people are mean in here. "

"I really enjoy this class! It is one of my favorite classes that I have taken. You run it very well and the structure is very organized and well done."

bounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready; pthread_cond_t space_ready;
BoundedQueue buffer;
Produce(item) {
    pthread_mutex_lock(&lock);
    while (buffer.full()) { pthread_cond_wait(&space_ready, &lock); }
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_cond_signal(&space_ready);
    pthread_mutex_unlock(&lock);
    return item;
}
```
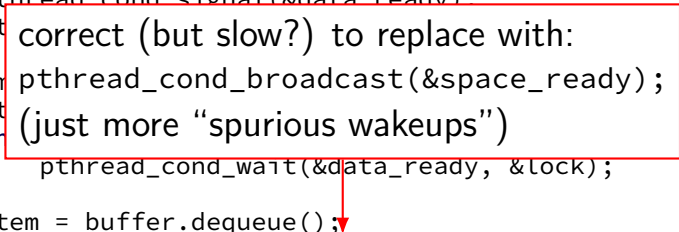
bounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready; pthread_cond_t space_ready;
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    pthread_mutex_lock(&lock);
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    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_cond_signal(&space_ready);
    pthread_mutex_unlock(&lock);
    return item;
}
```

bounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready; pthread_cond_t space_ready;
BoundedQueue buffer;
Produce(item) {
    pthread_mutex_lock(&lock);
    while (buffer.full()) { pthread_cond_wait(&space_ready, &lock); }
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pt
}
Consum
    pt
    wh
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_cond_signal(&space_ready);
    pthread_mutex_unlock(&lock);
    return item;
}
```

correct (but slow?) to replace with:
pthread_cond_broadcast(&space_ready);
(just more "spurious wakeups")

bounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready; pthread_cond_t space_ready;
BoundedQueue buffer;
Produce(item) {
    pthread_mutex_lock(&lock);
    while (buffer.full()) { pthread_cond_wait(&space_ready, &lock); }
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock)
    }
    item = buffer.dequeue();
    pthread_cond_signal(&space_ready);
    pthread_mutex_unlock(&lock);
    return item;
}
```

correct but slow to replace
`data_ready` and `space_ready`
with 'combined' condvar `ready`
and use broadcast
(just more "spurious wakeups")

monitor pattern

```
pthread_mutex_lock(&lock);
while (!condition A) {
    pthread_cond_wait(&condvar_for_A, &lock);
}
... /* manipulate shared data, changing other conditions */
if (set condition A) {
    pthread_cond_broadcast(&condvar_for_A);
    /* or signal, if only one thread cares */
}
if (set condition B) {
    pthread_cond_broadcast(&condvar_for_B);
    /* or signal, if only one thread cares */
}
...
pthread_mutex_unlock(&lock)
```

monitors rules of thumb

never touch shared data without holding the lock

keep lock held for entire operation:
  verifying condition (e.g. buffer not full) *up to and including*
  manipulating data (e.g. adding to buffer)

create condvar for every kind of scenario waited for

always write loop calling cond_wait to wait for condition X

broadcast/signal condition variable every time you change X

monitors rules of thumb

never touch shared data without holding the lock

keep lock held for entire operation:
> verifying condition (e.g. buffer not full) *up to and including*
> manipulating data (e.g. adding to buffer)

create condvar for every kind of scenario waited for

always write loop calling cond_wait to wait for condition X

broadcast/signal condition variable every time you change X

correct but slow to…
> broadcast when just signal would work
> broadcast or signal when nothing changed
> use one condvar for multiple conditions

wait for both finished

```
// MISSING: init calls, etc.
pthread_mutex_t lock;
bool finished[2];
pthread_cond_t both_finished_cv;

void WaitForBothFinished() {
  pthread_mutex_lock(&lock);
  while (_____) {
    pthread_cond_wait(&both_finished_cv, &lock);
  }
  pthread_mutex_unlock(&lock);
}

void Finish(int index) {
  pthread_mutex_lock(&lock);
  finished[index] = true;

  _____
  pthread_mutex_unlock(&lock);
}
```

wait for both finished

```
// MISSING: init calls, etc.
pthread_mutex_t lock;
bool finished[2];
pthread_cond_t both_finished_cv;

void WaitForBothFinished() {
  pthread_mutex_lock(&lock);
  while (_____) {
    pthread_cond_wait(&both_finished_cv, &lock);
  }
  pthread_mutex_unlock(&lock);
}

void Finish(int index) {
  pthread_mutex_lock(&lock);
  finished[index] = true;
  _____
  pthread_mutex_unlock(&lock);
}
```

A. `finished[0] && finished[1]`
B. `finished[0] || finished[1]`
C. `!finished[0] || !finished[1]`
D. `finished[0] != finished[1]`
E. something else

wait for both finished

```
// MISSING: init calls, etc.
pthread_mutex_t lock;
bool finished[2];
pthread_cond_t both_fini

void WaitForBothFinished
  pthread_mutex_lock(&lo
  while (_____
    pthread_cond_wait(&both_finished_cv, &lock);
  }
  pthread_mutex_unlock(&lock);
}

void Finish(int index) {
  pthread_mutex_lock(&lock);
  finished[index] = true;
  _____
  pthread_mutex_unlock(&lock);
}
```

A. pthread_cond_signal(&both_finished_cv)
B. pthread_cond_broadcast(&both_finished_cv)
C. if (finished[1−index])
        pthread_cond_singal(&both_finished_cv);
D. if (finished[1−index])
        pthread_cond_broadcast(&both_finished_cv);
E. something else

monitor exercise: barrier

suppose we want to implement a one-use barrier; fill in blanks:

```
struct BarrierInfo {
    pthread_mutex_t lock;
    int total_threads;  // initially total # of threads
    int number_reached; // initially 0
    _____
};

void BarrierWait(BarrierInfo *b) {
    pthread_mutex_lock(&b->lock);
    ++b->number_reached;
    if (b->number_reached == b->total_threads) {

        _____
    } else {

        _____
    }
    pthread_mutex_unlock(&b->lock);
}
```

generalizing locks: semaphores

semaphore has a non-negative integer **value** and two operations:

P() or **down** or **wait**:
wait for semaphore to become positive (> 0),
then decerement by 1

V() or **up** or **signal** or **post**:
increment semaphore by 1 (waking up thread if needed)

P, V from Dutch: *proberen* (test), *verhogen* (increment)

semaphores are kinda integers

semaphore like an integer, but...

cannot read/write directly
> down/up operaion only way to access (typically)
> exception: initialization

never negative — wait instead
> down operation wants to make negative? thread waits

reserving books

suppose tracking copies of library book…

```
Semaphore free_copies = Semaphore(3);
void ReserveBook() {
    // wait for copy to be free
    free_copies.down();
    ... // ... then take reserved copy
}

void ReturnBook() {
    ... // return reserved copy
    free_copies.up();
    // ... then wakeup waiting thread
}
```

counting resources: reserving books

suppose tracking copies of same library book
non-negative integer count = # how many books used?
up = give back book; down = take book

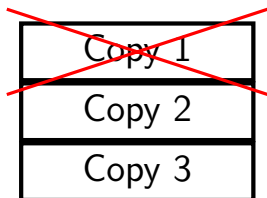| Copy 1 |
|--------|
| Copy 2 |
| Copy 3 |

free copies $\boxed{3}$

counting resources: reserving books

suppose tracking copies of same library book
non-negative integer count = # how many books used?
up = give back book; down = take book

taken out

| Copy 1 |
| Copy 2 |
| Copy 3 |

free copies

after calling down to reserve

counting resources: reserving books

suppose tracking copies of same library book
non-negative integer count = # how many books used?
up = give back book; down = take book

taken out

| Copy 1 |
| Copy 2 |
| Copy 3 |

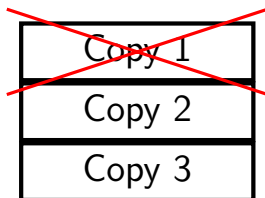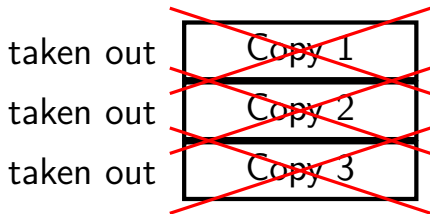free copies $\boxed{2}$

after calling down to reserve

counting resources: reserving books

suppose tracking copies of same library book
non-negative integer count = # how many books used?
up = give back book; down = take book

taken out | Copy 1
taken out | Copy 2
taken out | Copy 3
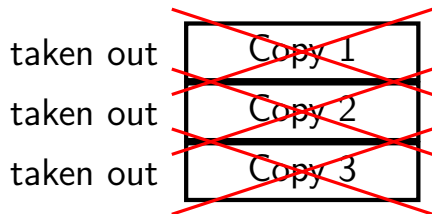
free copies $\boxed{0}$

after calling down three times
to reserve all copies

counting resources: reserving books

suppose tracking copies of same library book
non-negative integer count = # how many books used?
up = give back book; down = take book

taken out

free copies 0

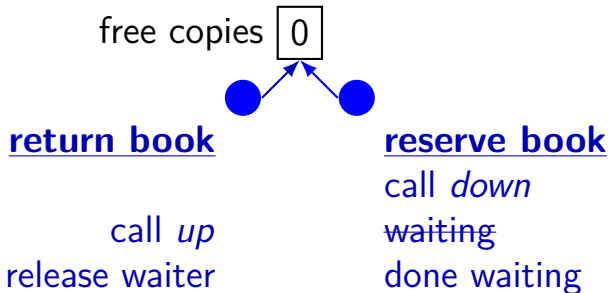**reserve book**
call *down* again
start waiting...

counting resources: reserving books

suppose tracking copies of same library book
non-negative integer count = # how many books used?
up = give back book; down = take book

taken out — Copy 1
taken out — Copy 2
taken out — Copy 3

free copies | 0 |

return book

call *up*
release waiter

reserve book
call *down*
~~waiting~~
done waiting
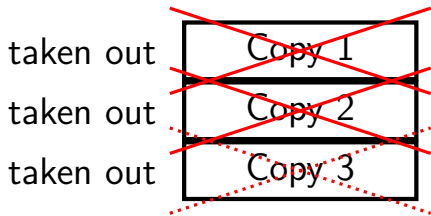
implementing mutexes with semaphores

```
struct Mutex {
    Semaphore s; /* with inital value 1 */
    /* value = 1 --> mutex if free */
    /* value = 0 --> mutex is busy */
}

MutexLock(Mutex *m) {
    m->s.down();
}

MutexUnlock(Mutex *m) {
    m->s.up();
}
```

implementing join with semaphores

```
struct Thread {
    ...
    Semaphore finish_semaphore; /* with initial value 0 */
    /* value = 0: either thread not finished OR already joined */
    /* value = 1: thread finished AND not joined */
};
thread_join(Thread *t) {
    t->finish_semaphore.down();
}

/* assume called when thread finishes */
thread_exit(Thread *t) {
    t->finish_semaphore.up();
    /* tricky part: deallocating struct Thread safely? */
}
```

POSIX semaphores

```c
#include <semaphore.h>
...
sem_t my_semaphore;
int process_shared = /* 1 if sharing between processes */;
sem_init(&my_semaphore, process_shared, initial_value);
...
sem_wait(&my_semaphore);  /* down */
sem_post(&my_semaphore);  /* up */
...
sem_destroy(&my_semaphore);
```

semaphore exercise

```
int value;  sem_t empty, ready;  // with some initial values

void PutValue(int argument) {
    sem_wait(&empty);
    value = argument;
    sem_post(&ready);
}

int GetValue() {
    int result;

    _____
    result = value;

    _____
    return result;
}
```

What goes in the blanks?
A: sem_post(&empty) / sem_wait(&ready)
B: sem_wait(&ready) / sem_post(&empty)
C: sem_post(&ready) / sem_wait(&empty)
D: sem_post(&ready) / sem_post(&empty)
E: sem_wait(&empty) / sem_post(&ready)
F: something else

GetValue() waits for PutValue() to happen, retrieves value, then allows next PutValue().

PutValue() waits for prior GetValue(), places value, then allows next GetValue().

semaphore intuition

What do you need to wait for?
> critical section to be finished
> queue to be non-empty
> array to have space for new items

what can you count that will be 0 when you need to wait?
> # of threads that can start critical section now
> # of threads that can join another thread without waiting
> # of items in queue
> # of empty spaces in array

use up/down operations to maintain count

producer/consumer constraints

consumer waits for producer(s) if buffer is empty

producer waits for consumer(s) if buffer is full

any thread waits while a thread is manipulating the buffer

producer/consumer constraints

consumer waits for producer(s) if buffer is empty

producer waits for consumer(s) if buffer is full

any thread waits while a thread is manipulating the buffer

one semaphore per constraint:

```
sem_t full_slots;    // consumer waits if empty
sem_t empty_slots;   // producer waits if full
sem_t mutex;         // either waits if anyone changing buffer
FixedSizedQueue buffer;
```

producer/consumer pseudocode

```
sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);
sem_init(&empty_slots, ..., BUFFER_CAPACITY);
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);
buffer.set_size(BUFFER_CAPACITY);
...
Produce(item) {
    sem_wait(&empty_slots);  // wait until free slot, reserve it
    sem_wait(&mutex);
    buffer.enqueue(item);
    sem_post(&mutex);
    sem_post(&full_slots);  // tell consumers there is more data
}

Consume() {
    sem_wait(&full_slots);  // wait until queued item, reserve it
    sem_wait(&mutex);
    item = buffer.dequeue();
    sem_post(&mutex);
    sem_post(&empty_slots);  // let producer reuse item slot
    return item;
}
```

producer/consumer pseudocode

```
sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);
sem_init(&empty_slots, ..., BUFFER_CAPACITY);
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);
buffer.set_size(BUFFER_CAPACITY);
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Produce(item) {
    sem_wait(&empty_slots);  // wait until free slot, reserve it
    sem_wait(&mutex);
    buffer.enqueue(item);
    sem_post(&mutex);
    sem_post(&full_slots);   // tell consumers there is more data
}

Consume() {
    sem_wait(&full_slots);   // wait until queued item, reserve it
    sem_wait(&mutex);
    item = buffer.dequeue();
    sem_post(&mutex);
    sem_post(&empty_slots);  // let producer reuse item slot
    return item;
}
```

producer/consumer pseudocode

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sem_init(&empty_slots, ..., BUFFER_CAPACITY);
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);
buffer.set_size(BUFFER_CAPACITY);
...
Produce(item) {
    sem_wait(&empty_slots);  // wait until free slot, reserve it
    sem_wait(&mutex);
    buffer.enqueue(item);
    sem_post(&mutex);
    sem_post(&full_slots);  // tell consumers there is more data
}

Consume() {
    sem_wait(&full_slots);  // wait until queued item, reserve it
    sem_wait(&mutex);
    item = buffer.dequeue();
    sem_post(&mutex);
    sem_post(&empty_slots);  // let producer reuse item slot
    return item;
}
```

producer/consumer pseudocode

```
sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);
sem_init(&empty_slots, ..., BUFFER_CAPACITY);
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);
buffer.set_size(BUFFER_CAPACITY);
...
Produce(item) {
    sem_wait(&empty_slots);   // wait until free slot, reserve it
    sem_wait(&mutex);
    buffer.enqueue(item);
    sem_post(&mutex);
    sem_post(&full_slots);                                          data
}

Consume() {
    sem_wait(&full_slots);   // wait until queued item, reserve it
    sem_wait(&mutex);
    item = buffer.dequeue();
    sem_post(&mutex);
    sem_post(&empty_slots);  // let producer reuse item slot
    return item;
}
```

Can we do
    sem_wait(&mutex);
    sem_wait(&empty_slots);
instead?

producer/consumer pseudocode

```
sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);
sem_init(&empty_slots, ..., BUFFER_CAPACITY);
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);
buffer.set_size(BUFFER_CAPACITY);
...
Produce(item) {
    sem_wait(&empty_slots);      // wait until free slot, reserve it
    sem_wait(&mutex);
    buffer.enqueue(item);
    sem_post(&mutex);
    sem_post(&full_slots);
}

Consume() {
    sem_wait(&full_slots);
    sem_wait(&mutex);
    item = buffer.dequeue()
    sem_post(&mutex);
    sem_post(&empty_slots);
    return item;
}
```

Can we do
  sem_wait(&mutex);
  sem_wait(&empty_slots);
instead?

No. Consumer waits on sem_wait(&mutex) so can't sem_post(&empty_slots) (result: producer waits forever problem called *deadlock*)

producer/consumer: cannot reorder mutex/empty

```
ProducerReordered() {            Consumer() {
  // BROKEN: WRONG ORDER           sem_wait(&full_slots);
  sem_wait(&mutex);
  sem_wait(&empty_slots);          // can't finish until
                                   // Producer's sem_post(&mutex):
  ...                              sem_wait(&mutex);

  sem_post(&mutex);                ...

                                   // so this is not reached
                                   sem_post(&full_slots);
```

producer/consumer pseudocode

```
sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);
sem_init(&empty_slots, ..., BUFFER_CAPACITY);
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);
buffer.set_size(BUFFER_CAPACITY);
...
Produce(item) {
    sem_wait(&empty_slots);    // wait until free slot, reserve it
    sem_wait(&mutex);
    buffer.enqueue(item);
    sem_post(&mutex);
    sem_post(&full_slots                              more data
}

Consume() {
    sem_wait(&full_slots                              reserve it
    sem_wait(&mutex);
    item = buffer.dequeu
    sem_post(&mutex);
    sem_post(&empty_slots);    // let producer reuse item slot
    return item;
}
```

Can we do
    sem_post(&full_slots);
    sem_post(&mutex);
instead?
Yes — post never waits

producer/consumer summary

producer: wait (down) empty_slots, post (up) full_slots

consumer: wait (down) full_slots, post (up) empty_slots

two producers or consumers?
    still works!

transactions

transaction: set of operations that occurs atomically

idea: something higher-level handles locking, etc.:
```
BeginTransaction();
int FromOldBalance = GetBalance(FromAccount);
int ToOldBalance = GetBalance(ToAccount);
SetBalance(FromAccount, FromOldBalance - 100);
SetBalance(ToAccount, FromOldBalance + 100);
EndTransaction();
```
idea: library/database/etc. makes "transaction" happens all at once

consistency / durability

"happens all at once" = could mean:

locking to make sure no other operations interfere (consistency)

making sure on crash, no partial transaction seen (durability)

(some systems provide both, some provide only one)

we'll just talk baout implementing consistency

implementing consistency: simple

simplest idea: only one run transaction at a time

implementing consistency: locking

everytime something read/written: acquire associated lock

on end transaction: release lock

if deadlock: undo everything, go back to BeginTransaction(), retry
    how to undo?
    one idea: keep list of writes instead of writing
    apply writes only at EndTransaction()

implementing consistency: locking

everytime something read/written: acquire associated lock

on end transaction: release lock

if deadlock: undo everything, go back to BeginTransaction(), retry
    how to undo?
    one idea: keep list of writes instead of writing
    apply writes only at EndTransaction()

implementing consistency: optimistic

on read: copy version $\#$ for value read

on write: record value to be written, but don't write yet

on end transaction:
    acquire locks on everything
    make sure values read haven't been changed since read

if they have changed, just retry transaction

backup slides

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
    pthread_mutex_lock(&lock);
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
    pthread_mutex_lock(&lock);
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

rule: never touch `buffer`
without acquiring lock

otherwise: what if two threads
simulatenously en/dequeue?
(both use same array/linked list entry?)
(both reallocate array?)

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
    pthread_mutex_lock(&lock);
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

check if empty
if so, dequeue

okay because have lock

other threads can**not** dequeue here

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
    pthread_mutex_lock(&lock);
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

wake one Consume thread
if any are waiting

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
    pthread_mutex_lock(&lock);
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready)
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

Thread 1

Produce()
...lock
...enqueue
...signal
...unlock

Thread 2

Consume()
...lock
...empty? no
...dequeue
...unlock
return

0 iterations: Produce() called before Consume()
1 iteration: Produce() signalled, probably
2+ iterations: spurious wakeup or ...?

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
    pthread_mutex_lock(&lock);
    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &loc
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

Thread 1	Thread 2
	Consume()
	…lock
	…empty? yes
	…unlock/start wait
Produce()	waiting for
…lock	data_ready
…enqueue	
…signal	stop wait
…unlock	lock
	…empty? no
	…dequeue
	…unlock
	return

0 iterations: Produce() called before Consume()
1 iteration: Produce() signalled, probably
2+ iterations: spurious wakeup or …?

33

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
    pthread_mutex_lock(&lock);
    buffer.enqueue(item);
    pthread_cond_signal(&data_rea
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_r
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

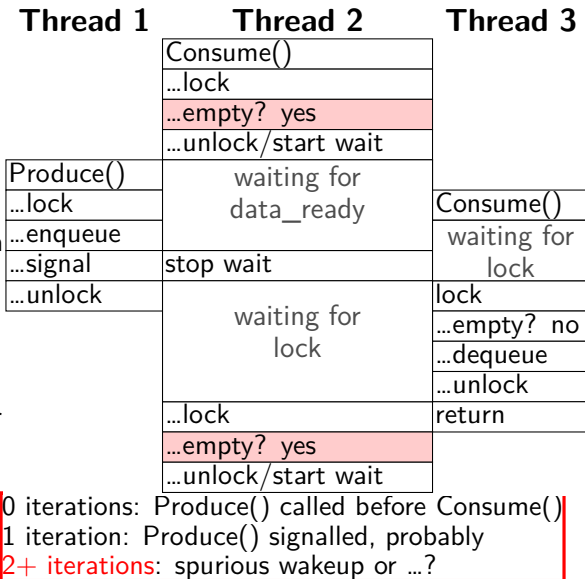| Thread 1	Thread 2	Thread 3
	Consume()	
	…lock	
	…empty? yes	
	…unlock/start wait	
Produce()	waiting for data_ready	
…lock		Consume()
…enqueue		waiting for lock
…signal	stop wait	
…unlock		lock
	waiting for lock	…empty? no
		…dequeue
		…unlock
	…lock	return
	…empty? yes	
	…unlock/start wait	

0 iterations: Produce() called before Consume()
1 iteration: Produce() signalled, probably
2+ iterations: spurious wakeup or …?

33

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;
```

in pthreads: signalled thread not
    gaurenteed to hold lock next);

alternate design:
signalled thread gets lock next
    called "Hoare scheduling"
not done by pthreads, Java, …

```
        pthread_cond_wait(&data_r
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

Thread 1	Thread 2	Thread 3
	Consume()	
	…lock	
	…empty? yes	
	…unlock/start wait	
Produce()	waiting for data_ready	
…lock		Consume()
…enqueue		waiting for lock
…signal	stop wait	
…unlock		lock
	waiting for lock	…empty? no
		…dequeue
		…unlock
	…lock	return
	…empty? yes	
	…unlock/start wait	

0 iterations: Produce() called before Consume()
1 iteration: Produce() signalled, probably
2+ iterations: spurious wakeup or …?

monitor exercise: ConsumeTwo

suppose we want producer/consumer, but...

but change Consume() to ConsumeTwo() which returns a pair of values
>   and don't want two calls to ConsumeTwo() to wait...
>   with each getting one item

what should we change below?

```
pthread_mutex_t lock;                   Consume() {
pthread_cond_t data_ready;                pthread_mutex_lock(&lock);
UnboundedQueue buffer;                     while (buffer.empty()) {
                                             pthread_cond_wait(&data_ready, &lock
Produce(item) {                            }
  pthread_mutex_lock(&lock);               item = buffer.dequeue();
  buffer.enqueue(item);                    pthread_mutex_unlock(&lock);
  pthread_cond_signal(&data_ready);        return item;
  pthread_mutex_unlock(&lock);           }
}
```

monitor exercise: ordering

suppose we want producer/consumer, but…

but want to ensure first call to Consume() **always** returns first

(no matter what ordering cond_signal/cond_broadcast use)

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
  pthread_mutex_lock(&lock);
  buffer.enqueue(item);
  pthread_cond_signal(&data_ready);
  pthread_mutex_unlock(&lock);
}
```

```
Consume() {
  pthread_mutex_lock(&lock);
  while (buffer.empty()) {
    pthread_cond_wait(&data_ready, &lock
  }
  item = buffer.dequeue();
  pthread_mutex_unlock(&lock);
  return item;
}
```

producer/consumer signal?

```
pthread_mutex_t lock;
pthread_cond_t data_ready;
UnboundedQueue buffer;

Produce(item) {
    pthread_mutex_lock(&lock);
    buffer.enqueue(item);
    /* GOOD CODE: pthread_cond_signal(&data_ready); */
    /* BAD CODE: */
    if (buffer.size() == 1)
        pthread_cond_signal(&item);
    pthread_mutex_unlock(&lock);
}

Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```

bad case (setup)

thread 0	1	2	3
Consume(): lock empty? wait on cv	Consume(): lock empty? wait on cv	Produce(): lock	Produce():

bad case

thread 0	1	2	3
Consume(): lock empty? wait on cv			
	Consume(): lock empty? wait on cv		
		Produce(): lock	Produce(): wait for lock
wait for lock		enqueue size = 1? signal unlock	
			gets lock enqueue size ≠ 1: don't signal unlock
gets lock dequeue			
	still waiting		

Anderson-Dahlin and semaphores

Anderson/Dahlin complains about semaphores

"Our view is that programming with locks and condition variables is
superior to programming with semaphores."

argument 1: clearer to have separate constructs for
waiting for condition to be come true, and
allowing only one thread to manipulate a thing at a time

arugment 2: tricky to verify thread calls up exactly once for every
down
alternatives allow one to be sloppier (in a sense)

monitors with semaphores: locks

```
sem_t semaphore;  // initial value 1

Lock() {
    sem_wait(&semaphore);
}

Unlock() {
    sem_post(&semaphore);
}
```

monitors with semaphores: [broken] cvs

start with only wait/signal:

```
sem_t threads_to_wakeup;  // initially 0
Wait(Lock lock) {
    lock.Unlock();
    sem_wait(&threads_to_wakeup);
    lock.Lock();
}
Signal() {
    sem_post(&threads_to_wakeup);
}
```

monitors with semaphores: [broken] cvs

start with only wait/signal:

```
sem_t threads_to_wakeup;  // initially 0
Wait(Lock lock) {
    lock.Unlock();
    sem_wait(&threads_to_wakeup);
    lock.Lock();
}
Signal() {
    sem_post(&threads_to_wakeup);
}
```

problem: signal wakes up non-waiting threads (in the far future)

monitors with semaphores: cvs (better)

start with only wait/signal:

```
sem_t private_lock;  // initially 1
int num_waiters;
sem_t threads_to_wakeup;  // initially 0
Wait(Lock lock) {                          Signal() {
  sem_wait(&private_lock);                   sem_wait(&private_lock);
  ++num_waiters;                             if (num_waiters > 0) {
  sem_post(&private_lock);                     sem_post(&threads_to_wakeup);
  lock.Unlock();                               --num_waiters;
  sem_wait(&threads_to_wakeup);              }
  lock.Lock();                               sem_post(&private_lock);
}                                          }
```

monitors with semaphores: broadcast

now allows broadcast:

```
sem_t private_lock;  // initially 1
int num_waiters;
sem_t threads_to_wakeup;  // initially 0
Wait(Lock lock) {
  sem_wait(&private_lock);
  ++num_waiters;
  sem_post(&private_lock);
  lock.Unlock();
  sem_wait(&threads_to_wakeup);
  lock.Lock();
}
```

```
Broadcast() {
  sem_wait(&private_lock);
  while (num_waiters > 0) {
    sem_post(&threads_to_wakeup);
    --num_waiters;
  }
  sem_post(&private_lock);
}
```

building semaphore with monitors

```
pthread_mutex_t lock;
```

lock to protect shared state

building semaphore with monitors

```
pthread_mutex_t lock;
unsigned int count;
```

lock to protect shared state
     shared state: semaphore tracks a count

building semaphore with monitors

```
pthread_mutex_t lock;
unsigned int count;
/* condition, broadcast when becomes count > 0 */
pthread_cond_t count_is_positive_cv;
```

lock to protect shared state
    shared state: semaphore tracks a count

add cond var for each reason we wait
    semaphore: wait for count to become positive (for down)

building semaphore with monitors

```
pthread_mutex_t lock;
unsigned int count;
/* condition, broadcast when becomes count > 0 */
pthread_cond_t count_is_positive_cv;
void down() {
    pthread_mutex_lock(&lock);
    while (!(count > 0)) {
        pthread_cond_wait(
            &count_is_positive_cv,
            &lock);
    }
    count -= 1;
    pthread_mutex_unlock(&lock);
}
```

lock to protect shared state
   shared state: semaphore tracks a count

add cond var for each reason we wait
   semaphore: wait for count to become positive (for down)

wait using condvar; broadcast/signal when condition changes

building semaphore with monitors

```
pthread_mutex_t lock;
unsigned int count;
/* condition, broadcast when becomes count > 0 */
pthread_cond_t count_is_positive_cv;
void down() {
    pthread_mutex_lock(&lock);
    while (!(count > 0)) {
        pthread_cond_wait(
            &count_is_positive_cv,
            &lock);
    }
    count -= 1;
    pthread_mutex_unlock(&lock);
}
```

```
void up() {
    pthread_mutex_lock(&lock);
    count += 1;
    /* count must now be
       positive, and at most
       one thread can go per
       call to Up() */
    pthread_cond_signal(
        &count_is_positive_cv
    );
    pthread_mutex_unlock(&lock);
}
```

lock to protect shared state
    shared state: semaphore tracks a count

add cond var for each reason we wait
    semaphore: wait for count to become positive (for down)

wait using condvar; broadcast/signal when condition changes

binary semaphores

binary semaphores — semaphores that are only zero or one

as powerful as normal semaphores
> exercise: simulate counting semaphores with binary semaphores (more than one) and an integer

counting semaphores with binary semaphores

```
// assuming initialValue > 0
BinarySemaphore mutex(1);
int value = initialValue ;
BinarySemaphore gate(1 /* if initialValue >= 1 */);
    /* gate = # threads that can Down() now */
```

```
void Down() {                          void Up() {
  gate.Down();                           mutex.Down();
  // wait, if needed                     value += 1;
  mutex.Down();                          if (value == 1) {
  value -= 1;                              gate.Up();
  if (value > 0) {                         // because down should finish now
    gate.Up();                             // but could not before
    // because next down should finish   }
    // now (but not marked to before)    mutex.Up();
  }                                    }
  mutex.Up();
}
```

gate intuition/pattern

pattern to allow one thread at a time:

```
sem_t gate; // 0 = closed; 1 = open
ReleasingThread() {
    ... // finish what the other thread is waiting for
    while (another thread is waiting and can go) {
        sem_post(&gate)  // allow EXACTLY ONE thread
        ... // other bookkeeping
    }
    ...
}
WaitingThread() {
    ... // indicate that we're waiting
    sem_wait(&gate) // wait for gate to be open
    ... // indicate that we're not waiting
}
```

exercise: forwarding paths (2)

                    cycle # 0 1 2 3 4 5 6 7 8

addq %r8, %r9
subq %r8, %r9
ret (goes to andq)
andq %r10, %r9

in subq, %r8 is _____ addq.

in subq, %r9 is _____ addq.

in andq, %r9 is _____ subq.

in andq, %r9 is _____ addq.

> A: not forwarded from
> B-D: forwarded to decode from {execute,memory,writeback} stage of

mutex/cond var init/destroy

```
pthread_mutex_t mutex;
pthread_cond_t cv;
pthread_mutex_init(&mutex, NULL);
pthread_cond_init(&cv, NULL);
// --OR--
pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cv = PTHREAD_COND_INITIALIZER;

// and when done:
...
pthread_cond_destroy(&cv);
pthread_mutex_destroy(&mutex);
```