CSSE132 Introduction

37 : Concurrency and Synchronization

May 13, 2013

Today

- **Thread concepts**
  - Book details processes and I/O multiplexing
  - pthreads
- **Sharing**
- **Mutual exclusion**
- **Semaphores**

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 this class.**

Creating Concurrent Flows

- **See book for example server using:**

- **1. Processes**
  - Kernel automatically interleaves multiple logical flows
  - Each flow has its own private address space
- **2. Threads**
  - Kernel automatically interleaves multiple logical flows
  - Each flow shares the same address space
- **3. I/O multiplexing with `select()`**
  - Programmer manually interleaves multiple logical flows
  - All flows share the same address space
  - Relies on lower-level system abstractions

Traditional View of a Process

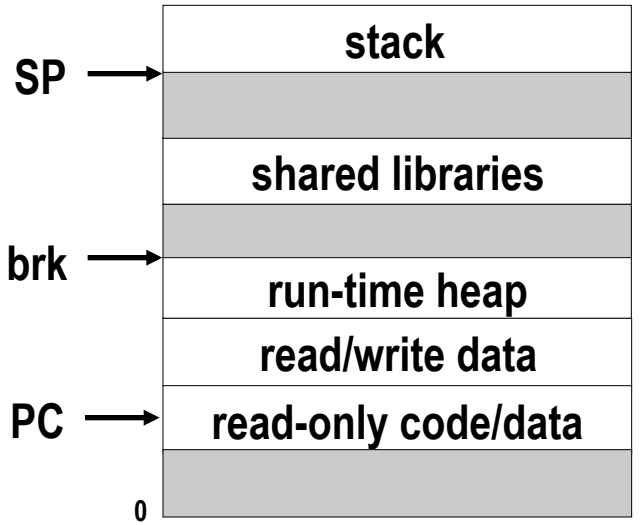
- Process = process context + code, data, and stack

Process context

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

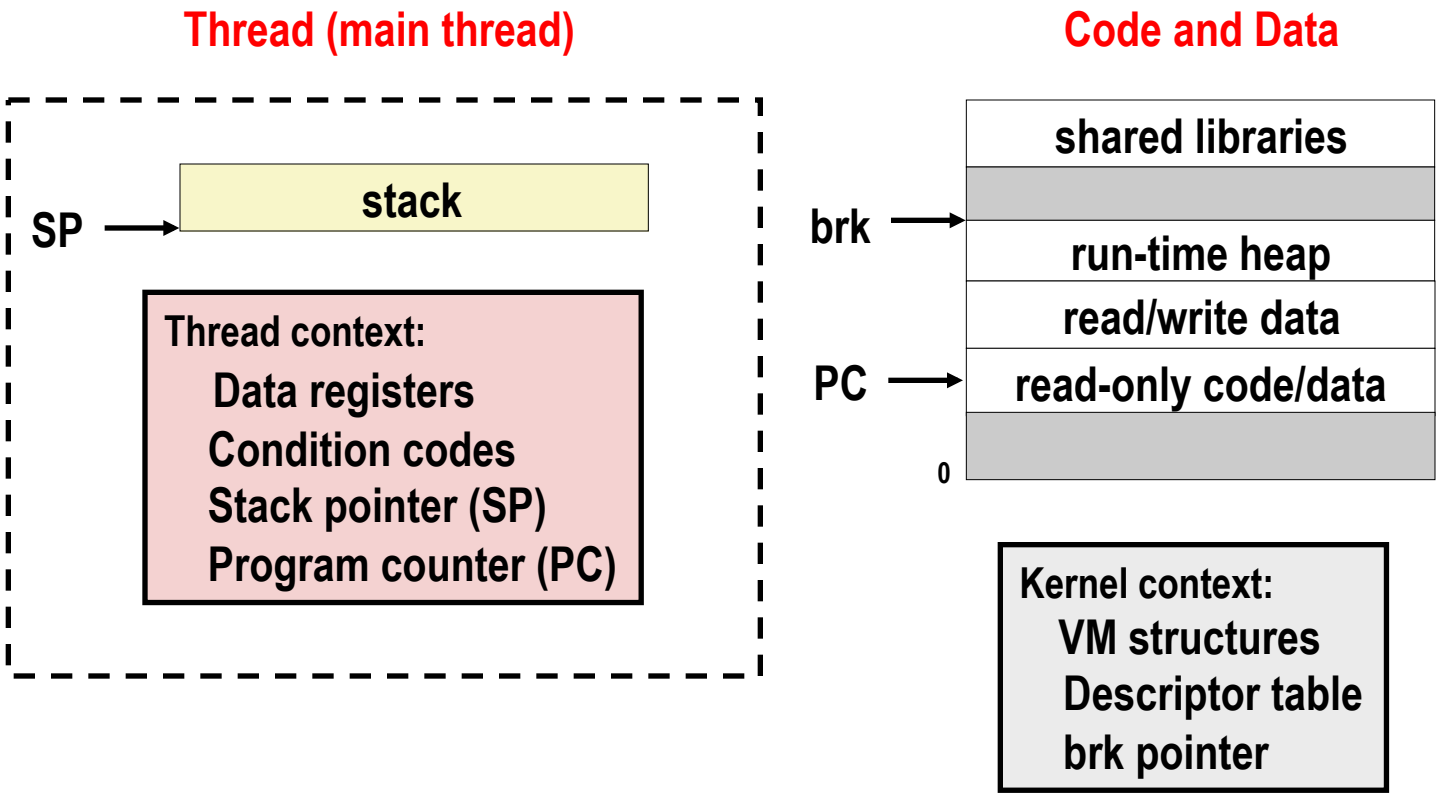
Kernel context:
- VM structures
- Descriptor table
- brk pointer

Code, data, and stack



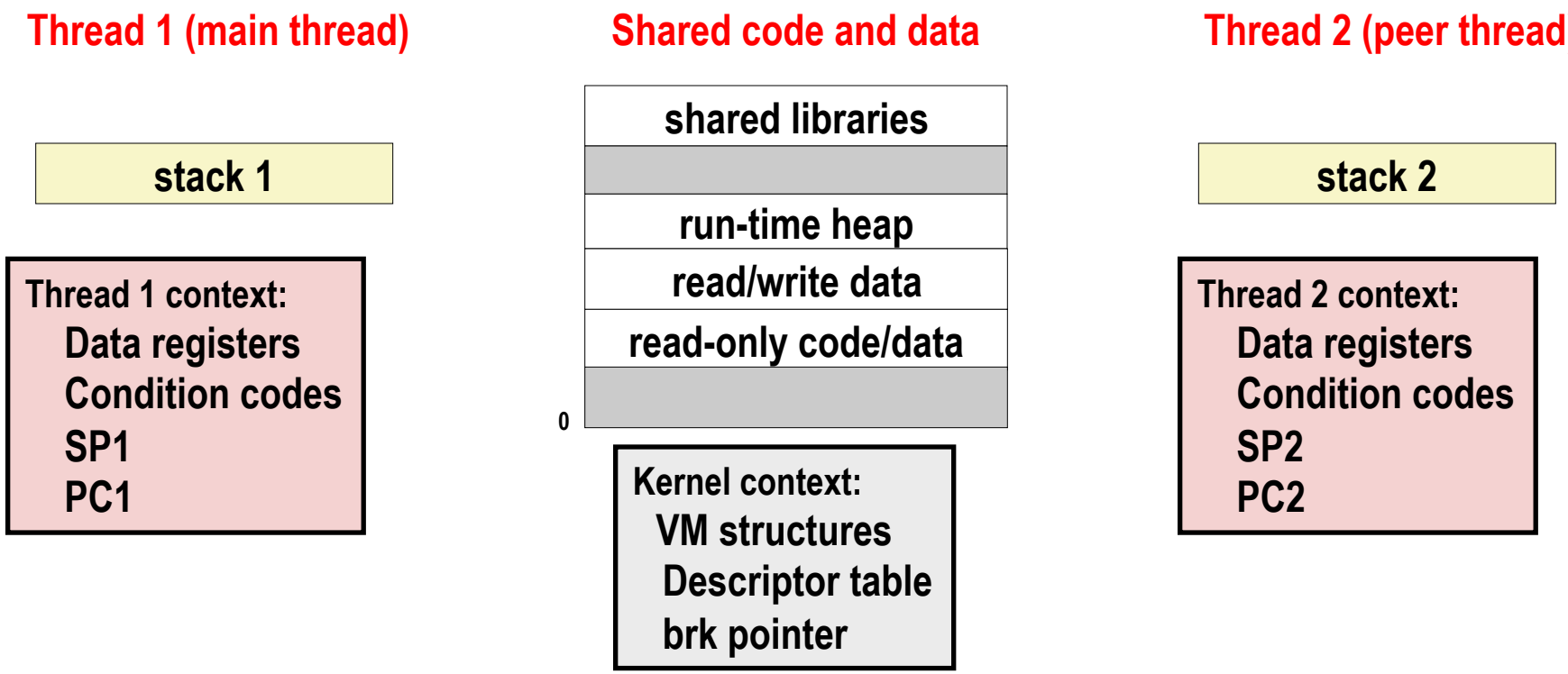
Alternate View of a Process

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



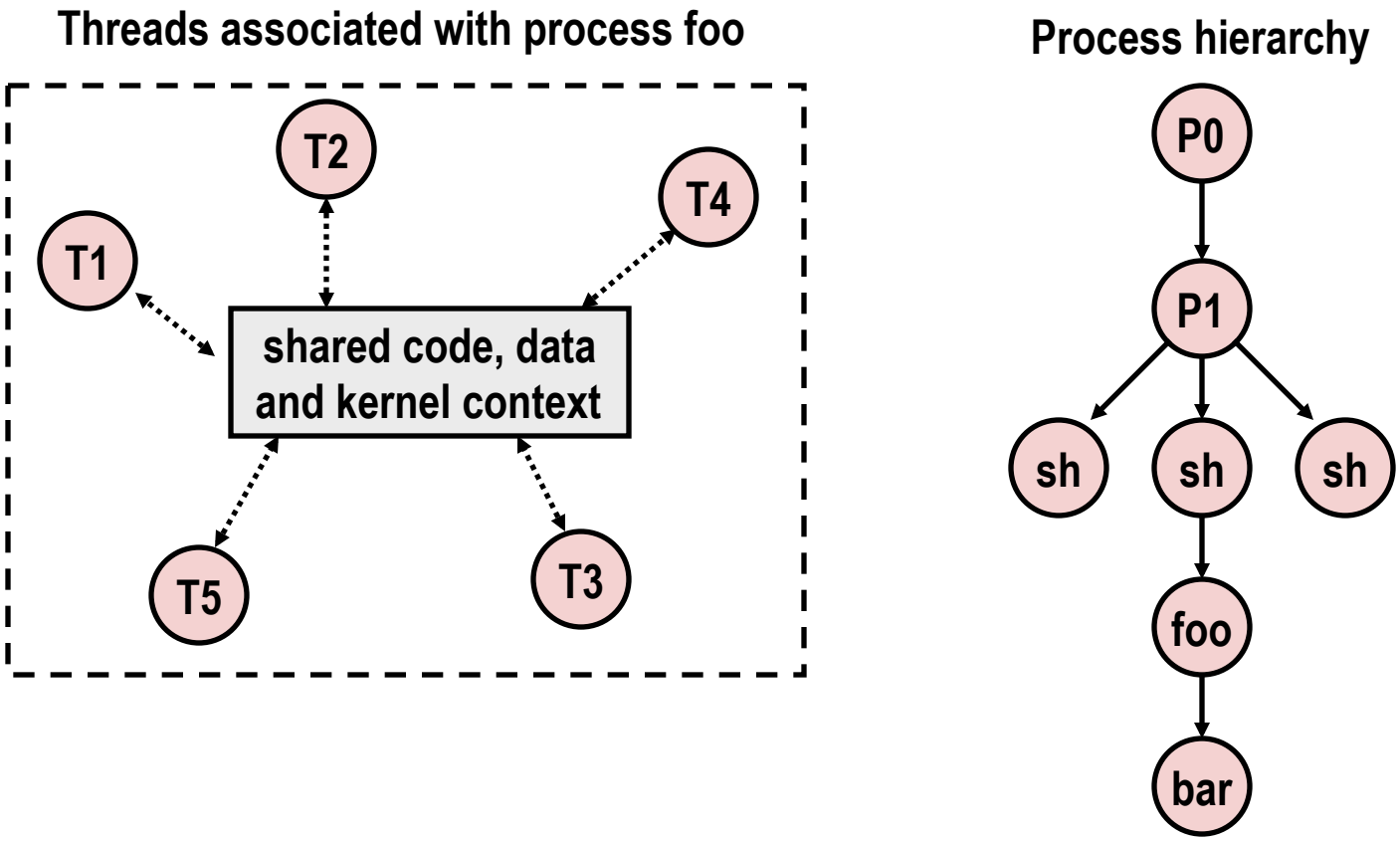
A Process With Multiple Threads

- **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
    - Share common virtual address space (inc. stacks)
  - Each thread has its own thread id (TID)



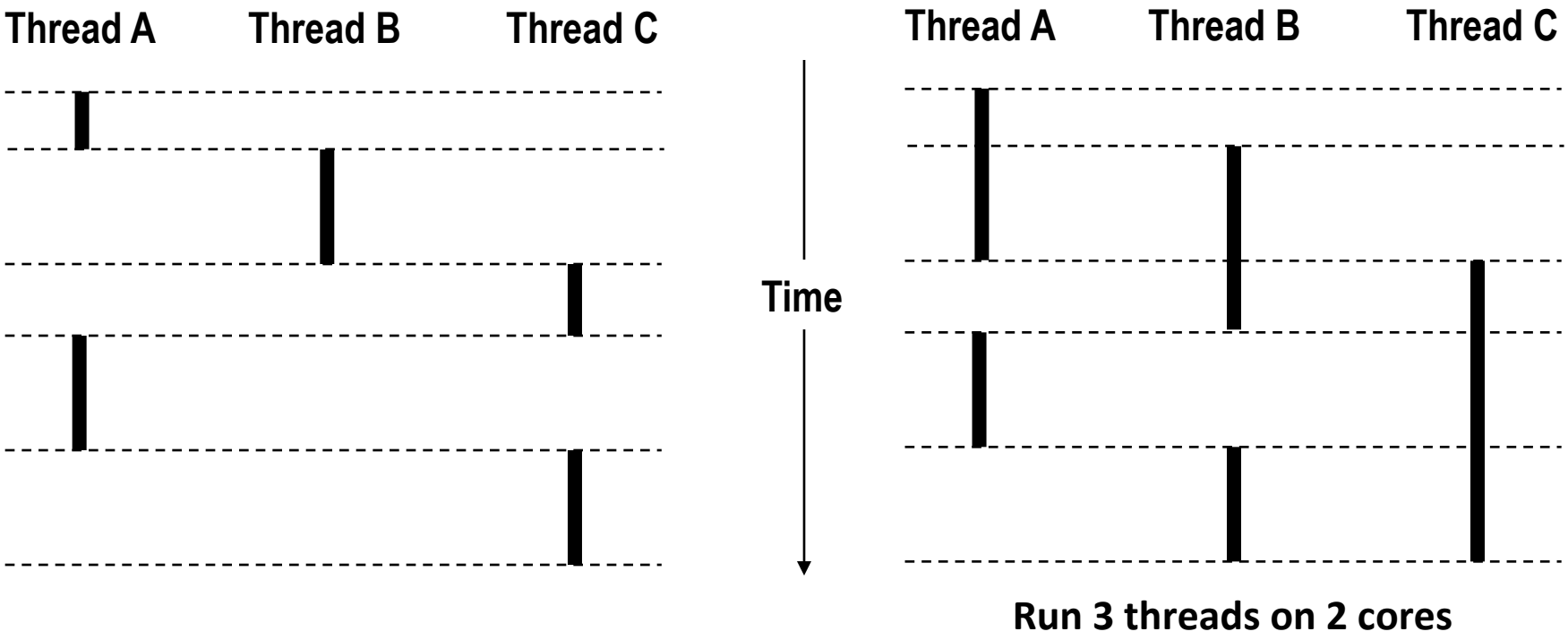
Logical View of Threads

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



Thread Execution

- **Single Core Processor**
  - Simulate concurrency by time slicing
- **Multi-Core Processor**
  - Can have true concurrency



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 code and some data
    - Processes (typically) do not
  - Threads are somewhat less expensive than processes
    - Process control (creating and reaping) is 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

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()`
    - `exit()` [terminates all threads] , `RET` [terminates current thread]
  - Synchronizing access to shared variables
    - `pthread_mutex_init`
    - `pthread_mutex_[un]lock`
    - `pthread_cond_init`
    - `pthread_cond_[timed]wait`

The Pthreads "hello, world" Program

```
/*
 * hello.c - Pthreads "hello, world" program
 */

void *thread(void *vargp);

int main() {
  pthread_t tid;

  pthread_create(&tid, NULL, thread, NULL);
  pthread_join(tid, NULL);
  exit(0);
}
```

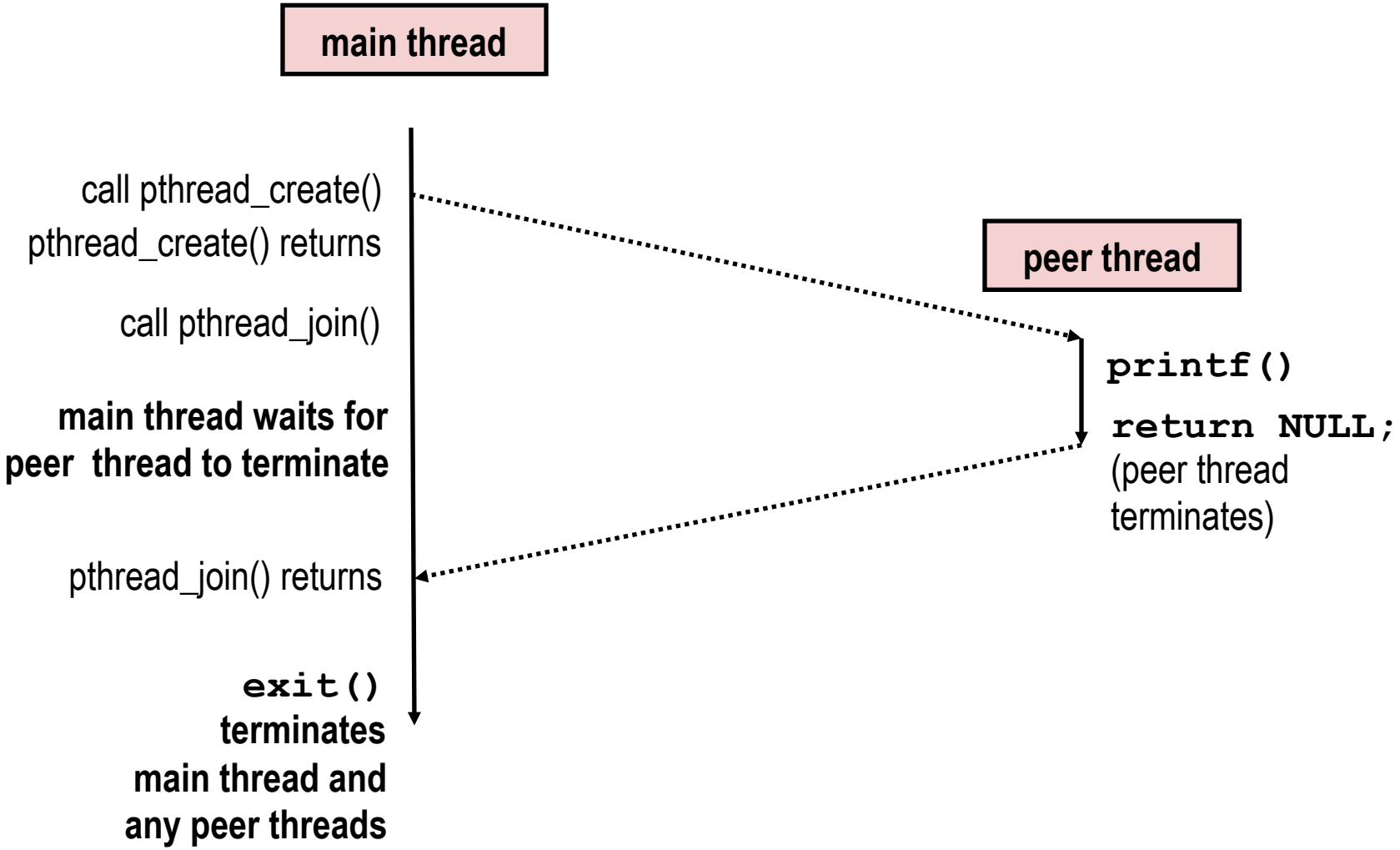
Thread attributes (usually NULL)

*Thread arguments (void *p)*

*return value (void **p)*

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

Execution of Threaded“hello, world”



Could this race occur?

Main

```
int i;
for (i = 0; i < 100; i++) {
  pthread_create(&tid, NULL,
                 thread, &i);
}
```

Thread

```
void *thread(void *vargp)
{
  int i = *((int *)vargp);
  pthread_detach(pthread_self());
  save_value(i);
  return NULL;
}
```

- **Race Test**
  - If no race, then each thread would get different value of i
  - Set of saved values would consist of one copy each of 0 through 99.
  - See `race.c`

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!**
  - 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!

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- **Thread concepts**
  - Book details processes and I/O multiplexing
  - pthreads
- **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

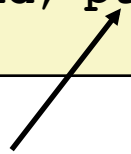
```
char **ptr;  /* global */

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?

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

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- **Thread concepts**
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- **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

```
        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:
```

Head (H_i)

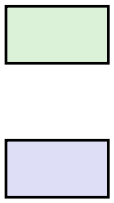
Load cnt (L_i)
Update cnt (U_i)
Store cnt (S_i)

Tail (T_i)

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)

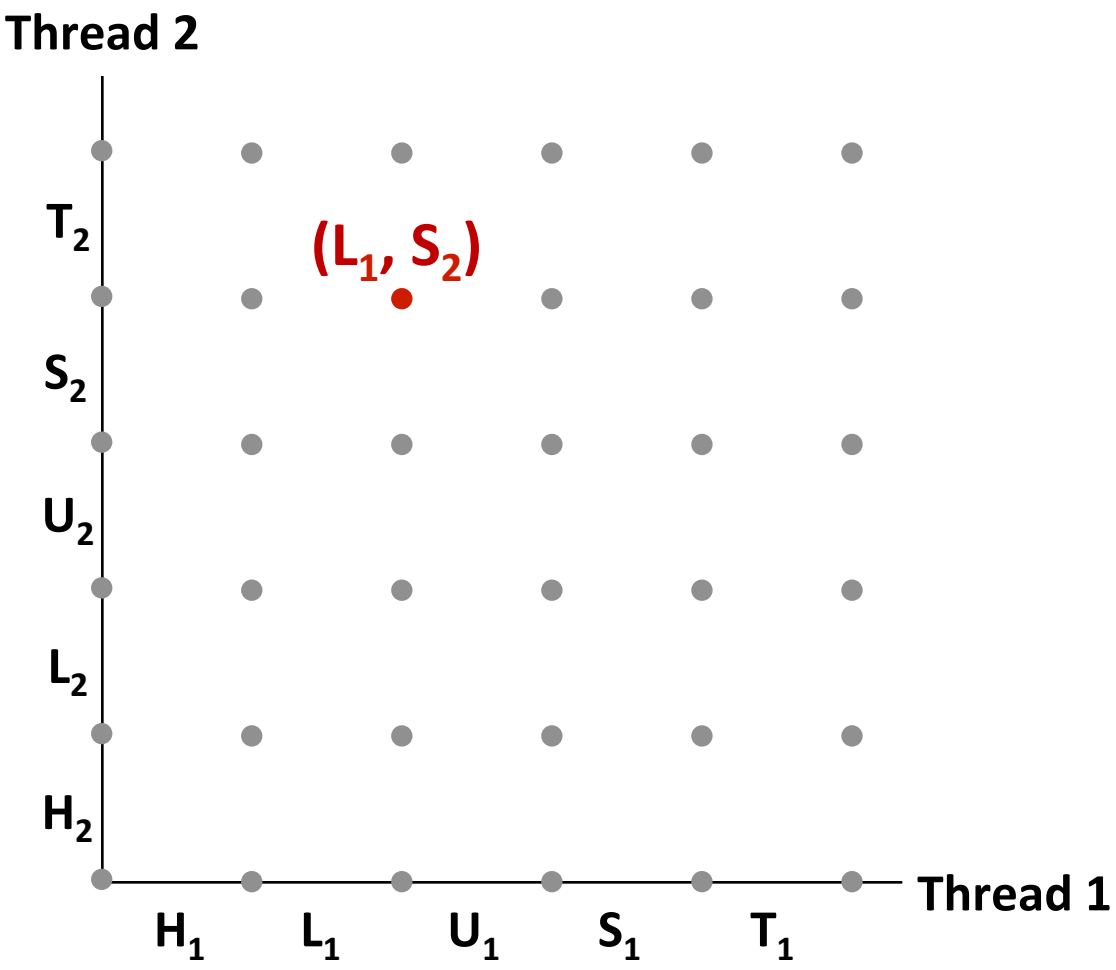
- How about this ordering?

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



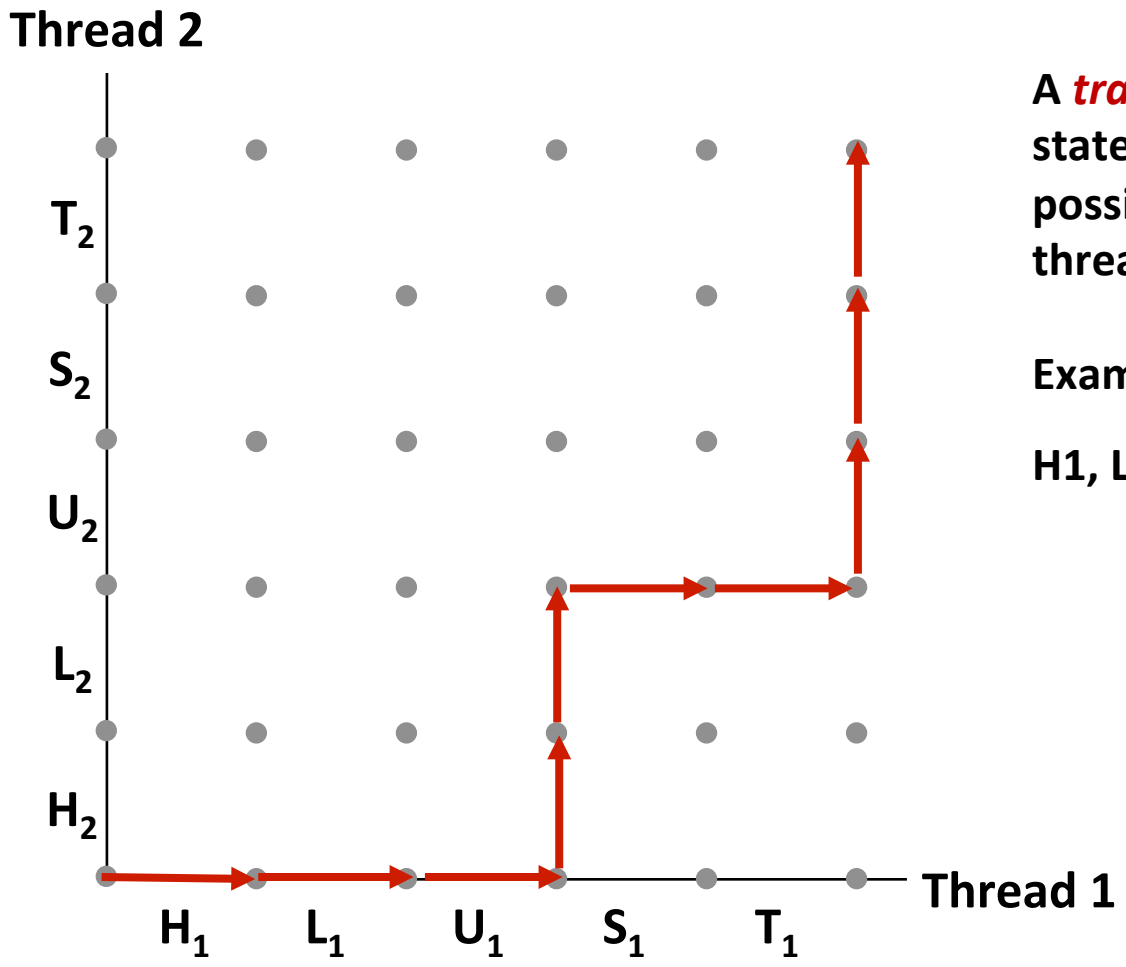
A *progress graph* depicts the discrete *execution state space* of concurrent threads.

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

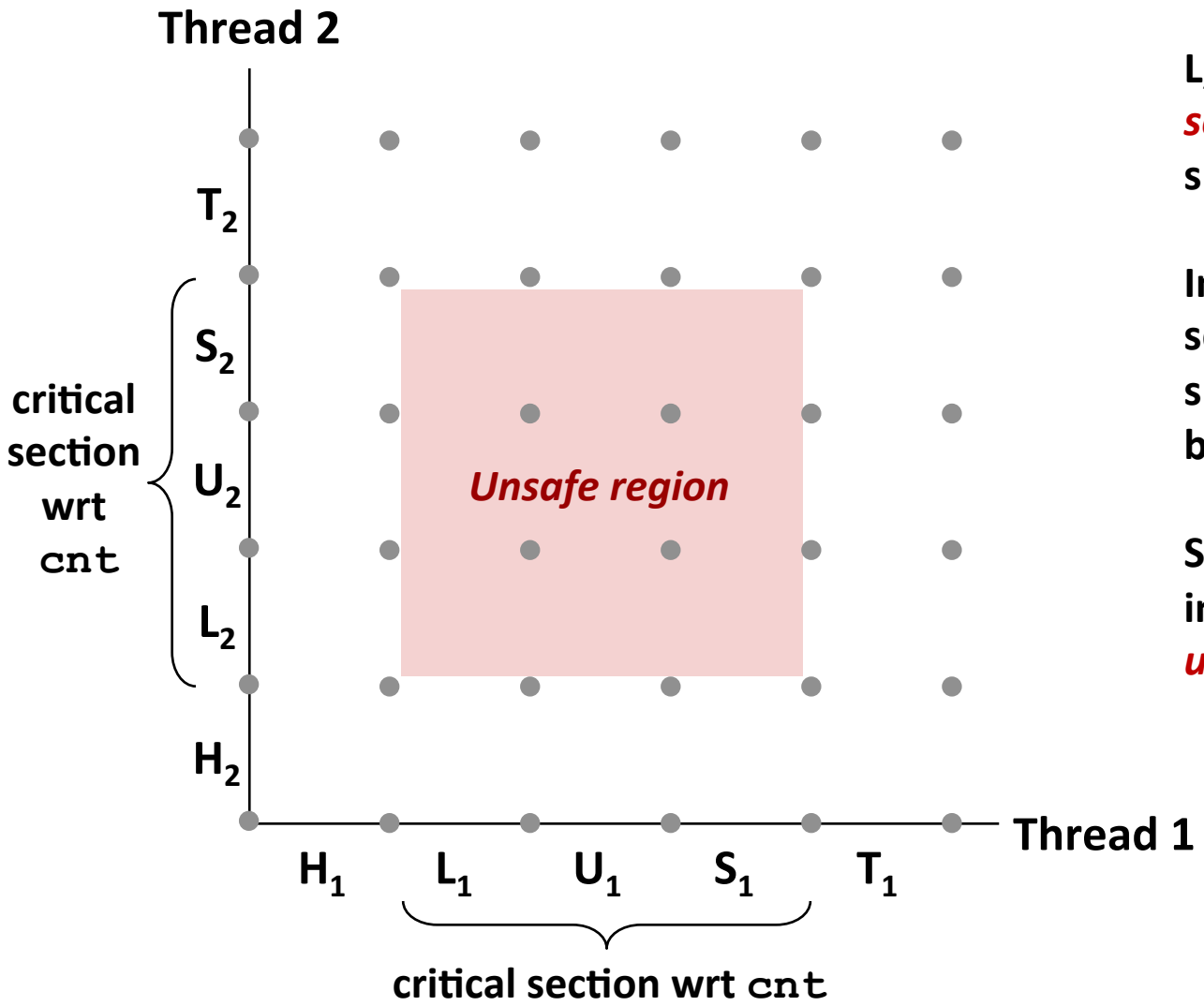


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Critical Sections and Unsafe Regions

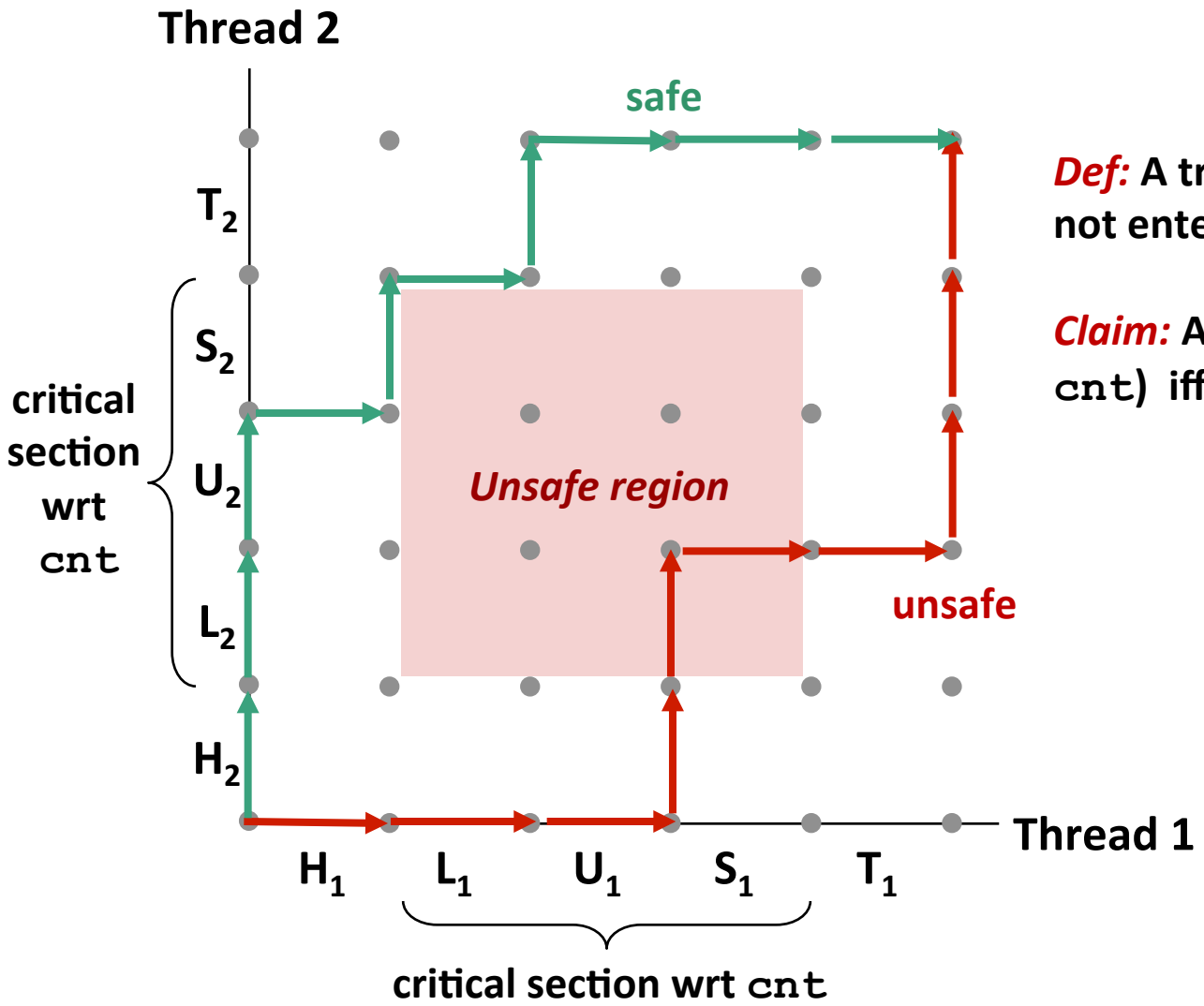


L, U, and S form a *critical section* with respect to the shared variable `cnt`

Instructions in critical sections (wrt 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)

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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 >= 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 (used in book)

```
#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 */
```

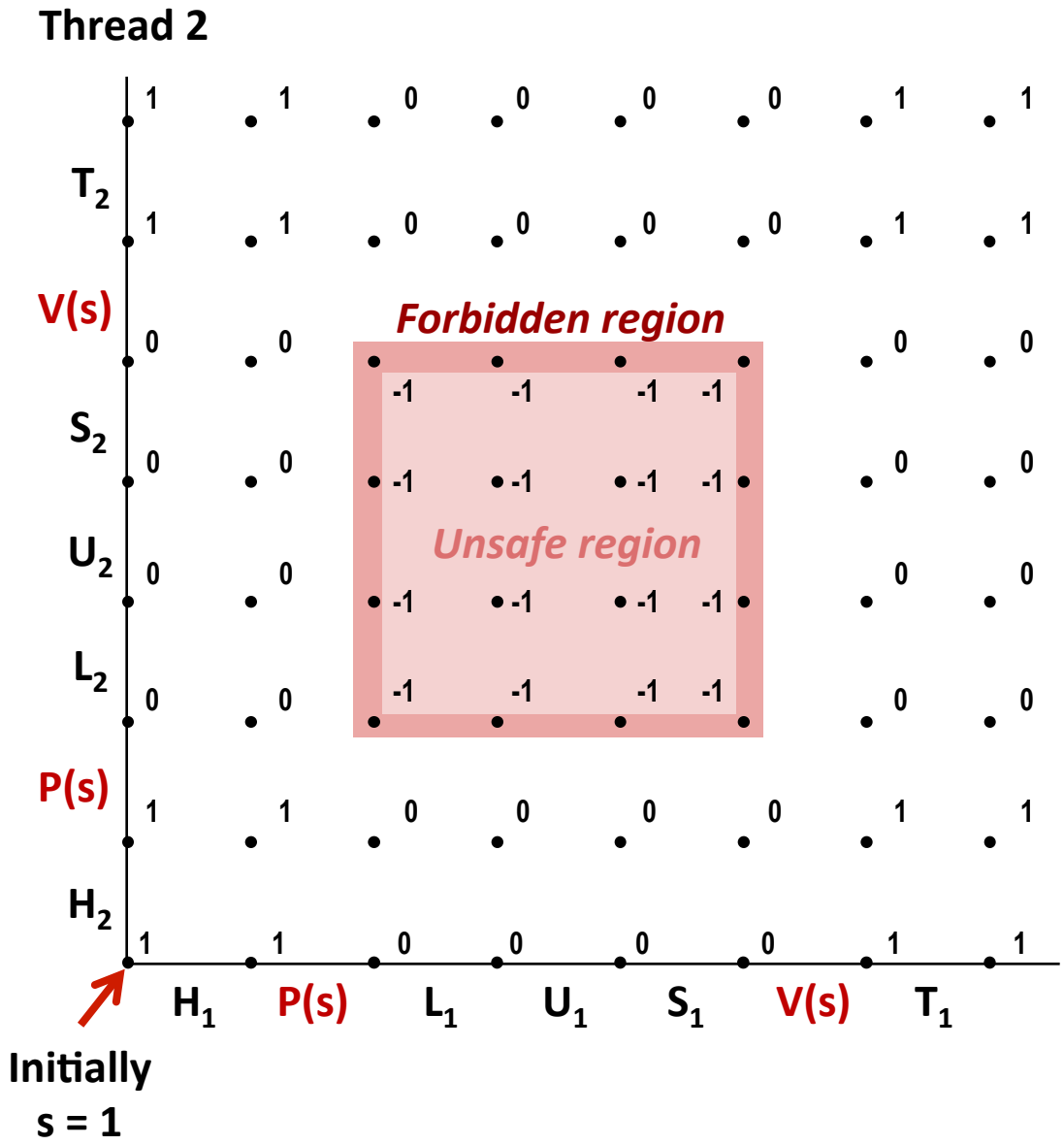
- Surround critical section with *P* and *V*:

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



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.

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.