

Concurrent Programming

Computer Systems

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Based on slides by:

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Concurrent Programming is Hard!

- The human mind tends to be sequential
- The notion of time is often misleading
- Thinking about all possible sequences of events in a computer system is at least error prone and frequently impossible

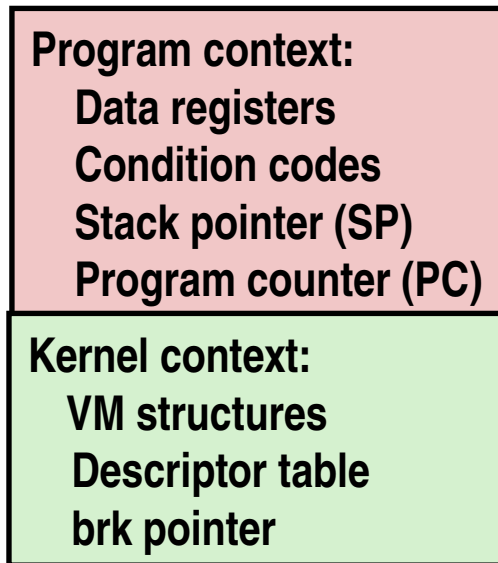
Concurrent Programming is Hard!

- **Classical problem classes of concurrent programs:**
 - ***Races***: outcome depends on arbitrary scheduling decisions elsewhere in the system
 - Example: who gets the last seat on the airplane?
 - ***Deadlock***: improper resource allocation prevents forward progress
 - Example: traffic gridlock
 - ***Livelock / Starvation / Fairness***: external events and/or system scheduling decisions can prevent sub-task progress
 - Example: people always jump in front of you in line
- **Many aspects of concurrent programming are beyond the scope of our course..**
 - but, not all 🏖️
 - We'll cover some of these aspects in the next few lectures.

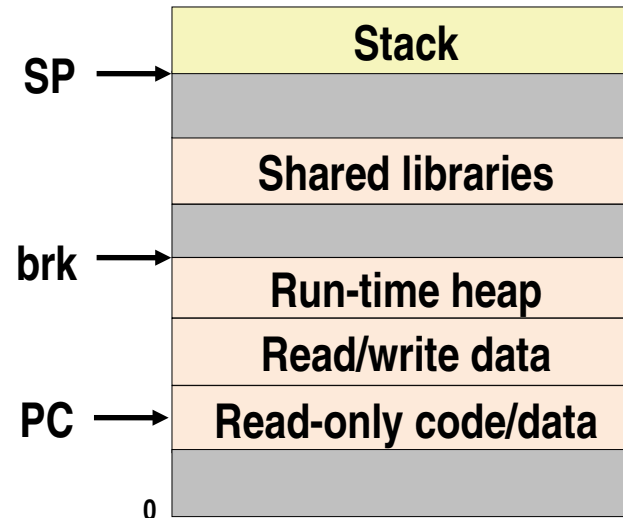
Traditional View of a Process

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

Process context



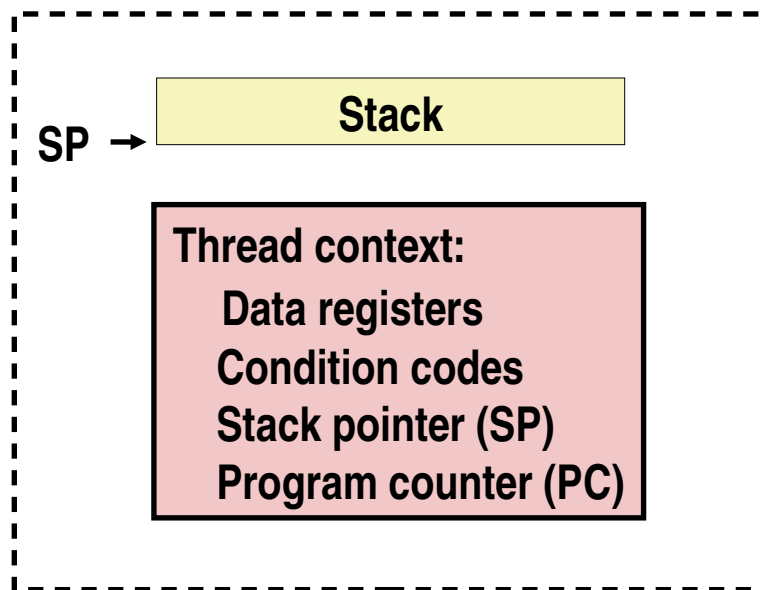
Code, data, and stack



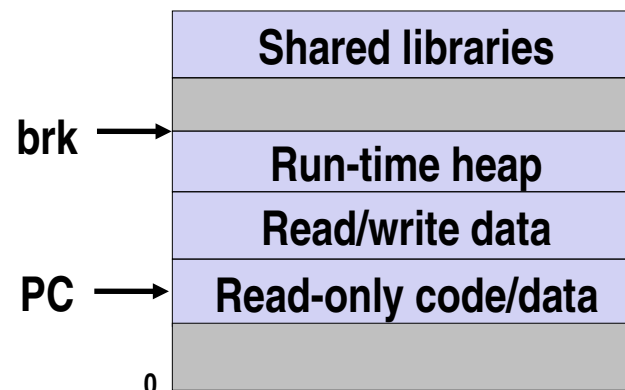
Alternate View of a Process

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

Thread (main thread)



Code, data, and kernel context



Kernel context:

- VM structures
- Descriptor table
- brk pointer

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)

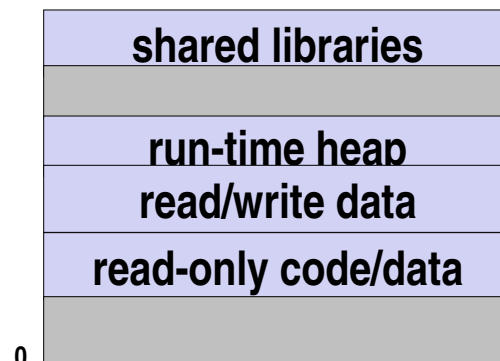
Shared code and data

stack 1

stack 2

Thread 1 context:
 Data registers
 Condition codes
 SP1
 PC1

Thread 2 context:
 Data registers
 Condition codes
 SP2
 PC2

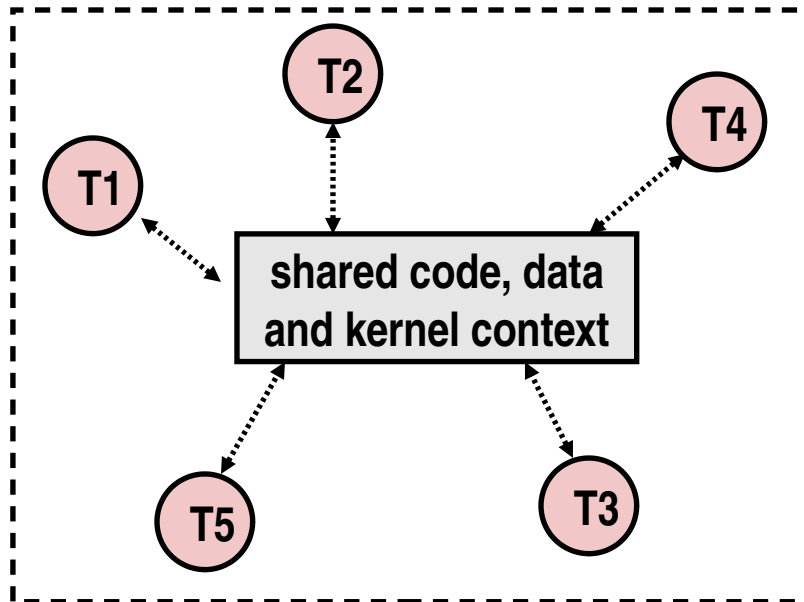


Kernel context:
 VM structures
 Descriptor table
 brk pointer

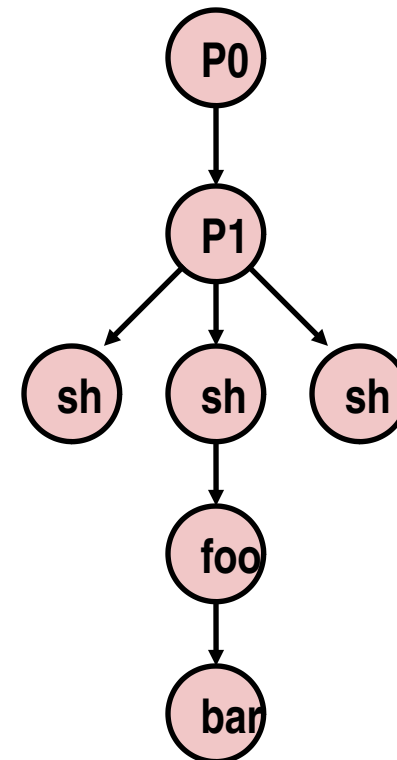
Logical View of Threads

- Threads associated with process form a pool of peers
 - Unlike processes which form a tree hierarchy

Threads associated with process foo



Process hierarchy



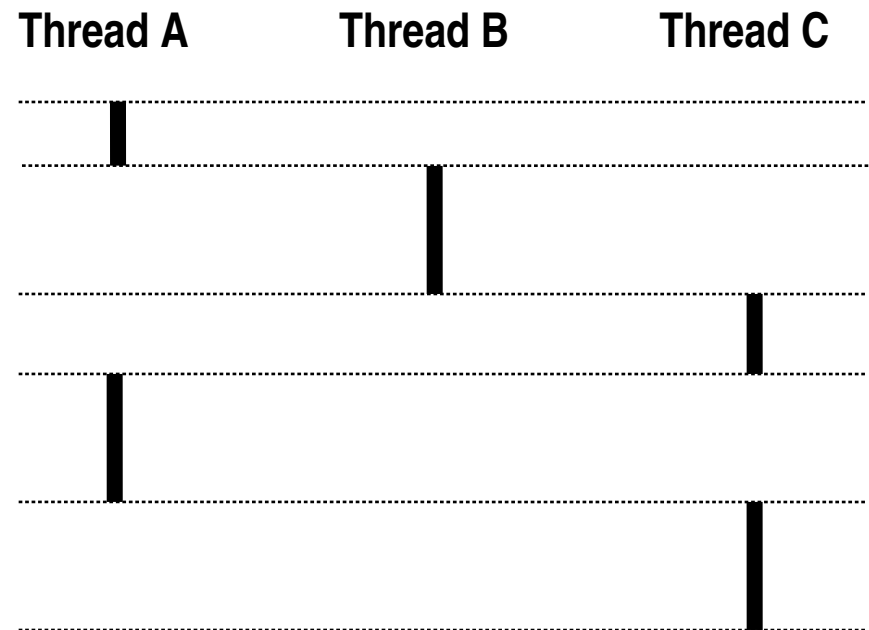
Concurrent Threads

- Two threads are *concurrent* if their flows overlap in time
- Otherwise, they are sequential

- **Examples:**

- Concurrent: A & B, A&C
- Sequential: B & C

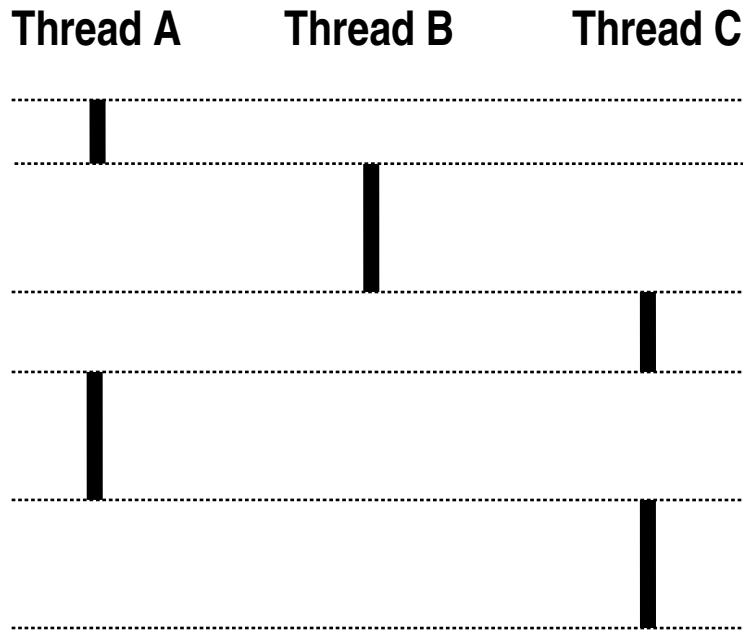
Time



Concurrent Thread Execution

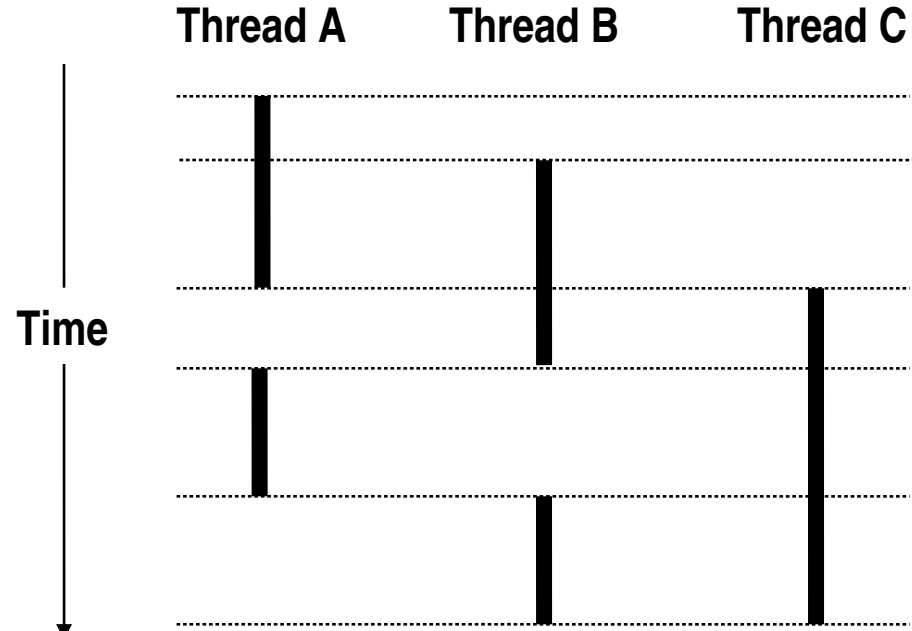
■ Single Core Processor

- Simulate parallelism by time slicing



■ Multi-Core Processor

- Can have true parallelism



Run 3 threads on 2 cores

Threads vs. Processes

■ How threads and processes are similar

- Each has its own logical control flow
- Each can run concurrently with others (possibly on different cores)
- Each is context switched

■ How threads and processes are different

- Threads share all code and data (except local stacks)
 - Processes (typically) do not
- Threads are somewhat less expensive than processes
 - Process control (creating and reaping) twice as expensive as thread control
 - Linux numbers:
 - ~20K cycles to create and reap a process
 - ~10K cycles (or less) to create and reap a thread
 - *Much* larger difference on non-Unices.

Posix Threads (Pthreads) Interface

- ***Pthreads***: Standard interface for ~60 functions that manipulate threads from C programs
 - Creating and reaping threads
 - `pthread_create()`
 - `pthread_join()`
 - Determining your thread ID
 - `pthread_self()`
 - Terminating threads
 - `pthread_cancel()`
 - `pthread_exit()` [terminates current thread]
 - `exit()` [terminates all threads]
 - Synchronizing access to shared variables
 - `pthread_mutex_init`
 - `pthread_mutex_[un]lock`

The Pthreads "hello, world" Program

```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"
void *thread(void *vargp);

int main()
{
    pthread_t tid;
    Pthread_create(&tid, NULL, thread, NULL);
    Pthread_join(tid, NULL);
    exit(0);
}
```

Thread ID

Thread attributes
(usually NULL)

Thread routine

Thread arguments
(void *p)

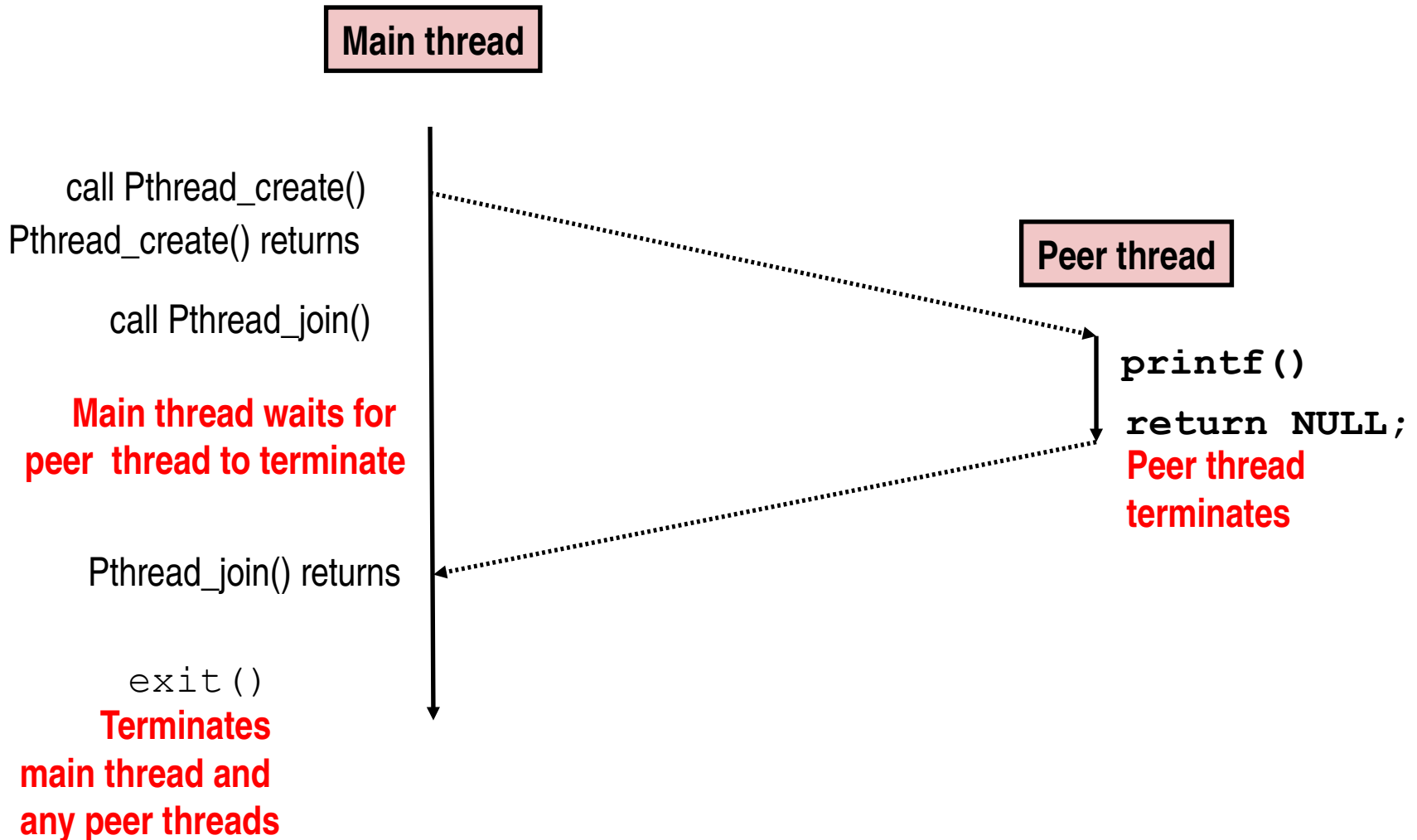
hello.c

```
void *thread(void *vargp) /* thread routine */
{
    printf("Hello, world!\n");
    return NULL;
}
```

Return value
(void **p)

hello.c

Execution of Threaded “hello, world”



Pros and Cons of Thread-Based Designs

- **+ Easy to share data structures between threads**
 - e.g., logging information, file cache
- **+ Threads are more efficient than processes**
 - ...take with a grain of salt.
- **– Unintentional sharing can introduce subtle and hard-to-reproduce errors!**
 - The ease with which data can be shared is both the greatest strength and the greatest weakness of threads
 - Hard to know which data shared & which private
 - Hard to detect by testing
 - Probability of bad race outcome very low
 - But nonzero!

Shared Variables in Threaded C Programs

- Question: Which variables in a threaded C program are shared among threads?
 - 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()
```

```
{
```

```
    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.**

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;
}

```

```

$ ./badcnt 10000
OK cnt=20000
$ ./badcnt 10000
BOOM! cnt=13051
$

```

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



Thread 1
critical section



Thread 2
critical section

OK

Concurrent Execution (cont)

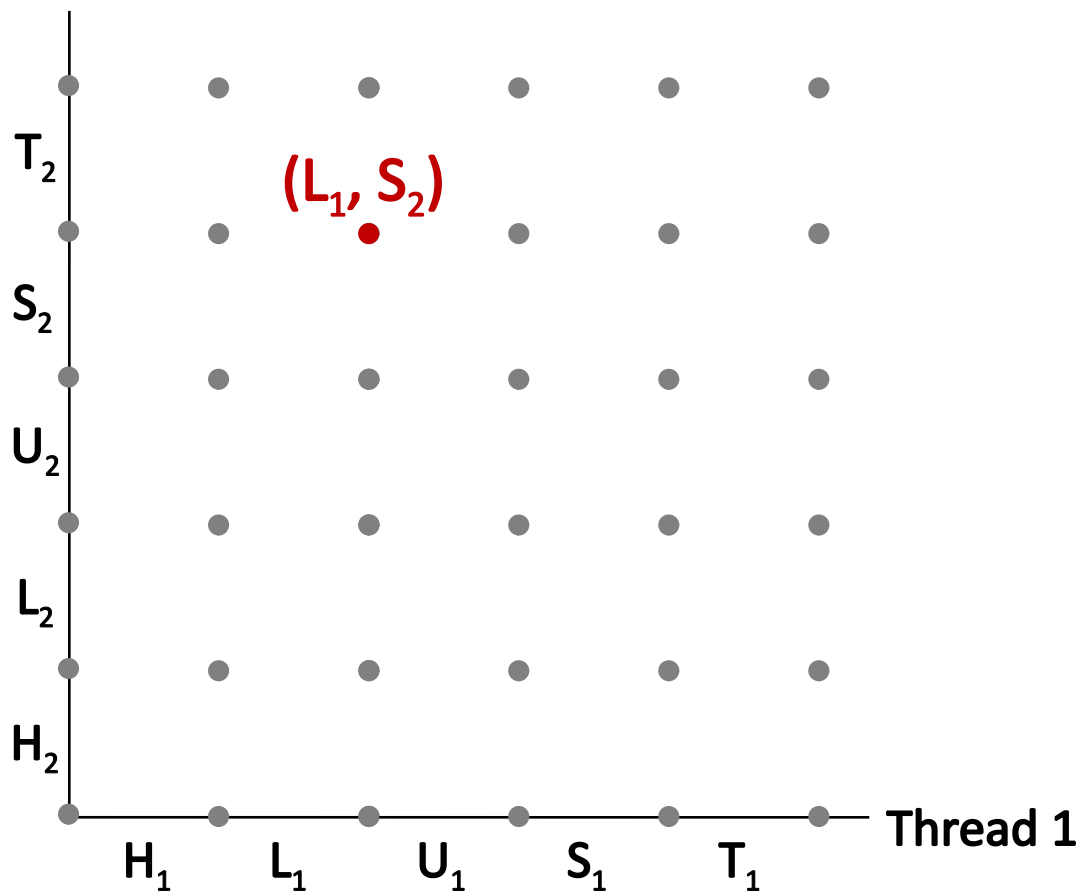
- Incorrect ordering: two threads increment the counter, but the result is 1 instead of 2

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!

Progress Graphs

Thread 2



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

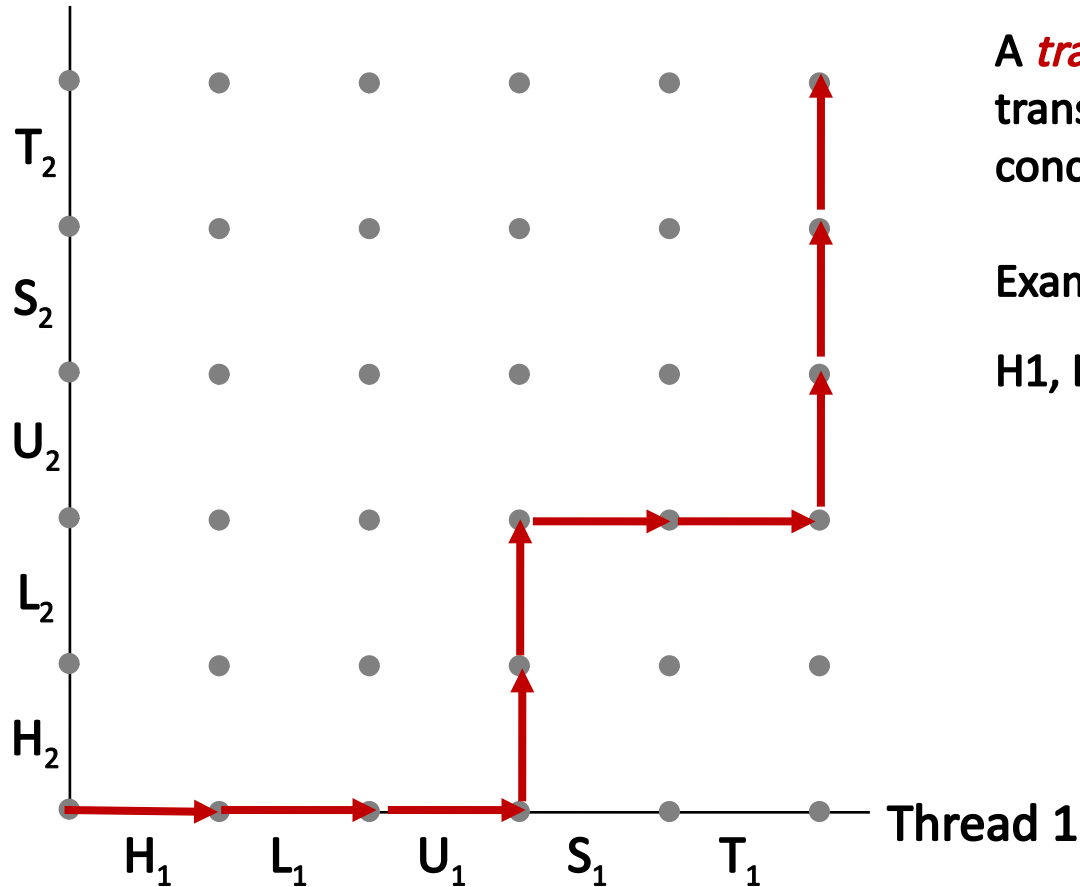
Each axis corresponds to the sequential order of instructions in a thread.

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

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

Thread 2



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

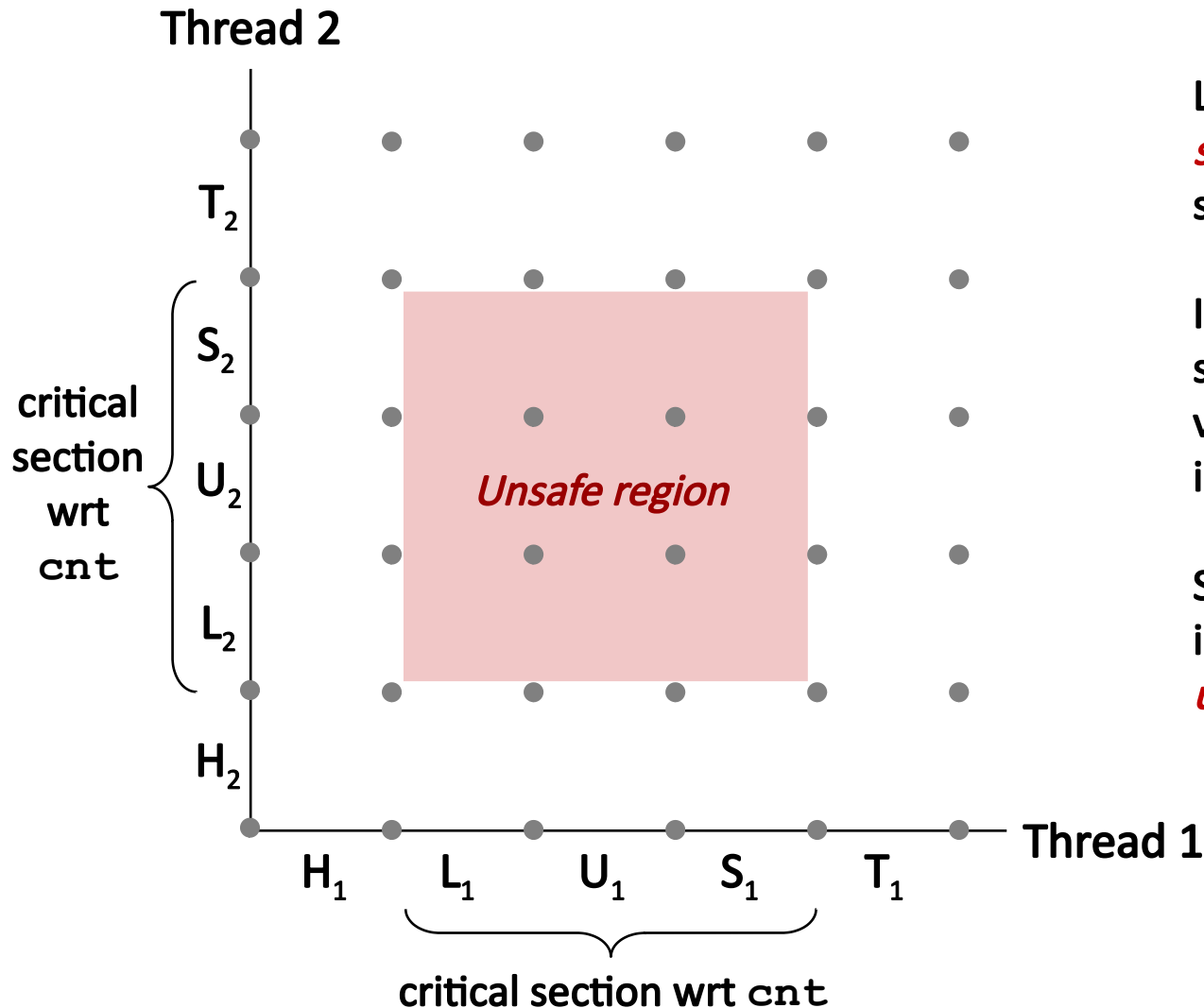
Example:

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

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**
 - Mutexes and condition variables from Pthreads
 - Monitors (Java) (boring languages are outside our scope)

Critical Sections and Unsafe Regions

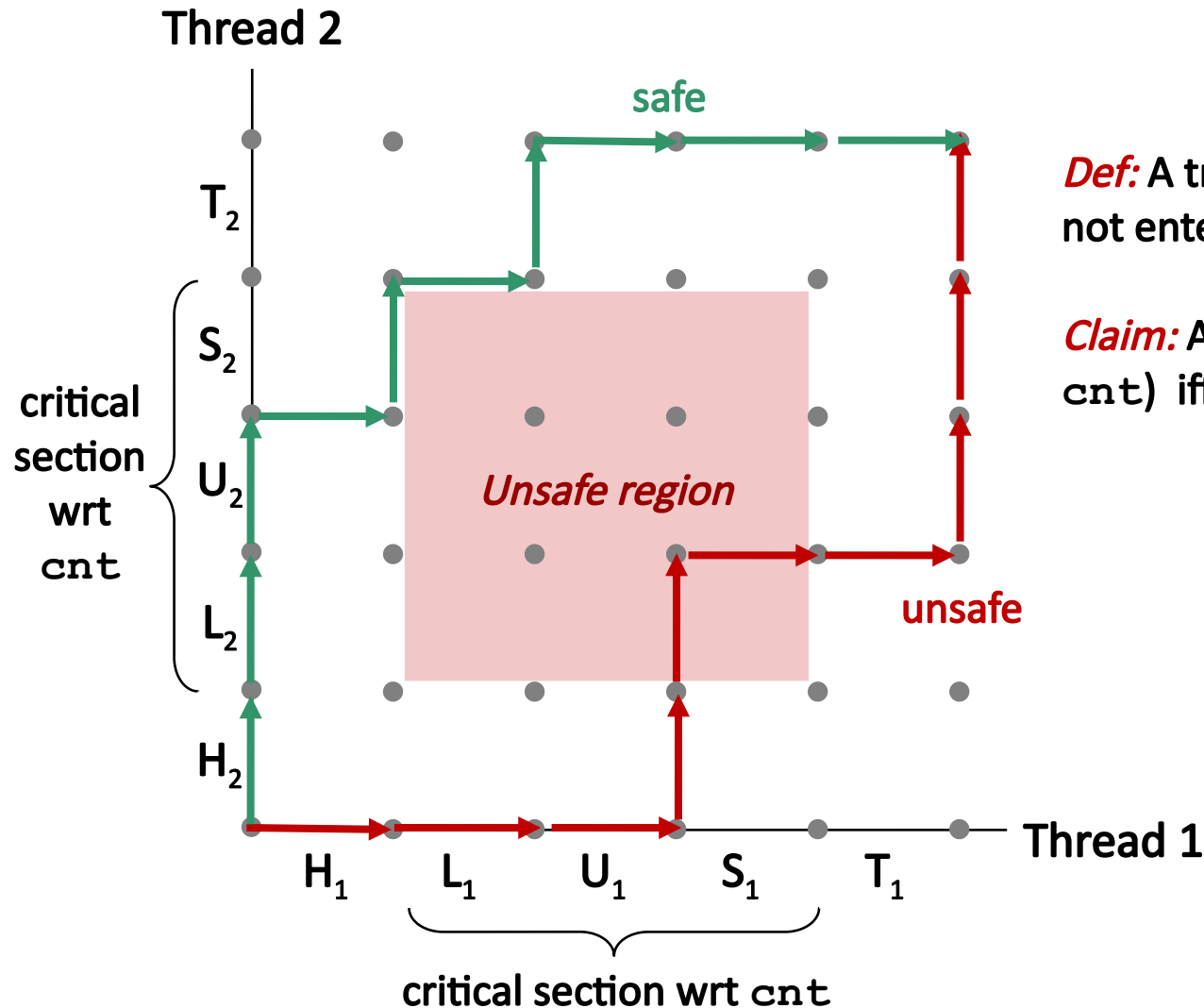


L , U , and S form a **critical section** with respect to the shared variable `cnt`

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

Semaphores

- ***Semaphore***: non-negative global integer synchronization variable. Manipulated by *P (passering)* and *V (vrijgave)* 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: ($s \geq 0$)**

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;
}

```

```

$ ./badcnt 10000
OK cnt=20000
$ ./badcnt 10000
BOOM! cnt=13051
$

```

cnt should equal 20,000.

What went wrong?

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);
}
```

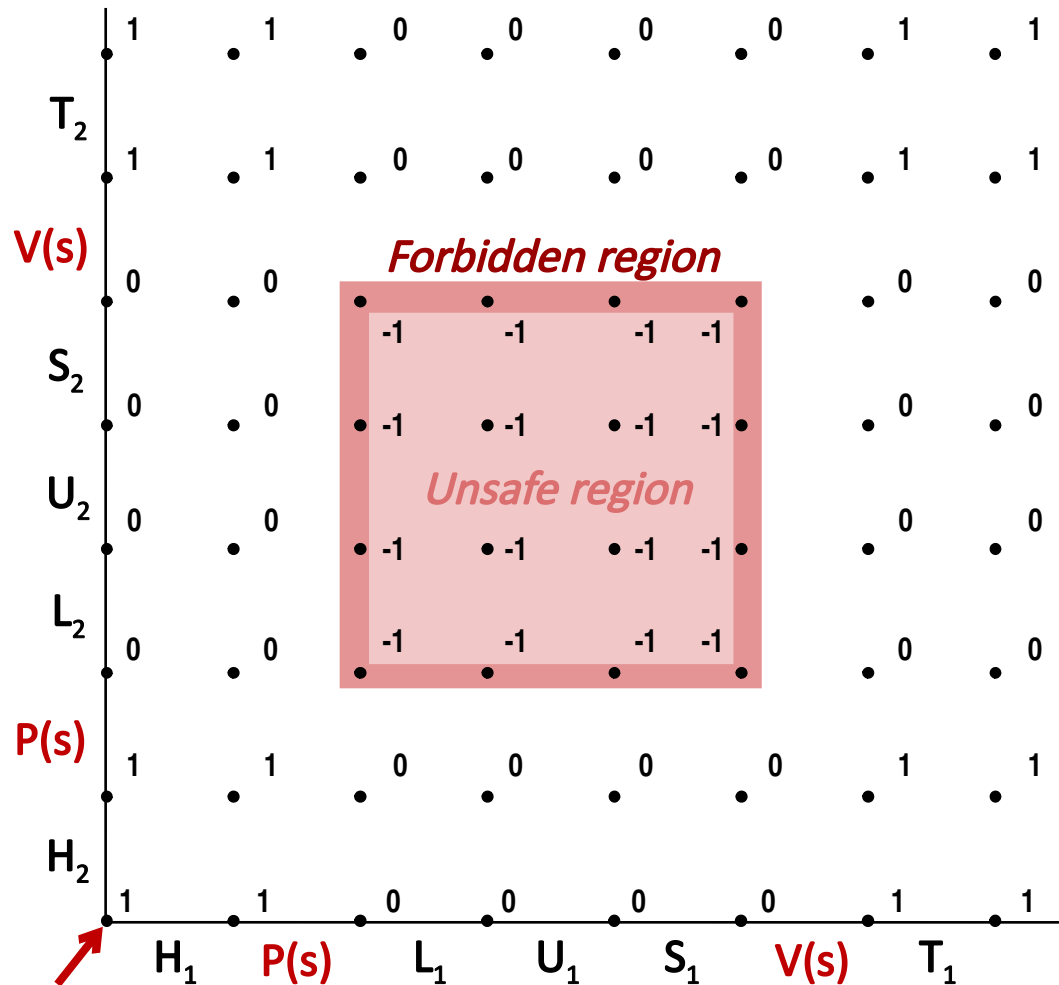
goodcnt.c

```
$ ./goodcnt 10000
OK cnt=20000
$ ./goodcnt 10000
OK cnt=20000
$
```

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

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
 $s = 1$

Thread 1

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.**