Synchronization: Basics

15-213/14-513/15-513: Introduction to Computer Systems
23rd Lecture, November 28, 2023

More Final Exam Logistics

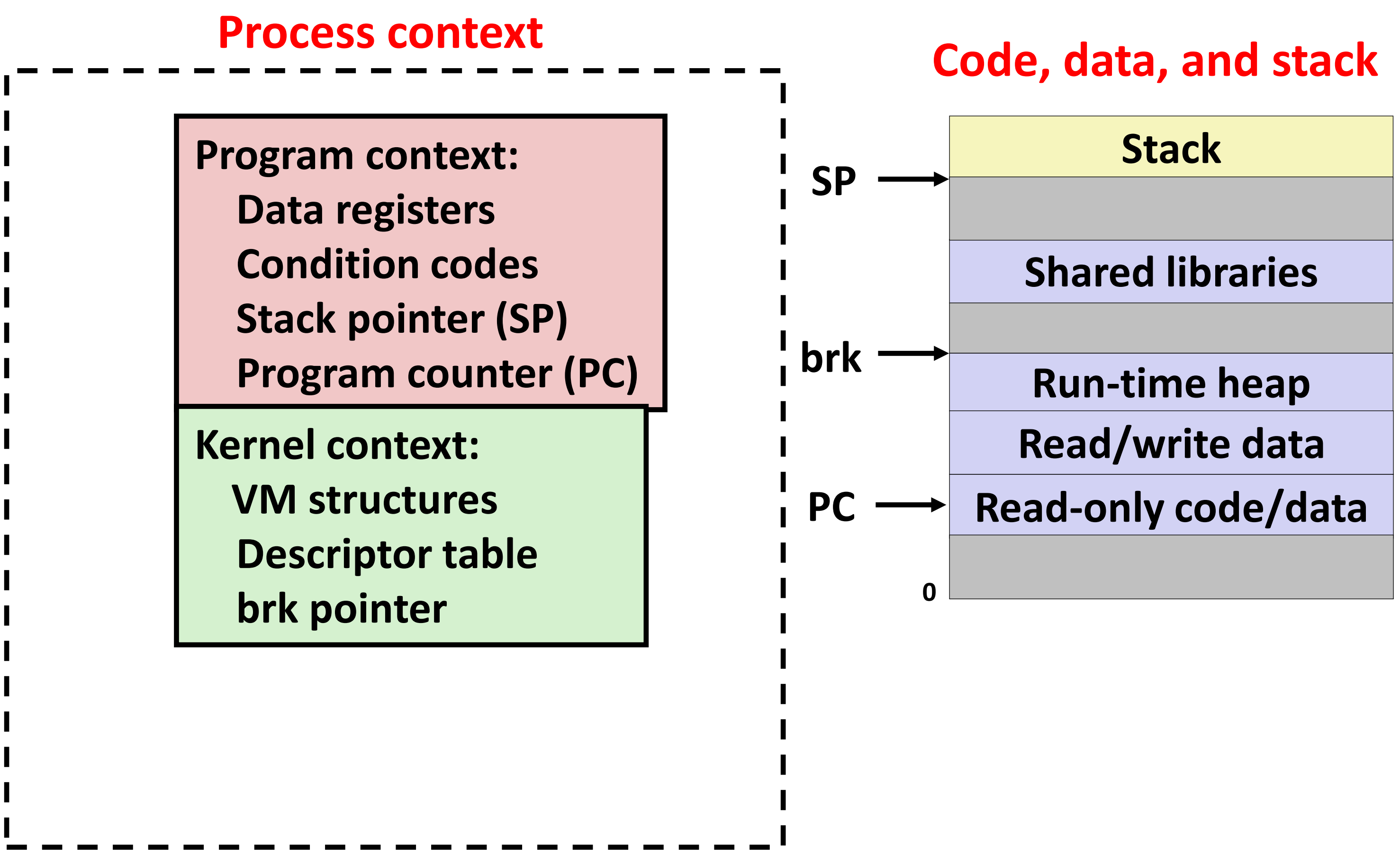
- **Make-up final exam session Monday 18 December**
  - Location and time TBD
- **Final exam review session: not yet scheduled**
- **If you have disability accommodations**
  - Make sure they're on file with the disabilities office
  - Also fill out the form below
  - You will take the exam at the Disability Resources Testing Center (5136 Margaret Morrison Street); do not go to Posner
- **Need any sort of adjustment to exam logistics?**
  - https://piazza.com/class/llpgaho5sjp63w/post/2195
- **More details:**
  - https://www.cs.cmu.edu/~213/exams.html

Today

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

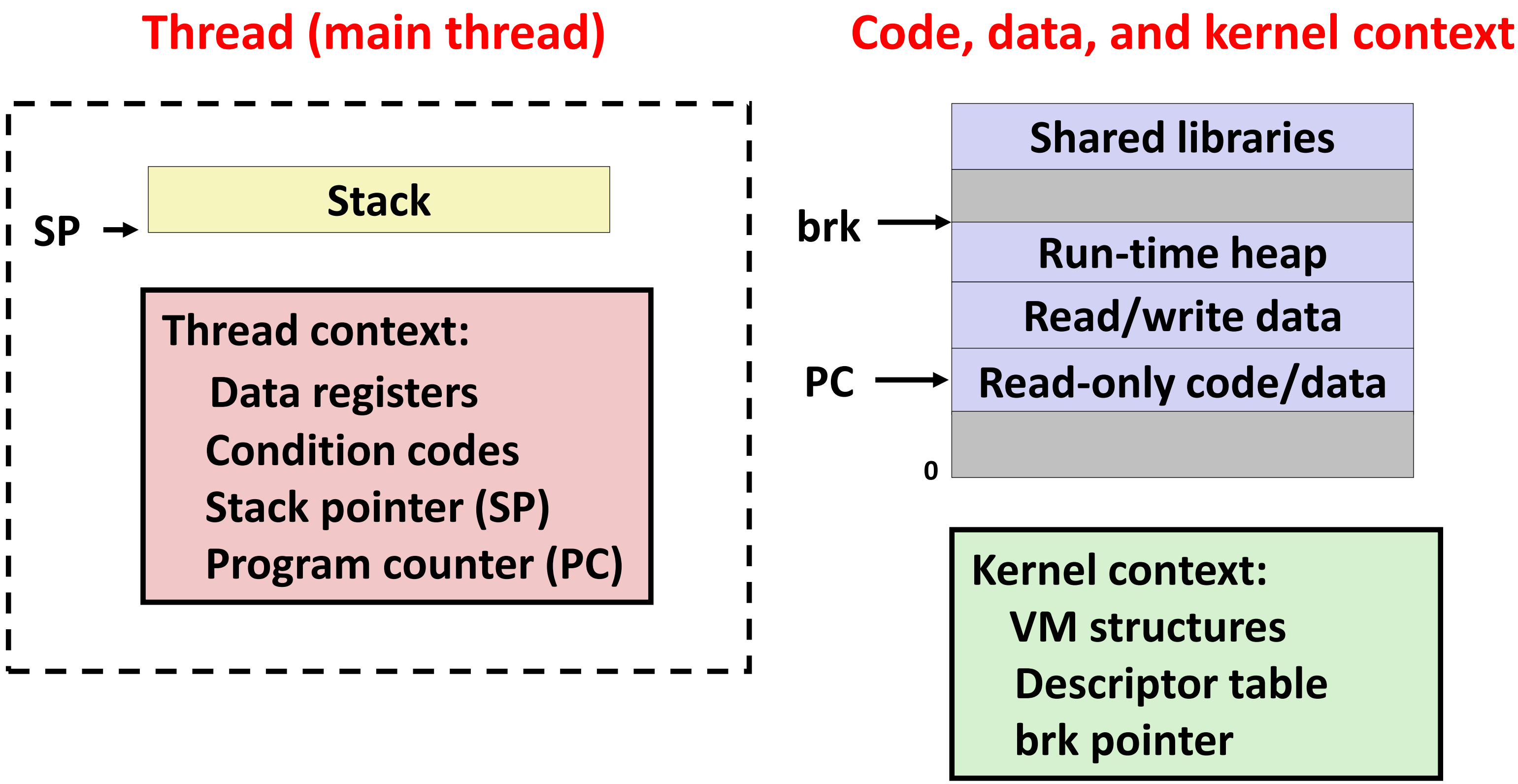
Traditional View of a Process

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



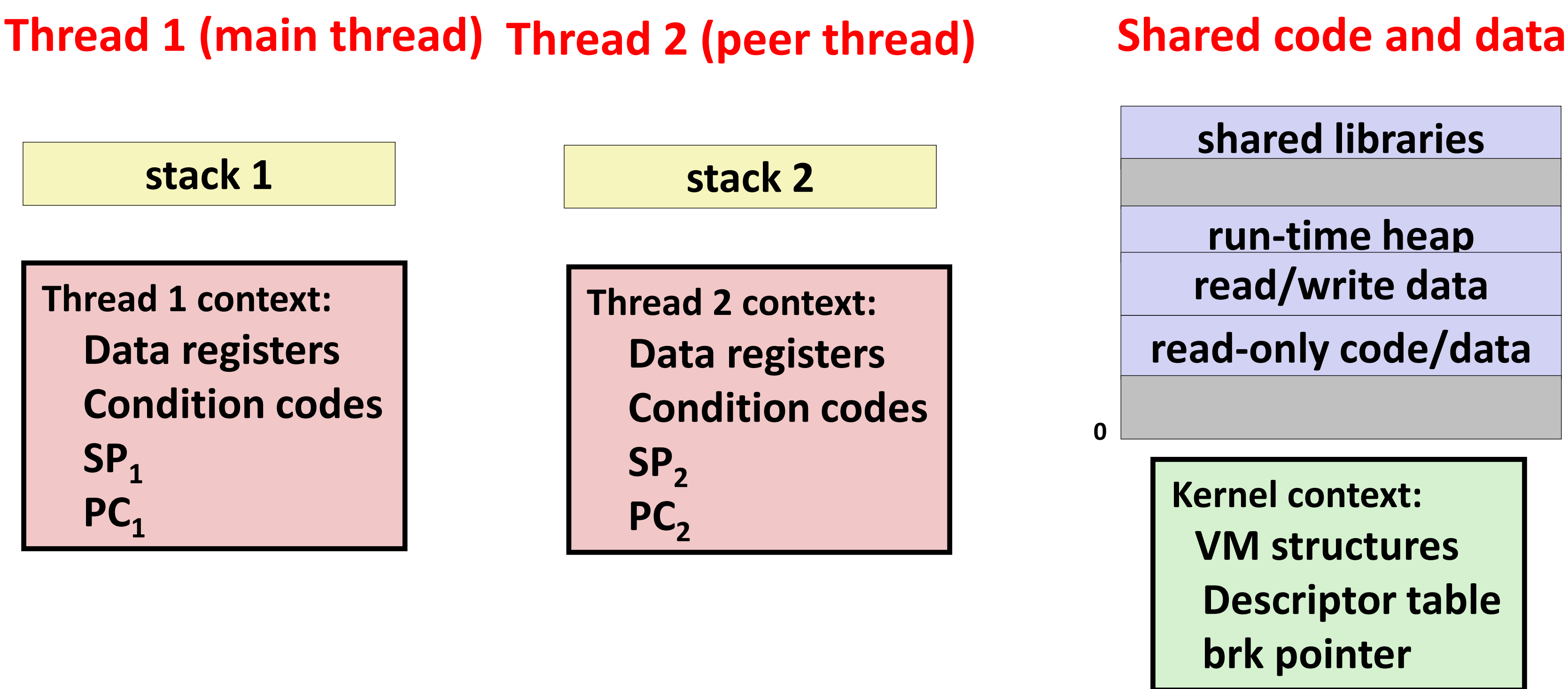
Alternate View of a Process

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

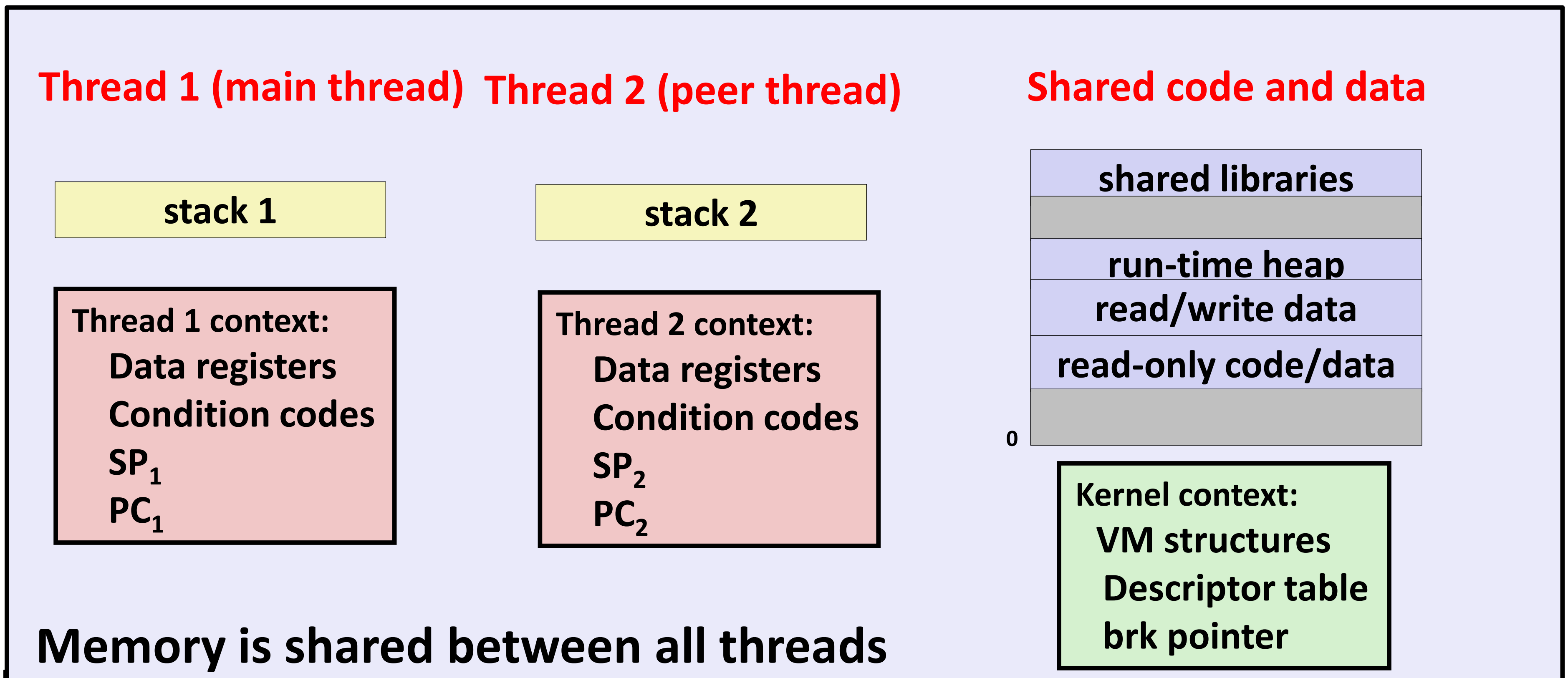


A Process With Multiple Threads

- **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)



Don’t let picture confuse you!



Today

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- Fixing Data Races
  - Mutexes
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  - Atomic memory operations

Shared Variables in Threaded C Programs

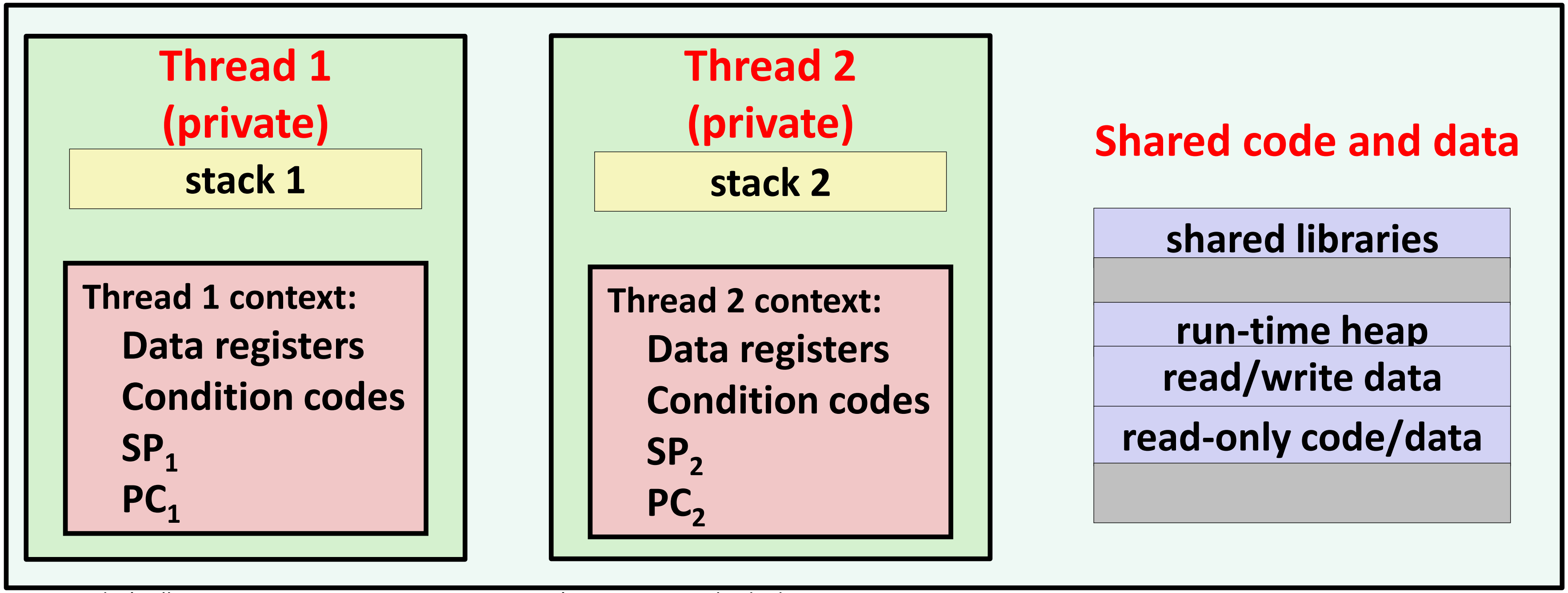
- **Question: Which variables in a threaded C program are shared?**
  - The answer is not as simple as "*global variables are shared*" and "*stack variables are private*"

- ***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?

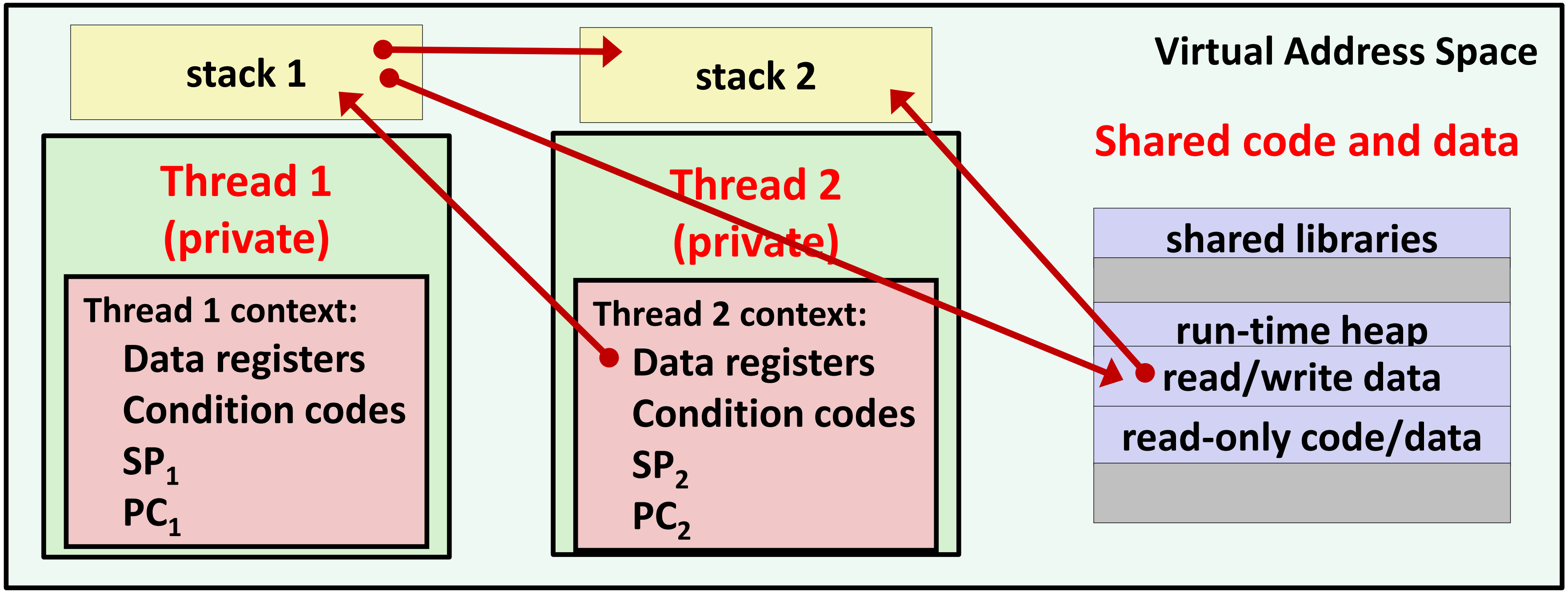
Threads Memory Model: Conceptual

- **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

```c
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

```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?**

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

Variable instance	*Referenced by main thread?*	*Referenced by peer thread 0?*	*Referenced by peer thread 1?*
`ptr`	yes	yes	yes
`cnt`	no	yes	yes
`i.m`	yes	no	no
`msgs.m`	yes	yes	yes
`myid.p0`	no	yes	no
`myid.p1`	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

```
    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:
```

H_i : Head

L_i : Load cnt
U_i : Update cnt
S_i : Store cnt

T_i : Tail

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

Oops!

Concurrent Execution (cont)

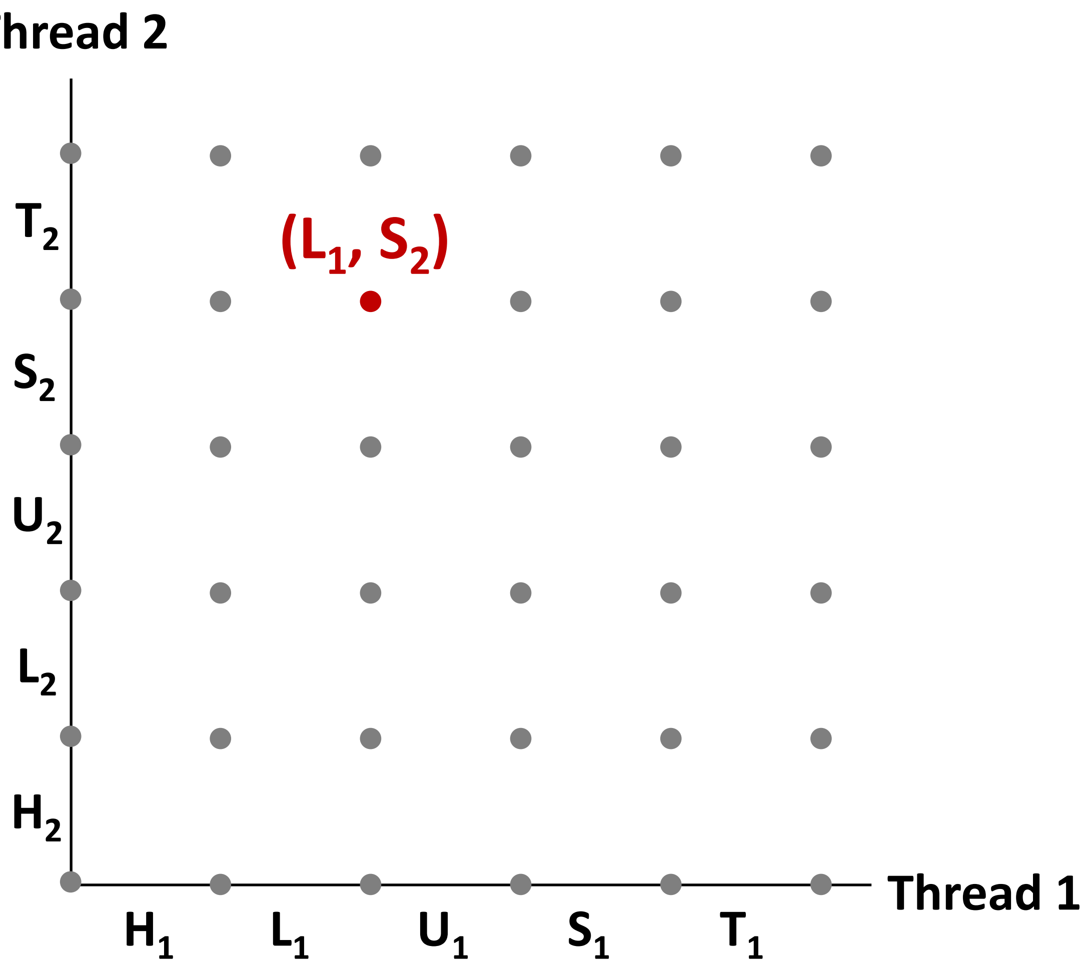
- How about this ordering?

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

Oops!

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

Progress Graphs



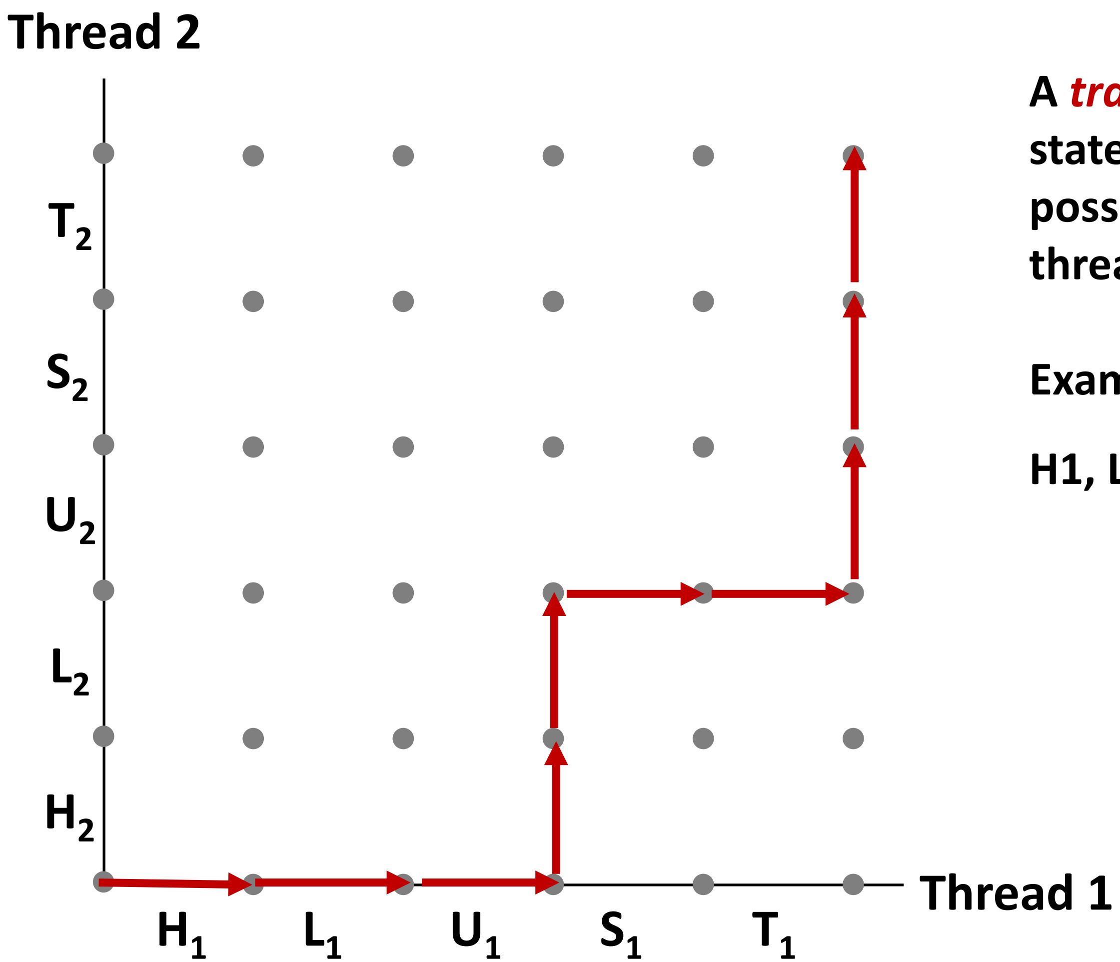
A *progress graph* depicts the discrete *execution state space* of concurrent threads.

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

Each point corresponds to a possible *execution state* $(Inst_1, Inst_2)$.

E.g., (L_1, S_2) denotes state where thread 1 has completed L_1 and thread 2 has completed S_2.

Trajectories in Progress Graphs

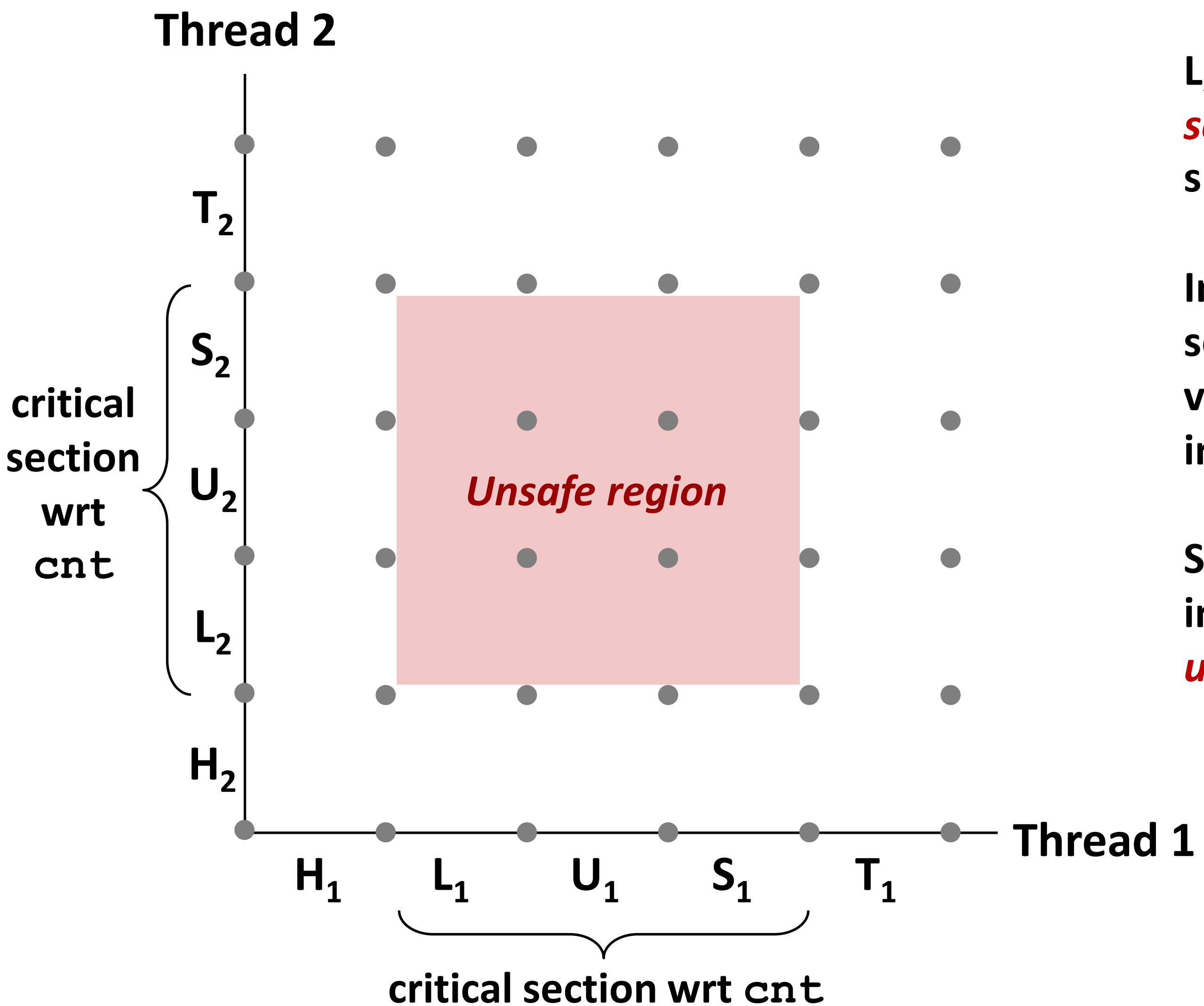


A ***trajectory*** is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

H1, L1, U1, H2, L2, S1, T1, U2, S2, T2

Critical Sections and Unsafe Regions

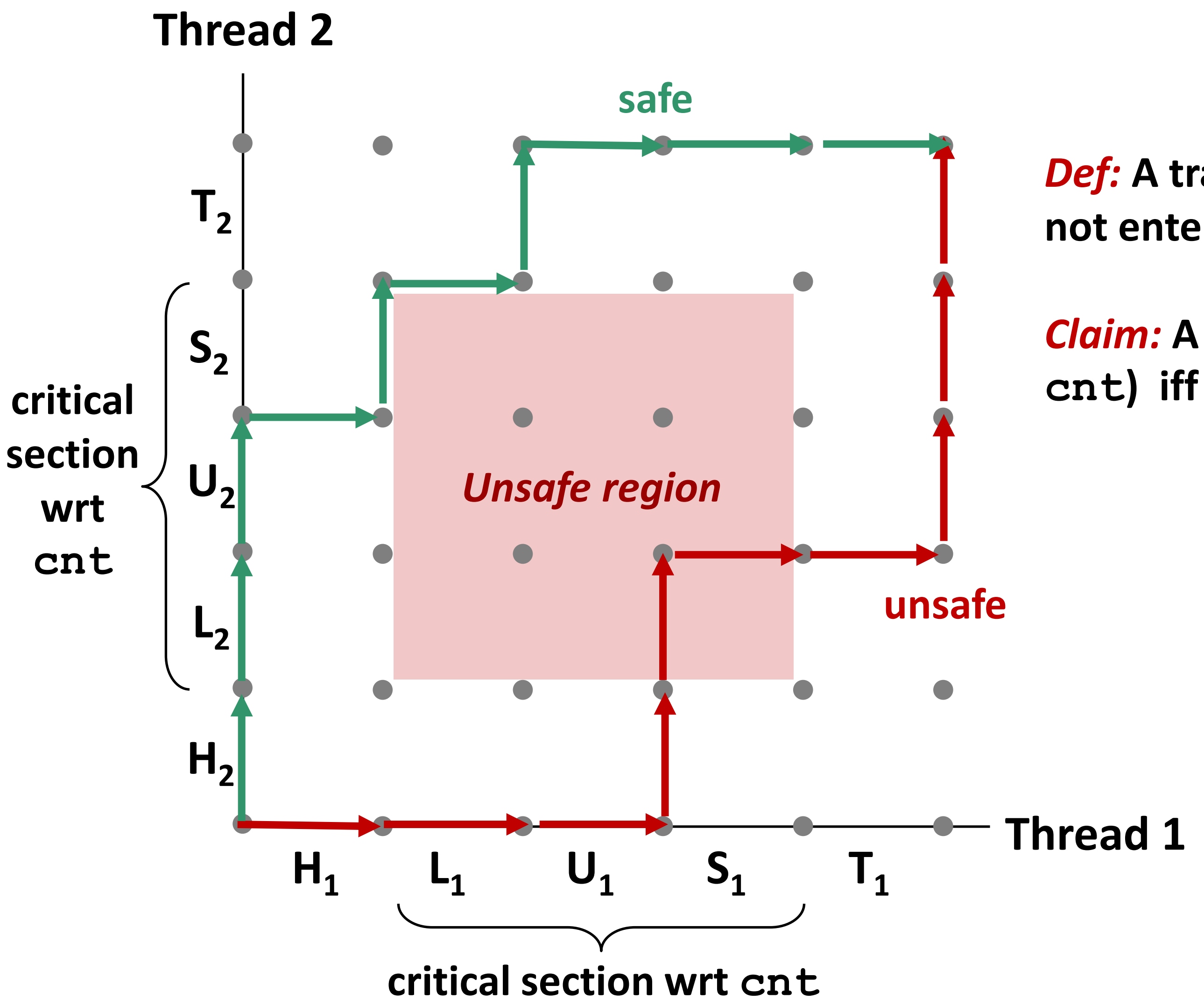


L, U, and S form a ***critical section*** with respect to the shared variable `cnt`

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/37116/quizzes/109929

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- 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)

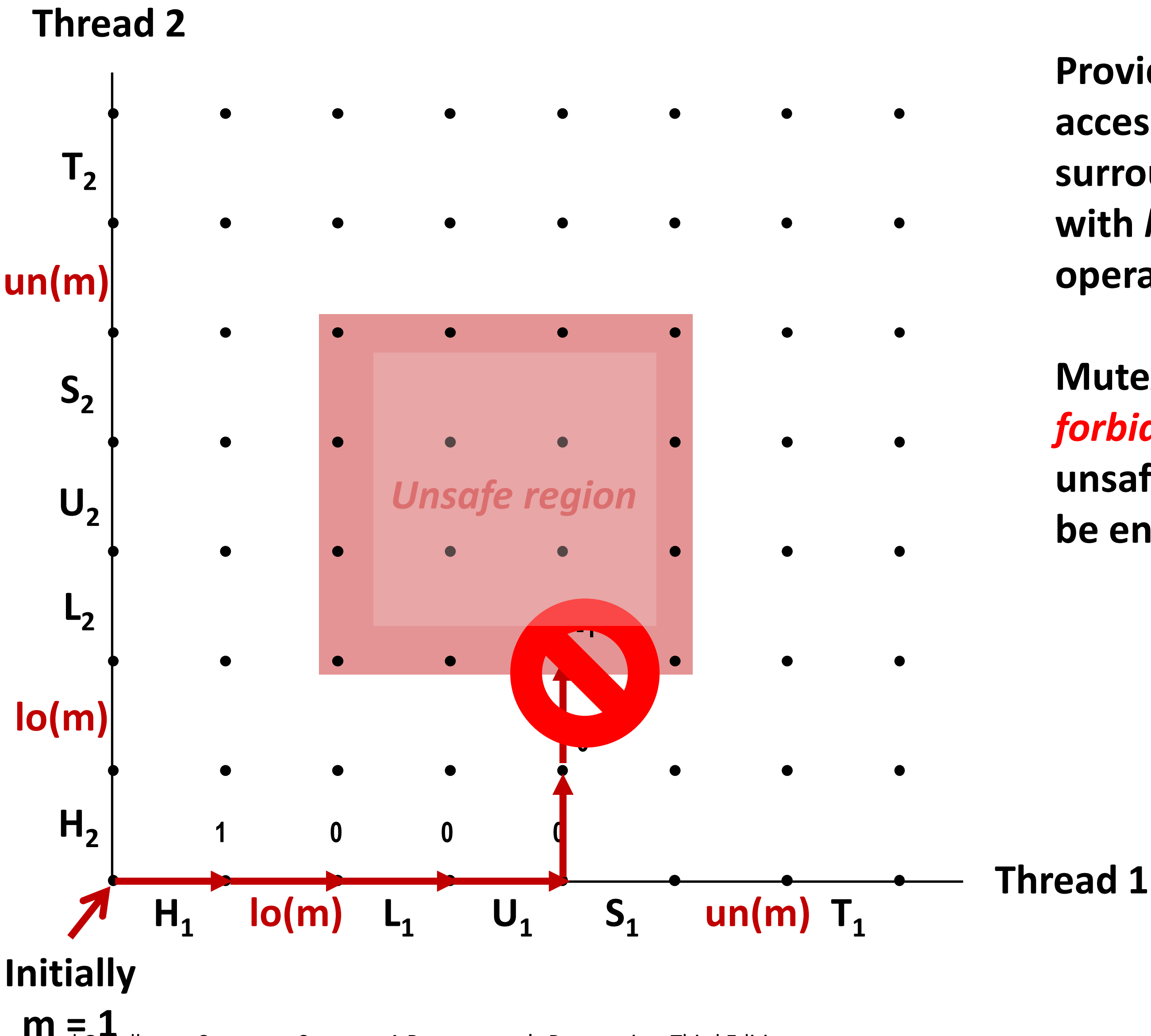
```
/**
 * void pthread_mutex_lock(pthread_mutex_t *mtx)
 * Lock the mutex pointed to by MTX.  If it is already locked,
 * first sleep until it becomes unlocked.
 */
pthread_mutex_lock:
        call    gettid           // current thread ID now in %eax
        mov     $1, %edx         // increment
  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

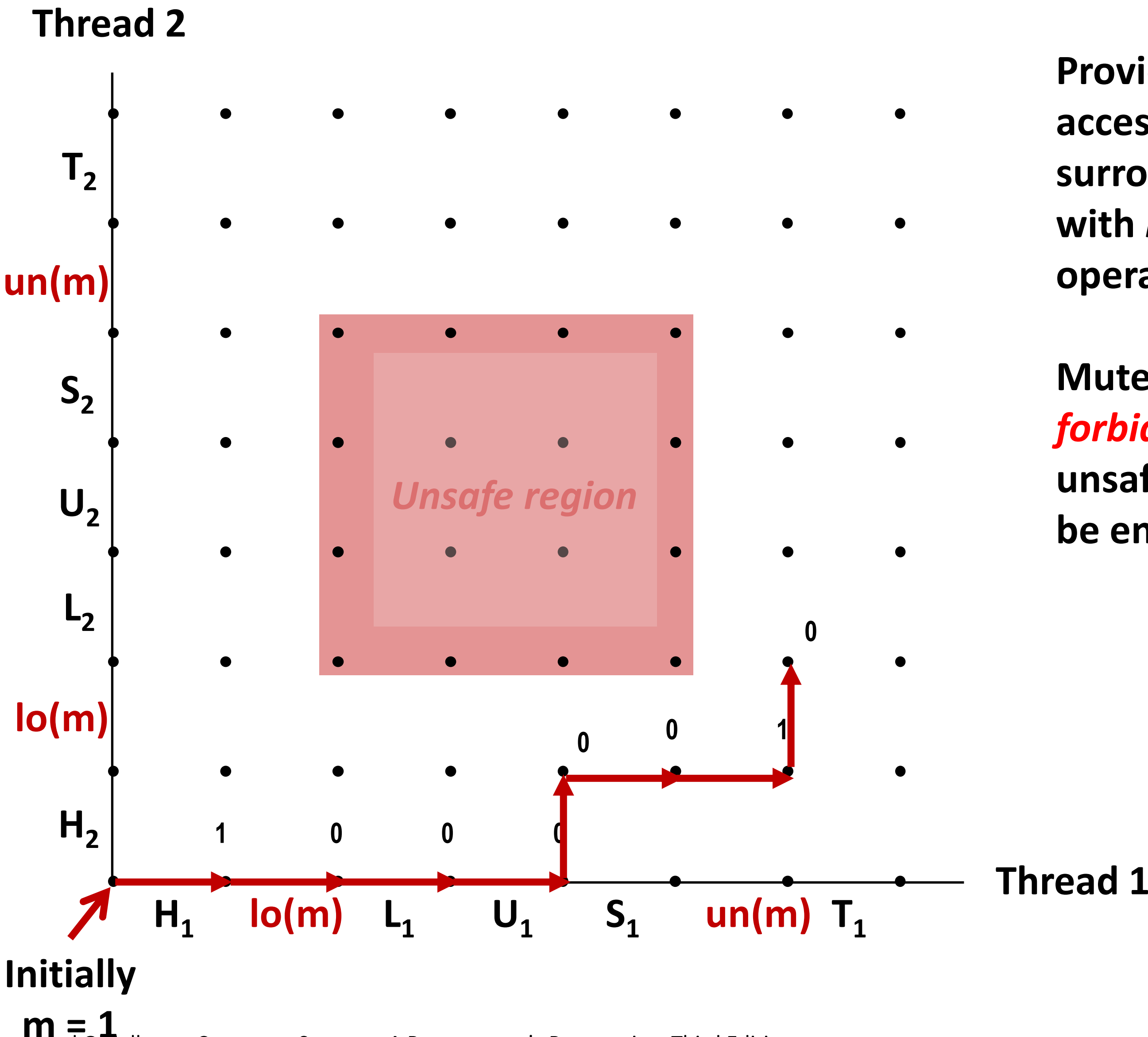
Why Mutexes Work



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.

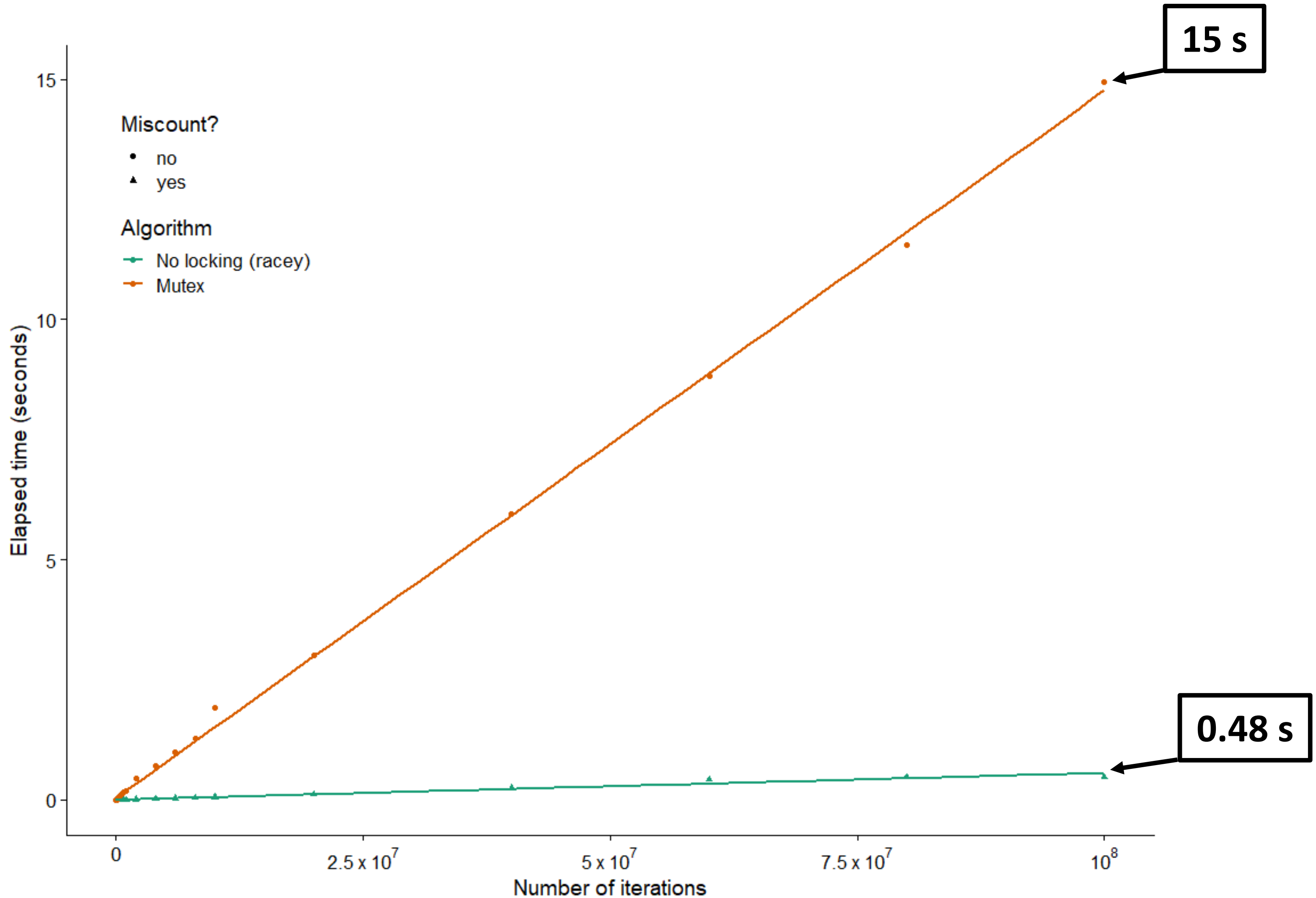
Why Mutexes Work



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.

The Cost of Mutexes



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- **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 >= 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) → pshared

Initial semaphore value → val

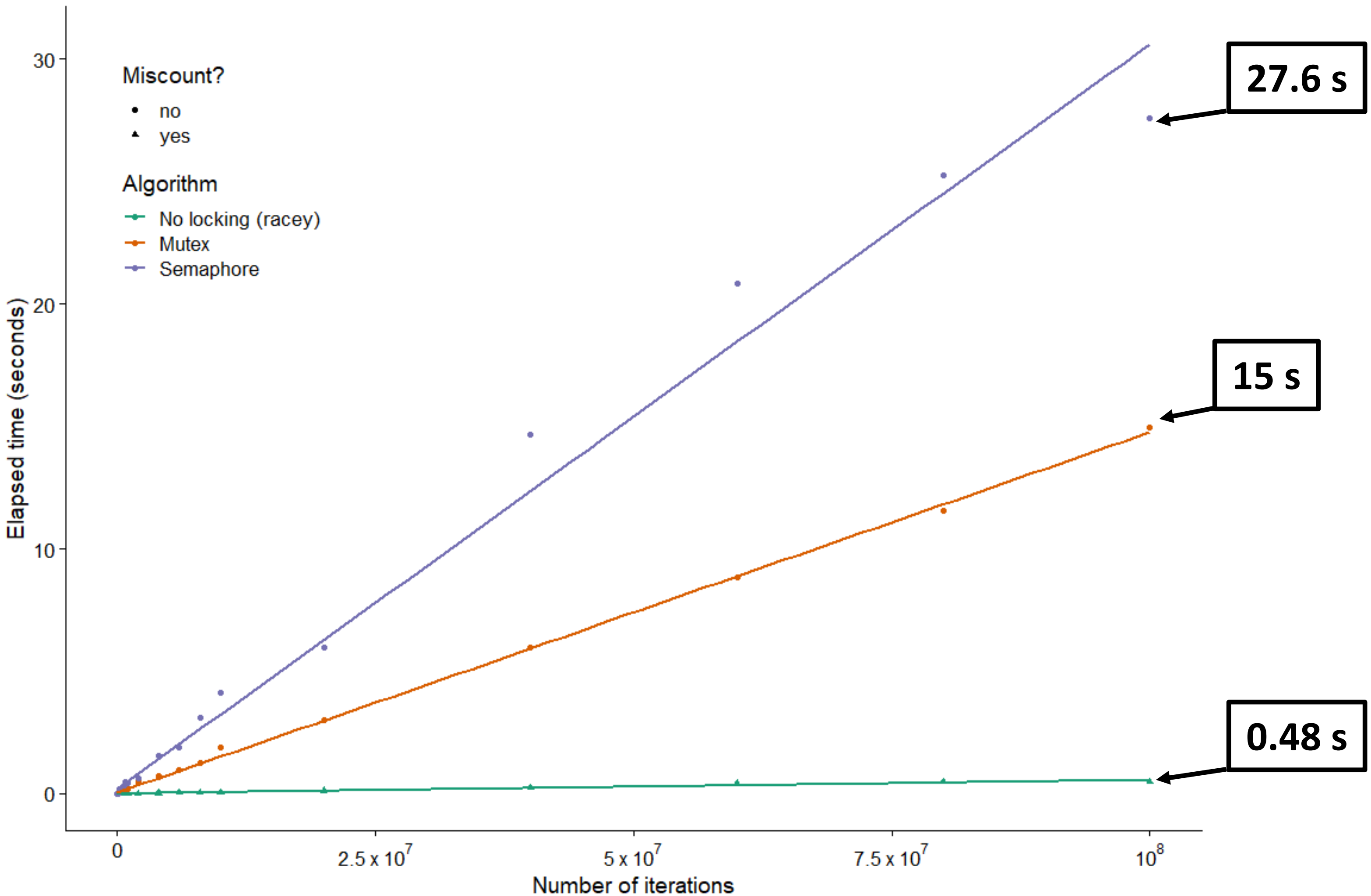
Semaphore implementation (partial)

```
/**
 * 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



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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)

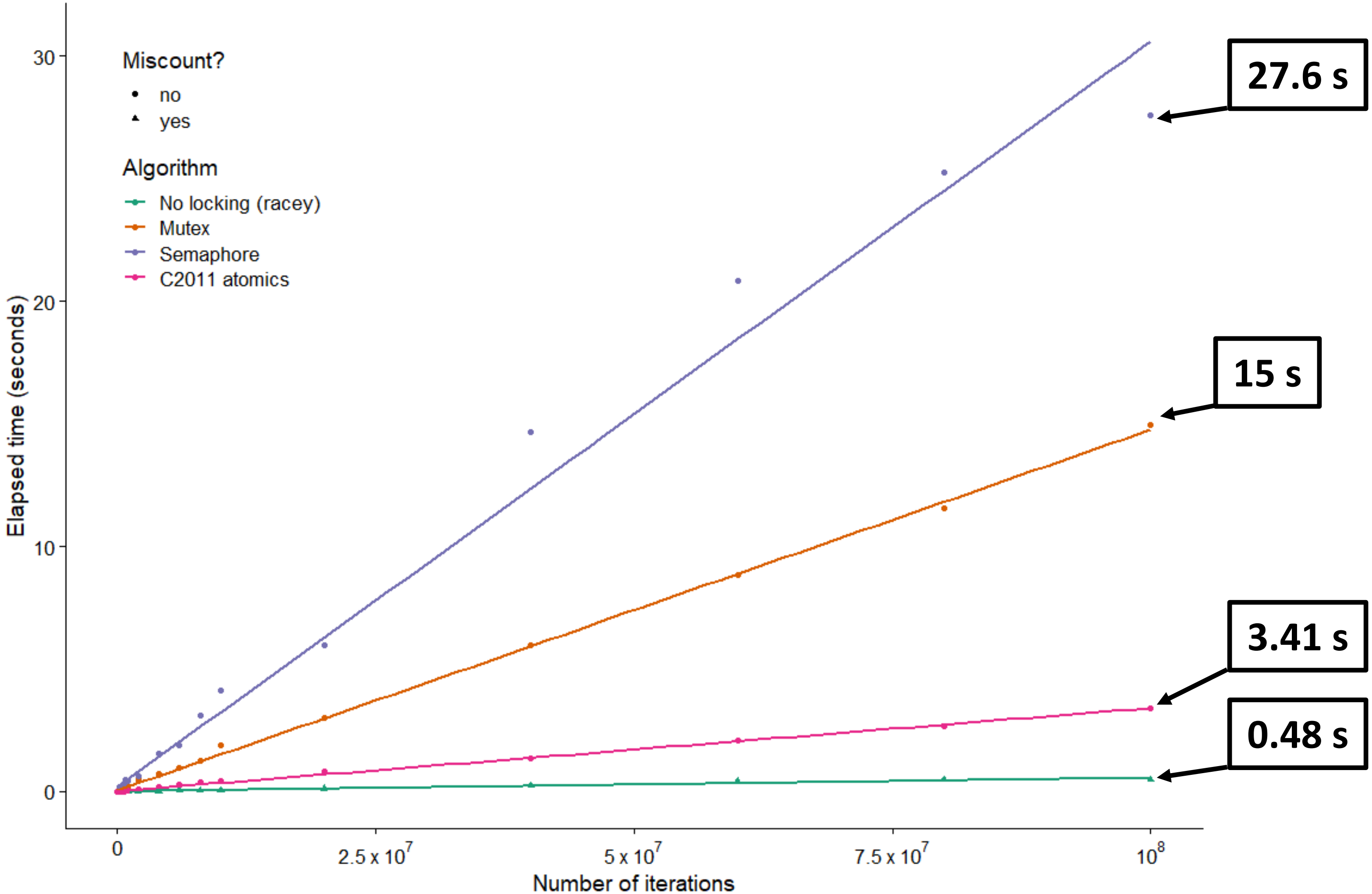
```
    movq   (%rdi), %rcx
    testq %rcx,%rcx
    jle    .L2
    movl   $0, %eax
.L3:
    movq   cnt(%rip),%rdx
    addq   $1, %rdx
    movq   %rdx, cnt(%rip)
    addq   $1, %rax
    cmpq   %rcx, %rax
    jne    .L3
.L2:
```

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)