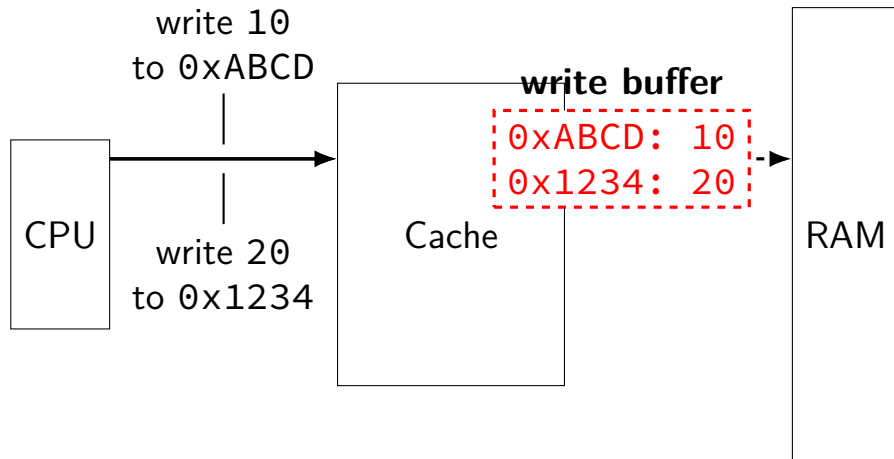


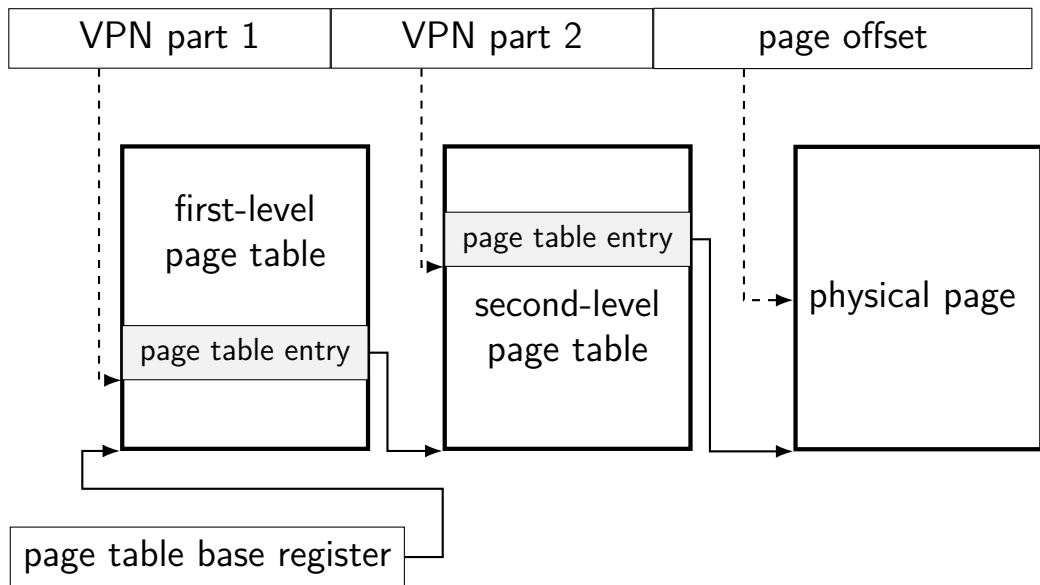
threads

fast writes

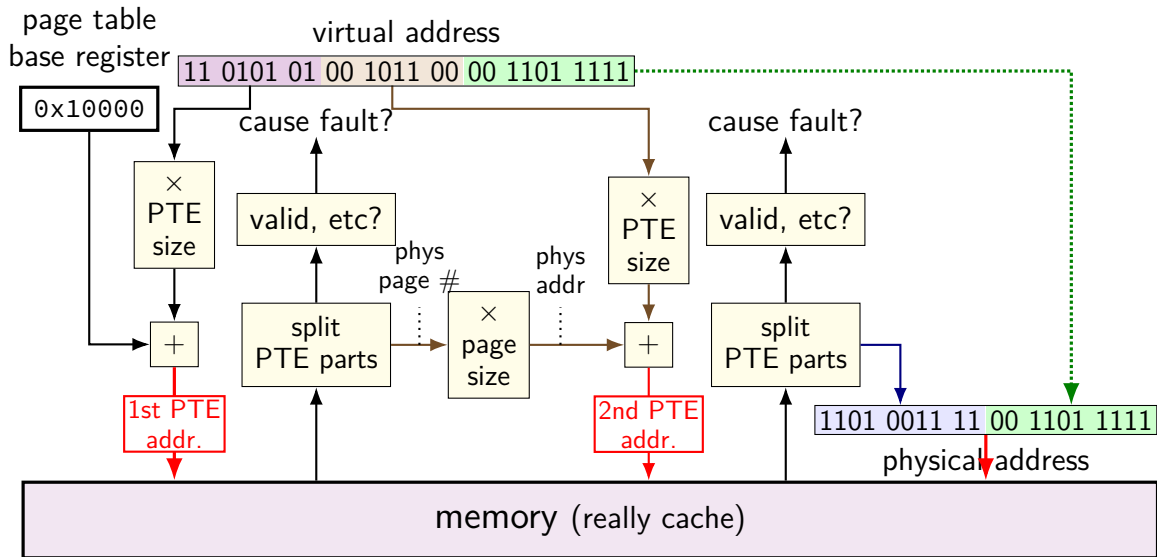


write appears to complete immediately when placed in buffer
memory can be much slower

another view



two-level page table lookup



cache accesses and multi-level PTs

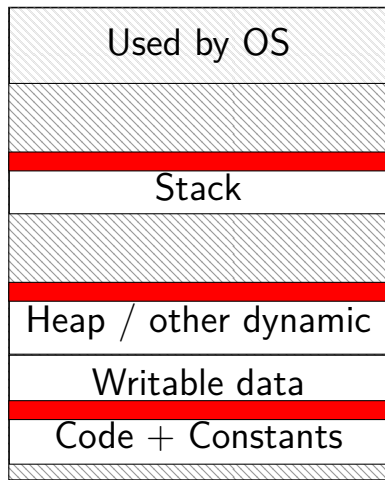
four-level page tables — five cache accesses per program memory access

L1 cache hits — typically a couple cycles each?

so add 8 cycles to each program memory access?

not acceptable

program memory active sets



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F...

small areas of memory active at a time
one or two pages in each area?

0x0000 0000 0040 0000

page table entries and locality

page table entries have **excellent temporal locality**

typically one or two pages of the stack active

typically one or two pages of code active

typically one or two pages of heap/globals active

each page contains **whole functions**, arrays, stack frames, etc.

page table entries and locality

page table entries have **excellent temporal locality**

typically one or two pages of the stack active

typically one or two pages of code active

typically one or two pages of heap/globals active

each page contains **whole functions**, arrays, stack frames, etc.

needed page table entries are **very small**

page table entry cache

called a **TLB** (translation lookaside buffer)

very small cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

page table entry cache

called a **TLB** (translation lookaside buffer)

very small cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries
only caches the page table lookup itself (generally) just entries from the last-level page tables	

page table entry cache

called a **TLB** (translation lookaside buffer)

very small cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

virtual page number divided into
index + tag

page table entry cache

called a **TLB** (translation lookaside buffer)

very small cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

not much spatial locality between page table entries
(they're used for kilobytes of data already)

page table entry cache

called a **TLB** (translation lookaside buffer)

very small cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

0 block offset bits

page table entry cache

called a **TLB** (translation lookaside buffer)

very small cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

few active page table entries at a time
enables highly associative cache designs

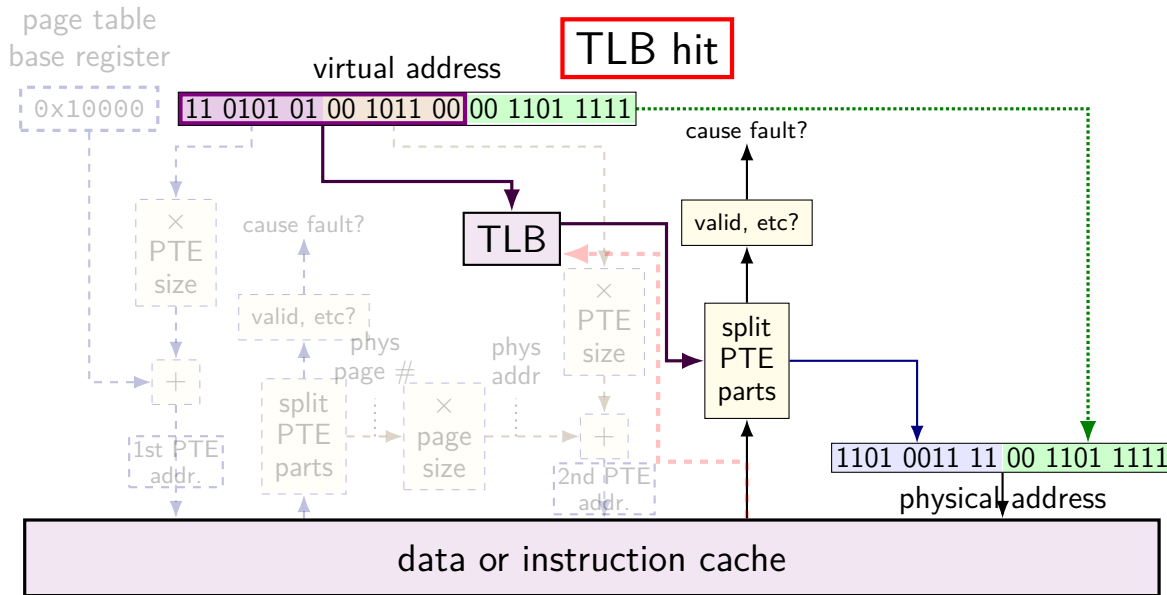
TLB and multi-level page tables

TLB caches **valid last-level page table entries**

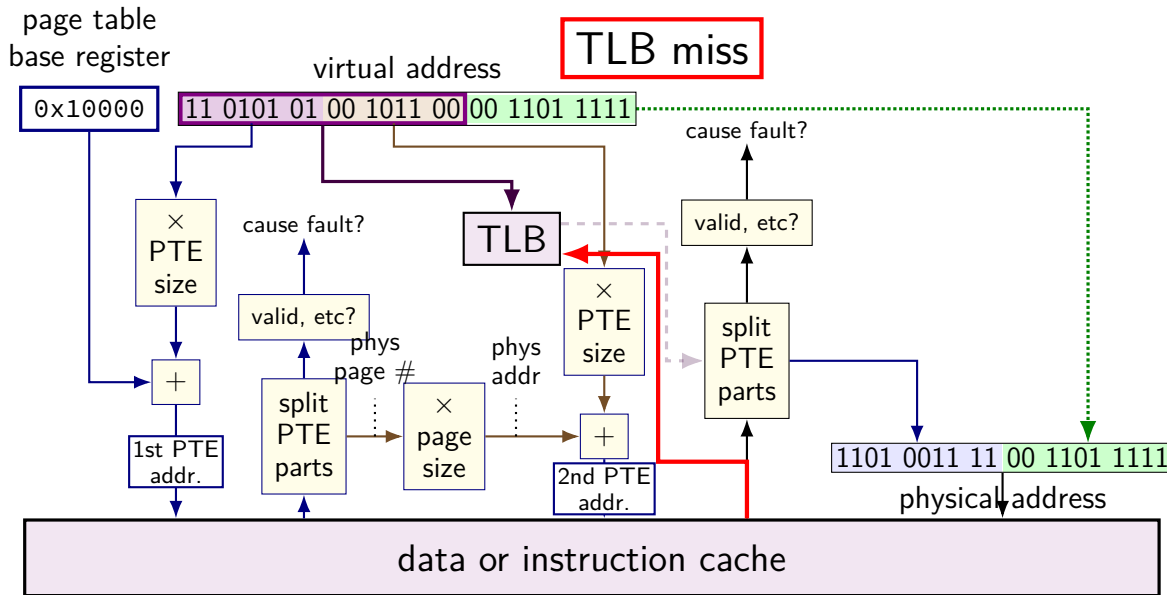
doesn't matter which last-level page table

means TLB output can be used directly to form address

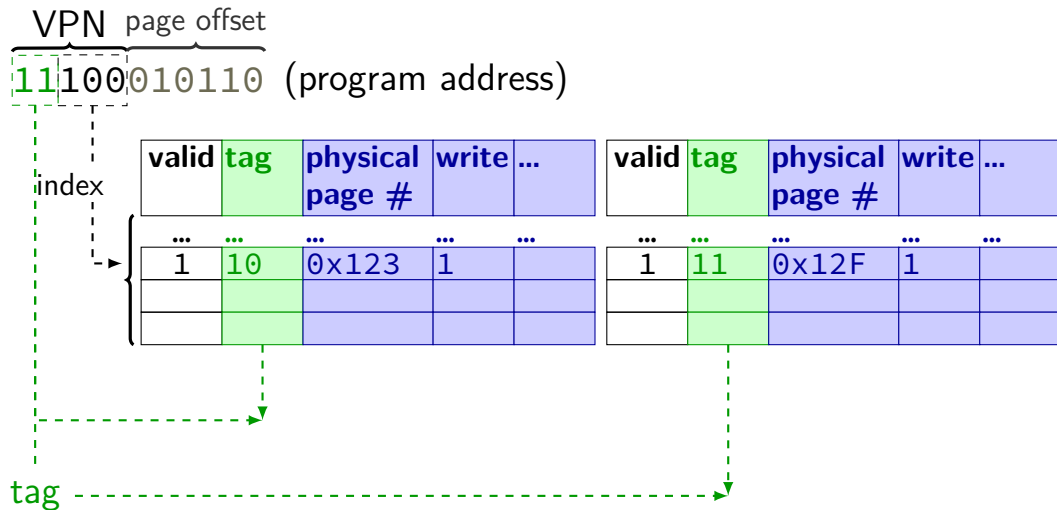
TLB and two-level lookup



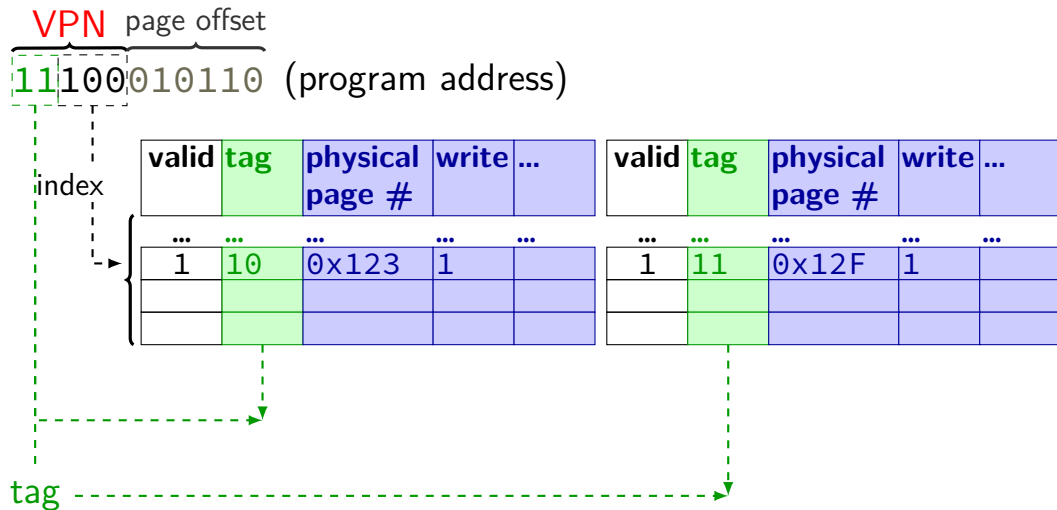
TLB and two-level lookup



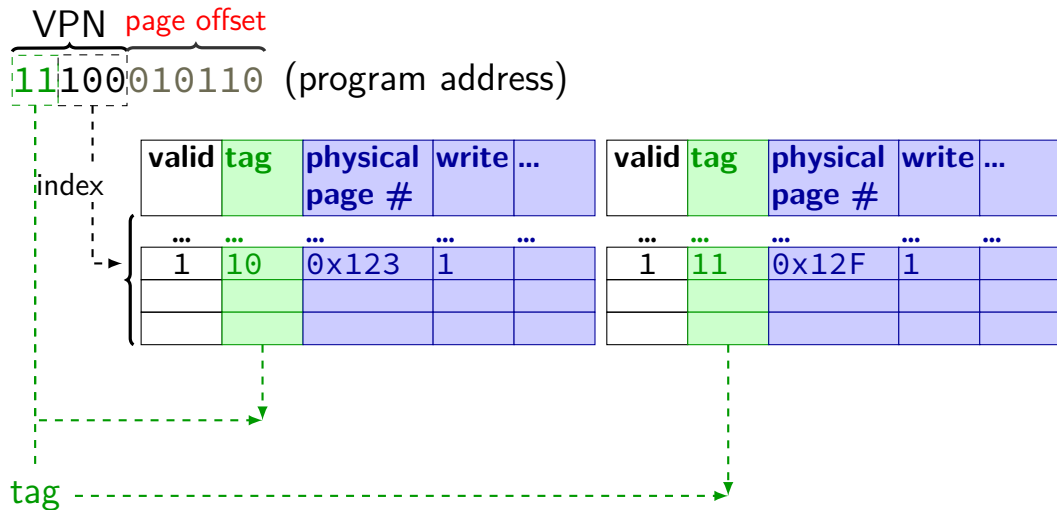
TLB organization (2-way set associative)



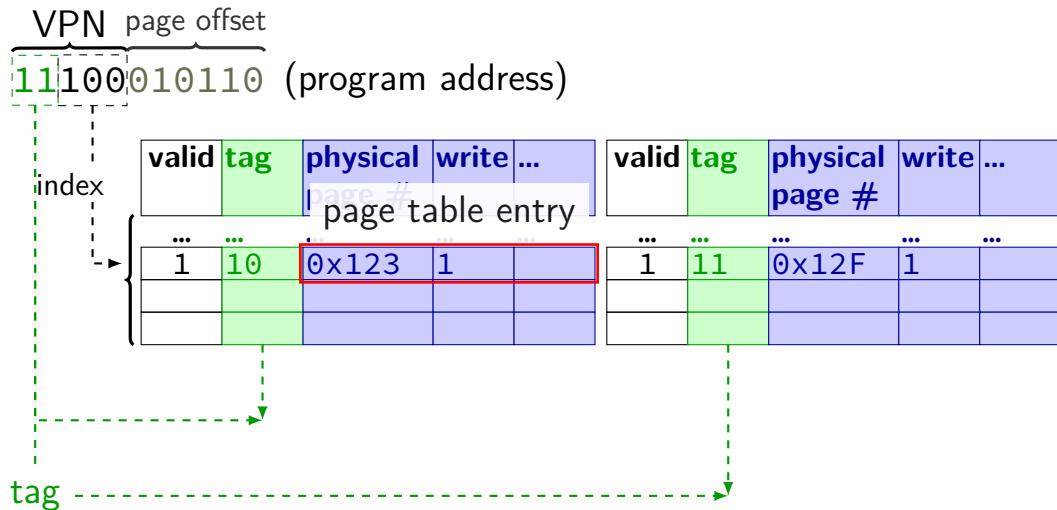
TLB organization (2-way set associative)



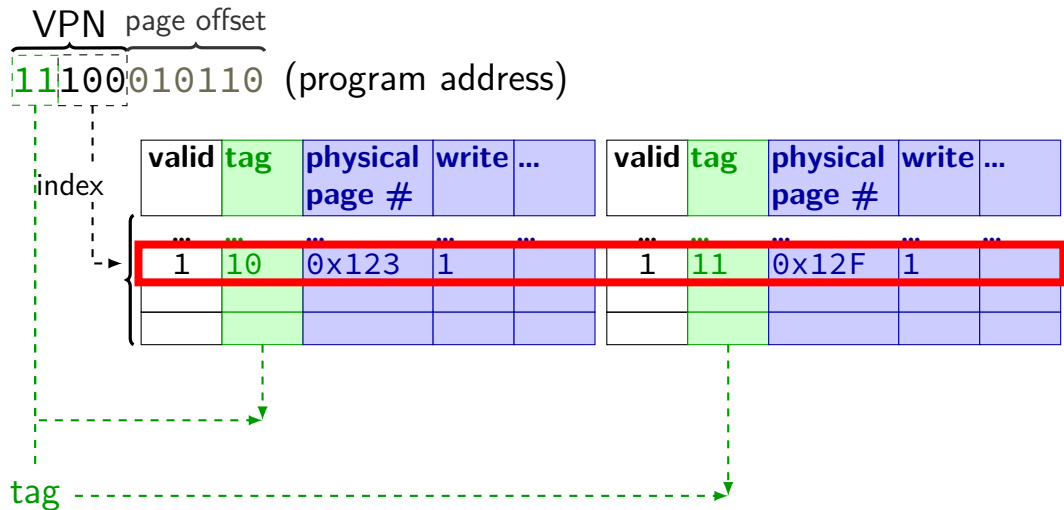
TLB organization (2-way set associative)



TLB organization (2-way set associative)



TLB organization (2-way set associative)



exercise: TLB access pattern (setup)

4-entry, 2-way TLB, LRU replacement policy, initially empty

4096 byte pages

how many index bits?

TLB index of virtual address 0x12345?

exercise: TLB access pattern

4-entry, 2-way TLB, LRU replacement policy, initially empty

4096 byte pages

type	virtual	physical
read	0x440030	0x554030
write	0x440034	0x554034
read	0x7FFFE008	0x556008
read	0x7FFFE000	0x556000
read	0x7FFFDFF8	0x5F8FF8
read	0x664080	0x5F9080
read	0x440038	0x554038
write	0x7FFFDFF0	0x5F8FF0

which are TLB hits? which are TLB misses? final contents of TLB?

why threads?

concurrency: different things happening at once

- one thread per user of web server?

- one thread per page in web browser?

- one thread to play audio, one to read keyboard, ...?

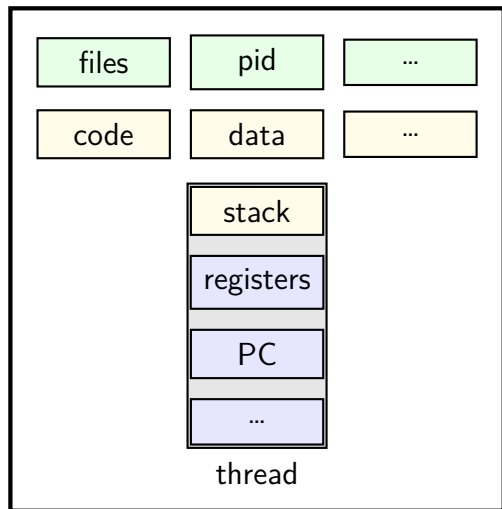
- ...

parallelism: do same thing with more resources

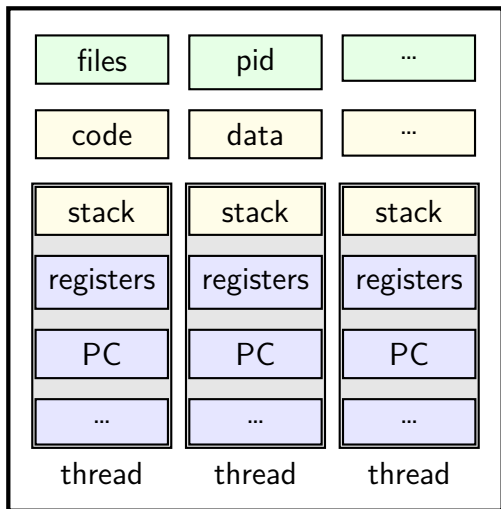
- multiple processors to speed-up simulation (life assignment)

single and multithread processes

single-threaded process

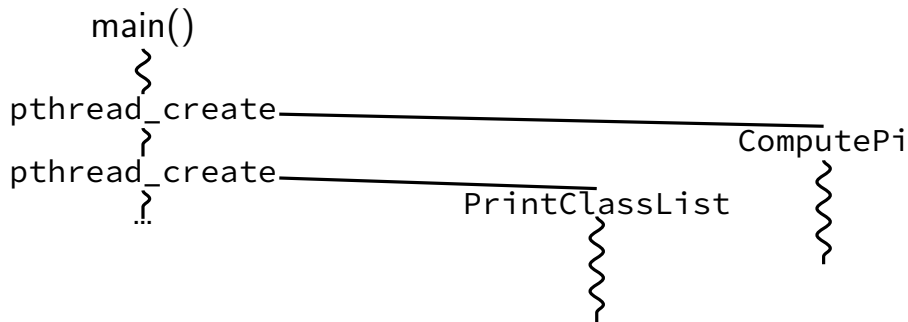


multi-threaded process



pthread_create

```
void *ComputePi(void *argument) { ... }  
void *PrintClassList(void *argument) { ... }  
int main() {  
    pthread_t pi_thread, list_thread;  
    pthread_create(&pi_thread, NULL, ComputePi, NULL);  
    pthread_create(&list_thread, NULL, PrintClassList, NULL);  
    ... /* more code */  
}
```



pthread_create

```
void *ComputePi(void *argument) { ... }  
void *PrintClassList(void *argument) { ... }  
int main() {  
    pthread_t pi_thread, list_thread;  
    pthread_create(&pi_thread, NULL, ComputePi, NULL);  
    pthread_create(&list_thread, NULL, PrintClassList, NULL);  
    ... /* more code */  
}
```

pthread_create arguments:

thread identifier

function to run thread starts here, terminates if this function returns

thread attributes (extra settings) and function argument

pthread_create

```
void *ComputePi(void *argument) { ... }
void *PrintClassList(void *argument) { ... }
int main() {
    pthread_t pi_thread, list_thread;
    pthread_create(&pi_thread, NULL, ComputePi, NULL);
    pthread_create(&list_thread, NULL, PrintClassList, NULL);
    ... /* more code */
}
```

pthread_create arguments:

thread identifier

function to run thread starts here, terminates if this function returns

thread attributes (extra settings) and function argument

pthread_create

```
void *ComputePi(void *argument) { ... }  
void *PrintClassList(void *argument) { ... }  
int main() {  
    pthread_t pi_thread, list_thread;  
    pthread_create(&pi_thread, NULL, ComputePi, NULL);  
    pthread_create(&list_thread, NULL, PrintClassList, NULL);  
    ... /* more code */  
}
```

pthread_create arguments:

thread identifier

function to run thread starts here, terminates if this function returns

thread attributes (extra settings) and function argument

pthread_create

```
void *ComputePi(void *argument) { ... }  
void *PrintClassList(void *argument) { ... }  
int main() {  
    pthread_t pi_thread, list_thread;  
    pthread_create(&pi_thread, NULL, ComputePi, NULL);  
    pthread_create(&list_thread, NULL, PrintClassList, NULL);  
    ... /* more code */  
}
```

pthread_create arguments:

thread identifier

function to run thread starts here, terminates if this function returns

thread attributes (extra settings) and function argument

a threading race

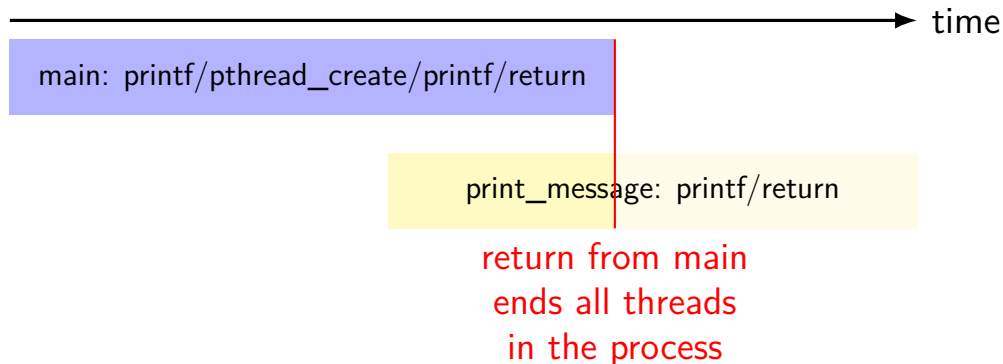
```
#include <pthread.h>
#include <stdio.h>
void *print_message(void *ignored_argument) {
    printf("In the thread\n"); return NULL;
}
int main() {
    printf("About to start thread\n");
    pthread_t the_thread;
    pthread_create(&the_thread, NULL, print_message, NULL);
    printf("Done starting thread\n");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



fixing the race (version 1)

```
#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");
    pthread_join(the_thread, NULL); /* WAIT FOR THREAD */
    return 0;
}
```

fixing the race (version 2; not recommended)

```
#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");
    pthread_exit(NULL);
}
```

pthread_join, pthread_exit

`pthread_join`: wait for thread, retrieves its return value
like `waitpid`, but for a thread
return value is pointer to anything

`pthread_exit`: exit current thread, returning a value
like `exit` or returning from `main`, but for a single thread
same effect as returning from function passed to `pthread_create`

sum example (only globals)

```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    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];
}
```

sum example (only globals)

values, results: global variables — shared

```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    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];
}
```

sum example (only globals)

two different functions

happen to be the same except for some numbers

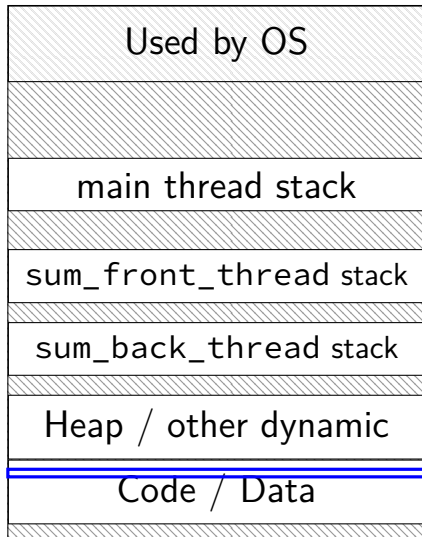
```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    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];
}
```

sum

values returned from threads
via global array instead of return value
(partly to illustrate that memory is shared,
partly because this pattern works when we don't join (later))

```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    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];
}
```


thread_sum memory layout



0xFFFF FFFF FFFF FFFF

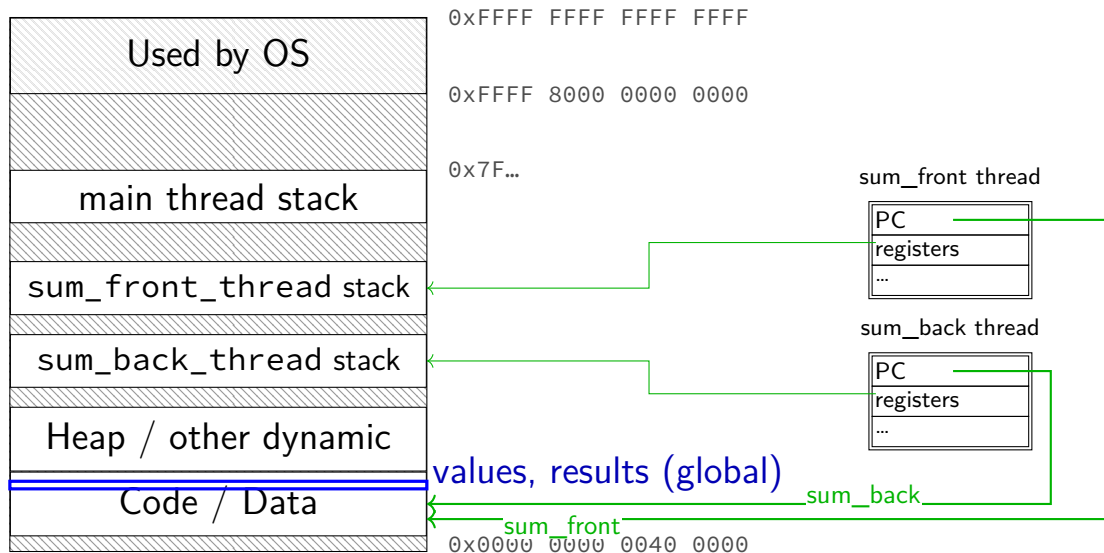
0xFFFF 8000 0000 0000

0x7F...

values, results (global)

0x0000 0000 0040 0000

thread_sum memory layout



sum example (to global, with thread IDs)

```
int values[1024];
int results[2];
void *sum_thread(void *argument) {
    int id = (int) argument;
    int sum = 0;
    for (int i = id * 512; i < (id + 1) * 512; ++i) {
        sum += values[i];
    }
    results[id] = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        pthread_create(&threads[i], NULL, sum_thread, (void *) i);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return results[0] + results[1];
}
```

sum example (to global, with thread IDs)

```
int values[1024];
int results[2];
void *sum_thread(void *argument) {
    int id = (int) argument;
    int sum = 0;
    for (int i = id * 512; i < (id + 1) * 512; ++i) {
        sum += values[i];
    }
    results[id] = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        pthread_create(&threads[i], NULL, sum_thread, (void *) i);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return results[0] + results[1];
}
```

values, results: global variables — shared

sum example (info struct)

```
int values[1024];
struct ThreadInfo {
    int start, end, result;
};

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

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

sum example (info struct)

```
int values[1024];
struct ThreadInfo
    int start, end, result;
};
void *sum_thread(void *argument) {
    struct tThreadInfo *my_info = (struct ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) { sum += values[i]; }
    my_info->result = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2]; struct ThreadInfo info[2];
    for (int i = 0; i < 2; ++i) {
        info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, &info[i]);
    }
    for (int i = 0; i < 2; ++i) { pthread_join(threads[i], NULL); }
    return info[0].result + info[1].result;
}
```

values: global variable — shared

sum example (info struct)

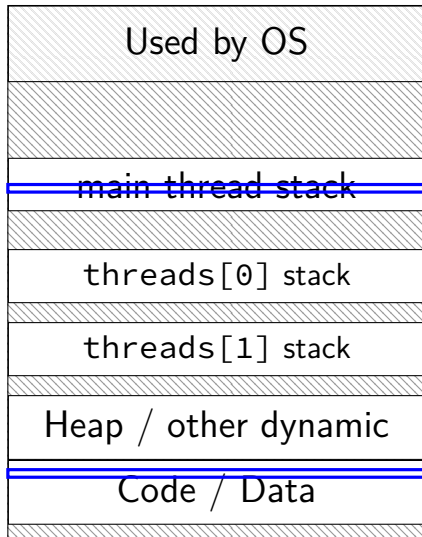
```
int values[1024];
struct ThreadInfo {
    int start, end, result;
};
void *sum_thread(void *argument) {
    struct tThreadInfo *my_info = (struct ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start;
        my_info->result = sum;
        return NULL;
    }
int sum_all() {
    pthread_t thread[2]; struct ThreadInfo info[2];
    for (int i = 0; i < 2; ++i) {
        info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, &info[i]);
    }
    for (int i = 0; i < 2; ++i) { pthread_join(threads[i], NULL); }
    return info[0].result + info[1].result;
}
```

my_info: pointer to sum_all's stack;
only okay because sum_all waits!

sum example (info struct)

```
int values[1024];
struct ThreadInfo {
    int start, end, result;
};
void *sum_thread(void *argument) {
    struct tThreadInfo *my_info = (struct ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) { sum += values[i]; }
    my_info->result = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2]; struct ThreadInfo info[2];
    for (int i = 0; i < 2; ++i) {
        info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, &info[i]);
    }
    for (int i = 0; i < 2; ++i) { pthread_join(threads[i], NULL); }
    return info[0].result + info[1].result;
}
```


thread_sum memory layout (info struct)



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F...

info array

my_info

my_info

values (global)

0x0000 0000 0040 0000

sum example (to main stack)

```
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) {
        sum += my_info->values[i];
    }
    my_info->result = sum;
    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;
}
```

sum example (to main stack)

```
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) {
        sum += my_info->values[i];
    }
    my_info->result = sum;
    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;
}
```

sum example (to main stack)

```
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) {
        sum += my_info->values[i];
    }
    my_info->result = sum;
    return NULL;
}

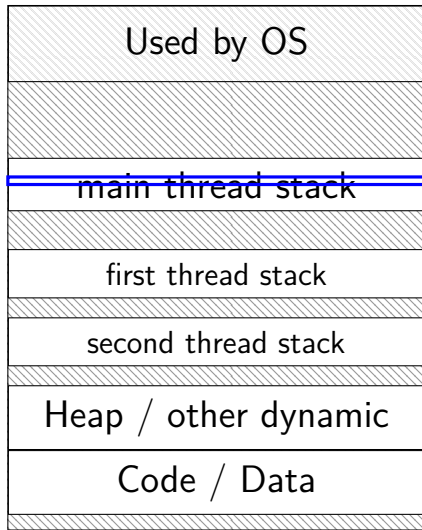
int sum_all(int *values) {
    ThreadInfo info[2]; pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)
 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

sum example (to main stack)

```
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) {
        sum += my_info->values[i];
    }
    my_info->result = sum;
    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;
}
```

program memory (to main stack)



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F...

info array

values (stack? heap?)

my_info

my_info

0x0000 0000 0040 0000

sum example (on heap)

```
struct ThreadInfo { pthread_t thread; int *values; int start; int end; int result;
void *sum_thread(void *argument) {
    ...
}

struct ThreadInfo *start_sum_all(int *values) {
    struct ThreadInfo *info = calloc(2, sizeof(struct ThreadInfo));
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&info[i].thread, NULL, sum_thread, (void *) &info[i]);
    }
    return info;
}

int finish_sum_all(ThreadInfo *info) {
    for (int i = 0; i < 2; ++i)
        pthread_join(info[i].thread, NULL);
    int result = info[0].result + info[1].result;
    free(info);
    return result;
}
```

sum example (on heap)

```
struct ThreadInfo { pthread_t thread; int *values; int start; int end; int result;
void *sum_thread(void *argument) {
    ...
}
```

```
struct ThreadInfo *start_sum_all(int *values) {
    struct ThreadInfo *info = calloc(2, sizeof(struct ThreadInfo));
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&info[i].thread, NULL, sum_thread, (void *) &info[i]);
    }
    return info;
}
```

```
int finish_sum_all(ThreadInfo *info) {
    for (int i = 0; i < 2; ++i)
        pthread_join(info[i].thread, NULL);
    int result = info[0].result + info[1].result;
    free(info);
    return result;
}
```

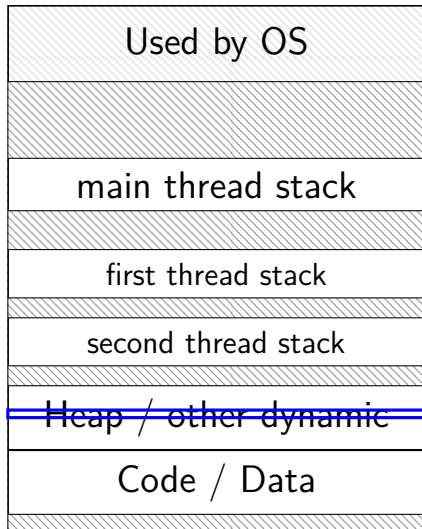

sum example (on heap)

```
struct ThreadInfo { pthread_t thread; int *values; int start; int end; int result;
void *sum_thread(void *argument) {
    ...
}

struct ThreadInfo *start_sum_all(int *values) {
    struct ThreadInfo *info = calloc(2, sizeof(struct ThreadInfo));
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&info[i].thread, NULL, sum_thread, (void *) &info[i]);
    }
    return info;
}

int finish_sum_all(ThreadInfo *info) {
    for (int i = 0; i < 2; ++i)
        pthread_join(info[i].thread, NULL);
    int result = info[0].result + info[1].result;
    free(info);
    return result;
}
```

thread_sum memory (heap version)



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F...

my_info

my_info

info array

values (stack? heap?)

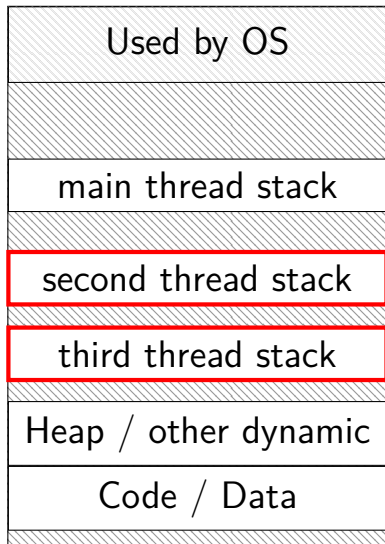
0x0000 0000 0040 0000

what's wrong with this?

```
/* omitted: headers */
void *create_string(void *ignored_argument) {
    char string[1024];
    ComputeString(string);
    return string;
}

int main() {
    pthread_t the_thread;
    pthread_create(&the_thread, NULL, create_string, NULL);
    char *string_ptr;
    pthread_join(the_thread, (void**) &string_ptr);
    printf("string is %s\n", string_ptr);
}
```

program memory



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

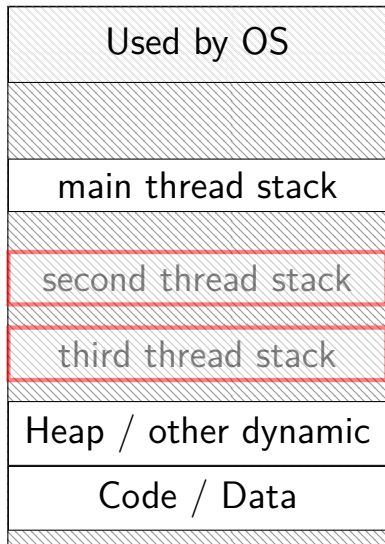
0x7F...

} dynamically allocated stacks
} string result allocated here
} string_ptr pointed to here

...stacks deallocated when
threads exit/are joined

0x0000 0000 0040 0000

program memory



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F...

} dynamically allocated stacks
} string result allocated here
} string_ptr pointed to here

...stacks deallocated when
threads exit/are joined

0x0000 0000 0040 0000

thread joining

`pthread_join` allows collecting thread return value

if you don't join joinable thread, then **memory leak!**

thread joining

pthread_join allows collecting thread return value

if you don't join joinable thread, then **memory leak!**

avoiding memory leak?

always join...or

“detach” thread to make it not joinable

pthread_detach

```
void *show_progress(void * ...) { ... }  
void spawn_show_progress_thread() {  
    pthread_t show_progress_thread;  
    pthread_create(&show_progress_thread, NULL,  
                  show_progress, NULL);
```

/ instead of keeping pthread_t around to join thread later: */*

```
pthread_detach(show_progress_thread);
```

```
}
```

```
int main() {  
    spawn_show_progress_thread();  
    do_other_stuff();  
    ...  
}
```

detach = don't care about return value, etc.
system will deallocate when thread terminates

starting threads detached

```
void *show_progress(void * ...) { ... }  
void spawn_show_progress_thread() {  
    pthread_t show_progress_thread;  
    pthread_attr_t attrs;  
    pthread_attr_init(&attrs);  
    pthread_attr_setdetachstate(&attrs, PTHREAD_CREATE_DETACHED);  
    pthread_create(&show_progress_thread, attrs,  
                  show_progress, NULL);  
    pthread_attr_destroy(&attrs);  
}
```

setting stack sizes

```
void *show_progress(void * ...) { ... }  
void spawn_show_progress_thread() {  
    pthread_t show_progress_thread;  
    pthread_attr_t attrs;  
    pthread_attr_init(&attrs);  
    pthread_attr_setstacksize(&attrs, 32 * 1024 /* bytes */);  
    pthread_create(&show_progress_thread, attrs,  
                  show_progress, NULL);  
}
```

a note on error checking

from pthread_create manpage:

ERRORS

EAGAIN Insufficient resources to create another thread, or a system-imposed limit on the number of threads was encountered. The latter case may occur in two ways: the **RLIMIT_NPROC** soft resource limit (set via **setrlimit(2)**), which limits the number of process for a real user ID, was reached; or the kernel's system-wide limit on the number of threads, [/proc/sys/kernel/threads-max](#), was reached.

EINVAL Invalid settings in [attr](#).

EPERM No permission to set the scheduling policy and parameters specified in [attr](#).

special constants for *return value*

same pattern for many other pthreads functions

will often omit error checking in slides for brevity

error checking pthread_create

```
int error = pthread_create(...);  
if (error != 0) {  
    /* print some error message */  
}
```

a threading race

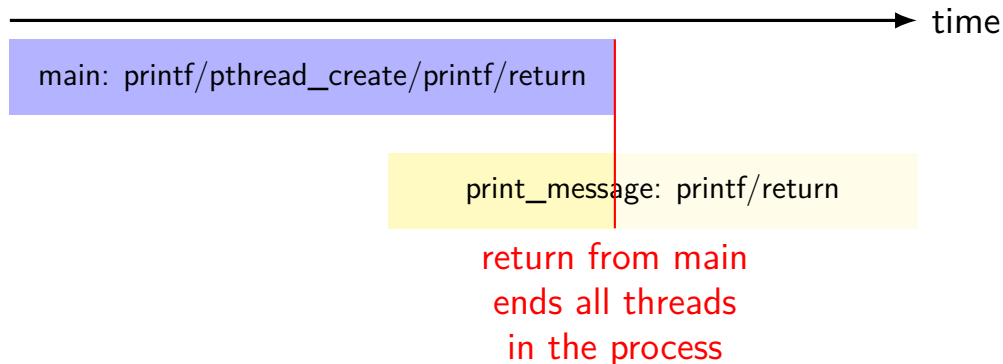
```
#include <pthread.h>
#include <stdio.h>
void *print_message(void *ignored_argument) {
    printf("In the thread\n"); return NULL;
}
int main() {
    printf("About to start thread\n");
    pthread_t the_thread;
    pthread_create(&the_thread, NULL, print_message, NULL);
    printf("Done starting thread\n");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

context switch

lost write to balance

lost track of thread A's money

Thread B

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

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

"winner" of the race

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

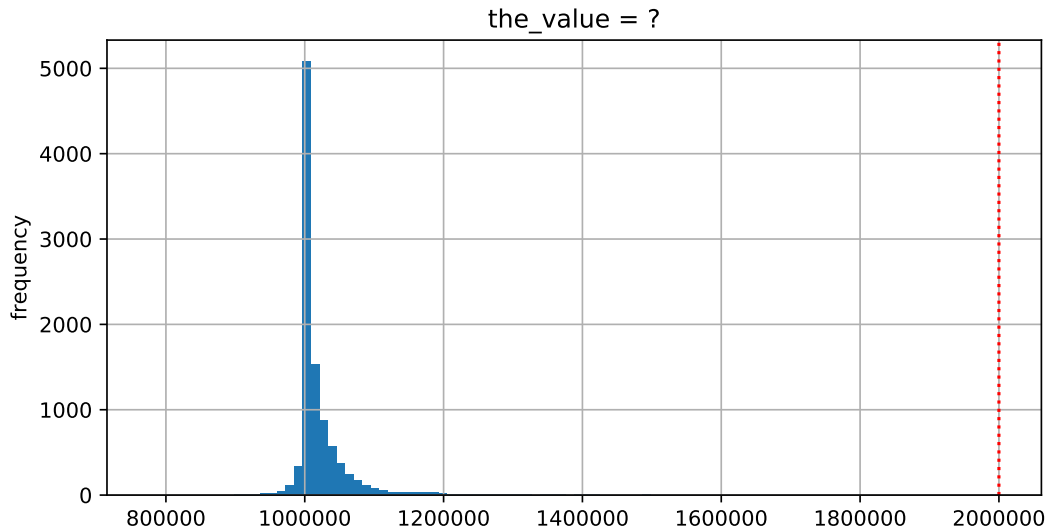
e.g. if cache blocks 0x40 bytes, load/store 4 byte from addr. 0x3E is not atomic

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

compilers move loads/stores (1)

```
void WaitForReady() {  
    do {} while (!ready);  
}
```

```
WaitForOther:  
    movl ready, %eax    // eax <- other_ready  
.L2:  
    testl %eax, %eax  
    je .L2              // while (eax == 0) repeat  
    ...
```

compilers move loads/stores (1)

```
void WaitForReady() {  
    do {} while (!ready);  
}
```

```
WaitForOther:  
    movl ready, %eax    // eax <- other_ready  
.L2:  
    testl %eax, %eax  
    je .L2              // while (eax == 0) repeat  
    ...
```

compilers move loads/stores (2)

```
void WaitForOther() {  
    is_waiting = 1;  
    do {} while (!other_ready);  
    is_waiting = 0;  
}
```

WaitForOther:

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

compilers move loads/stores (2)

```
void WaitForOther() {  
    is_waiting = 1;  
    do {} while (!other_ready);  
    is_waiting = 0;  
}
```

WaitForOther:

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

compilers move loads/stores (2)

```
void WaitForOther() {  
    is_waiting = 1;  
    do {} while (!other_ready);  
    is_waiting = 0;  
}
```

WaitForOther:

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

fixing compiler reordering?

isn't there a way to tell compiler not to do these optimizations?

yes, but that is **still not enough!**

processors sometimes do this kind of reordering too (between cores)

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_create, pthread_join, other tools we'll talk about ...

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

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

lock analogy

agreement: only change account balances while wearing this hat

normally hat kept on table

put on hat when editing balance

hopefully, only one person (= thread) can wear hat a time

need to wait for them to remove hat to put it on

lock analogy

agreement: only change account balances while wearing this hat

normally hat kept on table

put on hat when editing balance

hopefully, only one person (= thread) can wear hat a time

need to wait for them to remove hat to put it on

“lock (or acquire) the lock” = get and put on hat

“unlock (or release) the lock” = put hat back on table

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(account_lock);  
balance += ...;  
Unlock(account_lock);
```

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(account_lock);  
balance += ...;  
Unlock(account_lock);
```

waiting for lock?

when waiting — ideally:

not using processor (at least if waiting a while)

OS can context switch to other programs

pthread mutex

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

```
pthread_mutex_t account_lock;  
pthread_mutex_init(&account_lock, NULL);  
    // or: pthread_mutex_t account_lock =  
    //      PTHREAD_MUTEX_INITIALIZER;  
...  
pthread_mutex_lock(&account_lock);  
balance += ...;  
pthread_mutex_unlock(&account_lock);
```

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?

POSIX mutex restrictions

pthread_mutex rule: unlock from same thread you lock in

does this actually matter?

depends on how pthread_mutex is implemented

preview: general sync

lots of coordinating threads beyond locks/barriers

will talk about two general tools later:

- monitors/condition variables

- semaphores

big added feature: wait for arbitrary thing to happen

a bad idea

one **bad** idea to wait for an event:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER; bool ready = false;
void WaitForReady() {
    pthread_mutex_lock(&lock);
    do {
        pthread_mutex_unlock(&lock);
        /* only time MarkReady() can run */
        pthread_mutex_lock(&lock);
    } while (!ready);
    pthread_mutex_unlock(&lock);
}
void MarkReady() {
    pthread_mutex_lock(&lock);
    ready = true;
    pthread_mutex_unlock(&lock);
}
```

wastes processor time; MarkReady can stall waiting for unlock window

beyond locks

in practice: want more than locks for synchronization

for waiting for arbitrary events (without CPU-hogging-loop):

- monitors

- semaphores

for common synchronization patterns:

- barriers

- reader-writer locks

higher-level interface:

- transactions

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);
```


exercise

```
pthread_barrier_t barrier; int x = 0, y = 0;
void thread_one() {
    y = 10;
    pthread_barrier_wait(&barrier);
    y = x + y;
    pthread_barrier_wait(&barrier);
    pthread_barrier_wait(&barrier);
    printf("%d %d\n", x, y);
}
void thread_two() {
    x = 20;
    pthread_barrier_wait(&barrier);
    pthread_barrier_wait(&barrier);
    x = x + y;
    pthread_barrier_wait(&barrier);
}
```

output? (if both run at once, barrier set for 2 threads)

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

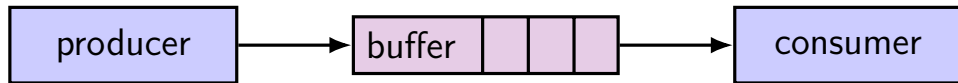
compute grid of values for time t from grid for time $t - 1$

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 $t + 1$

example: producer/consumer

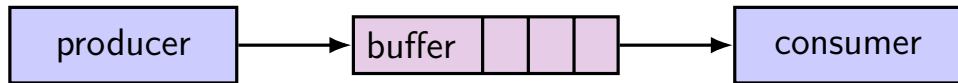


shared buffer (queue) of fixed size

one or more producers inserts into queue

one or more consumers removes from queue

example: producer/consumer



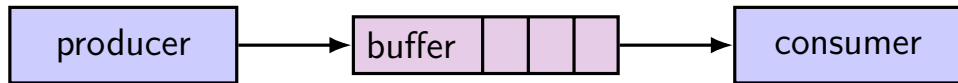
shared buffer (queue) of fixed size

- 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

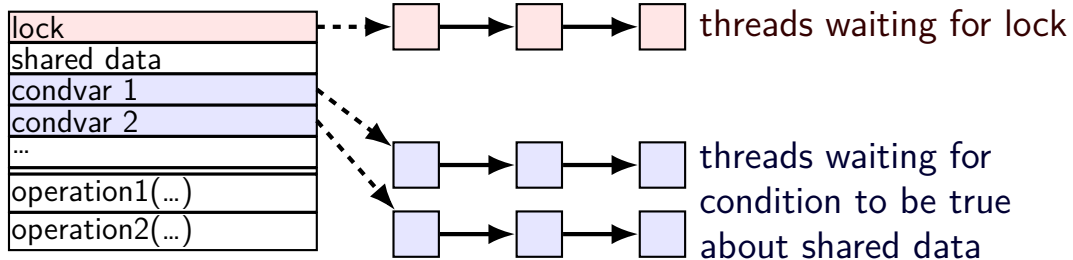
a monitor

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



monitor idea

a monitor



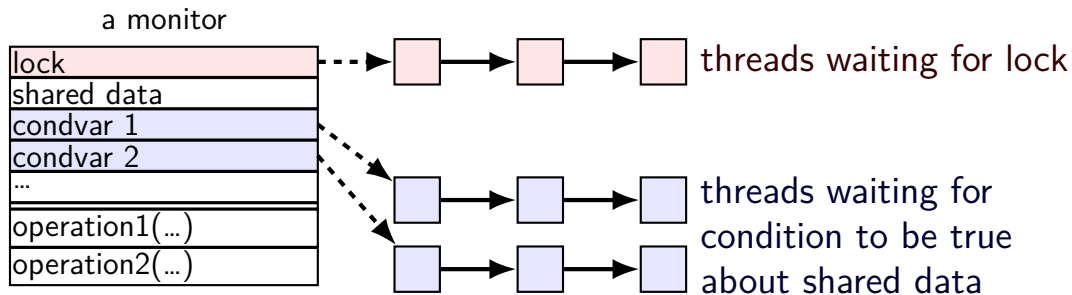
condvar operations

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

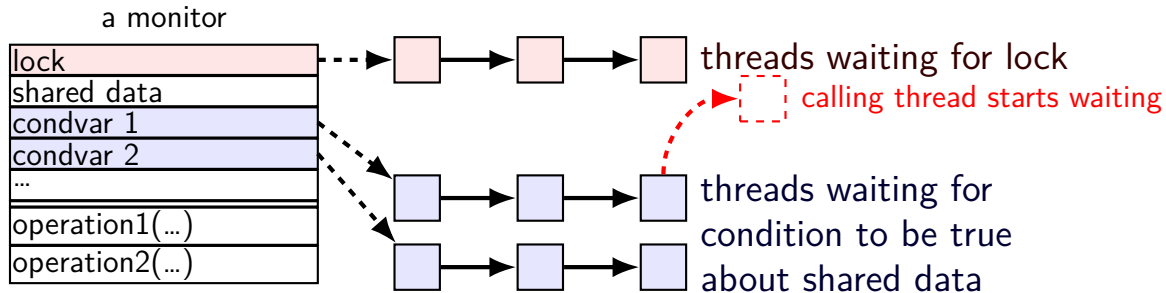
condvar operations:

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

...and reacquire lock before returning

Broadcast(cv) — remove all from condvar queue

Signal(cv) — remove one from condvar queue



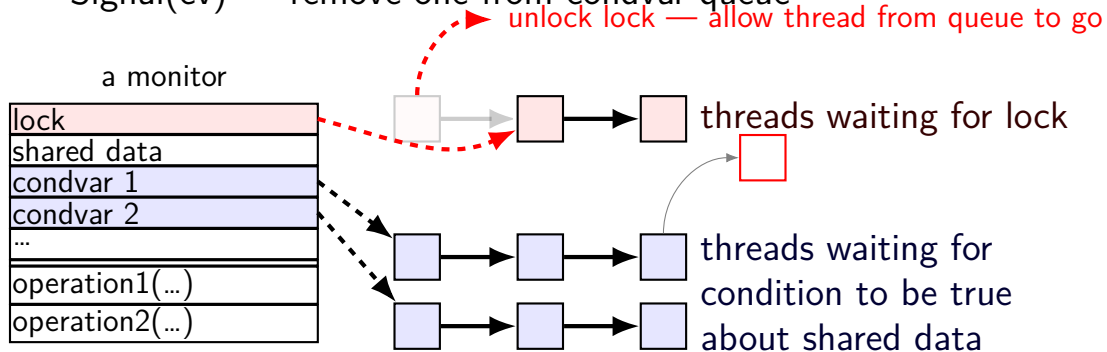
condvar operations

condvar operations:

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

Broadcast(cv) — remove all from condvar queue

Signal(cv) — remove one from condvar queue



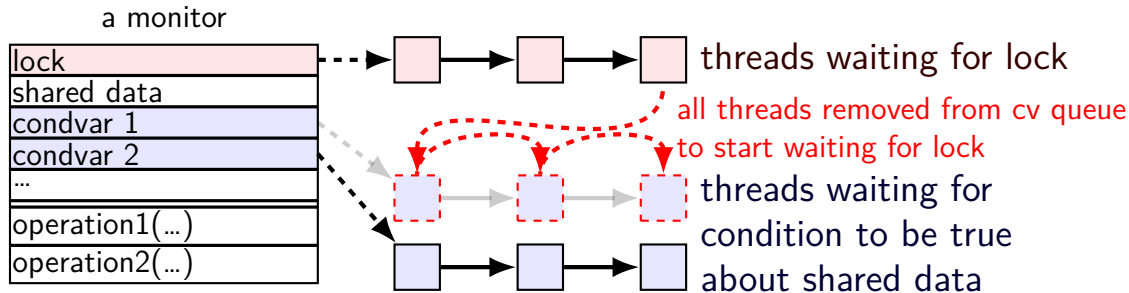
condvar operations

condvar operations:

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

Broadcast(cv) — remove all from condvar queue

Signal(cv) — remove one from condvar queue



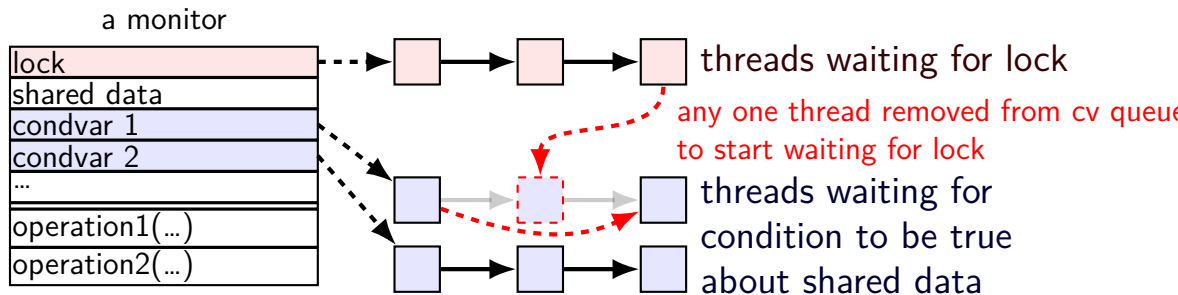
condvar operations

condvar operations:

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

Broadcast(cv) — remove all from condvar queue

Signal(cv) — remove one from condvar queue



pthread cv usage

// MISSING: init calls, etc.

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

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

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

pthread cv usage

// MISSING: init calls, etc.

```
pthread_mutex_t lock;
```

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

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

```
void WaitForFinished() {
```

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

```
    while (!finished) {
```

```
        pthread_cond_wait(&finished_cv, &lock);
```

```
    }
```

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

```
}
```

acquire lock before
reading or writing finished

```
void Finish() {
```

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

```
    finished = true;
```

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

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

```
}
```

pthread cv usage

// MISSING: init calls, etc.

```
pthread_mutex_t lock;
```

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

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

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

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

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

pthread cv usage

// MISSING: init calls, etc.

```
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;
```

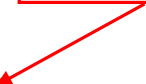
```
bool finished;    // data, only accessed with after acquiring lock
```

```
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

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

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

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

Thread 1

Produce()
...lock
...enqueue
...signal
...unlock

Thread 2

Consume()
...lock
...empty? no
...dequeue
...unlock
return

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

unbounded buffer producer/consumer

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

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

Thread 1

Thread 2

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

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

unbounded buffer producer/consumer

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

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

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

Thread 1

Produce()

...lock
...enqueue
...signal
...unlock

Thread 2

Consume()

...lock
...empty? yes
...unlock/start wait

Thread 3

Consume()

waiting for lock
lock
...empty? no
...dequeue
...unlock
return

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

unbounded buffer producer/consumer

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

in pthreads: signalled thread not
gaurenteed to hold lock next

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

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

Thread 1

```
Produce()
...lock
...enqueue
...signal
...unlock
```

Thread 2

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

Thread 3

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

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

Hoare versus Mesa monitors

Hoare-style monitors

- signal 'hands off' lock to awoken thread

Mesa-style monitors

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

every current threading library I know of does Mesa-style

bounded buffer producer/consumer

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

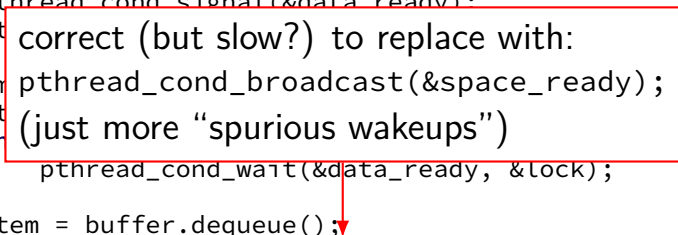
bounded buffer producer/consumer

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

bounded buffer producer/consumer

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

correct (but slow?) to replace with:
(just more “spurious wakeups”)



bounded buffer producer/consumer

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

correct but slow to replace
data_ready and space_ready
with 'combined' condvar ready
and use broadcast
(just more "spurious wakeups")

monitor pattern

```
pthread_mutex_lock(&lock);
while (!condition A) {
    pthread_cond_wait(&condvar_for_A, &lock);
}
... /* manipulate shared data, changing other conditions */
if (set condition A) {
    pthread_cond_broadcast(&condvar_for_A);
    /* or signal, if only one thread cares */
}
if (set condition B) {
    pthread_cond_broadcast(&condvar_for_B);
    /* or signal, if only one thread cares */
}
...
pthread_mutex_unlock(&lock)
```

monitors rules of thumb

never touch shared data without holding the lock

keep lock held for **entire operation**:

verifying condition (e.g. buffer not full) *up to and including*
manipulating data (e.g. adding to buffer)

create condvar for every kind of scenario waited for

always write **loop** calling cond_wait to wait for condition X

broadcast/signal condition variable **every time you change X**

monitors rules of thumb

never touch shared data without holding the lock

keep lock held for **entire operation**:

verifying condition (e.g. buffer not full) *up to and including*
manipulating data (e.g. adding to buffer)

create condvar for every kind of scenario waited for

always write **loop** calling cond_wait to wait for condition X

broadcast/signal condition variable **every time you change X**

correct but slow to...

broadcast when just signal would work

broadcast or signal when nothing changed

use one condvar for multiple conditions

mutex/cond var init/destroy

```
pthread_mutex_t mutex;  
pthread_cond_t cv;  
pthread_mutex_init(&mutex, NULL);  
pthread_cond_init(&cv, NULL);  
// --OR--  
pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;  
pthread_cond_t cv = PTHREAD_COND_INITIALIZER;  
  
// and when done:  
...  
pthread_cond_destroy(&cv);  
pthread_mutex_destroy(&mutex);
```

wait for both finished

```
// MISSING: init calls, etc.
```

```
pthread_mutex_t lock;  
bool finished[2];  
pthread_cond_t both_finished_cv;
```

```
void WaitForBothFinished() {  
    pthread_mutex_lock(&lock);  
    while (_____) {  
        pthread_cond_wait(&both_finished_cv, &lock);  
    }  
    pthread_mutex_unlock(&lock);  
}
```

```
void Finish(int index) {  
    pthread_mutex_lock(&lock);  
    finished[index] = true;  
    -----  
    pthread_mutex_unlock(&lock);  
}
```

wait for both finished

// MISSING: init calls, etc.

```
pthread_mutex_t lock;  
bool finished[2];  
pthread_cond_t both_finished_cv;
```

```
void WaitForBothFinished() {  
    pthread_mutex_lock(&lock);  
    while ( ) {  
        pthread_cond_wait(&both_finished_cv, &lock);  
    }  
    pthread_mutex_unlock(&lock);  
}
```

```
void Finish(int index) {  
    pthread_mutex_lock(&lock);  
    finished[index] = true;  
    -----  
    pthread_mutex_unlock(&lock);  
}
```

- A. `finished[0] && finished[1]`
- B. `finished[0] || finished[1]`
- C. `!finished[0] || !finished[1]`
- D. `finished[0] != finished[1]`
- E. something else

wait for both finished

// MISSING: init calls, etc.

```
pthread_mutex_t lock;  
bool finished[2];  
pthread_cond_t both_finished;
```

```
void WaitForBothFinished
```

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

```
    while ( _____ )
```

```
        pthread_cond_wait(&both_finished_cv, &lock);
```

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

```
}
```

```
void Finish(int index) {
```

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

```
    finished[index] = true;
```

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

```
}
```

A. pthread_cond_signal(&both_finished_cv)

B. pthread_cond_broadcast(&both_finished_cv)

C. if (finished[1-index])

pthread_cond_signal(&both_finished_cv);

D. if (finished[1-index])

pthread_cond_broadcast(&both_finished_cv);

E. something else

monitor exercise: barrier

suppose we want to implement a one-use barrier; fill in blanks:

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

void BarrierWait(BarrierInfo *b) {
    pthread_mutex_lock(&b->lock);
    ++b->number_reached;
    if (b->number_reached == b->total_threads) {
        -----
    } else {
        -----
        -----
    }
    pthread_mutex_unlock(&b->lock);
}
```

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

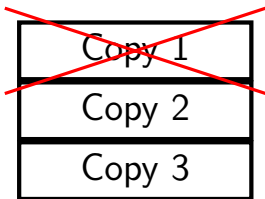
counting resources: reserving books

suppose tracking copies of same library book

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

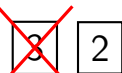
up = give back book; down = take book

taken out



Copy 1
Copy 2
Copy 3

free copies



3	2
---	---

after calling down to reserve

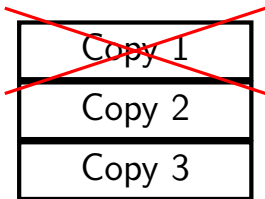
counting resources: reserving books

suppose tracking copies of same library book

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

up = give back book; down = take book

taken out



Copy 1
Copy 2
Copy 3

free copies 2

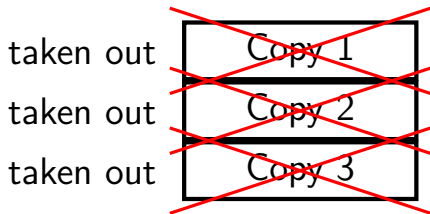
after calling down to reserve

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

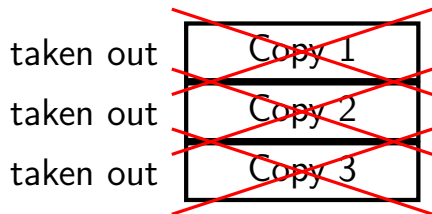
after calling down three times
to reserve all copies

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



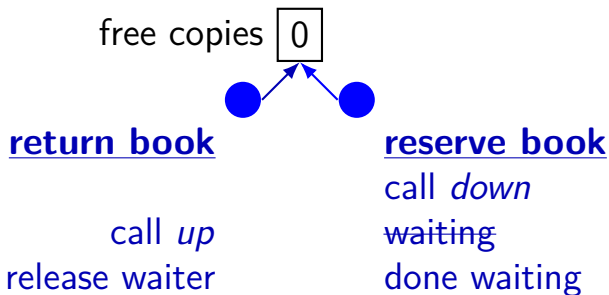
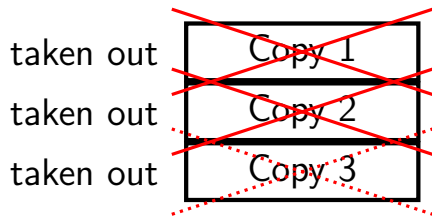
reserve book
call *down* again
start waiting...

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); 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); *data*
instead?

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

No. Consumer waits on sem_wait(&mutex)
so can't sem_post(&empty_slots)
(result: producer waits forever
problem called *deadlock*)

producer/consumer: cannot reorder mutex/empty

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

```
Consumer() {  
    sem_wait(&full_slots);  
  
    // can't finish until  
    // Producer's sem_post(&mutex):  
    sem_wait(&mutex);  
  
    ...  
  
    // so this is not reached  
    sem_post(&full_slots);  
}
```

producer/consumer pseudocode

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

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

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

Can we do
sem_post(&full_slots);
sem_post(&mutex);

instead?

Yes — post never waits

more data

reserve it

producer/consumer summary

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

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

two producers or consumers?

still works!

transactions

transaction: set of operations that occurs atomically

idea: something higher-level handles locking, etc.:

```
BeginTransaction();  
int FromOldBalance = GetBalance(FromAccount);  
int ToOldBalance = GetBalance(ToAccount);  
SetBalance(FromAccount, FromOldBalance - 100);  
SetBalance(ToAccount, FromOldBalance + 100);  
EndTransaction();
```

idea: library/database/etc. makes “transaction” happens all at once

consistency / durability

“happens all at once” = could mean:

locking to make sure no other operations interfere (consistency)

making sure on crash, no partial transaction seen (durability)

(some systems provide both, some provide only one)

we'll just talk about implementing consistency

implementing consistency: simple

simplest idea: only one run transaction at a time

implementing consistency: locking

everytime something read/written: acquire associated lock

on end transaction: release lock

if deadlock: undo everything, go back to BeginTransaction(), retry

how to undo?

one idea: keep list of writes instead of writing

apply writes only at EndTransaction()

implementing consistency: locking

everytime something read/written: acquire associated lock

on end transaction: release lock

if deadlock: **undo everything**, go back to BeginTransaction(), retry

how to undo?

one idea: keep list of writes instead of writing

apply writes only at EndTransaction()

implementing consistency: optimistic

on read: copy version # for value read

on write: record value to be written, but don't write yet

on end transaction:

- acquire locks on everything

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

if they have changed, just retry transaction

backup slides

cache tradeoffs briefly

deciding cache size, associativity, etc.?

lots of tradeoffs:

- more cache hits v. slower cache hits?

- faster cache hits v. fewer cache hits?

- more cache hits v. slower cache misses?

- ...

details depend on programs run

- how often is same block used again?

- how often is same index bits used?

simulation to assess impact of designs

exercise (1)

2-way set associative, LRU, write-allocate, writeback

index	valid	tag	value	dirty	valid	tag	value	dirty	LRU
0	1	001100	mem[0x30] mem[0x31]	0	1	010000	mem[0x40]* mem[0x41]*	1	0
1	1	011000	mem[0x62] mem[0x63]	0	1	001100	mem[0x32]* mem[0x33]*	1	1

for each of the following accesses, performed alone, would it require (a) reading a value from memory (or next level of cache) and (b) writing a value to the memory (or next level of cache)?

writing 1 byte to 0x33

reading 1 byte from 0x52

reading 1 byte from 0x50

exercise (2)

2-way set associative, LRU, write-no-allocate, write-through

index	valid	tag	value	valid	tag	value	LRU
0	1	001100	mem[0x30] mem[0x31]	1	010000	mem[0x40] mem[0x41]	0
1	1	011000	mem[0x62] mem[0x63]	1	001100	mem[0x32] mem[0x33]	1

for each of the following accesses, performed alone, would it require (a) reading a value from memory and (b) writing a value to the memory?

writing 1 byte to 0x33

reading 1 byte from 0x52

reading 1 byte from 0x50

thread versus process state

thread state

- registers (including stack pointer, program counter)

- ...

process state

- address space

- open files

- process id

- list of thread states

- ...

process info with threads

parent process info

thread infos	thread 0: {PC = 0x123456, rax = 42, rbx = ...} thread 1: {PC = 0x584390, rax = 32, rbx = ...} ...
page tables	
open files	fd 0: ... fd 1: ...
...	...

Linux idea: `task_struct`

Linux model: single “task” structure = thread

pointers to address space, open file list, etc.

pointers **can be shared**

e.g. shared open files: open fd 4 in one task → all sharing can use fd 4

`fork()`-like system call “clone”: **choose what to share**

`clone(0, ...)` — similar to `fork()`

`clone(CLONE_FILES, ...)` — like `fork()`, but **sharing** open files

`clone(CLONE_VM, new_stack_pointer, ...)` — like `fork()`, but **sharing** address space

Linux idea: `task_struct`

Linux model: single “task” structure = thread

pointers to address space, open file list, etc.

pointers **can be shared**

e.g. shared open files: open fd 4 in one task → all sharing can use fd 4

`fork()`-like system call “clone”: **choose what to share**

`clone(0, ...)` — similar to `fork()`

`clone(CLONE_FILES, ...)` — like `fork()`, but **sharing** open files

`clone(CLONE_VM, new_stack_pointer, ...)` — like `fork()`, but **sharing** address space

advantage: no special logic for threads (mostly)

two threads in same process = tasks sharing everything possible

aside: alternate threading models

we'll talk about **kernel threads**

OS scheduler deals **directly** with threads

alternate idea: library code handles threads

kernel doesn't know about threads w/in process

hierarchy of schedulers: one for processes, one within each process

not currently common model — awkward with multicore

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

higher level tools

usually we won't use atomic operations directly

instead rely on OS/standard libraries using them

(along with context switching, disabling interrupts, ...)

OS/standard libraries will provide higher-level tools like...

`pthread_join`

locks (`pthread_mutex`)

...and more

backup slides

backup slides

using atomic exchange?

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

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

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

recall: pthread mutex

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

```
pthread_mutex_t some_lock;
```

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

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

```
...
```

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

```
...
```

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

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

life homework even/odd

naive way has an operation that needs locking:

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

but this alternative needs less locking:

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

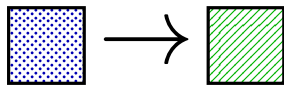
life homework even/odd

naive way has an operation that needs locking:

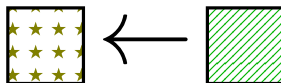
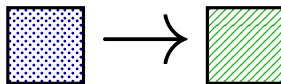
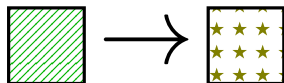
```
for (int time = 0; time < MAX_ITERATIONS; ++time) {  
    ... compute to_grid ...  
    swap(from_grid, to_grid);  
}
```

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)
```

```
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

 - 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

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) {  
    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;  
};
```

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);  
    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);  
}
```

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 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

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

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 stores
    // 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 stores
    // past this point, to ensure that the critical section's memory
    // references happen after the lock is acquired
    __asm__ volatile ("fence");
    ...
}
```

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

- problem: interruption might try to do something with the lock
- ...but that can never succeed until we release the lock
- ...but we won't release the lock until interruption finishes

xv6 spinlock: acquire

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

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

xchg wraps the lock xchg instruction
same loop as before

xv6 spinlock: acquire

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

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

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

xv6 spinlock: release

```
void
```

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

```
...
```

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

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

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

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

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

```
__sync_synchronize();
```

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

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

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

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

```
popcli();
```

```
}
```

xv6 spinlock: release

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

```
...
```

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

```
__sync_synchronize();
```

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

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

```
popcli  
}
```

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

xv6 spinlock: release

```
void
```

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

```
...
```

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

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

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

```
popcli();
```

```
}
```

turns into mov of constant 0 into lk->locked

xv6 spinlock: release

```
void
```

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

```
...
```

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

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

```
popcli();
```

```
}
```

reenable interrupts (taking nested locks into account)

fetch-and-add with CAS (1)

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

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

implementation sketch:

- fetch value from pointer `old`

- compute in temporary value result of addition `new`

- try to change value at pointer from `old` to `new`

- [compare-and-swap]

- if not successful, repeat

fetch-and-add with CAS (2)

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

exercise: append to singly-linked list

ListNode is a singly-linked list

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

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

- atomically change *pointer from old to new

- return true if successful

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

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

some common atomic operations (1)

// x86: emulate with exchange

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

// x86: xchg REGISTER, (ADDRESS)

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

some common atomic operations (2)

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

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

common atomic operation pattern

try to do operation, ...

detect if it failed

if so, repeat

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

cache coherency states

extra information for each cache block

overlaps with/replaces valid, dirty bits

stored in each cache

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

different caches may have different states for same block

MSI state summary

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

Shared value is the **same as memory**

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

MSI scheme

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

blue: transition requires sending message on bus

MSI scheme

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

blue: transition requires sending message on bus

example: write while Shared

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

MSI scheme

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

blue: transition requires sending message on bus

example: write while Shared

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

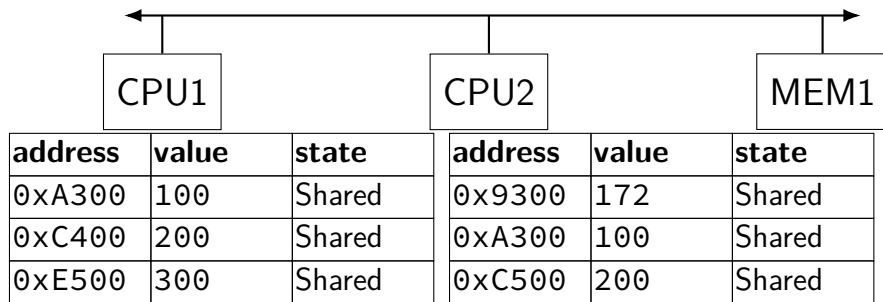
example: hear write while Shared

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

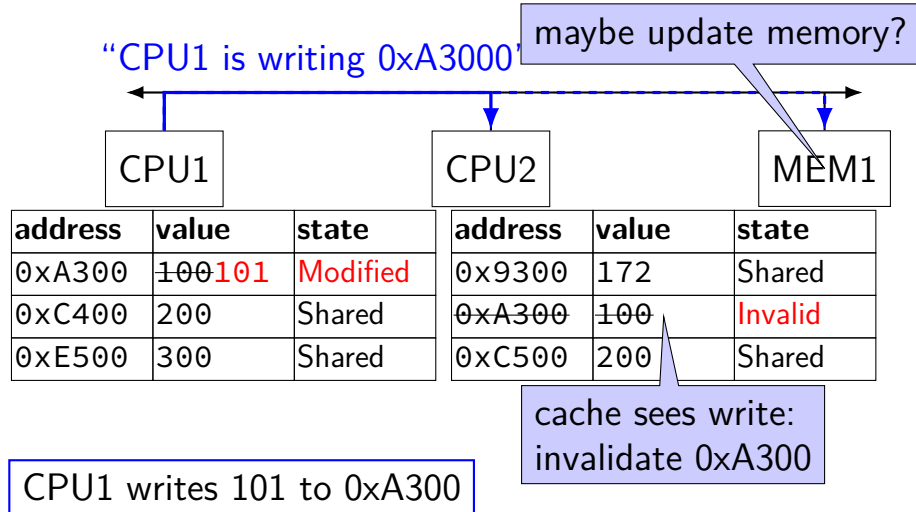
example: write while Modified

nothing to do — no other CPU can have a copy

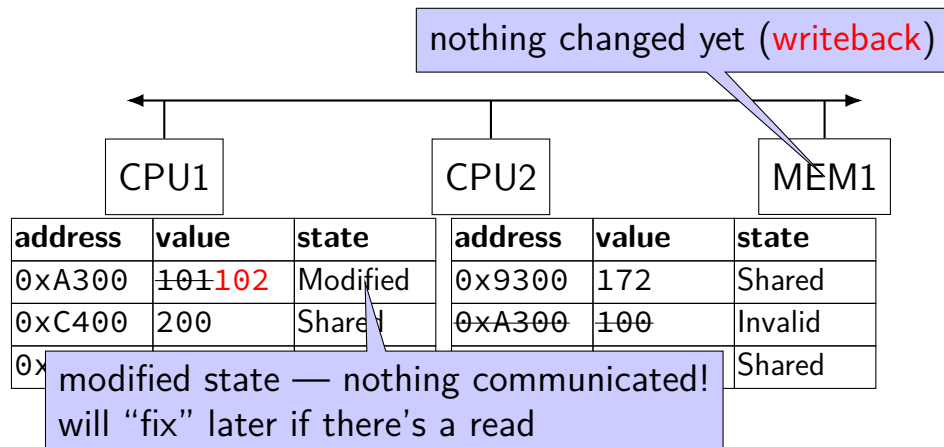
MSI example



MSI example

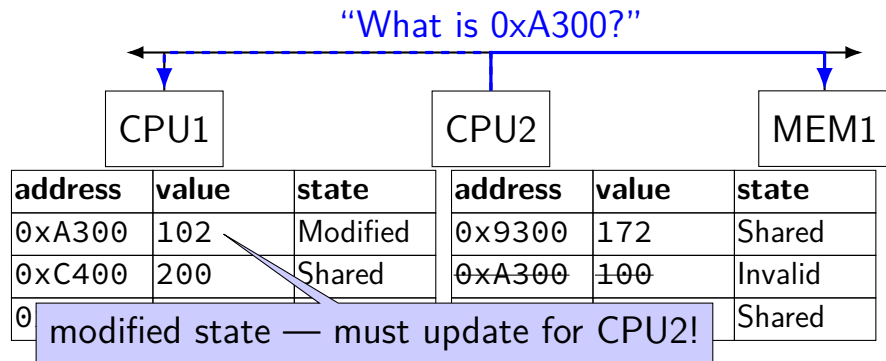


MSI example



CPU1 writes 102 to 0xA300

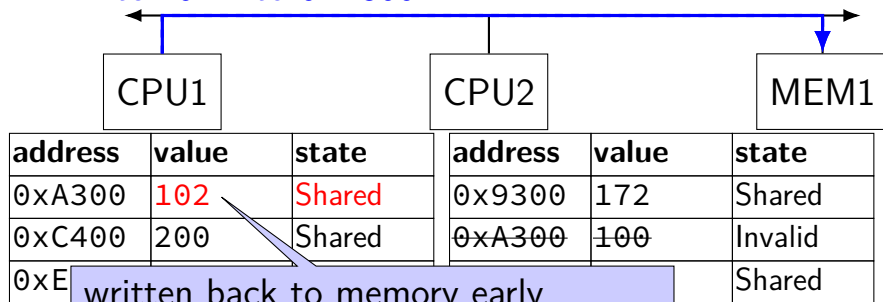
MSI example



CPU2 reads 0xA300

MSI example

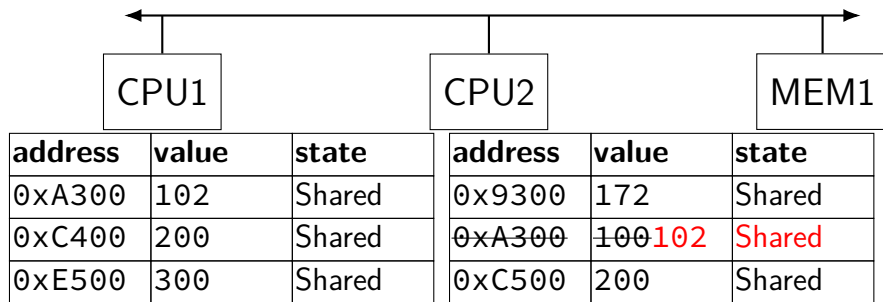
“Write 102 into 0xA300”



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

CPU2 reads 0xA300

MSI example



MSI: update memory

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

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

MSI: on cache replacement/writeback

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

changes state to **invalid**

requires writeback if modified (= dirty bit)

cache coherency exercise

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

CPU 1: read 0x1000

CPU 2: read 0x1000

CPU 1: write 0x1000

CPU 1: read 0x2000

CPU 2: read 0x1000

CPU 2: write 0x2008

CPU 3: read 0x1008

Q1: final state of 0x1000 in caches?

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

CPU 1: CPU 2: CPU 3:

Q2: final state of 0x2000 in caches?

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

CPU 1: CPU 2: CPU 3:

why load/store reordering?

fast processor designs can execute instructions out of order

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

more on this later in the semester

C++: preventing reordering

to help implementing things like `pthread_mutex_lock`

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

prevent CPU reordering *and* prevent compiler reordering

also provide other tools for implementing locks (more later)

could also hand-write assembly code

compiler can't know what assembly code is doing

C++: preventing reordering example

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

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

C++ atomics: no reordering

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

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

GCC: built-in atomic functions

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

predate `std::atomic`

builtin functions starting with `__sync` and `__atomic`

these are what `xv6` uses

aside: some x86 reordering rules

each core sees its own loads/stores in order

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

stores *from other cores* appear in a consistent order

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

causality:

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

how do you do anything with this?

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

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

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

spinlock problems

- lock abstraction is not powerful enough

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

 - common thing we want to do with threads

 - solution: other synchronization abstractions

- spinlocks waste CPU time more than needed

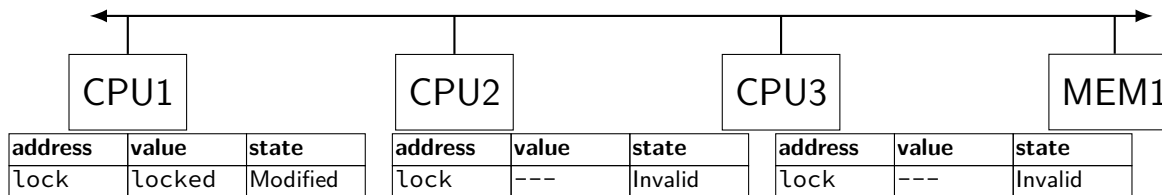
 - want to run another thread instead of infinite loop

 - solution: lock implementation integrated with scheduler

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

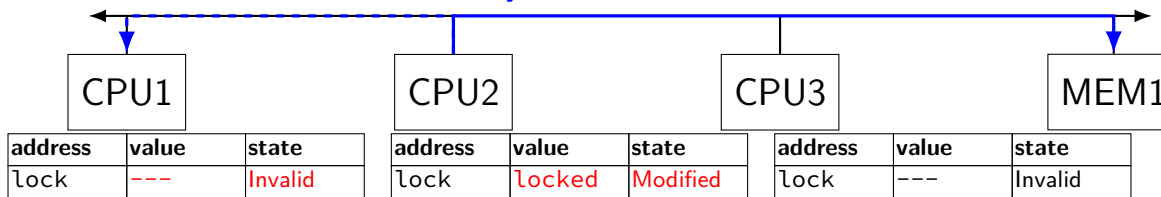
 - more efficient atomic operations to implement locks

ping-ponging



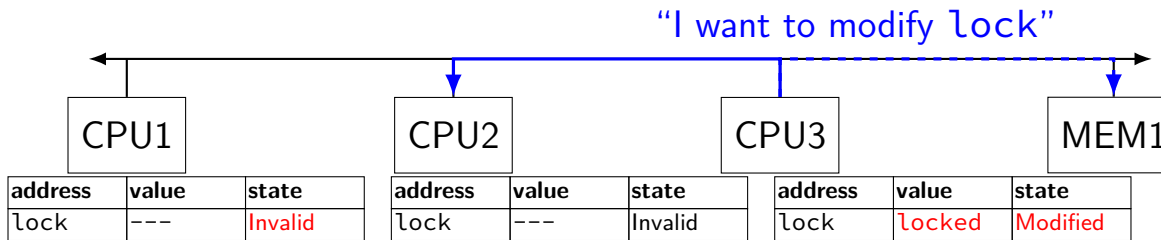
ping-ponging

“I want to modify lock?”



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

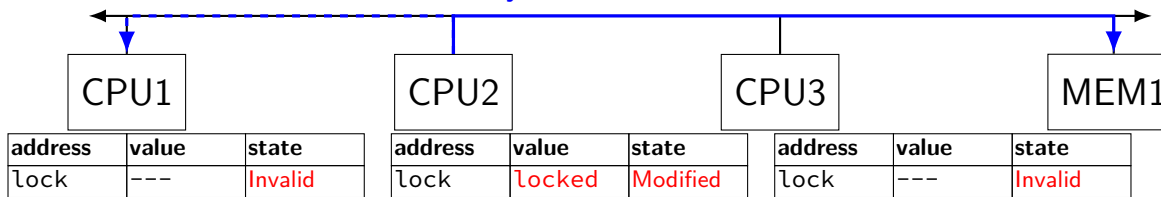
ping-ponging



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

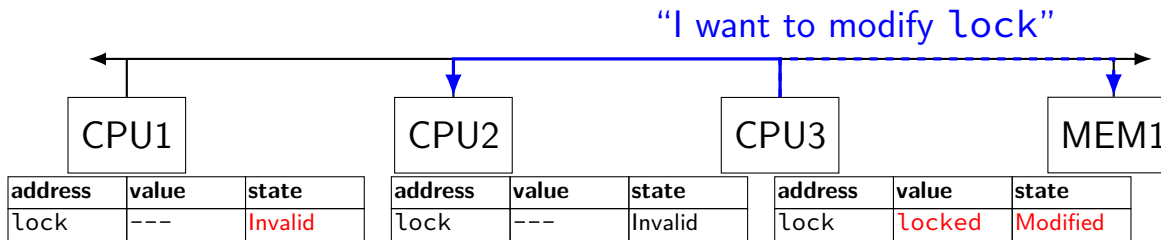
ping-ponging

“I want to modify lock?”



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

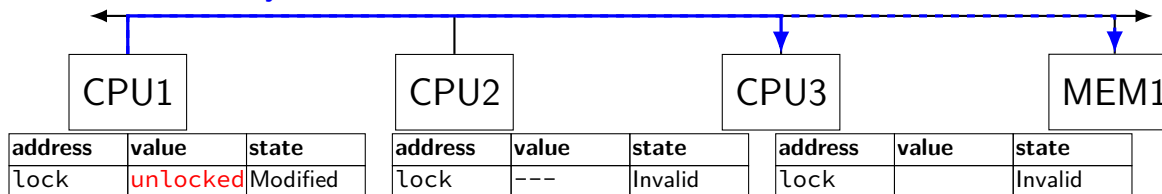
ping-ponging



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

ping-ponging

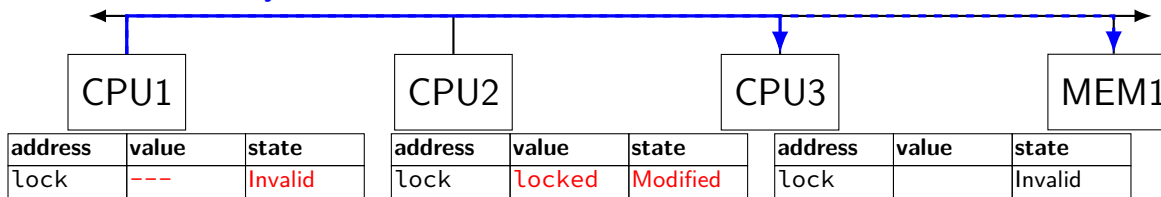
“I want to modify lock”



CPU1 sets lock to unlocked

ping-ponging

“I want to modify lock”



some CPU (this example: CPU2) acquires lock

ping-ponging

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

each transfer of block sends messages on bus

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

like what the processor with the lock is doing

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

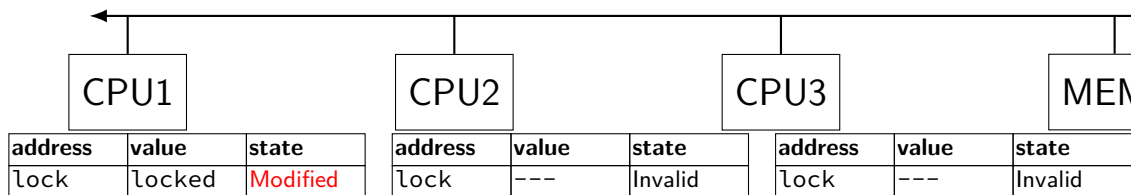
```
acquire(int *the_lock) {  
    do {  
        while (ATOMIC_READ(the_lock) == 0) { /* try again */ }  
    } while (ATOMIC_TEST_AND_SET(the_lock) == ALREADY_SET);  
}
```

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

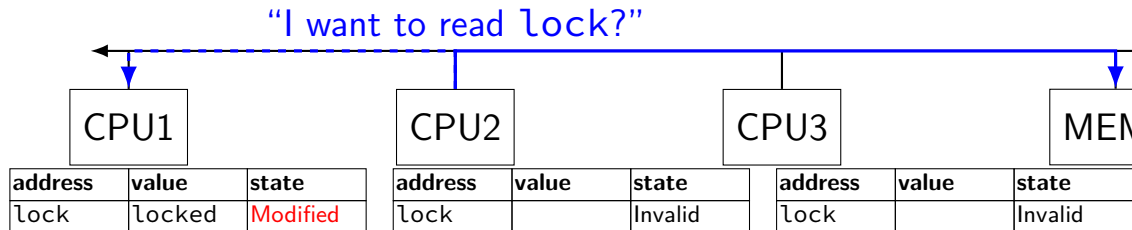
acquire:

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

less ping-ponging



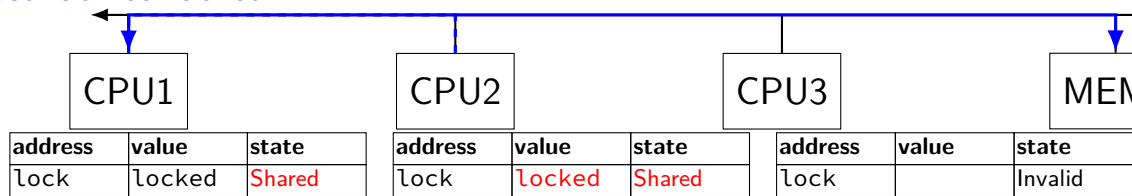
less ping-ponging



CPU2 reads lock
(to see it is still locked)

less ping-ponging

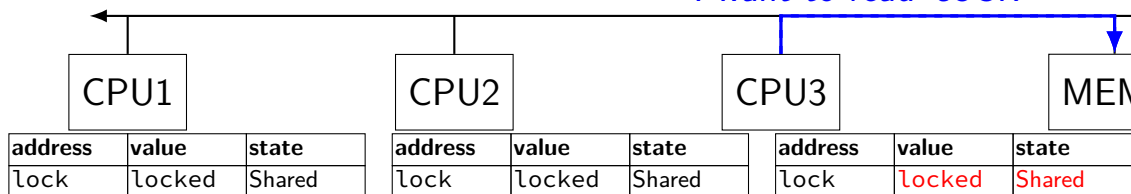
“set lock to locked”



CPU1 writes back lock value,
then CPU2 reads it

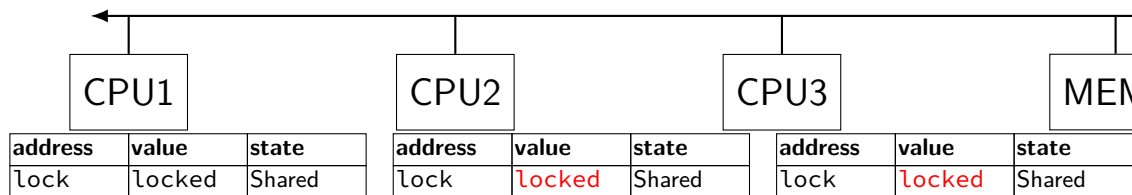
less ping-ponging

"I want to read lock"



CPU3 reads lock
(to see it is still locked)

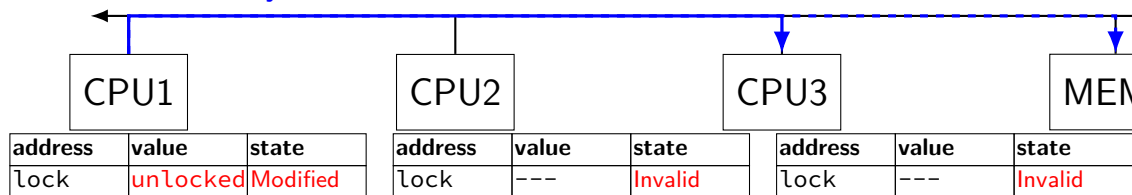
less ping-ponging



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

less ping-ponging

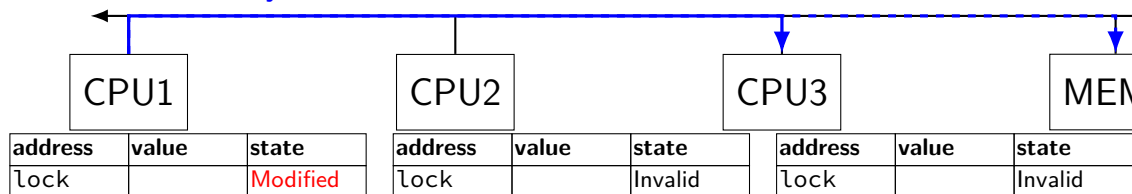
“I want to modify lock”



CPU1 sets lock to unlocked

less ping-ponging

“I want to modify lock”



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

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

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

and keep it in the shared state

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

more room for improvement?

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

there other spinlock designs that avoid this

- ticket locks

- MCS locks

- ...

MSI extensions

real cache coherency protocols sometimes more complex:

separate tracking modifications from whether other caches have copy

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

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

too much milk

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

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

how can Alice and Bob coordinate better?

too much milk “solution” 1 (algorithm)

leave a note: “I am buying milk”

place before buying, remove after buying

don't try buying if there's a note

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

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

too much milk “solution” 1 (algorithm)

leave a note: “I am buying milk”

place before buying, remove after buying

don't try buying if there's a note

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

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

exercise: why doesn't this work?

too much milk “solution” 1 (timeline)

Alice

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

Bob

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

too much milk “solution” 2 (algorithm)

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

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

too much milk: “solution” 2 (timeline)

Alice

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

too much milk: “solution” 2 (timeline)

Alice

```
leave note;
```

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

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

```
        buy milk;
```

```
    }
```

```
}
```

```
remove note;
```

too much milk: “solution” 2 (timeline)

Alice

```
leave note;
```

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

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

```
        buy milk;
```

```
    }
```

```
}
```

```
remove note;
```

← but there's **always a note**

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

“solution” 3: algorithm

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

computer equivalent: separate noteFromAlice and noteFromBob

variables

Alice

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

Bob

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


too much milk: “solution” 3 (timeline)

Alice

leave note from Alice

if (no milk) {

 if (no note from Bob) {

~~buy milk~~

 }

}

remove note from Alice

Bob

leave note from Bob

if (no milk) {

 if (no note from Alice) {

~~buy milk~~

 }

}

remove note from Bob

too much milk: is it possible

is there a solutions with writing/reading notes?

≈ loading/storing from shared memory

yes, but it's not very elegant

too much milk: solution 4 (algorithm)

Alice

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

Bob

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

too much milk: solution 4 (algorithm)

Alice

leave note from Alice

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

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

```
remove note from Alice
```

exercise (hard): prove (in)correctness

Bob

leave note from Bob

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

```
remove note from Bob
```

too much milk: solution 4 (algorithm)

Alice

leave note from Alice

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

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

```
remove note from Alice
```

exercise (hard): prove (in)correctness

Bob

leave note from Bob

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

```
remove note from Bob
```

too much milk: solution 4 (algorithm)

Alice

leave note from Alice

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

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

```
remove note from Alice
```

exercise (hard): prove (in)correctness

exercise (hard): extend to three people

Bob

leave note from Bob

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

```
remove note from Bob
```

Peterson's algorithm

general version of solution

see, e.g., Wikipedia

we'll use special hardware support instead

mfence

x86 instruction mfence

make sure all loads/stores in progress finish

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

fairly expensive

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

mfence

x86 instruction mfence

make sure all loads/stores in progress finish

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

fairly expensive

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

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

modifying cache blocks in parallel

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

typically how caches work — write instructions happen one at a time:

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

processor updates 4 bytes of 64-byte cache block

later, processor might give up cache block

modifying things in parallel (code)

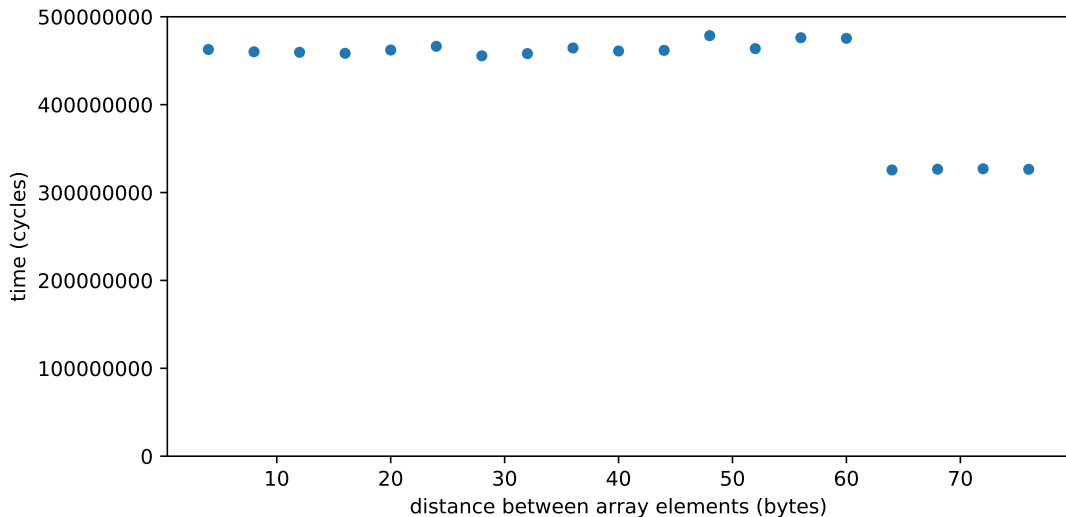
```
void *sum_up(void *raw_dest) {
    int *dest = (int *) raw_dest;
    for (int i = 0; i < 64 * 1024 * 1024; ++i) {
        *dest += data[i];
    }
}

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

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

performance v. array element gap

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



false sharing

synchronizing to access two independent things

two parts of same cache block

solution: separate them

exercise (1)

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

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

exercise (2)

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

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

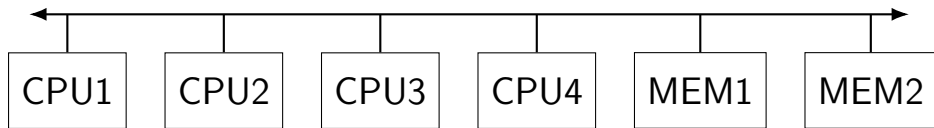
Where is false sharing likely to occur?

connecting CPUs and memory

multiple processors, common memory

how do processors communicate with memory?

shared bus



one possible design

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

tagged messages — everyone gets everything, filters

contention if multiple communicators

some hardware enforces only one at a time

shared buses and scaling

shared buses perform poorly with “too many” CPUs

so, there are other designs

we'll gloss over these for now

shared buses and caches

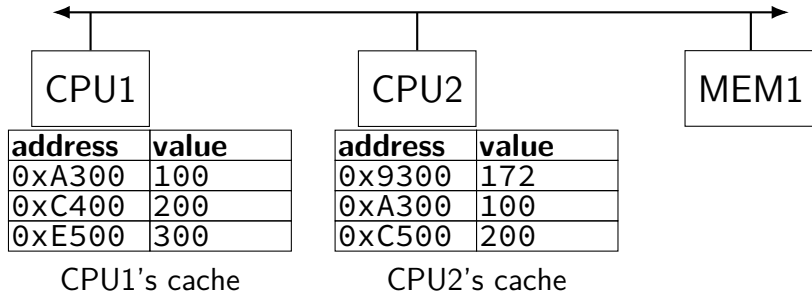
remember caches?

memory is pretty slow

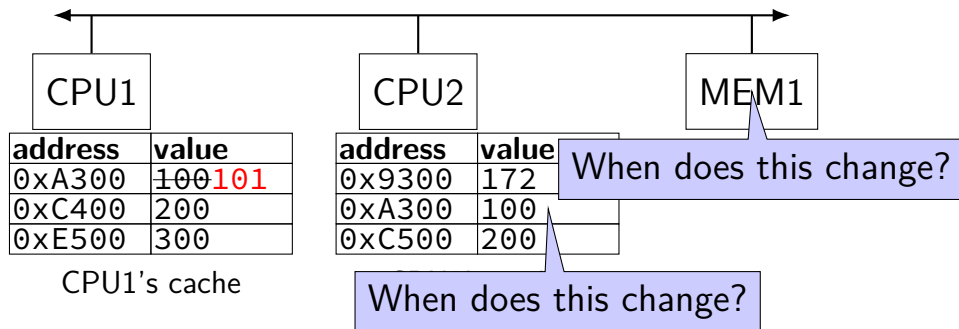
each CPU wants to keep local copies of memory

what happens when multiple CPUs cache same memory?

the cache coherency problem



the cache coherency problem



CPU1 writes 101 to 0xA300?

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		

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;  
}
```

Anderson-Dahlin and semaphores

Anderson/Dahlin complains about semaphores

“Our view is that programming with locks and condition variables is superior to programming with semaphores.”

argument 1: clearer to have **separate constructs** for

waiting for condition to become true, and

allowing only one thread to manipulate a thing at a time

argument 2: tricky to verify thread calls up exactly once for every down

alternatives allow one to be sloppier (in a sense)

monitors with semaphores: locks

```
sem_t semaphore;  // initial value 1
```

```
Lock() {  
    sem_wait(&semaphore);  
}
```

```
Unlock() {  
    sem_post(&semaphore);  
}
```

monitors with semaphores: [broken] cvs

start with only wait/signal:

```
sem_t threads_to_wakeup;  // initially 0
Wait(Lock lock) {
    lock.Unlock();
    sem_wait(&threads_to_wakeup);
    lock.Lock();
}
Signal() {
    sem_post(&threads_to_wakeup);
}
```

monitors with semaphores: [broken] cvs

start with only wait/signal:

```
sem_t threads_to_wakeup; // initially 0
Wait(Lock lock) {
    lock.Unlock();
    sem_wait(&threads_to_wakeup);
    lock.Lock();
}
Signal() {
    sem_post(&threads_to_wakeup);
}
```

problem: signal wakes up non-waiting threads (in the far future)

monitors with semaphores: cvs (better)

start with only wait/signal:

```
sem_t private_lock; // initially 1
int num_waiters;
sem_t threads_to_wakeup; // initially 0
Wait(Lock lock) {
    sem_wait(&private_lock);
    ++num_waiters;
    sem_post(&private_lock);
    lock.Unlock();
    sem_wait(&threads_to_wakeup);
    lock.Lock();
}
```

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

monitors with semaphores: broadcast

now allows broadcast:

```
sem_t private_lock; // initially 1
int num_waiters;
sem_t threads_to_wakeup; // initially 0
Wait(Lock lock) {
    sem_wait(&private_lock);
    ++num_waiters;
    sem_post(&private_lock);
    lock.Unlock();
    sem_wait(&threads_to_wakeup);
    lock.Lock();
}
```

```
Broadcast() {
    sem_wait(&private_lock);
    while (num_waiters > 0) {
        sem_post(&threads_to_wakeup);
        --num_waiters;
    }
    sem_post(&private_lock);
}
```


building semaphore with monitors

```
pthread_mutex_t lock;
```

lock to protect shared state

building semaphore with monitors

```
pthread_mutex_t lock;  
unsigned int count;
```

lock to protect shared state

shared state: semaphore tracks a count

building semaphore with monitors

```
pthread_mutex_t lock;
```

```
unsigned int count;
```

```
/* condition, broadcast when becomes count > 0 */
```

```
pthread_cond_t count_is_positive_cv;
```

lock to protect shared state

shared state: semaphore tracks a count

add cond var for each reason we wait

semaphore: wait for count to become positive (for down)

building semaphore with monitors

```
pthread_mutex_t lock;  
unsigned int count;  
/* condition, broadcast when becomes count > 0 */  
pthread_cond_t count_is_positive_cv;  
void down() {  
    pthread_mutex_lock(&lock);  
    while (!(count > 0)) {  
        pthread_cond_wait(  
            &count_is_positive_cv,  
            &lock);  
    }  
    count -= 1;  
    pthread_mutex_unlock(&lock);  
}
```

lock to protect shared state

shared state: semaphore tracks a count

add cond var for each reason we wait

semaphore: wait for count to become positive (for down)

wait using condvar; broadcast/signal when condition changes

building semaphore with monitors

```
pthread_mutex_t lock;  
unsigned int count;  
/* condition, broadcast when becomes count > 0 */  
pthread_cond_t count_is_positive_cv;  
void down() {  
    pthread_mutex_lock(&lock);  
    while (!(count > 0)) {  
        pthread_cond_wait(  
            &count_is_positive_cv,  
            &lock);  
    }  
    count -= 1;  
    pthread_mutex_unlock(&lock);  
}
```

```
void up() {  
    pthread_mutex_lock(&lock);  
    count += 1;  
    /* count must now be  
       positive, and at most  
       one thread can go per  
       call to Up() */  
    pthread_cond_signal(  
        &count_is_positive_cv  
    );  
    pthread_mutex_unlock(&lock);  
}
```

lock to protect shared state

shared state: semaphore tracks a count

add cond var for each reason we wait

semaphore: wait for count to become positive (for down)

wait using condvar; **broadcast/signal** when condition changes

binary semaphores

binary semaphores — semaphores that are **only zero or one**

as powerful as normal semaphores

exercise: simulate counting semaphores with binary semaphores (more than one) and an integer

counting semaphores with binary semaphores

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

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

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

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

gate intuition/pattern

pattern to allow one thread at a time:

```
sem_t gate; // 0 = closed; 1 = open
ReleasingThread() {
    ... // finish what the other thread is waiting for
    while (another thread is waiting and can go) {
        sem_post(&gate) // allow EXACTLY ONE thread
        ... // other bookkeeping
    }
    ...
}
WaitingThread() {
    ... // indicate that we're waiting
    sem_wait(&gate) // wait for gate to be open
    ... // indicate that we're not waiting
}
```