

a threading race

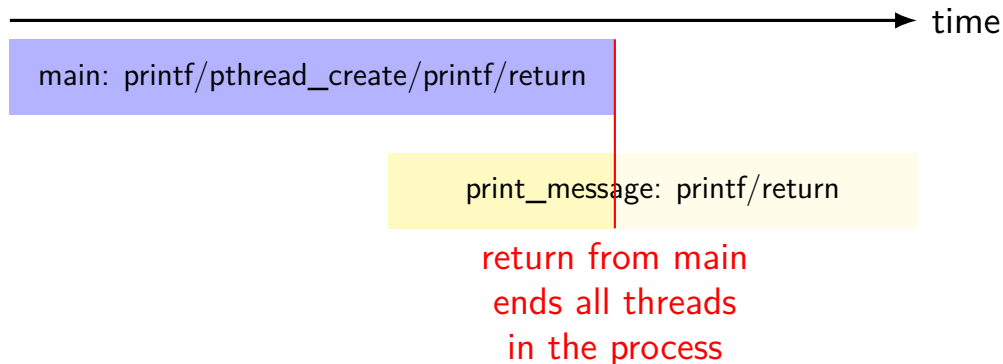
```
#include <pthread.h>
#include <stdio.h>
void *print_message(void *ignored_argument) {
    printf("In the thread\n"); return NULL;
}
int main() {
    printf("About to start thread\n");
    pthread_t the_thread;
    pthread_create(&the_thread, NULL, print_message, NULL);
    printf("Done starting thread\n");
    return 0;
}
```

My machine: outputs In the thread about 4% of the time.
What happened?

a race

returning from main **exits the entire process** (all its threads)
same as calling exit; not like other threads

race: main's return 0 or print_message's printf first?



the correctness problem

two threads?

introduces *non-determinism*

which one runs first?

allows for “race condition” bugs

...to be avoided with synchronization constructs

example application: ATM server

commands: withdraw, deposit

one correctness goal: don't lose money

ATM server

(pseudocode)

```
ServerLoop() {  
    while (true) {  
        ReceiveRequest(&operation, &accountNumber, &amount);  
        if (operation == DEPOSIT) {  
            Deposit(accountNumber, amount);  
        } else ...  
    }  
}  
  
Deposit(accountNumber, amount) {  
    account = GetAccount(accountNumber);  
    account->balance += amount;  
    SaveAccountUpdates(account);  
}
```

a threaded server?

```
Deposit(accountNumber, amount) {  
    account = GetAccount(accountId);  
    account->balance += amount;  
    SaveAccountUpdates(account);  
}
```

maybe GetAccount/SaveAccountUpdates can be slow?

read/write disk sometimes? contact another server sometimes?

maybe lots of requests to process?

maybe real logic has more checks than Deposit()

...

all reasons to handle multiple requests at once

→ many threads all running the server loop

multiple threads

```
main() {  
    for (int i = 0; i < NumberOfThreads; ++i) {  
        pthread_create(&server_loop_threads[i], NULL,  
                      ServerLoop, NULL);  
    }  
    ...  
}  
  
ServerLoop() {  
    while (true) {  
        ReceiveRequest(&operation, &accountNumber, &amount);  
        if (operation == DEPOSIT) {  
            Deposit(accountNumber, amount);  
        } else ...  
    }  
}
```


the lost write

account->balance += amount; (in two threads, same account)

Thread A

```
mov account->balance, %rax  
add amount, %rax
```

context switch

```
mov account->balance, %rax  
add amount, %rax
```

context switch

```
mov %rax, account->balance
```

context switch

```
mov %rax, account->balance
```

Thread B

the lost write

account->balance += amount; (in two threads, same account)

Thread A

```
mov account->balance, %rax  
add amount, %rax
```

context switch

```
mov %rax, account->balance
```

context switch

lost write to balance

Thread B

```
mov account->balance, %rax  
add amount, %rax
```

```
mov %rax, account->balance
```

“winner” of the race

the lost write

account->balance += amount; (in two threads, same account)

Thread A

```
mov account->balance, %rax  
add amount, %rax
```

context switch

```
mov %rax, account->balance
```

context switch

lost write to balance

Thread B

```
mov account->balance, %rax  
add amount, %rax
```

```
mov %rax, account->balance
```

“winner” of the race

lost track of thread A's money

thinking about race conditions (1)

what are the possible values of x ? (initially $x = y = 0$)

Thread A	Thread B
$x \leftarrow 1$	$y \leftarrow 2$

thinking about race conditions (2)

possible values of x ? (initially $x = y = 0$)

Thread A	Thread B
----------	----------

$x \leftarrow y + 1$	$y \leftarrow 2$
	$y \leftarrow y \times 2$

thinking about race conditions (2)

possible values of x ? (initially $x = y = 0$)

Thread A	Thread B
----------	----------

$x \leftarrow y + 1$	$y \leftarrow 2$
	$y \leftarrow y \times 2$

thinking about race conditions (3)

what are the possible values of x ?

(initially $x = y = 0$)

Thread A	Thread B
$x \leftarrow 1$	$x \leftarrow 2$

thinking about race conditions (2)

possible values of x ? (initially $x = y = 0$)

Thread A	Thread B
-----------------	-----------------

$x \leftarrow y + 1$	$y \leftarrow 2$
	$y \leftarrow y \times 2$

atomic operation

atomic operation = operation that runs to completion or not at all

we will use these to let threads work together

most machines: loading/storing (aligned) words is atomic

so can't get 3 from $x \leftarrow 1$ and $x \leftarrow 2$ running in parallel

aligned \approx address of word is multiple of word size (typically done by compilers)

but some instructions are not atomic; examples:

x86: integer add constant to memory location

many CPUs: loading/storing values that cross cache blocks

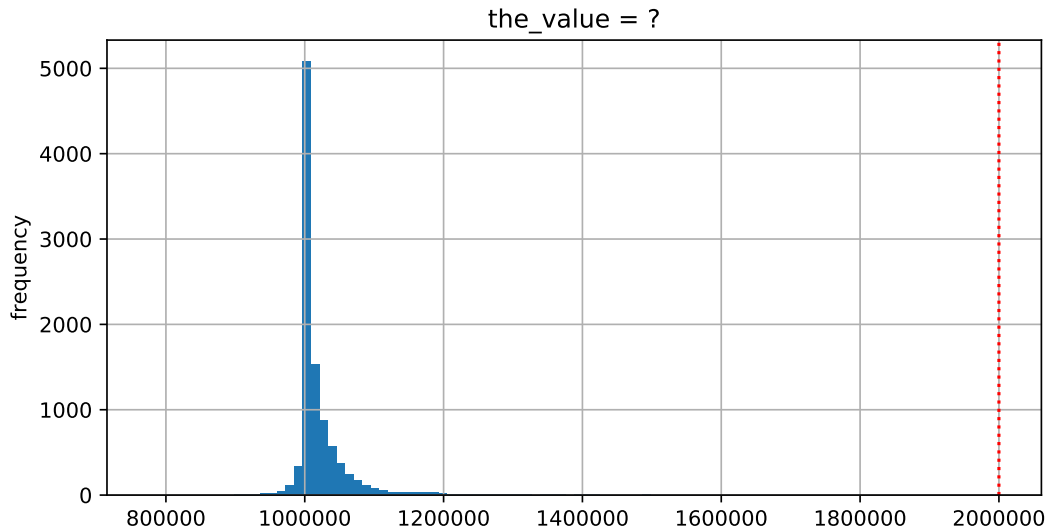
e.g. if cache blocks 0x40 bytes, load/store 4 byte from addr. 0x3E is not atomic

lost adds (program)

```
.global update_loop
update_loop:
    addl $1, the_value // the_value (global variable) += 1
    dec %rdi           // argument 1 -= 1
    jg update_loop     // if argument 1 >= 0 repeat
    ret
```

```
int the_value;
extern void *update_loop(void *);
int main(void) {
    the_value = 0;
    pthread_t A, B;
    pthread_create(&A, NULL, update_loop, (void*) 1000000);
    pthread_create(&B, NULL, update_loop, (void*) 1000000);
    pthread_join(A, NULL);
    pthread_join(B, NULL);
    // expected result: 1000000 + 1000000 = 2000000
    printf("the_value = %d\n", the_value);
}
```

lost adds (results)



but how?

probably not possible on single core

exceptions can't occur in the middle of add instruction

...but 'add to memory' implemented with multiple steps

still needs to load, add, store internally

can be interleaved with what other cores do

but how?

probably not possible on single core

exceptions can't occur in the middle of add instruction

...but 'add to memory' implemented with multiple steps

still needs to load, add, store internally

can be interleaved with what other cores do

(and actually it's more complicated than that — we'll talk later)

so, what is actually atomic

for now we'll assume: load/stores of 'words'
(64-bit machine = 64-bits words)

in general: processor designer will tell you

their job to design caches, etc. to work as documented

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

some definitions

mutual exclusion: ensuring only one thread does a particular thing at a time

like checking for and, if needed, buying milk

some definitions

mutual exclusion: ensuring only one thread does a particular thing at a time

like checking for and, if needed, buying milk

critical section: code that exactly one thread can execute at a time

result of critical section

some definitions

mutual exclusion: ensuring only one thread does a particular thing at a time

like checking for and, if needed, buying milk

critical section: code that exactly one thread can execute at a time

result of critical section

lock: object only one thread can hold at a time

interface for creating critical sections

atomic read-modify-write

really hard to build locks for atomic load store
and normal load/stores aren't even atomic...

...so processors provide **read/modify/write** operations

one instruction that
atomically
reads *and* modifies *and* writes back a value

used by OS to implement higher-level synchronization tools

x86 atomic exchange

`lock xchg (%ecx), %eax`

atomic exchange

$\text{temp} \leftarrow M[\text{ECX}]$

$M[\text{ECX}] \leftarrow \text{EAX}$

$\text{EAX} \leftarrow \text{temp}$

...without being interrupted by other processors, etc.

implementing atomic exchange

make sure other processors don't have cache block

probably need to be able to do this to keep caches in sync

do read+modify+write operation

the lock primitive

locks: an object with (at least) two operations:

acquire or *lock* — wait until lock is free, then “grab” it

release or *unlock* — let others use lock, wakeup waiters

typical usage: everyone acquires lock before using shared resource

forget to acquire lock? weird things happen

```
Lock(MilkLock);
```

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

```
    buy milk
```

```
}
```

```
Unlock(MilkLock);
```

pthread mutex

```
#include <pthread.h>

pthread_mutex_t MilkLock;
pthread_mutex_init(&MilkLock, NULL);
    // or: pthread_mutex_t MilkLock =
    //      PTHREAD_MUTEX_INITIALIZER;

...
pthread_mutex_lock(&MilkLock);
if (no milk) {
    buy milk
}
pthread_mutex_unlock(&MilkLock);
```

exercise

```
pthread_mutex_t lock1 = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_t lock2 = PTHREAD_MUTEX_INITIALIZER;
string one = "init one", two = "init two";
void ThreadA() {
    pthread_mutex_lock(&lock1);
    one = "one in ThreadA"; // (A1)
    pthread_mutex_unlock(&lock1);
    pthread_mutex_lock(&lock2);
    two = "two in ThreadA"; // (A2)
    pthread_mutex_unlock(&lock2);
}
void ThreadB() {
    pthread_mutex_lock(&lock1);
    one = "one in ThreadB"; // (B1)
    pthread_mutex_lock(&lock2);
    two = "two in ThreadB"; // (B2)
    pthread_mutex_unlock(&lock2);
    pthread_mutex_unlock(&lock1);
}
```

possible values of one/two after A+B run?

exercise (alternate 1)

```
pthread_mutex_t lock1 = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_t lock2 = PTHREAD_MUTEX_INITIALIZER;
string one = "init one", two = "init two";
void ThreadA() {
    pthread_mutex_lock(&lock2);
    two = "two in ThreadA"; // (A2)
    pthread_mutex_unlock(&lock2);
    pthread_mutex_lock(&lock1);
    one = "one in ThreadA"; // (A1)
    pthread_mutex_unlock(&lock1);
}
void ThreadB() {
    pthread_mutex_lock(&lock1);
    one = "one in ThreadB"; // (B1)
    pthread_mutex_lock(&lock2);
    two = "two in ThreadB"; // (B2)
    pthread_mutex_unlock(&lock2);
    pthread_mutex_unlock(&lock1);
}
```

possible values of one/two after A+B run?

exercise (alternate 2)

```
pthread_mutex_t lock1 = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_t lock2 = PTHREAD_MUTEX_INITIALIZER;
string one = "init one", two = "init two";
void ThreadA() {
    pthread_mutex_lock(&lock2);
    two = "two in ThreadA"; // (A2)
    pthread_mutex_unlock(&lock2);
    pthread_mutex_lock(&lock1);
    one = "one in ThreadA"; // (A1)
    pthread_mutex_unlock(&lock1);
}
void ThreadB() {
    pthread_mutex_lock(&lock1);
    one = "one in ThreadB"; // (B1)
    pthread_mutex_unlock(&lock1);
    pthread_mutex_lock(&lock2);
    two = "two in ThreadB"; // (B2)
    pthread_mutex_unlock(&lock2);
}
```

possible values of one/two after A+B run?

are locks enough?

do we need more than locks?

example 1: pipes?

pipes: one thread reads while other writes

want write to complete immediately if buffer space

want read operation to *wait* for write operation

not functionality provided by mutexes/barriers

barriers

compute minimum of 100M element array with 2 processors

algorithm:

compute minimum of 50M of the elements on each CPU

one thread for each CPU

wait for all computations to finish

take minimum of all the minimums

barriers

compute minimum of 100M element array with 2 processors

algorithm:

compute minimum of 50M of the elements on each CPU
one thread for each CPU

wait for all computations to finish

take minimum of all the minimums

barriers API

`barrier.Initialize(NumberOfThreads)`

`barrier.Wait()` — return after all threads have waited

idea: multiple threads perform computations in parallel

threads wait for **all other threads** to call `Wait()`

barrier: waiting for finish

```
barrier.Initialize(2);
```

Thread 0

```
partial_mins[0] =  
    /* min of first  
       50M elems */;
```

```
barrier.Wait();
```

```
total_min = min(  
    partial_mins[0],  
    partial_mins[1]  
);
```

Thread 1

```
partial_mins[1] =  
    /* min of last  
       50M elems */  
barrier.Wait();
```

barriers: reuse

Thread 0

```
results[0][0] = getInitial(0);  
barrier.Wait();
```

```
results[1][0] =  
    computeFrom(  
        results[0][0],  
        results[0][1]  
    );  
barrier.Wait();
```

```
results[2][0] =  
    computeFrom(  
        results[1][0],  
        results[1][1]  
    );
```

Thread 1

```
results[0][1] = getInitial(1);  
barrier.Wait();
```

```
results[1][1] =  
    computeFrom(  
        results[0][0],  
        results[0][1]  
    );  
barrier.Wait();
```

```
results[2][1] =  
    computeFrom(  
        results[1][0],  
        results[1][1]  
    );
```


barriers: reuse

Thread 0

```
results[0][0] = getInitial(0);  
barrier.Wait();
```

```
results[1][0] =  
    computeFrom(  
        results[0][0],  
        results[0][1]  
    );  
barrier.Wait();
```

```
results[2][0] =  
    computeFrom(  
        results[1][0],  
        results[1][1]  
    );
```

Thread 1

```
results[0][1] = getInitial(1);  
barrier.Wait();
```

```
results[1][1] =  
    computeFrom(  
        results[0][0],  
        results[0][1]  
    );  
barrier.Wait();
```

```
results[2][1] =  
    computeFrom(  
        results[1][0],  
        results[1][1]  
    );
```

barriers: reuse

Thread 0

```
results[0][0] = getInitial(0);  
barrier.Wait();
```

```
results[1][0] =  
    computeFrom(  
        results[0][0],  
        results[0][1]  
    );  
barrier.Wait();
```

```
results[2][0] =  
    computeFrom(  
        results[1][0],  
        results[1][1]  
    );
```

Thread 1

```
results[0][1] = getInitial(1);  
barrier.Wait();
```

```
results[1][1] =  
    computeFrom(  
        results[0][0],  
        results[0][1]  
    );  
barrier.Wait();
```

```
results[2][1] =  
    computeFrom(  
        results[1][0],  
        results[1][1]  
    );
```

pthread barriers

```
pthread_barrier_t barrier;  
pthread_barrier_init(  
    &barrier,  
    NULL /* attributes */,  
    numberOfThreads  
);  
...  
...  
pthread_barrier_wait(&barrier);
```

life homework (pseudocode)

```
for (int time = 0; time < MAX_ITERATIONS; ++time) {  
    for (int y = 0; y < size; ++y) {  
        for (int x = 0; x < size; ++x) {  
            to_grid(x, y) = computeValue(from_grid, x, y);  
        }  
    }  
    swap(from_grid, to_grid);  
}
```

life homework

compute grid of values for time t from grid for time $t - 1$

compute new value at i, j based on surrounding values

parallel version: produce parts of grid in different threads

use barriers to finish time t before going to time $t + 1$

a simple race

thread_A:

```
movl $1, x    /* x <- 1 */  
movl y, %eax  /* return y */  
ret
```

thread_B:

```
movl $1, y    /* y <- 1 */  
movl x, %eax  /* return x */  
ret
```

```
x = y = 0;  
pthread_create(&A, NULL, thread_A, NULL);  
pthread_create(&B, NULL, thread_B, NULL);  
pthread_join(A, &A_result); pthread_join(B, &B_result);  
printf("A:%d B:%d\n", (int) A_result, (int) B_result);
```

a simple race

thread_A:

```
movl $1, x    /* x <- 1 */  
movl y, %eax  /* return y */  
ret
```

thread_B:

```
movl $1, y    /* y <- 1 */  
movl x, %eax  /* return x */  
ret
```

```
x = y = 0;  
pthread_create(&A, NULL, thread_A, NULL);  
pthread_create(&B, NULL, thread_B, NULL);  
pthread_join(A, &A_result); pthread_join(B, &B_result);  
printf("A:%d B:%d\n", (int) A_result, (int) B_result);
```

if loads/stores atomic, then possible results:

- A:1 B:1 — both moves into x and y, then both moves into eax execute
- A:0 B:1 — thread A executes before thread B
- A:1 B:0 — thread B executes before thread A

a simple race: results

thread_A:

```
movl $1, x    /* x <- 1 */  
movl y, %eax  /* return y */  
ret
```

thread_B:

```
movl $1, y    /* y <- 1 */  
movl x, %eax  /* return x */  
ret
```

```
x = y = 0;  
pthread_create(&A, NULL, thread_A, NULL);  
pthread_create(&B, NULL, thread_B, NULL);  
pthread_join(A, &A_result); pthread_join(B, &B_result);  
printf("A:%d B:%d\n", (int) A_result, (int) B_result);
```

my desktop, 100M trials:

frequency	result	
99 823 739	A:0 B:1	('A executes before B')
171 161	A:1 B:0	('B executes before A')
4 706	A:1 B:1	('execute moves into x+y first')
394	A:0 B:0	???

a simple race: results

thread_A:

```
movl $1, x    /* x <- 1 */
movl y, %eax  /* return y */
ret
```

thread_B:

```
movl $1, y    /* y <- 1 */
movl x, %eax  /* return x */
ret
```

```
x = y = 0;
pthread_create(&A, NULL, thread_A, NULL);
pthread_create(&B, NULL, thread_B, NULL);
pthread_join(A, &A_result); pthread_join(B, &B_result);
printf("A:%d B:%d\n", (int) A_result, (int) B_result);
```

my desktop, 100M trials:

frequency	result	
99 823 739	A:0 B:1	('A executes before B')
171 161	A:1 B:0	('B executes before A')
4 706	A:1 B:1	('execute moves into x+y first')
394	A:0 B:0	???

why reorder here?

thread_A:

```
movl $1, x    /* x <- 1 */  
movl y, %eax  /* return y */  
ret
```

thread_B:

```
movl $1, y    /* y <- 1 */  
movl x, %eax  /* return x */  
ret
```

thread A: faster to load y right now!

...rather than wait for write of x to finish

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

compilers move loads/stores (1)

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

Alice:

```
    movl $1, note_from_alice    // note_from_alice <- 1  
    movl note_from_bob, %eax    // eax <- note_from_bob
```

.L2:

```
    testl %eax, %eax  
    jne .L2                    // while (eax == 0) repeat  
    cmpl $0, no_milk          // if (no_milk != 0) ...  
    ...
```

compilers move loads/stores (1)

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

Alice:

```
    movl $1, note_from_alice    // note_from_alice <- 1  
    movl note_from_bob, %eax    // eax <- note_from_bob
```

.L2:

```
    testl %eax, %eax  
    jne .L2                    // while (eax == 0) repeat  
    cmpl $0, no_milk           // if (no_milk != 0) ...  
    ...
```

compilers move loads/stores too (2)

```
void Alice() {  
    note_from_alice = 1; // "Alice waiting" signal for Bob()  
    do {} while (note_from_bob);  
    if (no_milk) {++milk;}  
    note_from_alice = 2;  
}
```

Alice:

*// compiler optimization: don't set note_from_alice to 1,
// (why? it will be set to 2 anyway)*

`movl` note_from_bob, %eax *// eax <- note_from_bob*

.L2:

`testl` %eax, %eax

`jne` .L2 *// while (eax == 0) repeat*

...

`movl` \$2, note_from_alice *// note_from_alice <- 2*

compilers move loads/stores too (2)

```
void Alice() {  
    note_from_alice = 1; // "Alice waiting" signal for Bob()  
    do {} while (note_from_bob);  
    if (no_milk) {++milk;}  
    note_from_alice = 2;  
}
```

Alice:

```
// compiler optimization: don't set note_from_alice to 1,  
// (why? it will be set to 2 anyway)  
movl note_from_bob, %eax // eax <- note_from_bob  
.L2:  
    testl %eax, %eax  
    jne .L2 // while (eax == 0) repeat  
    ...  
    movl $2, note_from_alice // note_from_alice <- 2
```

compilers move loads/stores too (2)

```
void Alice() {  
    note_from_alice = 1; // "Alice waiting" signal for Bob()  
    do {} while (note_from_bob);  
    if (no_milk) {++milk;}  
    note_from_alice = 2;  
}
```

Alice:

*// compiler optimization: don't set note_from_alice to 1,
// (why? it will be set to 2 anyway)*

```
movl note_from_bob, %eax // eax <- note_from_bob
```

.L2:

```
testl %eax, %eax
```

```
jne .L2 // while (eax == 0) repeat
```

...

```
movl $2, note_from_alice // note_from_alice <- 2
```


pthread and reordering

many pthreads functions **prevent reordering**

everything before function call actually happens before

includes **preventing some optimizations**

e.g. keeping global variable in register for too long

pthread_mutex_lock/unlock, pthread_create, pthread_join, ...

basically: if pthreads is waiting for/starting something, no weird ordering

implementation part 1: prevent compiler reordering

implementation part 2: use special instructions

example: x86 mfence instruction

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

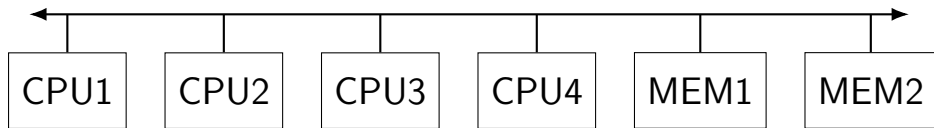
aside: this instruction did not exist in the original x86
so xv6 uses something older that's equivalent

connecting CPUs and memory

multiple processors, common memory

how do processors communicate with memory?

shared bus



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

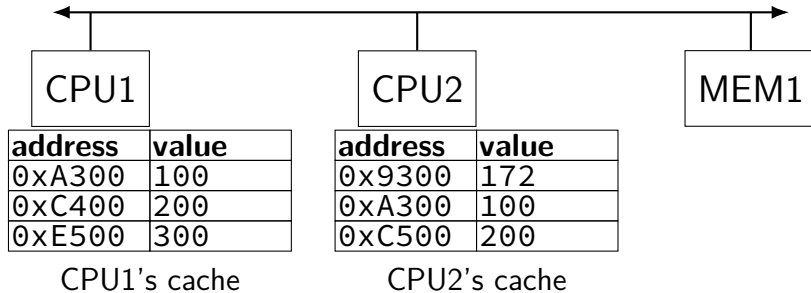
remember caches?

memory is pretty slow

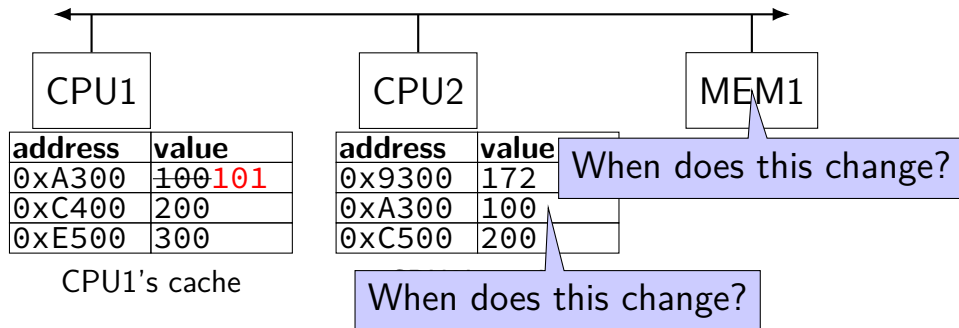
each CPU wants to keep local copies of memory

what happens when multiple CPUs cache same memory?

the cache coherency problem



the cache coherency problem



CPU1 writes 101 to 0xA300?

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)

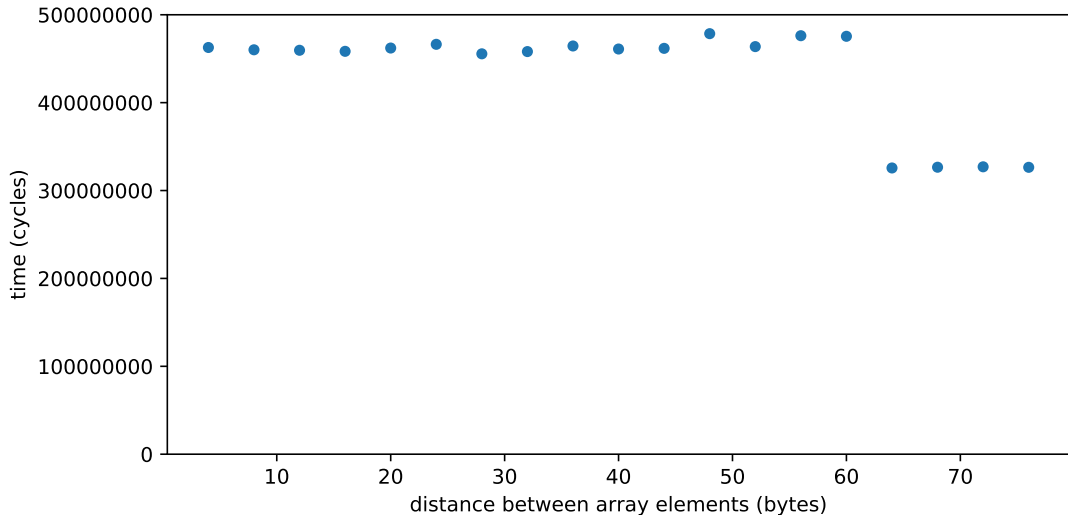
```
void *sum_up(void *raw_dest) {  
    int *dest = (int *) raw_dest;  
    for (int i = 0; i < 64 * 1024 * 1024; ++i) {  
        *dest += data[i];  
    }  
}
```

```
__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?

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);
```


POSIX mutex restrictions

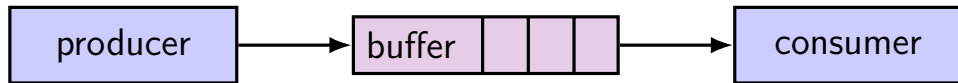
pthread_mutex rule: unlock from same thread you lock in

implementation I gave before — not a problem

...but there other ways to implement mutexes

e.g. might involve comparing with “holding” thread ID

example: producer/consumer

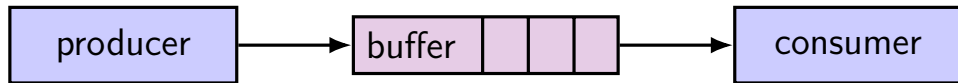


shared buffer (queue) of fixed size

one or more producers inserts into queue

one or more consumers removes from queue

example: producer/consumer



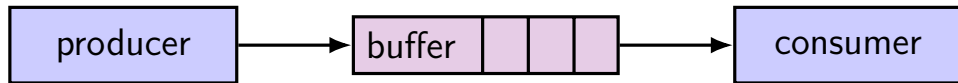
shared buffer (queue) of fixed size

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

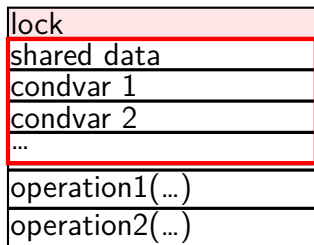
a monitor

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

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

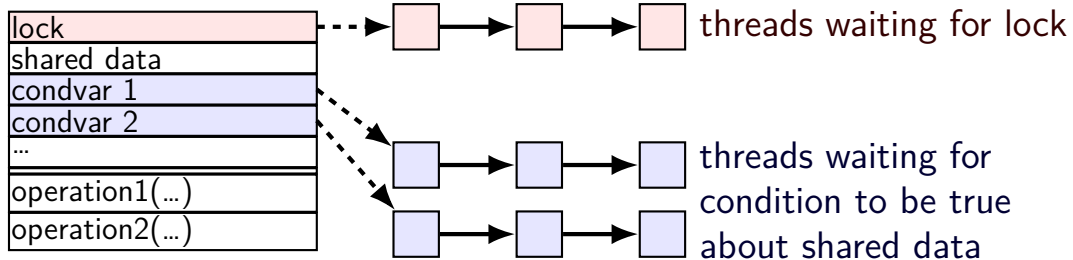
monitor idea

a monitor



monitor idea

a monitor



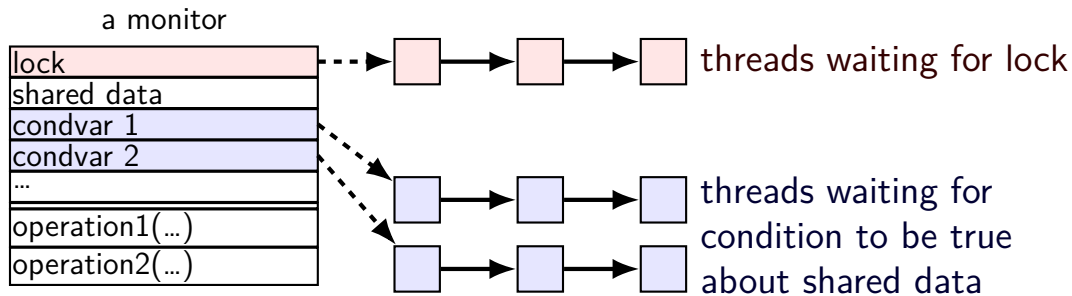
condvar operations

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

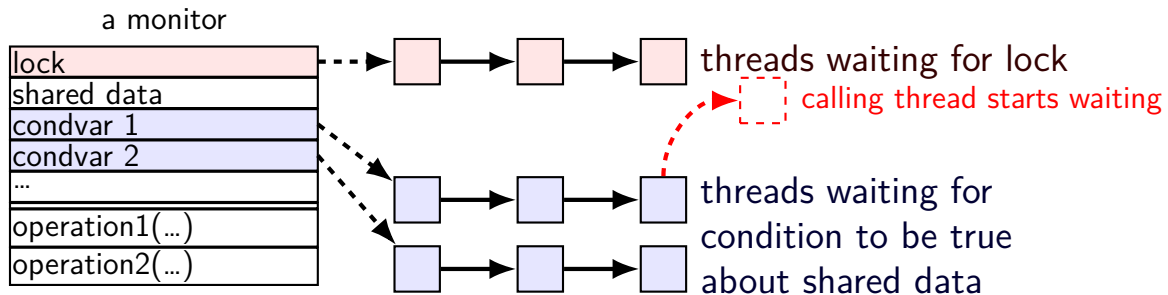
condvar operations:

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

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condvar operations

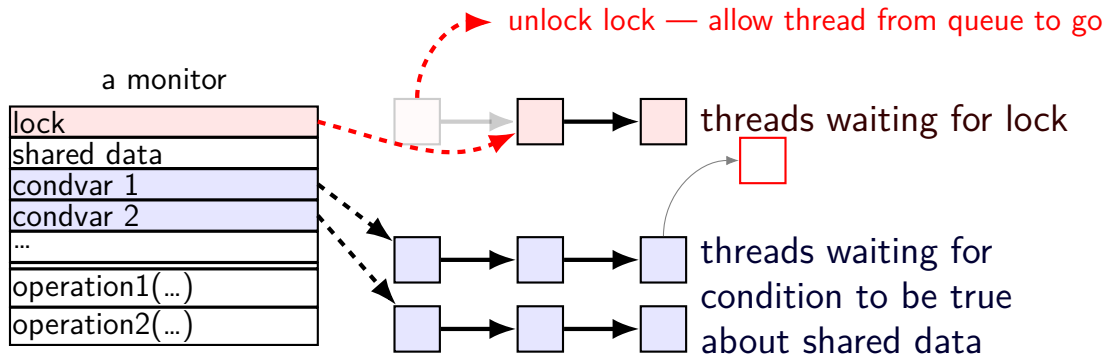
condvar operations:

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

...and **reacquire** lock before returning

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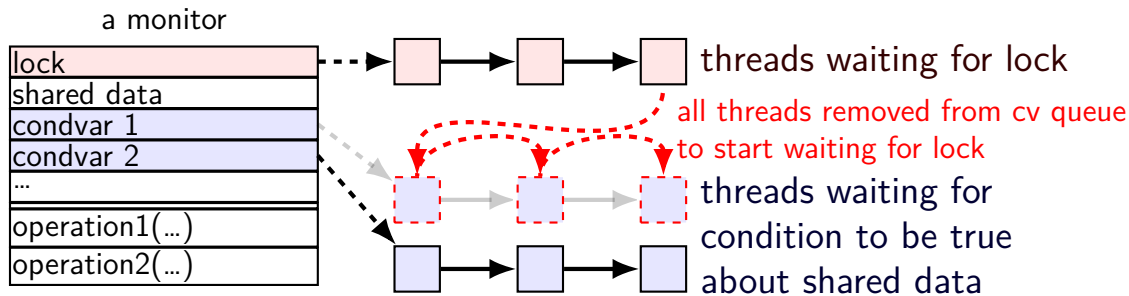
condvar operations

condvar operations:

Wait(cv, lock) — unlock lock, add current thread to cv queue
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Broadcast(cv) — remove all from condvar queue

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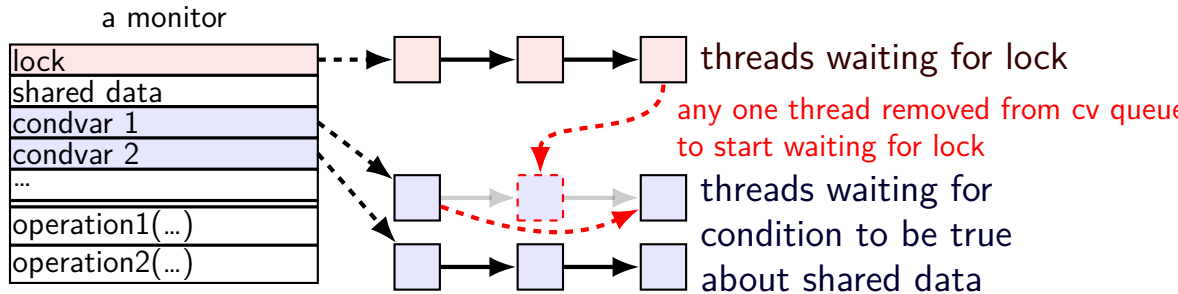
condvar operations

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);
```

```
}
```

```
void Finish() {
```

```
    pthread_mutex_lock(&lock);
```

```
    finished = true;
```

```
    pthread_cond_broadcast(&finished_cv);
```

```
    pthread_mutex_unlock(&lock);
```

```
}
```

check whether we need to wait at all

(why a loop? we'll explain later)

pthread cv usage

// MISSING: init calls, etc.

```
pthread_mutex_t lock;  
bool finished;    // data, only accessed with after acquiring lock  
pthread_cond_t finished_cv; // to wait for 'finished' to be true
```

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

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

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

pthread cv usage

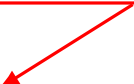
// MISSING: init calls, etc.

```
pthread_mutex_t lock;  
bool finished;    // data, only accessed with after acquiring lock  
pthread_cond_t finished_cv; // to wait for 'finished' to be true
```

```
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

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

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

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

```
Consume() {
    pthread_mutex_lock(&lock);
    while (buffer.empty()) {
        pthread_cond_wait(&data_ready, &lock);
    }
    item = buffer.dequeue();
    pthread_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
gaurenteed to hold lock next

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

```
while (buffer.empty()) {
    pthread_cond_wait(&data_r
}
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);  
    pthread_mutex_unlock(&lock);  
}
```

correct (but slow?) to replace with:

```
pthread_cond_broadcast(&space_ready);  
(just more "spurious wakeups")  
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;  
}
```

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);  
}
```

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		

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

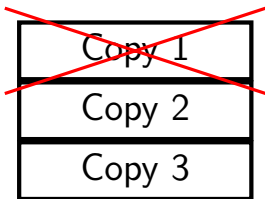
counting resources: reserving books

suppose tracking copies of same library book

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

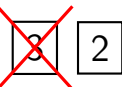
up = give back book; down = take book

taken out



Copy 1
Copy 2
Copy 3

free copies



after calling down to reserve

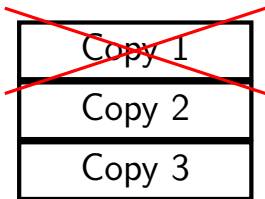
counting resources: reserving books

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

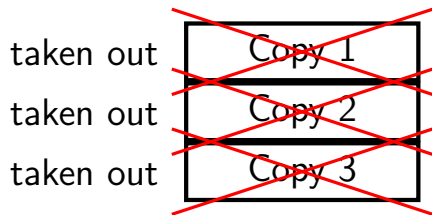
after calling down to reserve

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

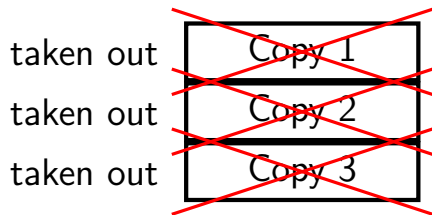
after calling down three times
to reserve all copies

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



free copies

0



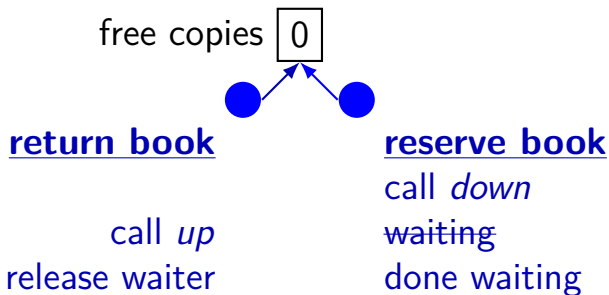
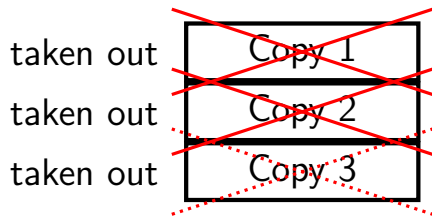
reserve book
call *down* again
start waiting...

counting resources: reserving books

suppose tracking copies of same library book

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

up = give back book; **down** = take book



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  
    sem_wait(&mutex);  
    buffer.enqueue(item);  
    sem_post(&mutex);  
    sem_post(&full_slots); // tell consumers there is more data  
}
```

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

producer/consumer pseudocode

```
sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);  
sem_init(&empty_slots, ..., BUFFER_CAPACITY);  
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);  
buffer.set_size(BUFFER_CAPACITY);  
...
```

```
Produce(item) {  
    sem_wait(&empty_slots); // wait until free slot, reserve it  
    sem_wait(&mutex);  
    buffer.enqueue(item);  
    sem_post(&mutex);  
    sem_post(&full_slots); // tell consumers there is more data  
}
```

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

producer/consumer pseudocode

```
sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);
sem_init(&empty_slots, ..., BUFFER_CAPACITY);
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);
buffer.set_size(BUFFER_CAPACITY);
...
```

```
Produce(item) {
    sem_wait(&empty_slots); // wait until free slot, reserve it
    sem_wait(&mutex);
    buffer.enqueue(item);
    sem_post(&mutex);
    sem_post(&full_slots);
}
```

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

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

producer/consumer pseudocode

```
sem_init(&full_slots, ..., 0 /* # buffer slots initially used */);  
sem_init(&empty_slots, ..., BUFFER_CAPACITY);  
sem_init(&mutex, ..., 1 /* # thread that can use buffer at once */);  
buffer.set_size(BUFFER_CAPACITY);  
...
```

```
Produce(item) {  
    sem_wait(&empty_slots); // wait until free slot, reserve it  
    sem_wait(&mutex);  
    buffer.enqueue(item);  
    sem_post(&mutex);  
    sem_post(&full_slots);  
}
```

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

`sem_post(&mutex);` instead? *, reserve it*

Yes — post never waits

producer/consumer summary

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

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

two producers or consumers?

still works!

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

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
}
```

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)

reader/writer problem

some shared data

only one thread modifying (read+write) at a time

read-only access from multiple threads is safe

reader/writer problem

some shared data

only one thread modifying (read+write) at a time

read-only access from multiple threads is safe

could use lock — but doesn't allow multiple readers

reader/writer locks

abstraction: lock that distinguishes readers/writers

operations:

- read lock: wait until no writers

- read unlock: stop being registered as reader

- write lock: wait until no readers and no writers

- write unlock: stop being registered as writer

reader/writer locks

abstraction: lock that distinguishes readers/writers

operations:

- read lock: wait until no writers

- read unlock: stop being registered as reader

- write lock: wait until **no readers and no writers**

- write unlock: stop being registered as writer

pthread_rwlock_t

```
pthread_rwlock_t rwlock;  
pthread_rwlock_init(&rwlock, NULL /* attributes */);  
...  
    pthread_rwlock_rdlock(&rwlock);  
    ... /* read shared data */  
    pthread_rwlock_unlock(&rwlock);  
  
    pthread_rwlock_wrlock(&rwlock);  
    ... /* read+write shared data */  
    pthread_rwlock_unlock(&rwlock);  
  
...  
pthread_rwlock_destroy(&rwlock);
```

rwlock effects exercise

```
pthread_rwlock_t lock;
void ThreadA() {
    pthread_rwlock_rdlock(&lock);
    puts("a");
    ...
    puts("A");
    pthread_rwlock_unlock(&lock);
}
void ThreadB() {
    pthread_rwlock_rdlock(&lock);
    puts("b");
    ...
    puts("B");
    pthread_rwlock_unlock(&lock);
}
void ThreadC() {
    pthread_rwlock_wrlock(&lock);
    puts("c");
    ...
    puts("C");
    pthread_rwlock_unlock(&lock);
}
void ThreadD() {
    pthread_rwlock_wrlock(&lock);
    puts("d");
    ...
    puts("D");
    pthread_rwlock_unlock(&lock);
}
```

exercise: which of these outputs are possible?

1. aAbBcCdD
2. abABcdDC
3. cCabBAdD
4. cdCDaAbB
5. caACdDbB

rwlocks with monitors (attempt 1)

```
mutex_t lock;
```

lock to protect shared state

rwlocks with monitors (attempt 1)

```
mutex_t lock;  
unsigned int readers, writers;
```

state: number of active readers, writers

rwlocks with monitors (attempt 1)

```
mutex_t lock;  
unsigned int readers, writers;  
/* condition, signal when writers becomes 0 */  
cond_t ok_to_read_cv;  
/* condition, signal when readers + writers becomes 0 */  
cond_t ok_to_write_cv;
```

conditions to wait for (no readers or writers, no writers)

rwlocks with monitors (attempt 1)

```
mutex_t lock;  
unsigned int readers, writers;  
/* condition, signal when writers becomes 0 */  
cond_t ok_to_read_cv;  
/* condition, signal when readers + writers becomes 0 */  
cond_t ok_to_write_cv;
```

```
ReadLock() {  
    mutex_lock(&lock);  
    while (writers != 0) {  
        cond_wait(&ok_to_read_cv, &lock);  
    }  
    ++readers;  
    mutex_unlock(&lock);  
}  
ReadUnlock() {  
    mutex_lock(&lock);  
    --readers;  
    if (readers == 0) {  
        cond_signal(&ok_to_write_cv);  
    }  
    mutex_unlock(&lock);  
}
```

```
WriteLock() {  
    mutex_lock(&lock);  
    while (readers + writers != 0) {  
        cond_wait(&ok_to_write_cv);  
    }  
    ++writers;  
    mutex_unlock(&lock);  
}  
WriteUnlock() {  
    mutex_lock(&lock);  
    --writers;  
    cond_signal(&ok_to_write_cv);  
    cond_broadcast(&ok_to_read_cv);  
    mutex_unlock(&lock);  
}
```

broadcast — wakeup all readers when no writers

rwlocks with monitors (attempt 1)

```
mutex_t lock;
unsigned int readers, writers;
/* condition, signal when writers becomes 0 */
cond_t ok_to_read_cv;
/* condition, signal when readers + writers becomes 0 */
cond_t ok_to_write_cv;

ReadLock() {
    mutex_lock(&lock);
    while (writers != 0) {
        cond_wait(&ok_to_read_cv, &lock);
    }
    ++readers;
    mutex_unlock(&lock);
}

ReadUnlock() {
    mutex_lock(&lock);
    --readers;
    if (readers == 0) {
        cond_signal(&ok_to_write_cv);
    }
    mutex_unlock(&lock);
}

WriteLock() {
    mutex_lock(&lock);
    while (readers + writers != 0) {
        cond_wait(&ok_to_write_cv);
    }
    ++writers;
    mutex_unlock(&lock);
}

WriteUnlock() {
    mutex_lock(&lock);
    --writers;
    cond_signal(&ok_to_write_cv);
    cond_broadcast(&ok_to_read_cv);
    mutex_unlock(&lock);
}
```

wakeup a single writer when no readers or writers

rwlocks with monitors (attempt 1)

```
mutex_t lock;
unsigned int readers, writers;
/* condition, signal when writers becomes 0 */
cond_t ok_to_read_cv;
/* condition, signal when readers + writers becomes 0 */
cond_t ok_to_write_cv;

ReadLock() {
    mutex_lock(&lock);
    while (writers != 0) {
        cond_wait(&ok_to_read_cv, &lock);
    }
    ++readers;
    mutex_unlock(&lock);
}

ReadUnlock() {
    mutex_lock(&lock);
    --readers;
    if (readers == 0) {
        cond_signal(&ok_to_write_cv);
    }
    mutex_unlock(&lock);
}

WriteLock() {
    mutex_lock(&lock);
    while (readers + writers != 0) {
        cond_wait(&ok_to_write_cv);
    }
    ++writers;
    mutex_unlock(&lock);
}

WriteUnlock() {
    mutex_lock(&lock);
    --writers;
    cond_signal(&ok_to_write_cv);
    cond_broadcast(&ok_to_read_cv);
    mutex_unlock(&lock);
}
```

problem: wakeup readers first or writer first?

this solution: wake them all up and they fight! inefficient!

reader/writer-priority

policy question: writers first or readers first?

- writers-first: no readers go when writer waiting

- readers-first: no writers go when reader waiting

previous implementation: whatever randomly happens

- writers signalled first, maybe gets lock first?

- ...but non-deterministic in pthreads

can make **explicit decision**

reader/writer-priority

policy question: writers first or readers first?

- writers-first: no readers go when writer waiting

- readers-first: no writers go when reader waiting

previous implementation: whatever randomly happens

- writers signalled first, maybe gets lock first?

- ...but non-deterministic in pthreads

can make **explicit decision**

key method: **track number of waiting readers/writers**

writer-priority (1)

```
mutex_t lock; cond_t ok_to_read_cv; cond_t ok_to_write_cv;
int readers = 0, writers = 0;
int waiting_writers = 0;

ReadLock() {
    mutex_lock(&lock);
    while (writers != 0
           || waiting_writers != 0) {
        cond_wait(&ok_to_read_cv, &lock);
    }
    ++readers;
    mutex_unlock(&lock);
}

ReadUnlock() {
    mutex_lock(&lock);
    --readers;
    if (readers == 0) {
        cond_signal(&ok_to_write_cv);
    }
    mutex_unlock(&lock);
}

WriteLock() {
    mutex_lock(&lock);
    ++waiting_writers;
    while (readers + writers != 0) {
        cond_wait(&ok_to_write_cv, &lock);
    }
    --waiting_writers;
    ++writers;
    mutex_unlock(&lock);
}

WriteUnlock() {
    mutex_lock(&lock);
    --writers;
    if (waiting_writers != 0) {
        cond_signal(&ok_to_write_cv);
    } else {
        cond_broadcast(&ok_to_read_cv);
    }
    mutex_unlock(&lock);
}
```

writer-priority (1)

```
mutex_t lock; cond_t ok_to_read_cv; cond_t ok_to_write_cv;
int readers = 0, writers = 0;
int waiting_writers = 0;

ReadLock() {
    mutex_lock(&lock);
    while (writers != 0
           || waiting_writers != 0) {
        cond_wait(&ok_to_read_cv, &lock);
    }
    ++readers;
    mutex_unlock(&lock);
}

ReadUnlock() {
    mutex_lock(&lock);
    --readers;
    if (readers == 0) {
        cond_signal(&ok_to_write_cv);
    }
    mutex_unlock(&lock);
}

WriteLock() {
    mutex_lock(&lock);
    ++waiting_writers;
    while (readers + writers != 0) {
        cond_wait(&ok_to_write_cv, &lock);
    }
    --waiting_writers;
    ++writers;
    mutex_unlock(&lock);
}

WriteUnlock() {
    mutex_lock(&lock);
    --writers;
    if (waiting_writers != 0) {
        cond_signal(&ok_to_write_cv);
    } else {
        cond_broadcast(&ok_to_read_cv);
    }
    mutex_unlock(&lock);
}
```

writer-priority (1)

```
mutex_t lock; cond_t ok_to_read_cv; cond_t ok_to_write_cv;
int readers = 0, writers = 0;
int waiting_writers = 0;

ReadLock() {
    mutex_lock(&lock);
    while (writers != 0
           || waiting_writers != 0) {
        cond_wait(&ok_to_read_cv, &lock);
    }
    ++readers;
    mutex_unlock(&lock);
}

ReadUnlock() {
    mutex_lock(&lock);
    --readers;
    if (readers == 0) {
        cond_signal(&ok_to_write_cv);
    }
    mutex_unlock(&lock);
}

WriteLock() {
    mutex_lock(&lock);
    ++waiting_writers;
    while (readers + writers != 0) {
        cond_wait(&ok_to_write_cv, &lock);
    }
    --waiting_writers;
    ++writers;
    mutex_unlock(&lock);
}

WriteUnlock() {
    mutex_lock(&lock);
    --writers;
    if (waiting_writers != 0) {
        cond_signal(&ok_to_write_cv);
    } else {
        cond_broadcast(&ok_to_read_cv);
    }
    mutex_unlock(&lock);
}
```

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
				0	1	0

ReadLock

```
mutex_lock(&lock);  
while (writers != 0 || waiting_writers != 0) {  
    cond_wait(&ok_to_read_cv, &lock);  
}  
++readers;  
mutex_unlock(&lock);
```


simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
ReadLock				0	1	0
(reading)	ReadLock			0	2	0

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
ReadLock				0	1	0
(reading)	ReadLock			0	2	0
(reading)	(reading)	WriteLock wait		0	2	1

```
mutex_lock(&lock);
++waiting_writers;
while (readers + writers != 0) {
    cond_wait(&ok_to_write_cv, &lock);
}
```

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
ReadLock				0	1	0
(reading)	ReadLock			0	2	0
(reading)	(reading)	WriteLock wait		0	2	1
(reading)	(reading)	WriteLock wait	ReadLock wait	0	2	1

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
ReadLock				0	1	0
(reading)	ReadLock			0	2	0
(reading)	(reading)	WriteLock wait		0	2	1
(reading)	(read	mutex_lock(&lock); --readers; if (readers == 0) ...	wait	0	2	1
ReadUnlock			ReadLock wait	0	1	1

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
ReadLock				0	1	0
(reading)	ReadLock			0	2	0
(reading)	(reading)	WriteLock wait		0	2	1
(reading)	(reading)	WriteLock wait	ReadLock wait	0	2	1
ReadUnlock	(reading)	Write			1	1
	ReadUnlock	Write			0	1

```

mutex_lock(&lock);
--readers;
if (readers == 0)
    cond_signal(&ok_to_write_cv);
mutex_unlock(&lock);
    
```

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1		reader 2		writer 1	reader 3	W	R	WW
ReadLock						0	0	0
(reading)		Read				0	1	0
(reading)		(read)				0	2	0
(reading)		(read)				0	2	1
ReadUnlock		(reading)		WriteLock wait	ReadLock wait	0	1	1
		ReadUnlock		WriteLock wait	ReadLock wait	0	0	1
				WriteLock	ReadLock wait	1	0	0

```

while (readers + writers != 0) {
    cond_wait(&ok_to_write_cv, &lock);
}
--waiting_writers; ++writers;
mutex_unlock(&lock);
    
```

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
ReadLock				0	1	0
(reading)	ReadLock			0	2	0
(reading)	(reading)	WriteLock wait		0	2	1
(reading)	(reading)	WriteLock wait	ReadLock wait	0	2	1
ReadUnlock	(reading)	WriteLock wait	ReadLock wait	0	1	1
	ReadUnlock	WriteLock wait	ReadLock wait	0	0	1
		WriteLock	ReadLock wait	1	0	0
		(read+writing)	ReadLock wait	1	0	0

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
ReadLock				0	1	0
(reading)	ReadLock			0	2	0
(reading)	(reading)			0	2	1
(reading)	(reading)			0	2	1
ReadUnlock	(reading)			0	1	1
	ReadUnlock			0	0	1
		WriteLock	ReadLock wait	1	0	0
		(read+writing)	ReadLock wait	1	0	0
		WriteUnlock	ReadLock wait	0	0	0

```
mutex_lock(&lock);
if (waiting_writers != 0) {
    cond_signal(&ok_to_write_cv);
} else {
    cond_broadcast(&ok_to_read_cv);
}
```


simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW	
				0	0	0	
ReadLock				0	1	0	
(reading)	ReadLock			0	2	0	
(reading)	(reading)	<pre>while (writers != 0 && waiting_writers != 0) { cond_wait(&ok_to_read_cv, &lock); } ++readers; mutex_unlock(&lock);</pre>					
(reading)	(reading)						
ReadUnlock	(reading)						
	ReadUnlock						
		WriteLock	ReadLock wait	1	0	0	
		(read+writing)	ReadLock wait	1	0	0	
		WriteUnlock	ReadLock wait	0	0	0	
			ReadLock	0	1	0	

simulation of reader/write lock

writer-priority version

W = writers, R = readers, WW = waiting_writers

reader 1	reader 2	writer 1	reader 3	W	R	WW
				0	0	0
ReadLock				0	1	0
(reading)	ReadLock			0	2	0
(reading)	(reading)	WriteLock wait		0	2	1
(reading)	(reading)	WriteLock wait	ReadLock wait	0	2	1
ReadUnlock	(reading)	WriteLock wait	ReadLock wait	0	1	1
	ReadUnlock	WriteLock wait	ReadLock wait	0	0	1
		WriteLock	ReadLock wait	1	0	0
		(read+writing)	ReadLock wait	1	0	0
		WriteUnlock	ReadLock wait	0	0	0
			ReadLock	0	1	0

reader-priority (1)

```
...  
int waiting_readers = 0;
```

```
ReadLock() {  
    mutex_lock(&lock);  
    ++waiting_readers;  
    while (writers != 0) {  
        cond_wait(&ok_to_read_cv, &lock);  
    }  
    --waiting_readers;  
    ++readers;  
    mutex_unlock(&lock);  
}
```

```
ReadUnlock() {  
    ...  
    if (waiting_readers == 0) {  
        cond_signal(&ok_to_write_cv);  
    }  
}
```

```
WriteLock() {  
    mutex_lock(&lock);  
    while (waiting_readers +  
           readers + writers != 0) {  
        cond_wait(&ok_to_write_cv);  
    }  
    ++writers;  
    mutex_unlock(&lock);  
}
```

```
WriteUnlock() {  
    mutex_lock(&lock);  
    --writers;  
    if (readers == 0 && waiting_readers == 0) {  
        cond_signal(&ok_to_write_cv);  
    } else {  
        cond_broadcast(&ok_to_read_cv);  
    }  
    mutex_unlock(&lock);  
}
```

reader-priority (1)

```
...  
int waiting_readers = 0;
```

```
ReadLock() {  
    mutex_lock(&lock);  
    ++waiting_readers;  
    while (writers != 0) {  
        cond_wait(&ok_to_read_cv, &lock);  
    }  
    --waiting_readers;  
    ++readers;  
    mutex_unlock(&lock);  
}
```

```
ReadUnlock() {  
    ...  
    if (waiting_readers == 0) {  
        cond_signal(&ok_to_write_cv);  
    }  
}
```

```
WriteLock() {  
    mutex_lock(&lock);  
    while (waiting_readers +  
           readers + writers != 0) {  
        cond_wait(&ok_to_write_cv);  
    }  
    ++writers;  
    mutex_unlock(&lock);  
}
```

```
WriteUnlock() {  
    mutex_lock(&lock);  
    --writers;  
    if (readers == 0 && waiting_readers == 0) {  
        cond_signal(&ok_to_write_cv);  
    } else {  
        cond_broadcast(&ok_to_read_cv);  
    }  
    mutex_unlock(&lock);  
}
```

rwlock exercise

suppose we want something in-between reader and writer priority:

reader-priority except if writers wait more than 1 second

exercise: what do we change?

```
...
int waiting_readers = 0;
ReadLock() {
    mutex_lock(&lock);
    ++waiting_readers;
    while (writers != 0) {
        cond_wait(&ok_to_read_cv, &lock);
    }
    --waiting_readers;
    ++readers;
    mutex_unlock(&lock);
}

ReadUnlock() {
    mutex_lock(&lock);
    --readers;
    if (waiting_readers == 0 &&
        readers == 0) {
        cond_signal(&ok_to_write_cv);
    }
}
```

```
WriteLock() {
    mutex_lock(&lock);
    while (waiting_readers + readers + writers != 0)
        cond_wait(&ok_to_write_cv);
    ++writers;
    mutex_unlock(&lock);
}

WriteUnlock() {
    mutex_lock(&lock);
    --writers;
    if (waiting_readers == 0) {
        cond_signal(&ok_to_write_cv);
    } else {
        cond_broadcast(&ok_to_read_cv);
    }
    mutex_unlock(&lock);
}
```


backup slides

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 ...  
}
```

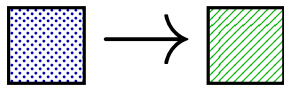

life homework even/odd

naive way has an operation that needs locking:

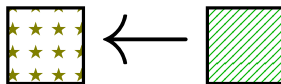
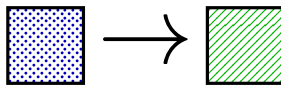
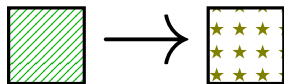
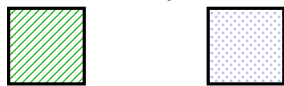
```
for (int time = 0; time < MAX_ITERATIONS; ++time) {  
    ... compute to_grid ...  
    swap(from_grid, to_grid);  
}
```

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 %eax == 1, then lock is taken
jne acquire              // if not equal, jump to acquire
ret                      // 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

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
```

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

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

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

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

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

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) {  
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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);  
    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;  
};
```

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

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UnlockMutex(Mutex *m) {  
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    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

intuition: context switch only happens on interrupt
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

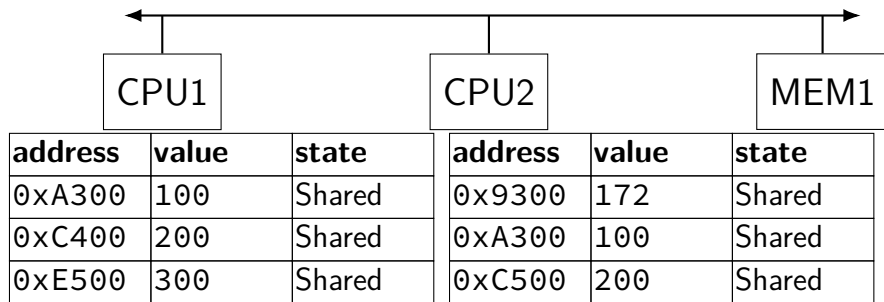
example: hear write while Shared

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

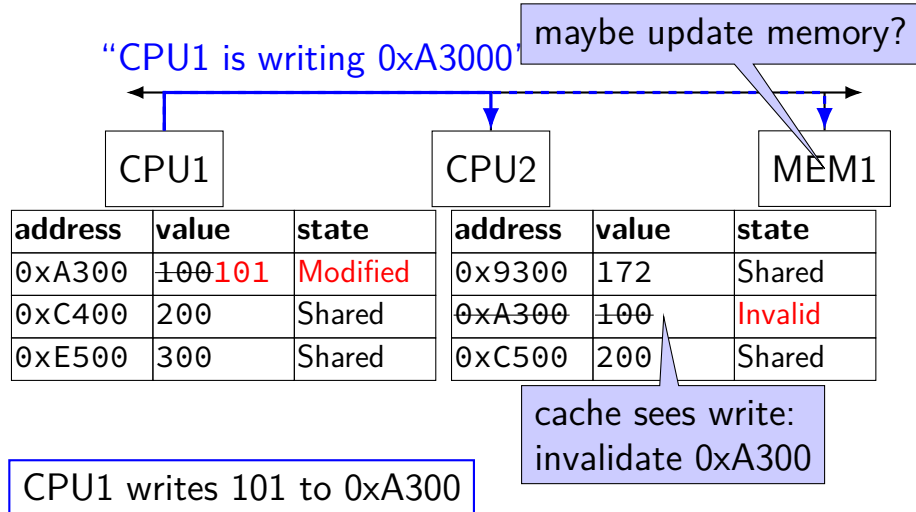
example: write while Modified

nothing to do — no other CPU can have a copy

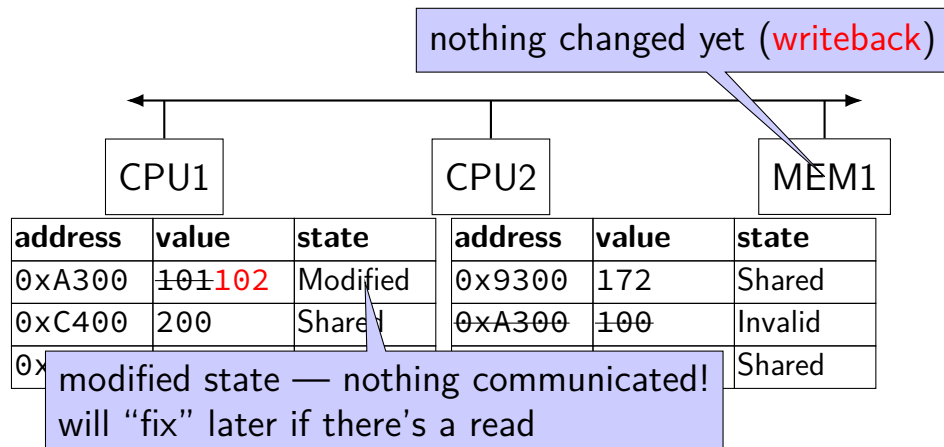
MSI example



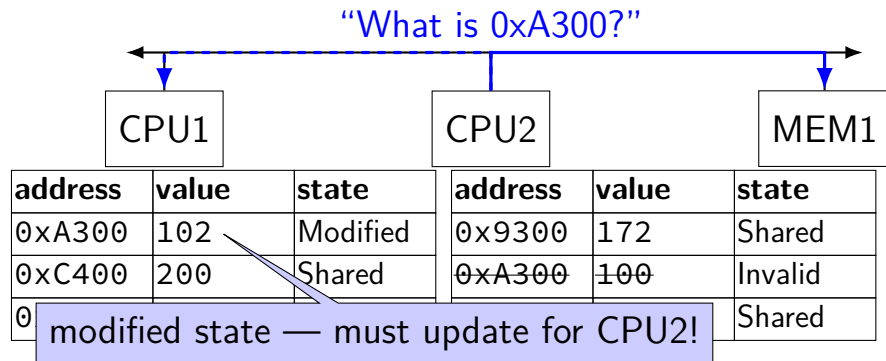
MSI example



MSI example



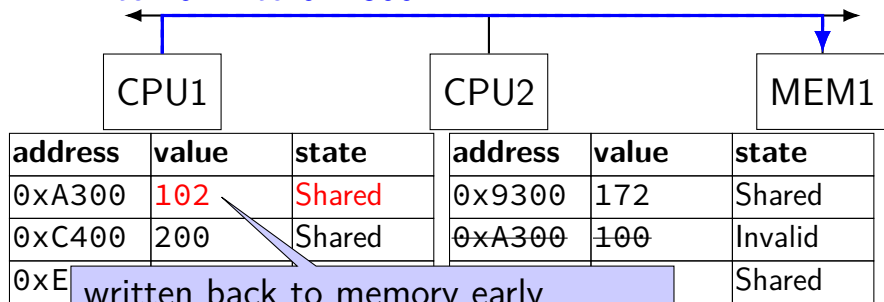
MSI example



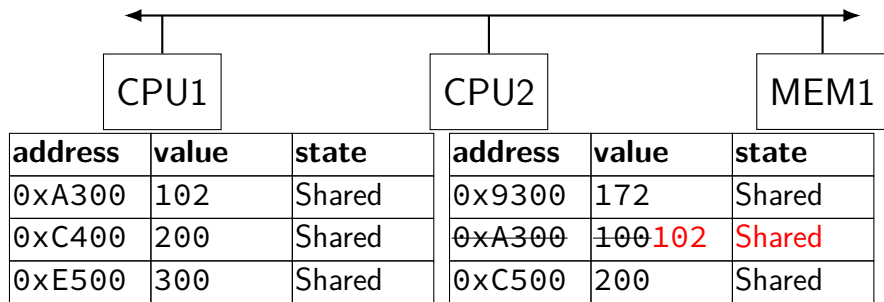
CPU2 reads 0xA300

MSI example

“Write 102 into 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

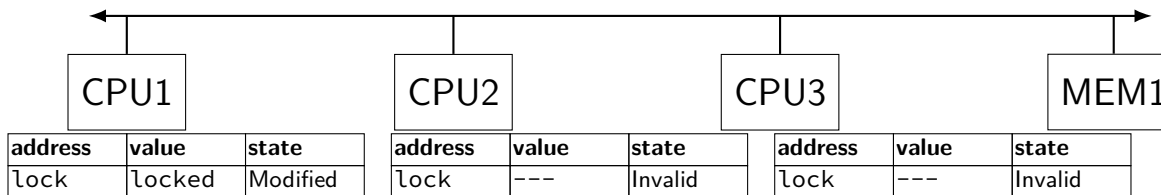
 - want to run another thread instead of infinite loop

 - solution: lock implementation integrated with scheduler

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

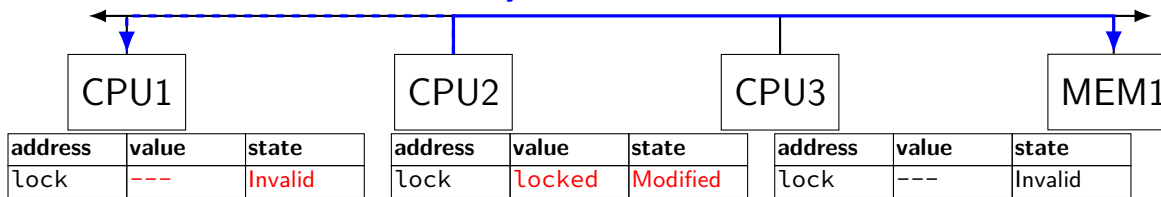
 - more efficient atomic operations to implement locks

ping-ponging



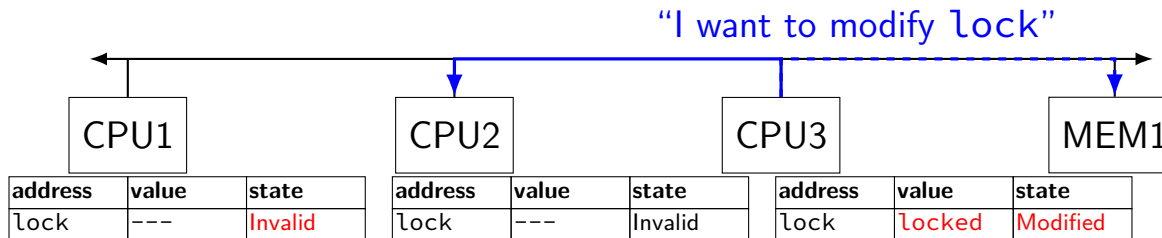
ping-ponging

"I want to modify lock?"



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

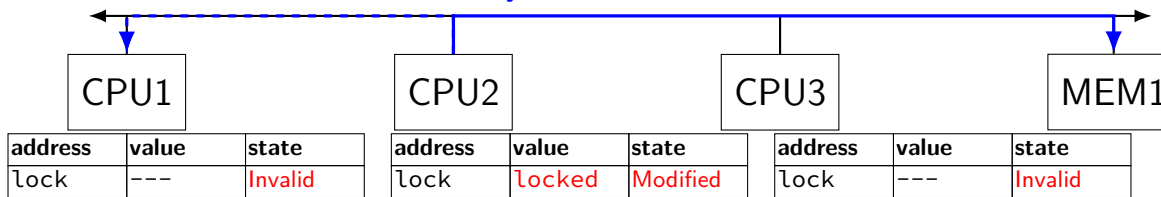
ping-ponging



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

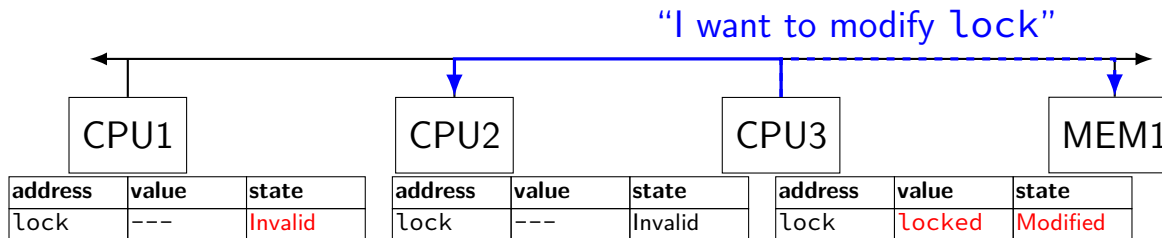
ping-ponging

"I want to modify lock?"



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

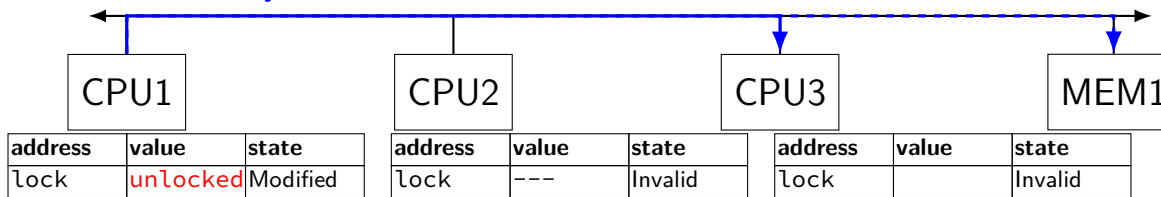
ping-ponging



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

ping-ponging

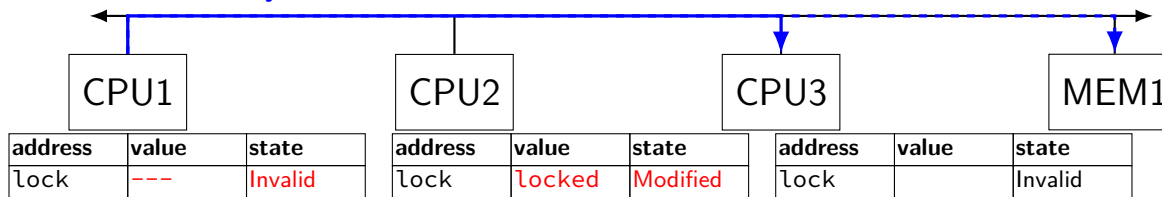
“I want to modify lock”



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)

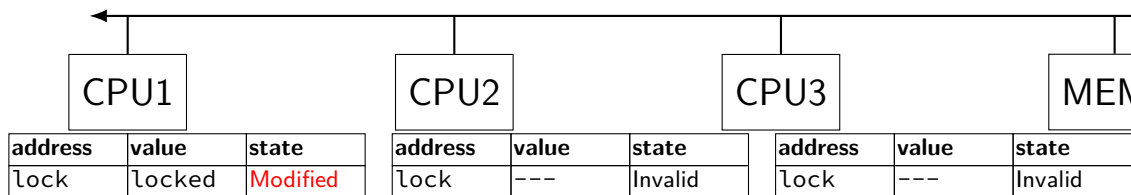
```
acquire(int *the_lock) {  
    do {  
        while (ATOMIC-READ(the_lock) == 0) { /* try again */ }  
    } while (ATOMIC-TEST-AND-SET(the_lock) == ALREADY_SET);  
}
```

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

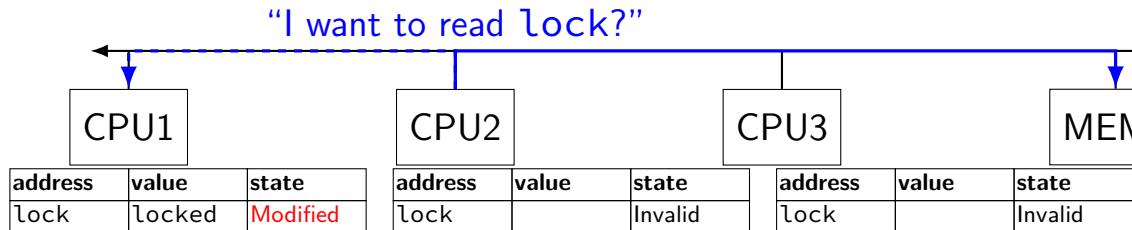
acquire:

```
    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



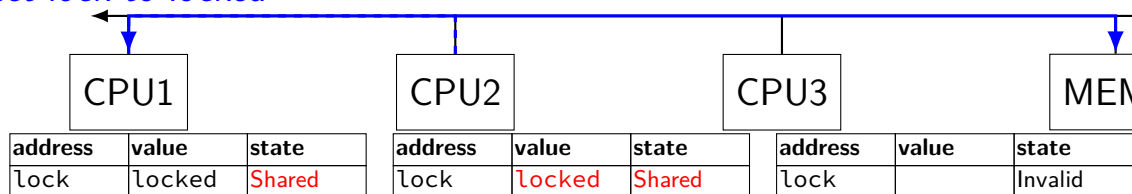
less ping-ponging



CPU2 reads lock
(to see it is still locked)

less ping-ponging

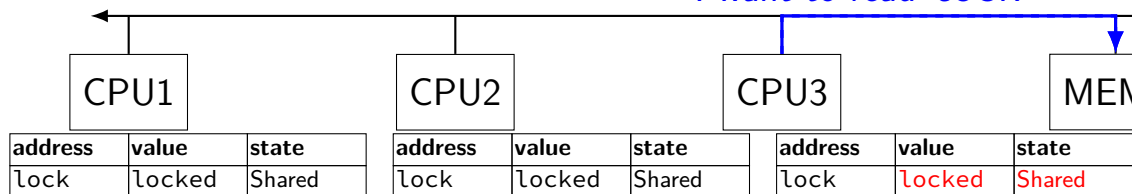
“set lock to locked”



CPU1 writes back lock value,
then CPU2 reads it

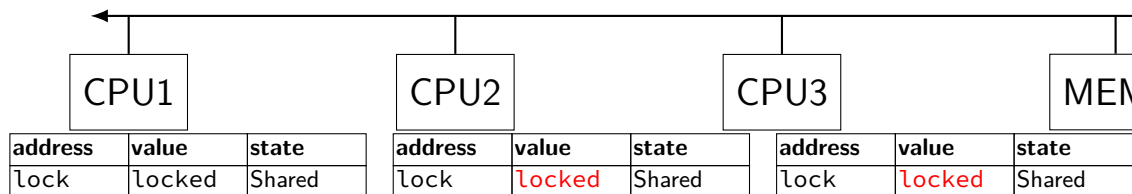
less ping-ponging

"I want to read lock"



CPU3 reads lock
(to see it is still locked)

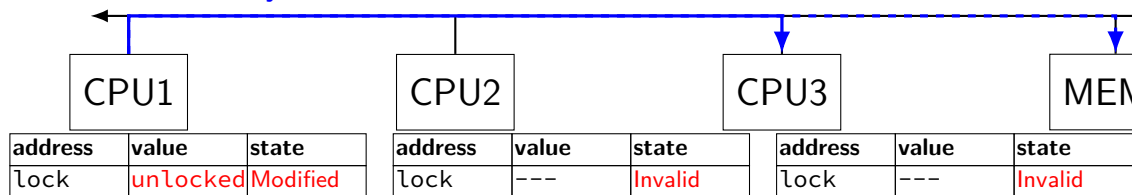
less ping-ponging



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

less ping-ponging

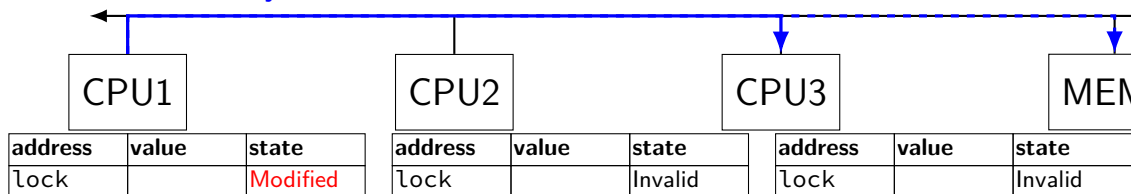
“I want to modify lock”



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)

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

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();
```

```
}
```

backup slides