

# Synchronization: Basics

15-213/15-513: Introduction to Computer Systems  
24<sup>th</sup> Lecture, July 26, 2023

## Instructors:

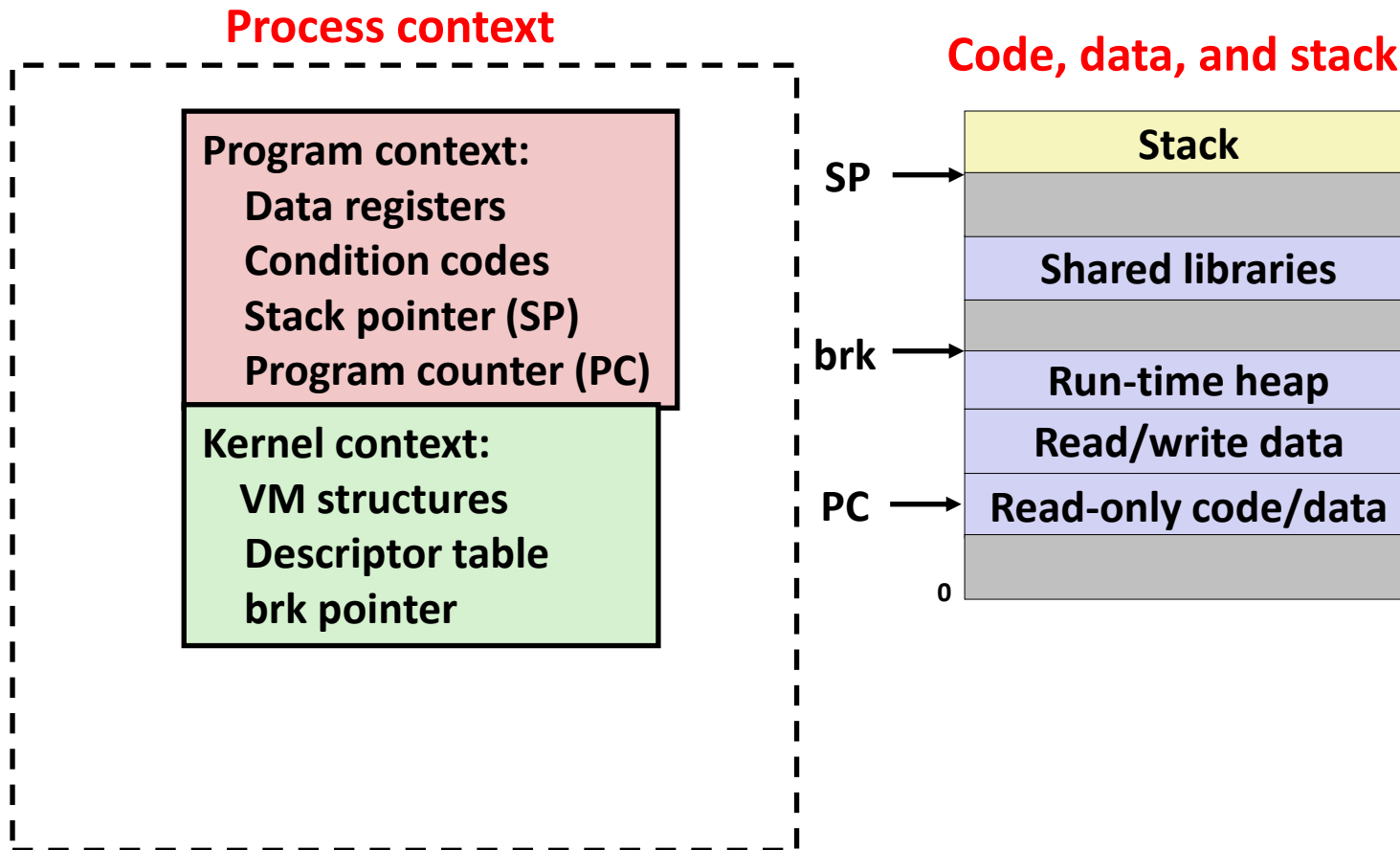
Brian Railing

# Today

- **Threads review**
- **Sharing and Data Races**
- **Fixing Data Races**
  - Mutexes
  - Semaphores
  - Atomic memory operations

# Traditional View of a Process

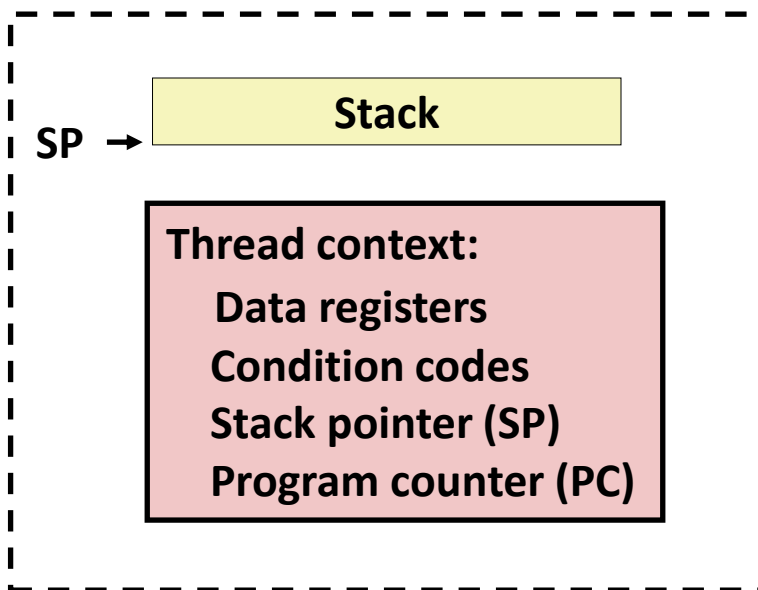
- Process = process context + code, data, and stack



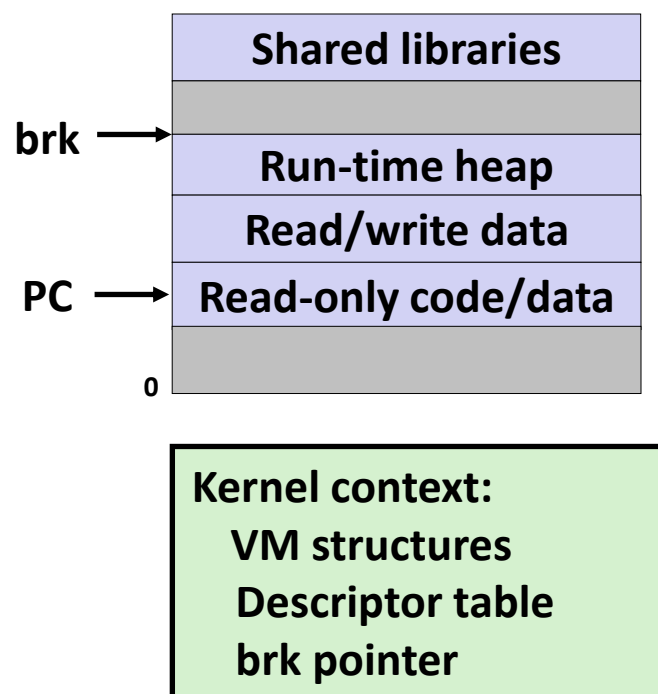
# Alternate View of a Process

- Process = thread + (code, data, and kernel context)

## Thread (main thread)



## Code, data, and kernel context



# A Process With Multiple Threads

- **Multiple threads can be associated with a process**
  - Each thread has its own logical control flow
  - Each thread shares the same code, data, and kernel context
  - Each thread has its own stack for local variables
    - but not protected from other threads
  - Each thread has its own thread id (TID)

**Thread 1 (main thread) Thread 2 (peer thread)**

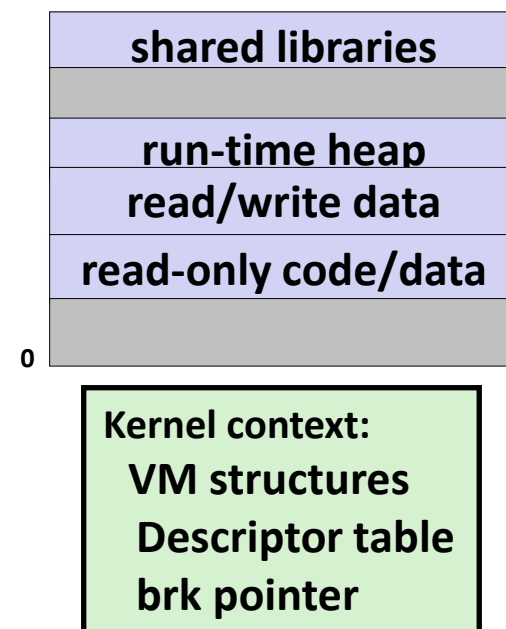
**stack 1**

**stack 2**

**Thread 1 context:**  
 Data registers  
 Condition codes  
 $SP_1$   
 $PC_1$

**Thread 2 context:**  
 Data registers  
 Condition codes  
 $SP_2$   
 $PC_2$

**Shared code and data**



# Don't let picture confuse you!

**Thread 1 (main thread) Thread 2 (peer thread)**

stack 1

stack 2

Thread 1 context:  
Data registers  
Condition codes  
 $SP_1$   
 $PC_1$

Thread 2 context:  
Data registers  
Condition codes  
 $SP_2$   
 $PC_2$

**Shared code and data**

shared libraries

run-time heap

read/write data

read-only code/data

0

Kernel context:  
VM structures  
Descriptor table  
brk pointer

**Memory is shared between all threads**

# Today

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- **Fixing Data Races**
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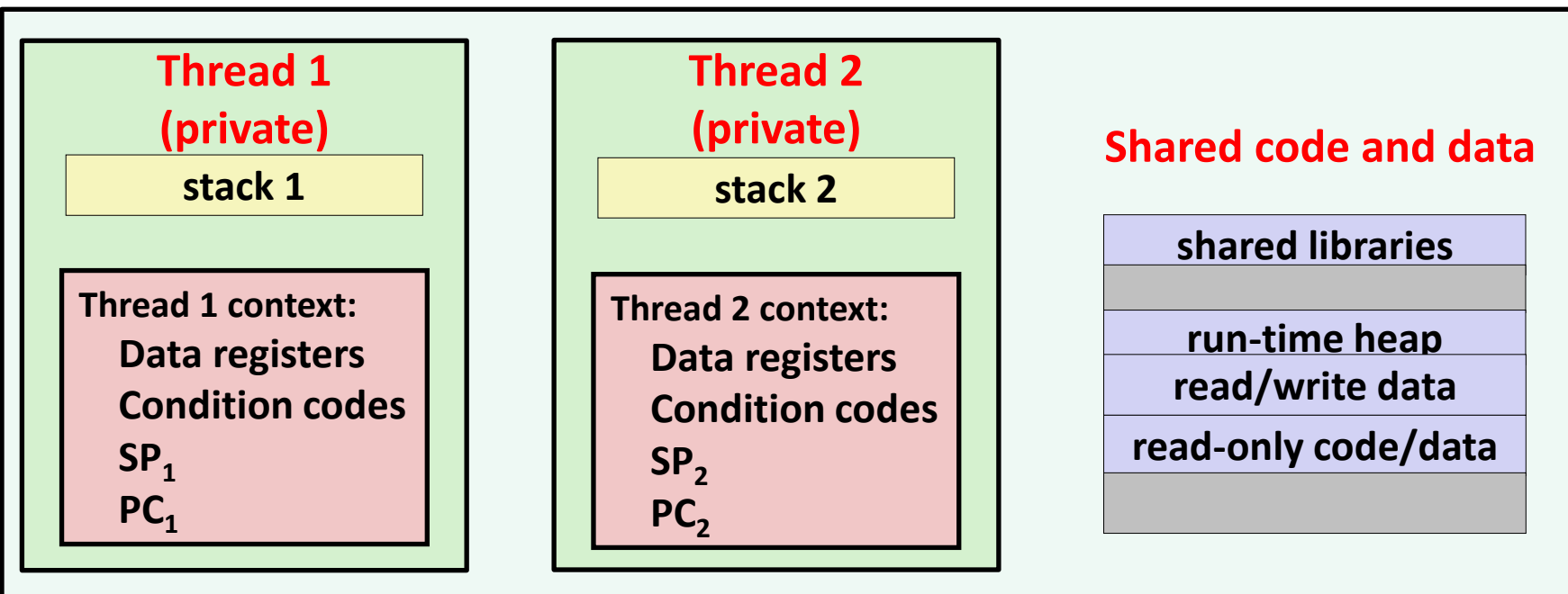
# Shared Variables in Threaded C Programs

- **Question: Which variables in a threaded C program are shared?**
  - The answer is not as simple as “*global variables are shared*” and “*stack variables are private*”
- **Def: A variable  $x$  is *shared* if and only if multiple threads reference some instance of  $x$ .**
- **Requires answers to the following questions:**
  - What is the memory model for threads?
  - How are instances of variables mapped to memory?
  - How many threads might reference each of these instances?



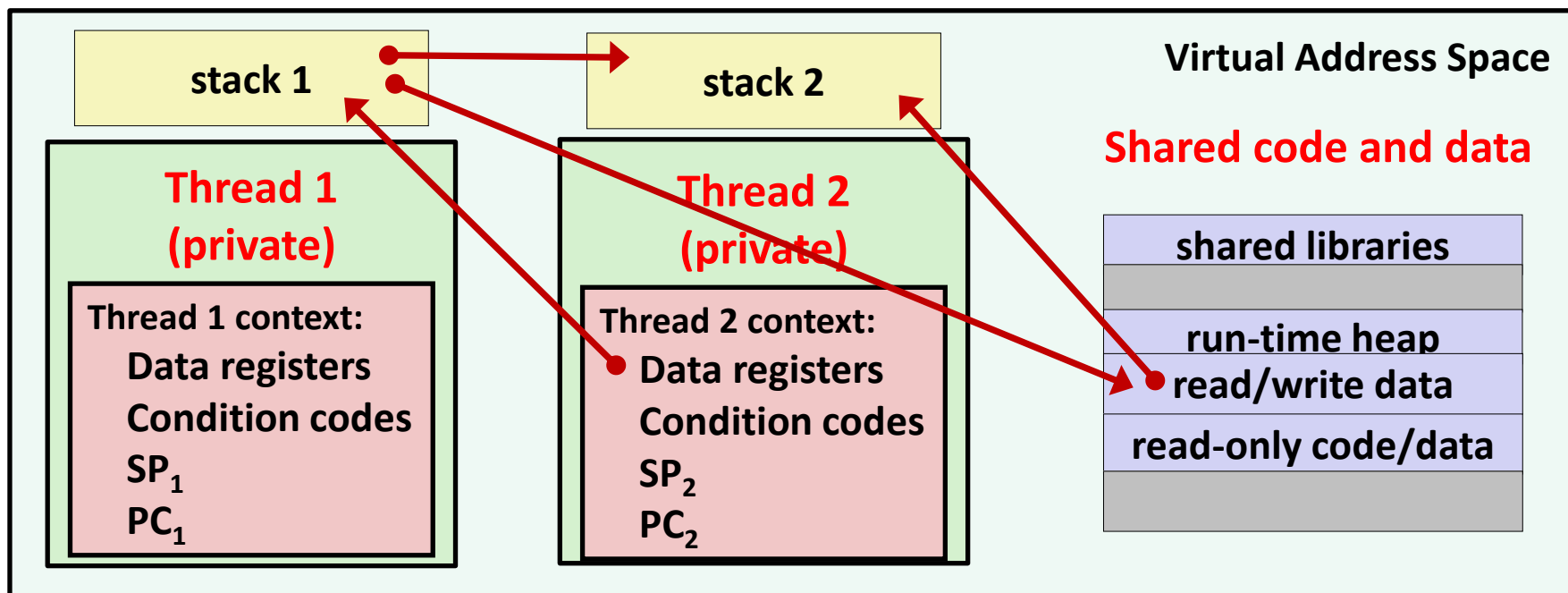
# Threads Memory Model: Conceptual

- Multiple threads run within the context of a single process
- Each thread has its own separate thread context
  - Thread ID, stack, stack pointer, PC, condition codes, and GP registers
- All threads share the remaining process context
  - Code, data, heap, and shared library segments of the process virtual address space
  - Open files and installed handlers



# Threads Memory Model: Actual

- Separation of data is not strictly enforced:
  - Register values are truly separate and protected, but...
  - Any thread can read and write the stack of any other thread



*The mismatch between the conceptual and operation model  
is a source of confusion and errors*

# Three Ways to Pass Thread Arg

## ■ Malloc/free

- Producer malloc's space, passes pointer to pthread\_create
- Consumer dereferences pointer, frees space
- Always works; necessary for passing large amounts of data

## ■ Cast of int

- Producer casts an int/long to void\*, passes to pthread\_create
- Consumer casts void\* argument back to int/long
- Works for small amounts of data (one number)

## ■ **INCORRECT: Pointer to stack slot**

- Producer passes address to producer's stack in pthread\_create
- Consumer dereferences pointer
- Why is this unsafe?

# Passing an argument to a thread

```
int hist[N] = {0};

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++)
        Pthread_create(&tids[i],
                       NULL,
                       thread,
                       &hist[i]);

    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    check();
}
```

```
void *thread(void *vargp)
{
    *(int *)vargp += 1;
    return NULL;
}
```

- Each thread receives a *unique pointer*

```
void check(void) {
    for (int i=0; i<N; i++) {
        if (hist[i] != 1) {
            printf("Failed at %d\n", i);
            exit(-1);
        }
    }
    printf("OK\n");
}
```

# Passing an argument to a thread – Also OK

```
int hist[N] = {0};

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++)
        Pthread_create(&tids[i],
                       NULL,
                       thread,
                       (void *)i);
    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    check();
}
```

```
void *thread(void *vargp)
{
    hist[(long)vargp] += 1;
    return NULL;
}
```

- Each thread receives a *unique array index*
- Casting from long to void\* and back is safe

# Passing an argument to a thread – Also OK

```
int hist[N] = {0};

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++)
        long* p = Malloc(sizeof(long));
        *p = i;
        Pthread_create(&tids[i],
                       NULL,
                       thread,
                       p);
    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    check();
}
```

```
void *thread(void *vargp)
{
    hist[* (long *)vargp] += 1;
    free(vargp);
    return NULL;
}
```

- Each thread receives a *unique array index*
- Malloc in parent, free in thread
- Necessary if passing structs

# Passing an argument to a thread – **WRONG!**

```
int hist[N] = {0};

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++)
        Pthread_create(&tids[i],
                       NULL,
                       thread,
                       &i);

    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    check();
}
```

```
void *thread(void *vargp)
{
    hist[* (long *)vargp] += 1;
    return NULL;
}
```

- Each thread receives *the same pointer*, to `i` in main
- Data race: each thread *may or may not* read a unique array index from `i` in main

# Shared Variables in Threaded C Programs

- **Question: Which variables in a threaded C program are shared?**
  - The answer is not as simple as “*global variables are shared*” and “*stack variables are private*”
- **Def: A variable  $x$  is *shared* if and only if multiple threads reference some instance of  $x$ .**
- **Requires answers to the following questions:**
  - What is the memory model for threads?
  - How are instances of variables mapped to memory?
  - How many threads might reference each of these instances?



# Mapping Variable Instances to Memory

## ■ Global variables

- Variable declared outside of a function
- **Virtual memory contains exactly one instance of any global variable**

## ■ Local automatic variables

- Variable declared inside function without `static` attribute
- **Each thread stack contains one instance of each local variable**

## ■ Local static variables

- Variable declared inside function with the `static` attribute
- **Virtual memory contains exactly one instance of any local static variable.**

## ■ `errno` is special

- Declared outside a function, but **each thread stack contains one instance**

# Mapping Variable Instances to Memory

```
char **ptr; /* global var */

int main(int main, char *argv[])
{
    long i;
    pthread_t tid;
    char *msgs[2] = {
        "Hello from foo",
        "Hello from bar"
    };

    ptr = msgs;
    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
            NULL,
            thread,
            (void *)i);
    Pthread_exit(NULL);
}
```

sharing.c

```
void *thread(void *vargp)
{
    long myid = (long)vargp;
    static int cnt = 0;

    printf("[%ld]: %s (cnt=%d)\n",
        myid, ptr[myid], ++cnt);
    return NULL;
}
```

# Mapping Variable Instances to Memory

**Global var:** 1 instance (ptr [data])

**Local auto vars:** 1 instance (i.m, msgs.m, tid.m)

```
char **ptr; /* global var */

int main(int main, char *argv[])
{
    long i;
    pthread_t tid;
    char *msgs[2] = {
        "Hello from foo",
        "Hello from bar"
    };

    ptr = msgs;
    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
            NULL,
            thread,
            (void *)i);
    Pthread_exit(NULL);
}
```

sharing.c

**Local auto var:** 2 instances (  
myid.p0 [peer thread 0's stack],  
myid.p1 [peer thread 1's stack]  
)

```
void *thread(void *vargp)
{
    long myid = (long)vargp;
    static int cnt = 0;

    printf("[%ld]: %s (cnt=%d)\n",
        myid, ptr[myid], ++cnt);
    return NULL;
}
```

**Local static var:** 1 instance (cnt [data])

# Shared Variable Analysis

## ■ Which variables are shared?

<i>Variable instance</i>	<i>Referenced by main thread?</i>	<i>Referenced by peer thread 0?</i>	<i>Referenced by peer thread 1?</i>
<code>ptr</code>	yes	yes	yes
<code>cnt</code>	no	yes	yes
<code>i.m</code>	yes	no	no
<code>msgs.m</code>	yes	yes	yes
<code>myid.p0</code>	no	yes	no
<code>myid.p1</code>	no	no	yes

```

char **ptr; /* global var */
int main(int main, char *argv[]) {
    long i; pthread_t tid;
    char *msgs[2] = {"Hello from foo",
                    "Hello from bar" };

    ptr = msgs;
    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
                       NULL, thread, (void *)i);
    Pthread_exit(NULL);
}

```

```

void *thread(void *vargp)
{
    long myid = (long)vargp;
    static int cnt = 0;

    printf("[%ld]: %s (cnt=%d)\n",
           myid, ptr[myid], ++cnt);
    return NULL;
}

```

# Shared Variable Analysis

## ■ Which variables are shared?

<i>Variable instance</i>	<i>Referenced by main thread?</i>	<i>Referenced by peer thread 0?</i>	<i>Referenced by peer thread 1?</i>
<code>ptr</code>	yes	yes	yes
<code>cnt</code>	no	yes	yes
<code>i.m</code>	yes	no	no
<code>msgs.m</code>	yes	yes	yes
<code>myid.p0</code>	no	yes	no
<code>myid.p1</code>	no	no	yes

## ■ Answer: A variable $x$ is shared iff multiple threads reference at least one instance of $x$ . Thus:

- `ptr`, `cnt`, and `msgs` are shared
- `i` and `myid` are *not* shared

# Synchronizing Threads

- Shared variables are handy...
- ...but you risk *data races* and *synchronization errors*.

```
static unsigned long cnt = 0;

void *incr_thread(void *arg) {
    unsigned long i;
    unsigned long niters =
        (unsigned long) arg;

    for (i = 0; i < niters; i++) {
        cnt++;
    }
}
```

```
int main(int argc, char **argv) {
    unsigned long niters =
        strtoul(argv[1], NULL, 10);

    pthread_t t1, t2;
    Pthread_create(&t1, NULL,
                  incr_thread,
                  (void *)niters);
    Pthread_create(&t2, NULL,
                  incr_thread,
                  (void *)niters);

    Pthread_join(&t1, NULL);
    Pthread_join(&t2, NULL);
    if (cnt != 2*niters) {
        printf("FAIL: cnt=%lu not %lu\n",
              cnt, 2*niters);
        return 1;
    } else {
        printf("OK: cnt=%lu\n", cnt);
        return 0;
    }
}
```

**Coding demo 1:**  
**Counting to 20,000 incorrectly**  
**(with threads)**

# Assembly Code for Counter Loop

## C code for counter loop in thread $i$

```
for (i = 0; i < niters; i++)
    cnt++;
```

### Asm code for thread $i$

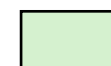
<pre> movq  (%rdi), %rcx testq %rcx,%rcx jle   .L2 movl  \$0, %eax ----- .L3: movq  cnt(%rip), %rdx addq  \$1, %rdx movq  %rdx, cnt(%rip) ----- addq  \$1, %rax cmpq  %rcx, %rax jne   .L3 .L2: </pre>	<p style="font-size: 2em;">}</p> <p><math>H_i</math> : Head</p> <p style="font-size: 2em;">}</p> <p><math>L_i</math> : Load cnt  <math>U_i</math> : Update cnt  <math>S_i</math> : Store cnt</p> <p style="font-size: 2em;">}</p> <p><math>T_i</math> : Tail</p>
--	--

# Concurrent Execution

- **Key idea:** Any interleaving of instructions is possible, and some give an unexpected result!

- $I_i$  denotes that thread  $i$  executes instruction  $I$
- $\%rdx_i$  is the content of  $\%rdx$  in thread  $i$ 's context

$i$ (thread)	$instr_i$	$\%rdx_1$	$\%rdx_2$	cnt
1	$H_1$	-	-	0
1	$L_1$	0	-	0
1	$U_1$	1	-	0
1	$S_1$	1	-	1
2	$H_2$	-	-	1
2	$L_2$	-	1	1
2	$U_2$	-	2	1
2	$S_2$	-	2	2
2	$T_2$	-	2	2
1	$T_1$	1	-	2



Thread 1  
critical section



Thread 2  
critical section

**OK**



# Concurrent Execution (cont)

- Incorrect ordering: two threads increment the counter, but the result is 1 instead of 2

i (thread)	instr <sub>i</sub>	%rdx <sub>1</sub>	%rdx <sub>2</sub>	cnt
1	H <sub>1</sub>	-	-	0
1	L <sub>1</sub>	0	-	0
1	U <sub>1</sub>	1	-	0
2	H <sub>2</sub>	-	-	0
2	L <sub>2</sub>	-	0	0
1	S <sub>1</sub>	1	-	1
1	T <sub>1</sub>	1	-	1
2	U <sub>2</sub>	-	1	1
2	S <sub>2</sub>	-	1	1
2	T <sub>2</sub>	-	1	1

*Oops!*

# Concurrent Execution (cont)

- How about this ordering?

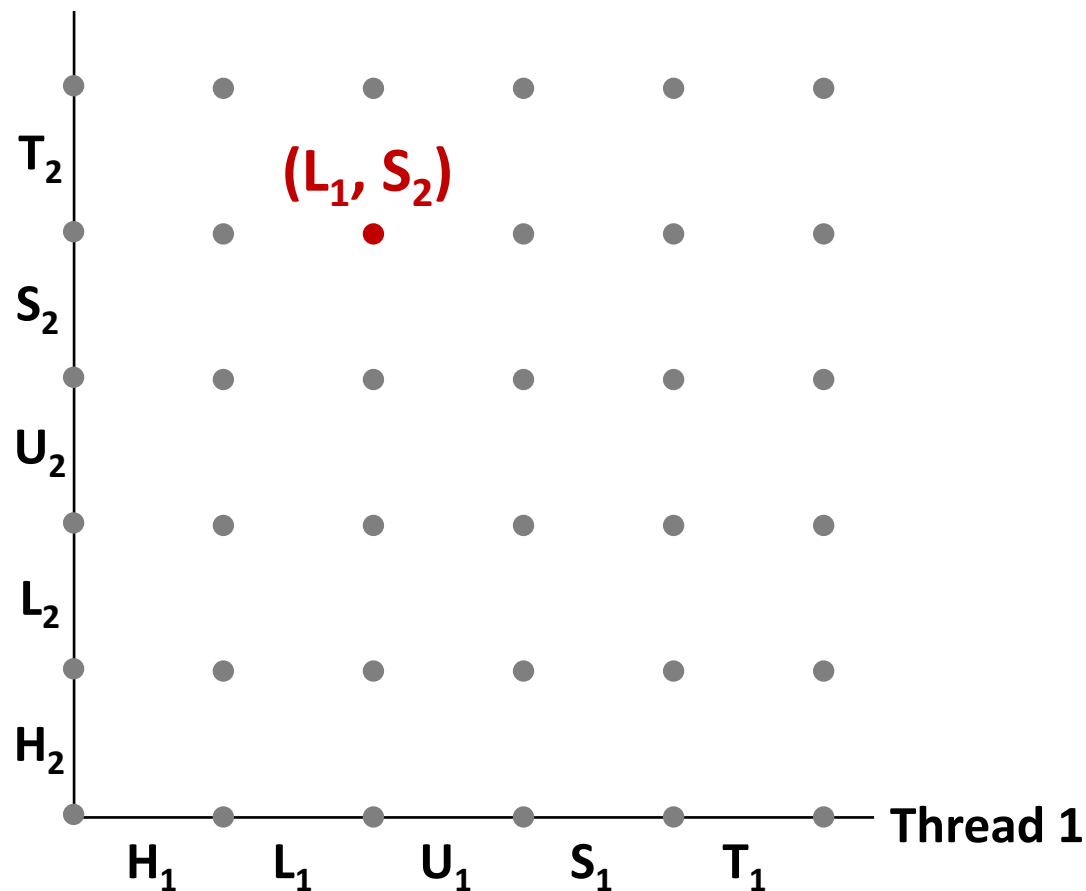
i (thread)	instr <sub>i</sub>	%rdx <sub>1</sub>	%rdx <sub>2</sub>	cnt
1	H <sub>1</sub>			0
1	L <sub>1</sub>	0		
2	H <sub>2</sub>			
2	L <sub>2</sub>		0	
2	U <sub>2</sub>		1	
2	S <sub>2</sub>		1	1
1	U <sub>1</sub>	1		
1	S <sub>1</sub>	1		1
1	T <sub>1</sub>			1
2	T <sub>2</sub>			1

*Oops!*

- We can analyze the behavior using a *progress graph*

# Progress Graphs

Thread 2



A *progress graph* depicts the discrete *execution state space* of concurrent threads.

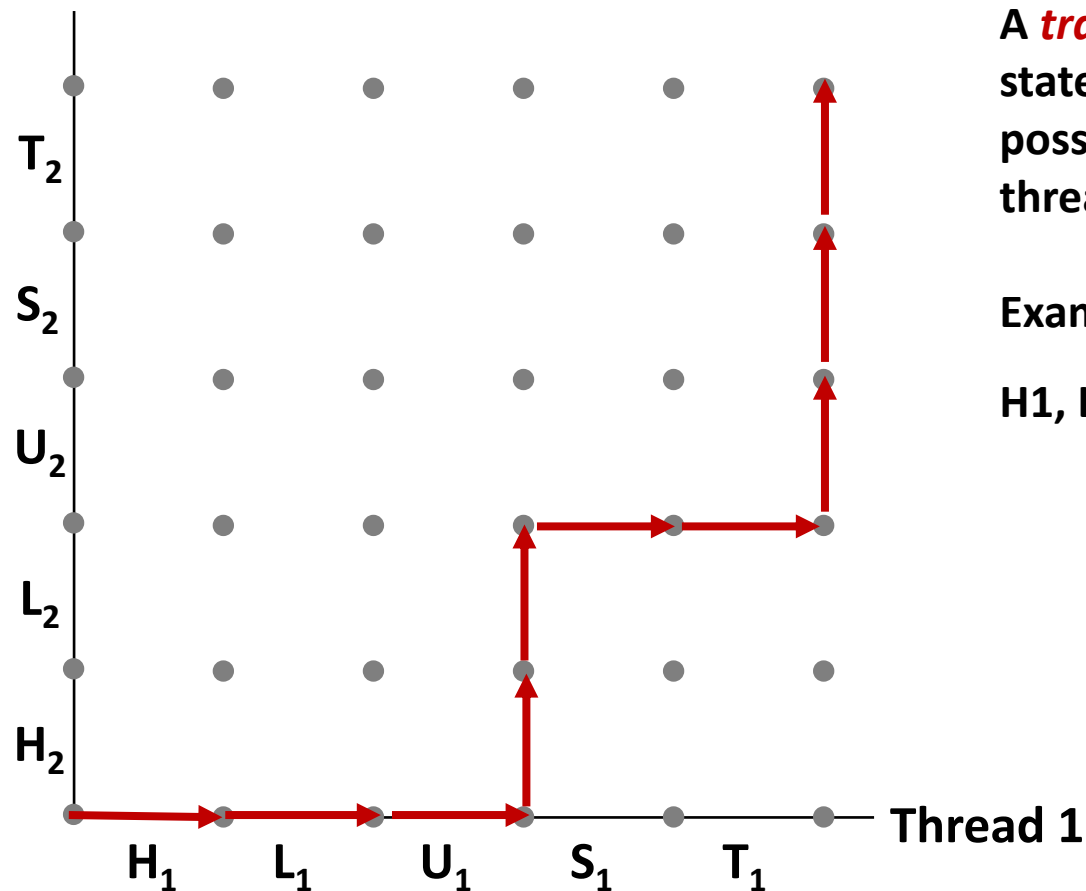
Each axis corresponds to the sequential order of instructions in a thread.

Each point corresponds to a possible *execution state* (Inst<sub>1</sub>, Inst<sub>2</sub>).

E.g., (L<sub>1</sub>, S<sub>2</sub>) denotes state where thread 1 has completed L<sub>1</sub> and thread 2 has completed S<sub>2</sub>.

# Trajectories in Progress Graphs

Thread 2

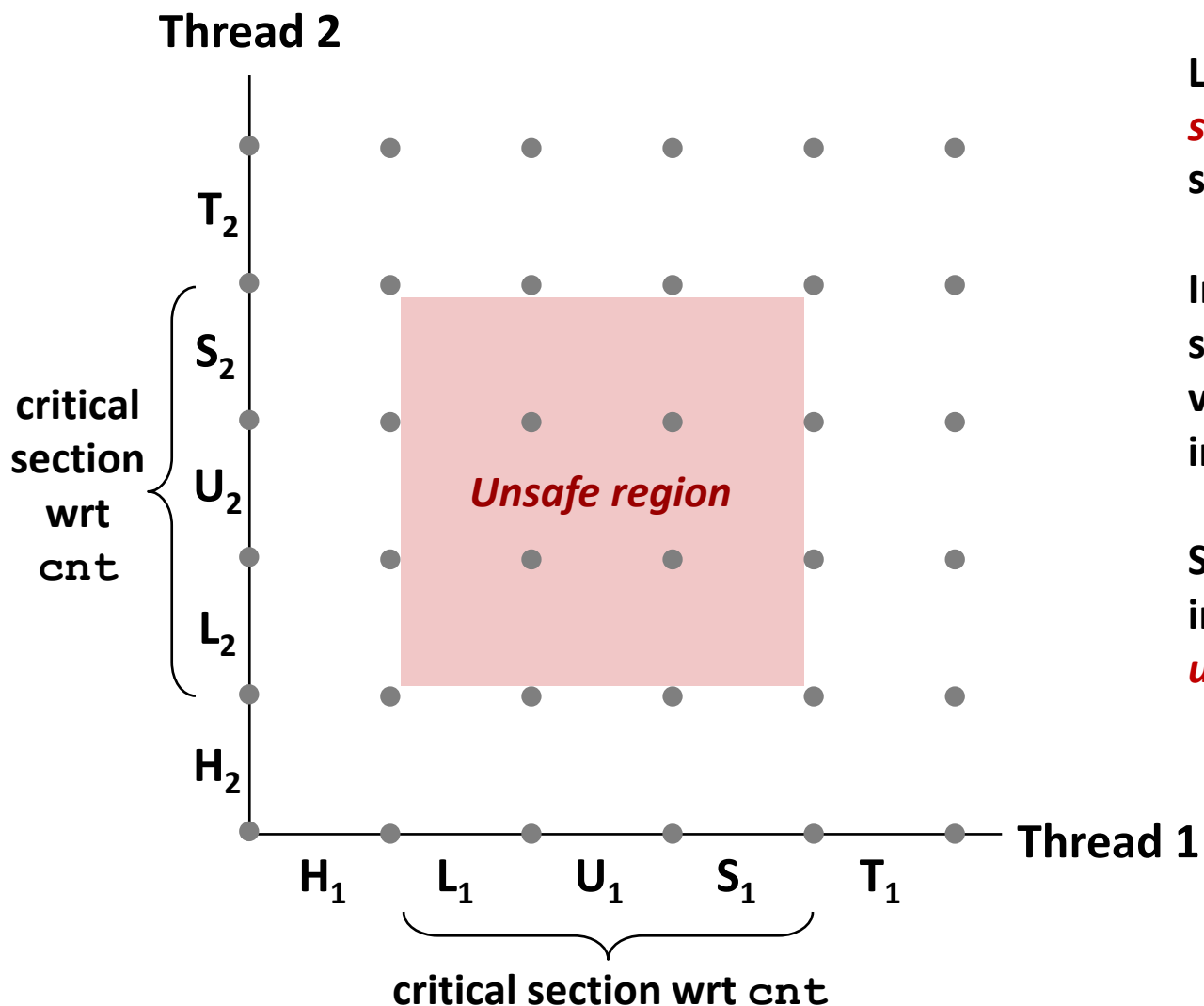


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

$H_1, L_1, U_1, H_2, L_2, S_1, T_1, U_2, S_2, T_2$

# Critical Sections and Unsafe Regions

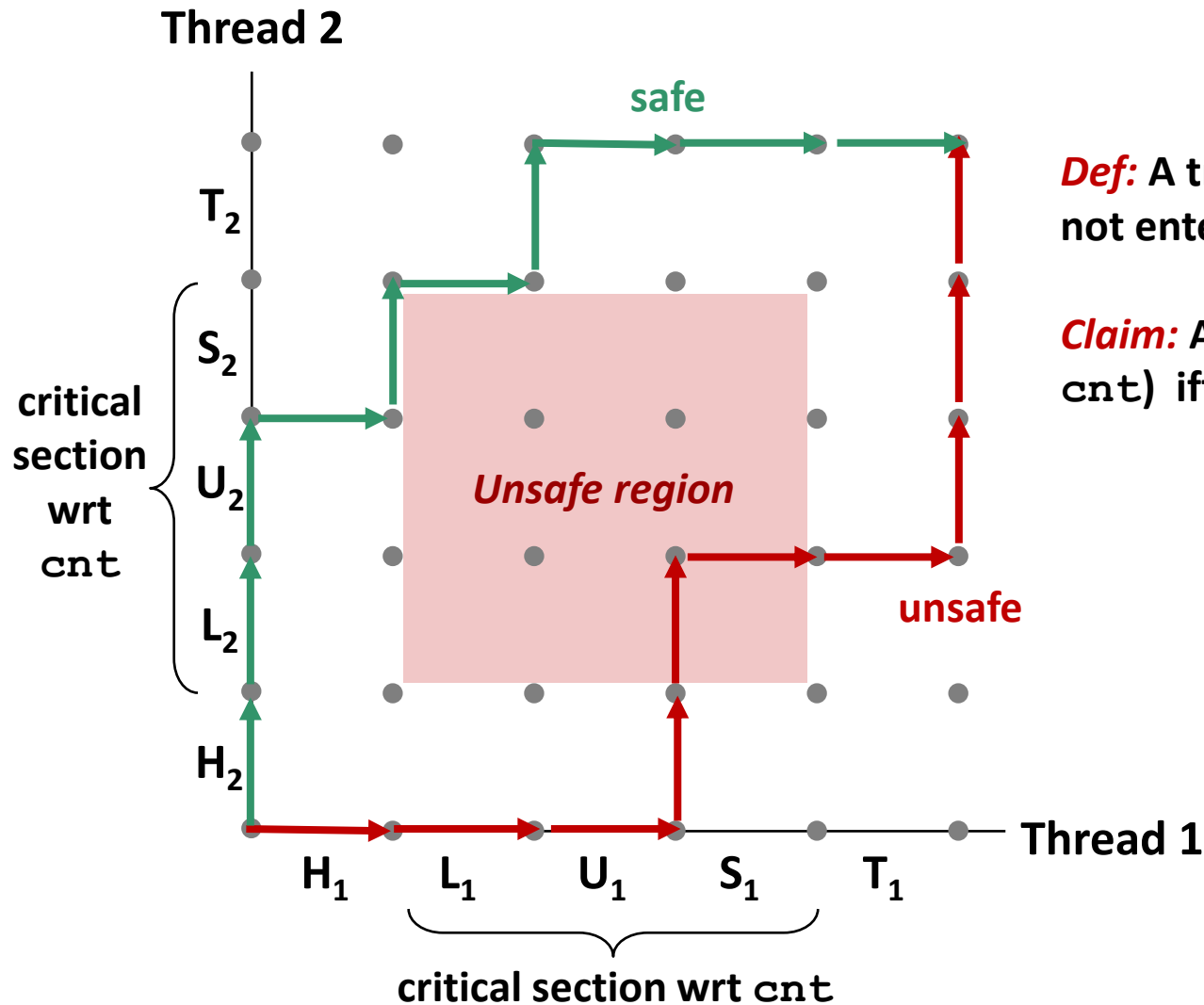


$L$ ,  $U$ , and  $S$  form a **critical section** with respect to the shared variable `cnt`

Instructions in critical sections (wrt some shared variable) should not be interleaved

Sets of states where such interleaving occurs form **unsafe regions**

# Critical Sections and Unsafe Regions



**Def:** A trajectory is *safe* iff it does not enter any unsafe region

**Claim:** A trajectory is correct (wrt cnt) iff it is safe

# Quiz time!

<https://canvas.cmu.edu/courses/34989/quizzes/103068>

# Today

- Threads review
- Sharing and Data Races
- **Fixing Data Races**
  - Mutexes
  - Semaphores
  - Atomic memory operations



# Enforcing Mutual Exclusion

- **Question:** How can we guarantee a safe trajectory?
- **Answer:** We must *synchronize* the execution of the threads so that they can never have an unsafe trajectory.
  - Need to guarantee *mutually exclusive access* to each critical section.

```
static unsigned long cnt = 0;
static pthread_mutex_t lock =
    PTHREAD_MUTEX_INITIALIZER;

void *incr_thread(void *arg) {
    unsigned long i;
    unsigned long niters =
        (unsigned long) arg;

    for (i = 0; i < niters; i++) {
        pthread_mutex_lock(&lock);
        cnt++;
        pthread_mutex_unlock(&lock);
    }
}
```

**Coding demo 2:**  
**Counting to 20,000 correctly**  
**(with threads and a mutex)**

# MUTual EXclusion (mutex)

- **Mutex: opaque object which is either *locked* or *unlocked***
  - Boolean value, but cannot do math on it
  - Starts out unlocked
  - Two operations:
- **lock(m)**
  - If the mutex is currently not locked, lock it and return
  - Otherwise, wait until it becomes unlocked, then retry
- **unlock(m)**
  - Can only be called when mutex is locked, by the code that locked it
  - Change mutex to unlocked

# Mutex implementation (partial)

```

/**
 * void pthread_mutex_lock(pthread_mutex_t *mtx)
 * Lock the mutex pointed to by MTX.  If it is already locked,
 * first sleep until it becomes unlocked.
 */
pthread_mutex_lock:
    call    gettid          // current thread ID now in %eax
    mov     $1, %edx        // increment
    lock xadd    %edx, MUTEX_CONTENTENDERS(%rdi)
    // %edx now holds _previous_ value of mtx->contentenders
    test   %edx, %edx
    jne    .Lcontended

    // The lock was unlocked, and now we hold it.
    mov    %eax, MUTEX_HOLDER(%rdi)
    ret

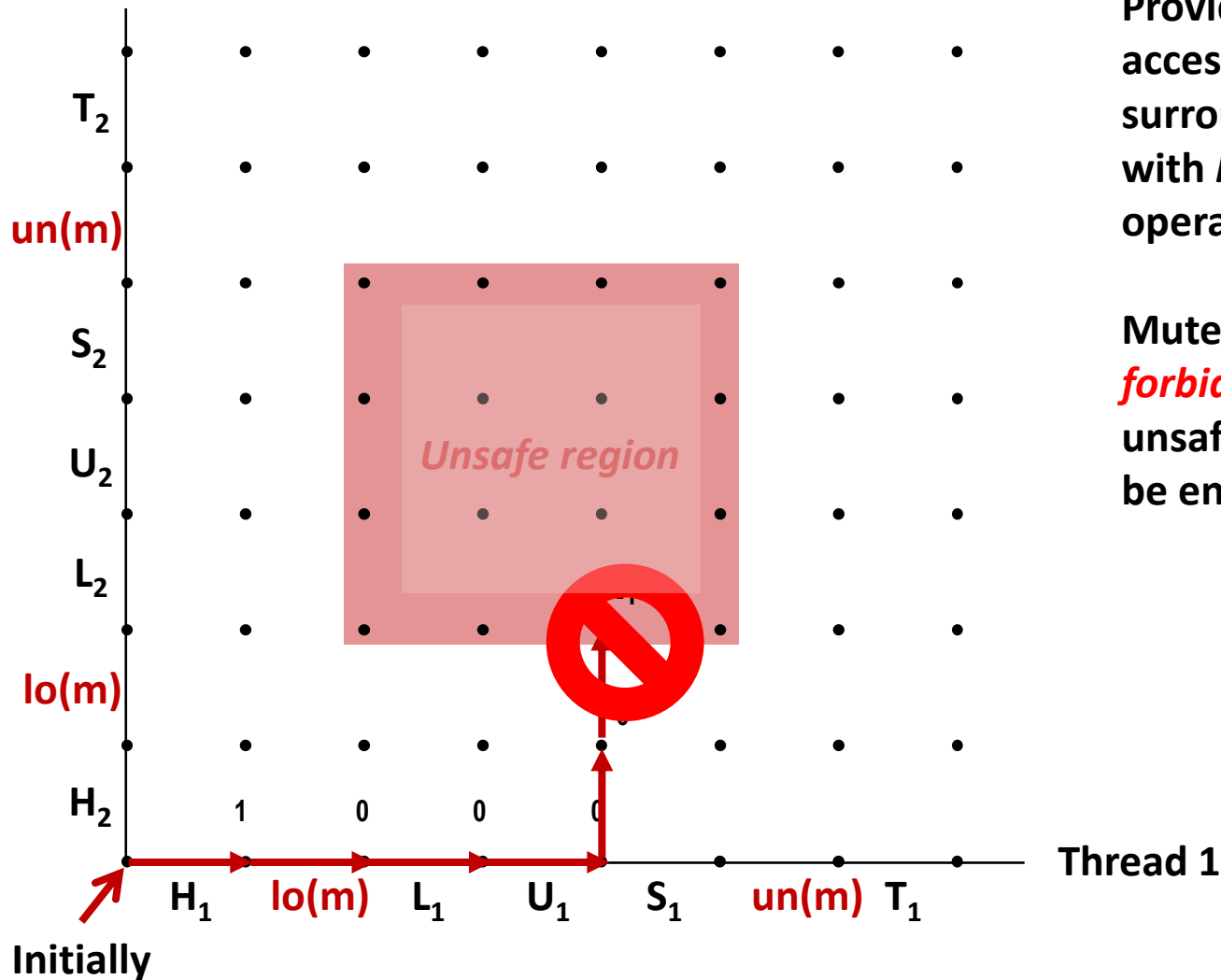
.Lcontended:
    // Sleep until another thread calls pthread_mutex_unlock
    // (30 more machine instructions and a system call)

```

*Just one of many ways to implement (discussed in 15-410, -418, etc)  
All require assistance from the CPU (special instructions)*

# Why Mutexes Work

Thread 2

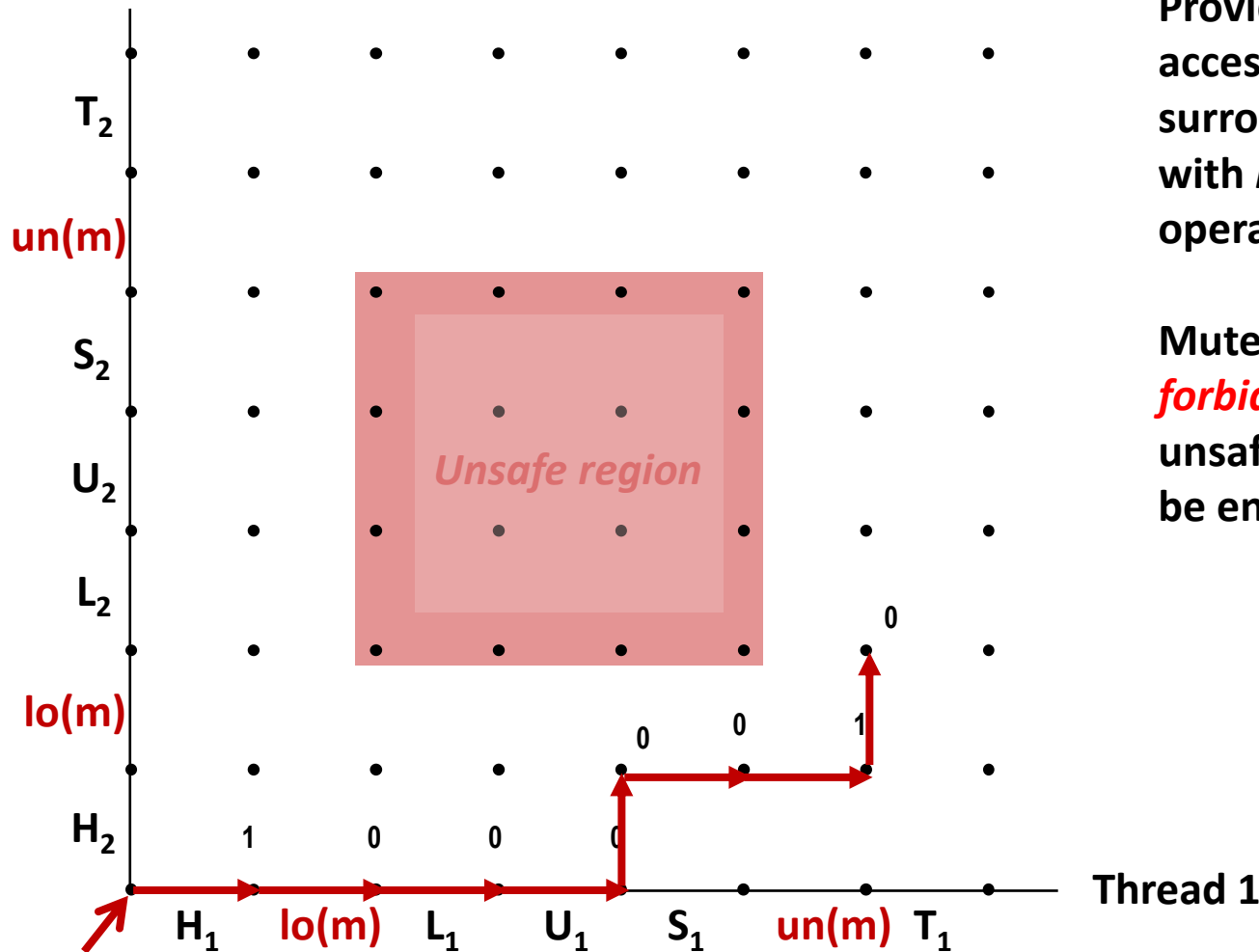


Provide mutually exclusive access to shared variable by surrounding critical section with *lock* and *unlock* operations

Mutex invariant creates a **forbidden region** that encloses unsafe region and that cannot be entered by any trajectory.

# Why Mutexes Work

Thread 2

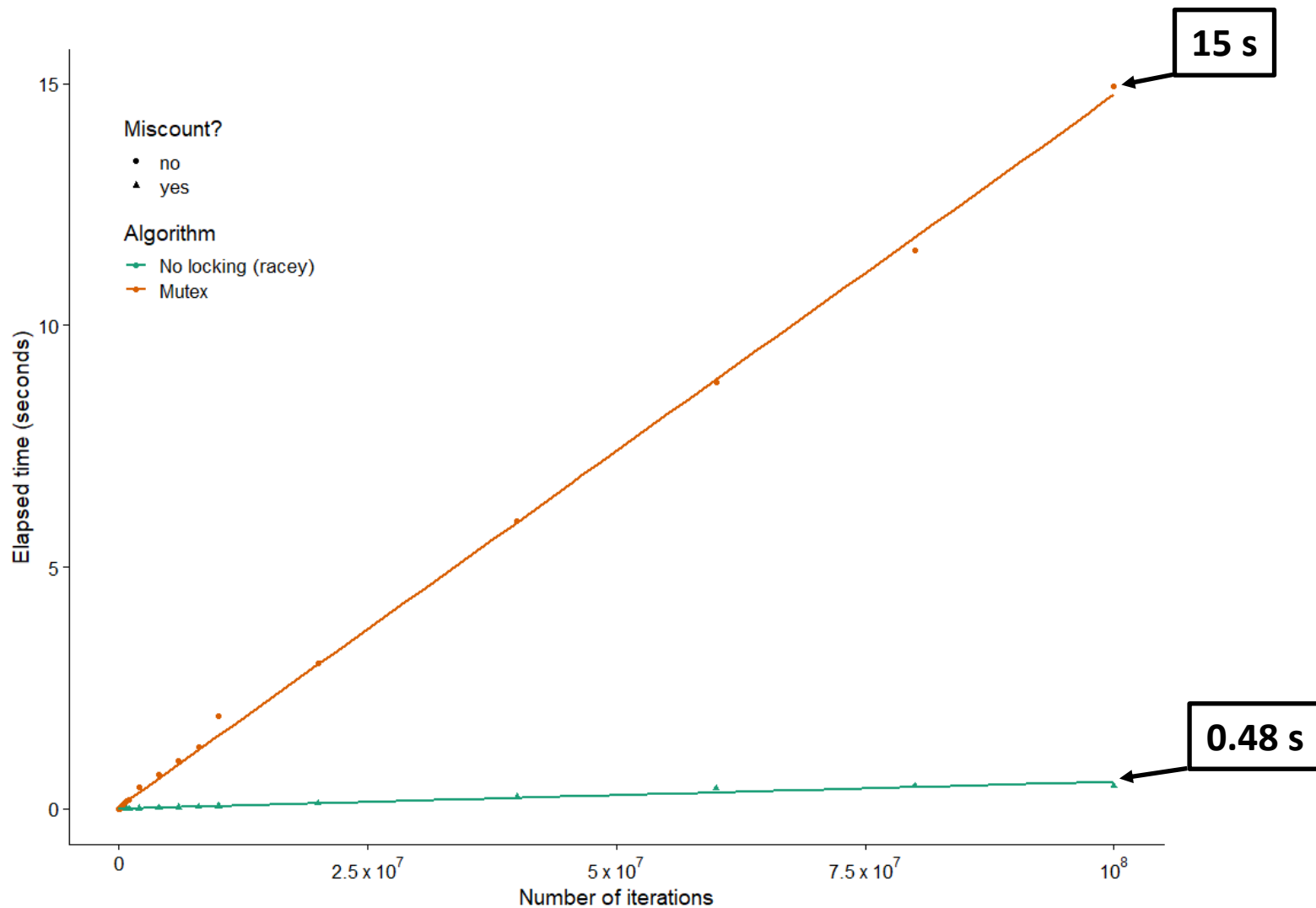


Provide mutually exclusive access to shared variable by surrounding critical section with *lock* and *unlock* operations

Mutex invariant creates a **forbidden region** that encloses unsafe region and that cannot be entered by any trajectory.

Thread 1

# The Cost of Mutexes



# Today

- Threads review
- Sharing and Data Races
- Fixing Data Races
  - Mutexes
  - Semaphores
  - Atomic memory operations

```
static unsigned long cnt = 0;
static sem_t lock;

void *incr_thread(void *arg) {
    unsigned long i;
    unsigned long niters =
        (unsigned long) arg;

    for (i = 0; i < niters; i++) {
        sem_wait(&lock);
        cnt++;
        sem_post(&lock);
    }
}
```

```
int main(int argc, char **argv) {
    unsigned long niters =
        strtoul(argv[1], NULL, 10);
    sem_init(&lock, 0, 1);
    // ...
}
```

**Coding demo 3:  
Counting to 20,000 correctly  
(with threads and a semaphore)**

# Semaphores

- ***Semaphore*: generalization of mutex**
  - Unsigned integer value, but cannot do math on it.
  - Created with some value  $\geq 0$
  - Two operations:
- **P(s) [“Prolaag,” Dutch shorthand for “try to reduce”]**
  - If  $s$  is zero, wait for a  $V$  operation to happen.
  - Then subtract 1 from  $s$  and return.
- **V(s) [“Verhogen,” Dutch for “increase”]**
  - Add 1 to  $s$ .
  - If there are any threads waiting inside a  $P$  operation, resume *one* of them
- **Unlike mutexes, no requirement to call P before calling V**



# C Semaphore Operations

## Pthreads functions:

```
#include <semaphore.h>

int sem_wait(sem_t *s); /* P(s) */
int sem_post(sem_t *s); /* V(s) */

int sem_init(sem_t *s, int pshared, unsigned int val);
```

Share among processes?  
(normally you want to  
pass zero, see manpage  
for details)

Initial semaphore value

# Semaphore implementation (partial)

```

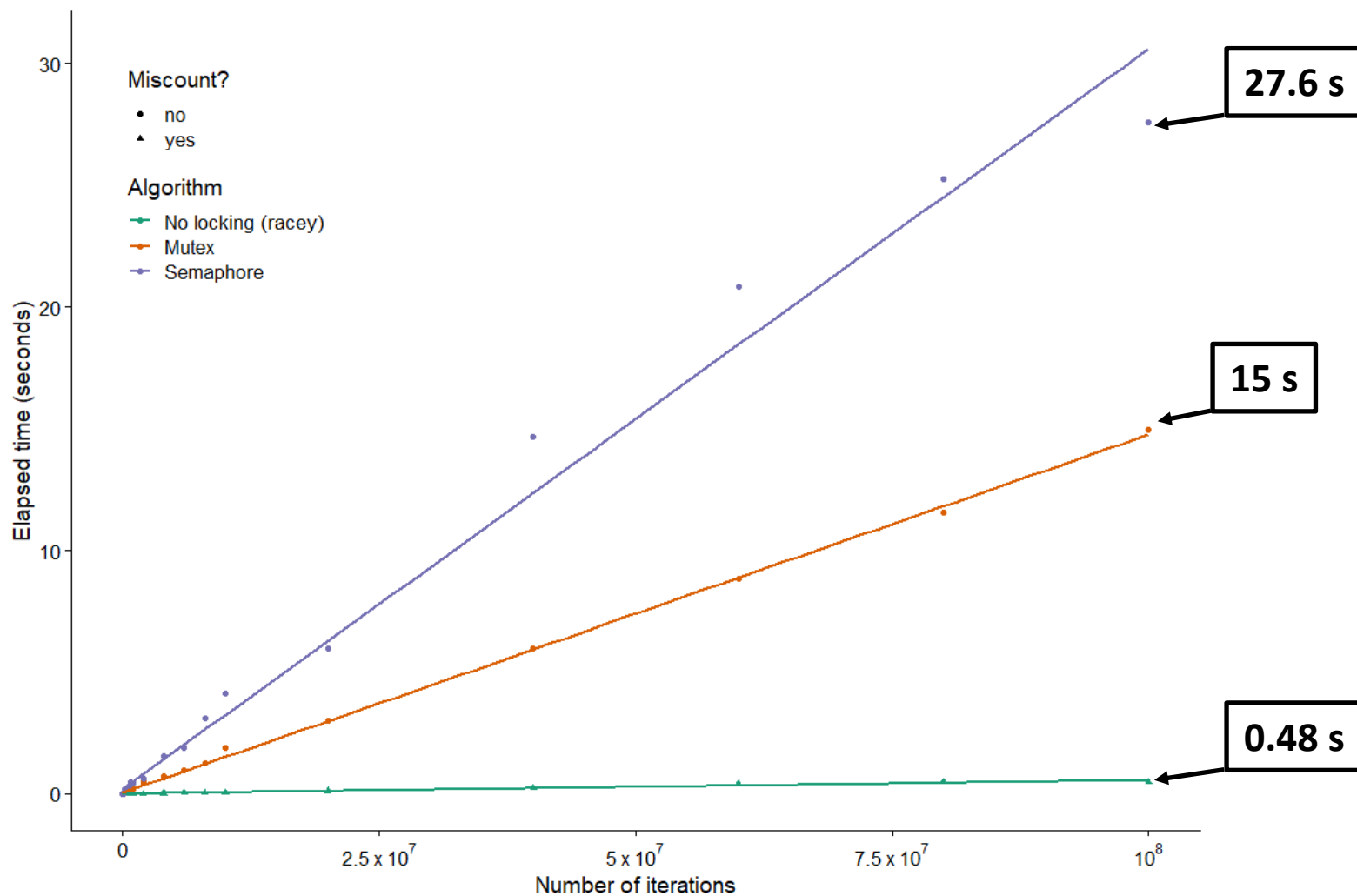
/**
 * void sem_wait(sem_t *sem)
 * Decrement the count of the semaphore pointed to by SEM.  If this
 * would make the count negative, first sleep until it is possible to
 * decrement the count without making it negative.
 */
sem_wait:
    mov     $-1, %edx        // decrement
    lock xadd %edx, SEM_COUNT(%rdi)
    // %edx now holds _previous_ value of sem->count
    test   %edx, %edx
    jle    .Lclosed
    // The semaphore was open.
    ret

.Lclosed:
    // Sleep until another thread calls sem_post
    // (30 more machine instructions and a system call)

```

**Suspiciously similar to a mutex, huh?**  
**(This implementation makes sem\_post do most of the work)**

# The cost of semaphores



# Today

- Threads review
- Sharing and Data Races
- **Fixing Data Races**
  - Mutexes
  - Semaphores
  - Atomic memory operations

# Atomic memory operations

## ■ Special hardware instructions

- “Test and set,” “compare and swap”, “exchange and add”, ...
- Do a read-modify-write on memory; hardware prevents data races
- Used to implement mutexes, semaphores, etc.

## ■ Not going to get into details, but...

- Wouldn't it be nice if we could use them directly?
- Especially when we just want to increment a counter?

```
static Atomic unsigned long cnt = 0;

void *incr_thread(void *arg) {
    unsigned long i;
    unsigned long niters =
        (unsigned long) arg;
    for (i = 0; i < niters; i++) {
        cnt++;
    }
}
```

**Coding demo 4:**  
**Counting to 20,000 correctly**  
**(with threads and C2011 atomics)**

# Assembly Code for Counter Loop

## C code

```
for (i = 0; i < niters; i++)
    cnt++;
```

## Assembly (*unsigned long*)

```
movq  (%rdi), %rcx
testq %rcx,%rcx
jle   .L2
movl  $0, %eax
-----
.L3:
movq  cnt(%rip), %rdx
addq  $1, %rdx
movq  %rdx, cnt(%rip)
-----
addq  $1, %rax
cmpq  %rcx, %rax
jne   .L3
```

.L2:

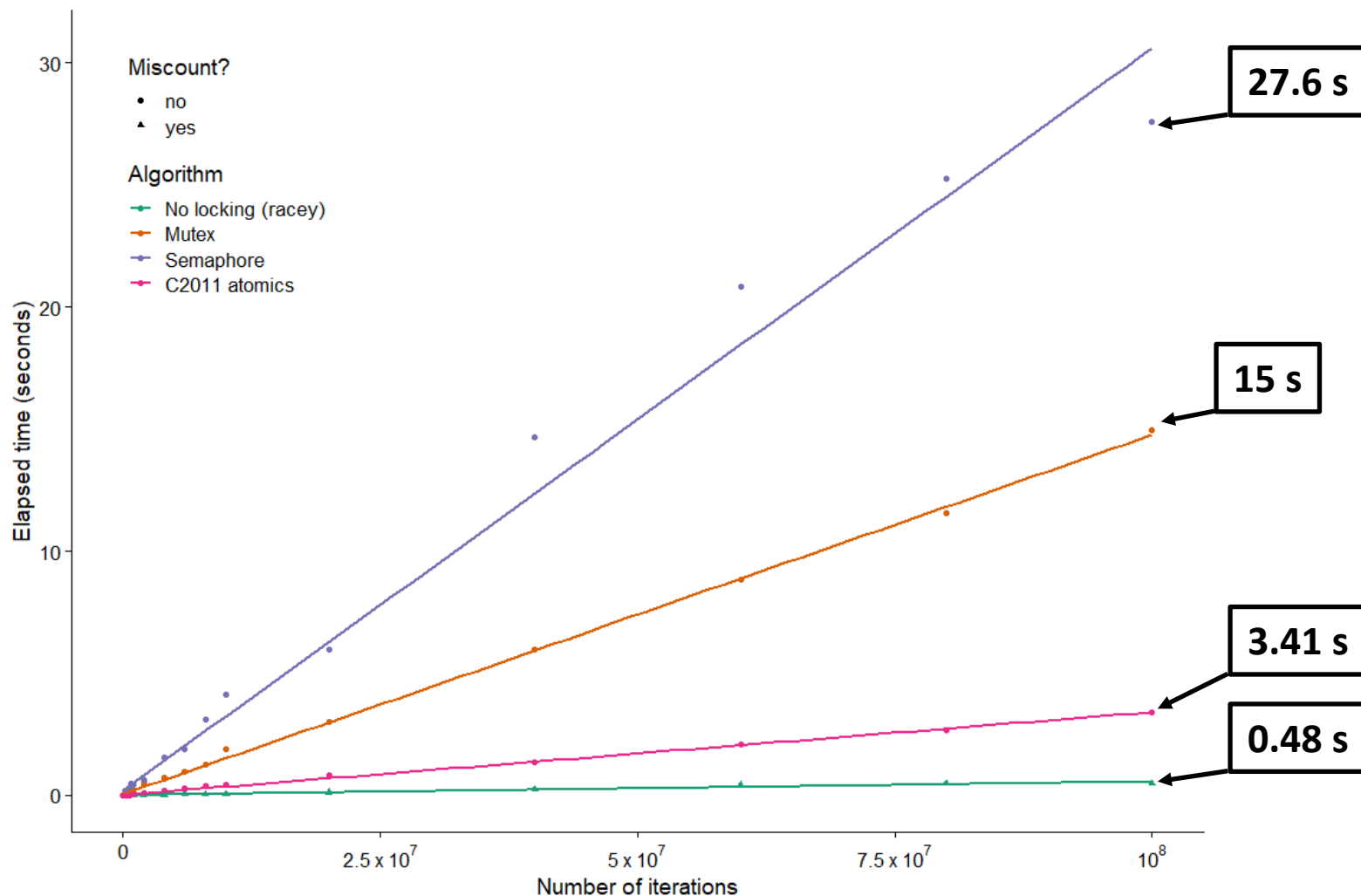
## Assembly (*\_Atomic unsigned long*)

```
movq  (%rdi), %rcx
testq %rcx,%rcx
jle   .L2
movl  $0, %eax
-----
.L3:
lock addq $1, cnt(%rip)
```

```
-----
addq  $1, %rax
cmpq  %rcx, %rax
jne   .L3
```

.L2:

# The cost of atomic memory operations



# Summary

- **Access shared variables with care to avoid data races.**
  - Crucial to understand which variables are shared in the first place
  - Avoid sharing, if you can
  - Avoid writing from multiple threads, if you can
  
- **Mutexes help, but...**
  - They're slow
  - (Next time: They can cause problems as well as solve them)
  
- **Don't use a semaphore when a mutex will do**
  - They're even slower
  - (Next time: When is a semaphore actually useful?)
  
- **Atomic memory ops are handy, but...**
  - The hardware might not provide the operation you need
  - (Later courses: Tricky to use correctly)