so far

building processes

- virtual memory + virtual CPU (thread) + files (virtual storage)

connecting machines (networking, security)

caching — speedy memories

interfaces for controlling processes

revisiting threads

- multi-threaded processes
- passing values to/waiting for threads

last time

reordering of loads/stores by compilers, processors

locks

- way to take turns
- don't actually restrict access to resourcej

barriers

- wait for every other thread

deadlock problem

anonymous feedback

locks not covered in F2022 DSA1 due to end-of-semester stuff

- think we went into full detail last time

captions on recordings not there

- some not-so-automatically imported automated (low-quality) captions
- was missing some I tried to import due to filename problem, probably fixes

complimentary feedback

- I really appreciate all of your patience in answering questions that students have, guidance on homework questions (that may seem easy to understand for you but may be a bit more challenging for students), and your responsiveness on piazza. I'm thankful for how you are willing to sit down with students in office hours to walk them through problems they are encountering step by step in an encouraging manner. It really makes me feel like I have all the support I need to be successful in this class, and it's something that not a lot of other teachers can offer, so I just wanted to express my gratitude amidst all the other negative complaints.

Quiz: pthread_join mistakes

`pthread_join(pthread_t, void**)`

I wrote code as if it was `pthread_join(pthread_t, void**)`

meant that:

needed to accept "most likely crash" as valid answer for Q2

in Q3 pthread_joins would not actually wait for threads to finish, so option F was correct!

wasn't my intention to test this kind of API detail

since it's something you'd notice by reading compiler warnings/errors

quiz Q1

```
void foo() {
    int array[4] = {0, 0, 0, 0}; /* <--- on stack of foo() */
    ...
    int *q = &array[i]; /* <--- q points to stack of foo() */
    /* same as: int *q; q = &array[i]; */
    pthread_create(...., (void *) q); /* passing 'q' to thread */
    ...
}

void *thread_func(void *arg) {
    int *p;
    p = (int*) arg; /* <-- p = q, so p points to stack of foo() */
    *p = 1; /* <--- modifies what p points to */
    ...
}
```

quiz Q4b

“assume that all code follows the convention that dynamic_array structs are only read or modified while holding the lock in the struct”

```
pthread_mutex_unlock(&to_add->lock);
...  /* <-- to_dad->data, to_add->size could change here */
pthread_mutex_lock(&to_add->lock);
/* but not while executing the below: */
memcpy(dest->new_data + dest->size, to_add->data, to_add->size
dest->size += to_add->size;
```

will either copy from new allocation or from original allocation *before new allocation is made*

should’ve written ‘out-of-date allocation’ instead of ‘old allocation’ in quiz option (or made it clearer that it needed to be a *problem*)

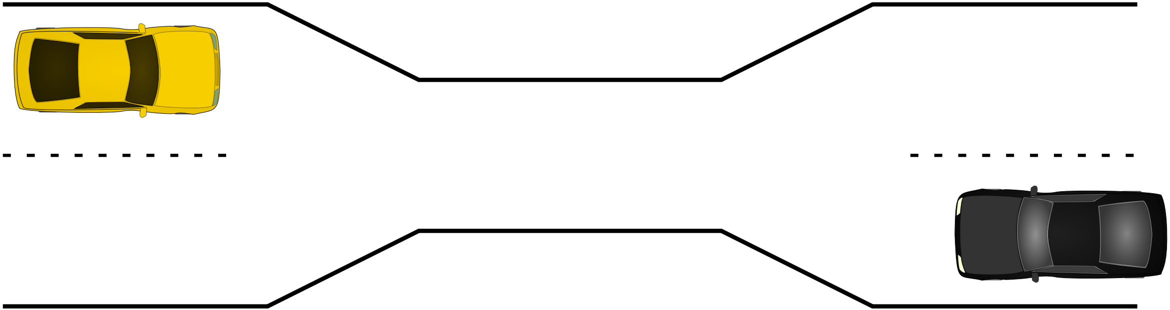
quiz Q4c

append_to_array(dest, A) + append_to_array(dest, B)

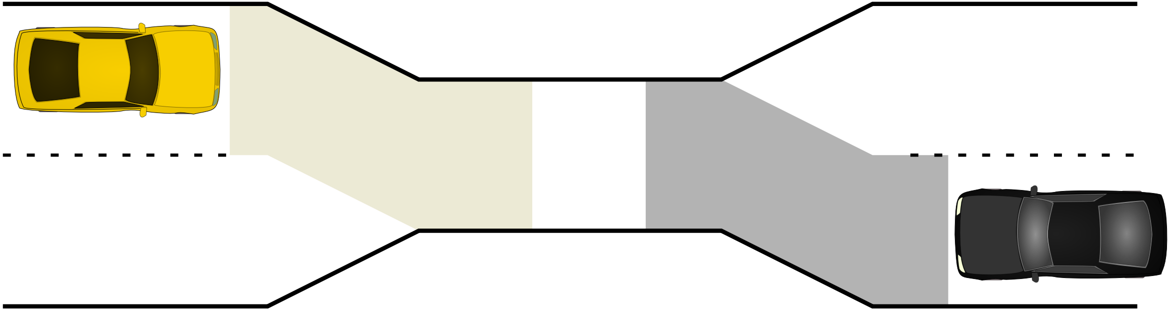
lock for dest is held during whole function

so the two calls take turns

the one-way bridge



the one-way bridge



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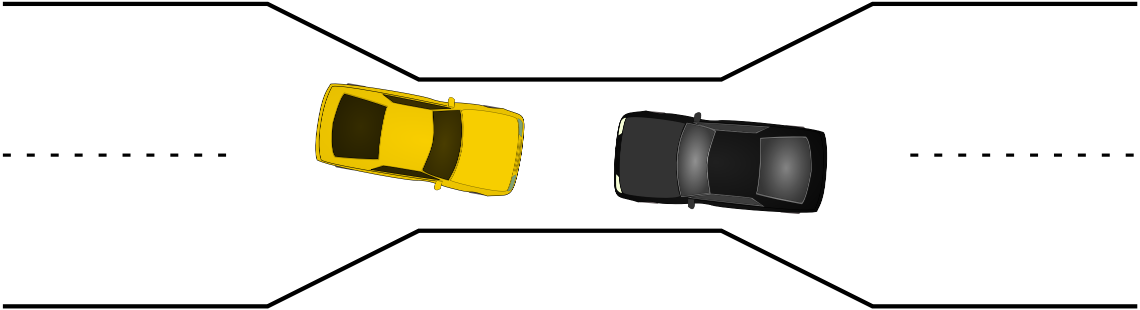
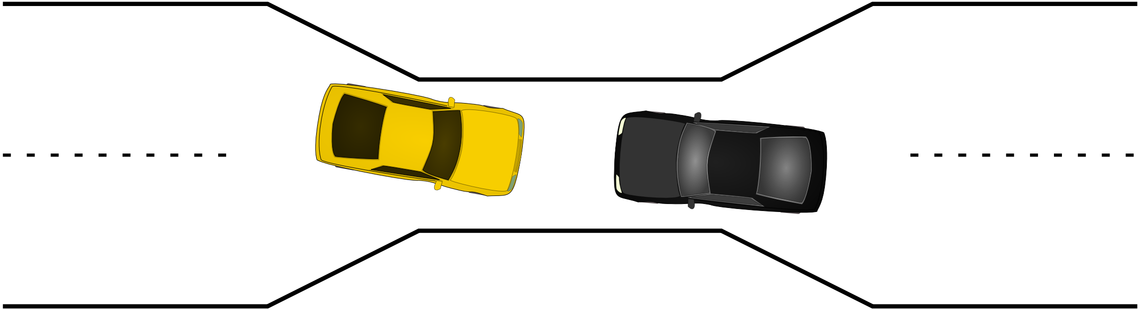


the one-way bridge



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

moving two files: lucky timeline (2)

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

moving two files: unlucky timeline

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

moving two files: unlucky timeline

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

moving two files: unlucky timeline

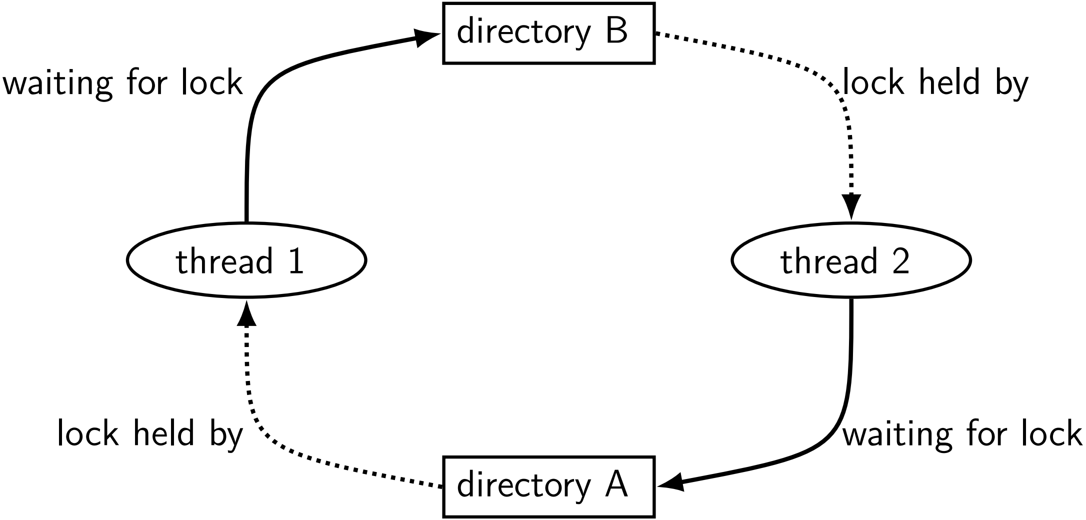
Thread 1 `MoveFile(A, B, "foo")`	Thread 2 `MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`
`lock(&B->lock…` stalled	
(waiting for lock on B)	`lock(&A->lock…` stalled
(waiting for lock on B)	(waiting for lock on A)
~~(do move)~~ unreachable	~~(do move)~~ unreachable
~~`unlock(&B->lock);`~~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

moving two files: unlucky timeline

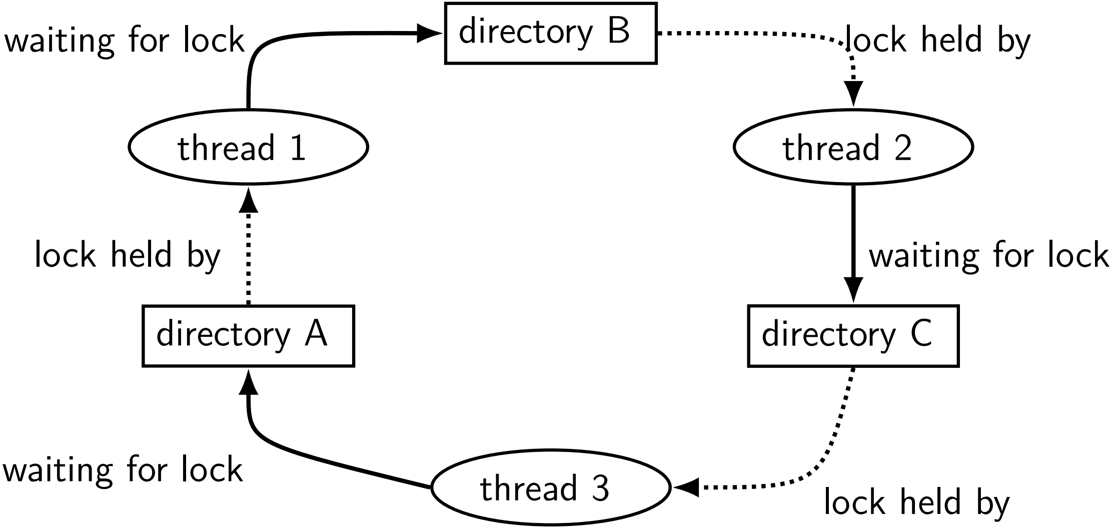
Thread 1	Thread 2
`MoveFile(A, B, "foo")`	`MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`
`lock(&B->lock…` stalled	
(waiting for lock on B)	`lock(&A->lock…` stalled
(waiting for lock on B)	(waiting for lock on A)
~~(do move)~~ unreachable	~~(do move)~~ unreachable
~~`unlock(&B->lock);`~~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

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

moving two files: dependencies



moving three files: dependencies



moving three files: unlucky timeline

Thread 1	Thread 2	Thread 3
`MoveFile(A, B, "foo")`	`MoveFile(B, C, "bar")`	`MoveFile(C, A, "quux")`
`lock(&A->lock);`		
	`lock(&B->lock);`	
		`lock(&C->lock);`
`lock(&B->lock...` stalled		
	`lock(&C->lock...` stalled	
		`lock(&A->lock...` stalled

deadlock with free space

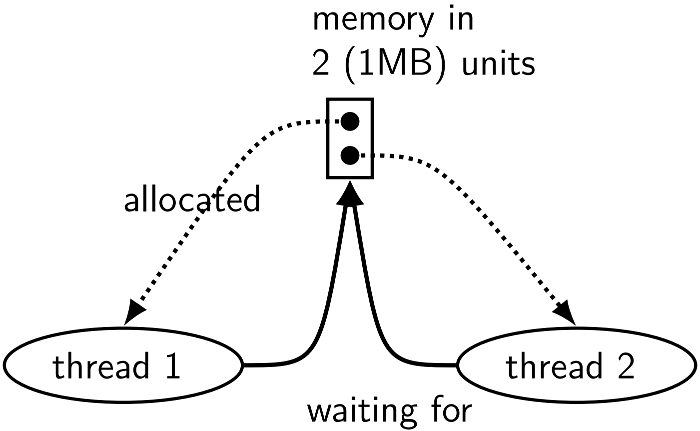
Thread 1	Thread 2
`AllocateOrWaitFor(1 MB)`	`AllocateOrWaitFor(1 MB)`
`AllocateOrWaitFor(1 MB)`	`AllocateOrWaitFor(1 MB)`
`(do calculation)`	`(do calculation)`
`Free(1 MB)`	`Free(1 MB)`
`Free(1 MB)`	`Free(1 MB)`

2 MB of space — deadlock possible with unlucky order

deadlock with free space (unlucky case)

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

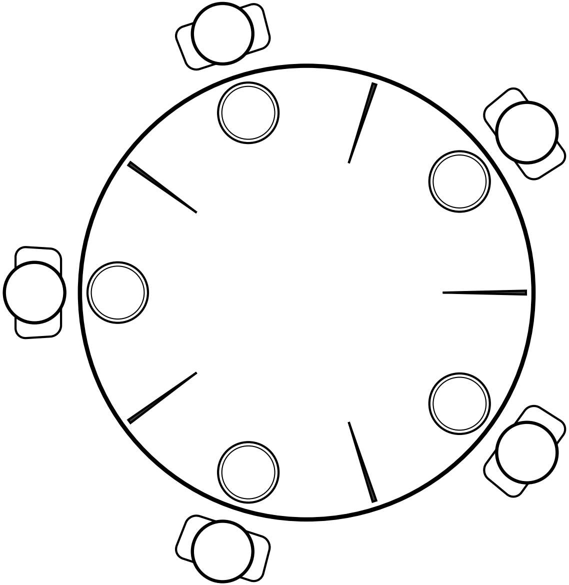
free space: dependency graph



deadlock with free space (lucky case)

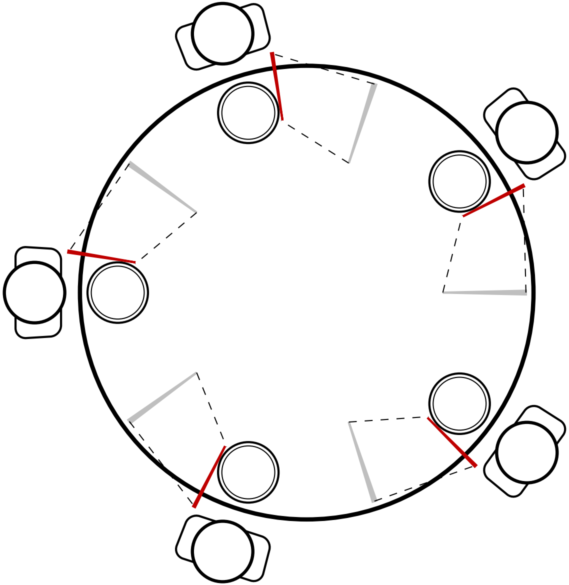
Thread 1	Thread 2
`AllocateOrWaitFor(1 MB)`	
`AllocateOrWaitFor(1 MB)`	
`(do calculation)`	
`Free(1 MB);`	
`Free(1 MB);`	
	`AllocateOrWaitFor(1 MB)`
	`AllocateOrWaitFor(1 MB)`
	`(do calculation)`
	`Free(1 MB);`
	`Free(1 MB);`

dining philosophers



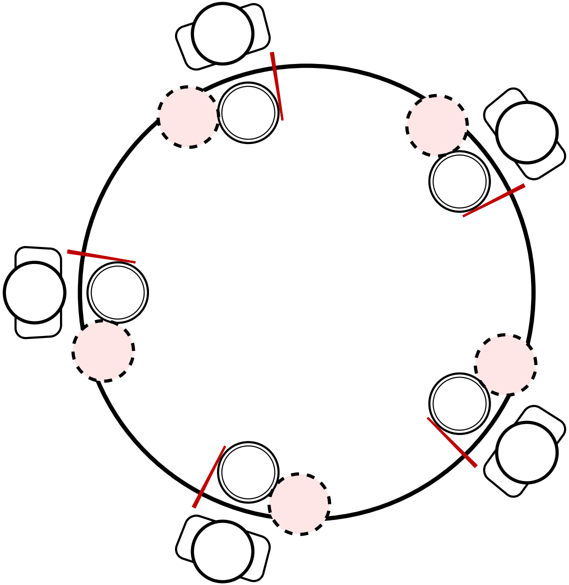
five philosophers either think or eat
to eat:
grab chopstick on left, then
grba chopstick on right, then
then eat, then
return chopsticks

dining philosophers



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

dining philosophers



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

deadlock

deadlock — circular waiting for resources

resource = something needed by a thread to do work

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

often non-deterministic in practice

most common example: when acquiring multiple locks

deadlock

deadlock — circular waiting for resources

resource = something needed by a thread to do work

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

often non-deterministic in practice

most common example: when acquiring multiple locks

deadlock 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 $\{T_1, \ldots, T_n\}$ of waiting threads such that

T_1 is waiting for a resource held by T_2

T_2 is waiting for a resource held by T_3

…

T_n is waiting for a resource held by T_1

how is deadlock possible?

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

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

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

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

how is deadlock — solution

Remove B	Remove C
lock B	lock C
lock A (prev)	wait to lock B (prev)
wait to lock C (next)	

With B and D — only overlap in in node C — no circular wait possible

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*

deadlock prevention techniques

infinite resources — no *mutual exclusion*

or at least enough that never run out

no shared resources — no *mutual exclusion*

no waiting — no *hold and wait*/*preemption*

“busy signal” — abort and (maybe) retry

revoke/preempt resources

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

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revoke/preempt resources

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

deadlock prevention techniques

infinite resources

or at least enough that never run out

no *mutual exclusion*

memory allocation: malloc() fails rather than waiting (no deadlock)
locks: `pthread_mutex_trylock` fails rather than waiting
...

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*

stealing locks???

how do we make stealing locks possible

unclean: just kill the thread

- problem: inconsistent state?

clean: have code to undo partial oepration

- 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 — no *mutual exclusion*

or at least enough that never run out

no shared resources — no *mutual exclusion*

no waiting — no *hold and wait*/*preemption*

"busy signal" — abort and (maybe) retry

revoke/preempt resources

acquire resources in **consistent order** — no *circular 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, fil
  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")`	Thread 2 `MoveFile(B, A, "bar")`
`lock(&A->lock)` → LOCKED	
	`lock(&B->lock)` → LOCKED
`trylock(&B->lock)` → FAILED	
	`trylock(&A->lock)` → FAILED
`unlock(&A->lock)`	
	`unlock(&B->lock)`
`lock(&A->lock)` → LOCKED	
	`lock(&B->lock)` → LOCKED
`trylock(&B->lock)` → FAILED	
	`trylock(&A->lock)` → FAILED
`unlock(&A->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 waiti

"busy signal" — abort and (maybe) retry

revoke/preempt resources

no *hold and wait*/ *preemption*

acquire resources in **consistent order**

no *circular 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*

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*

deadlock detection

why? debugging or fix deadlock by aborting operations

idea: search for cyclic dependencies

detecting deadlocks on locks

let's say I want to detect deadlocks that only involve mutexes

- goal: help programmers debug deadlocks

…by modifying my threading library:

```
struct Thread {
    ... /* stuff for implementing thread */
    /* what extra fields go here? */



};

struct Mutex {
    ... /* stuff for implementing mutex */
    /* what extra fields go here? */



};
```

deadlock detection

why? debugging or fix deadlock by aborting operations

idea: search for cyclic dependencies

need:

- list of all contended resources
- what thread is waiting for what?
- what thread ‘owns’ what?

aside: divisible resources

deadlock is possible with divislbe resources like memory,...

example: suppose 6MB of RAM for threads total:

- thread 1 has 2MB allocated, waiting for 2MB
- thread 2 has 2MB allocated, waiting for 2MB
- thread 3 has 1MB allocated, waiting for keypress

cycle: thread 1 waiting on memory owned by thread 2?

not a deadlock — thread 3 can still finish

- and after it does, thread 1 or 2 can finish

aside: divisible resources

deadlock is possible with divislbe resources like memory,...

example: suppose 6MB of RAM for threads total:

- thread 1 has 2MB allocated, waiting for 2MB
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- thread 3 has 1MB allocated, waiting for keypress

cycle: thread 1 waiting on memory owned by thread 2?

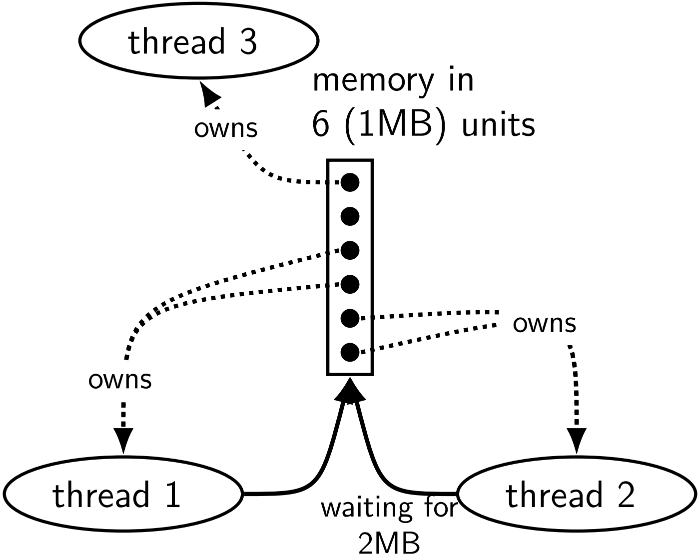
not a deadlock — thread 3 can still finish

- and after it does, thread 1 or 2 can finish

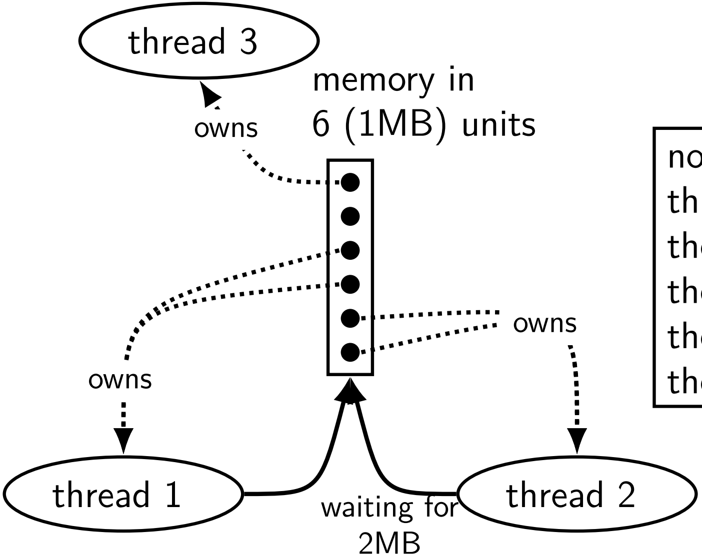
...but would be deadlock

- ...if thread 3 waiting lock held by thread 1
- ...with 5MB of RAM

divisible resources: not deadlock

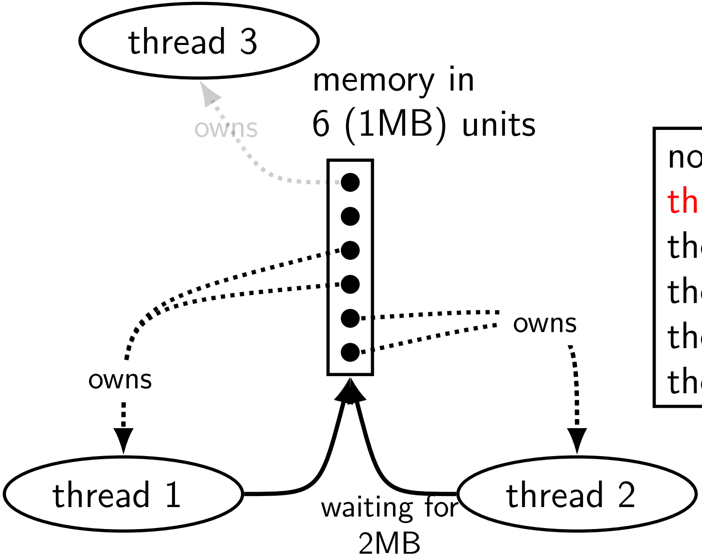


divisible resources: not deadlock



not deadlock:
thread 3 finishes
then thread 1 can get memory
then thread 1 finishes
then thread 2 can get resources
then thread 2 can finish

divisible resources: not deadlock



not deadlock:
thread 3 finishes
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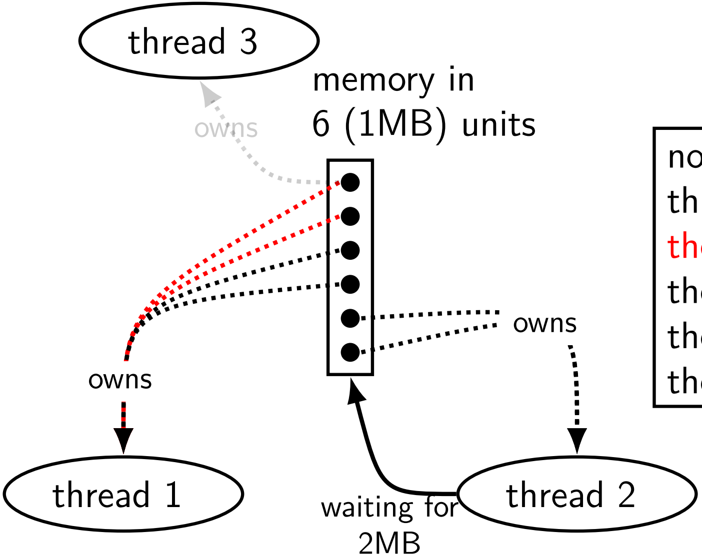
divisible resources: not deadlock



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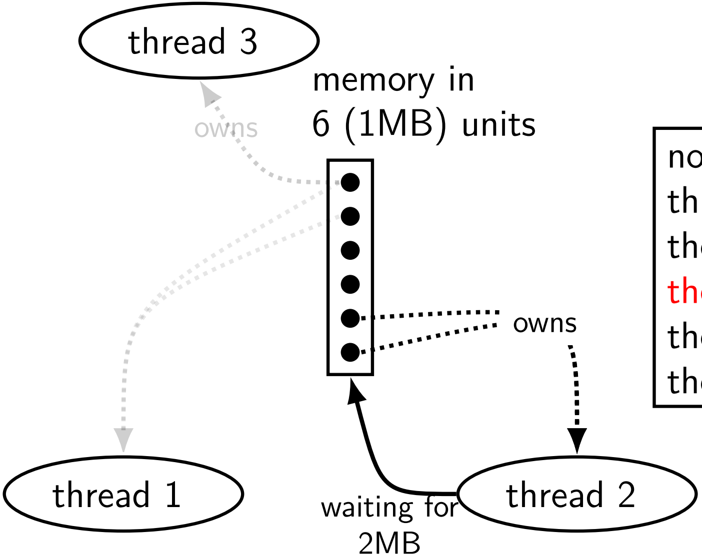
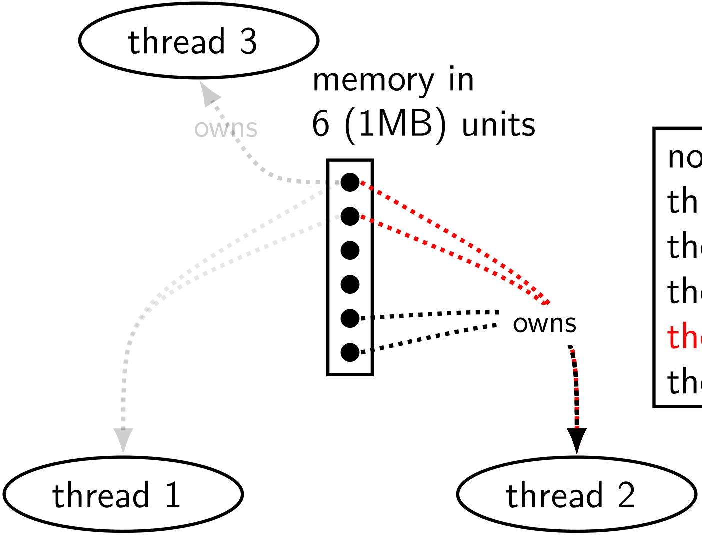
divisible resources: not deadlock



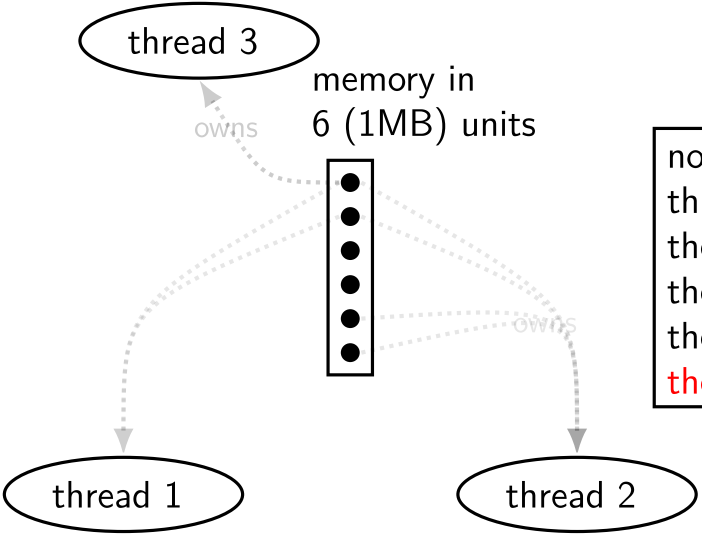
not deadlock:
thread 3 finishes
then thread 1 can get memory
then thread 1 finishes
then thread 2 can get resources
then thread 2 can finish

divisible resources: not deadlock



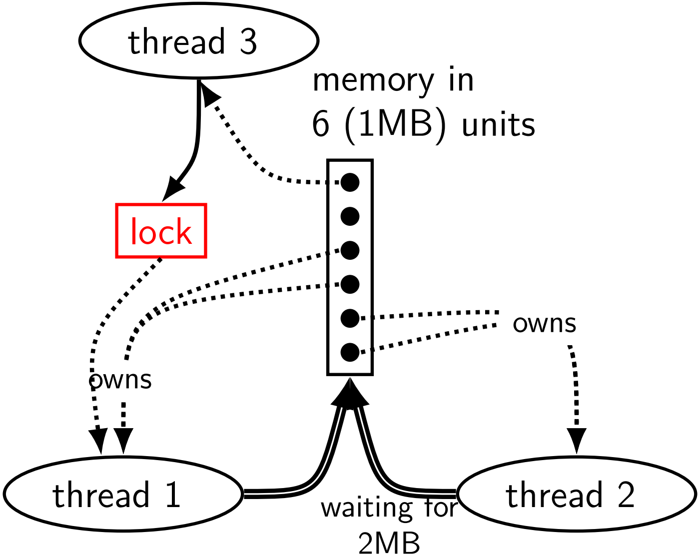
not deadlock:
thread 3 finishes
then thread 1 can get memory
then thread 1 finishes
then thread 2 can get resources
then thread 2 can finish

divisible resources: not deadlock

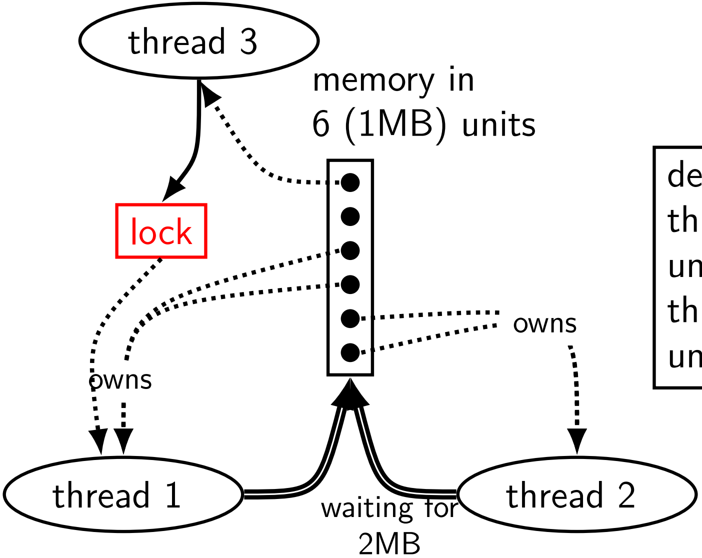


not deadlock:
thread 3 finishes
then thread 1 can get memory
then thread 1 finishes
then thread 2 can get resources
then thread 2 can finish

divisible resources: is deadlock

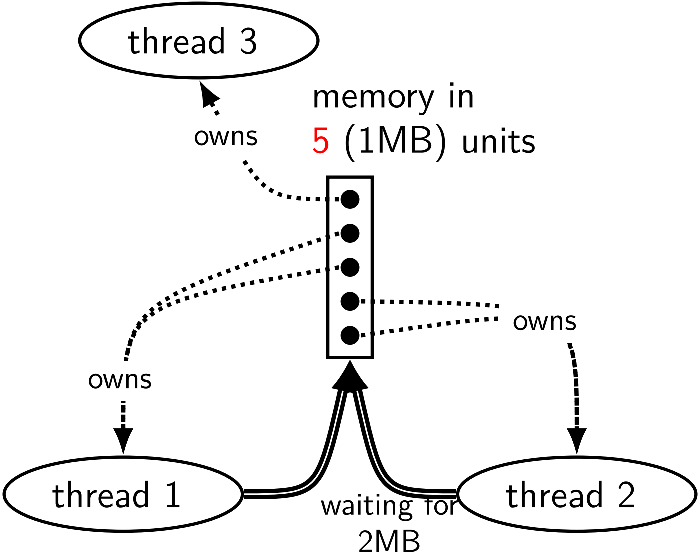


divisible resources: is deadlock

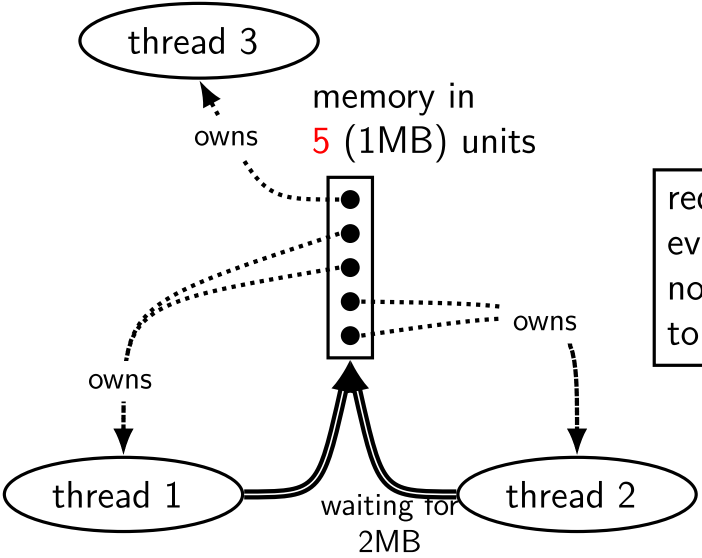


deadlock:
thread 3 can't finish
until thread 1 releases lock, but
thread 1 can't finish
until thread 3 releases memory

divisible resources: is deadlock

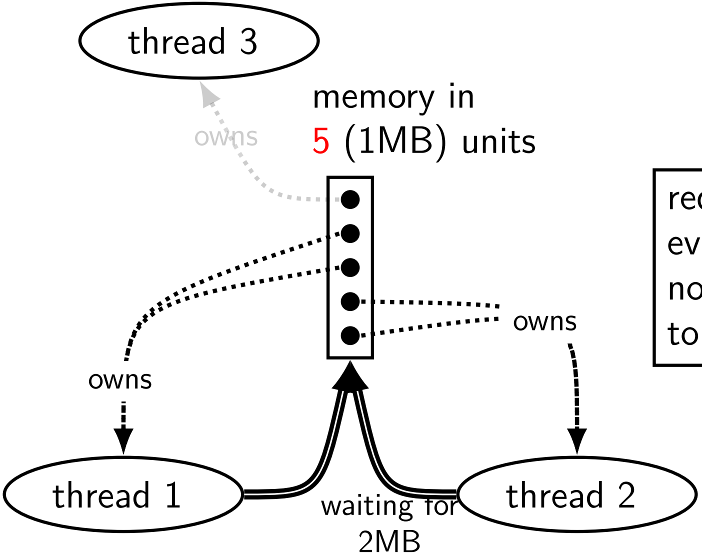


divisible resources: is deadlock



reducing memory: deadlock:
even after thread 3 finishes
no way for thread 1+2
to get what they want

divisible resources: is deadlock



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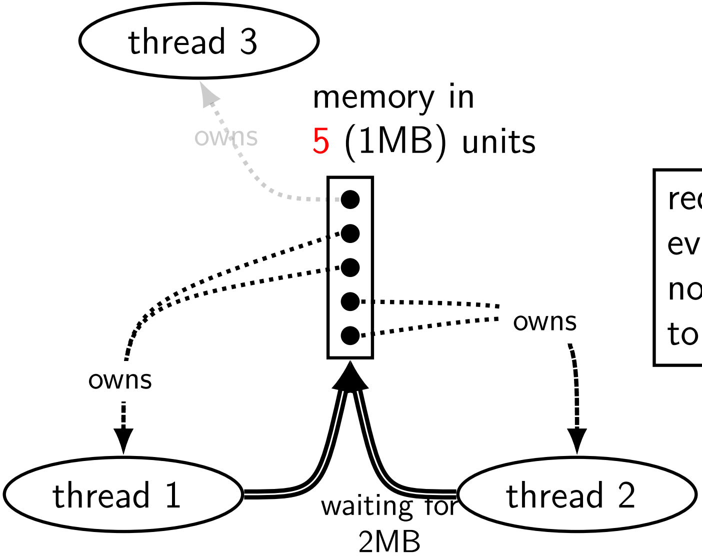

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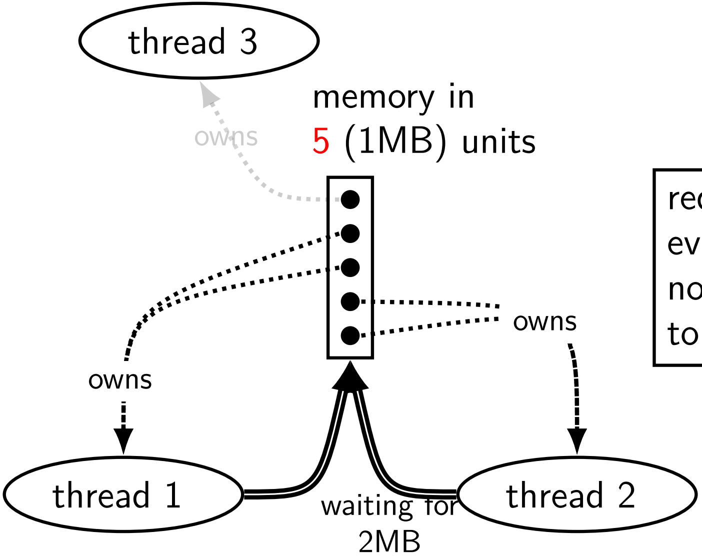

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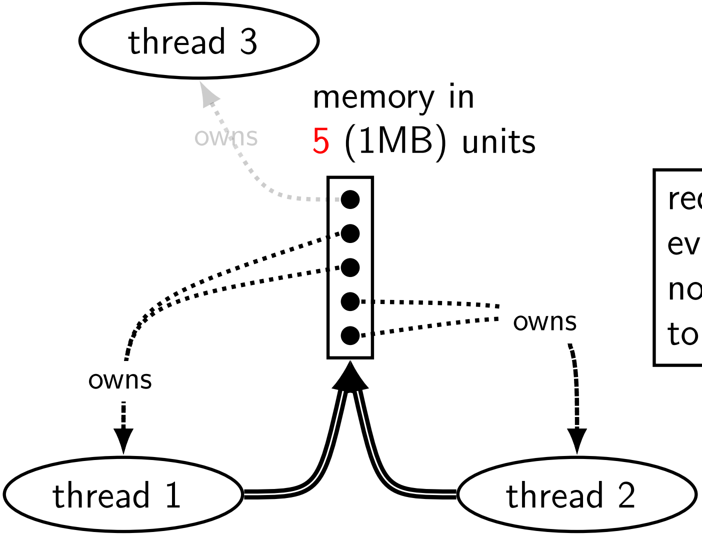


reducing memory: deadlock:
even after thread 3 finishes
no way for thread 1+2
to get what they want

deadlock detection with divisible resources

for each resource: track which threads have those resources

for each thread: resources they are waiting for

repeatedly:

find a thread where all the resources it needs are available
remove that thread and mark the resources it has as free — it can complete now!

either: all threads eliminated *or* found deadlock

aside: deadlock detection in reality

requires:

- instrumenting contended resources
- "undo" to get out of deadlock

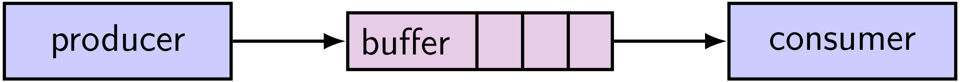
common example: for locks in a database

- database typically has customized locking code
- "undo" exists as side-effect of code for handling power/disk failures

related idea: *avoid* deadlock with detection on "what if" scenario

- see Banker's algorithm

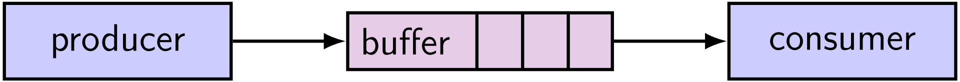
example: producer/consumer



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

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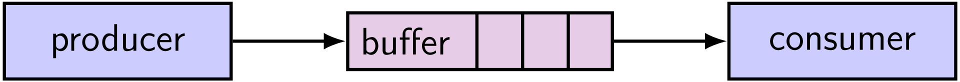
producer(s) and consumer(s) don't work in lockstep

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

example: producer/consumer



shared buffer (queue) of fixed size

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producer(s) and consumer(s) don't work in lockstep

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

example: C compiler

- preprocessor → compiler → assembler → linker

monitors/condition variables

locks for mutual exclusion

condition variables for waiting for event

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

related data structures

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

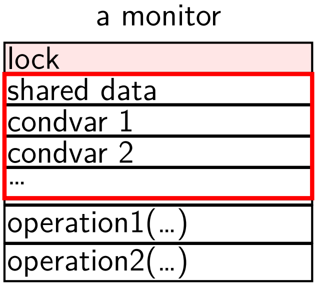
- Java: every object is a monitor (has instance variables, built-in lock, cond. var)
- pthreads: build your own: provides you locks + condition variables

monitor idea

a monitor

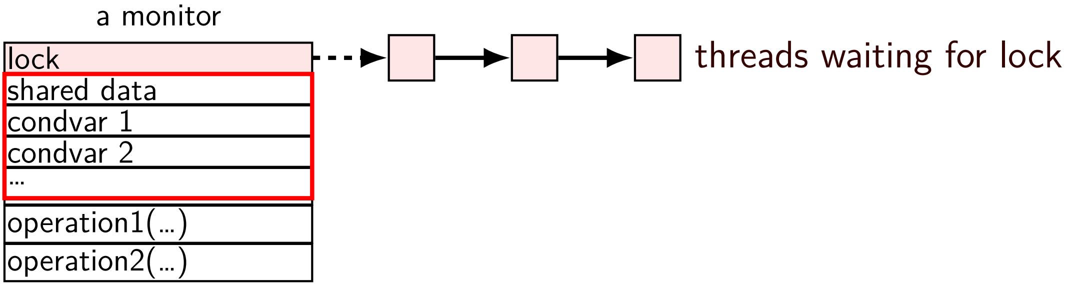
lock
shared data
condvar 1
condvar 2
...
operation1(…)
operation2(…)

monitor idea

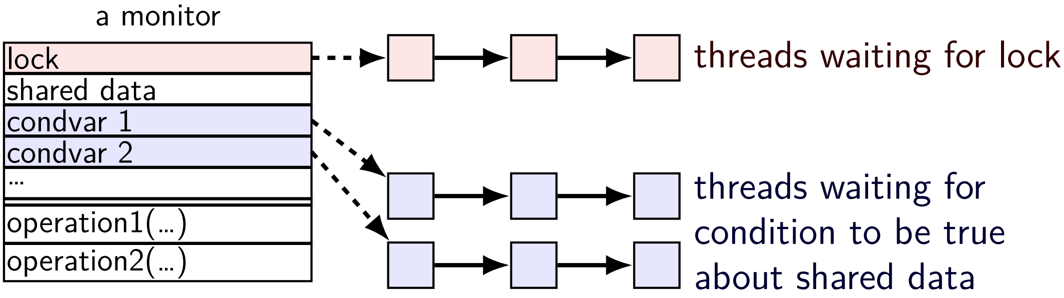


lock must be acquired
before accessing
any part of monitor's stuff

monitor idea

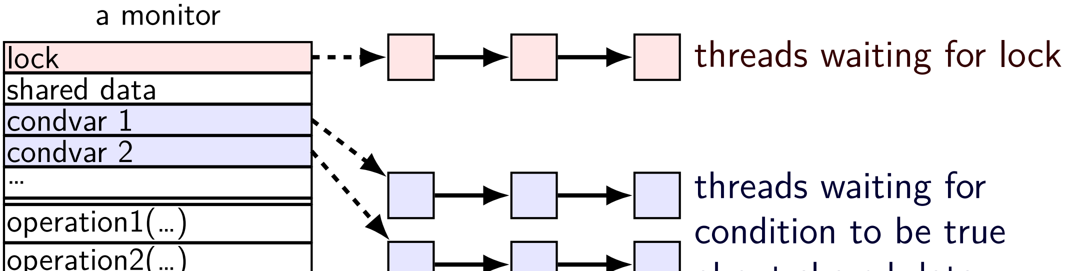


monitor idea



condvar operations

condvar operations:
Wait(cv, lock) — unlock lock, add current thread to cv queue
...and reacquire lock before returning
Broadcast(cv) — remove all from condvar queue
Signal(cv) — remove one from condvar queue



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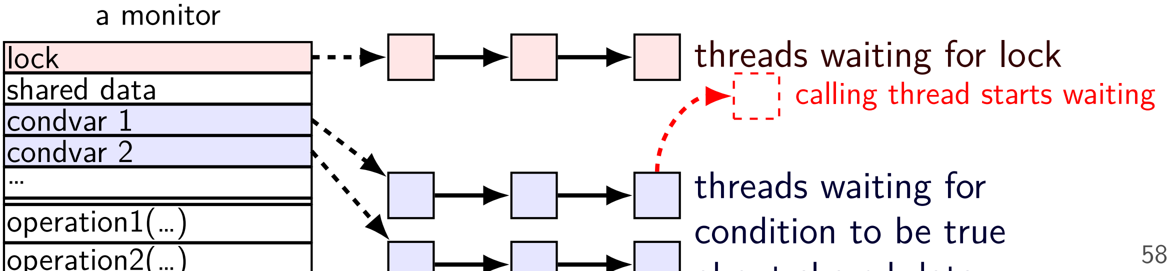

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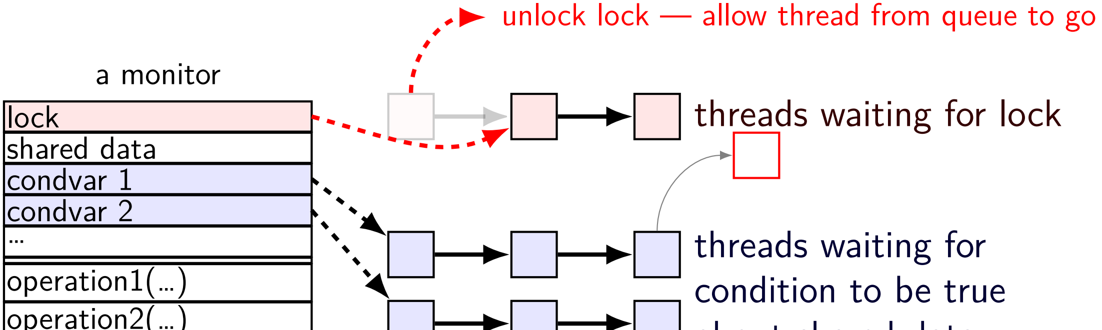

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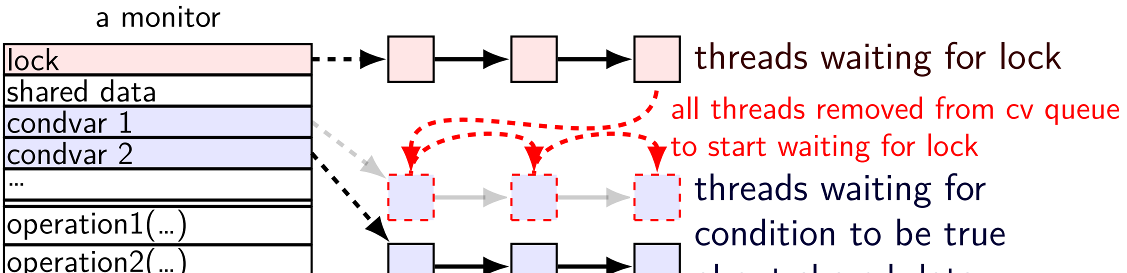

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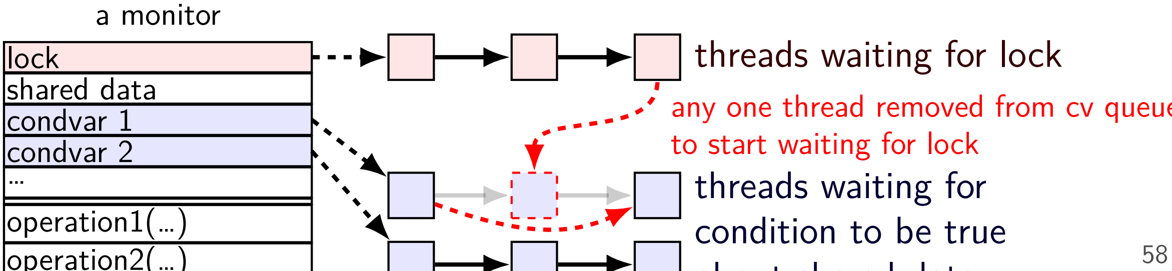

pthread cv usage

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

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

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

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}

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

acquire lock before reading or writing `finished`

pthread cv usage

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

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  }
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}

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

check whether we need to wait at all

(why a loop? we'll explain later)

pthread cv usage

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}

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

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}

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

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

WaitForFinish timeline 1

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

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

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

WaitForFinish timeline 2

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

why the loop

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

we only `broadcast` if `finished` is true

so why check `finished` afterwards?

why the loop

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

we only `broadcast` if `finished` is true

so why check `finished` afterwards?

pthread_cond_wait manual page:

> "Spurious wakeups ... may occur."

spurious wakeup = `wait` returns even though nothing happened

unbounded buffer producer/consumer

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

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

unbounded buffer producer/consumer

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

rule: never touch buffer without acquiring lock

otherwise: what if two threads simulatenously en/dequeue?

(both use same array/linked list entry?)

(both reallocate array?)

unbounded buffer producer/consumer

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

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

check if empty
if so, dequeue

okay because have lock

other threads can**not** dequeue here

unbounded buffer producer/consumer

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

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

wake one Consume thread *if any are waiting*

unbounded buffer producer/consumer

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

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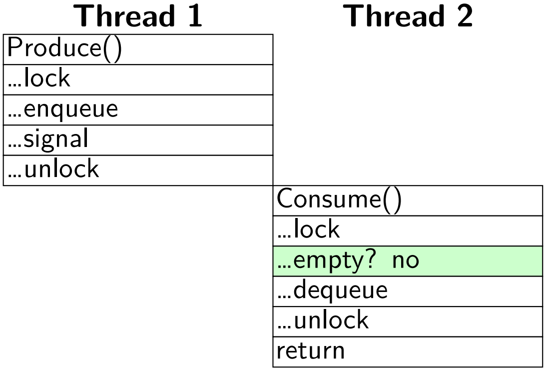
    pthread_mutex_unlock(&lock);
}
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_mutex_unlock(&lock);
    return item;
}
```



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

unbounded buffer producer/consumer

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

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

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

unbounded buffer producer/consumer

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

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

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

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

unbounded buffer producer/consumer

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

in pthreads: signalled thread not gaurenteed to hold lock next

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

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

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

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

backup slides

backup slides

pipe() deadlock

BROKEN example:

```
int child_to_parent_pipe[2], parent_to_child_pipe[2];
pipe(child_to_parent_pipe); pipe(parent_to_child_pipe);
if (fork() == 0) {
    /* child */
    write(child_to_parent_pipe[1], buffer, HUGE_SIZE);
    read(parent_to_child_pipe[0], buffer, HUGE_SIZE);
    exit(0);
} else {
    /* parent */
    write(parent_to_child_pipe[1], buffer, HUGE_SIZE);
    read(child_to_parent_pipe[0], buffer, HUGE_SIZE);
}
```

This will hang forever (if HUGE_SIZE is big enough).

deadlock waiting

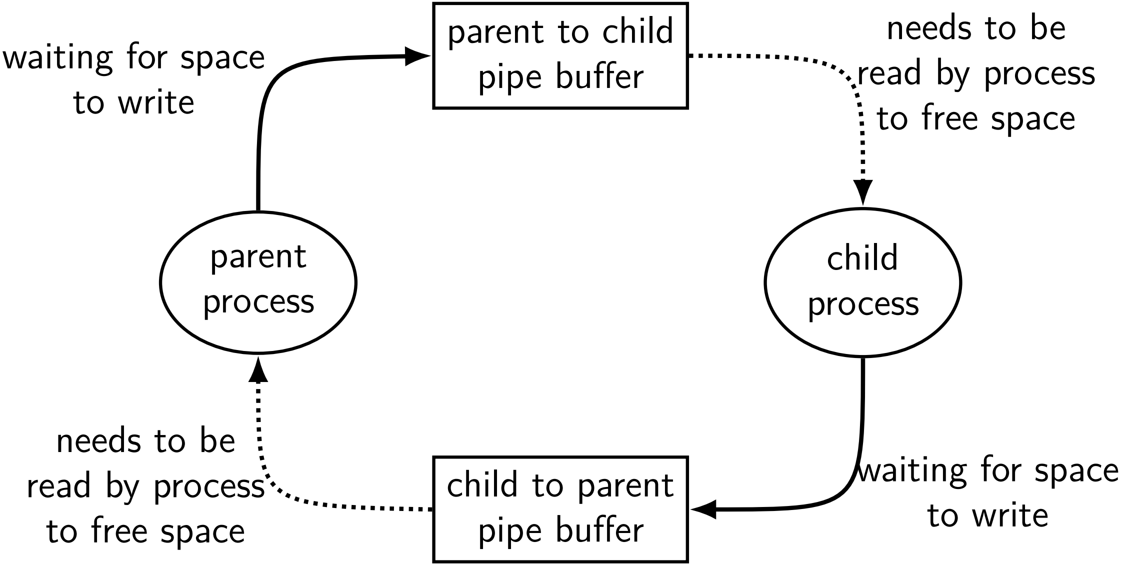
child writing to pipe waiting for free buffer space

...which will not be available until parent reads

parent writing to pipe waiting for free buffer space

...which will not be available until child reads

circular dependency



allocating all at once?

for resources like disk space, memory

figure out maximum allocation when starting thread

- "only" need conservative estimate

only start thread if those resources are available

okay solution for embedded systems?

deadlock with free space

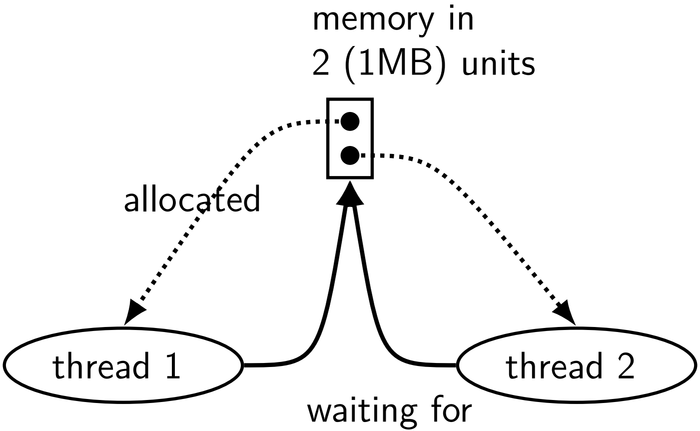
Thread 1	Thread 2
`AllocateOrWaitFor(1 MB)`	`AllocateOrWaitFor(1 MB)`
`AllocateOrWaitFor(1 MB)`	`AllocateOrWaitFor(1 MB)`
`(do calculation)`	`(do calculation)`
`Free(1 MB)`	`Free(1 MB)`
`Free(1 MB)`	`Free(1 MB)`

2 MB of space — deadlock possible with unlucky order

deadlock with free space (unlucky case)

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

free space: dependency graph



deadlock with free space (lucky case)

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

AllocateOrFail

Thread 1	Thread 2
`AllocateOrFail(1 MB)`	
	`AllocateOrFail(1 MB)`
`AllocateOrFail(1 MB)` fails!	
	`AllocateOrFail(1 MB)` fails!
`Free(1 MB)` (cleanup after failure)	
	`Free(1 MB)` (cleanup after failure)

okay, now what?

- give up?
- both try again? — maybe this will keep happening? (called livelock)
- try one-at-a-time? — gaurenteed to work, but tricky to implement

AllocateOrSteal

Thread 1	Thread 2
`AllocateOrSteal(1 MB)`	
	`AllocateOrSteal(1 MB)`
`AllocateOrSteal(1 MB)`	`Thread killed to free 1MB`
(do work)	

problem: can one actually implement this?

problem: can one kill thread and keep system in consistent state?

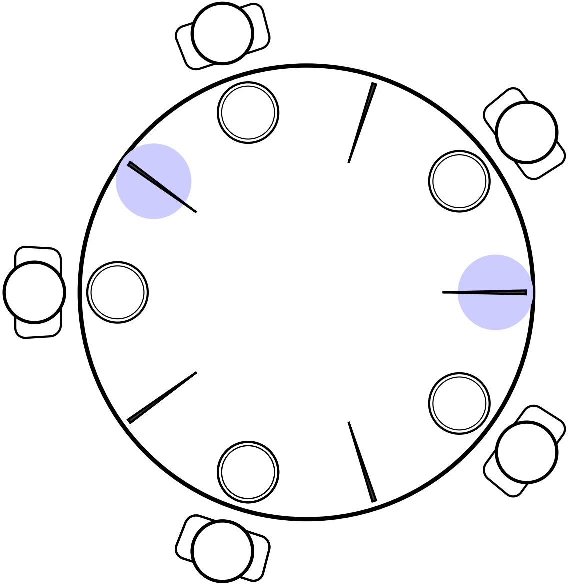
fail/steal with locks

pthreads provides pthread_mutex_trylock — "lock or fail"

some databases implement *revocable locks*

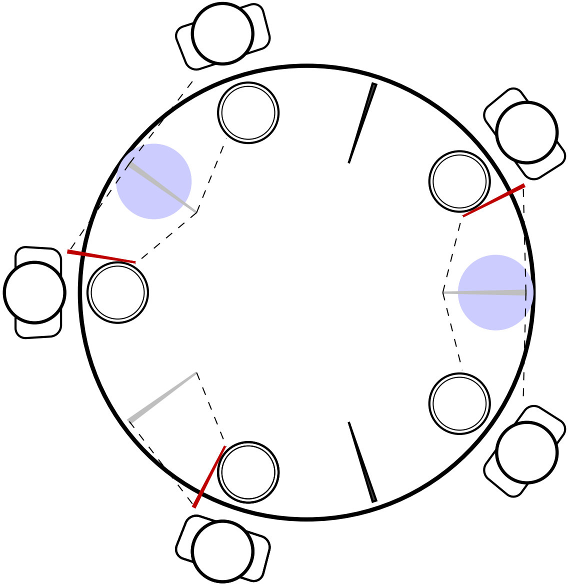
- do equivalent of throwing exception in thread to 'steal' lock
- need to carefully arrange for operation to be cleaned up

dining philosophers — ordering



mark some chopsticks places
rule: grab from marked place first
only grab other chopstick after that

dining philosophers — ordering



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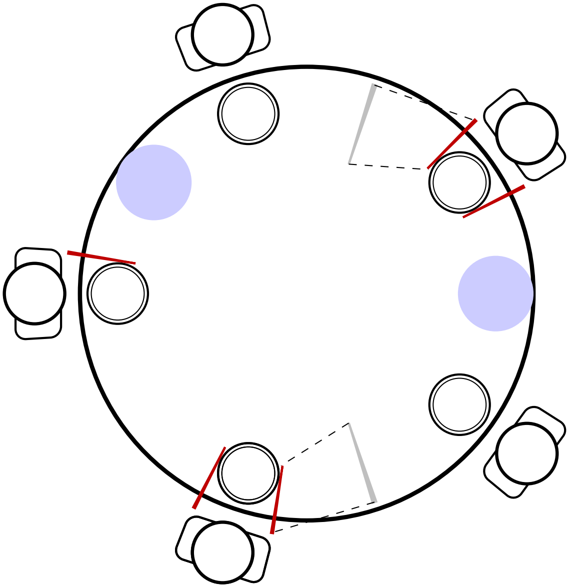

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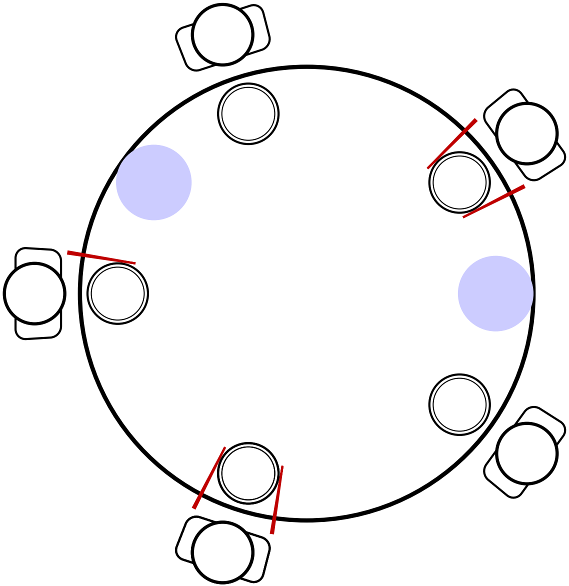
dining philosophers — ordering



mark some chopsticks places
rule: grab from marked place first
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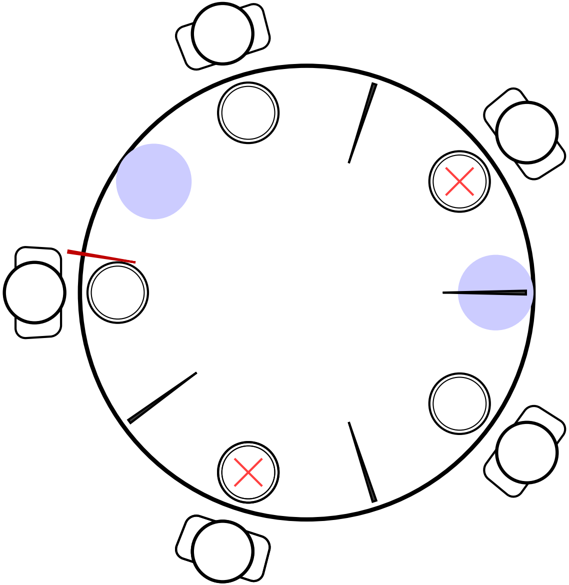
avoids circular dependency,
means everyone else
eventually gets a turn

dining philosophers — ordering



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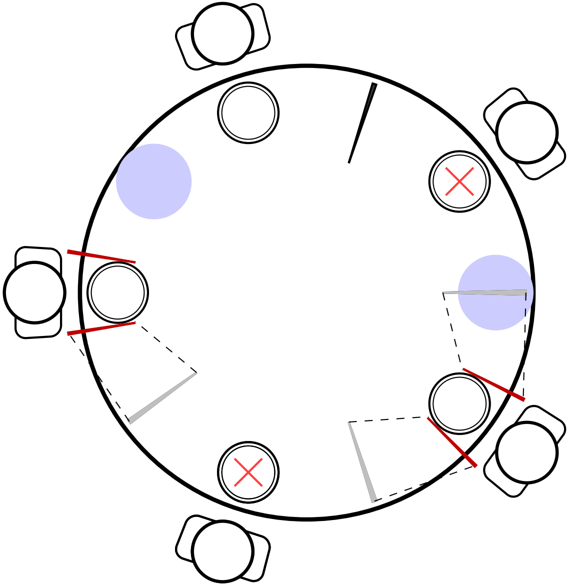

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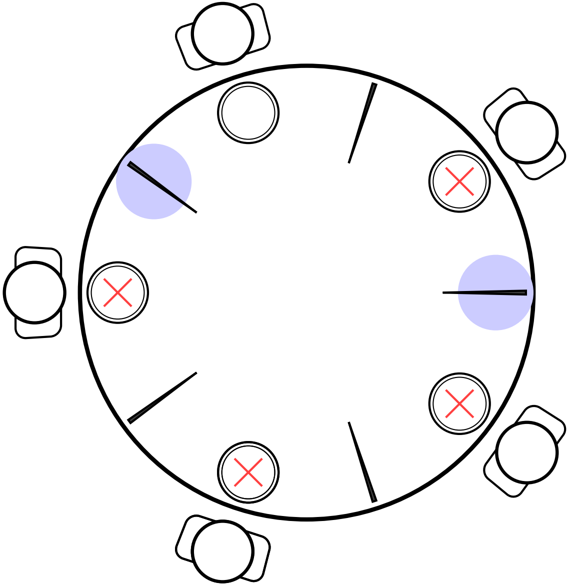

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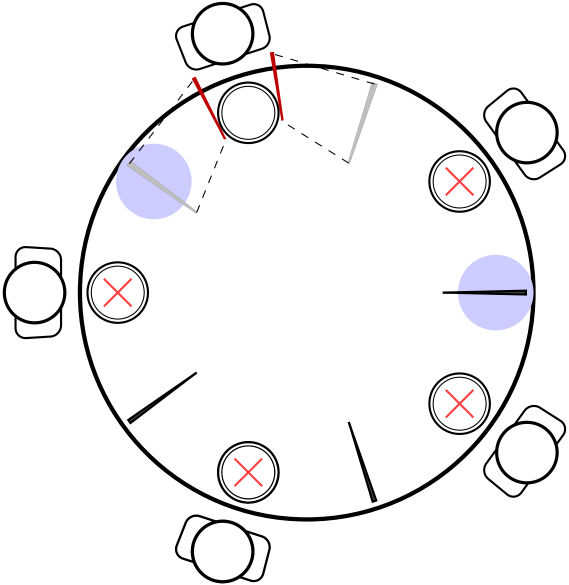

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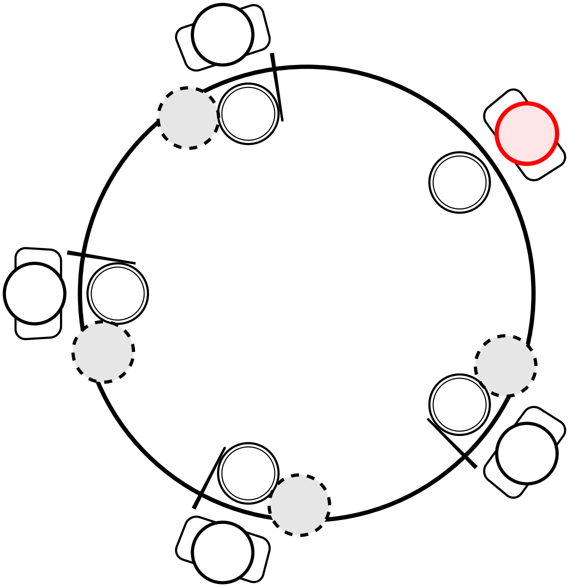

dining philosopher
what if someone's impatient
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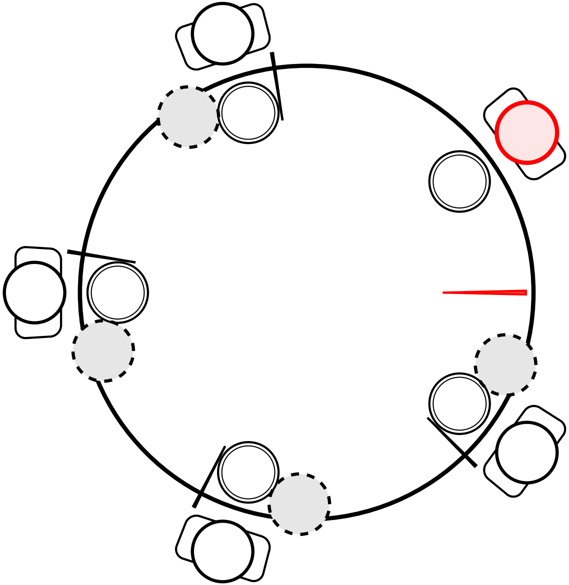

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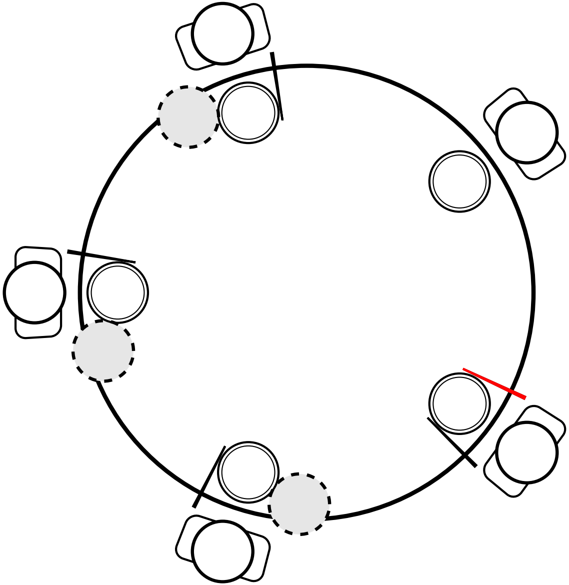

now everyone else can eat

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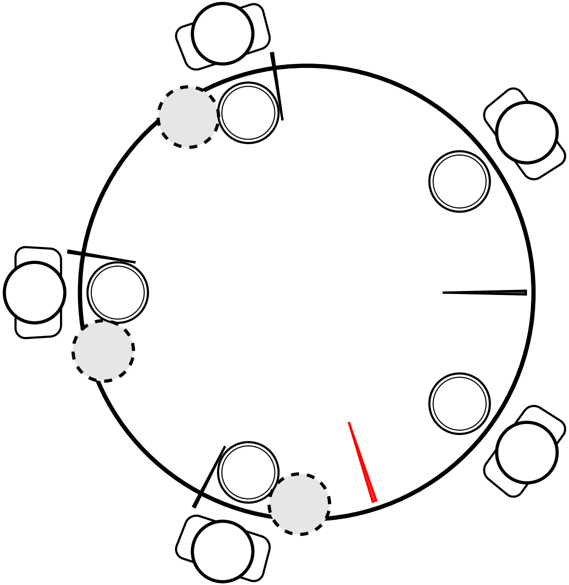

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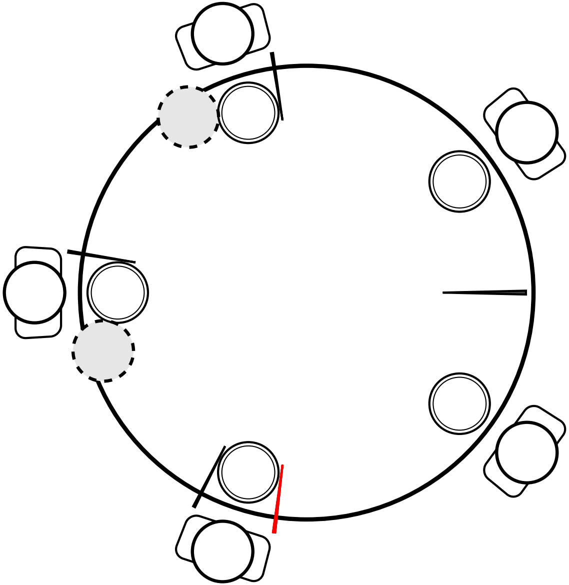

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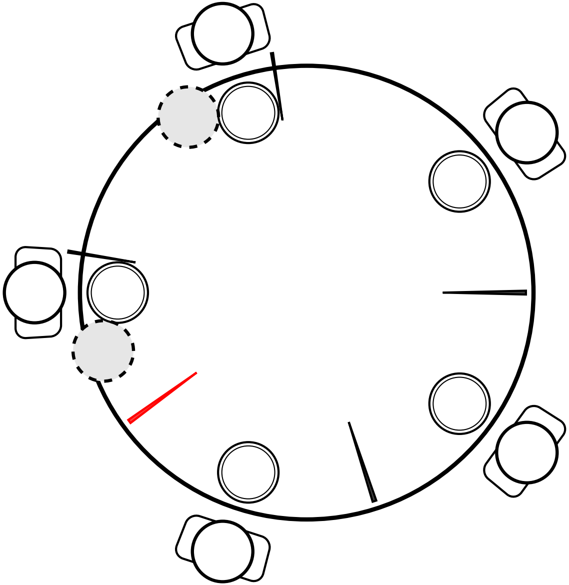

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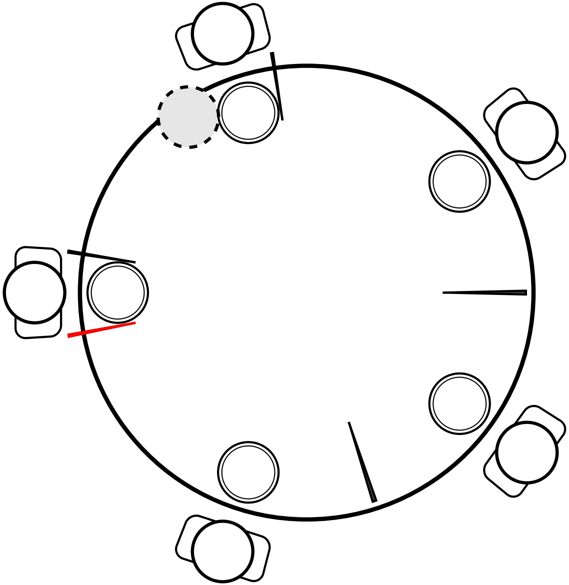

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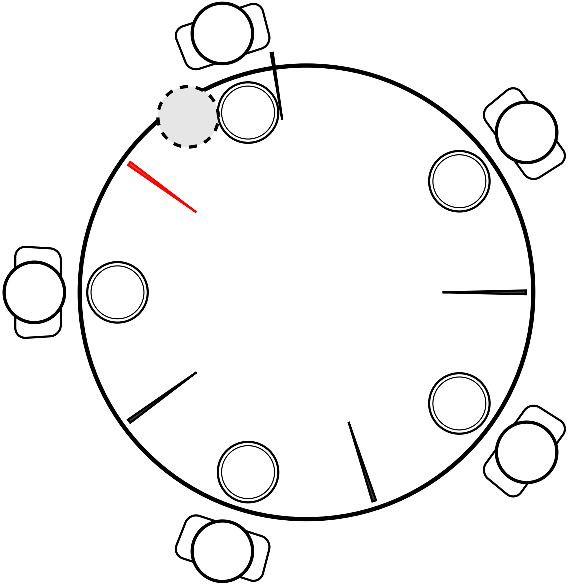

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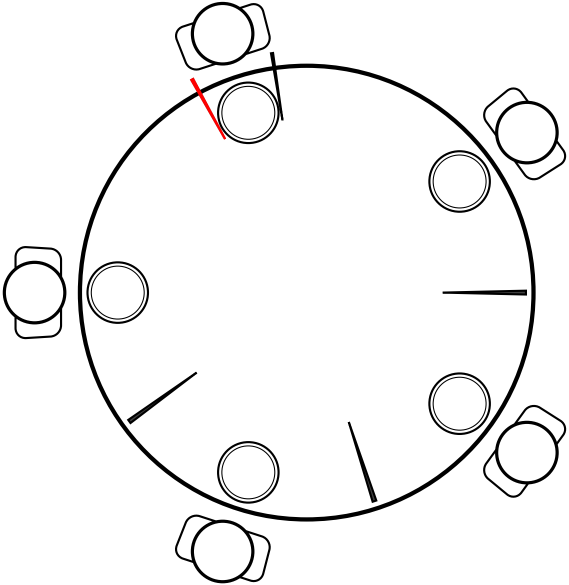

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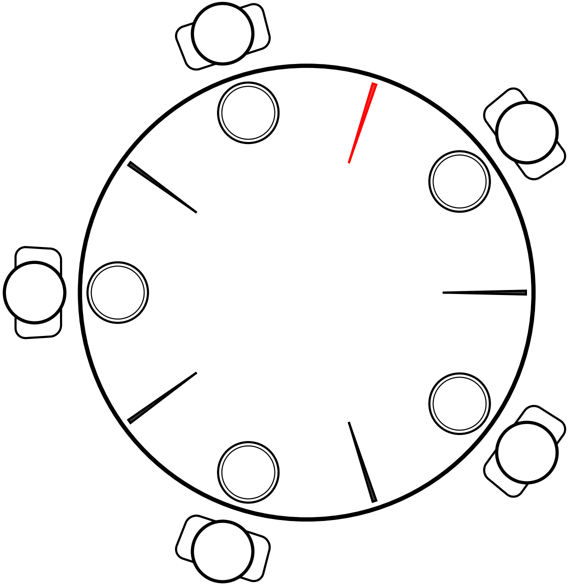

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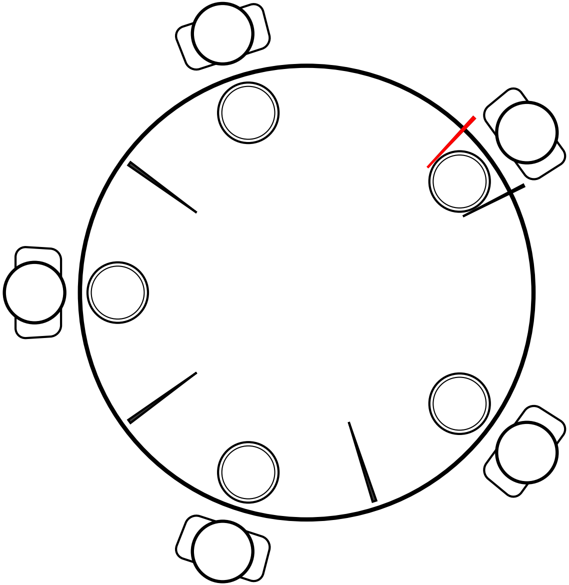

and person who gave up
might succeed later

using deadlock detection for prevention

suppose you know the *maximum resources* a process could request

make decision when starting process ("*admission control*")

using deadlock detection for prevention

suppose you know the *maximum resources* a process could request

make decision when starting process ("*admission control*")

ask "what if every process was waiting for maximum resources"

including the one we're starting

would it cause deadlock? then don't let it start

called Banker's algorithm

backup slides

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

naive way has an operation that needs locking:

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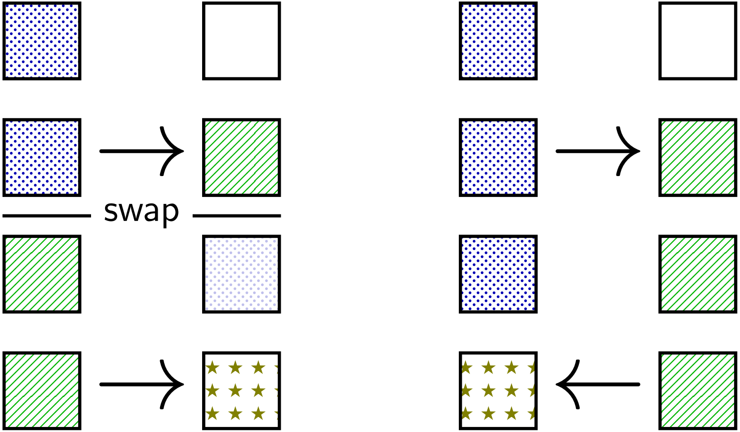
swap

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 t
    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
```

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    test %eax, %eax                // if
    jne acquire                    //
    ret

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

set lock variable to 1 (taken)

read old value

x86-64 spinlock with xchg

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release:
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    movl $0, the_lock           // then, set the_lock to 0 (not taken
    ret
```

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

x86-64 spinlock with xchg

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    jne acquire
    ret

release:
    mfence                      // for memory order reasons
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    ret
```

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

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
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    test %eax, %eax
    jne acquire
    ret

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

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

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

exercise: spin wait

```
finished: .quad 0
ThreadFinish:
    __________A______________
    ret
ThreadWaitForFinish:
    _________B______________
    lock xchg %eax, finished
    cmp $0, %eax
    __C_ ThreadWaitForFinish
    ret
```

```
/* or without using a writing instr
mov %eax, finished
mfence
cmp $0, %eax
je ThreadWaitForFinish
ret
```

A. `mfence; mov $1, finished`
B. `mov $1, finished; mfence`
C. `mov $0, %eax`
D. `mov $1, %eax`
E. je
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

spinlock problems

- 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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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

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one possible implementation

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

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    SpinLock guard_spinlock;
    bool lock_taken = false;
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};
```

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;
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one possible implementation

```
struct Mutex {
    SpinLock guard_spinlock;
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};
```

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

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LockMutex(Mutex *m) {
  LockSpinlock(&m->guard_spinlock);
  if (m->lock_taken) {
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}
```

one possible implementation

```
struct Mutex {
    SpinLock guard_spinlock;
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};
```

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) {
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  }
  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

mutex and scheduler subtly

core 0 (thread A)	core 1 (thread B)	
start LockMutex		
acquire spinlock		
discover lock taken		
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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

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

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x86 instructions:

- `cli` — disable interrupts
- `sti` — enable interrupts

naive interrupt enable/disable (1)

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

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

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problem: user can hang the system:

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

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

naive interrupt enable/disable (2)

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Lock() {
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```
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}
```

naive interrupt enable/disable (2)

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

```
Unlock() {
    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 fe
  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

```
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;
}
```

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)
    ;

  //                                                  or sto
  //                                                  emory
  //
  --
  ..
}
```

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 sto
  // past this point, to ensure that the critical section's memory
  // references happen after the lock is acquired.
  __sync_synchr
  ...
}
```

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 sto
  // past this point, to ensure that the critical section's memory
  //
  __
  ..
}
```

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 sto
  // 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 sto
  // 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
  asm vo

  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 sto
  // 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 sto
  // 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) {
    ...
}
```

append to singly-linked list

```
/* assumption: other threads may be appending to list,
 *             but nodes are not being removed, reordered, etc.
 */
void append_to_list(ListNode *head, ListNode *new_last_node) {
  memory_ordering_fence();
  ListNode *current_last_node;
  do {
    current_last_node = head;
    while (current_last_node->next) {
      current_last_node = current_last_node->next;
    }
  } while (
    !compare-and-swap(&current_last_node->next,
                      NULL, 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

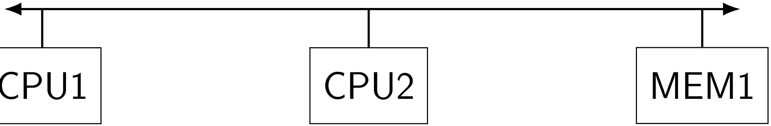
example: hear write while Shared

- 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

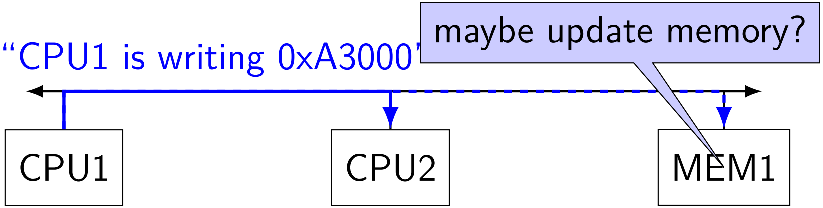
MSI example



address	value	state
0xA300	100	Shared
0xC400	200	Shared
0xE500	300	Shared

address	value	state
0x9300	172	Shared
0xA300	100	Shared
0xC500	200	Shared

MSI example



address	value	state
0xA300	~~100~~101	Modified
0xC400	200	Shared
0xE500	300	Shared

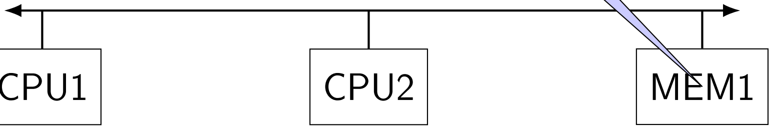
address	value	state
0x9300	172	Shared
~~0xA300~~	~~100~~	Invalid
0xC500	200	Shared

cache sees write: invalidate 0xA300

CPU1 writes 101 to 0xA300

MSI example

nothing changed yet (writeback)



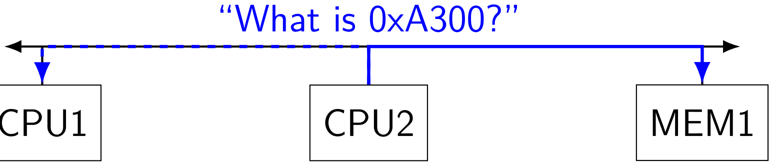
address	value	state
0xA300	~~101~~102	Modified
0xC400	200	Shared
0x		

address	value	state
0x9300	172	Shared
~~0xA300~~	~~100~~	Invalid
		Shared

modified state — nothing communicated!
will "fix" later if there's a read

CPU1 writes 102 to 0xA300

MSI example



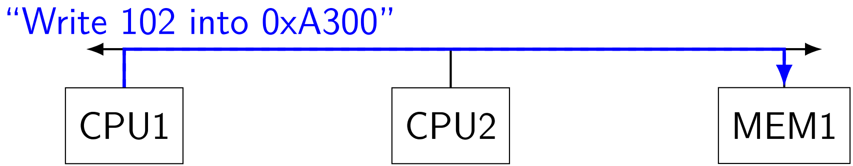
address	value	state
0xA300	102	Modified
0xC400	200	Shared
0		

address	value	state
0x9300	172	Shared
~~0xA300~~	~~100~~	Invalid
		Shared

modified state — must update for CPU2!

CPU2 reads 0xA300

MSI example



CPU1:

address	value	state
0xA300	102	Shared
0xC400	200	Shared
0xE		

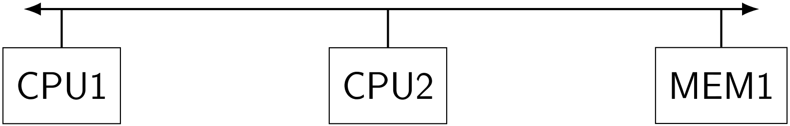
CPU2:

address	value	state
0x9300	172	Shared
~~0xA300~~	~~100~~	Invalid
		Shared

written back to memory early
(could also become Invalid at CPU1)

CPU2 reads 0xA300

MSI example



address	value	state
0xA300	102	Shared
0xC400	200	Shared
0xE500	300	Shared

address	value	state
0x9300	172	Shared
~~0xA300~~	~~100~~102	Shared
0xC500	200	Shared

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

cache coherency exercise solution

action	0x1000-0x101f CPU 1	CPU 2	CPU 3	0x2000-0x201f CPU 1	CPU 2	CPU
	I	I	I	I	I	I
CPU 1: read 0x1000	S	I	I	I	I	I
CPU 2: read 0x1000	S	S	I	I	I	I
CPU 1: write 0x1000	M	I	I	I	I	I
CPU 1: read 0x2000	M	I	I	S	I	I
CPU 2: read 0x1000	S	S	I	S	I	I
CPU 2: write 0x2008	S	S	I	I	M	I
CPU 3: read 0x1008	S	S	S	I	M	I

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

Source: Intel 64 and IA-32 Software Developer's Manual, Volume 3A, Chapter 8

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

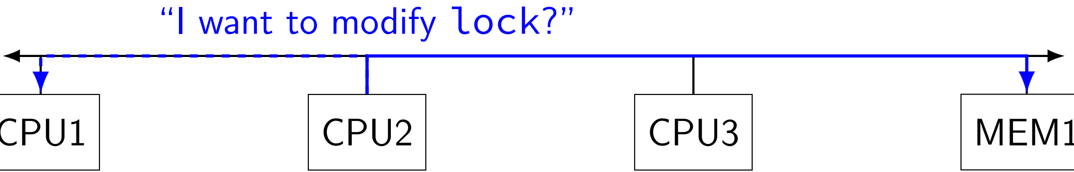
ping-ponging

address	value	state
lock	locked	Modified

address	value	state
lock	---	Invalid

address	value	state
lock	---	Invalid

ping-ponging



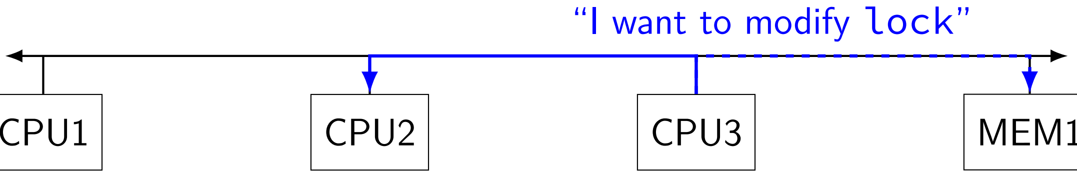
address	value	state
lock	---	Invalid

address	value	state
lock	locked	Modified

address	value	state
lock	---	Invalid

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

ping-ponging



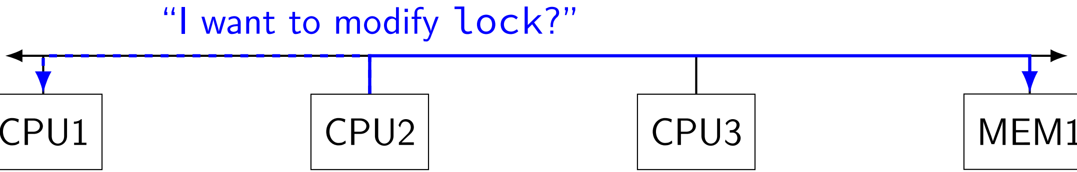
address	value	state
lock	---	Invalid

address	value	state
lock	---	Invalid

address	value	state
lock	locked	Modified

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

ping-ponging



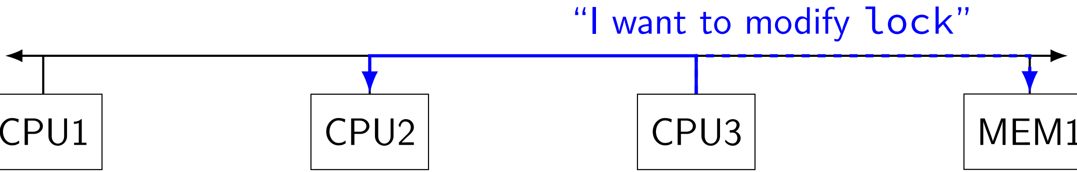
address	value	state
lock	---	Invalid

address	value	state
lock	locked	Modified

address	value	state
lock	---	Invalid

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

ping-ponging



address	value	state
lock	---	Invalid

address	value	state
lock	---	Invalid

address	value	state
lock	locked	Modified

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

ping-ponging

"I want to modify `lock`"

address	value	state
`lock`	`unlocked`	Modified

address	value	state
`lock`	---	Invalid

address	value	state
`lock`		Invalid

CPU1 sets lock to unlocked

ping-ponging

"I want to modify `lock`"

address	value	state
`lock`	---	Invalid

address	value	state
`lock`	`locked`	Modified

address	value	state
`lock`		Invalid

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 wtih 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
```

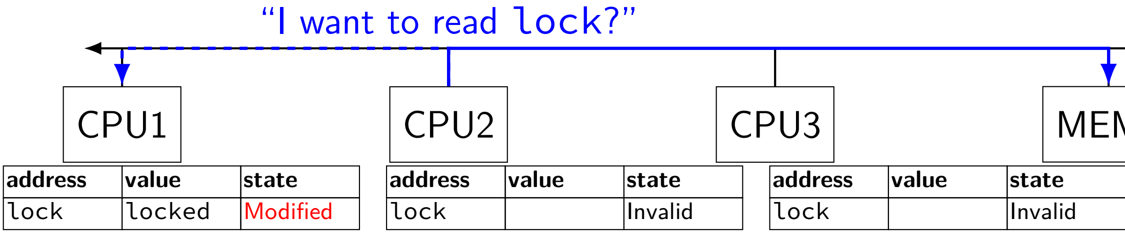
less ping-ponging

address	value	state
lock	locked	Modified

address	value	state
lock	---	Invalid

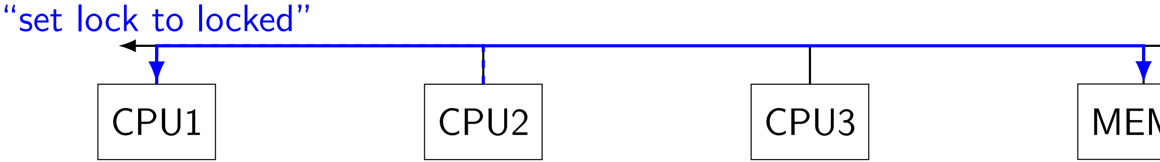
address	value	state
lock	---	Invalid

less ping-ponging



CPU2 reads lock
(to see it is still locked)

less ping-ponging



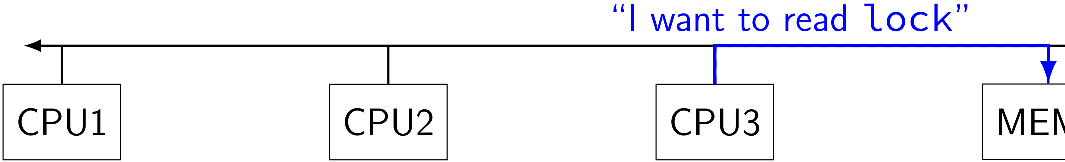
address	value	state
lock	locked	Shared

address	value	state
lock	locked	Shared

address	value	state
lock		Invalid

CPU1 writes back lock value, then CPU2 reads it

less ping-ponging



address	value	state
lock	locked	Shared

address	value	state
lock	locked	Shared

address	value	state
lock	locked	Shared

CPU3 reads lock
(to see it is still locked)

less ping-ponging

address	value	state
lock	locked	Shared

address	value	state
lock	locked	Shared

address	value	state
lock	locked	Shared

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

less ping-ponging

“I want to modify `lock`”

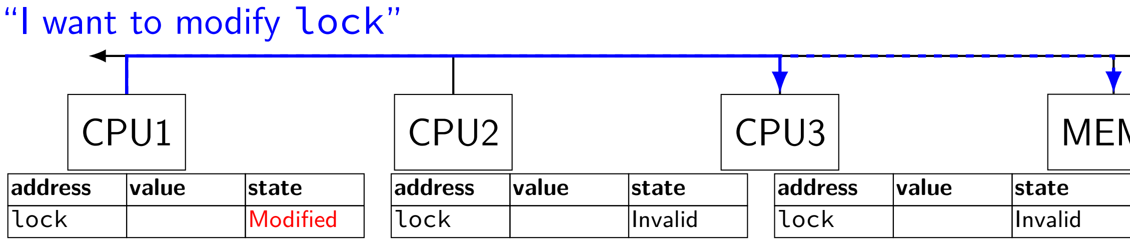
address	value	state
lock	unlocked	Modified

address	value	state
lock	---	Invalid

address	value	state
lock	---	Invalid

CPU1 sets lock to unlocked

less ping-ponging



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) {
        buy milk;
    }
}
remove note;
```

← but there's always a 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	Bob
`leave note from Alice`	
`if (no milk) {`	
	`leave note from Bob`
`    if (no note from Bob) {`	
`        ~~buy milk~~`	
`    }`	
`}`	
	`if (no milk) {`
	`    if (no note from Alice) {`
	`        ~~buy milk~~`
	`    }`
	`}`
	`remove note from Bob`
`remove note from Alice`	

too much milk: is it possible

is there a solutions with writing/reading notes?

$\approx$ 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
```

Bob

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

exercise (hard): prove (in)correctness

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

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 is 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)

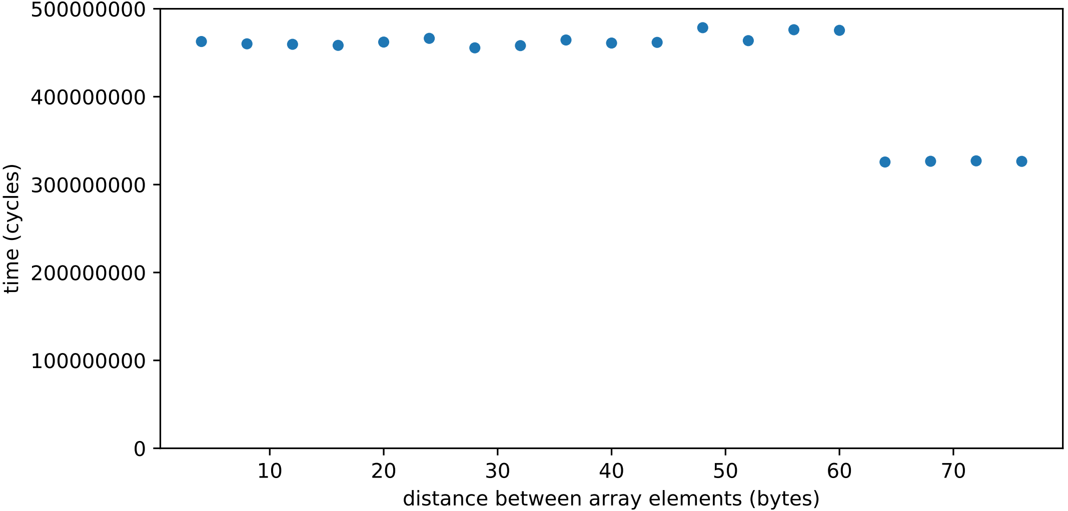
```
void *sum_up(void *raw_dest) {
    int *dest = (int *) raw_dest;
    for (int i = 0; i < 64 * 1024 * 1024; ++i) {
        *dest += data[i];
    }
}

__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];
}
```

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;

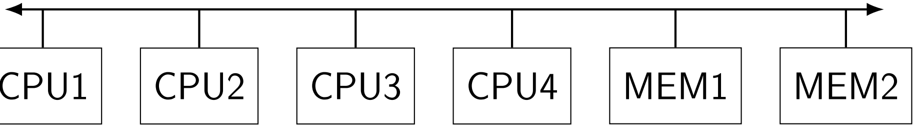
}
int sum_all(int *values) {
    ThreadInfo info[2]; pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)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

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

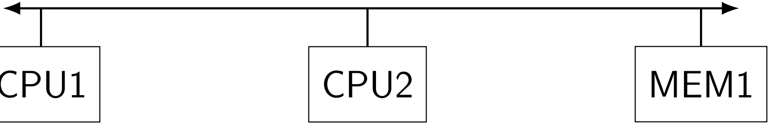
remember caches?

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



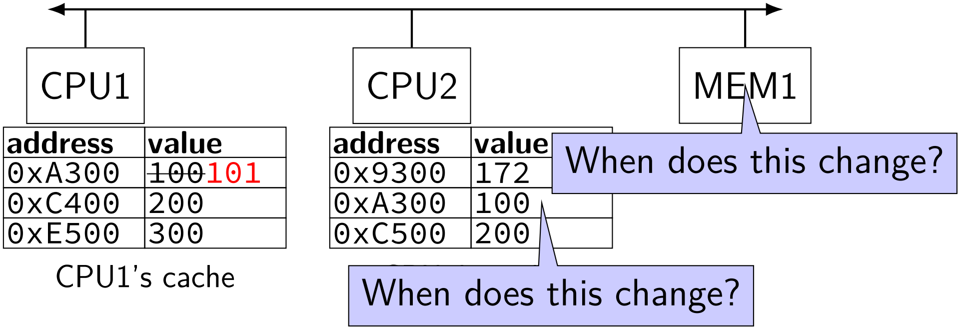
address	value
0xA300	100
0xC400	200
0xE500	300

CPU1's cache

address	value
0x9300	172
0xA300	100
0xC500	200

CPU2's cache

the cache coherency problem



address	value
0xA300	~~100~~101
0xC400	200
0xE500	300

CPU1's cache

address	value
0x9300	172
0xA300	100
0xC500	200

CPU1 writes 101 to 0xA300?