

Synchronization: Basics

15-213/18-243: Introduction to Computer Systems
25th Lecture, Apr. 19, 2011

Instructors:

Gregory Kesden and Anthony Rowe

Exam

- **Closed book and notes**
- **Processes and Signals (Chapter 8)**
 - Fork / Exec / Sig Handlers
- **System I/O (Chapter 10)**
 - Files
- **Virtual Memory (Chapter 9)**
 - Address Translation
 - Multi-Level Page Tables
- **Dynamic Memory (Chapter 9)**
- **Linking (Chapter 7)**
 - Symbols
 - ELF Components

Today

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

Process: Traditional View

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

Process context

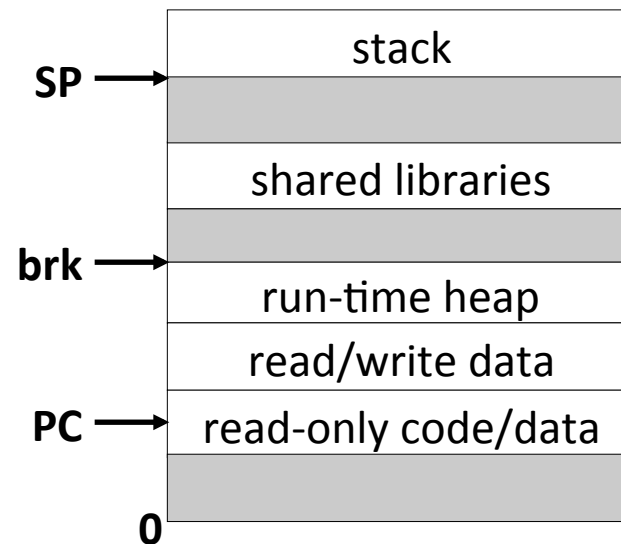
Program context:

Data registers
Condition codes
Stack pointer (SP)
Program counter (PC)

Kernel context:

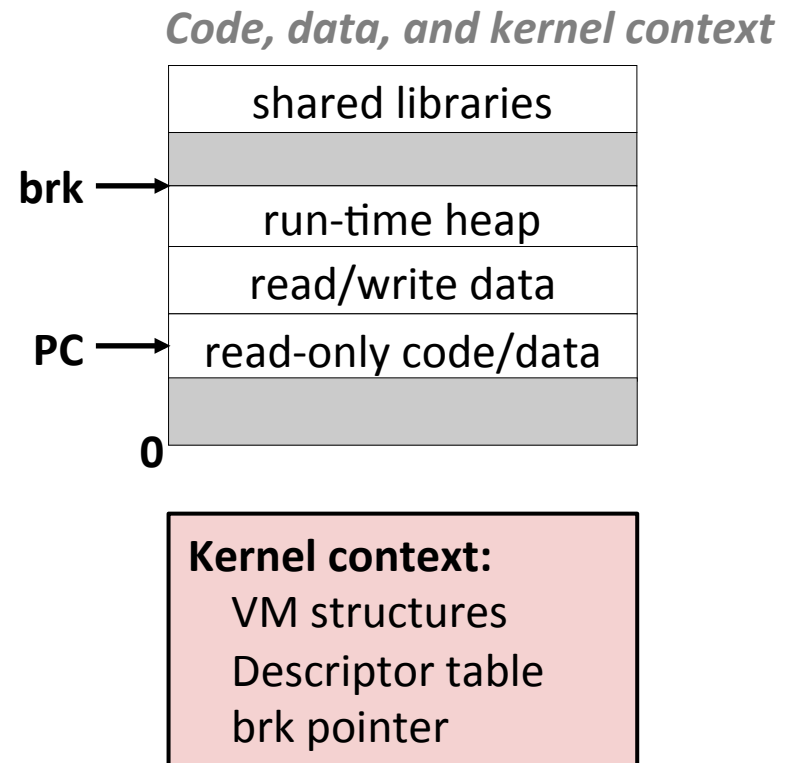
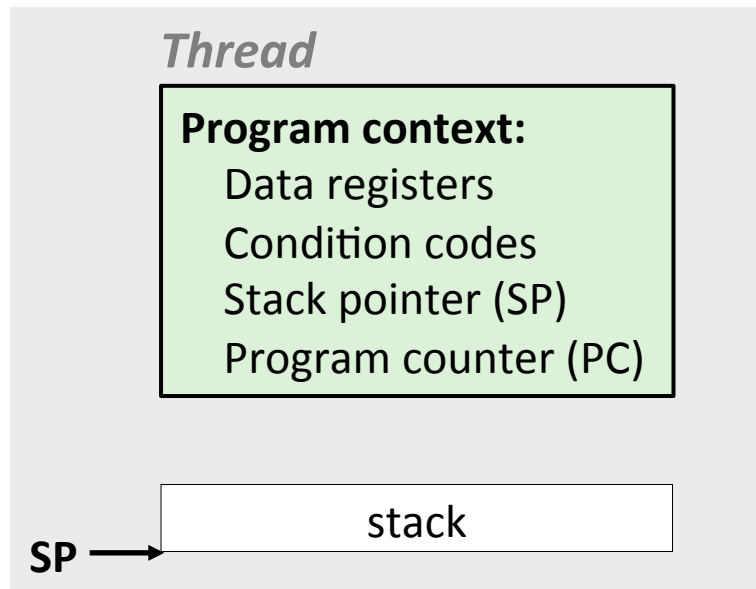
VM structures
Descriptor table
brk pointer

Code, data, and stack



Process: Alternative View

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



Process with Two Threads

Thread 1

Program context:

Data registers
Condition codes
Stack pointer (SP)
Program counter (PC)



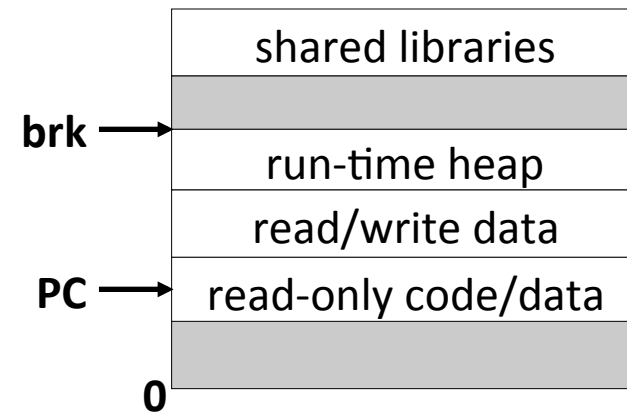
Thread 2

Program context:

Data registers
Condition codes
Stack pointer (SP)
Program counter (PC)



Code, data, and kernel context



Kernel context:

VM structures
Descriptor table
brk pointer

Threads vs. Processes

■ Threads and processes: similarities

- Each has its own logical control flow
- Each can run concurrently with others
- Each is context switched (scheduled) by the kernel

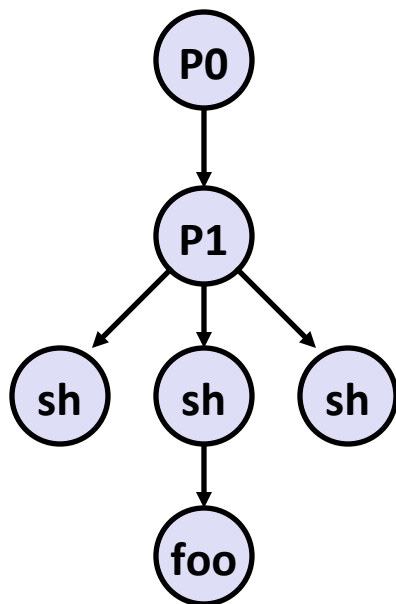
■ Threads and processes: differences

- Threads share code and data, processes (typically) do not
- Threads are less expensive than processes
 - Process control (creating and reaping) is more expensive as thread control
 - Context switches for processes more expensive than for threads

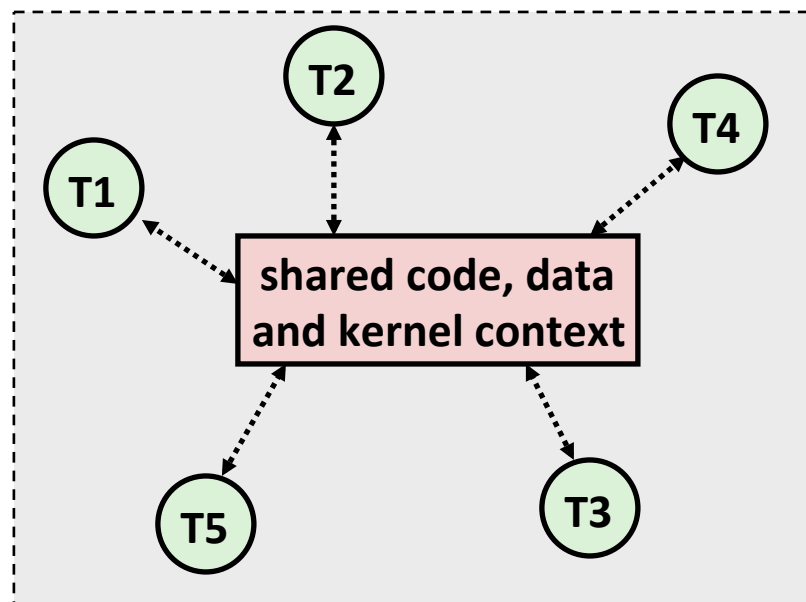
Threads vs. Processes (cont.)

- Processes form a tree hierarchy
- Threads form a pool of peers
 - Each thread can kill any other
 - Each thread can wait for any other thread to terminate
 - Main thread: first thread to run in a process

Process hierarchy



Thread pool



Posix Threads (Pthreads) Interface

- ***Pthreads***: Standard interface for ~60 functions that manipulate threads from C programs
 - Threads run thread routines:
 - `void *threadroutine(void *vargp)`
 - Creating and reaping threads
 - `pthread_create(pthread_t *tid, ..., func *f, void *arg)`
 - `pthread_join(pthread_t tid, void **thread_return)`
 - Determining your thread ID
 - `pthread_self()`
 - Terminating threads
 - `pthread_cancel(pthread_t tid)`
 - `pthread_exit(void *thread_return)`
 - `return` (in primary thread routine terminates the thread)
 - `exit` (terminates all threads)

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

*Thread attributes
(usually NULL)*

*Thread arguments
(void *p)*

*assigns return value
(void **p)*

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**
- **– Unintentional sharing can introduce subtle and hard-to-reproduce errors!**

Today

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

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*”

- **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?

- ***Def:* A variable x is *shared* if and only if multiple threads reference some instance of x .**

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

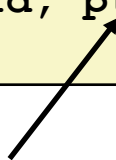
```
char **ptr; /* global */

int main()
{
    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,
            NULL,
            thread,
            (void *)i);
    Pthread_exit(NULL);
}
```

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

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



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 */

int main()
{
    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,
            NULL,
            thread,
            (void *)i);
    Pthread_exit(NULL);
}
```

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

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

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

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

■ 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

Today

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

badcnt.c: Improper Synchronization

```
volatile int cnt = 0; /* global */

int main(int argc, char **argv)
{
    int niters = atoi(argv[1]);
    pthread_t tid1, tid2;

    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=%d\n", cnt);
    else
        printf("OK cnt=%d\n", cnt);
    exit(0);
}
```

```
/* Thread routine */
void *thread(void *vargp)
{
    int i, niters = *((int *)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++;
```

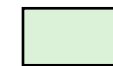
Corresponding assembly code

<pre> movl (%rdi), %ecx movl \$0, %edx cmpl %ecx, %edx jge .L13 ----- .L11: movl cnt(%rip), %eax incl %eax movl %eax, cnt(%rip) ----- incl %edx cmpl %ecx, %edx jl .L11 .L13: </pre>	<div style="display: flex; align-items: center;"> <div style="font-size: 3em; margin-right: 10px;">}</div> <div>Head (H_i)</div> </div> <div style="display: flex; align-items: center; margin-top: 10px;"> <div style="font-size: 3em; margin-right: 10px;">}</div> <div>Load cnt (L_i)</div> </div> <div style="display: flex; align-items: center; margin-top: 10px;"> <div style="font-size: 3em; margin-right: 10px;">}</div> <div>Update cnt (U_i)</div> </div> <div style="display: flex; align-items: center; margin-top: 10px;"> <div style="font-size: 3em; margin-right: 10px;">}</div> <div>Store cnt (S_i)</div> </div> <div style="display: flex; align-items: center; margin-top: 10px;"> <div style="font-size: 3em; margin-right: 10px;">}</div> <div>Tail (T_i)</div> </div>
--	---

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
 - $\%eax_i$ is the content of $\%eax$ in thread i 's context

i (thread)	$instr_i$	$\%eax_1$	$\%eax_2$	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	%eax ₁	%eax 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)

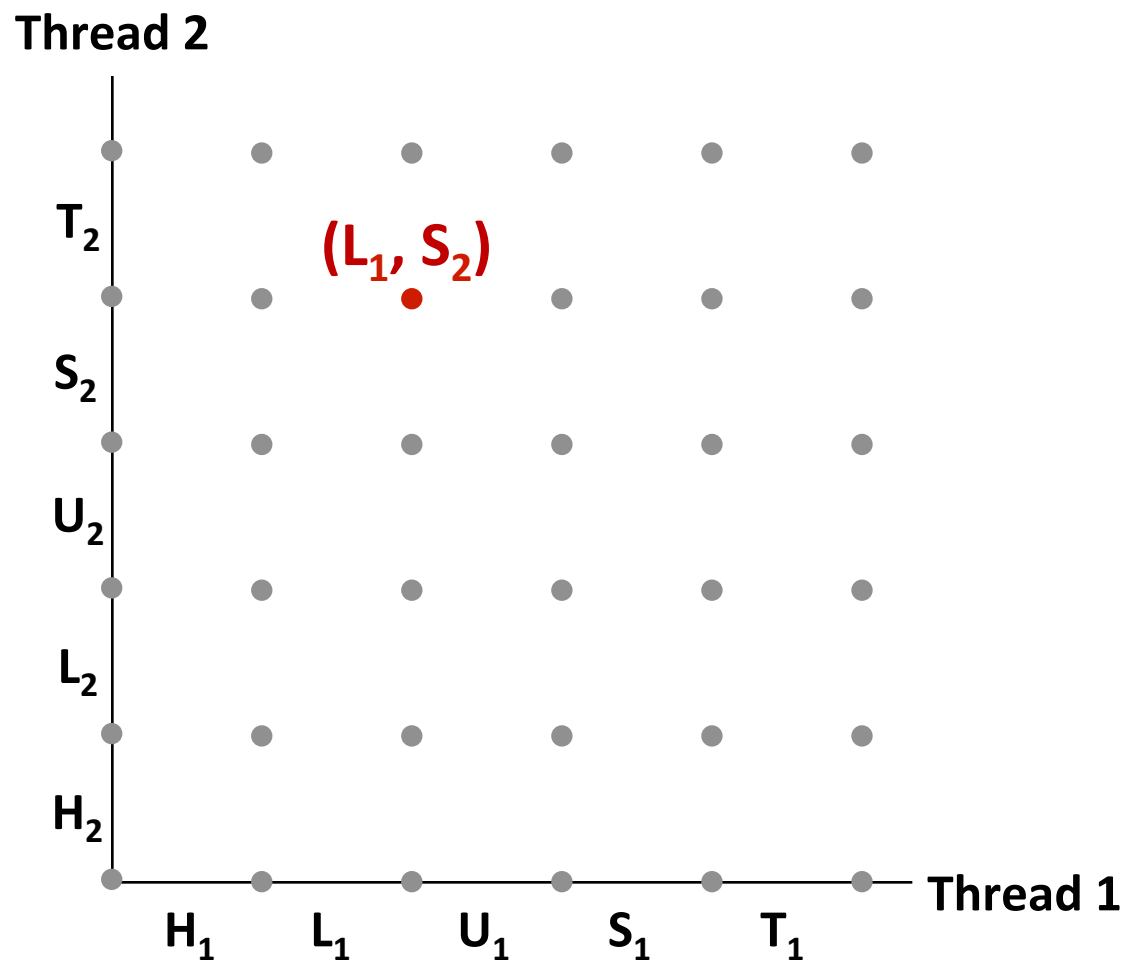
- How about this ordering?

i (thread)	instr _i	%eax ₁	%eax 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			
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.

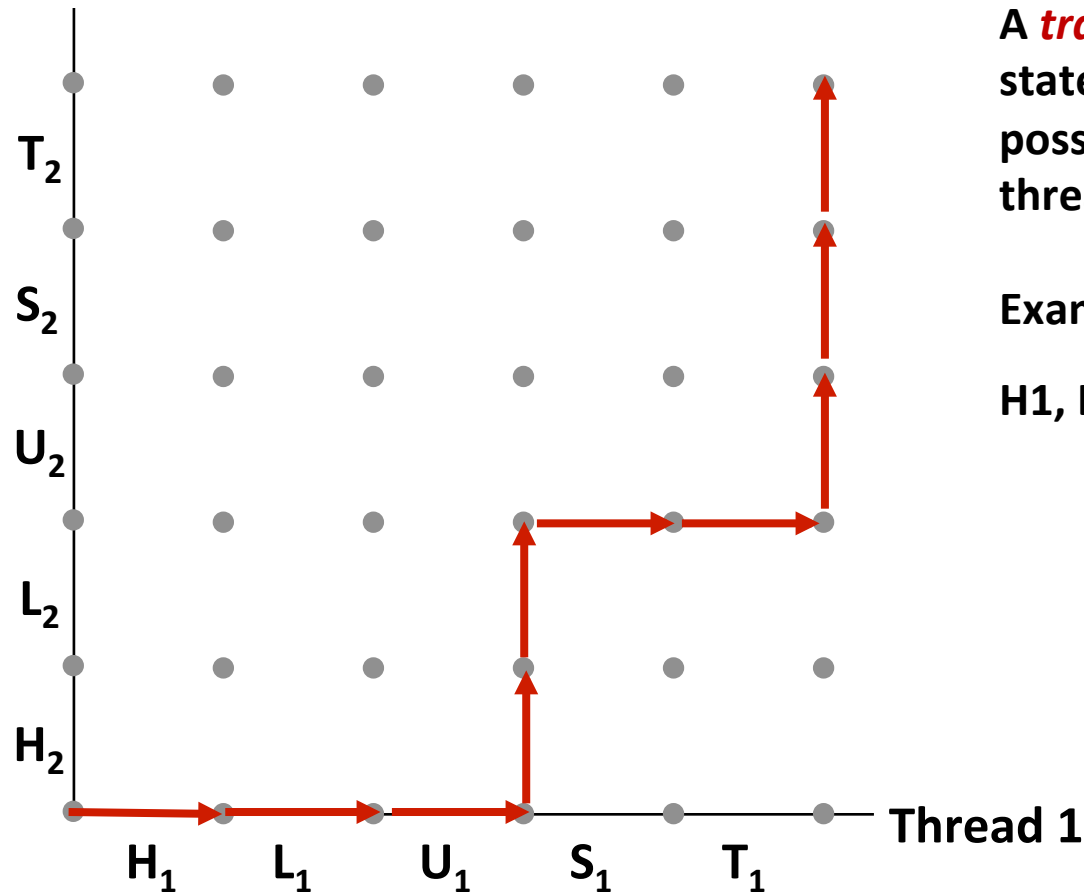
Each axis corresponds to the sequential order of instructions in a thread.

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

Thread 2

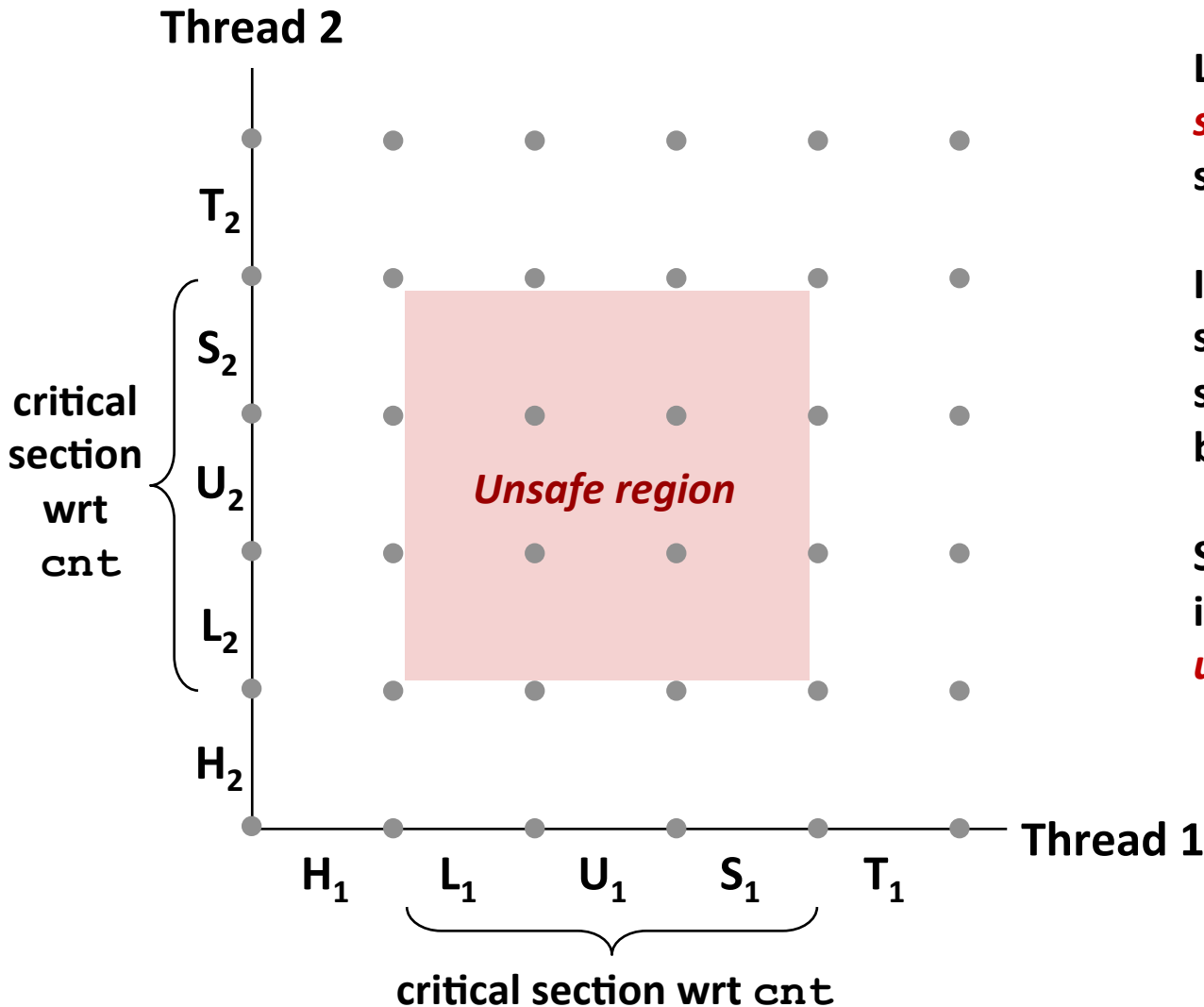


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

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

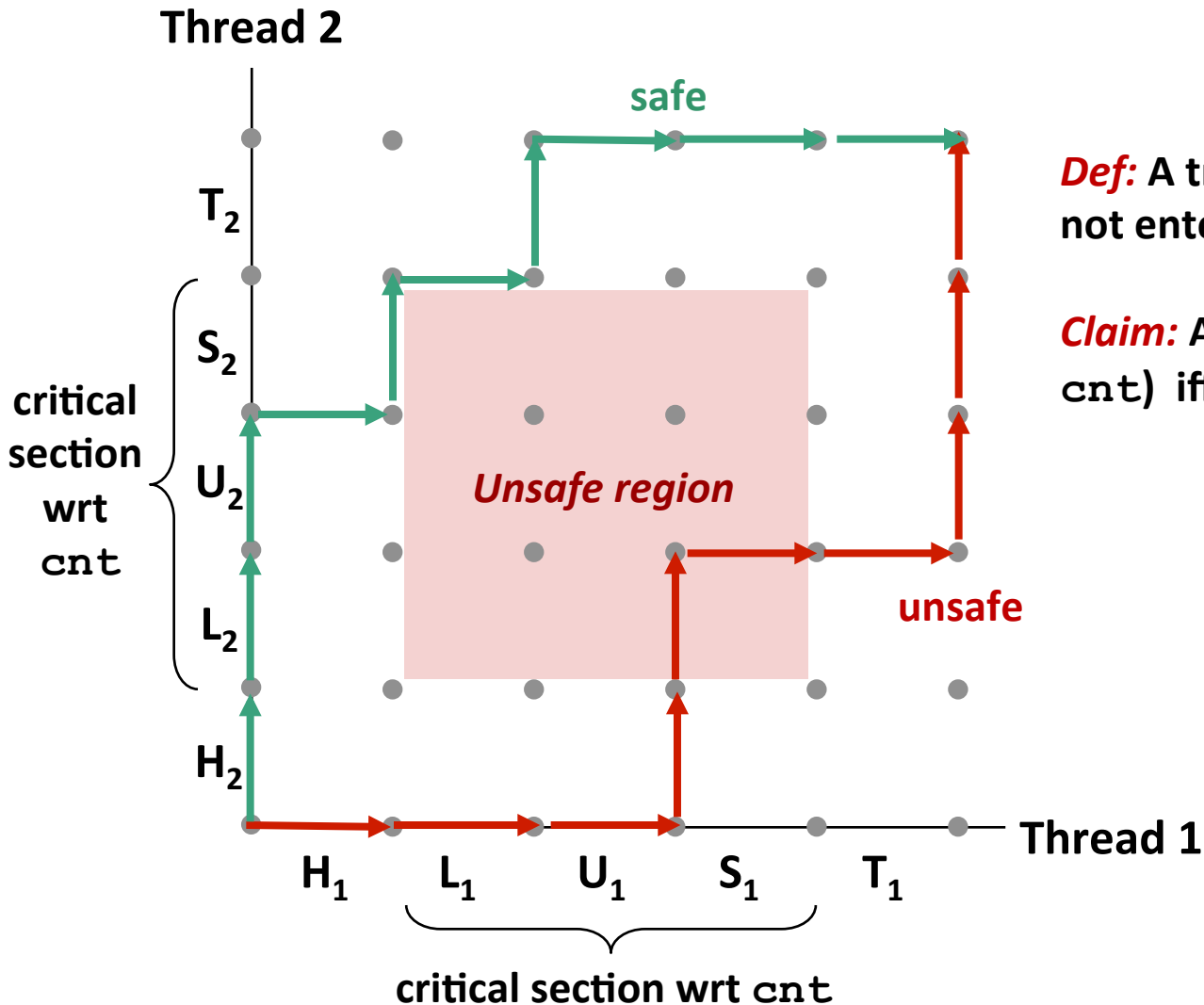


L , U , and S form a **critical section** with respect to the shared variable `cnt`

Instructions in critical sections (wrt to 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

Enforcing Mutual Exclusion

- **Question:** How can we guarantee a safe trajectory?
- **Answer:** We must *synchronize* the execution of the threads so that they never have an unsafe trajectory.
 - i.e., need to guarantee *mutually exclusive access* to critical regions
- **Classic solution:**
 - Semaphores (Edsger Dijkstra)
- **Other approaches (out of our scope)**
 - Mutex and condition variables (Pthreads)
 - Monitors (Java)

Today

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

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 *sem, 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

```
volatile int cnt = 0; /* global */

int main(int argc, char **argv)
{
    int niters = atoi(argv[1]);
    pthread_t tid1, tid2;

    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=%d\n", cnt);
    else
        printf("OK cnt=%d\n", cnt);
    exit(0);
}
```

```
/* Thread routine */
void *thread(void *vargp)
{
    int i, niters = *((int *)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 int cnt = 0;      /* Counter */
sem_t mutex;              /* Semaphore that protects cnt */

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

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

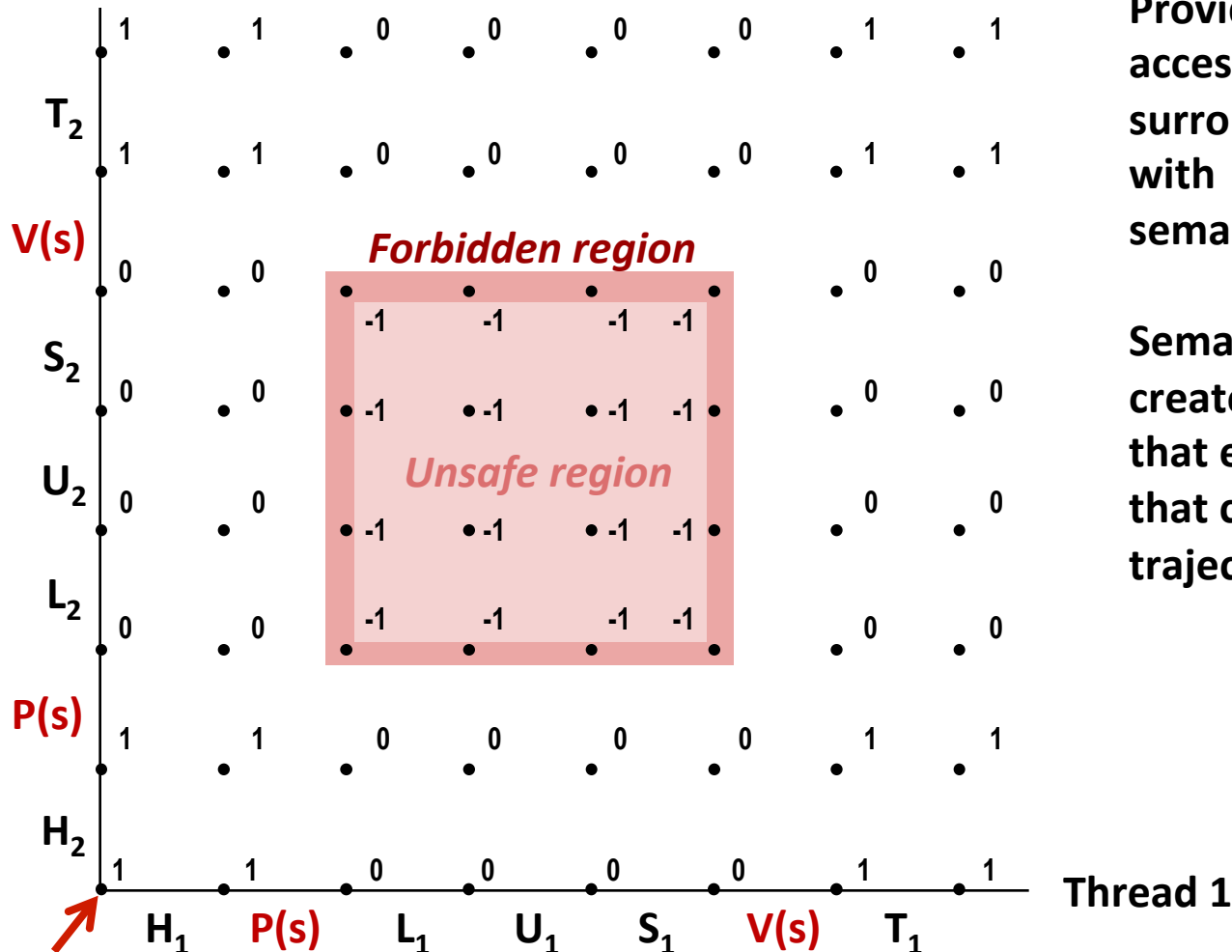
```
for (i = 0; i < niters; i++) {
    P(&mutex);
    cnt++;
    V(&mutex);
}
```

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

Warning: It's much 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 that cannot be entered by any trajectory.

Initially
 $s = 1$

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.**