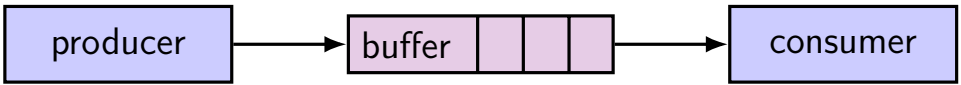
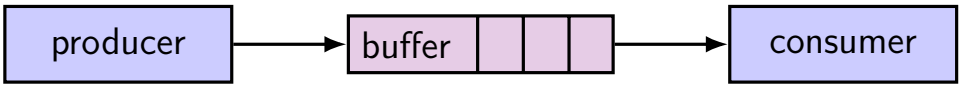
example: producer/consumer



shared buffer (queue) of fixed size

- one or more producers inserts into queue
- one or more consumers removes from queue

example: producer/consumer



shared buffer (queue) of fixed size

- one or more producers inserts into queue
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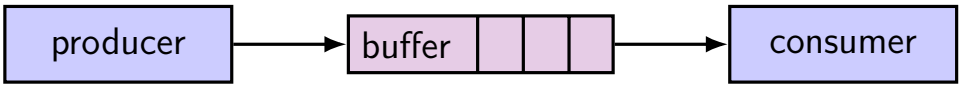
producer(s) and consumer(s) don't work in lockstep

- (might need to wait for each other to catch up)

example: producer/consumer



shared buffer (queue) of fixed size

- one or more producers inserts into queue
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producer(s) and consumer(s) don't work in lockstep

- (might need to wait for each other to catch up)

example: C compiler

- preprocessor → compiler → assembler → linker

monitors/condition variables

locks for mutual exclusion

condition variables for waiting for event

- operations: wait (for event); signal/broadcast (that event happened)

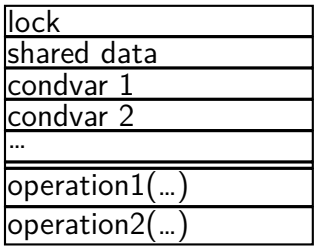
related data structures

monitor = lock + 0 or more condition variables + shared data

- Java: every object is a monitor (has instance variables, built-in lock, cond. var)
- pthreads: build your own: provides you locks + condition variables

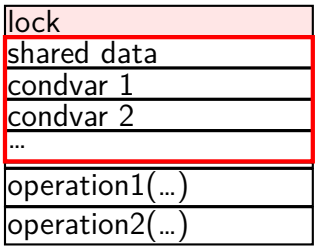
monitor idea

a monitor



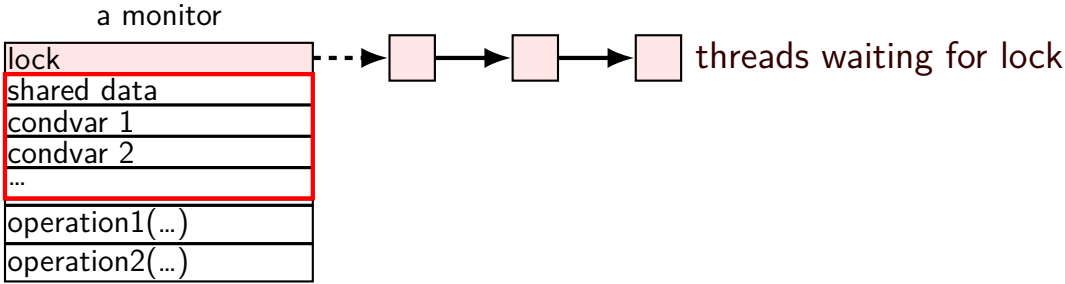
monitor idea

a monitor

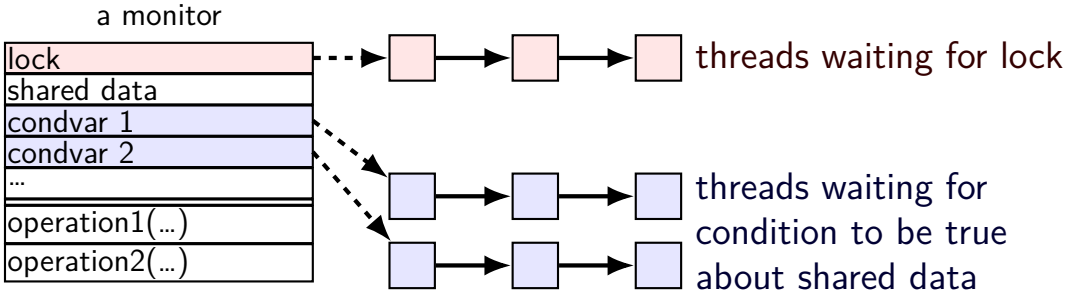


lock must be acquired
before accessing
any part of monitor's stuff

monitor idea



monitor idea



condvar operations

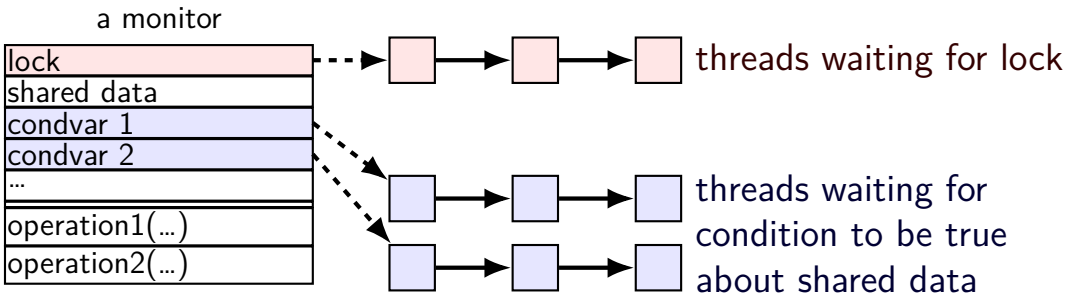
condvar operations:

Wait(cv, lock) — unlock lock, add current thread to cv queue

…and reacquire lock before returning

Broadcast(cv) — remove all from condvar queue

Signal(cv) — remove one from condvar queue



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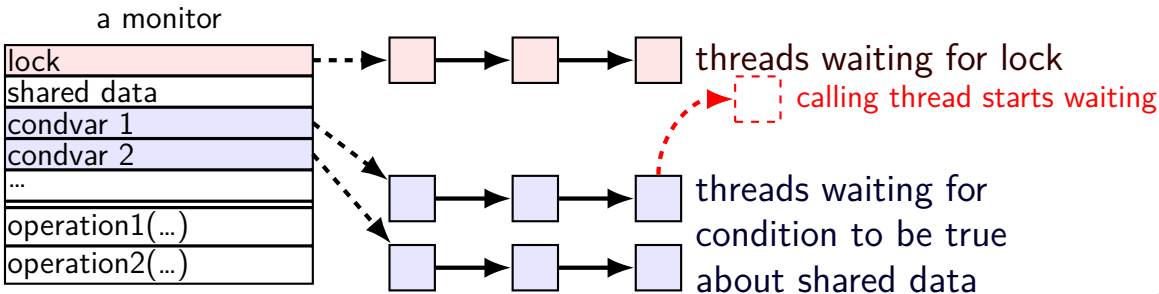

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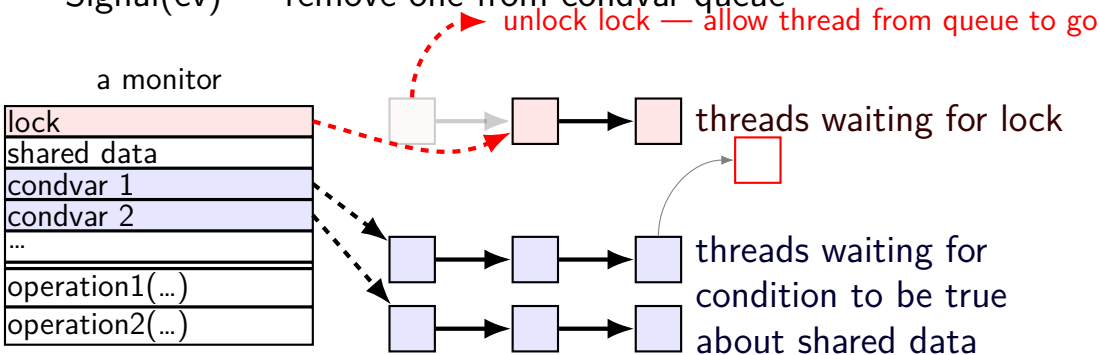

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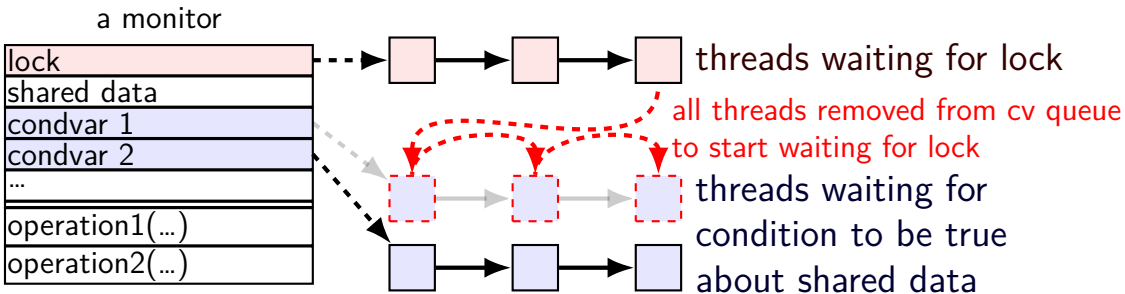

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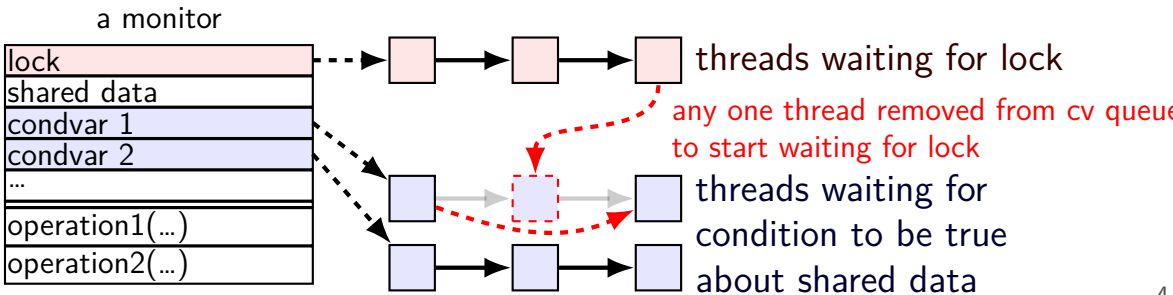

pthread cv usage

```
// MISSING: init calls, etc.
pthread_mutex_t lock;
bool finished;   // data, only accessed with after acquiring lock
pthread_cond_t finished_cv;  // to wait for 'finished' to be true

void WaitForFinished() {
  pthread_mutex_lock(&lock);
  while (!finished) {
    pthread_cond_wait(&finished_cv, &lock);
  }
  pthread_mutex_unlock(&lock);
}

void Finish() {
  pthread_mutex_lock(&lock);
  finished = true;
  pthread_cond_broadcast(&finished_cv);
  pthread_mutex_unlock(&lock);
}
```

pthread cv usage

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// MISSING: init calls, etc.
pthread_mutex_t lock;
bool finished;   // data, only accessed with after acquiring lock
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void WaitForFinished() {
  pthread_mutex_lock(&lock);
  while (!finished) {
    pthread_cond_wait(&finished_cv, &l
  }
  pthread_mutex_unlock(&lock);
}

void Finish() {
  pthread_mutex_lock(&lock);
  finished = true;
  pthread_cond_broadcast(&finished_cv);
  pthread_mutex_unlock(&lock);
}
```

acquire lock before reading or writing `finished`

pthread cv usage

```
// MISSING: init calls, etc.
pthread_mutex_t lock;
bool finished;   // data, only accessed with after acquiring lock
pthread_cond_t finished_cv;  // to wait for 'finished' to be true

void WaitForFinished() {
  pthread_mutex_lock(&lock);
  while (!finished) {
    pthread_cond_wait(&finished_cv, &lock);
  }
  pthread_mutex_unlock(&lock);
}

void Finish() {
  pthread_mutex_lock(&lock);
  finished = true;
  pthread_cond_broadcast(&finished_cv);
  pthread_mutex_unlock(&lock);
}
```

check whether we need to wait at all

(why a loop? we'll explain later)

pthread cv usage

```
// MISSING: init calls, etc.
pthread_mutex_t lock;
bool finished;   // data, only accessed with after acquiring lock
pthread_cond_t finished_cv;  // to wait for 'finished' to be true

void WaitForFinished() {
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  while (!finished) {
    pthread_cond_wait(&finished_cv, &lock);
  }
  pthread_mutex_unlock(&lock);
}

void Finish() {
  pthread_mutex_lock(&lock);
  finished = true;
  pthread_cond_broadcast(&finished_cv);
  pthread_mutex_unlock(&lock);
}
```

know we need to wait
(finished can't change while we have lock)
so wait, releasing lock…

pthread cv usage

```
// MISSING: init calls, etc.
pthread_mutex_t lock;
bool finished;   // data, only accessed with after acquiring lock
pthread_cond_t finished_cv;  // to wait for 'finished' to be true

void WaitForFinished() {
  pthread_mutex_lock(&lock);
  while (!finished) {
    pthread_cond_wait(&finished_cv, &lock);
  }
  pthread_mutex_unlock(&lock);
}

void Finish() {
  pthread_mutex_lock(&lock);
  finished = true;
  pthread_cond_broadcast(&finished_cv);
  pthread_mutex_unlock(&lock);
}
```

allow all waiters to proceed (once we unlock the lock)

WaitForFinish timeline 1

WaitForFinish thread	Finish thread
`mutex_lock(&lock)` (thread has lock)	
	`mutex_lock(&lock)` (start waiting for lock)

`while (!finished) ...`
`cond_wait(&finished_cv, &lock);`
(start waiting for cv)
	
	(done waiting for lock)

	`finished = true` `cond_broadcast(&finished_cv)`
(done waiting for cv) (start waiting for lock)	
	`mutex_unlock(&lock)`
(done waiting for lock) `while (!finished) ...` (finished now true, so return)	

WaitForFinish timeline 2

WaitForFinish thread	Finish thread

	`mutex_lock(&lock)`
	`finished = true`
	`cond_broadcast(&finished_cv)`
	`mutex_unlock(&lock)`

`mutex_lock(&lock)`
`while (!finished) ...`
(finished now true, so return)
`mutex_unlock(&lock)`	

why the loop

```
while (!finished) {
  pthread_cond_wait(&finished_cv, &lock);
}
```

we only `broadcast` if `finished` is true

so why check `finished` afterwards?

why the loop

```
while (!finished) {
  pthread_cond_wait(&finished_cv, &lock);
}
```

we only `broadcast` if `finished` is true

so why check `finished` afterwards?

pthread_cond_wait manual page:

> "Spurious wakeups ... may occur."

spurious wakeup = `wait` returns even though nothing happened

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;
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Produce(item) {
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    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 cannot dequeue here

unbounded buffer producer/consumer

```
pthread_mutex_t lock;
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UnboundedQueue buffer;

Produce(item) {
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    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);
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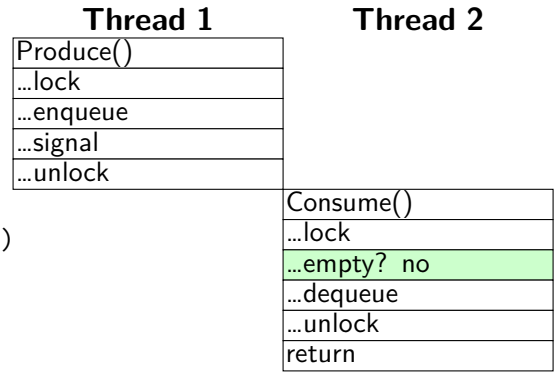
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```



unbounded buffer producer/consumer

```
pthread_mutex_t lock;
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    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;
}
```

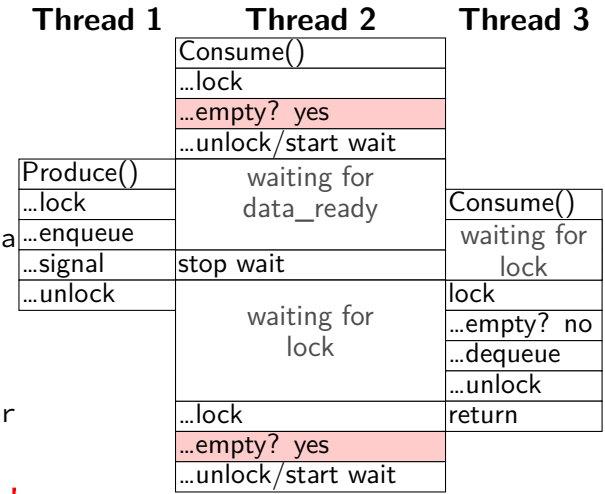
Thread 1	Thread 2
	Consume()
	…lock
	…empty? yes
	…unlock/start wait
Produce()	waiting for data_ready
…lock	
…enqueue	
…signal	stop wait
…unlock	lock
	…empty? no
	…dequeue
	…unlock
	return

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

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;
}
```



unbounded buffer producer/consumer

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

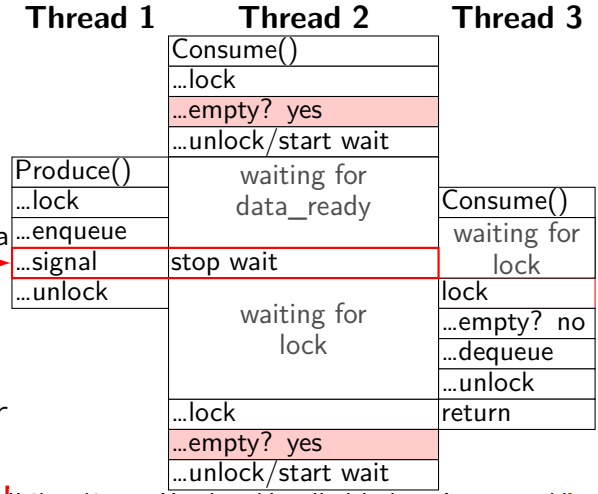
in pthreads: signalled thread not gaurenteed to hold lock next

alternate design: signalled thread gets lock next

called "Hoare scheduling"

not done by pthreads, Java, ...

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



Hoare versus Mesa monitors

Hoare-style monitors

- signal 'hands off' lock to awoken thread

Mesa-style monitors

- any eligible thread gets lock next
- (maybe some other idea of priority?)

every current threading library I know of does Mesa-style

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

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

bounded buffer producer/consumer

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    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

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);
```

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);
```

monitor exercise: barrier

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

void BarrierWait(BarrierInfo *b) {
    pthread_mutex_lock(&b->lock);
    ++b->number_reached;
    if (b->number_reached == b->total_threads) {
        pthread_cond_broadcast(&b->cv);
    } else {
        while (b->number_reached < b->total_threads)
            pthread_cond_wait(&b->cv, &b->lock);
    }
    pthread_mutex_unlock(&b->lock);
}
```

extra exercises

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);
```

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
		enqueue	
wait for lock		size $= 1$? signal	
		unlock	gets lock
			enqueue
			size $\neq 1$: don't signal
			unlock
gets lock			
dequeue			

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;
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;
}
```

monitor exercise: solution (1)

(one of many possible solutions)

Assuming ConsumeTwo **replaces** Consume:

```
Produce() {
  pthread_mutex_lock(&lock);
  buffer.enqueue(item);
  if (buffer.size() > 1) { pthread_cond_signal(&data_ready); }
  pthread_mutex_unlock(&lock);
}
ConsumeTwo() {
    pthread_mutex_lock(&lock);
    while (buffer.size() < 2) { pthread_cond_wait(&data_ready, &lock); }
    item1 = buffer.dequeue(); item2 = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return Combine(item1, item2);
}
```

monitor exercise: solution (2)

(one of many possible solutions)

Assuming ConsumeTwo is **in addition to** Consume (using two CVs):

```
Produce() {
  pthread_mutex_lock(&lock);
  buffer.enqueue(item);
  pthread_cond_signal(&one_ready);
  if (buffer.size() > 1) { pthread_cond_signal(&two_ready); }
  pthread_mutex_unlock(&lock);
}
Consume() {
  pthread_mutex_lock(&lock);
  while (buffer.size() < 1) { pthread_cond_wait(&one_ready, &lock); }
  item = buffer.dequeue();
  pthread_mutex_unlock(&lock);
  return item;
}
ConsumeTwo() {
  pthread_mutex_lock(&lock);
  while (buffer.size() < 2) { pthread_cond_wait(&two_ready, &lock); }
  item1 = buffer.dequeue(); item2 = buffer.dequeue();
  pthread_mutex_unlock(&lock);
```

monitor exercise: slower solution

(one of many possible solutions)

Assuming ConsumeTwo is **in addition to** Consume (using one CV):

```
Produce() {
  pthread_mutex_lock(&lock);
  buffer.enqueue(item);
  // broadcast and not signal, b/c we might wakeup only ConsumeTwo() otherwise
  pthread_cond_broadcast(&data_ready);
  pthread_mutex_unlock(&lock);
}
Consume() {
  pthread_mutex_lock(&lock);
  while (buffer.size() < 1) { pthread_cond_wait(&data_ready, &lock); }
  item = buffer.dequeue();
  pthread_mutex_unlock(&lock);
  return item;
}
ConsumeTwo() {
  pthread_mutex_lock(&lock);
  while (buffer.size() < 2) { pthread_cond_wait(&data_ready, &lock); }
  item1 = buffer.dequeue(); item2 = buffer.dequeue();
  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;
}
```

monitor ordering exercise: solution

(one of many possible solutions)

```
struct Waiter {
    pthread_cond_t cv;
    bool done;
    T item;
}
Queue<Waiter*> waiters;

Produce(item) {
 pthread_mutex_lock(&lock);
 if (!waiters.empty()) {
   Waiter *waiter = waiters.dequeue();
   waiter->done = true;
   waiter->item = item;
   cond_signal(&waiter->cv);
   ++num_pending;
 } else {
   buffer.enqueue(item);
 }
 pthread_mutex_unlock(&lock);
```

```
Consume() {
  pthread_mutex_lock(&lock);
  if (buffer.empty()) {
    Waiter waiter;
    cond_init(&waiter.cv);
    waiter.done = false;
    waiters.enqueue(&waiter);
    while (!waiter.done)
      cond_wait(&waiter.cv, &lock);
    item = waiter.item;
  } else {
    item = buffer.dequeue();
  }
  pthread_mutex_unlock(&lock):
  return item;
}
```