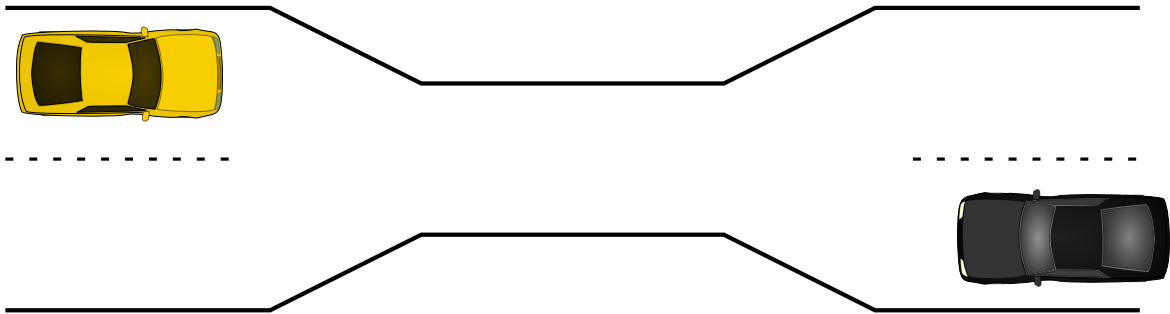
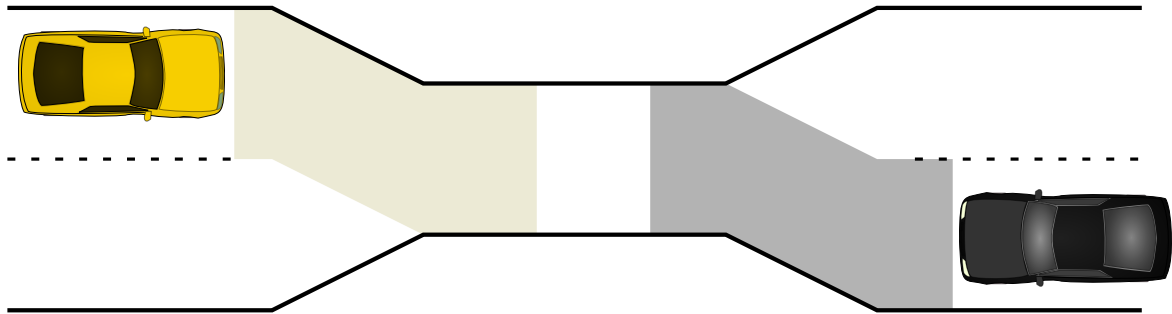


deadlock

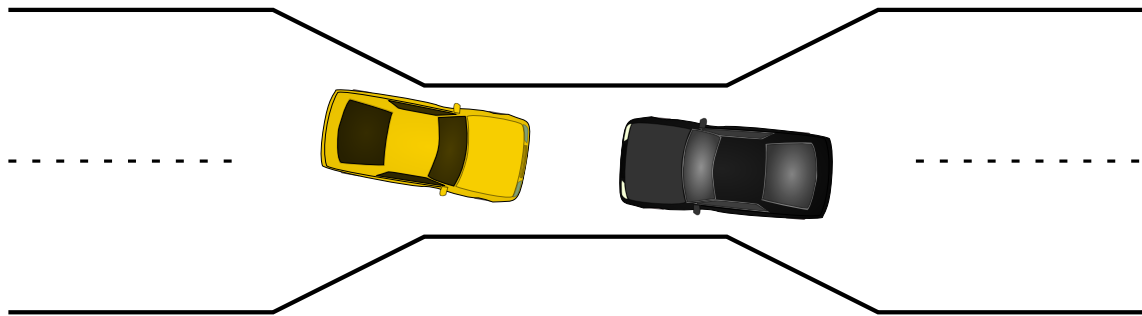
the one-way bridge



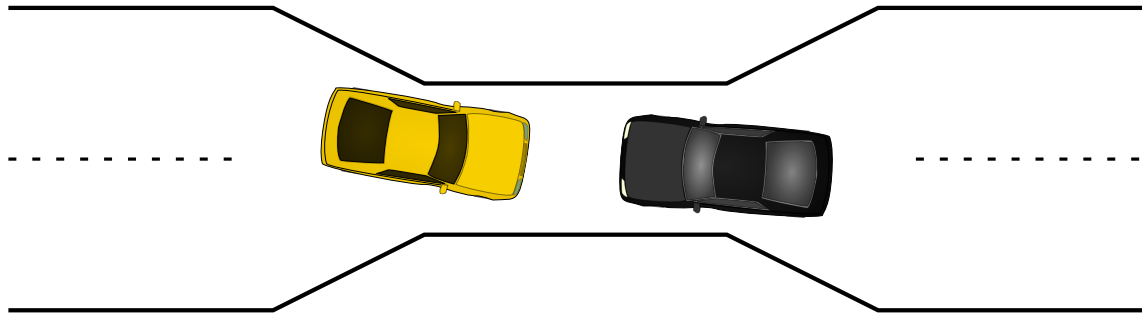
the one-way bridge



the one-way bridge



the one-way bridge



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

MoveFile(A, B, "foo")

lock(&A->lock);

lock(&B->lock);

(do move)

unlock(&B->lock);

unlock(&A->lock);

Thread 2

MoveFile(B, A, "bar")

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")

lock(&A->lock);

lock(&B->lock);

(do move)

unlock(&B->lock);

unlock(&A->lock);

Thread 2

MoveFile(B, A, "bar")

lock(&B->lock...

(waiting for B lock)

lock(&B->lock);

lock(&A->lock...

lock(&A->lock);

(do move)

unlock(&A->lock);

unlock(&B->lock);

moving two files: unlucky timeline

Thread 1

```
MoveFile(A, B, "foo")
```

```
lock(&A->lock);
```

Thread 2

```
MoveFile(B, A, "bar")
```

```
lock(&B->lock);
```

moving two files: unlucky timeline

Thread 1

```
MoveFile(A, B, "foo")
```

```
lock(&A->lock);
```

```
lock(&B->lock... stalled
```

```
(waiting for lock on B)
```

```
(waiting for lock on B)
```

Thread 2

```
MoveFile(B, A, "bar")
```

```
lock(&B->lock);
```

```
lock(&A->lock... stalled
```

```
(waiting for lock on A)
```

moving two files: unlucky timeline

Thread 1

```
MoveFile(A, B, "foo")
```

```
lock(&A->lock);
```

```
lock(&B->lock... stalled
```

```
(waiting for lock on B)
```

```
(waiting for lock on B)
```

```
(do move) unreachable
```

```
unlock(&B->lock); unreachable
```

```
unlock(&A->lock); unreachable
```

Thread 2

```
MoveFile(B, A, "bar")
```

```
lock(&B->lock);
```

```
lock(&A->lock... stalled
```

```
(waiting for lock on A)
```

```
(do move) unreachable
```

```
unlock(&A->lock); unreachable
```

```
unlock(&B->lock); unreachable
```

moving two files: unlucky timeline

Thread 1

```
MoveFile(A, B, "foo")
```

```
lock(&A->lock);
```

```
lock(&B->lock... stalled
```

```
(waiting for lock on B)
```

```
(waiting for lock on B)
```

```
(do move) unreachable
```

```
unlock(&B->lock); unreachable
```

```
unlock(&A->lock); unreachable
```

Thread 2

```
MoveFile(B, A, "bar")
```

```
lock(&B->lock);
```

```
lock(&A->lock... stalled
```

```
(waiting for lock on A)
```

```
(do move) unreachable
```

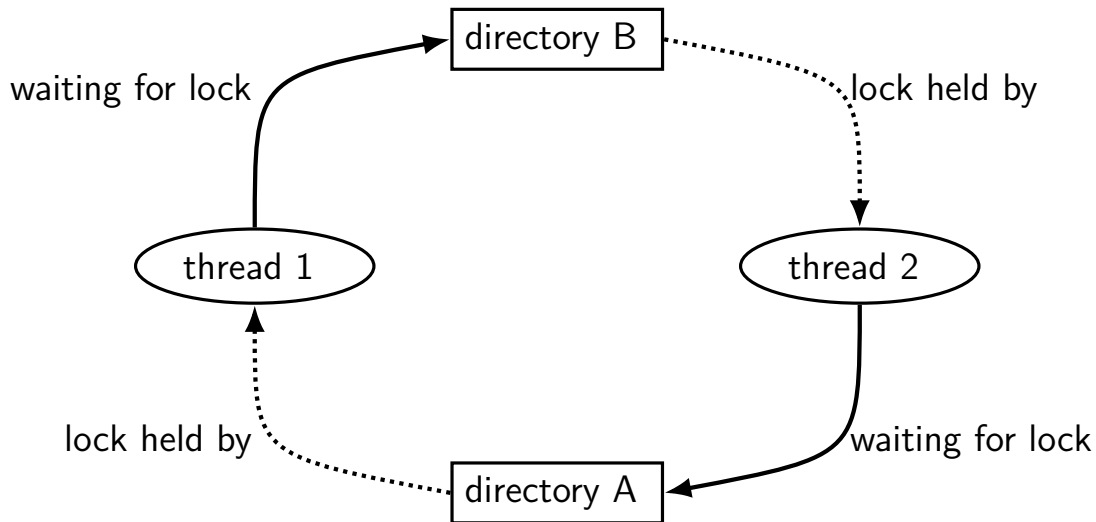
```
unlock(&A->lock); unreachable
```

```
unlock(&B->lock); unreachable
```

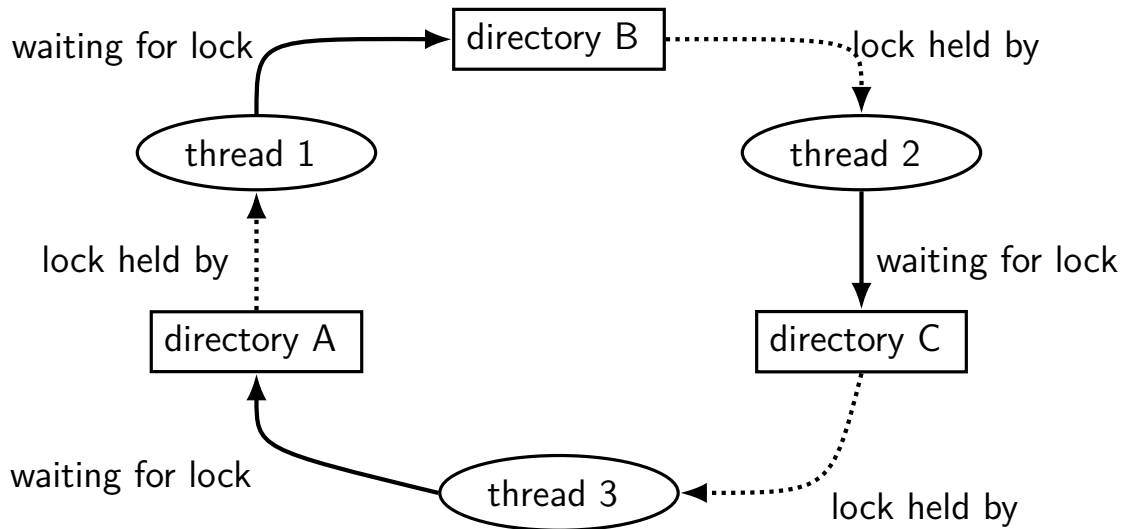
Thread 1 holds A lock, waiting for Thread 2 to release B lock

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

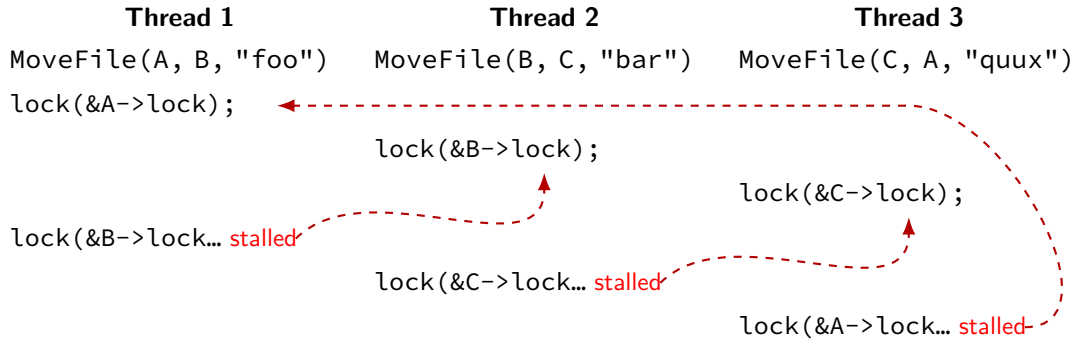
moving two files: dependencies



moving three files: dependencies



moving three files: unlucky timeline



deadlock with free space

Thread 1

```
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)
```

2 MB of space — deadlock possible with unlucky order

deadlock with free space (unlucky case)

Thread 1

AllocateOrWaitFor(1 MB)

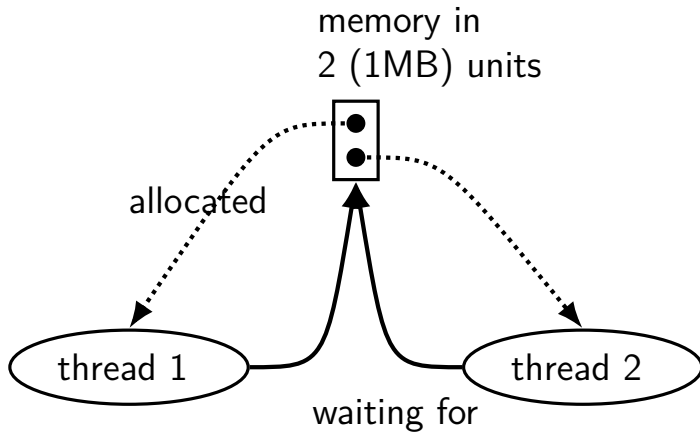
AllocateOrWaitFor(1 MB... stalled

Thread 2

AllocateOrWaitFor(1 MB)

AllocateOrWaitFor(1 MB... stalled

free space: dependency graph



deadlock with free space (lucky case)

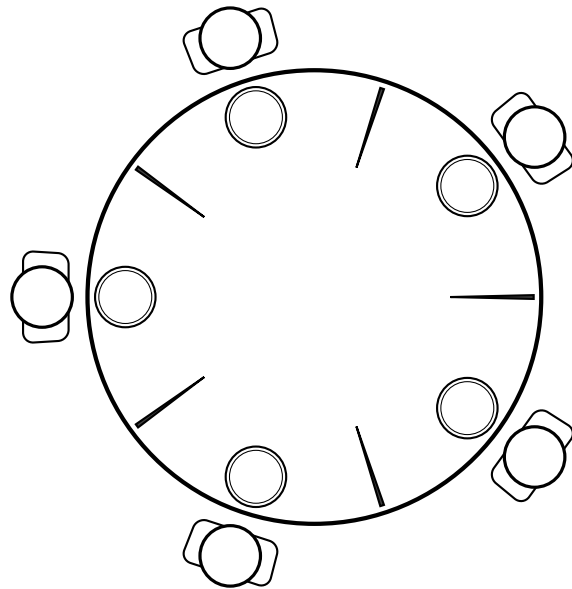
Thread 1

```
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);
```

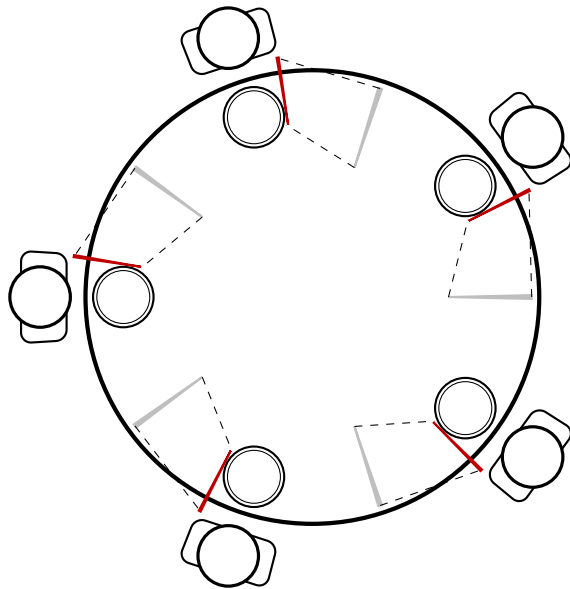
dining philosophers



five philosophers either think or eat
to eat:

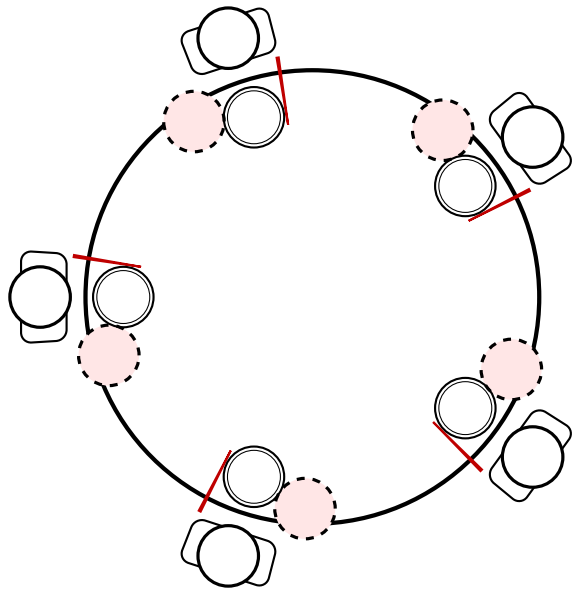
grab chopstick on left, then
grab chopstick on right, then
eat, then
return chopsticks

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 versus starvation

starvation: one+ unlucky (no progress), one+ lucky (yes progress)

example: low priority threads versus high-priority threads

deadlock: no one involved in deadlock makes progress

deadlock versus starvation

starvation: one+ unlucky (no progress), one+ lucky (yes progress)

example: low priority threads versus high-priority threads

deadlock: no one involved in deadlock makes progress

starvation: once starvation happens, taking turns will resolve

low priority thread just needed a chance...

deadlock: once it happens, taking turns won't fix

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 $\{T_1, \dots, T_n\}$ 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->prev->lock);  
    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

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no *mutual exclusion*

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revoke/preempt resources

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acquire resources in **consistent order**

no *circular wait*

request **all resources at once**

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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

...

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

stealing locks???

how do we make stealing locks possible

unclean: just kill the thread

problem: inconsistent state?

clean: have code to undo partial operation

some databases do this

won't go into detail in this class

revokable locks?

```
try {  
    AcquireLock();  
    use shared data  
} catch (LockRevokedException le) {  
    undo operation hopefully?  
} finally {  
    ReleaseLock();  
}
```

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*

abort and retry limits?

abort-and-retry

pthread's mutexes:

`pthread_mutex_trylock`

`pthread_mutex_timedlock`

how many times will you retry?

moving two files: abort-and-retry

```
struct Dir { mutex_t lock; HashMap entries; };  
void MoveFile(Dir *from_dir, Dir *to_dir, string filename) {  
    while (true) {  
        mutex_lock(&from_dir->lock);  
        if (mutex_trylock(&to_dir->lock) == LOCKED) break;  
        mutex_unlock(&from_dir->lock);  
    }
```

```
    Map_put(to_dir->entries, filename, Map_get(from_dir->entries, filename));  
    from_dir->entries.erase(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: lots of bad luck?

Thread 1

MoveFile(A, B, "foo")

lock(&A->lock) → LOCKED

trylock(&B->lock) → FAILED

unlock(&A->lock)

lock(&A->lock) → LOCKED

trylock(&B->lock) → FAILED

unlock(&A->lock)

Thread 2

MoveFile(B, A, "bar")

lock(&B->lock) → LOCKED

trylock(&A->lock) → FAILED

unlock(&B->lock)

lock(&B->lock) → LOCKED

trylock(&A->lock) → FAILED

unlock(&B->lock)

livelock

livelock: keep aborting and retrying without end

like deadlock — no one's making progress
potentially forever

unlike deadlock — threads are not waiting

preventing livelock

make schedule random — e.g. random waiting after abort

make threads run one-at-a-time if lots of aborting

other ideas?

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 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
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*

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

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 about 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

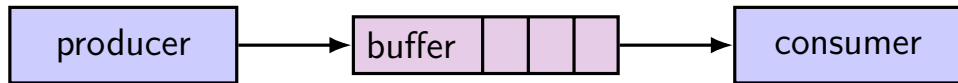
on end transaction:

- acquire locks on everything

- make sure values read haven't been changed since read

if they have changed, just retry transaction

example: producer/consumer

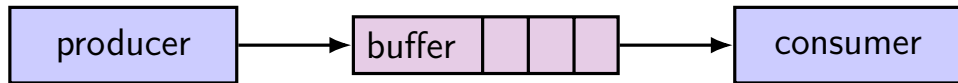


shared buffer (queue) of fixed size

one or more producers inserts into queue

one or more consumers removes from queue

example: producer/consumer



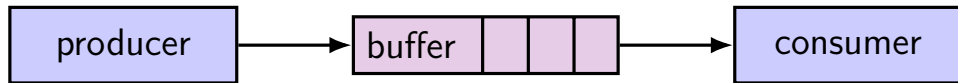
shared buffer (queue) of fixed size

- one or more producers inserts into queue

- one or more consumers removes from queue

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

one or more consumers removes from queue

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)

threads: build your own: provides you locks + condition variables

monitor idea

a monitor

lock
shared data
condvar 1
condvar 2
...
operation1(...)
operation2(...)

monitor idea

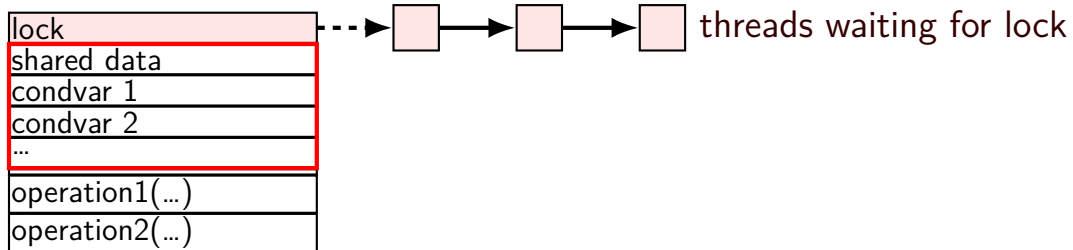
a monitor

lock
shared data
condvar 1
condvar 2
...
operation1(...)
operation2(...)

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

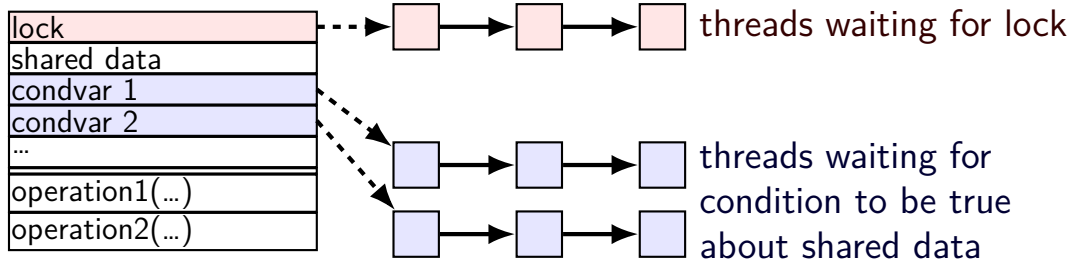
monitor idea

a monitor



monitor idea

a monitor



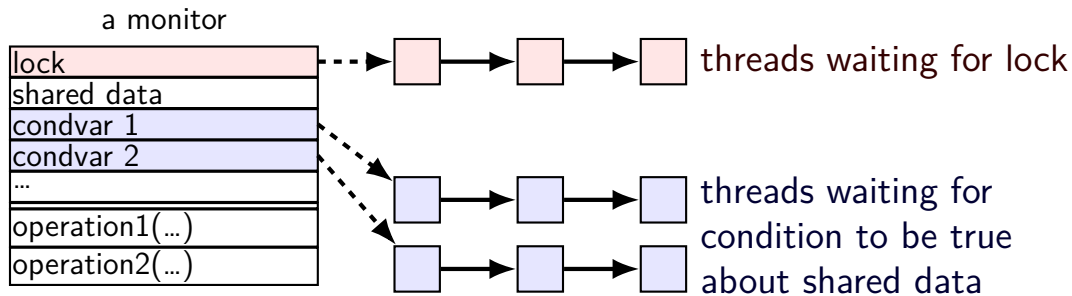
condvar operations

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



condvar operations

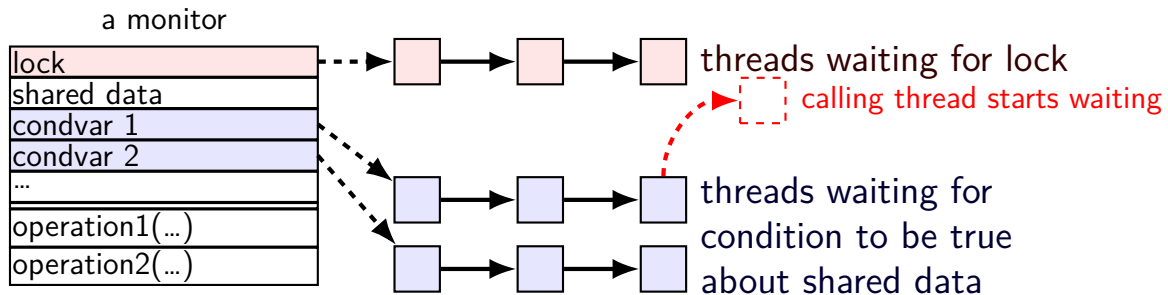
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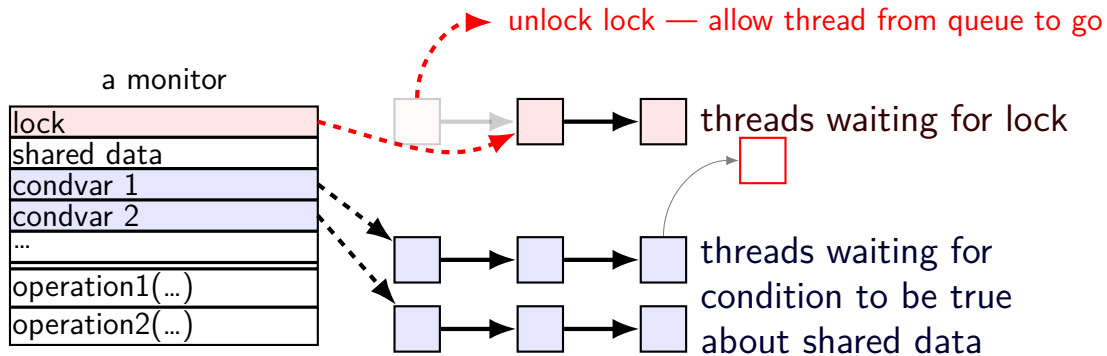
condvar operations

condvar operations:

Wait(cv, lock) — **unlock** lock, add current thread to cv queue
...and **reacquire** lock before returning

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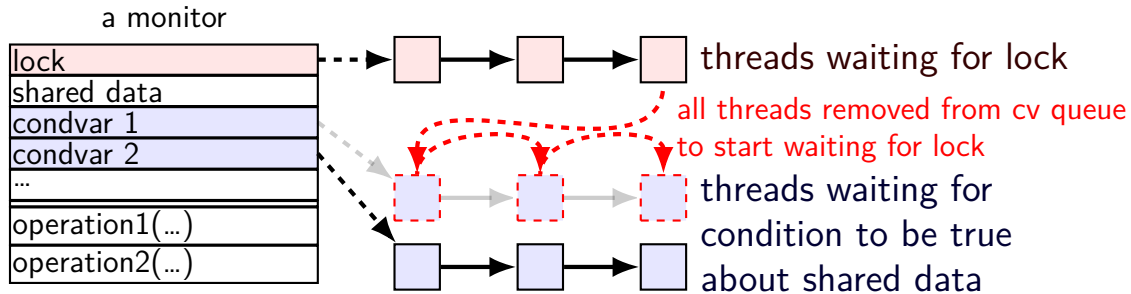
condvar operations

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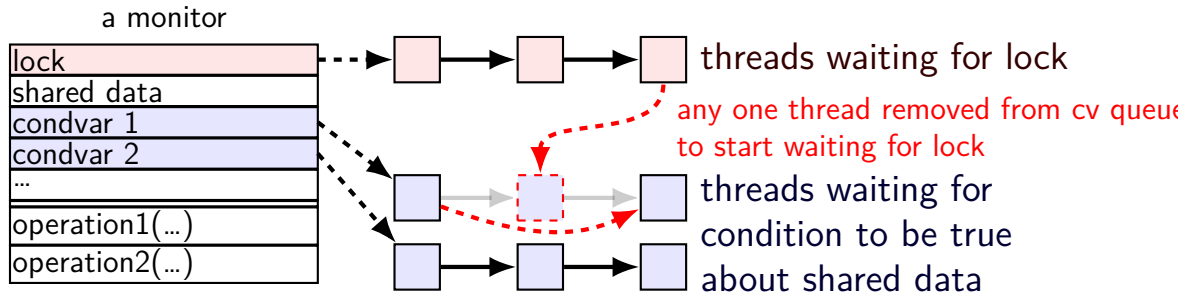
condvar operations

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



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;

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);

}

acquire lock before
reading or writing finished

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;
```

```
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);  
}
```

check whether we need to wait at all
(why a loop? we'll explain later)

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

pthread cv usage

// MISSING: init calls, etc.

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```

```
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;
```

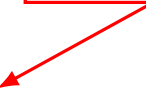
```
bool finished;    // data, only accessed with after acquiring lock
```

```
pthread_cond_t finished_cv; // to wait for 'finished' to be true
```

```
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
<code>mutex_lock(&lock)</code> (thread has lock)	
	<code>mutex_lock(&lock)</code> (start waiting for lock)
<code>while (!finished) ...</code> <code>cond_wait(&finished_cv, &lock);</code> (start waiting for cv)	(done waiting for lock)
	<code>finished = true</code> <code>cond_broadcast(&finished_cv)</code>
(done waiting for cv) (start waiting for lock)	
	<code>mutex_unlock(&lock)</code>
(done waiting for lock) <code>while (!finished) ...</code> (finished now true, so return) <code>mutex_unlock(&lock)</code>	

WaitForFinish timeline 2

WaitForFinish thread	Finish thread
	<code>mutex_lock(&lock)</code> <code>finished = true</code> <code>cond_broadcast(&finished_cv)</code> <code>mutex_unlock(&lock)</code>
<code>mutex_lock(&lock)</code> <code>while (!finished) ...</code> (finished now true, so return) <code>mutex_unlock(&lock)</code>	

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;  
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
simultaneously 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;  
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);  
}
```

wake one Consume thread
if any are waiting

```
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;  
}
```

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, &lock);  
    }  
    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_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? yes
...unlock/start wait

Thread 3

Consume()

waiting for lock
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;
```

in pthreads: signalled thread not
guaranteed to hold lock next

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

```
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? yes
...unlock/start wait
waiting for data_ready
stop wait
waiting for lock
...lock
...empty? yes
...unlock/start wait
```

Thread 3

```
Consume()
waiting for lock
lock
...empty? no
...dequeue
...unlock
return
```

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

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;
}
```

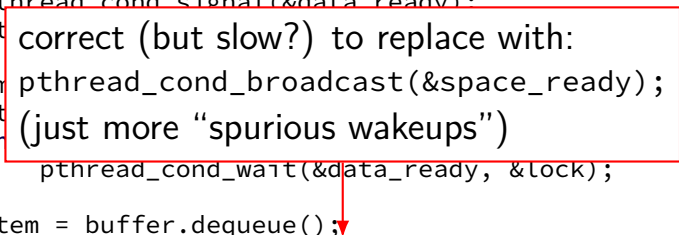
bounded buffer producer/consumer

```
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;
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);
}
Consume() {
    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:
(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_finished;
```

```
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. pthread_cond_signal(&both_finished_cv)
- B. pthread_cond_broadcast(&both_finished_cv)
- C. if (finished[1-index])
pthread_cond_signal(&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

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 decrement 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 operation 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

3

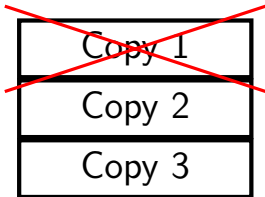
counting resources: reserving books

suppose tracking copies of same library book

non-negative integer count = # how many books used?

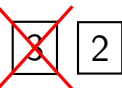
up = give back book; down = take book

taken out



Copy 1
Copy 2
Copy 3

free copies



after calling down to reserve

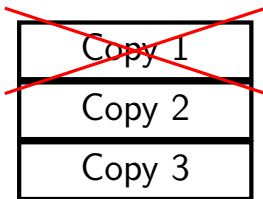
counting resources: reserving books

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 2

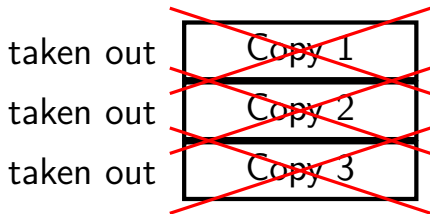
after calling down to reserve

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



free copies 0

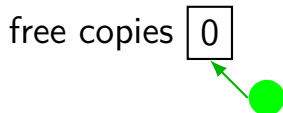
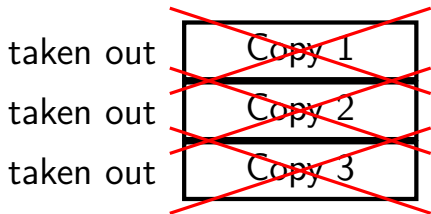
after calling down three times
to reserve all copies

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



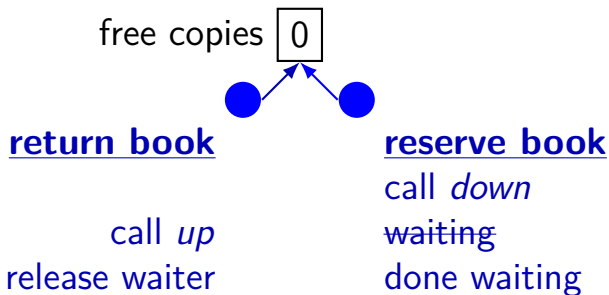
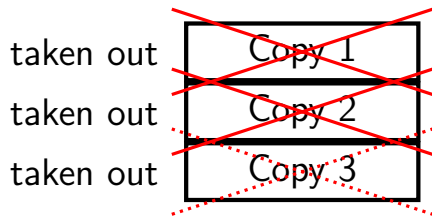
reserve book
call *down* again
start waiting...

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



implementing mutexes with semaphores

```
struct Mutex {  
    Semaphore s; /* with initial 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

```
#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);
...
Produce(item) {
    sem_wait(&empty_slots); // wait until free slot, reserve it
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Consume() {
    sem_wait(&full_slots); // wait until queued item, reserve it
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}
```

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sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);
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...
Produce(item) {
    sem_wait(&empty_slots); // wait until free slot, reserve it
    sem_wait(&mutex);
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}

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(&full_slots, ..., 0 /* # buffer slots initially used */);  
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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);  
}
```

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

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

producer/consumer pseudocode

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sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);  
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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);  
}
```

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

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

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() {  
    // BROKEN: WRONG ORDER  
    sem_wait(&mutex);  
    sem_wait(&empty_slots);  
  
    ...  
  
    sem_post(&mutex);  
}
```

```
Consumer() {  
    sem_wait(&full_slots);  
  
    // can't finish until  
    // Producer's sem_post(&mutex):  
    sem_wait(&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);  
}
```

```
Consume() {  
    sem_wait(&full_slots);  
    sem_wait(&mutex);  
    item = buffer.dequeue();  
    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

more data

reserve it

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!

backup slides

backup slides

using atomic exchange?

example: OS wants something done by whichever core tries first
does not want it started twice!

if two cores try at once, only one should do it

```
int global_flag = 0;
void DoThingIfFirstToTry() {
    int my_value = 1;
    AtomicExchange(&my_value, &global_flag);
    if (my_value == 0) {
        /* flag was zero before, so I was first!*/
        DoThing();
    } else {
        /* flag was already 1 when we exchanged */
        /* I was second, so some other core is handling it */
    }
}
```

recall: pthread mutex

```
#include <pthread.h>
```

```
pthread_mutex_t some_lock;
```

```
pthread_mutex_init(&some_lock, NULL);
```

```
// or: pthread_mutex_t some_lock = PTHREAD_MUTEX_INITIALIZER;
```

```
...
```

```
pthread_mutex_lock(&some_lock);
```

```
...
```

```
pthread_mutex_unlock(&some_lock);
```

```
pthread_mutex_destroy(&some_lock);
```

life homework even/odd

naive way has an operation that needs locking:

```
for (int time = 0; time < MAX_ITERATIONS; ++time) {  
    ... compute to_grid ...  
    swap(from_grid, to_grid);  
}
```

but this alternative needs less locking:

```
Grid grids[2];  
for (int time = 0; time < MAX_ITERATIONS; ++time) {  
    from_grid = &grids[time % 2];  
    to_grid = &grids[(time % 2) + 1];  
    ... compute to_grid ...  
}
```

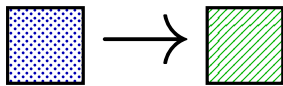
life homework even/odd

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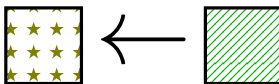
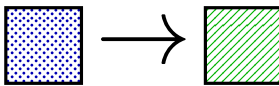
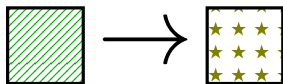
```
for (int time = 0; time < MAX_ITERATIONS; ++time) {  
    ... compute to_grid ...  
    swap(from_grid, to_grid);  
}
```

but this alternative needs less locking:

```
Grid grids[2];  
for (int time = 0; time < MAX_ITERATIONS; ++time) {  
    from_grid = &grids[time % 2];  
    to_grid = &grids[(time % 2) + 1];  
    ... compute to_grid ...  
}
```

swap



x86-64 spinlock with xchg

lock variable in shared memory: `the_lock`

if 1: someone has the lock; if 0: lock is free to take

acquire:

```
    movl $1, %eax           // %eax <- 1
    lock xchg %eax, the_lock // swap %eax and the_lock
                             // sets the_lock to 1 (taken)
                             // sets %eax to prior val. of the_lock
    test %eax, %eax         // if the_lock wasn't 0 before:
    jne acquire             //   try again
    ret
```

release:

```
    mfence                 // for memory order reasons
    movl $0, the_lock      // then, set the_lock to 0 (not taken)
    ret
```

x86-64 spinlock with xchg

lock variable in shared memory: the_lock

if 1: someone has the lock; if 0: lock is free to take

acquire:

```
movl $1, %eax           // %eax <- 1
lock xchg %eax, the_lock // swap %eax and the_lock
                        // sets the_lock to 1 (taken)
                        // sets %eax to prior val. of the_lock

test %eax, %eax          // if the_lock == 1, %eax == 1
jne acquire              // if not equal, jump to acquire
ret                      // set lock variable to 1 (taken)
                        // read old value
```

release:

```
mfence                  // for memory order reasons
movl $0, the_lock       // then, set the_lock to 0 (not taken)
ret
```

x86-64 spinlock with xchg

lock variable in shared memory: `the_lock`

if 1: someone has the lock; if 0: lock is free to take

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movl $1, %eax           // %eax <- 1
lock xchg %eax, the_lock // swap %eax and the_lock
                        // sets the_lock to 1 (taken)
                        // sets %eax to prior val of the_lock
```

```
test %eax, %eax
jne acquire
ret
```

if lock was already locked retry
“spin” until lock is released elsewhere

release:

```
mfence                // for memory order reasons
movl $0, the_lock     // then, set the_lock to 0 (not taken)
ret
```

x86-64 spinlock with xchg

lock variable in shared memory: `the_lock`

if 1: someone has the lock; if 0: lock is free to take

acquire:

```
movl $1, %eax           // %eax <- 1
lock xchg %eax, the_lock // swap %eax and the_lock
                        // sets the_lock to 1 (taken)
                        // sets %eax to prior val of the_lock
```

```
test %eax, %eax
jne acquire
ret
```

release lock by setting it to 0 (not taken)
allows looping acquire to finish

release:

```
mfence                // for memory order reasons
movl $0, the_lock     // then, set the_lock to 0 (not taken)
ret
```

x86-64 spinlock with xchg

lock variable in shared memory: `the_lock`

if 1: someone has the lock; if 0: lock is free to take

acquire:

```
movl $1, %eax           // %eax <- 1
lock xchg %eax, the_lock // swap %eax and the_lock
                        // sets the_lock to 1 (taken) of t
```

```
test %eax, %eax
jne acquire
ret
```

Intel's manual says:
no reordering of loads/stores across a `lock`
or `mfence` instruction

release:

```
mfence                // for memory order reasons
movl $0, the_lock     // then, set the_lock to 0 (not taken)
ret
```

exercise: spin wait

consider implementing 'waiting' functionality of pthread_join

thread calls ThreadFinish() when done

complete code below:

finished: .quad 0

ThreadFinish:

ret

ThreadWaitForFinish:

lock xchg %eax, finished

cmp \$0, %eax

---- ThreadWaitForFinish

ret

A. mfence; mov \$1, finished C. mov \$0, %eax E. je

B. mov \$1, finished; mfence D. mov \$1, %eax F. jne

spinlock problems

- lock abstraction is not powerful enough

 - lock/unlock operations don't handle "wait for event"

 - common thing we want to do with threads

 - solution: other synchronization abstractions

- spinlocks waste CPU time more than needed

 - want to run another thread instead of infinite loop

 - solution: lock implementation integrated with scheduler

- spinlocks can send a lot of messages on the shared bus

 - more efficient atomic operations to implement locks

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- lock abstraction is not powerful enough

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 - more efficient atomic operations to implement locks

mutexes: intelligent waiting

want: locks that wait better

example: POSIX mutexes

instead of running infinite loop, give away CPU

lock = go to sleep, add self to list

sleep = scheduler runs something else

unlock = wake up sleeping thread

mutexes: intelligent waiting

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example: POSIX mutexes

instead of running infinite loop, give away CPU

lock = go to sleep, add self to list

sleep = scheduler runs something else

unlock = wake up sleeping thread

better lock implementation idea

shared list of waiters

spinlock protects list of waiters from concurrent modification

lock = use spinlock to add self to list, then wait without spinlock

unlock = use spinlock to remove item from list

better lock implementation idea

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spinlock protects list of waiters from concurrent modification

lock = use spinlock to add self to list, then wait without spinlock

unlock = use spinlock to remove item from list

one possible implementation

```
struct Mutex {  
    SpinLock guard_spinlock;  
    bool lock_taken = false;  
    WaitQueue wait_queue;  
};
```

one possible implementation

```
struct Mutex {  
    SpinLock guard_spinlock;  
    bool lock_taken = false;  
    WaitQueue wait_queue;  
};
```

spinlock protecting `lock_taken` and `wait_queue`
only held for very short amount of time (compared to mutex itself)

one possible implementation

```
struct Mutex {  
    SpinLock guard_spinlock;  
    bool lock_taken = false;  
    WaitQueue wait_queue;  
};
```

tracks whether any thread has locked and not unlocked

one possible implementation

```
struct Mutex {  
    SpinLock guard_spinlock;  
    bool lock_taken = false;  
    WaitQueue wait_queue;  
};
```

list of threads that discovered lock is taken
and are waiting for it be free
these threads are **not runnable**

one possible implementation

```
struct Mutex {  
    SpinLock guard_spinlock;  
    bool lock_taken = false;  
    WaitQueue wait_queue;  
};
```

```
LockMutex(Mutex *m) {  
    LockSpinlock(&m->guard_spinlock);  
    if (m->lock_taken) {  
        put current thread on m->wait_queue  
        mark current thread as waiting  
        /* xv6: myproc()->state = SLEEPING; */  
        UnlockSpinlock(&m->guard_spinlock);  
        run scheduler (context switch)  
    } else {  
        m->lock_taken = true;  
        UnlockSpinlock(&m->guard_spinlock);  
    }  
}
```

```
UnlockMutex(Mutex *m) {  
    LockSpinlock(&m->guard_spinlock);  
    if (m->wait_queue not empty) {  
        remove a thread from m->wait_queue  
        mark thread as no longer waiting  
        /* xv6: myproc()->state = RUNNABLE; */  
    } else {  
        m->lock_taken = false;  
    }  
    UnlockSpinlock(&m->guard_spinlock);  
}
```

one possible implementation

```
struct Mutex {  
    SpinLock guard_spinlock;  
    bool lock_taken = false;  
    WaitQueue wait_queue;  
};
```

instead of setting lock_taken to false
choose thread to hand-off lock to

```
LockMutex(Mutex *m) {  
    LockSpinlock(&m->guard_spinlock);  
    if (m->lock_taken) {  
        put current thread on m->wait_queue  
        mark current thread as waiting  
        /* xv6: myproc()->state = SLEEPING; */  
        UnlockSpinlock(&m->guard_spinlock);  
        run scheduler (context switch)  
    } else {  
        m->lock_taken = true;  
        UnlockSpinlock(&m->guard_spinlock);  
    }  
}
```

```
UnlockMutex(Mutex *m) {  
    LockSpinlock(&m->guard_spinlock);  
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        remove a thread from m->wait_queue  
        mark thread as no longer waiting  
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    } else {  
        m->lock_taken = false;  
    }  
    UnlockSpinlock(&m->guard_spinlock);  
}
```

one possible implementation

```
struct Mutex {  
    SpinLock guard_spinlock;  
    bool lock_taken = false;  
    WaitQueue wait_queue;  
};
```

subtly: if UnlockMutex runs here on another core
need to make sure scheduler on the other core doesn't switch to thread
while it is still running (would 'clone' thread/mess up registers)

```
LockMutex(Mutex *m) {  
    LockSpinlock(&m->guard_spinlock);  
    if (m->lock_taken) {  
        put current thread on m->wait_queue  
        mark current thread as waiting  
        /* xv6: myproc()->state = SLEEPING; */  
        UnlockSpinlock(&m->guard_spinlock);  
        run scheduler (context switch)  
    } else {  
        m->lock_taken = true;  
        UnlockSpinlock(&m->guard_spinlock);  
    }  
}
```

```
UnlockMutex(Mutex *m) {  
    LockSpinlock(&m->guard_spinlock);  
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        remove a thread from m->wait_queue  
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        m->lock_taken = false;  
    }  
    UnlockSpinlock(&m->guard_spinlock);  
}
```

one possible implementation

```
struct Mutex {  
    SpinLock guard_spinlock;  
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LockMutex(Mutex *m) {  
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        /* xv6: myproc()->state = SLEEPING; */  
        UnlockSpinlock(&m->guard_spinlock);  
        run scheduler (context switch)  
    } else {  
        m->lock_taken = true;  
        UnlockSpinlock(&m->guard_spinlock);  
    }  
}
```

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UnlockMutex(Mutex *m) {  
    LockSpinlock(&m->guard_spinlock);  
    if (m->wait_queue not empty) {  
        remove a thread from m->wait_queue  
        mark thread as no longer waiting  
        /* xv6: myproc()->state = RUNNABLE; */  
    } else {  
        m->lock_taken = false;  
    }  
    UnlockSpinlock(&m->guard_spinlock);  
}
```

mutex and scheduler subtly

core 0 (thread A)	core 1 (thread B)	
start LockMutex		
acquire spinlock		
discover lock taken		
enqueue thread A		
thread A set not runnable		
release spinlock	start UnlockMutex	
	thread A set runnable	
	finish UnlockMutex	
	run scheduler	
	scheduler switches to A	
	...with old verison of registers	
thread A runs scheduler		...
...finally saving registers		...

Linux soln.: track 'thread running' separately from 'thread runnable'

xv6 soln.: hold scheduler lock until thread A saves registers

mutex and scheduler subtly

core 0 (thread A)	core 1 (thread B)	
start LockMutex		
acquire spinlock		
discover lock taken		
enqueue thread A		
thread A set not runnable		
release spinlock	start UnlockMutex	
	thread A set runnable	
	finish UnlockMutex	
	run scheduler	
	scheduler switches to A	
	...with old version of registers	
thread A runs scheduler		...
...finally saving registers		...

Linux soln.: track 'thread running' separately from 'thread runnable'

xv6 soln.: hold scheduler lock until thread A saves registers

mutex efficiency

'normal' mutex **uncontended** case:

lock: acquire + release spinlock, see lock is free

unlock: acquire + release spinlock, see queue is empty

not much slower than spinlock

implementing locks: single core

intuition: context switch only happens on interrupt
timer expiration, I/O, etc. causes OS to run

solution: disable them
reenable on unlock

implementing locks: single core

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timer expiration, I/O, etc. causes OS to run

solution: disable them
reenable on unlock

x86 instructions:
`cli` — disable interrupts
`sti` — enable interrupts

naive interrupt enable/disable (1)

```
Lock() {  
    disable interrupts  
}
```

```
Unlock() {  
    enable interrupts  
}
```

naive interrupt enable/disable (1)

```
Lock() {                               Unlock() {  
    disable interrupts                 enable interrupts  
}
```

problem: user can hang the system:

```
    Lock(some_lock);  
    while (true) {}
```

naive interrupt enable/disable (1)

```
Lock() {                                Unlock() {  
    disable interrupts                    enable interrupts  
}
```

problem: user can **hang the system**:

```
    Lock(some_lock);  
    while (true) {}
```

problem: can't do I/O within lock

```
    Lock(some_lock);  
    read from disk  
    /* waits forever for (disabled) interrupt  
       from disk IO finishing */
```

naive interrupt enable/disable (2)

```
Lock() {  
    disable interrupts  
}
```

```
Unlock() {  
    enable interrupts  
}
```

naive interrupt enable/disable (2)

```
Lock() {  
    disable interrupts  
}
```

```
Unlock() {  
    enable interrupts  
}
```

naive interrupt enable/disable (2)

```
Lock() {  
    disable interrupts  
}
```

```
Unlock() {  
    enable interrupts  
}
```


naive interrupt enable/disable (2)

Lock() {	Unlock() {
disable interrupts	enable interrupts
}	}

problem: nested locks

```
Lock(milk_lock);
if (no milk) {
    Lock(store_lock);
    buy milk
    Unlock(store_lock);
    /* interrupts enabled here?? */
}
Unlock(milk_lock);
```

C++ containers and locking

can you use a vector from multiple threads?

...question: how is it implemented?

C++ containers and locking

can you use a vector from multiple threads?

...question: how is it implemented?

- dynamically allocated array
- reallocated on size changes

C++ containers and locking

can you use a vector from multiple threads?

...question: how is it implemented?

- dynamically allocated array
- reallocated on size changes

can access from multiple threads ...as long as not
append/erase/etc.?

assuming it's implemented like we expect...

- but can we really depend on that?

- e.g. could shrink internal array after a while with no expansion save memory?

C++ standard rules for containers

multiple threads can read anything at the same time

can only read element if no other thread is modifying it

can safely add/remove elements if no other threads are accessing container

(sometimes can safely add/remove in extra cases)

exception: vectors of bools — can't safely read and write at same time

might be implemented by putting multiple bools in one int

GCC: preventing reordering example (1)

```
void Alice() {  
    int one = 1;  
    __atomic_store(&note_from_alice, &one, __ATOMIC_SEQ_CST);  
    do {  
    } while (__atomic_load_n(&note_from_bob, __ATOMIC_SEQ_CST));  
    if (no_milk) {++milk;}  
}
```

```
Alice:  
    movl $1, note_from_alice  
    mfence  
.L2:  
    movl note_from_bob, %eax  
    testl %eax, %eax  
    jne .L2  
    ...
```

GCC: preventing reordering example (2)

```
void Alice() {  
    note_from_alice = 1;  
    do {  
        __atomic_thread_fence(__ATOMIC_SEQ_CST);  
    } while (note_from_bob);  
    if (no_milk) {++milk;}  
}
```

Alice:

```
    movl $1, note_from_alice  // note_from_alice <- 1
```

.L3:

```
    mfence  // make sure store is visible to other cores before  
            // on x86: not needed on second+ iteration of loop
```

```
    cmpl $0, note_from_bob  // if (note_from_bob == 0) repeat forever
```

```
    jne .L3
```

```
    cmpl $0, no_milk
```

```
    ...
```

exercise: fetch-and-add with compare-and-swap

exercise: implement fetch-and-add with compare-and-swap

```
compare_and_swap(address, old_value, new_value) {  
    if (memory[address] == old_value) {  
        memory[address] = new_value;  
        return true;    // x86: set ZF flag  
    } else {  
        return false;   // x86: clear ZF flag  
    }  
}
```


solution

xv6 spinlock: acquire

```
void
```

```
acquire(struct spinlock *lk)
```

```
{
```

```
    pushcli(); // disable interrupts to avoid deadlock.
```

```
    ...
```

```
    // The xchg is atomic.
```

```
    while(xchg(&lk->locked, 1) != 0)
```

```
        ;
```

```
    // Tell the C compiler and the processor to not move loads or sto
```

```
    // past this point, to ensure that the critical section's memory
```

```
    // references happen after the lock is acquired.
```

```
    __sync_synchronize();
```

```
    ...
```

```
}
```

xv6 spinlock: acquire

```
void
```

```
acquire(struct spinlock *lk)
```

```
{
```

```
    pushcli(); // disable interrupts to avoid deadlock.
```

```
    ...
```

```
    // The xchg is atomic.
```

```
    while(xchg(&lk->locked, 1) != 0)
```

```
    ;
```

```
    // Tell the C compiler and the processor to not move loads or sto
```

```
    // past this point, to ensure that the critical section's memory
```

```
    // references happen after the lock is acquired
```

```
    --
```

don't let us be interrupted after while have the lock

```
    •  
}
```

problem: interruption might try to do something with the lock

...but that can never succeed until we release the lock

...but we won't release the lock until interruption finishes

xv6 spinlock: acquire

```
void
acquire(struct spinlock *lk)
{
    pushcli(); // disable interrupts to avoid deadlock.
    ...
    // The xchg is atomic.
    while(xchg(&lk->locked, 1) != 0)
        ;

    // Tell the C compiler and the processor to not move loads or stores
    // past this point, to ensure that the critical section's memory
    // references happen after the lock is acquired.
    __sync_synchronize();
    ...
}
```

xchg wraps the lock xchg instruction
same loop as before

xv6 spinlock: acquire

```
void
acquire(struct spinlock *lk)
{
    pushcli(); // disable interrupts to avoid deadlock.
    ...
    // The xchg is atomic.
    while(xchg(&lk->locked, 1) != 0)
        ;

    // Tell the C compiler and the processor to not move loads or stores
    // past this point, to ensure that the critical section's memory
    // references happen after the lock is acquired.
    __sync_synchronize();
    ..
}
```

avoid load store reordering (including by compiler)
on x86, xchg alone is enough to avoid processor's reordering
(but compiler may need more hints)

xv6 spinlock: release

```
void
```

```
release(struct spinlock *lk)
```

```
...
```

```
// Tell the C compiler and the processor to not move loads or stores
```

```
// past this point, to ensure that all the stores in the critical
```

```
// section are visible to other cores before the lock is released
```

```
// Both the C compiler and the hardware may re-order loads and
```

```
// stores; __sync_synchronize() tells them both not to.
```

```
__sync_synchronize();
```

```
// Release the lock, equivalent to lk->locked = 0.
```

```
// This code can't use a C assignment, since it might
```

```
// not be atomic. A real OS would use C atomics here.
```

```
asm volatile("movl $0, %0" : "+m" (lk->locked) : );
```

```
popcli();
```

```
}
```

xv6 spinlock: release

```
void
```

```
release(struct spinlock *lk)
```

```
...
```

```
// Tell the C compiler and the processor to not move loads or stores  
// past this point, to ensure that all the stores in the critical  
// section are visible to other cores before the lock is released.  
// Both the C compiler and the hardware may re-order loads and  
// stores; __sync_synchronize() tells them both not to.
```

```
__sync_synchronize();
```

```
// Release the lock, equivalent to lk->locked = 0.  
// This code can't use a C assignment, since it might  
// not be atomic. A real OS would use C atomics here.
```

```
asm volatile("movl $0, %0" : "+m" (lk->locked) : );
```

```
popcli
```

turns into instruction to tell processor not to reorder
plus tells compiler not to reorder

```
}
```

xv6 spinlock: release

```
void
```

```
release(struct spinlock *lk)
```

```
...
```

```
// Tell the C compiler and the processor to not move loads or stores  
// past this point, to ensure that all the stores in the critical  
// section are visible to other cores before the lock is released.  
// Both the C compiler and the hardware may re-order loads and  
// stores; __sync_synchronize() tells them both not to.  
__sync_synchronize();
```

```
// Release the lock, equivalent to lk->locked = 0.  
// This code can't use a C assignment, since it might  
// not be atomic. A real OS would use C atomics here.
```

```
asm volatile("movl $0, %0" : "+m" (lk->locked) : );
```

```
popcli();
```

```
}
```

turns into mov of constant 0 into lk->locked

xv6 spinlock: release

```
void
```

```
release(struct spinlock *lk)
```

```
...
```

```
// Tell the C compiler and the processor to not move loads or stores  
// past this point, to ensure that all the stores in the critical  
// section are visible to other cores before the lock is released.  
// Both the C compiler and the hardware may re-order loads and  
// stores; __sync_synchronize() tells them both not to.  
__sync_synchronize();
```

```
// Release the lock, equivalent to lk->locked = 0.  
// This code can't use a C assignment, since it might  
// not be atomic. A real OS would use C atomics here.  
asm volatile("movl $0, %0" : "+m" (lk->locked) : );
```

```
popcli();
```

```
}
```

reenable interrupts (taking nested locks into account)

fetch-and-add with CAS (1)

```
compare-and-swap(address, old_value, new_value) {  
    if (memory[address] == old_value) {  
        memory[address] = new_value;  
        return true;  
    } else {  
        return false;  
    }  
}
```

```
long my_fetch_and_add(long *pointer, long amount) { ... }
```

implementation sketch:

- fetch value from pointer `old`
- compute in temporary value result of addition `new`
- try to change value at pointer from `old` to `new`
[compare-and-swap]
- if not successful, repeat

fetch-and-add with CAS (2)

```
long my_fetch_and_add(long *p, long amount) {  
    long old_value;  
    do {  
        old_value = *p;  
    } while (!compare_and_swap(p, old_value, old_value + amount));  
    return old_value;  
}
```

exercise: append to singly-linked list

ListNode is a singly-linked list

assume: threads *only* append to list (no deletions, reordering)

use compare-and-swap(pointer, old, new):

- atomically change *pointer from old to new

- return true if successful

- return false (and change nothing) if *pointer is not old

```
void append_to_list(ListNode *head, ListNode *new_last_node) {  
    ...  
}
```

some common atomic operations (1)

// x86: emulate with exchange

```
test_and_set(address) {  
    old_value = memory[address];  
    memory[address] = 1;  
    return old_value != 0; // e.g. set ZF flag  
}
```

// x86: xchg REGISTER, (ADDRESS)

```
exchange(register, address) {  
    temp = memory[address];  
    memory[address] = register;  
    register = temp;  
}
```

some common atomic operations (2)

```
// x86: mov OLD_VALUE, %eax; lock cmpxchg NEW_VALUE, (ADDRESS)
compare-and-swap(address, old_value, new_value) {
    if (memory[address] == old_value) {
        memory[address] = new_value;
        return true;    // x86: set ZF flag
    } else {
        return false;   // x86: clear ZF flag
    }
}
```

```
// x86: lock xaddl REGISTER, (ADDRESS)
fetch-and-add(address, register) {
    old_value = memory[address];
    memory[address] += register;
    register = old_value;
}
```

common atomic operation pattern

try to do operation, ...

detect if it failed

if so, repeat

atomic operation does “try and see if it failed” part

cache coherency states

extra information for each cache block

overlaps with/replaces valid, dirty bits

stored in each cache

update states based on reads, writes and heard messages on bus

different caches may have different states for same block

MSI state summary

Modified value may be **different than memory** *and* I am the only one who has it

Shared value is the **same as memory**

Invalid I don't have the value; I will need to ask for it

MSI scheme

from state	hear read	hear write	read	write
Invalid	—	—	to Shared	to Modified
Shared	—	to Invalid	—	to Modified
Modified	to Shared	to Invalid	—	—

blue: transition requires sending message on bus

MSI scheme

from state	hear read	hear write	read	write
Invalid	—	—	to Shared	to Modified
Shared	—	to Invalid	—	to Modified
Modified	to Shared	to Invalid	—	—

blue: transition requires sending message on bus

example: write while Shared

must send write — inform others with Shared state
then change to Modified

MSI scheme

from state	hear read	hear write	read	write
Invalid	—	—	to Shared	to Modified
Shared	—	to Invalid	—	to Modified
Modified	to Shared	to Invalid	—	—

blue: transition requires sending message on bus

example: write while Shared

must send write — inform others with Shared state
then change to Modified

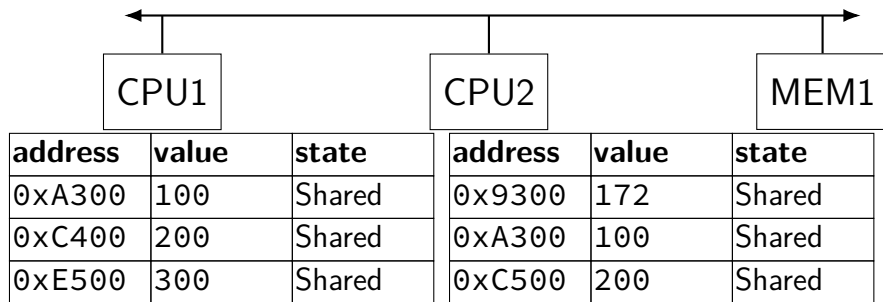
example: hear write while Shared

change to Invalid
can send read later to get value from writer

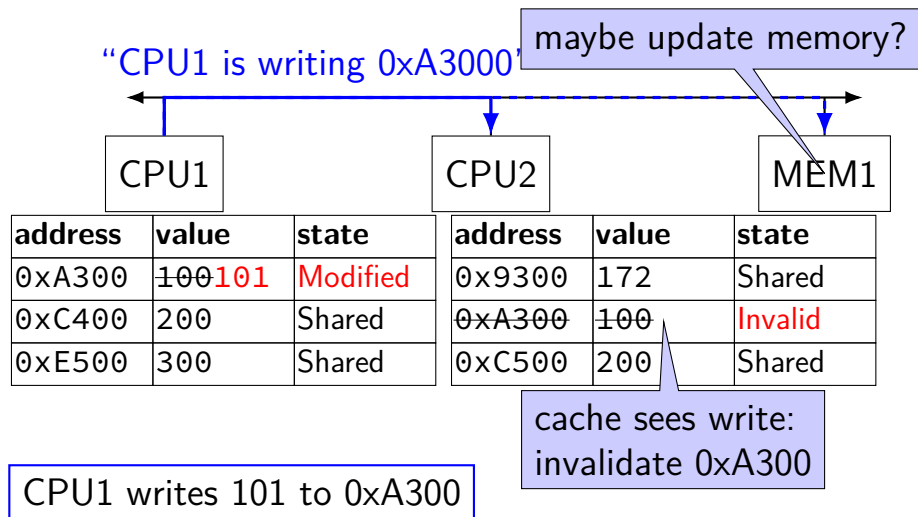
example: write while Modified

nothing to do — no other CPU can have a copy

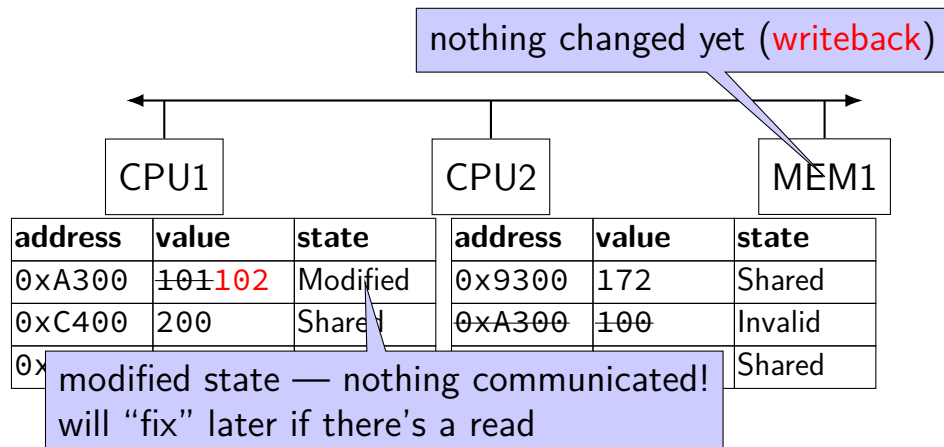
MSI example



MSI example

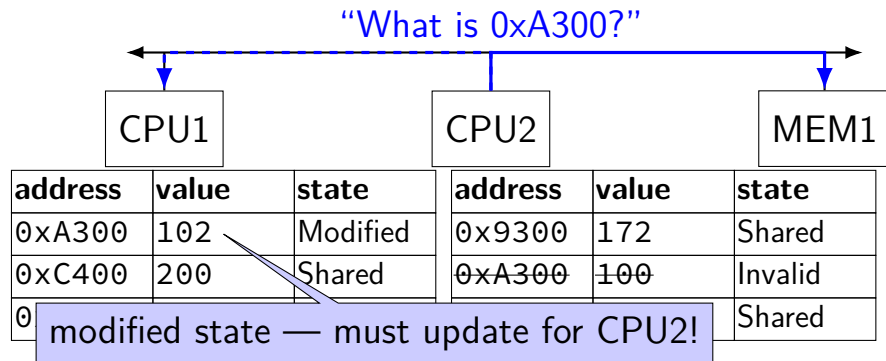


MSI example



CPU1 writes 102 to 0xA300

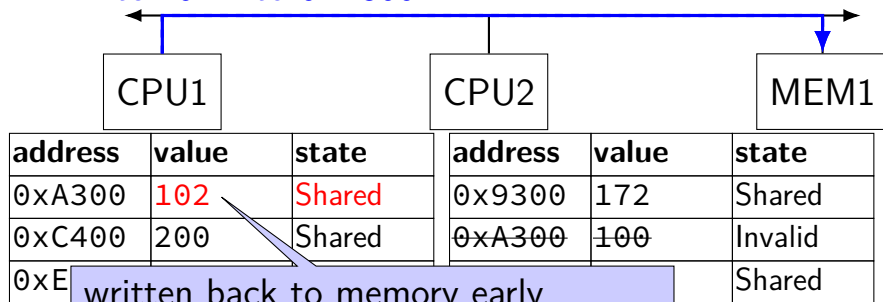
MSI example



CPU2 reads 0xA300

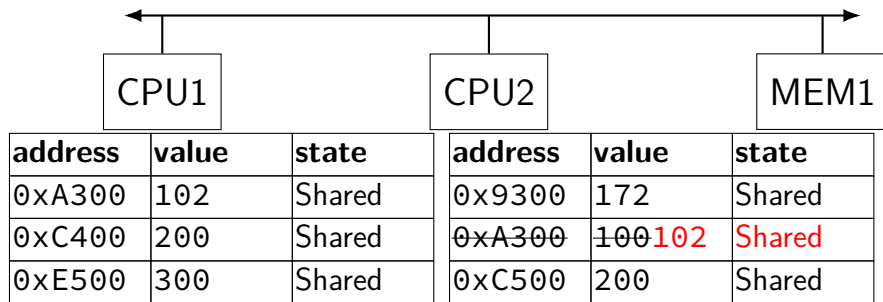
MSI example

“Write 102 into 0xA300”



CPU2 reads 0xA300

MSI example



MSI: update memory

to write value (enter modified state), need to **invalidate** others
can avoid sending actual value (shorter message/faster)

“I am writing address X ” versus “I am writing Y to address X ”

MSI: on cache replacement/writeback

still happens — e.g. want to store something else

changes state to **invalid**

requires writeback if modified (= dirty bit)

cache coherency exercise

modified/shared/invalid; all initially invalid; 32B blocks, 8B read/writes

CPU 1: read 0x1000

CPU 2: read 0x1000

CPU 1: write 0x1000

CPU 1: read 0x2000

CPU 2: read 0x1000

CPU 2: write 0x2008

CPU 3: read 0x1008

Q1: final state of 0x1000 in caches?

Modified/Shared/Invalid for CPU 1/2/3

CPU 1: CPU 2: CPU 3:

Q2: final state of 0x2000 in caches?

Modified/Shared/Invalid for CPU 1/2/3

CPU 1: CPU 2: CPU 3:

why load/store reordering?

fast processor designs can execute instructions out of order

goal: do something instead of waiting for slow memory accesses, etc.

more on this later in the semester

C++: preventing reordering

to help implementing things like `pthread_mutex_lock`

C++ 2011 standard: *atomic* header, *std::atomic* class

prevent CPU reordering *and* prevent compiler reordering

also provide other tools for implementing locks (more later)

could also hand-write assembly code

compiler can't know what assembly code is doing

C++: preventing reordering example

```
#include <atomic>
void Alice() {
    note_from_alice = 1;
    do {
        std::atomic_thread_fence(std::memory_order_seq_cst);
    } while (note_from_bob);
    if (no_milk) {++milk;}
}
```

```
Alice:
    movl $1, note_from_alice  // note_from_alice <- 1
.L2:
    mfence // make sure store visible on/from other cores
    cmpl $0, note_from_bob // if (note_from_bob == 0) repeat fence
    jne .L2
    cmpl $0, no_milk
    ...
```


C++ atomics: no reordering

```
std::atomic<int> note_from_alice, note_from_bob;  
void Alice() {  
    note_from_alice.store(1);  
    do {  
    } while (note_from_bob.load());  
    if (no_milk) {++milk;}  
}
```

```
Alice:  
    movl $1, note_from_alice  
    mfence  
.L2:  
    movl note_from_bob, %eax  
    testl %eax, %eax  
    jne .L2  
    ...
```

GCC: built-in atomic functions

used to implement `std::atomic`, etc.

predate `std::atomic`

builtin functions starting with `__sync` and `__atomic`

these are what xv6 uses

aside: some x86 reordering rules

each core sees its own loads/stores in order

(if a core stores something, it can always load it back)

stores *from other cores* appear in a consistent order

(but a core might observe its own stores too early)

causality:

if a core reads $X=a$ and (after reading $X=a$) writes $Y=b$,
then a core that reads $Y=b$ cannot later read X =older value than a

how do you do anything with this?

difficult to reason about what modern CPU's reordering rules do
typically: don't depend on details, instead:

special instructions with stronger (and simpler) ordering rules
 often same instructions that help with implementing locks in other ways

special instructions that restrict ordering of instructions around
them (“fences”)
 loads/stores can't cross the fence

spinlock problems

- lock abstraction is not powerful enough

 - lock/unlock operations don't handle "wait for event"

 - common thing we want to do with threads

 - solution: other synchronization abstractions

- spinlocks waste CPU time more than needed

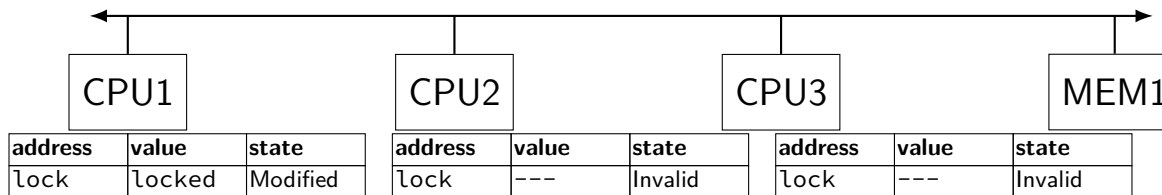
 - want to run another thread instead of infinite loop

 - solution: lock implementation integrated with scheduler

- spinlocks can send a lot of messages on the shared bus

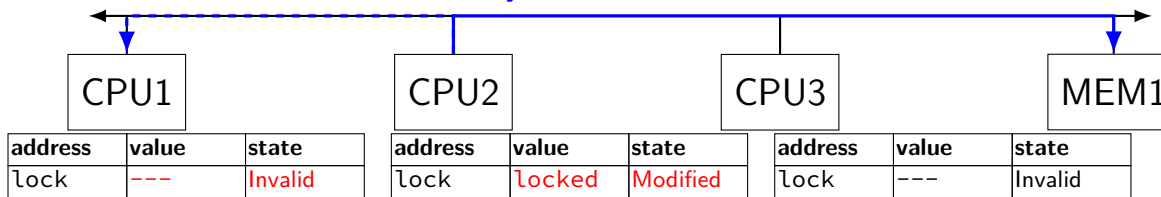
 - more efficient atomic operations to implement locks

ping-ponging



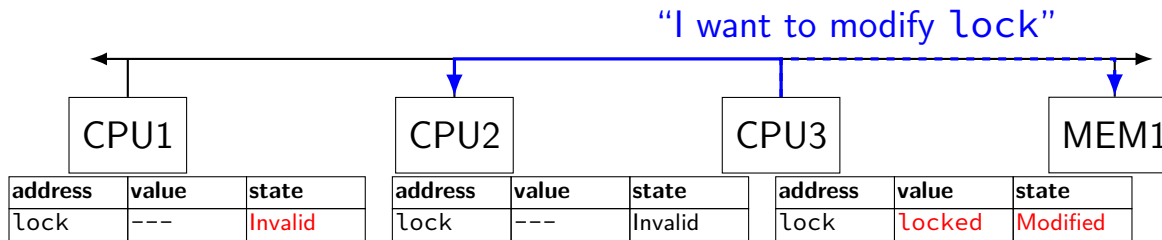
ping-ponging

"I want to modify lock?"



CPU2 read-modify-writes lock
(to see it is still locked)

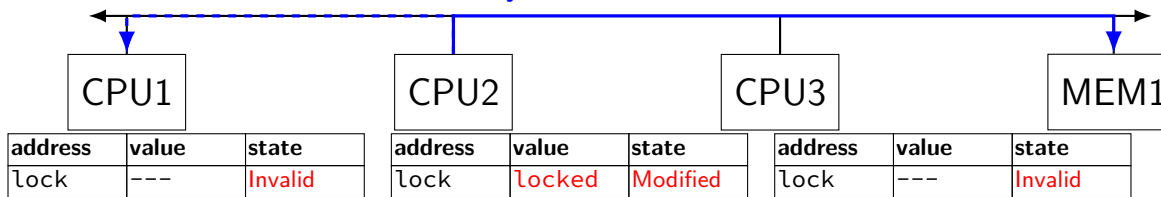
ping-ponging



CPU3 read-modify-writes lock
(to see it is still locked)

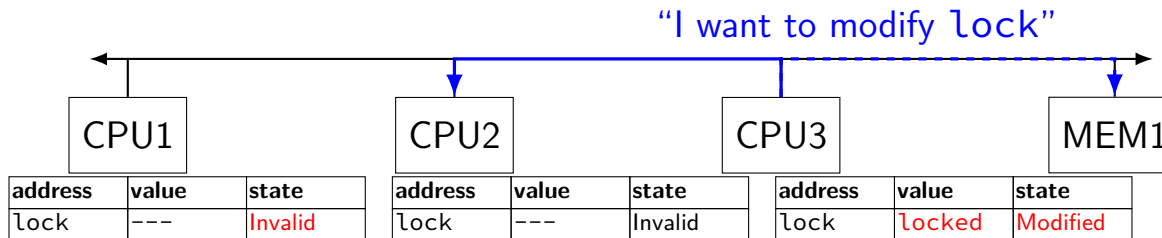
ping-ponging

“I want to modify lock?”



CPU2 read-modify-writes lock
(to see it is still locked)

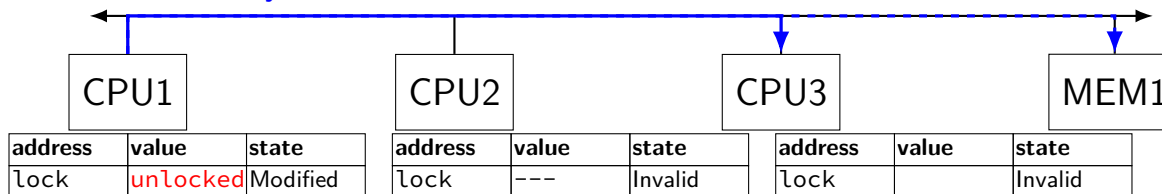
ping-ponging



CPU3 read-modify-writes lock
(to see it is still locked)

ping-ponging

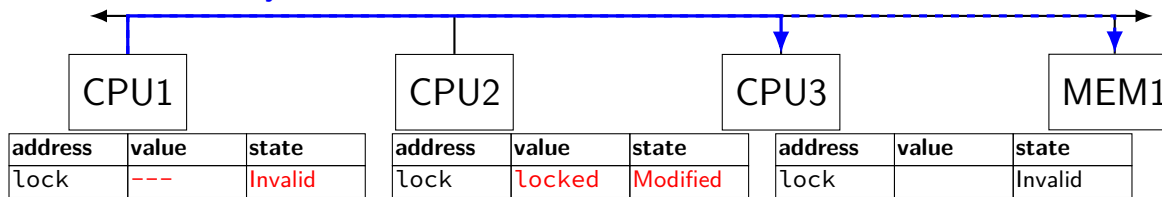
“I want to modify lock”



CPU1 sets lock to unlocked

ping-ponging

“I want to modify lock”



some CPU (this example: CPU2) acquires lock

ping-ponging

test-and-set problem: cache block “ping-pongs” between caches
each waiting processor reserves block to modify
could maybe wait until it determines modification needed — but not
typical implementation

each transfer of block sends messages on bus

...so bus can't be used for real work

like what the processor with the lock is doing

test-and-test-and-set (pseudo-C)

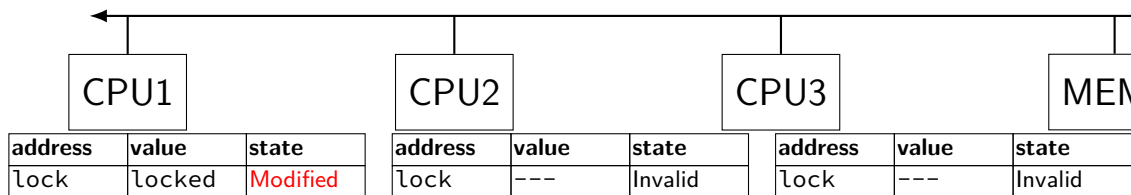
```
acquire(int *the_lock) {  
    do {  
        while (ATOMIC-READ(the_lock) == 0) { /* try again */ }  
    } while (ATOMIC-TEST-AND-SET(the_lock) == ALREADY_SET);  
}
```

test-and-test-and-set (assembly)

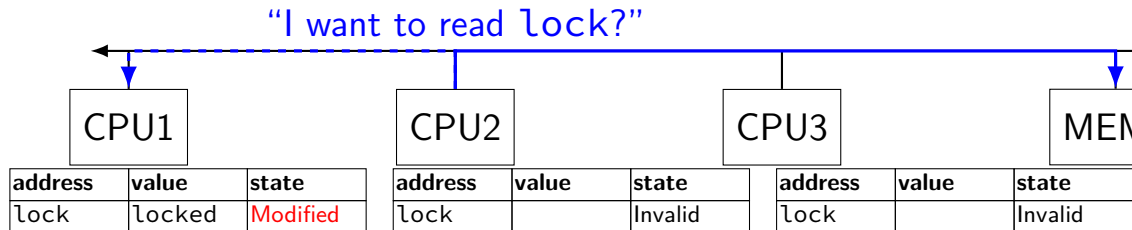
acquire:

```
    cmp $0, the_lock           // test the lock non-atomically
                                // unlike lock xchg --- keeps lock in Shared state!
    jne acquire                // try again (still locked)
    // lock possibly free
    // but another processor might lock
    // before we get a chance to
    // ... so try with atomic swap:
    movl $1, %eax              // %eax <- 1
    lock xchg %eax, the_lock    // swap %eax and the_lock
                                // sets the_lock to 1
                                // sets %eax to prior value of the_lock
    test %eax, %eax            // if the_lock wasn't 0 (someone else)
    jne acquire                // try again
    ret
```

less ping-ponging



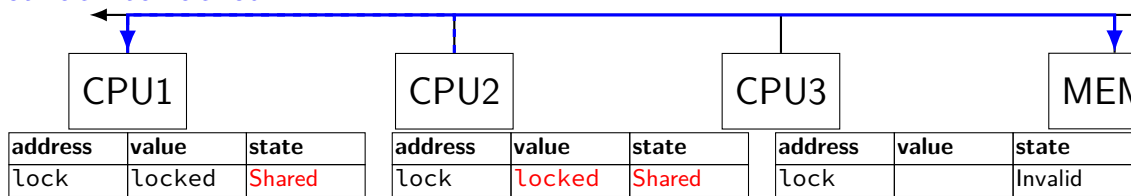
less ping-ponging



CPU2 reads lock
(to see it is still locked)

less ping-ponging

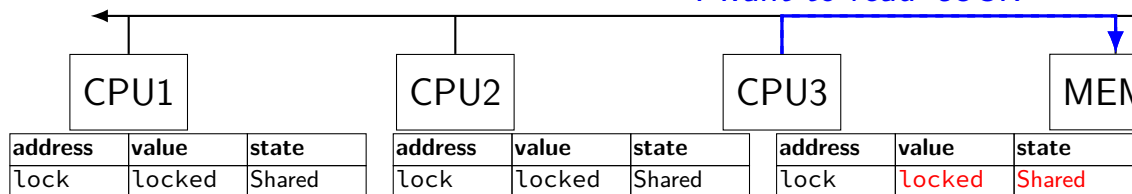
“set lock to locked”



CPU1 writes back lock value,
then CPU2 reads it

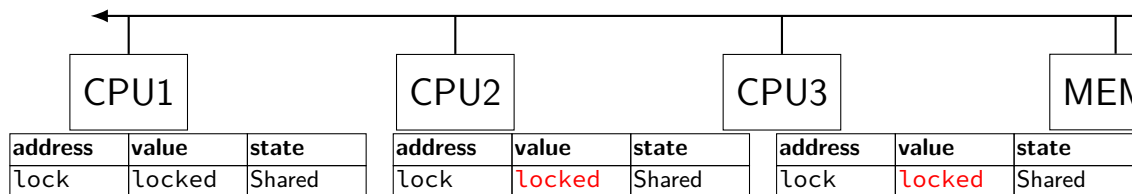
less ping-ponging

"I want to read lock"



CPU3 reads lock
(to see it is still locked)

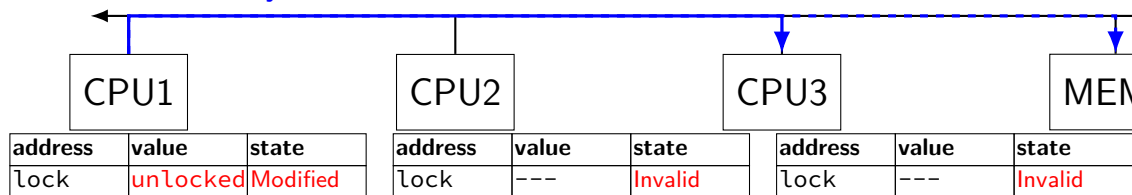
less ping-ponging



CPU2, CPU3 continue to read lock from cache
no messages on the bus

less ping-ponging

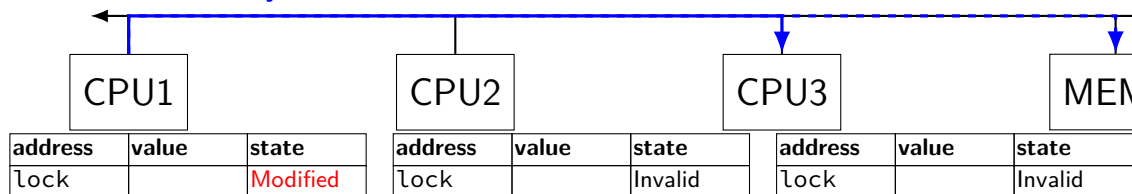
“I want to modify lock”



CPU1 sets lock to unlocked

less ping-ponging

“I want to modify lock”



some CPU (this example: CPU2) acquires lock
(CPU1 writes back value, then CPU2 reads + modifies it)

couldn't the read-modify-write instruction...

notice that the value of the lock isn't changing...

and keep it in the shared state

maybe — but extra step in “common” case
(swapping different values)

more room for improvement?

can still have a lot of attempts to modify locks after unlocked

there other spinlock designs that avoid this

- ticket locks

- MCS locks

- ...

MSI extensions

real cache coherency protocols sometimes more complex:

separate tracking modifications from whether other caches have copy

send values directly between caches (maybe skip write to memory)

send messages only to cores which might care (no shared bus)

too much milk

roommates Alice and Bob want to keep fridge stocked with milk:

time	Alice	Bob
3:00	look in fridge. no milk	
3:05	leave for store	
3:10	arrive at store	look in fridge. no milk
3:15	buy milk	leave for store
3:20	return home, put milk in fridge	arrive at store
3:25		buy milk
3:30		return home, put milk in fridge

how can Alice and Bob coordinate better?

too much milk “solution” 1 (algorithm)

leave a note: “I am buying milk”

place before buying, remove after buying

don't try buying if there's a note

≈ setting/checking a variable (e.g. “note = 1”)
with atomic load/store of variable

```
if (no milk) {  
    if (no note) {  
        leave note;  
        buy milk;  
        remove note;  
    }  
}
```

too much milk “solution” 1 (algorithm)

leave a note: “I am buying milk”

place before buying, remove after buying

don't try buying if there's a note

≈ setting/checking a variable (e.g. “note = 1”)
with atomic load/store of variable

```
if (no milk) {  
    if (no note) {  
        leave note;  
        buy milk;  
        remove note;  
    }  
}
```

exercise: why doesn't this work?

too much milk “solution” 1 (timeline)

Alice

```
if (no milk) {  
  if (no note) {  
  
    leave note;  
    buy milk;  
    remove note;  
  }  
}
```

Bob

```
if (no milk) {  
  if (no note) {  
  
    leave note;  
    buy milk;  
    remove note;  
  }  
}
```

too much milk “solution” 2 (algorithm)

intuition: leave note when buying or checking if need to buy

```
leave note;  
if (no milk) {  
    if (no note) {  
        buy milk;  
    }  
}  
remove note;
```

too much milk: “solution” 2 (timeline)

Alice

```
leave note;  
if (no milk) {  
    if (no note) {  
        buy milk;  
    }  
}  
remove note;
```

too much milk: “solution” 2 (timeline)

Alice

```
leave note;
```

```
if (no milk) {
```

```
    if (no note) { ← but there's always a note
```

```
        buy milk;
```

```
    }
```

```
}
```

```
remove note;
```


too much milk: “solution” 2 (timeline)

Alice

```
leave note;
```

```
if (no milk) {
```

```
    if (no note) {
```

```
        buy milk;
```

```
    }
```

```
}
```

```
remove note;
```

← but there's **always a note**

...will never buy milk (twice or once)

“solution” 3: algorithm

intuition: label notes so Alice knows which is hers (and vice-versa)

computer equivalent: separate noteFromAlice and noteFromBob

variables

Alice

```
leave note from Alice;  
if (no milk) {  
    if (no note from Bob) {  
        buy milk  
    }  
}  
remove note from Alice;
```

Bob

```
leave note from Bob;  
if (no milk) {  
    if (no note from Alice) {  
        buy milk  
    }  
}  
remove note from Bob;
```

too much milk: “solution” 3 (timeline)

Alice

leave note from Alice

if (no milk) {

 if (no note from Bob) {

~~buy milk~~

 }

}

remove note from Alice

Bob

leave note from Bob

if (no milk) {

 if (no note from Alice) {

~~buy milk~~

 }

}

remove note from Bob

too much milk: is it possible

is there a solutions with writing/reading notes?

≈ loading/storing from shared memory

yes, but it's not very elegant

too much milk: solution 4 (algorithm)

Alice

```
leave note from Alice
while (note from Bob) {
    do nothing
}
if (no milk) {
    buy milk
}
remove note from Alice
```

Bob

```
leave note from Bob
if (no note from Alice) {
    if (no milk) {
        buy milk
    }
}
remove note from Bob
```

too much milk: solution 4 (algorithm)

Alice

leave note from Alice

```
while (note from Bob) {  
    do nothing  
}
```

```
if (no milk) {  
    buy milk  
}
```

```
remove note from Alice
```

exercise (hard): prove (in)correctness

Bob

leave note from Bob

```
if (no note from Alice) {  
    if (no milk) {  
        buy milk  
    }  
}
```

```
remove note from Bob
```

too much milk: solution 4 (algorithm)

Alice

leave note from Alice

```
while (note from Bob) {  
    do nothing  
}
```

```
if (no milk) {  
    buy milk  
}
```

```
remove note from Alice
```

exercise (hard): prove (in)correctness

Bob

leave note from Bob

```
if (no note from Alice) {  
    if (no milk) {  
        buy milk  
    }  
}
```

```
remove note from Bob
```

too much milk: solution 4 (algorithm)

Alice

leave note from Alice

```
while (note from Bob) {  
    do nothing  
}
```

```
if (no milk) {  
    buy milk  
}
```

```
remove note from Alice
```

Bob

leave note from Bob

```
if (no note from Alice) {  
    if (no milk) {  
        buy milk  
    }  
}
```

```
remove note from Bob
```

exercise (hard): prove (in)correctness

exercise (hard): extend to three people

Peterson's algorithm

general version of solution

see, e.g., Wikipedia

we'll use special hardware support instead

mfence

x86 instruction mfence

make sure all loads/stores in progress finish

...and make sure no loads/stores were started early

fairly expensive

Intel 'Skylake': order 33 cycles + time waiting for pending stores/loads

mfence

x86 instruction mfence

make sure all loads/stores in progress finish

...and make sure no loads/stores were started early

fairly expensive

Intel 'Skylake': order 33 cycles + time waiting for pending stores/loads

aside: this instruction did not exist in the original x86
so xv6 uses something older that's equivalent

modifying cache blocks in parallel

cache coherency works on **cache blocks**

but typical memory access — less than cache block

e.g. one 4-byte array element in 64-byte cache block

what if two processors modify different parts same cache block?

4-byte writes to 64-byte cache block

cache coherency — write instructions happen one at a time:

processor 'locks' 64-byte cache block, fetching latest version

processor updates 4 bytes of 64-byte cache block

later, processor might give up cache block

modifying things in parallel (code)

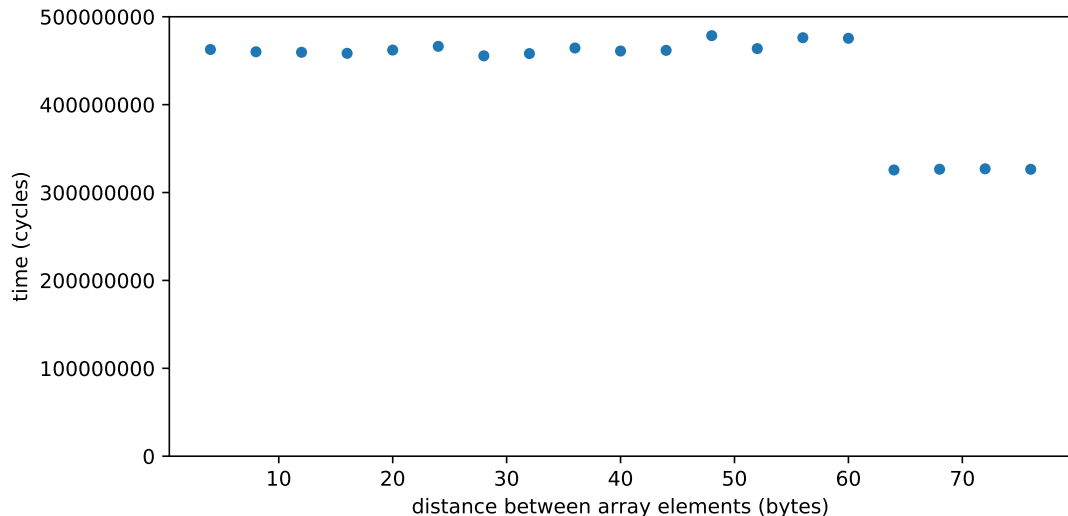
```
void *sum_up(void *raw_dest) {  
    int *dest = (int *) raw_dest;  
    for (int i = 0; i < 64 * 1024 * 1024; ++i) {  
        *dest += data[i];  
    }  
}
```

```
__attribute__((aligned(4096)))  
int array[1024]; /* aligned = address is mult. of 4096 */
```

```
void sum_twice(int distance) {  
    pthread_t threads[2];  
    pthread_create(&threads[0], NULL, sum_up, &array[0]);  
    pthread_create(&threads[1], NULL, sum_up, &array[distance]);  
    pthread_join(threads[0], NULL);  
    pthread_join(threads[1], NULL);  
}
```

performance v. array element gap

(assuming `sum_up` compiled to not omit memory accesses)



false sharing

synchronizing to access two independent things

two parts of same cache block

solution: separate them

exercise (1)

```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    results[0] = 0;
    for (int i = 0; i < 512; ++i)
        results[0] += values[i];
    return NULL;
}
void *sum_back(void *ignored_argument) {
    results[1] = 0;
    for (int i = 512; i < 1024; ++i)
        results[1] += values[i];
    return NULL;
}
int sum_all() {
    pthread_t sum_front_thread, sum_back_thread;
    pthread_create(&sum_front_thread, NULL, sum_front, NULL);
    pthread_create(&sum_back_thread, NULL, sum_back, NULL);
    pthread_join(sum_front_thread, NULL);
    pthread_join(sum_back_thread, NULL);
    return results[0] + results[1];
}
```

Where is false sharing likely to occur? How to fix?

exercise (2)

```
struct ThreadInfo { int *values; int start; int end; int result };
void *sum_thread(void *argument) {
    ThreadInfo *my_info = (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) {
        my_info->result += my_info->values[i];
    }
    return NULL;
}

int sum_all(int *values) {
    ThreadInfo info[2]; pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return info[0].result + info[1].result;
}
```

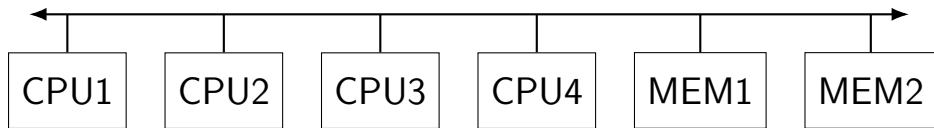
Where is false sharing likely to occur?

connecting CPUs and memory

multiple processors, common memory

how do processors communicate with memory?

shared bus



one possible design

we'll revisit later when we talk about I/O

tagged messages — everyone gets everything, filters

contention if multiple communicators

some hardware enforces only one at a time

shared buses and scaling

shared buses perform poorly with “too many” CPUs

so, there are other designs

we'll gloss over these for now

shared buses and caches

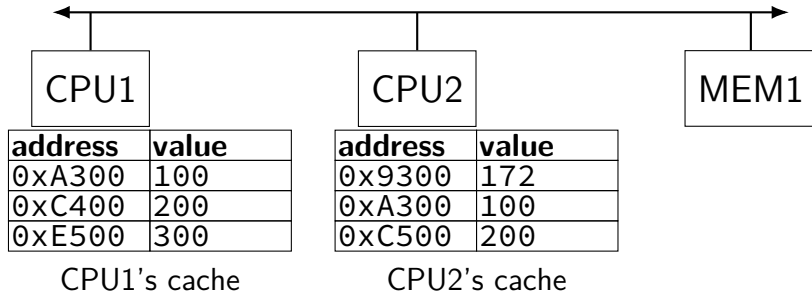
remember caches?

memory is pretty slow

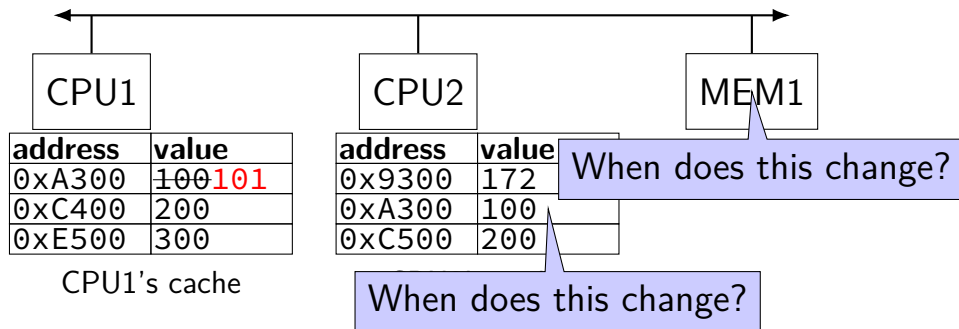
each CPU wants to keep local copies of memory

what happens when multiple CPUs cache same memory?

the cache coherency problem



the cache coherency problem



CPU1 writes 101 to 0xA300?

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: 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(&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;  
}
```

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 enqueue size = 1? signal unlock	Produce(): wait for lock gets lock enqueue size \neq 1: don't signal unlock
wait for lock			
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 become true, and

allowing only one thread to manipulate a thing at a time

argument 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) {
    sem_wait(&private_lock);
    ++num_waiters;
    sem_post(&private_lock);
    lock.Unlock();
    sem_wait(&threads_to_wakeup);
    lock.Lock();
}
```

```
Signal() {
    sem_wait(&private_lock);
    if (num_waiters > 0) {
        sem_post(&threads_to_wakeup);
        --num_waiters;
    }
    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

via Hemmendinger, "Comments on 'A correct and unrestrictive implementation of general semaphores' " (1989); Barz, "Implementing semaphores by binary semaphores" (1983)

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

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

```
void Up() {
    mutex.Down();
    value += 1;
    if (value == 1) {
        gate.Up();
        // because down should finish now
        // but could not before
    }
    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
}
```