last time

race conditions

- inconsistent results due to timing variation
- example: "lose" update due to reading value while update being computed

compilers, processors and memory access reordering

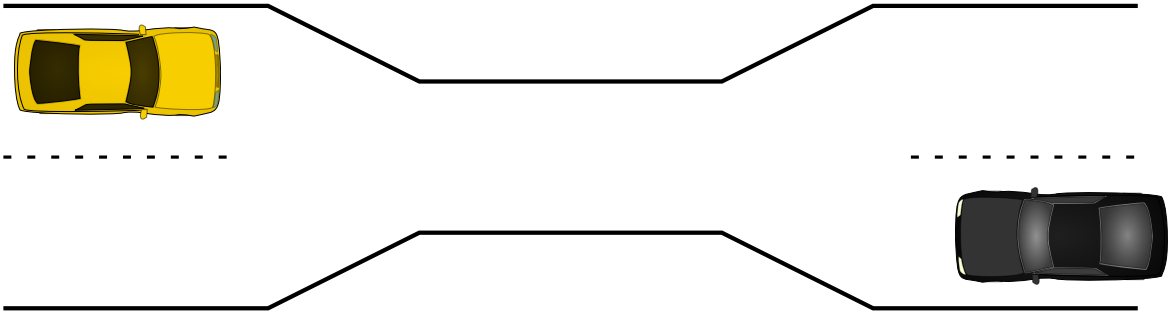
- order you write in C code [or even assembly] might not be order of accesses
- need special operations that gaurentee consistent order (e.g. locks)

locks for taking turns

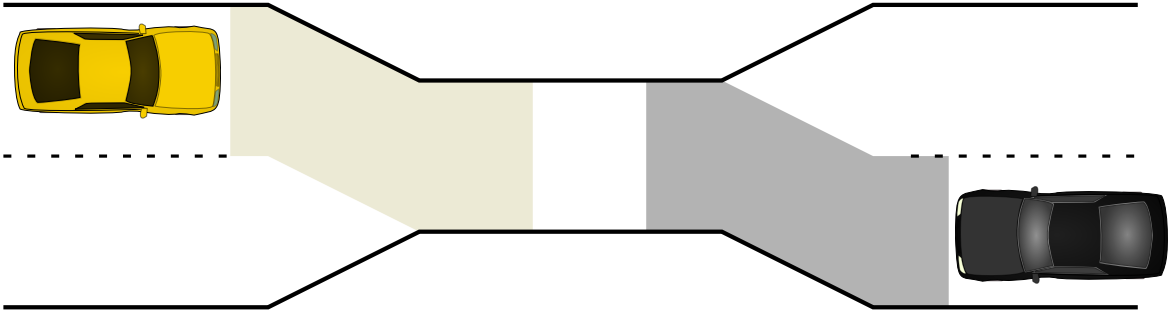
- one thread can "hold" lock at a time
- lock operation waits for lock to be available (unlock'd)
- requires threads agree to get lock before using shared thing

barriers — advance threads in lock-step

the one-way bridge



the one-way bridge



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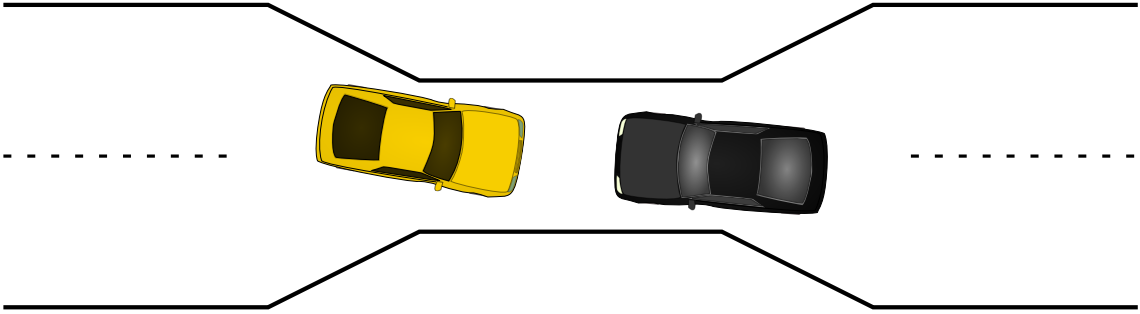

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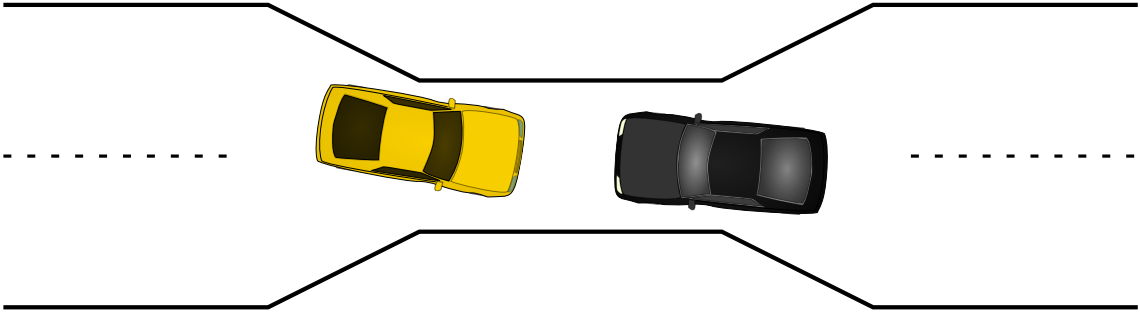


moving two files

```
struct Dir {
  mutex_t lock; HashMap entries;
};
void MoveFile(Dir *from_dir, Dir *to_dir, string filename) {
  mutex_lock(&from_dir->lock);
  mutex_lock(&to_dir->lock);

  Map_put(to_dir->entries, filename,
        Map_get(from_dir->entries, filename));
  Map_erase(from_dir->entries, filename);

  mutex_unlock(&to_dir->lock);
  mutex_unlock(&from_dir->lock);
}
```

Thread 1: `MoveFile(A, B, "foo")`
Thread 2: `MoveFile(B, A, "bar")`

moving two files: lucky timeline (1)

Thread 1	Thread 2
`MoveFile(A, B, "foo")`	`MoveFile(B, A, "bar")`
`lock(&A->lock);`	
`lock(&B->lock);`	
(do move)	
`unlock(&B->lock);`	
`unlock(&A->lock);`	
	`lock(&B->lock);`
	`lock(&A->lock);`
	(do move)
	`unlock(&B->lock);`
	`unlock(&A->lock);`

moving two files: lucky timeline (2)

Thread 1 `MoveFile(A, B, "foo")`	Thread 2 `MoveFile(B, A, "bar")`
`lock(&A->lock);`	
`lock(&B->lock);`	
	`lock(&B->lock…`
(do move)	(waiting for B lock)
`unlock(&B->lock);`	
	`lock(&B->lock);`
	`lock(&A->lock…`
`unlock(&A->lock);`	
	`lock(&A->lock);`
	(do move)
	`unlock(&A->lock);`
	`unlock(&B->lock);`

moving two files: unlucky timeline

Thread 1	Thread 2
`MoveFile(A, B, "foo")`	`MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`

moving two files: unlucky timeline

Thread 1 `MoveFile(A, B, "foo")`	Thread 2 `MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`
`lock(&B->lock…` stalled	
(waiting for lock on B)	`lock(&A->lock…` stalled
(waiting for lock on B)	(waiting for lock on A)

moving two files: unlucky timeline

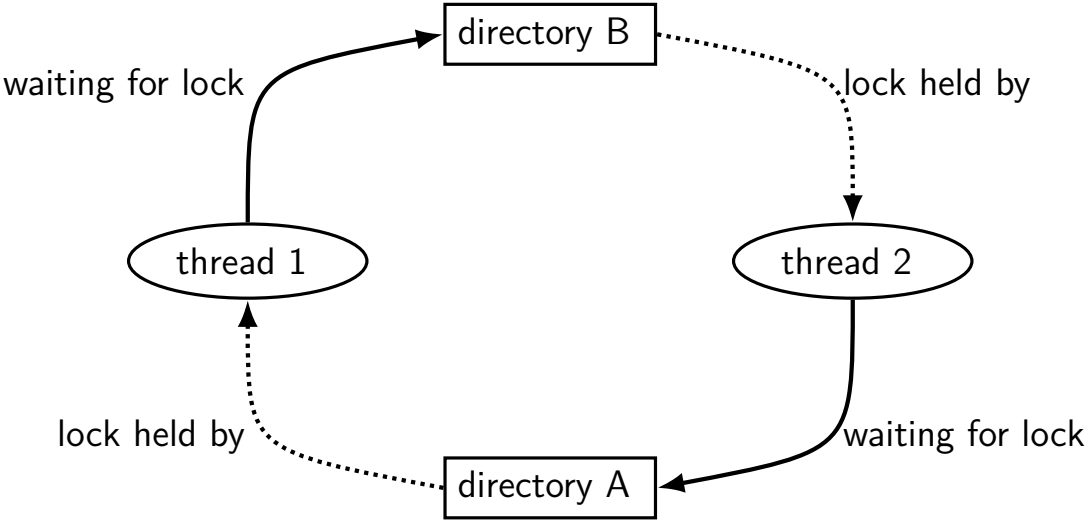
Thread 1 `MoveFile(A, B, "foo")`	Thread 2 `MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`
`lock(&B->lock…` stalled	
(waiting for lock on B)	`lock(&A->lock…` stalled
(waiting for lock on B)	(waiting for lock on A)
~~(do move)~~ unreachable	~~(do move)~~ unreachable
~~`unlock(&B->lock);`~~ unreachable	~~`unlock(&A->lock);`~~ unreachable
~~`unlock(&A->lock);`~~ unreachable	~~`unlock(&B->lock);`~~ unreachable

moving two files: unlucky timeline

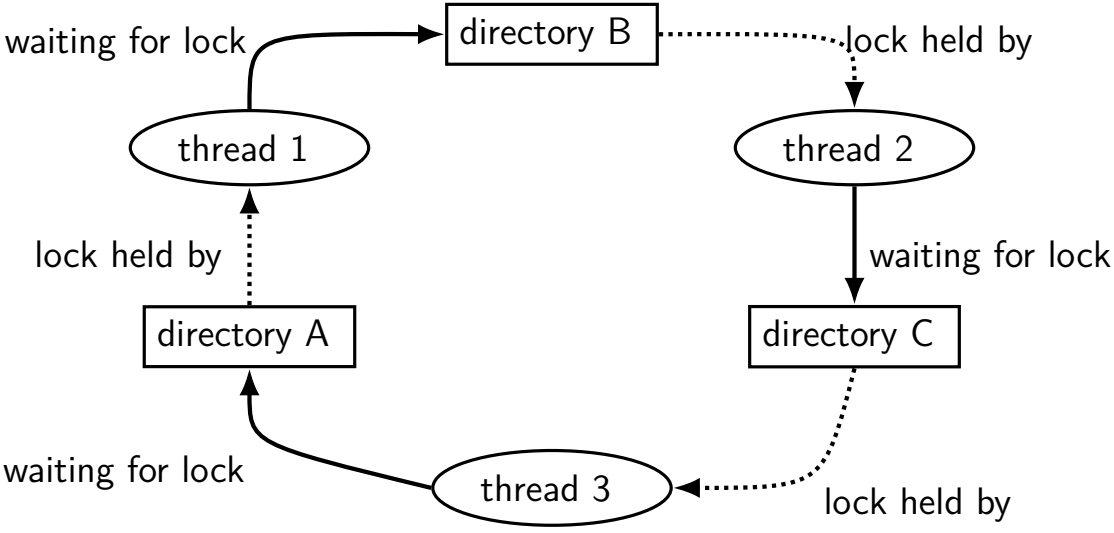
Thread 1 `MoveFile(A, B, "foo")`	Thread 2 `MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`
`lock(&B->lock…` stalled	
(waiting for lock on B)	`lock(&A->lock…` stalled
(waiting for lock on B)	(waiting for lock on A)
~~(do move)~~ unreachable	~~(do move)~~ unreachable
~~`unlock(&B->lock);`~~ unreachable	~~`unlock(&A->lock);`~~ unreachable
~~`unlock(&A->lock);`~~ unreachable	~~`unlock(&B->lock);`~~ unreachable

Thread 1 holds A lock, waiting for Thread 2 to release B lock
Thread 2 holds B lock, waiting for Thread 1 to release A lock

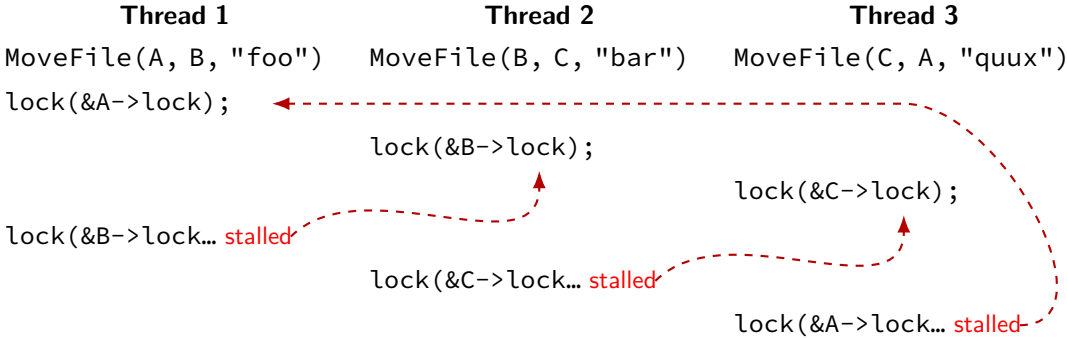
moving two files: dependencies



moving three files: dependencies



moving three files: unlucky timeline



deadlock with free space

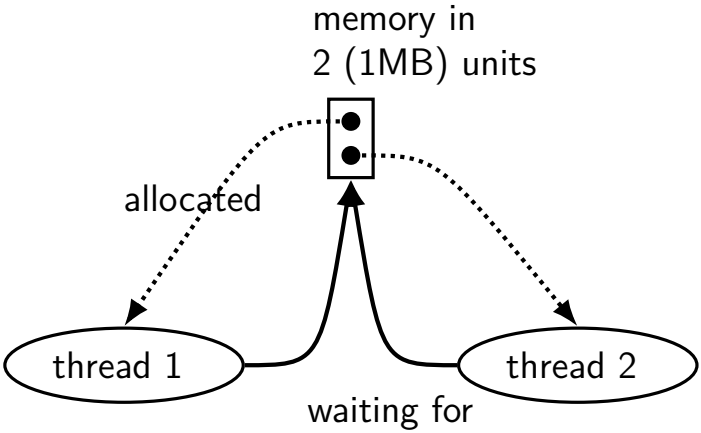
Thread 1	Thread 2
`AllocateOrWaitFor(1 MB)`	`AllocateOrWaitFor(1 MB)`
`AllocateOrWaitFor(1 MB)`	`AllocateOrWaitFor(1 MB)`
`(do calculation)`	`(do calculation)`
`Free(1 MB)`	`Free(1 MB)`
`Free(1 MB)`	`Free(1 MB)`

2 MB of space — deadlock possible with unlucky order

deadlock with free space (unlucky case)

Thread 1	Thread 2
`AllocateOrWaitFor(1 MB)`	
	`AllocateOrWaitFor(1 MB)`
`AllocateOrWaitFor(1 MB…` stalled	
	`AllocateOrWaitFor(1 MB…` stalled

free space: dependency graph



deadlock with free space (lucky case)

Thread 1

```
AllocateOrWaitFor(1 MB)
AllocateOrWaitFor(1 MB)
(do calculation)
Free(1 MB);
Free(1 MB);
```

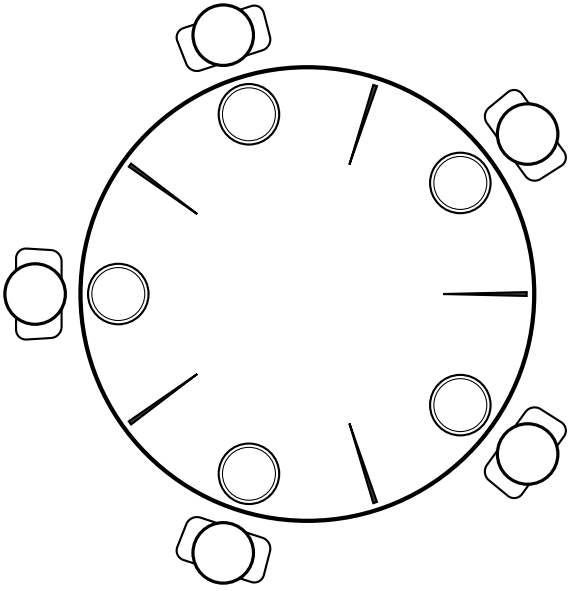
Thread 2

```
AllocateOrWaitFor(1 MB)
AllocateOrWaitFor(1 MB)
(do calculation)
Free(1 MB);
Free(1 MB);
```

lab next week

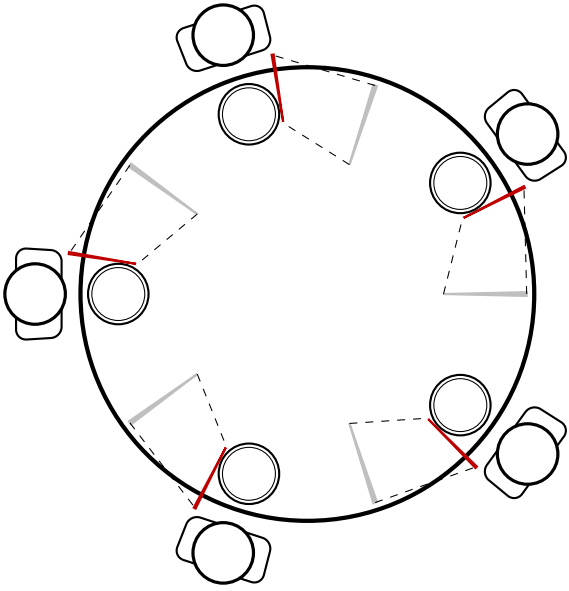
applying solutions to deadlock to classic *dining philosphers* problem

dining philosophers



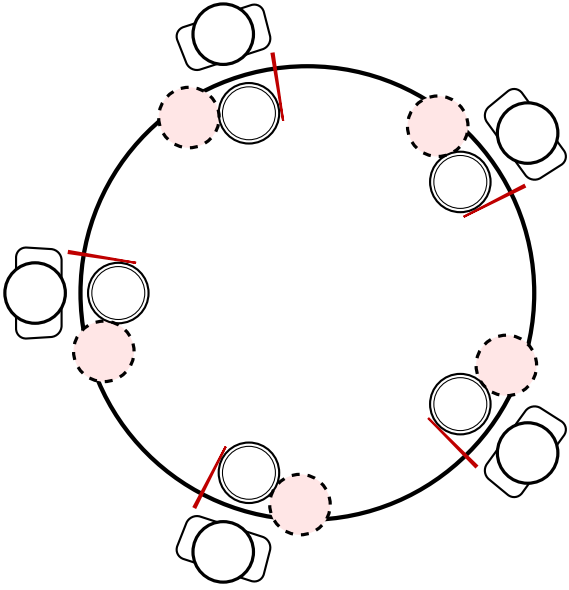
five philosophers either think or eat
to eat:
grab chopstick on left, then
grba chopstick on right, then
then eat, then
return chopsticks

dining philosophers



everyone eats at the same time?
grab left chopstick, then...

dining philosophers



everyone eats at the same time?
grab left chopstick, then
try to grab right chopstick, ...
we're at an impasse

deadlock

deadlock — circular waiting for resources

resource = something needed by a thread to do work

- locks
- CPU time
- disk space
- memory
- ...

often non-deterministic in practice

most common example: when acquiring multiple locks

deadlock

deadlock — circular waiting for resources

resource = something needed by a thread to do work

- locks
- CPU time
- disk space
- memory
- ...

often non-deterministic in practice

most common example: when acquiring multiple locks

deadlock requirements

mutual exclusion

one thread at a time can use a resource

hold and wait

thread holding a resources waits to acquire *another* resource

no preemption of resources

resources are only released voluntarily
thread trying to acquire resources can't 'steal'

circular wait

there exists a set $\{T_1, \ldots, T_n\}$ of waiting threads such that

T_1 is waiting for a resource held by T_2
T_2 is waiting for a resource held by T_3
...
T_n is waiting for a resource held by T_1

how is deadlock possible?

Given list: A, B, C, D, E

```
RemoveNode(LinkedListNode *node) {
    pthread_mutex_lock(&node->lock);
    pthread_mutex_lock(&node->prev->lock);
    pthread_mutex_lock(&node->next->lock);
    node->next->prev = node->prev; node->prev->next = node->next;
    pthread_mutex_unlock(&node->next->lock); pthread_mutex_unlock(&node->p
    pthread_mutex_unlock(&node->lock);
}
```

Which of these (all run in parallel) can deadlock?

A. RemoveNode(B) and RemoveNode(C)
B. RemoveNode(B) and RemoveNode(D)
C. RemoveNode(B) and RemoveNode(C) and RemoveNode(D)
D. A and C
E. B and C
F. all of the above
G. none of the above

deadlock prevention techniques

infinite resources or at least enough that never run out	no *mutual exclusion*
no shared resources	no *mutual exclusion*
no waiting "busy signal" — abort and (maybe) retry revoke/preempt resources	no *hold and wait*/ *preemption*
acquire resources in **consistent order**	no *circular wait*
request **all resources at once**	no *hold and wait*

deadlock prevention techniques

infinite resources
or at least enough that never run out — no *mutual exclusion*

no shared resources — no *mutual exclusion*

no waiting
"busy signal" — abort and (maybe) retry
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acquire resources in **consistent order** — no *circular wait*

request **all resources at once** — no *hold and wait*

deadlock prevention techniques

infinite resources

or at least enough that never run out

no *mutual exclusion*

memory allocation: malloc() fails rather than waiting (no deadlock)
locks: `pthread_mutex_trylock` fails rather than waiting
problem: retry how many times? no bound on number of tries needed
...

exclusion

no waiting

"busy signal" — abort and (maybe) retry

revoke/preempt resources

no *hold and wait*/ *preemption*

acquire resources in **consistent order**

no *circular wait*

request **all resources at once**

no *hold and wait*

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deadlock prevention techniques

infinite resources
or at least enough that never run out — no *mutual exclusion*

no shared resources — no *mutual exclusion*

requires some way to undo partial changes to avoid errors
common approach for databases
...

no waiti
"busy signal" — abort and (maybe) retry
revoke/preempt resources — no *hold and wait*/ *preemption*

acquire resources in **consistent order** — no *circular wait*

request **all resources at once** — no *hold and wait*

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acquire resources in **consistent order** — no *circular wait*

request **all resources at once** — no *hold and wait*

acquiring locks in consistent order (1)

```
MoveFile(Dir* from_dir, Dir* to_dir, string filename) {
  if (from_dir->path < to_dir->path) {
    lock(&from_dir->lock);
    lock(&to_dir->lock);
  } else {
    lock(&to_dir->lock);
    lock(&from_dir->lock);
  }
  ...
}
```

acquiring locks in consistent order (1)

```
MoveFile(Dir* from_dir, Dir* to_dir, string filename) {
  if (from_dir->path < to_dir->path) {
    lock(&from_dir->lock);
    lock(&to_dir->lock);
  } else {
    lock(&to_dir->lock);
    lock(&from_dir->lock);
  }
  ...
}
```

any ordering will do
e.g. compare pointers

acquiring locks in consistent order (2)

often by convention, e.g. Linux kernel comments:

```
/*
 * ...
 * Lock order:
 *      contex.ldt_usr_sem
 *        mmap_sem
 *          context.lock
 */
```

```
/*
 * ...
 * Lock order:
 *   1. slab_mutex (Global Mutex)
 *   2. node->list_lock
 *   3. slab_lock(page) (Only on some arches and for debugging)
 * ...
 */
```

deadlock prevention techniques

infinite resources
or at least enough that never run out — no *mutual exclusion*

no shared resources — no *mutual exclusion*

no waiting
"busy signal" — abort and (maybe) retry
revoke/preempt resources — no *hold and wait*/*preemption*

acquire resources in **consistent order** — no *circular wait*

request **all resources at once** — no *hold and wait*

monitors/condition variables

locks for mutual exclusion

condition variables for waiting for event

- represents **list of waiting threads**
- operations: wait (for event); signal/broadcast (that event happened)

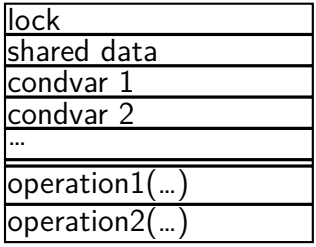
related data structures

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

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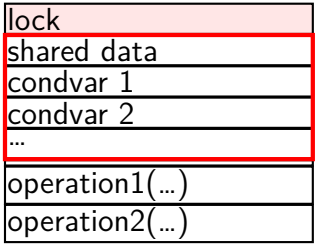
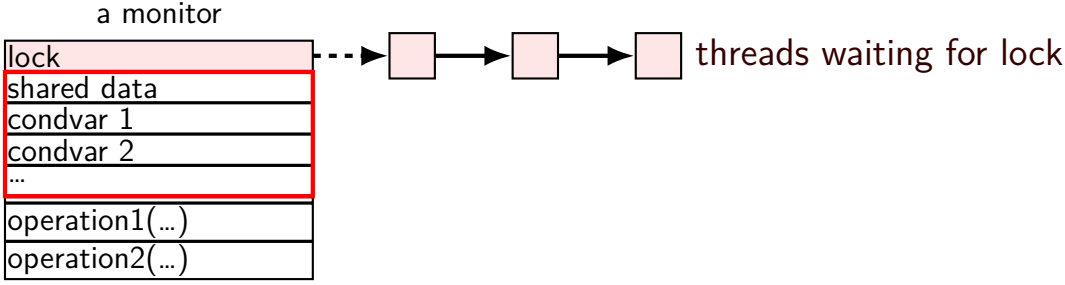
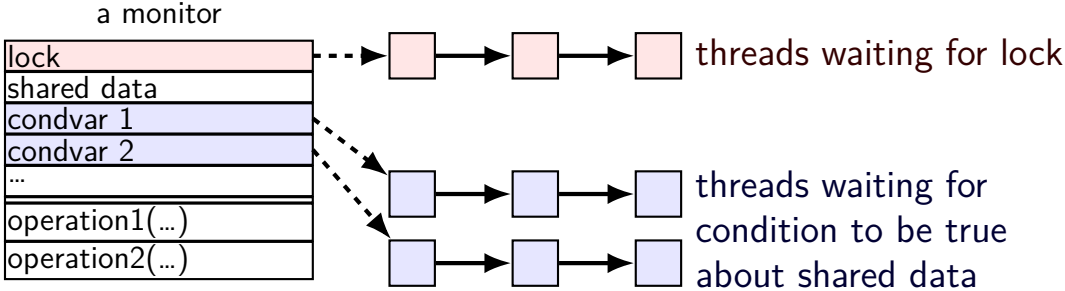


lock must be acquired
before accessing
any part of monitor's stuff

monitor idea



monitor idea



condvar operations

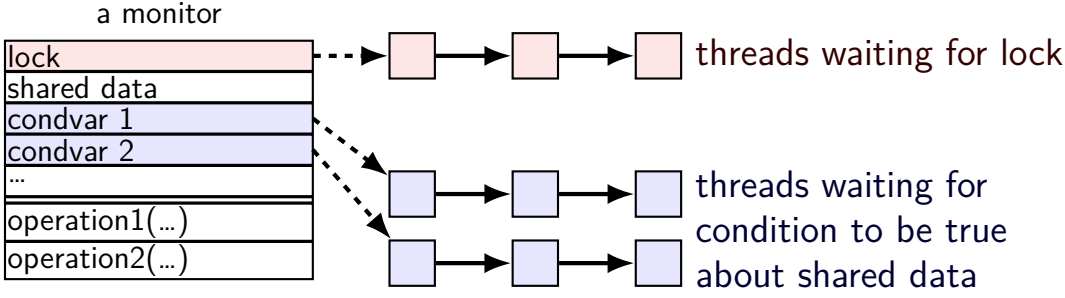
condvar operations:

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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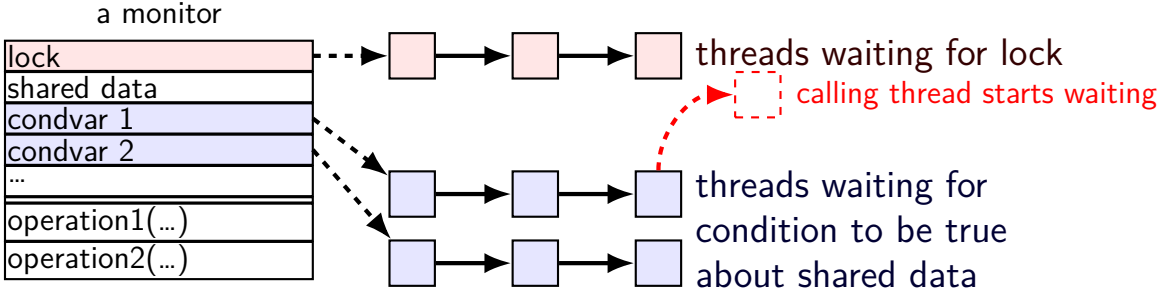

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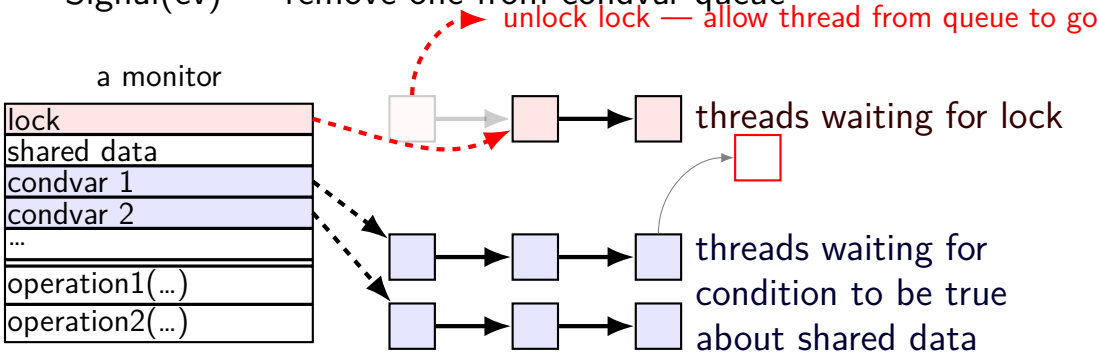

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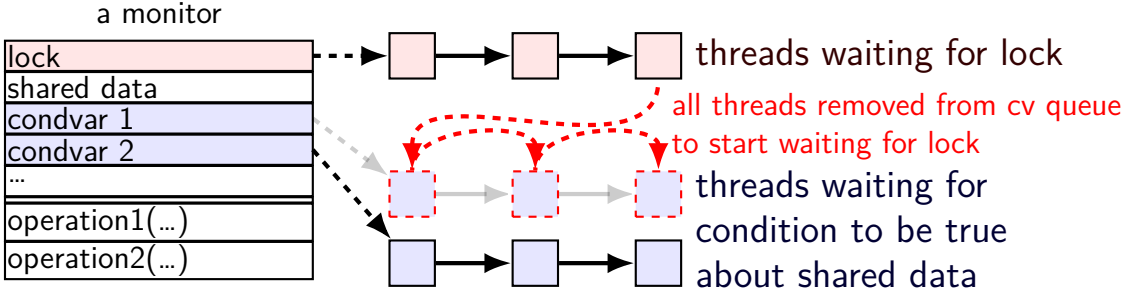

condvar operations

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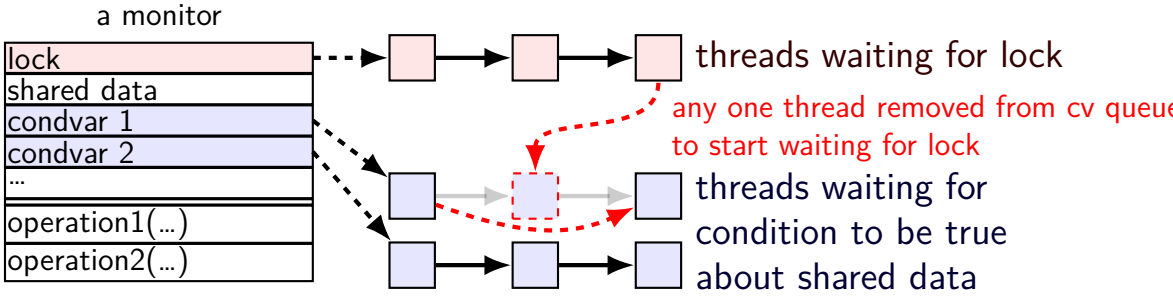

pthread cv usage

```
// 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

```
// MISSING: init calls, etc.
pthread_mutex_t lock;
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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);
}
```

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() {
  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);
}
```

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

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}

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)
`mutex_unlock(&lock)`	

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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    }
    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

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    while (buffer.empty()) {
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    }
    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

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

wake one Consume thread *if any are waiting*

unbounded buffer producer/consumer

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

Thread 1	Thread 2
Produce()	
…lock	
…enqueue	
…signal	
…unlock	
	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

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

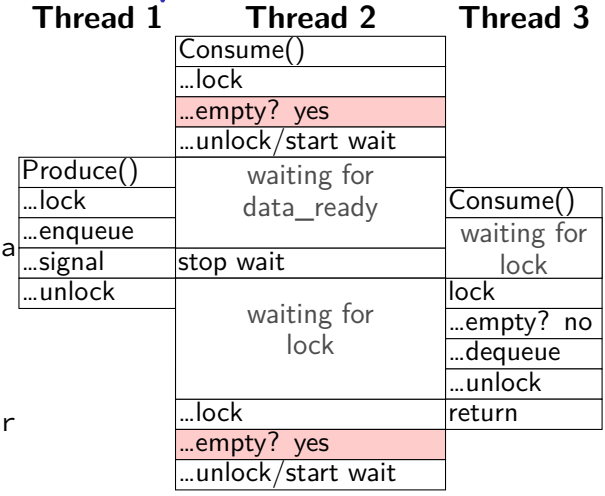
Thread 1	Thread 2
	Consume()
	…lock
	…empty? yes
	…unlock/start wait
Produce()	waiting for data_ready
…lock	
…enqueue	
…signal	stop wait
…unlock	lock
	…empty? no
	…dequeue
	…unlock
	return

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;
```

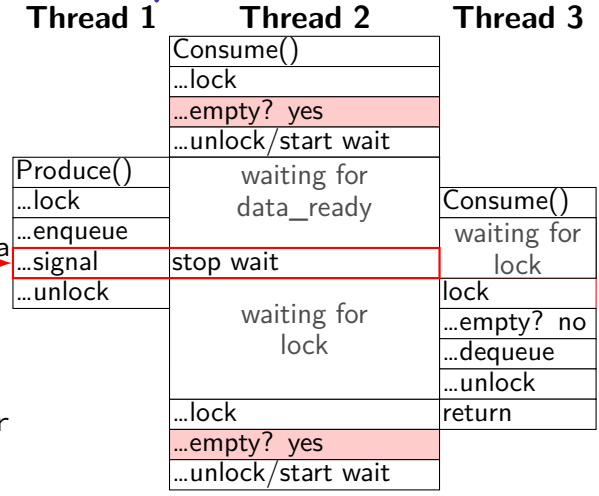
in pthreads: signalled thread not gaurenteed to hold lock next

alternate design: signalled thread gets lock next

called "Hoare scheduling"

not done by pthreads, Java, ...

```
    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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pthread_mutex_t lock;
pthread_cond_t data_ready; pthread_cond_t space_ready;
BoundedQueue buffer;
Produce(item) {
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    buffer.enqueue(item);
    pthread_cond_signal(&data_ready);
    pthread_mutex_unlock(&lock);
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    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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pthread_mutex_t lock;
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    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

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);
}
```

backup slides