Synchronization

15-213/18-243: Introduction to Computer Systems

26th Lecture, 27 April 2010

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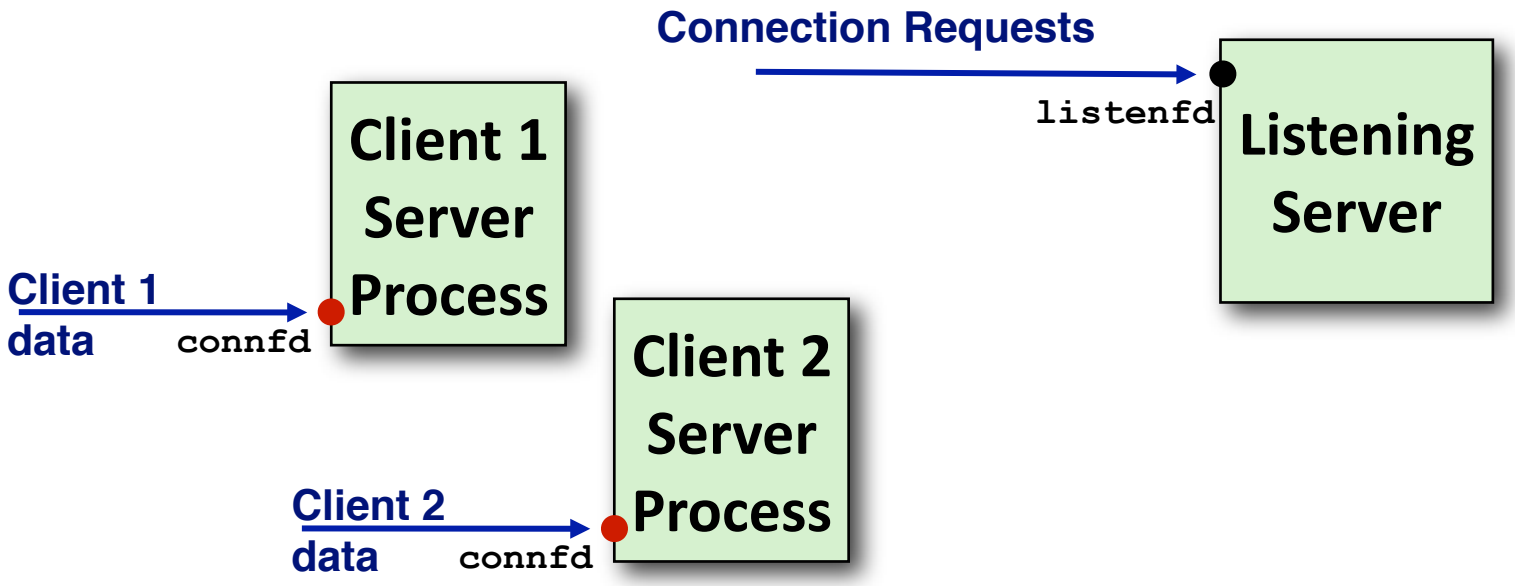
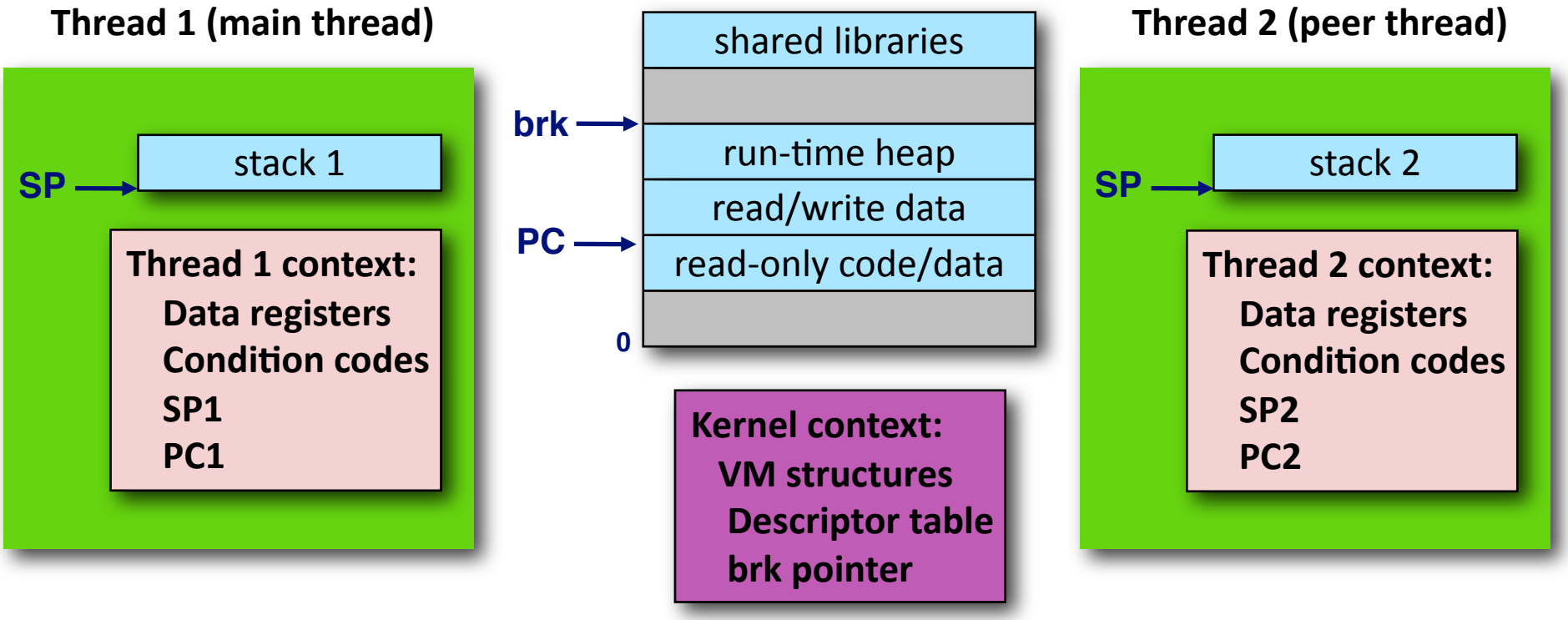
Last Time: Process-based Server



- Each client handled by independent process
- No shared state between them
- When child created, each has copy of `listenfd` and `connfd`
  - Parent must close **`connfd`**, child must close **`listenfd`**

Last Time: 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
  - Each thread has its own thread id (TID)



Today

- Synchronization
- Races, deadlocks, thread safety

Shared Variables in Threaded C Programs

- **Question: Which variables in a threaded C program are shared variables?**
  - 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 variables mapped to each memory instance?
  - How many threads might reference each of these instances?

Threads Memory Model

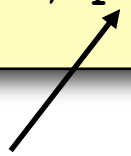
- **Conceptual model:**
  - Multiple threads run within the context of a single process
  - Each thread has its own separate thread context
    - Thread ID, stack, stack pointer, program counter, condition codes, and general purpose registers
  - All threads share the remaining process context
    - Code, data, heap, and shared library segments
    - 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

- ***Mismatch between the conceptual and operation model is a source of confusion and errors***

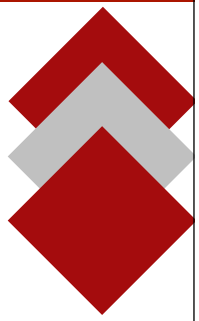
Thread Accessing Another Thread's Stack

```
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 svar = 0;

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



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



Mapping Variables to Memory Instances

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 svar = 0;

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

Local static var: 1 instance (`svar` [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`
`svar`	`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`**, **`svar`**, and **`msgs`** are shared
  - **`i`** and **`myid`** are not shared

badcnt.c: Improper Synchronization

```
/* shared */
volatile unsigned int cnt = 0;
#define NITERS 100000000

int main() {
  pthread_t tid1, tid2;
  Pthread_create(&tid1, NULL,
                 count, NULL);
  Pthread_create(&tid2, NULL,
                 count, NULL);

  Pthread_join(tid1, NULL);
  Pthread_join(tid2, NULL);

  if (cnt != (unsigned)NITERS*2)
    printf("BOOM! cnt=%d\n", cnt);
  else
    printf("OK cnt=%d\n", cnt);
}
```

```
/* thread routine */
void *count(void *arg) {
  int i;
  for (i=0; i<NITERS; i++)
    cnt++;
  return NULL;
}
```

```
linux> ./badcnt
BOOM! cnt=198841183

linux> ./badcnt
BOOM! cnt=198261801

linux> ./badcnt
BOOM! cnt=198269672
```

cnt should be equal to 200,000,000
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

Head (H_i)

```
.L9:
    movl -4(%ebp),%eax
    cmpl $99999999,%eax
    jle .L12
    jmp .L10
```

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

```
.L12:
    movl cnt,%eax       # Load
    leal 1(%eax),%edx   # Update
    movl %edx,cnt       # Store
```

Tail (T_i)

```
.L11:
    movl -4(%ebp),%eax
    leal 1(%eax),%edx
    movl %edx,-4(%ebp)
    jmp .L9
.L10:
```

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

Time

i (thread)	$instr_i$	$\%eax_i$	$\%eax_2$	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

OK

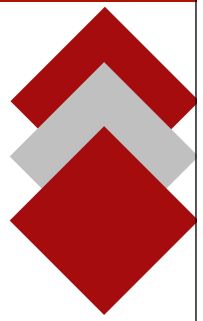
Concurrent Execution (cont)

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

Time

i (thread)	$instr_i$	$\%eax_i$	$\%eax_2$	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)

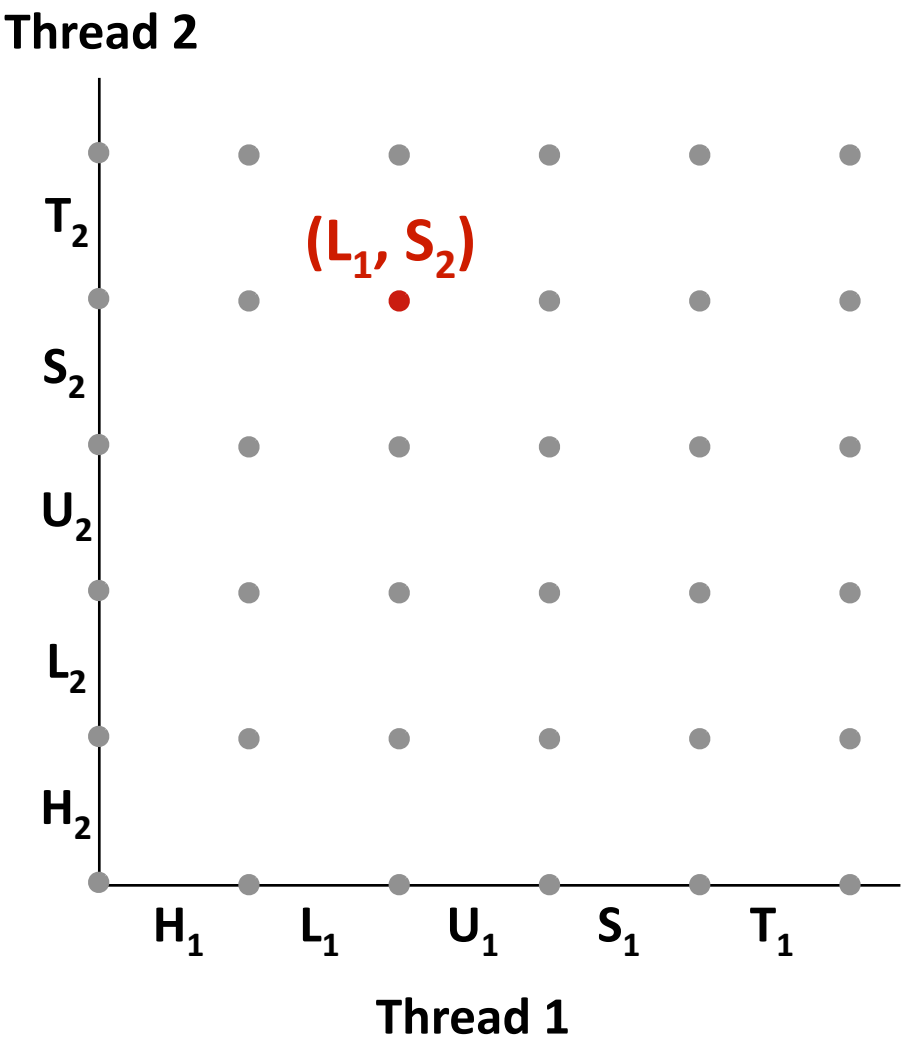
- How about this ordering?

Time

i (thread)	$instr_i$	$\%eax_i$	$\%eax_2$	cnt
1	H_1			
1	L_1			
2	H_2			
2	L_2			
2	U_2			
2	S_2			
1	U_1			
1	S_1			
1	T_1			
2	T_2			

- We can analyze the behavior using a process graph

Progress Graphs



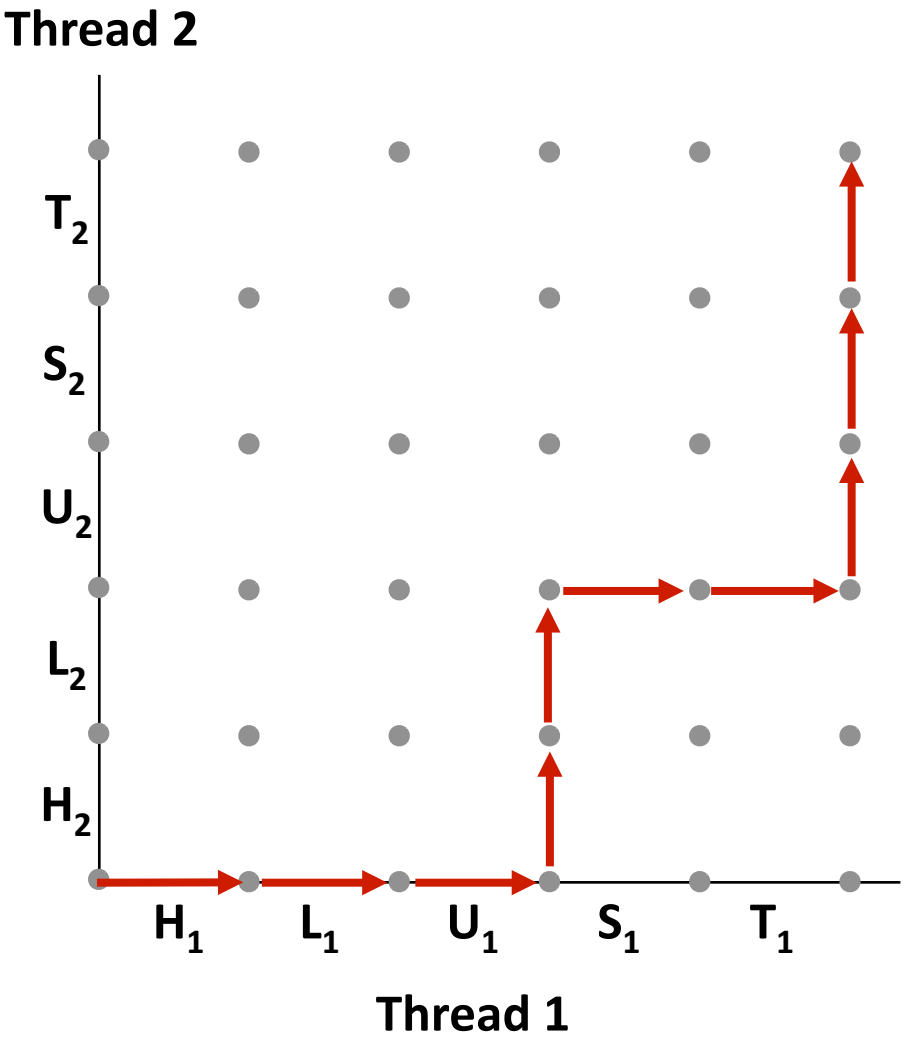
A *progress graph* depicts the discrete *execution state space* of concurrent threads

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

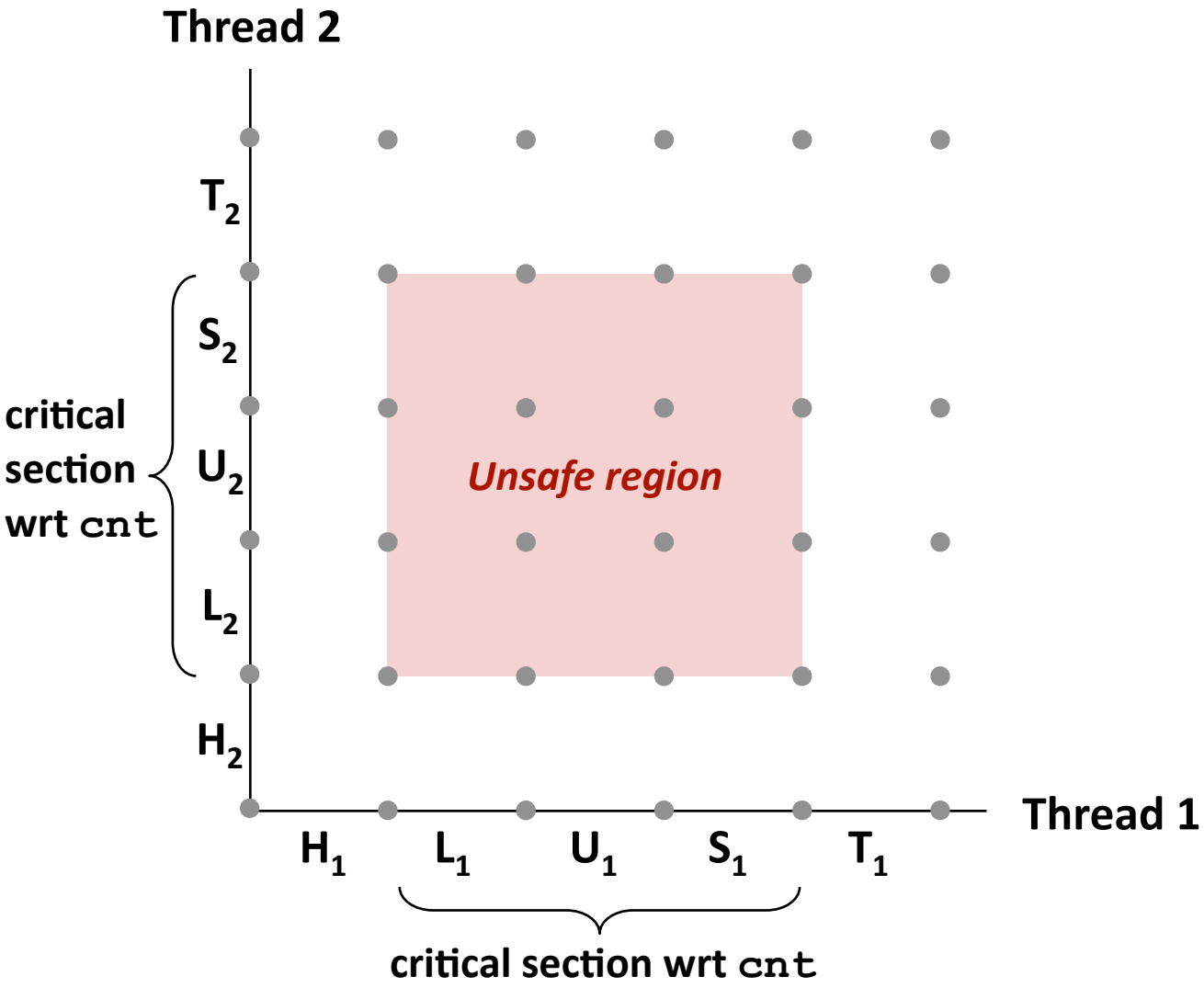


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Critical Sections and Unsafe Regions

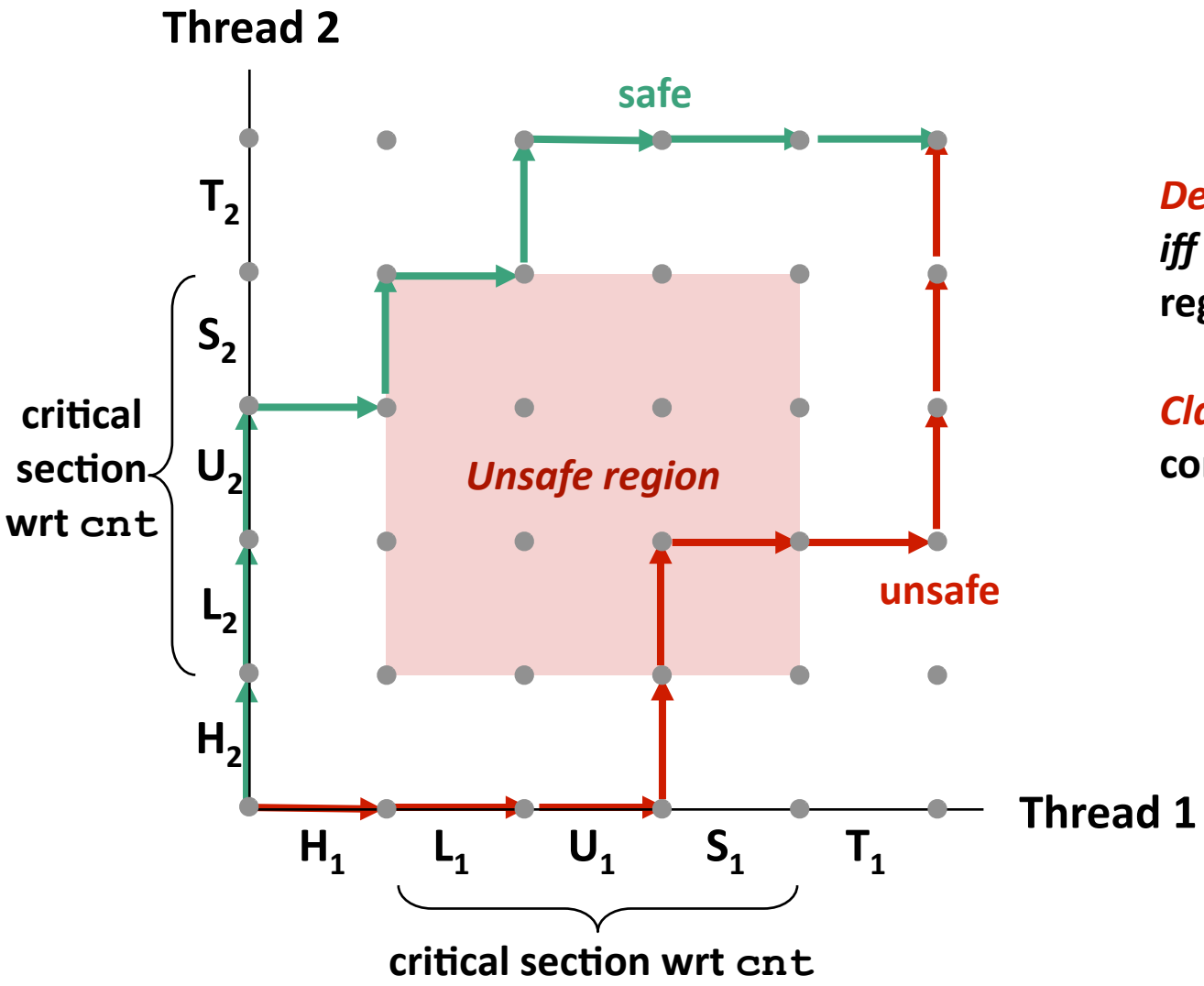


L, U, and S form a *critical section* with respect to the shared variable `cnt`

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



Definition: A trajectory is ***safe*** ***iff*** it does not enter any unsafe region

Claim: A trajectory is correct (wrt `cnt`) ***iff*** it is safe

Semaphores

- ***Question*: How can we guarantee a safe trajectory?**
  - We must ***synchronize*** the threads so that they never enter an unsafe state

- ***Classic solution*: Dijkstra's P and V operations on *semaphores***
  - ***Semaphore***: non-negative global integer synchronization variable
    - P(s): [`while (s == 0) wait(); s--;`]
      - Dutch for "Proberen" (test)
    - V(s): [`s++;`]
      - Dutch for "Verhogen" (increment)
  - OS 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)***

badcnt.c: Improper Synchronization

```
/* shared */
volatile unsigned int cnt = 0;
#define NITERS 100000000

int main() {
  pthread_t tid1, tid2;
  Pthread_create(&tid1, NULL,
                 count, NULL);
  Pthread_create(&tid2, NULL,
                 count, NULL);

  Pthread_join(tid1, NULL);
  Pthread_join(tid2, NULL);

  if (cnt != (unsigned)NITERS*2)
    printf("BOOM! cnt=%d\n", cnt);
  else
    printf("OK cnt=%d\n", cnt);
}
```

```
/* thread routine */
void *count(void *arg) {
  int i;
  for (i=0; i<NITERS; i++)
    cnt++;
  return NULL;
}
```

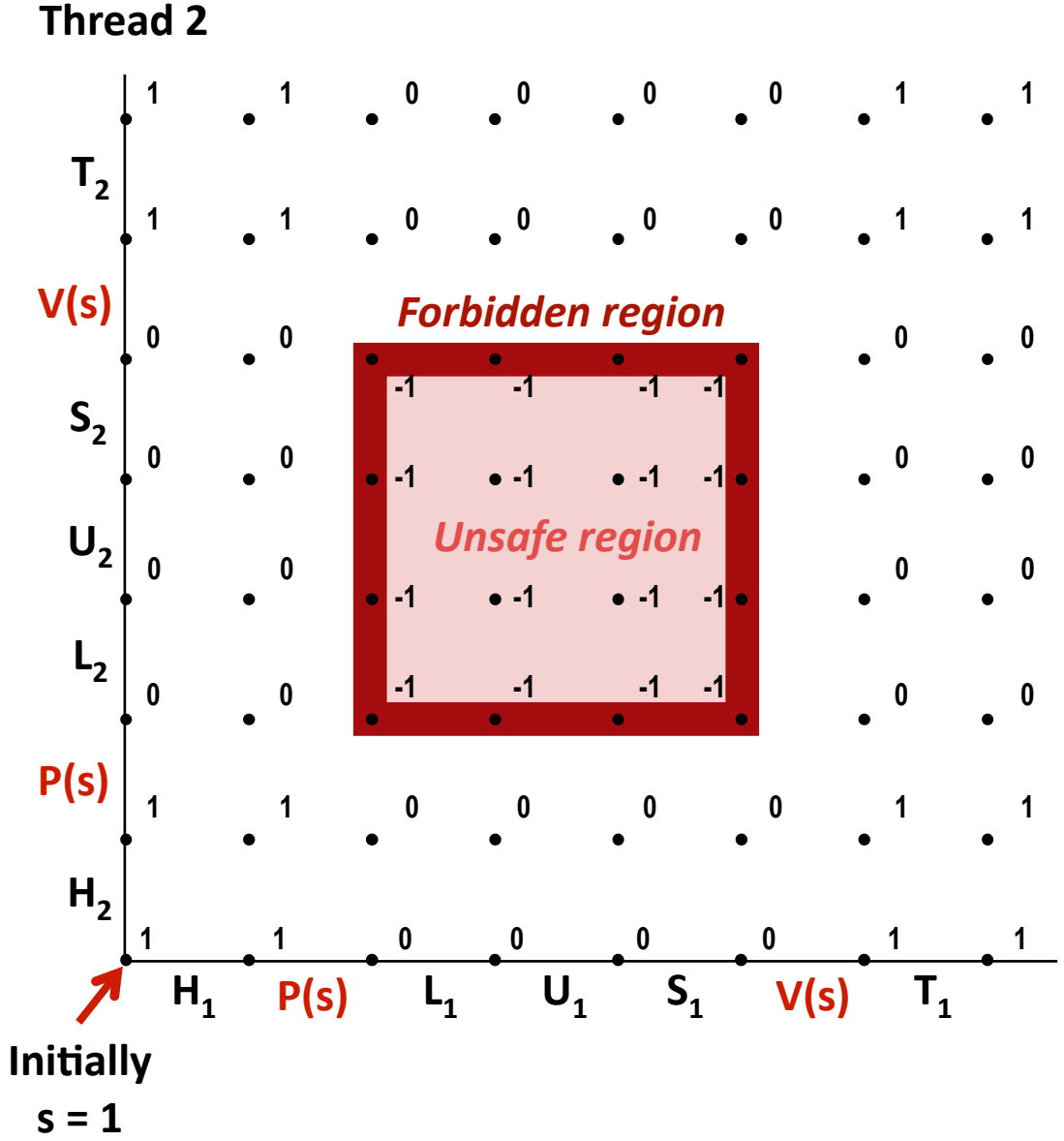
How to fix using semaphores?

Safe Sharing with Semaphores

- One semaphore per shared variable
- Initially set to 1
- Here is how we would use P and V operations to synchronize the threads that update cnt

```
/* Semaphore s is initially 1 */

/* Thread routine */
void *count(void *arg)
{
  int i;

  for (i=0; i<NITERS; i++) {
    P(s);
    cnt++;
    V(s);
  }
  return NULL;
}
```

Safe Sharing With Semaphores



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 is entered by any trajectory

Wrappers on POSIX Semaphores

```
/* Initialize semaphore sem to value */
/* pshared=0 if thread, pshared=1 if process */
void Sem_init(sem_t *sem, int pshared, unsigned int value) {
  if (sem_init(sem, pshared, value) < 0)
    unix_error("Sem_init");
}

/* P operation on semaphore sem */
void P(sem_t *sem) {
  if (sem_wait(sem))
    unix_error("P");
}

/* V operation on semaphore sem */
void V(sem_t *sem) {
  if (sem_post(sem))
    unix_error("V");
}
```

Sharing With POSIX Semaphores

```
/* properly sync'd counter program */
#include "csapp.h"
#define NITERS 10000000

volatile unsigned int cnt;
sem_t sem;          /* semaphore */

int main() {
  pthread_t tid1, tid2;

  Sem_init(&sem, 0, 1); /* sem=1 */

  /* create 2 threads and wait */
  ...

 if (cnt != (unsigned)NITERS*2)
   printf("BOOM! cnt=%d\n", cnt);
 else
   printf("OK cnt=%d\n", cnt);
 exit(0);
}
```

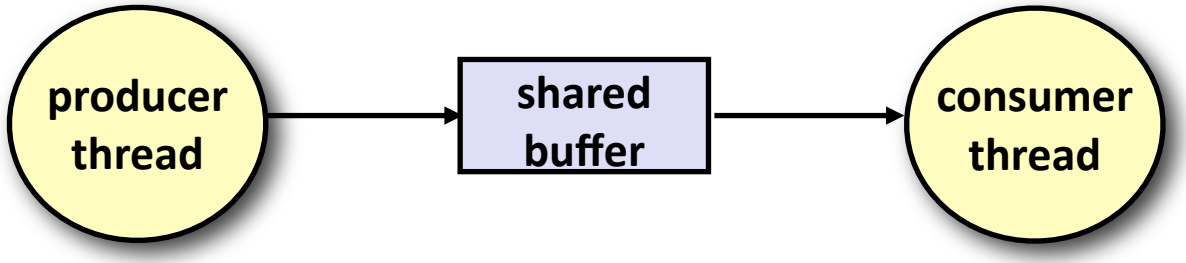
```
/* thread routine */
void *count(void *arg)
{
  int i;

  for (i=0; i<NITERS; i++) {
    P(&sem);
    cnt++;
    V(&sem);
  }
  return NULL;
}
```

```
linux> ./goodcnt 100000000
OK cnt=200000000

linux> ./goodcnt 100000000
OK cnt=200000000
```

Warning:

Extremely slow!

Notifying With Semaphores



- **Common synchronization pattern:**
  - Producer waits for slot, inserts item in buffer, and notifies consumer
  - Consumer waits for item, removes it from buffer, and notifies producer
- **Examples**
  - Multimedia processing:
    - Producer creates MPEG video frames, consumer renders them
  - Event-driven graphical user interfaces
    - Producer detects mouse clicks, mouse movements, and keyboard hits and inserts corresponding events in buffer
    - Consumer retrieves events from buffer and paints the display

Producer-Consumer on a Buffer That Holds One Item

```
/* buf1.c - producer-consumer
on 1-element buffer */
#include "csapp.h"

#define NITERS 5

void *producer(void *arg);
void *consumer(void *arg);

struct {
  int buf; /* shared var */
  sem_t full; /* sems */
  sem_t empty;
} shared;
```

```
int main() {
  pthread_t tid_producer;
  pthread_t tid_consumer;

  /* initialize the semaphores */
  Sem_init(&shared.empty, 0, 1);
  Sem_init(&shared.full,  0, 0);

  /* create threads and wait */
  Pthread_create(&tid_producer, NULL,
                 producer, NULL);
  Pthread_create(&tid_consumer, NULL,
                 consumer, NULL);
  Pthread_join(tid_producer, NULL);
  Pthread_join(tid_consumer, NULL);

  exit(0);
}
```

Producer-Consumer (cont)

Initially: empty = 1, full = 0

```
/* producer thread */
void *producer(void *arg) {
  int i, item;

  for (i=0; i<NITERS; i++) {
    /* produce item */
    item = i;
    printf("produced %d\n", item);

    /* write item to buf */
    P(&shared.empty);
    shared.buf = item;
    V(&shared.full);
  }
  return NULL;
}
```

```
/* consumer thread */
void *consumer(void *arg) {
  int i, item;

  for (i=0; i<NITERS; i++) {
    /* read item from buf */
    P(&shared.full);
    item = shared.buf;
    V(&shared.empty);

    /* consume item */
    printf("consumed %d\n", item);
  }
  return NULL;
}
```

Counting with Semaphores

- **Remember, it's a non-negative integer**
  - So, values greater than 1 are legal
- **Lets repeat `thing_5()` 5 times for every 3 of `thing_3()`**

```
/* thing_5 and thing_3 */
#include "csapp.h"

sem_t five;
sem_t three;

void *five_times(void *arg);
void *three_times(void *arg);
```

```
int main() {
  pthread_t tid_five, tid_three;

  /* initialize the semaphores */
  Sem_init(&five, 0, 5);
  Sem_init(&three,  0, 3);

  /* create threads and wait */
  Pthread_create(&tid_five, NULL,
                 five_times, NULL);
  Pthread_create(&tid_three, NULL,
                 three_times, NULL);
  .
  .
  .
}
```

Counting with Semaphores (cont)

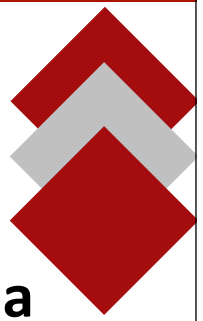
Initially: five = 5, three = 3

```
/* thing_5() thread */
void *five_times(void *arg) {
  int i;

  while (1) {
    for (i=0; i<5; i++) {
      /* wait & thing_5() */
      P(&five);
      thing_5();
    }
    V(&three);
    V(&three);
    V(&three);
  }
  return NULL;
}
```

```
/* thing_3() thread */
void *three_times(void *arg) {
  int i;

  while (1) {
    for (i=0; i<3; i++) {
      /* wait & thing_3() */
      P(&three);
      thing_3();
    }
    V(&five);
    V(&five);
    V(&five);
    V(&five);
    V(&five);
  }
  return NULL;
}
```

Today

- Synchronization
- **Races, deadlocks, thread safety**



One worry: races

- A *race* occurs when correctness of the program depends on a thread reaching point x before another thread reaches point y

```
/* a threaded program with a race */
int main() {
    pthread_t tid[N];
    int i;
    for (i = 0; i < N; i++)
        Pthread_create(&tid[i], NULL, thread, &i);
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    exit(0);
}

/* thread routine */
void *thread(void *vargp) {
    int myid = *((int *)vargp);
    printf("Hello from thread %d\n", myid);
    return NULL;
}
```

Race Elimination

- Make sure there is no unintended sharing of state

```
/* a threaded program with a race removed*/
int main() {
    pthread_t tid[N];
    int i;
    for (i = 0; i < N; i++) {
        int *valp = malloc(sizeof(int));
        *valp = i;
        Pthread_create(&tid[i], NULL, thread, valp);
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    exit(0);
}

/* thread routine */
void *thread(void *vargp) {
    int myid = *((int *)vargp);
    free(vargp);
    printf("Hello from thread %d\n", myid);
    return NULL;
}
```

Another worry: Deadlock

- **Processes wait for condition that will never be true**

- **Typical Scenario**
  - Processes 1 and 2 needs two resources (A and B) to proceed
  - Process 1 acquires A, waits for B
  - Process 2 acquires B, waits for A
  - Both will wait forever!

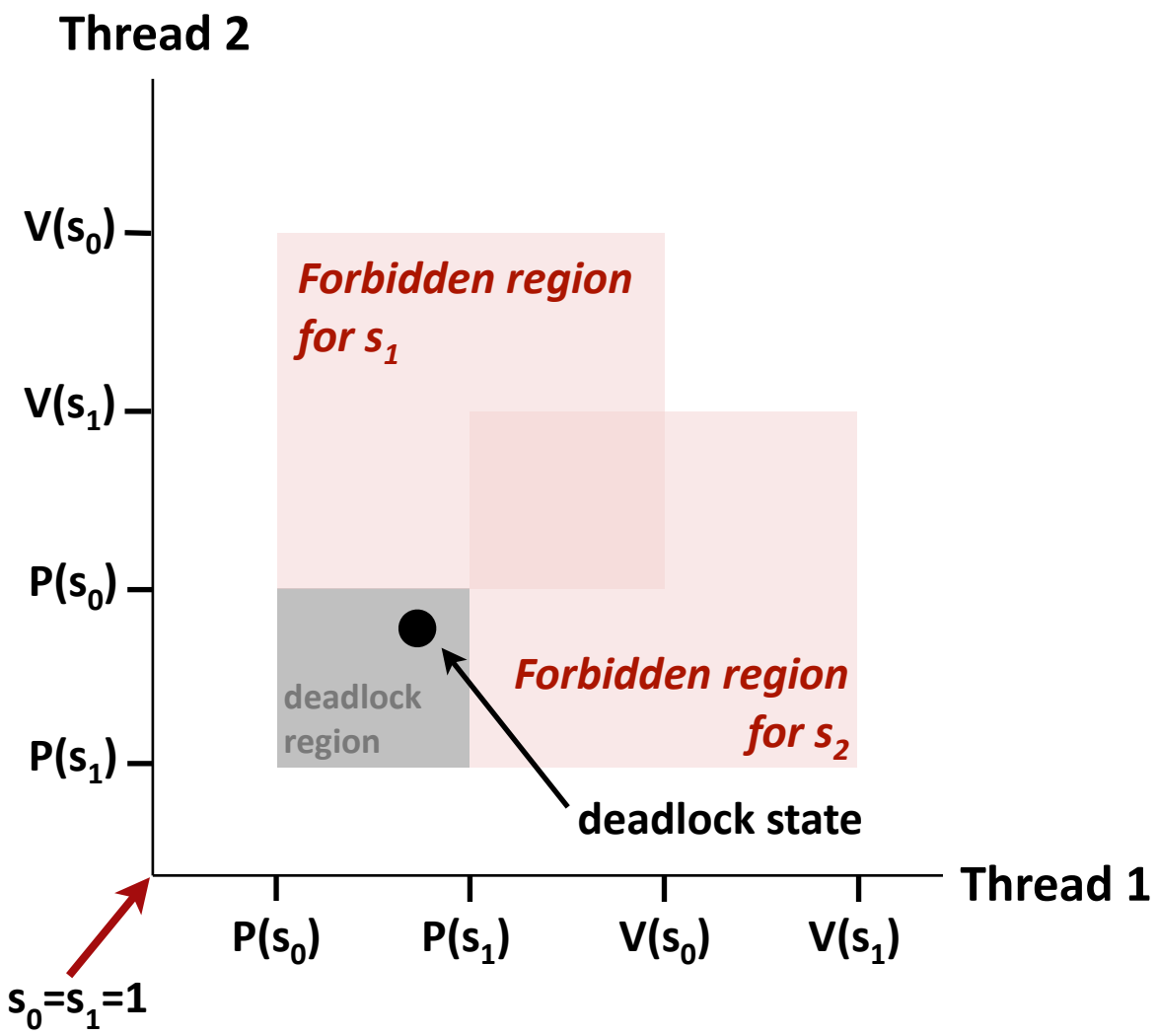
Deadlocking With POSIX Semaphores

```
int main()
{
  pthread_t tid[2];
  Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
  Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
  Pthread_create(&tid[0], NULL, count, (void*) 0);
  Pthread_create(&tid[1], NULL, count, (void*) 1);
  Pthread_join(tid[0], NULL);
  Pthread_join(tid[1], NULL);
  printf("cnt=%d\n", cnt);
  exit(0);
}
```

```
void *count(void *vargp)
{
  int i;
  int id = (int) vargp;
  for (i = 0; i < NITERS; i++) {
    P(&mutex[id]); P(&mutex[1-id]);
    cnt++;
    V(&mutex[id]); V(&mutex[1-id]);
  }
  return NULL;
}
```

Tid[0]:	Tid[1]:
$P(s_0)$;	$P(s_1)$;
$P(s_1)$;	$P(s_0)$;
cnt++;	cnt++;
$V(s_0)$;	$V(s_1)$;
$V(s_1)$;	$V(s_0)$;

Deadlock Visualized in Progress Graph



Locking introduces the potential for *deadlock:* waiting for a condition that will never be true

Any trajectory that enters the *deadlock region* will eventually reach the *deadlock state,* waiting for either s_0 or s_1 to become nonzero

Other trajectories luck out and skirt the deadlock region

Unfortunate fact: deadlock is often non-deterministic

Avoiding Deadlock

Acquire shared resources in the same order

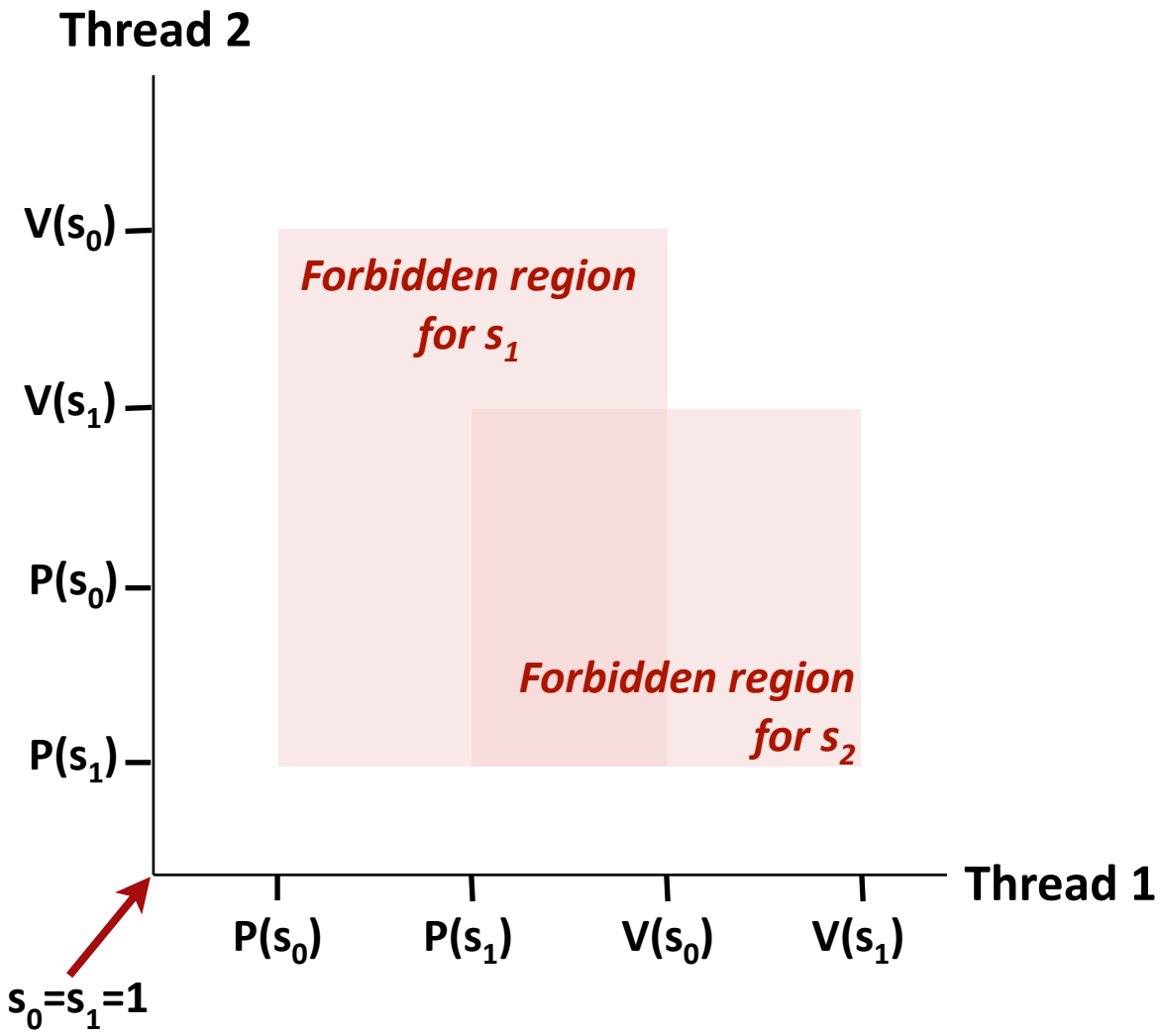
```
int main()
{
  pthread_t tid[2];
  Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
  Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
  Pthread_create(&tid[0], NULL, count, (void*) 0);
  Pthread_create(&tid[1], NULL, count, (void*) 1);
  Pthread_join(tid[0], NULL);
  Pthread_join(tid[1], NULL);
  printf("cnt=%d\n", cnt);
  exit(0);
}
```

```
void *count(void *vargp)
{
  int i;
  int id = (int) vargp;
  for (i = 0; i < NITERS; i++) {
    P(&mutex[0]); P(&mutex[1]);
    cnt++;
    V(&mutex[id]); V(&mutex[1-id]);
  }
  return NULL;
}
```

```
Tid[0]:
P(s0);
P(s1);
cnt++;
V(s0);
V(s1);
```

```
Tid[1]:
P(s0);
P(s1);
cnt++;
V(s1);
V(s0);
```

Avoided Deadlock in Progress Graph



No way for trajectory to enter a deadlock region

Threads acquire locks in the same order

Order in which locks are released is immaterial

Crucial concept: Thread Safety

- **Functions called from a thread (without external synchronization) must be *thread-safe***
  - Meaning: it must always produce correct results when called repeatedly from multiple concurrent threads

- **Some examples of thread-unsafe activities:**
  - Failing to protect shared variables
  - Relying on persistent state across invocations
  - Returning a pointer to a static variable
  - Calling a thread-unsafe functions

Thread-Unsafe Functions (Class 1)

- **Failing to protect shared variables**
  - Fix: Use P and V semaphore operations
  - Example: **`goodcnt.c`**
  - Issue: Synchronization operations will slow down code
    - e.g., **`badcnt`** requires 0.5s, **`goodcnt`** requires 7.9s

Thread-Unsafe Functions (Class 2)

- **Relying on persistent state across multiple function invocations**
  - Example: Random number generator (RNG) that relies on static state

```
/* rand: return pseudo-random integer on 0..32767 */
static unsigned int next = 1;
int rand(void)
{
    next = next*1103515245 + 12345;
    return (unsigned int)(next/65536) % 32768;
}

/* srand: set seed for rand() */
void srand(unsigned int seed)
{
    next = seed;
}
```

Making Thread-Safe RNG

- **Pass state as part of argument**
  - and, thereby, eliminate static state

```
/* rand - return pseudo-random integer on 0..32767 */

int rand_r(int *nextp)
{
  *nextp = *nextp*1103515245 + 12345;
  return (unsigned int)(*nextp/65536) % 32768;
}
```

- **Consequence: programmer using `rand_r` must maintain seed**

Thread-Unsafe Functions (Class 3)

- **Returning a ptr to a `static` variable**

```
struct hostent
*gethostbyname(char name)
{
  static struct hostent h;
  <contact DNS and fill in h>
  return &h;
}
```

- **Fixes:**
  - 1. Rewrite code so caller passes pointer to **`struct`**
    - Issue: Requires changes in caller and callee

```
hostp = Malloc(...);
gethostbyname_r(name, hostp);
```

  - 2. ***Lock-and-copy***
    - Issue: Requires only simple changes in caller (and none in callee)
    - However, caller must free memory

```
struct hostent
*gethostbyname_ts(char *name)
{
  struct hostent *q = Malloc(...);
  struct hostent *p;
  P(&mutex); /* lock */
  p = gethostbyname(name);
  *q = *p;   /* copy */
  V(&mutex);
  return q;
}
```

Thread-Unsafe Functions (Class 4)

- **Calling thread-unsafe functions**
  - Calling one thread-unsafe function makes the entire function that calls it thread-unsafe
  - Fix: Modify the function so it calls only thread-safe functions ☺

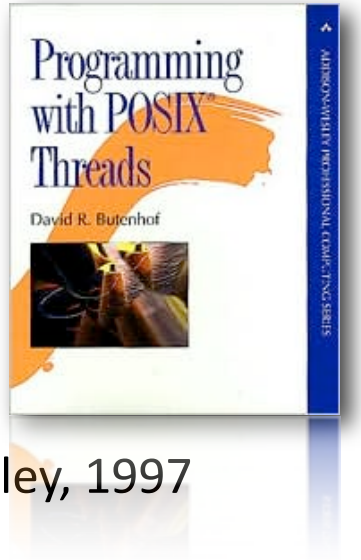
Thread-Safe Library Functions

- **All functions in the Standard C Library (at the back of your K&R text) are thread-safe**
  - Examples: `malloc`, `free`, `printf`, `scanf`
- **Most Unix system calls are thread-safe, with a few exceptions:**

Thread-unsafe function	Class	Reentrant version
`asctime`	3	`asctime_r`
`ctime`	3	`ctime_r`
`gethostbyaddr`	3	`gethostbyaddr_r`
`gethostbyname`	3	`gethostbyname_r`
`inet_ntoa`	3	`(none)`
`localtime`	3	`localtime_r`
`rand`	2	`rand_r`

Threads Summary

- **Threads provide another mechanism for writing concurrent programs**
- **Threads are growing in popularity**
  - Somewhat cheaper than processes
  - Easy to share data between threads
- **However, the ease of sharing has a cost:**
  - Easy to introduce subtle synchronization errors
    - Which are very, very, very, very, very difficult to discover
  - Tread carefully with threads!



- **For more info:**
  - D. Butenhof, “Programming with Posix Threads”, Addison-Wesley, 1997

Summary

- **Synchronization**
  - Shared variables
  - Process graphs
- **Thread Safety**
  - Deadlocks, semaphores

- **Next Time:**
  - Multi-core Architectures