

Synchronization: Basics

15-213: Introduction to Computer Systems
24th Lecture, November 17, 2016

Instructor:

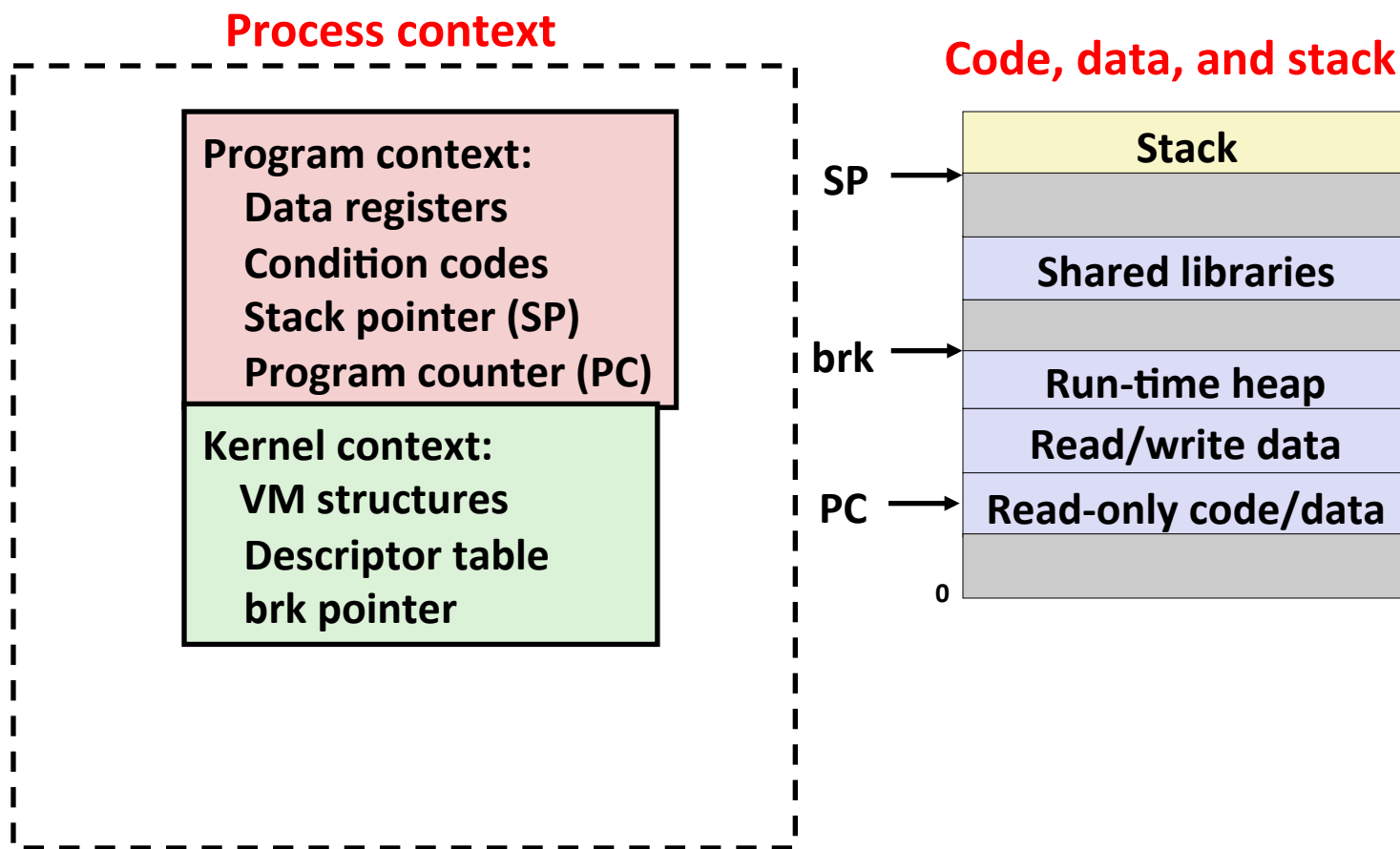
Phil Gibbons

Today

- **Threads review**
- Sharing
- Mutual exclusion
- Semaphores

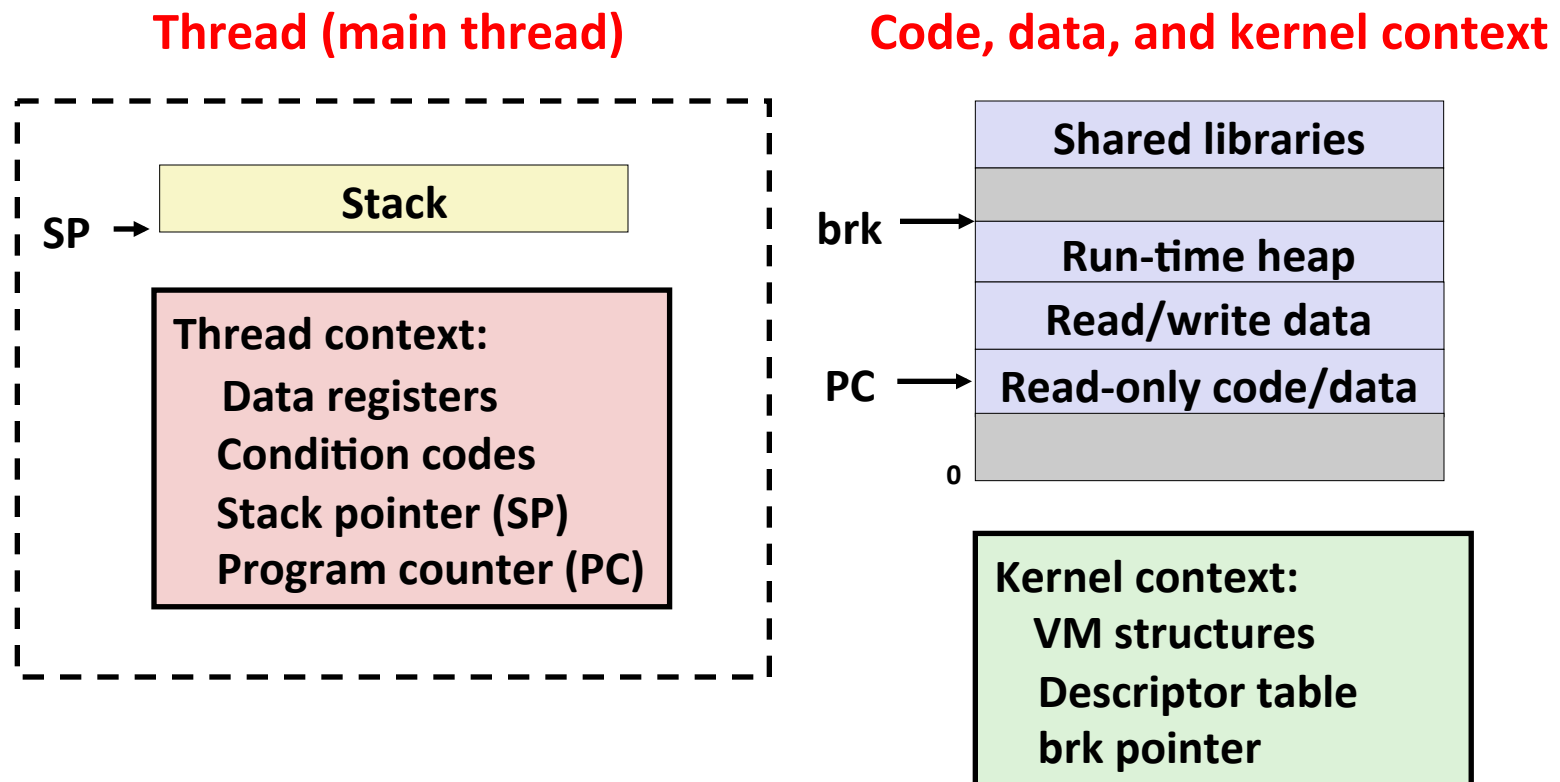
Traditional View of a Process

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



Alternate View of a Process

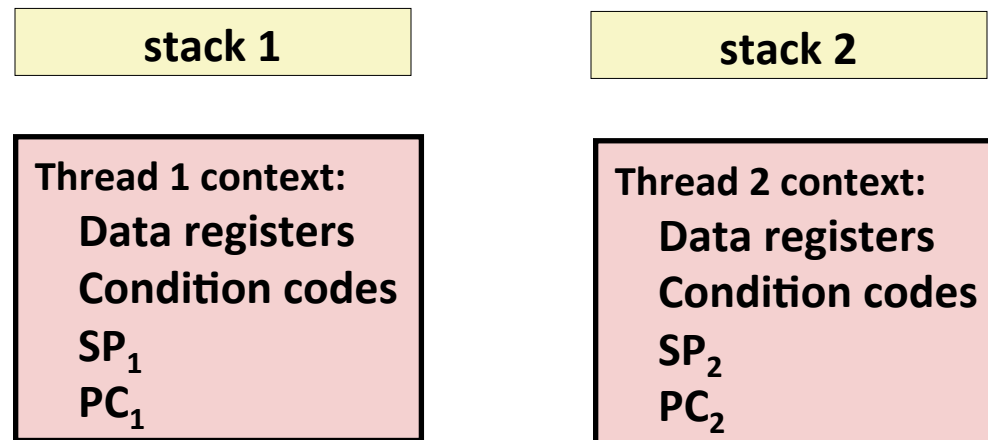
- Process = thread + code, data, and kernel context



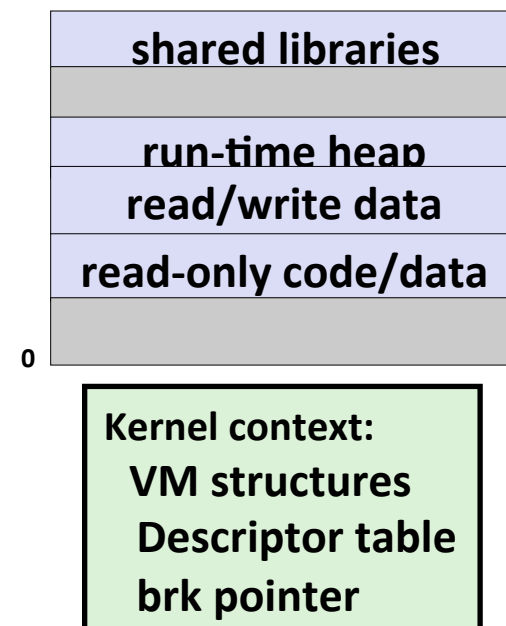
A Process With Multiple Threads

- **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)

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



Shared code and data



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 model:

- 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

■ Operationally, this model 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

Example Program to Illustrate Sharing

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


int main(int argc, 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;
}
```



Peer threads reference main thread's stack indirectly through global ptr variable

Mapping Variable Instances to Memory

■ Global variables

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

■ Local variables

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

■ Local static variables

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

Mapping Variable Instances to Memory

Global var: 1 instance (ptr [data])

Local vars: 1 instance (i.m, msgs.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 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>
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 */
int main(int argc, char *argv[]) {
    int i;
    pthread_t tid;
    char *msgs[2] = {"Hello from foo",
                    "Hello from bar"};

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

```

```

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

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

```

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 introduce the possibility of nasty *synchronization* errors.

badcnt.c: Improper Synchronization

```

/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    Pthread_create(&tid1, NULL,
                  thread, &niters);
    Pthread_create(&tid2, NULL,
                  thread, &niters);
    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    /* Check result */
    if (cnt != (2 * niters))
        printf("BOOM! cnt=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}

```

badcnt.c

```

/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
        *((long *)vargp);

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

    return NULL;
}

```

```

linux> ./badcnt 10000
OK cnt=20000
linux> ./badcnt 10000
BOOM! cnt=13051
linux>

```

cnt should equal 20,000.

What went wrong?

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</pre>	} H_i : Head
<pre>----- .L3: movq cnt(%rip), %rdx addq \$1, %rdx movq %rdx, cnt(%rip)</pre>	} L_i : Load cnt U_i : Update cnt S_i : Store cnt
<pre>----- addq \$1, %rax cmpq %rcx, %rax jne .L3 .L2:</pre>	} T_i : Tail

Concurrent Execution

- **Key idea:** In general, any sequentially consistent interleaving is possible, but 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

OK

Concurrent Execution

- **Key idea:** In general, any sequentially consistent interleaving is possible, but 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)

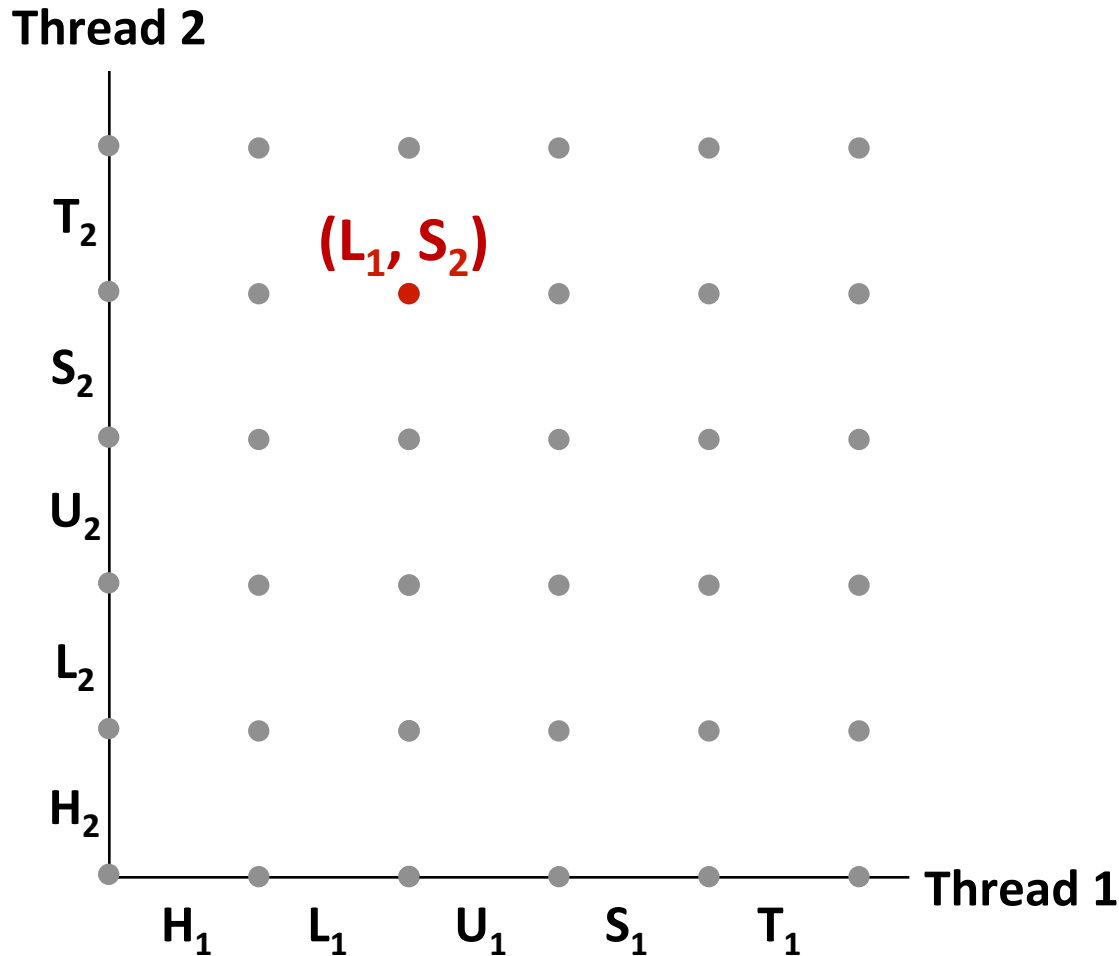
- How about this ordering?

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.

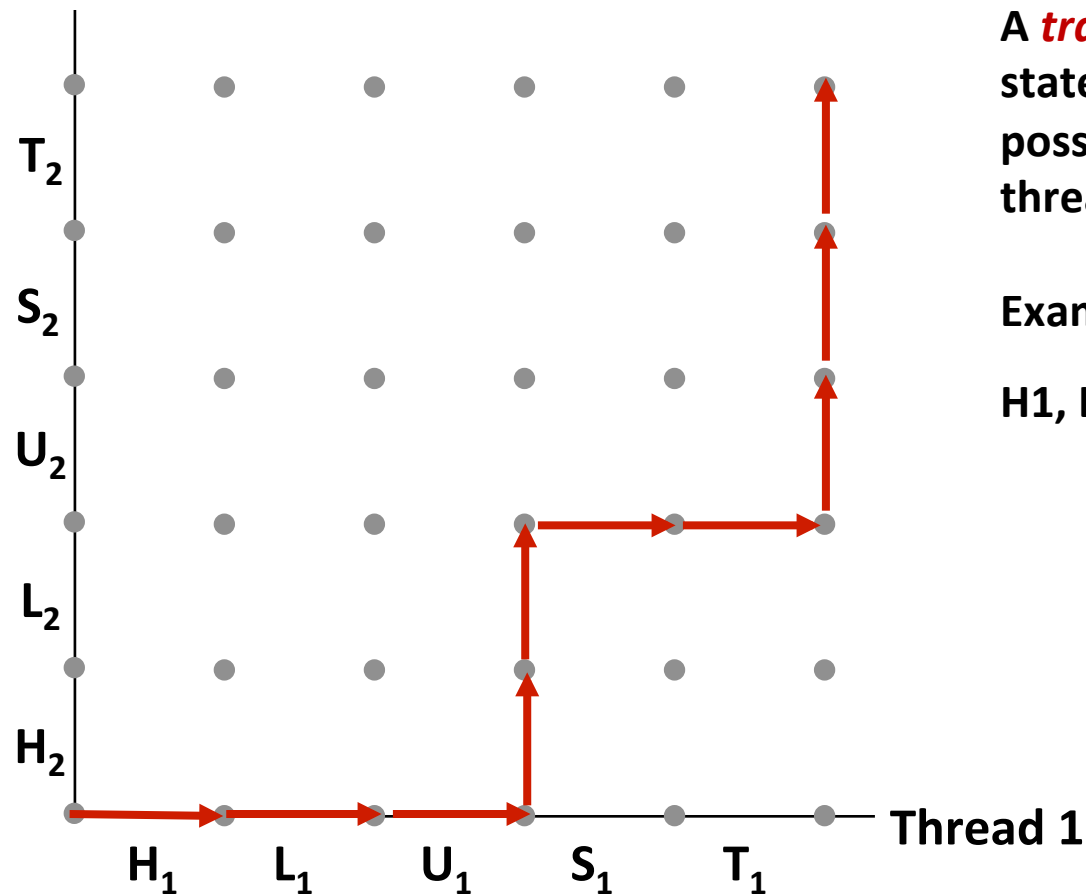
Each axis corresponds to the sequential order of instructions in a thread.

Each point corresponds to a possible *execution state* (Inst₁, Inst₂).

E.g., (L_1, S_2) denotes state where thread 1 has completed L₁ and thread 2 has completed S₂.

Trajectories in Progress Graphs

Thread 2

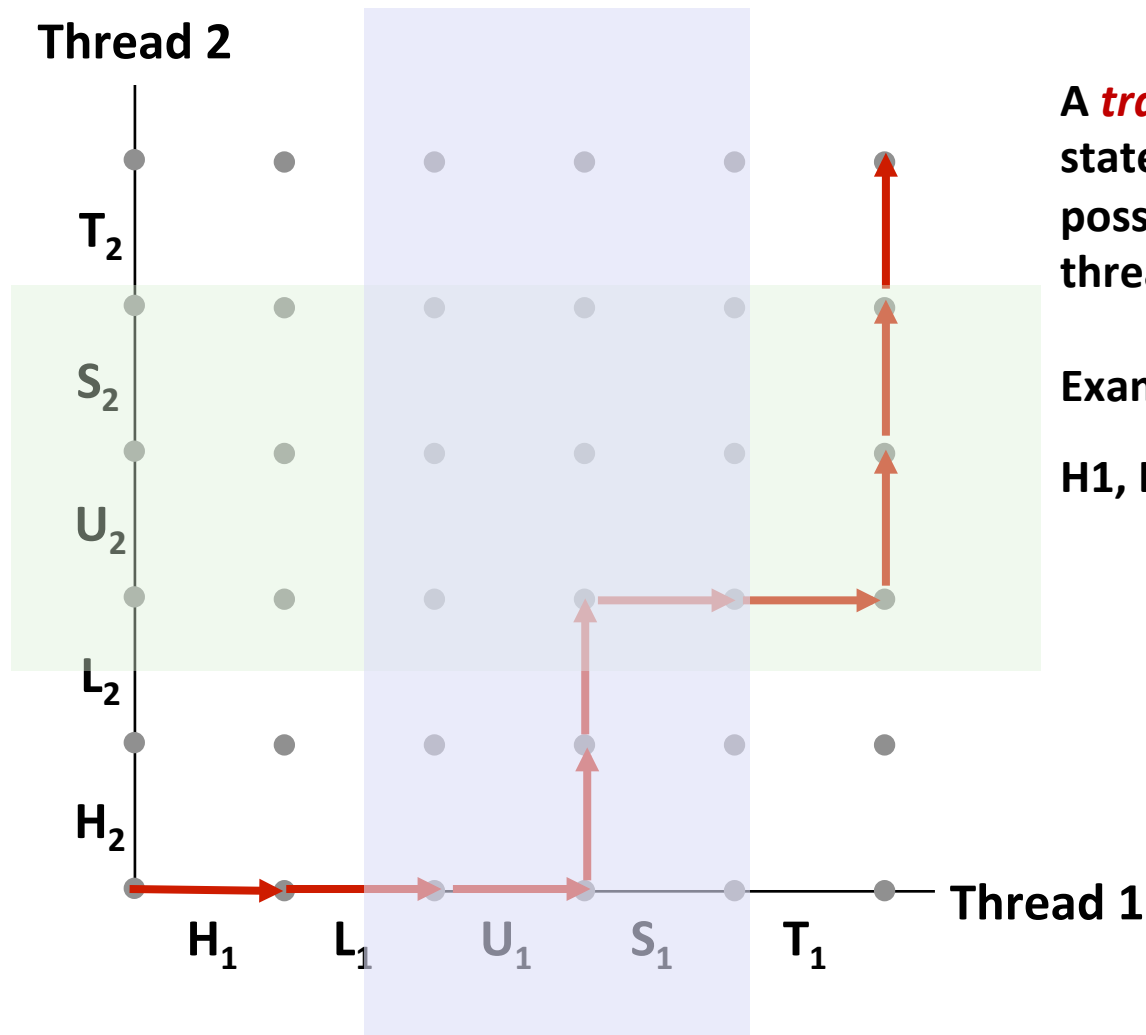


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Trajectories in Progress Graphs

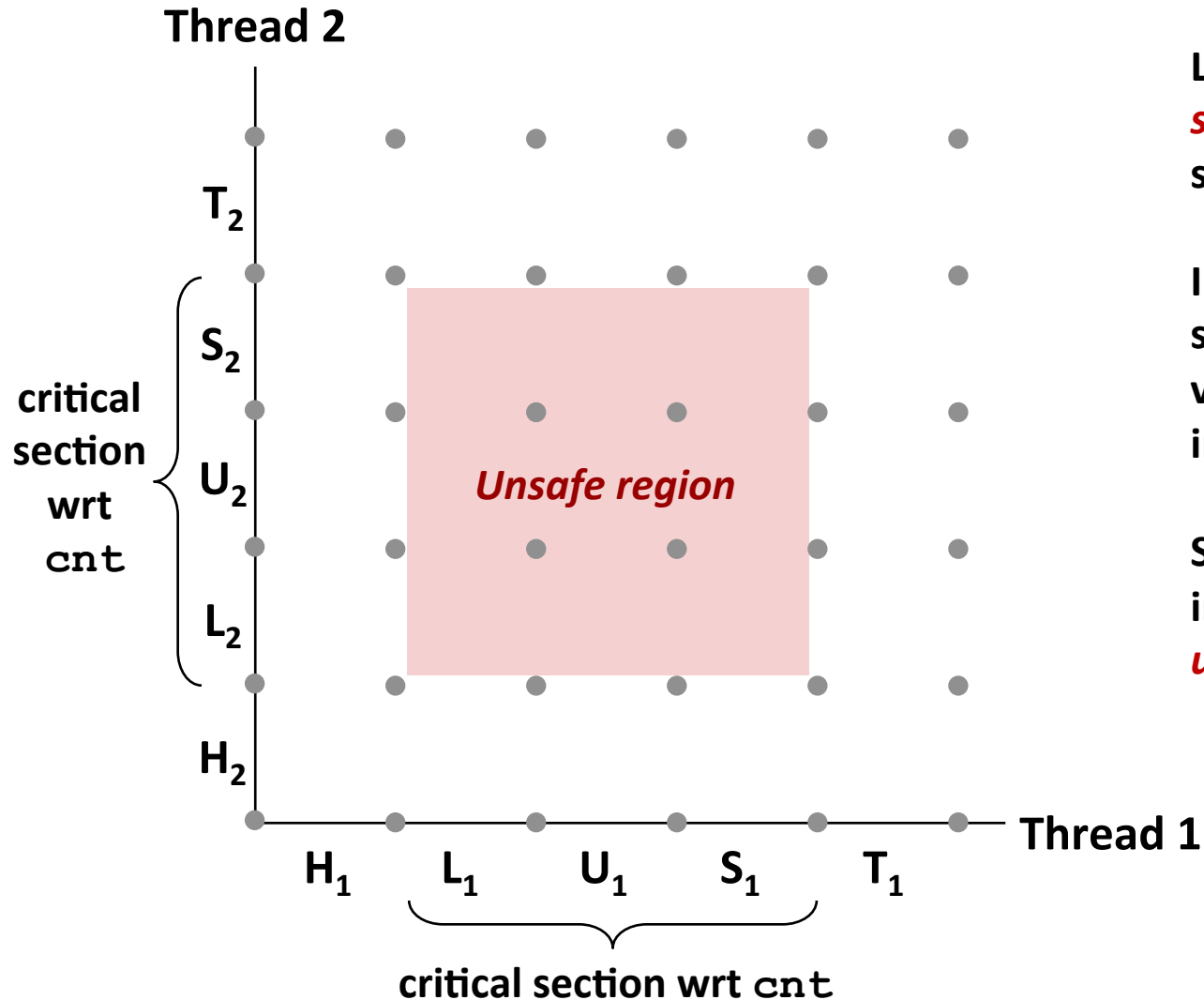


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

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

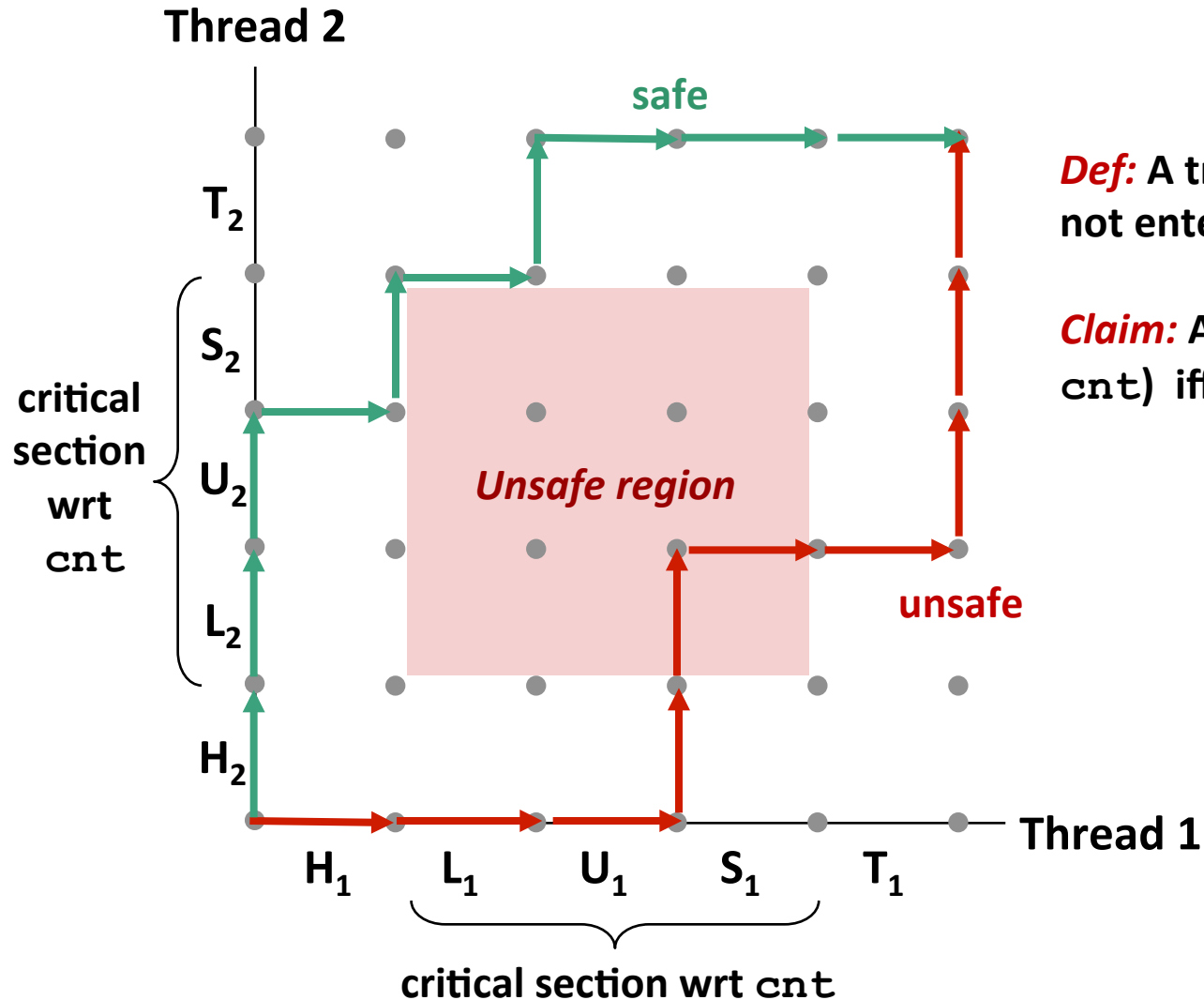


L , U , and S form a **critical section** with respect to the shared variable `cnt`

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

badcnt.c: Improper Synchronization

```

/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    Pthread_create(&tid1, NULL,
                  thread, &niters);
    Pthread_create(&tid2, NULL,
                  thread, &niters);
    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    /* Check result */
    if (cnt != (2 * niters))
        printf("BOOM! cnt=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}

```

badcnt.c

```

/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
        *((long *)vargp);

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

    return NULL;
}

```

Variable	main	thread1	thread2
cnt	yes*	yes	yes
niters.m	yes	no	no
tid1.m	yes	no	no
i.1	no	yes	no
i.2	no	no	yes
niters.1	no	yes	no
niters.2	no	no	yes

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.
 - i.e., need to guarantee *mutually exclusive access* for each critical section.
- **Classic solution:**
 - Semaphores (Edsger Dijkstra)
- **Other approaches (out of our scope)**
 - Mutex and condition variables (Pthreads)
 - Monitors (Java)

Semaphores

- ***Semaphore***: non-negative global integer synchronization variable. Manipulated by *P* and *V* operations.
- ***P(s)***
 - If *s* is nonzero, then decrement *s* by 1 and return immediately.
 - Test and decrement operations occur atomically (indivisibly)
 - If *s* is zero, then suspend thread until *s* becomes nonzero and the thread is restarted by a *V* operation.
 - After restarting, the *P* operation decrements *s* and returns control to the caller.
- ***V(s)***:
 - Increment *s* by 1.
 - Increment operation occurs atomically
 - If there are any threads blocked in a *P* operation waiting for *s* to become non-zero, then restart exactly one of those threads, which then completes its *P* operation by decrementing *s*.
- **Semaphore invariant: $(s \geq 0)$**

Semaphores

- ***Semaphore***: non-negative global integer synchronization variable
- **Manipulated by P and V operations:**
 - $P(s)$: [`while (s == 0) wait(); s--;`]
 - Dutch for "Proberen" (test)
 - $V(s)$: [`s++;`]
 - Dutch for "Verhogen" (increment)
- **OS kernel guarantees that operations between brackets [] are executed indivisibly**
 - Only one P or V operation at a time can modify s .
 - When `while` loop in P terminates, only that P can decrement s
- **Semaphore invariant: $(s \geq 0)$**

C Semaphore Operations

Pthreads functions:

```
#include <semaphore.h>

int sem_init(sem_t *s, 0, unsigned int val);} /* s = val */

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

CS:APP wrapper functions:

```
#include "csapp.h"

void P(sem_t *s); /* Wrapper function for sem_wait */
void V(sem_t *s); /* Wrapper function for sem_post */
```

badcnt.c: Improper Synchronization

```

/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    Pthread_create(&tid1, NULL,
                  thread, &niters);
    Pthread_create(&tid2, NULL,
                  thread, &niters);
    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    /* Check result */
    if (cnt != (2 * niters))
        printf("BOOM! cnt=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}

```

badcnt.c

```

/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
        *((long *)vargp);

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

    return NULL;
}

```

How can we fix this using semaphores?

Using Semaphores for Mutual Exclusion

■ Basic idea:

- Associate a unique semaphore *mutex*, initially 1, with each shared variable (or related set of shared variables).
- Surround corresponding critical sections with $P(mutex)$ and $V(mutex)$ operations.

■ Terminology:

- *Binary semaphore*: semaphore whose value is always 0 or 1
- *Mutex*: binary semaphore used for mutual exclusion
 - P operation: “locking” the mutex
 - V operation: “unlocking” or “releasing” the mutex
 - “*Holding*” a mutex: locked and not yet unlocked.
- *Counting semaphore*: used as a counter for set of available resources.

goodcnt.c: Proper Synchronization

- Define and initialize a mutex for the shared variable `cnt`:

```
volatile long cnt = 0; /* Counter */
sem_t mutex;          /* Semaphore that protects cnt */

sem_init(&mutex, 0, 1); /* mutex = 1 */
```

- Surround critical section with *P* and *V*:

```
for (i = 0; i < niters; i++) {
    P(&mutex);
    cnt++;
    V(&mutex);
}
goodcnt.c
```

```
linux> ./goodcnt 10000
OK cnt=20000
linux> ./goodcnt 10000
OK cnt=20000
linux>
```

Warning: It's orders of magnitude slower than `badcnt.c`.

goodcnt.c: Proper Synchronization

- Define and initialize a mutex for the shared variable cnt:

```
volatile long cnt = 0; /* Counter */
sem_t mutex;          /* Semaphore that protects cnt */

sem_init(&mutex, 0, 1); /* mutex = 1 */
```

Surround critical section with Deadlock

	OK cnt=2000000	BOOM! cnt=1036525	Slowdown
real	0m0.138s	0m0.007s	20X
user	0m0.120s	0m0.008s	15X
sys	0m0.108s	0m0.000s	NaN

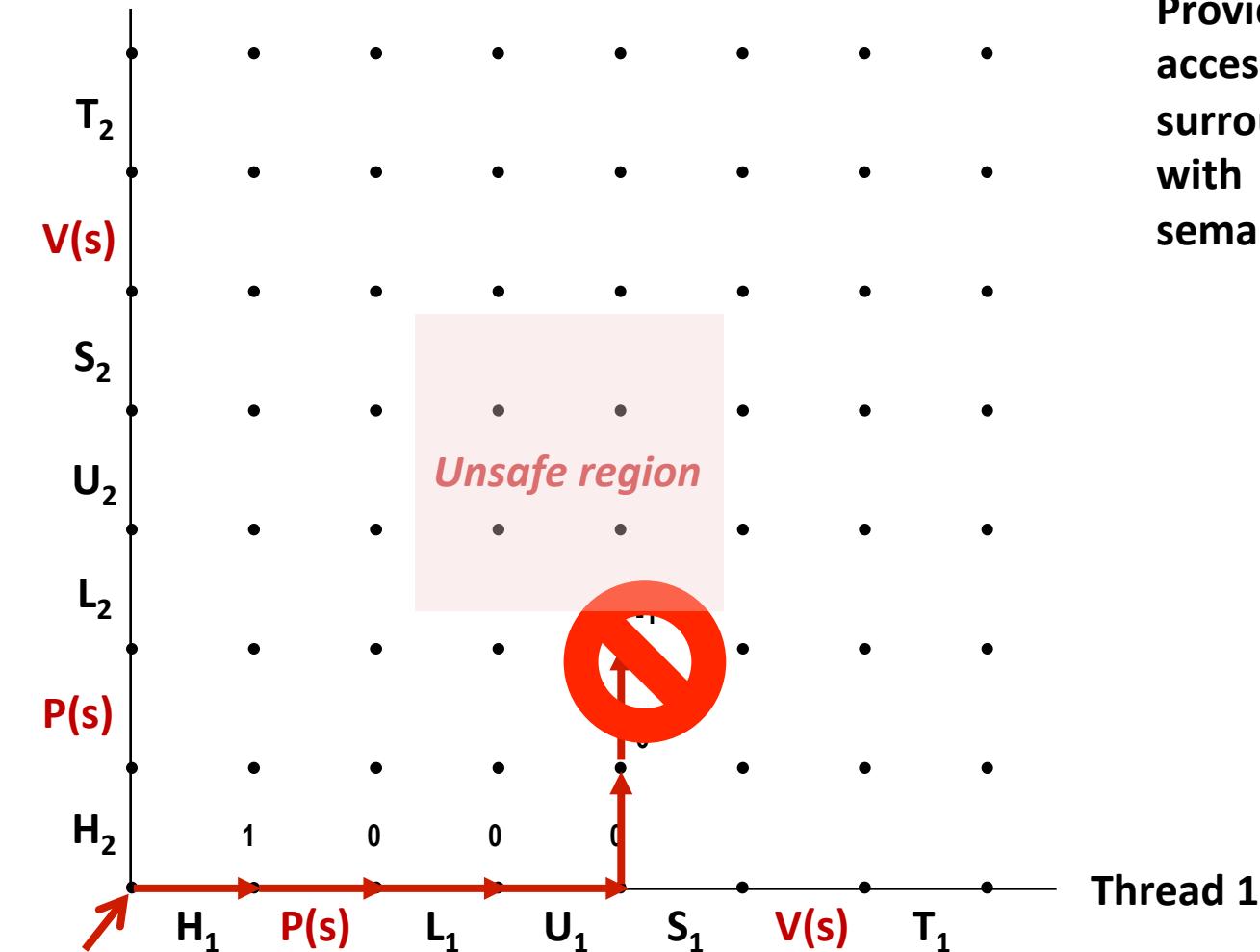
And slower means much slower!

ver

Why Mutexes Work

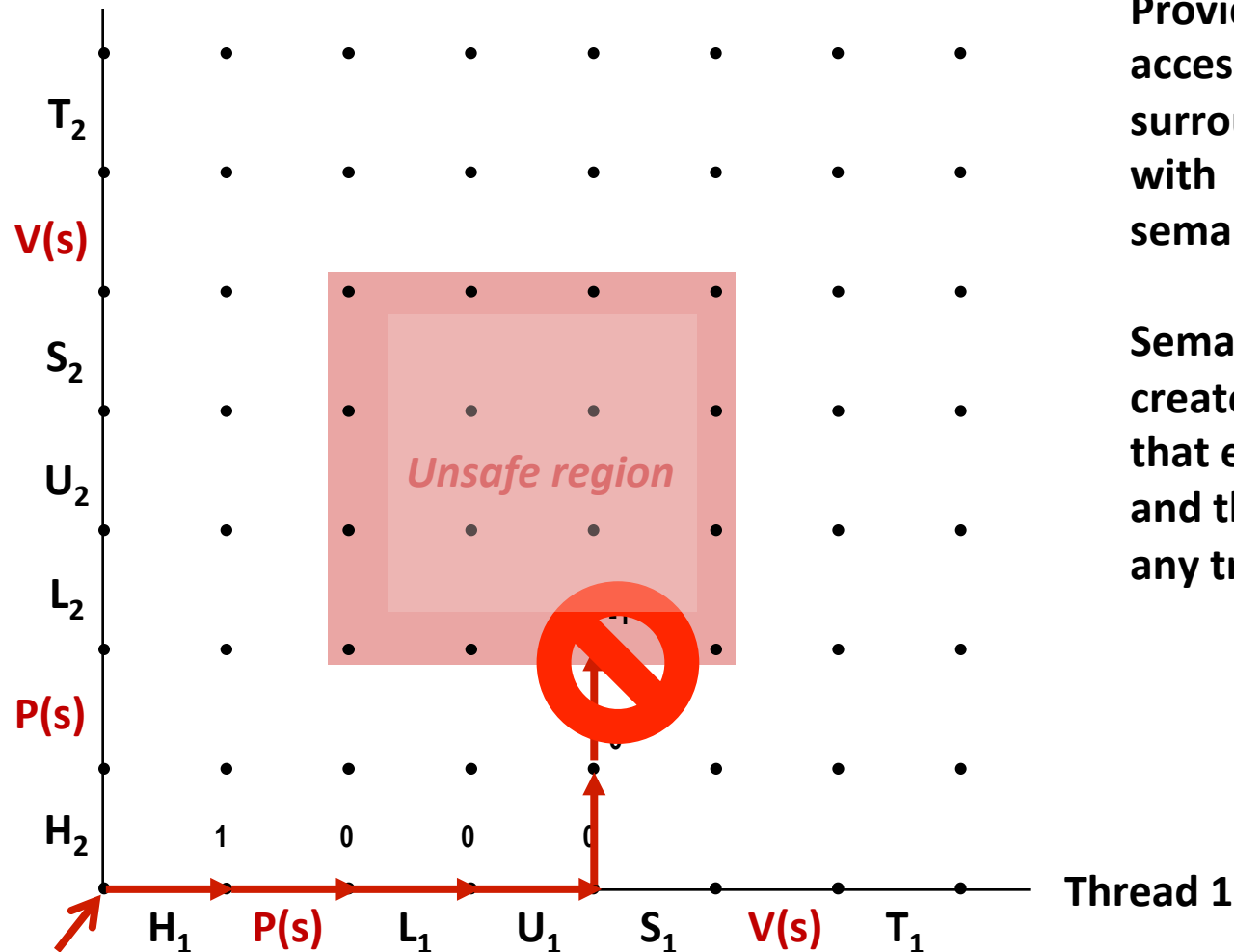
Thread 2

Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore s (initially set to 1)



Why Mutexes Work

Thread 2



Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore s (initially set to 1)

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

Initially

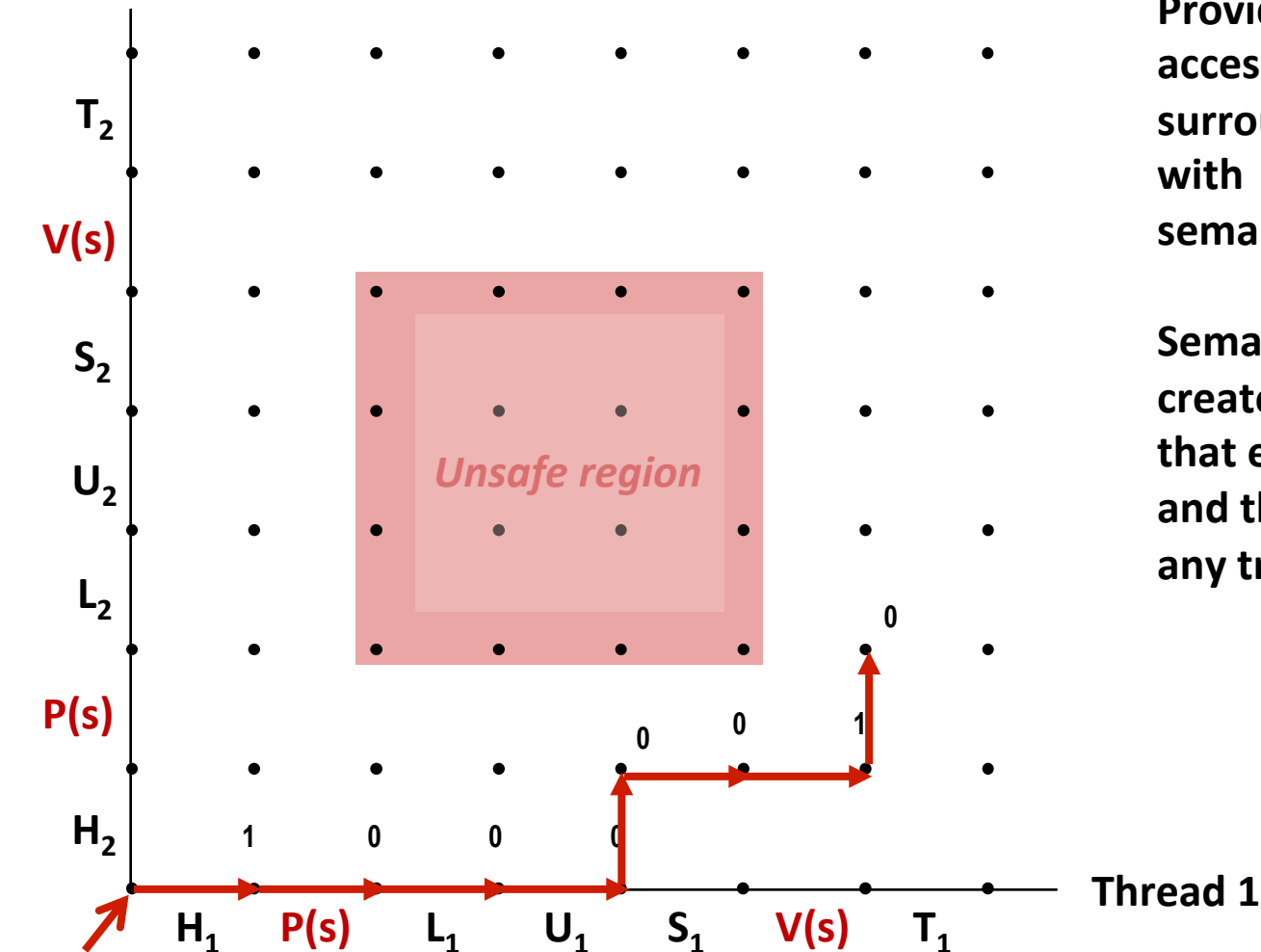
$s = 1$

Why Mutexes Work

Thread 2

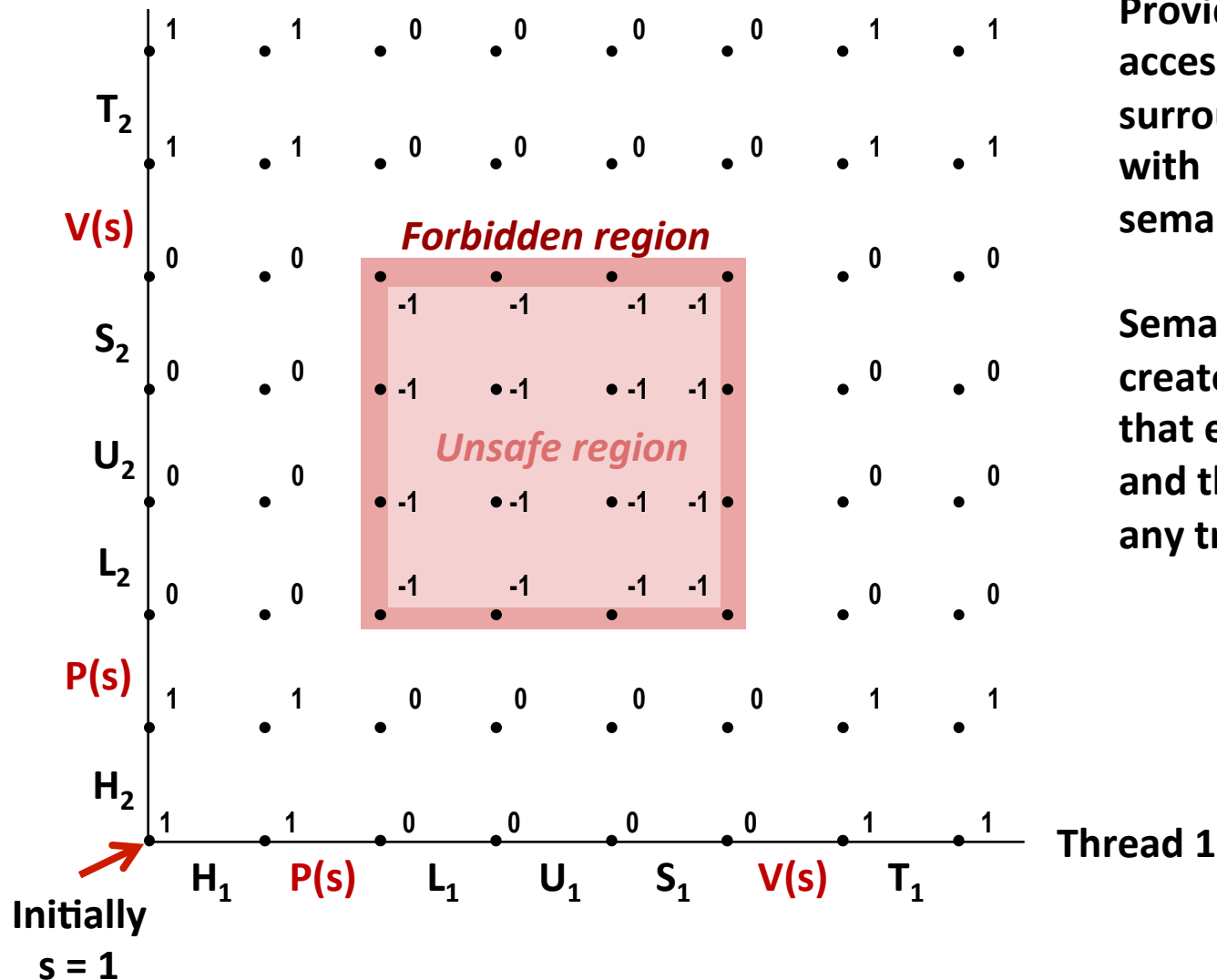
Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore s (initially set to 1)

Semaphore 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 P and V operations on semaphore s (initially set to 1)

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

Summary

- **Programmers need a clear model of how variables are shared by threads.**
- **Variables shared by multiple threads must be protected to ensure mutually exclusive access.**
- **Semaphores are a fundamental mechanism for enforcing mutual exclusion.**