Introduction to Computer Systems

15-213, fall 2009
26th Lecture, Nov. 25th

Instructors:

Majd Sakr and Khaled Harras

Today

- Threads: basics
- Synchronization
- Races, deadlocks, thread safety

Process: Traditional View

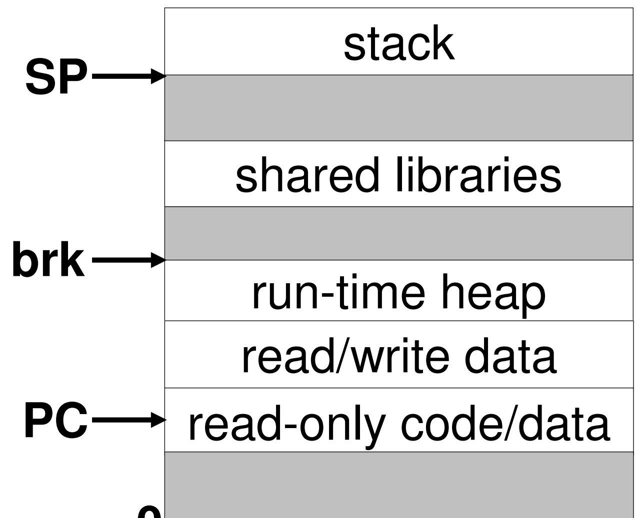
- **Process = process context + code, data, and stack**

Process context

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

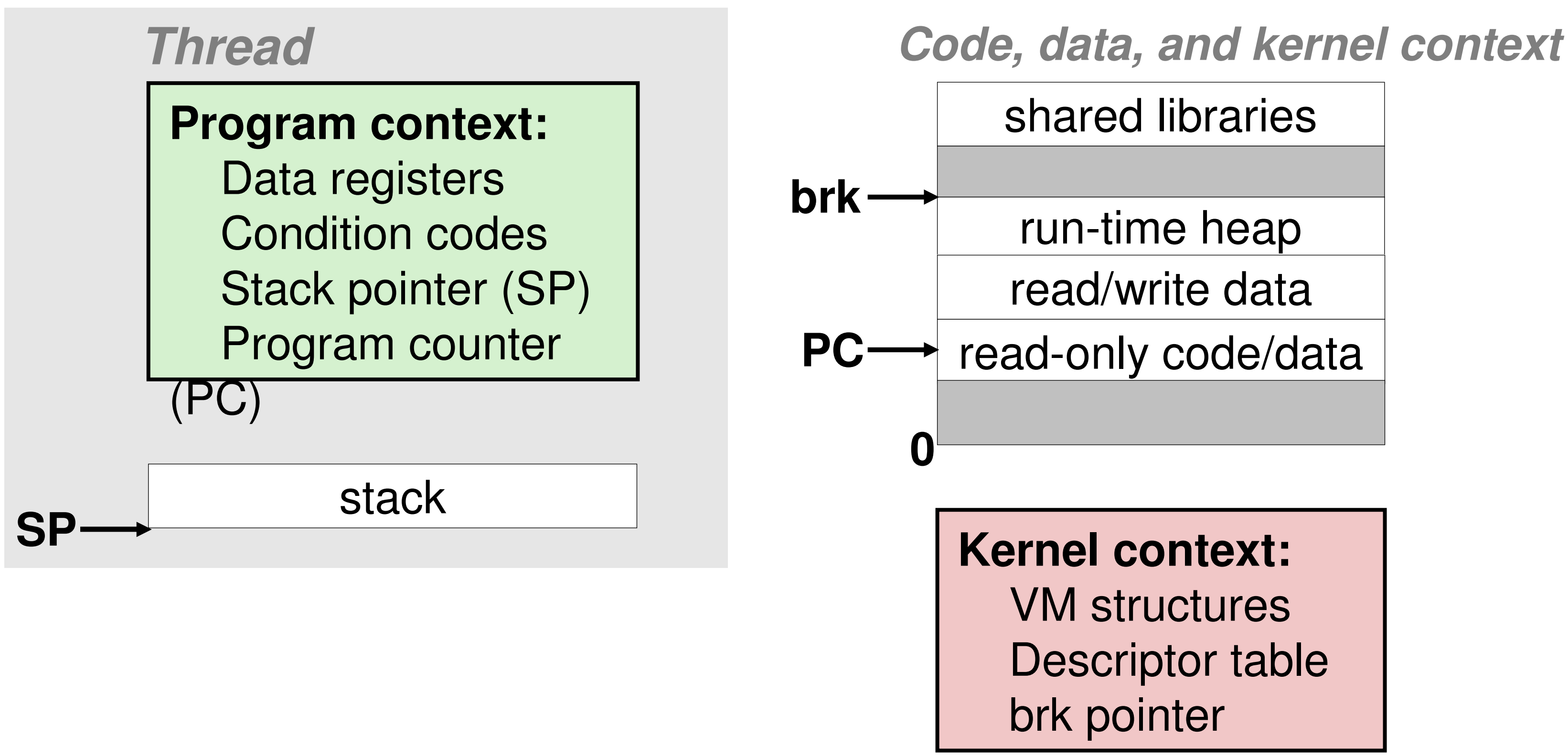
Kernel context:
VM structures
Descriptor table
brk pointer

Code, data, and stack

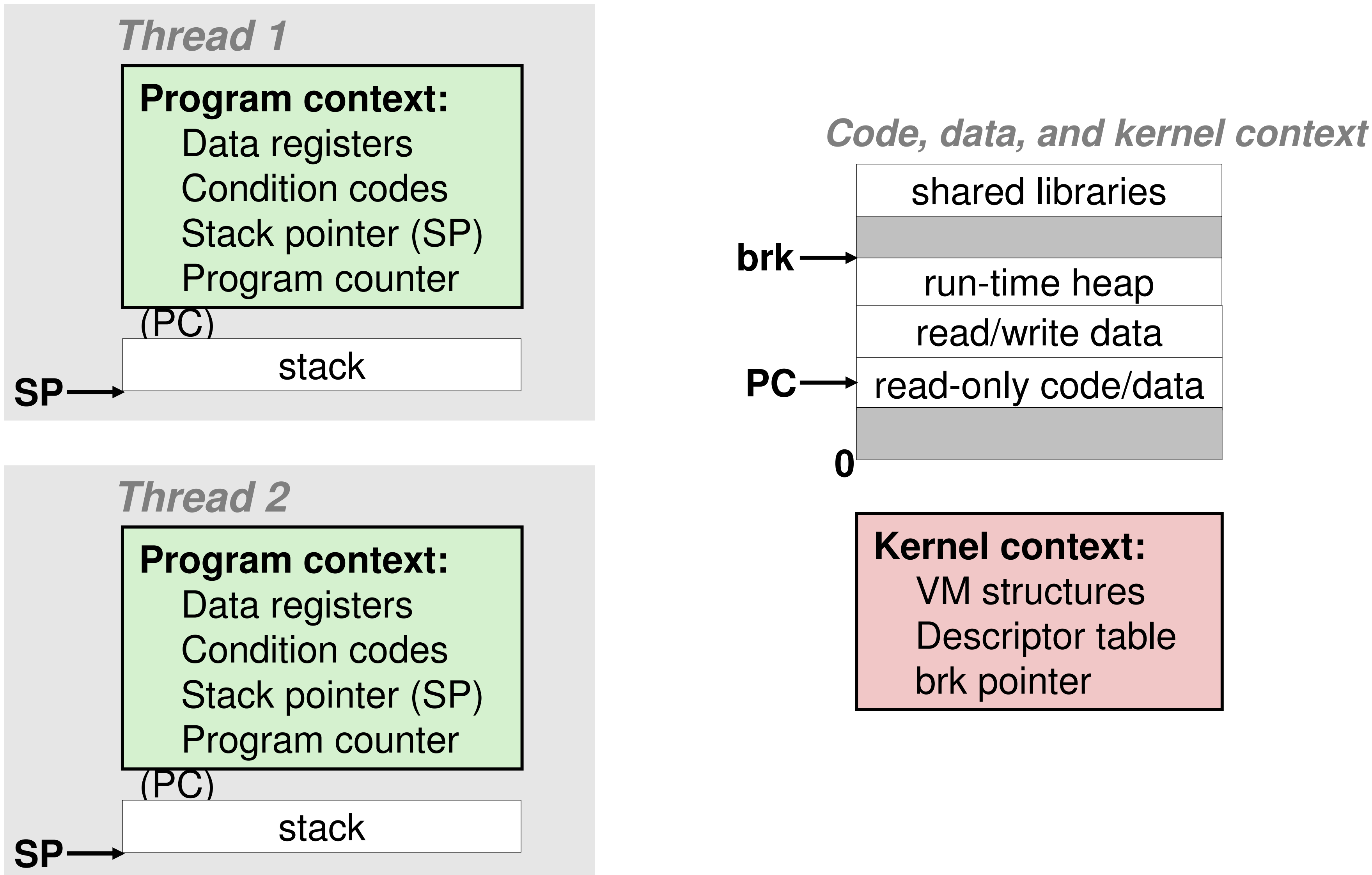


Process: Alternative View

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



Process with Two Threads



Threads vs. Processes

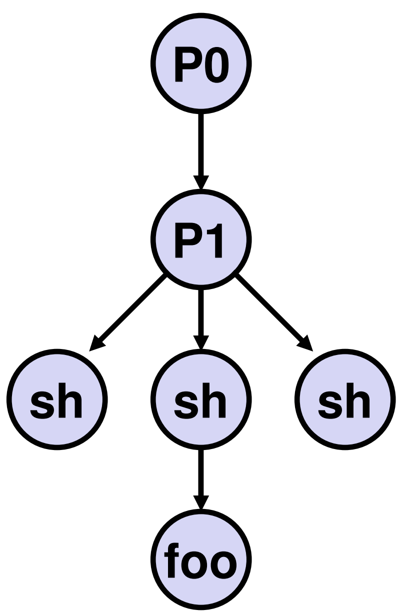
- **Threads and processes: similarities**
  - Each has its own logical control flow
  - Each can run concurrently with others
  - Each is context switched (scheduled) by the kernel

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

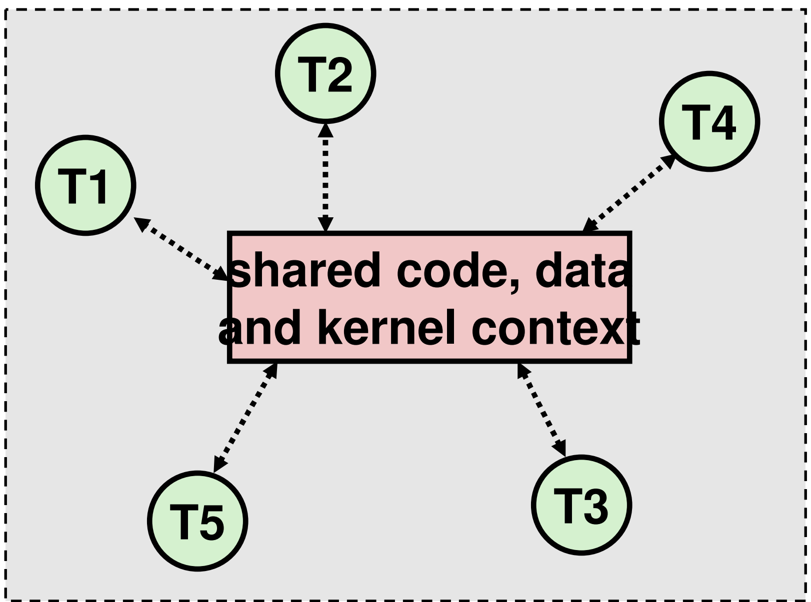
Threads vs. Processes (contd.)

- **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 *tread_return)`
    - `return` (in primary thread routine terminates the thread)
    - `exit()` (terminates all threads)
  - Synchronizing access to shared variables

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)*

Detaching Threads

- **Thread-based servers: Use "detached" threads to avoid memory leaks**
  - At any point in time, a thread is either ***joinable*** or ***detached***
  - ***Joinable*** thread can be reaped and killed by other threads
    - must be reaped (with **`pthread_join`**) to free memory resources
  - ***Detached*** thread cannot be reaped or killed by other threads
    - resources are automatically reaped on termination
  - Default state is joinable
    - use **`pthread_detach(pthread_self())`** to make detached

- **Must be careful to avoid unintended sharing**
  - For example, what happens if we pass the address of connfd to the thread routine?
    - ```
      Pthread_create(&tid, NULL, thread,
         (void *)&connfd);
      ```
      ```

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

Today

- Threads: basics
- **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 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

- ***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

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

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!

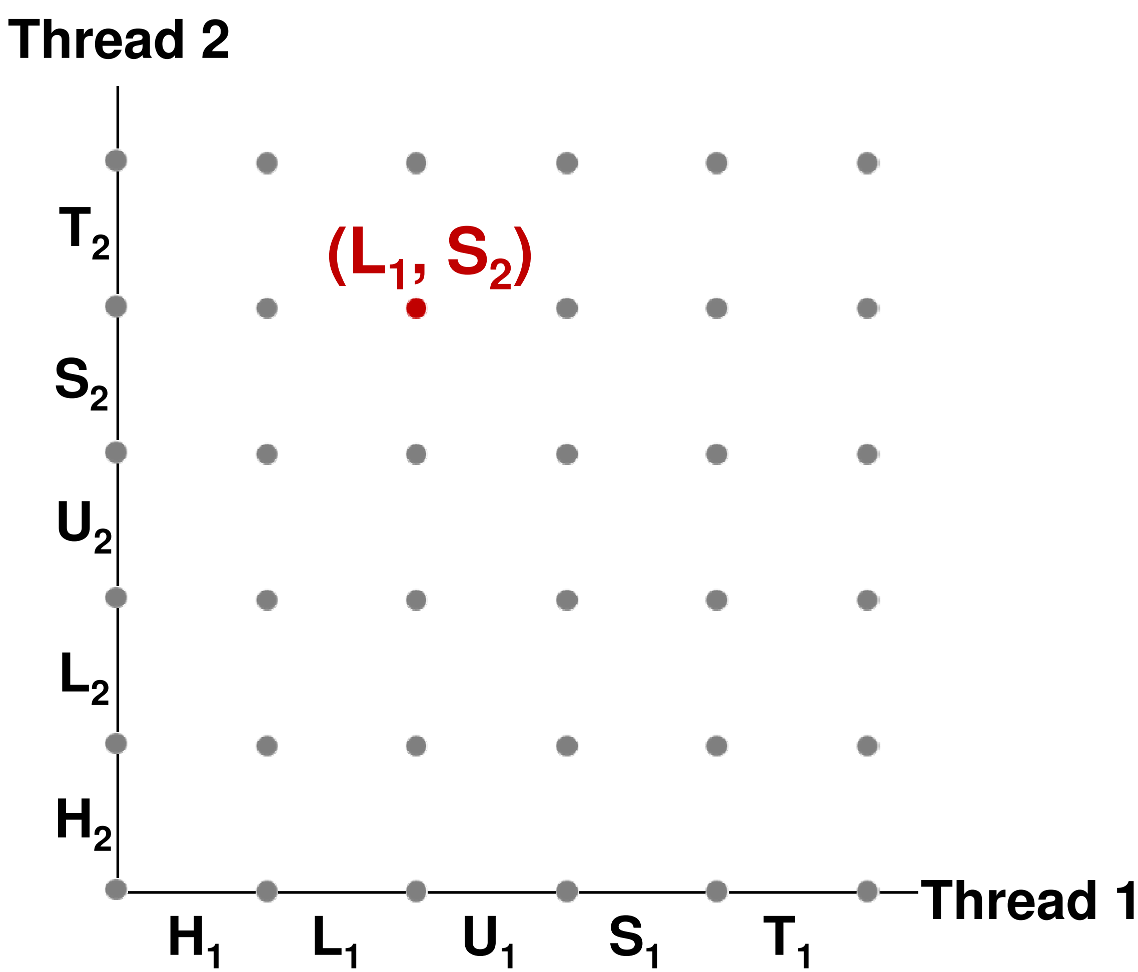
Concurrent Execution (cont)

- How about this ordering?

i (thread)	$instr_i$	$\%eax_1$	$\%eax_2$	cnt
1	H_1			
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 behaviour using a ***process graph***

Progress Graphs



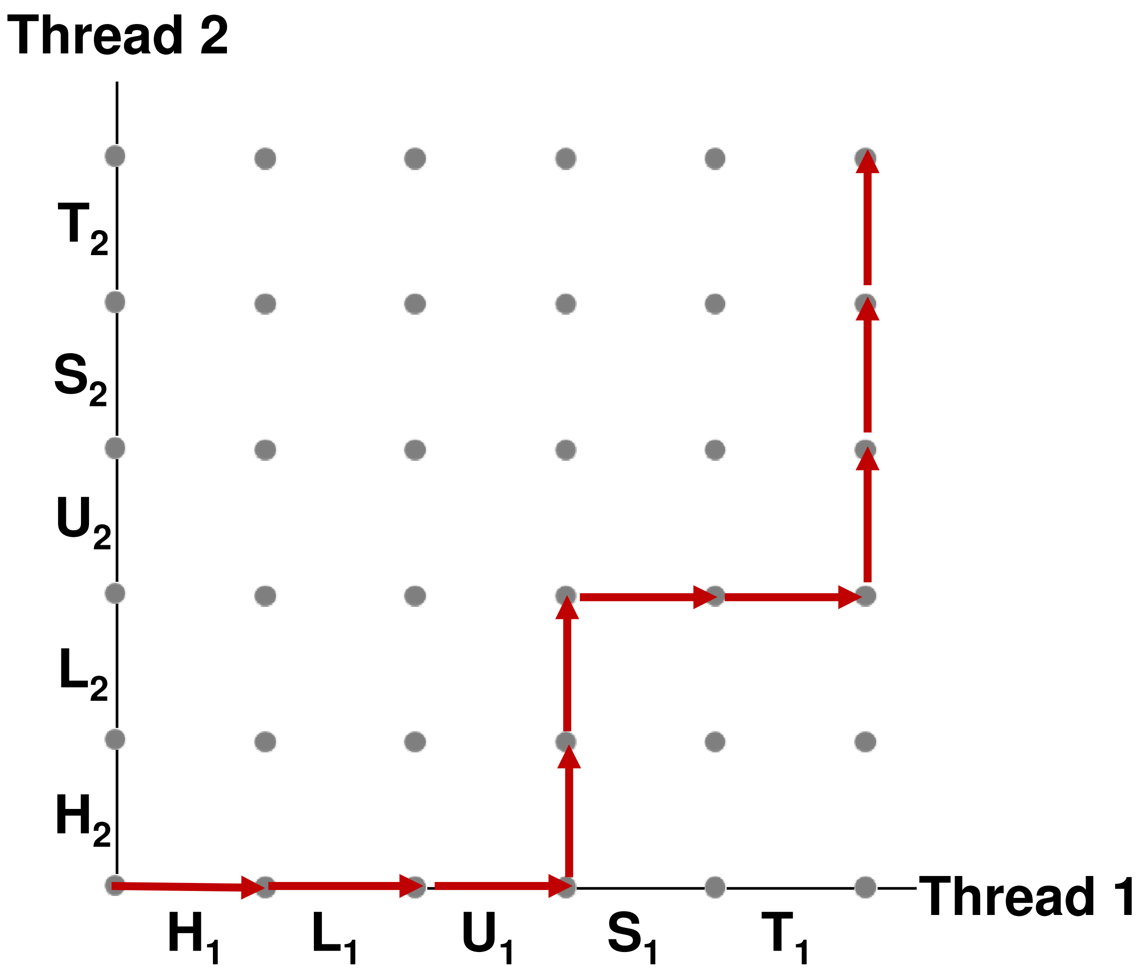
A ***progress graph*** depicts the discrete ***execution state space*** of concurrent threads.

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

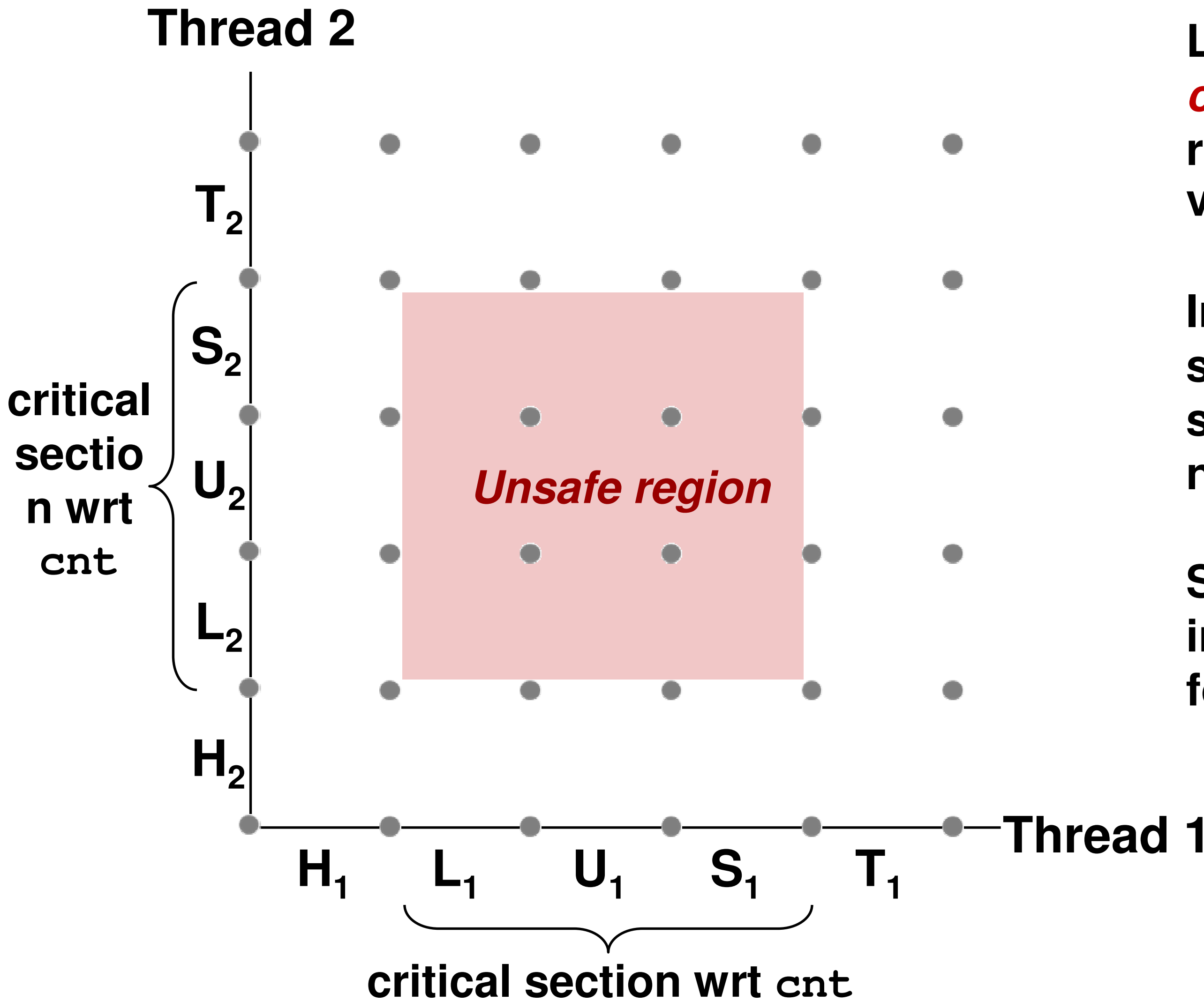


A ***trajectory*** is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Critical Sections and Unsafe Regions

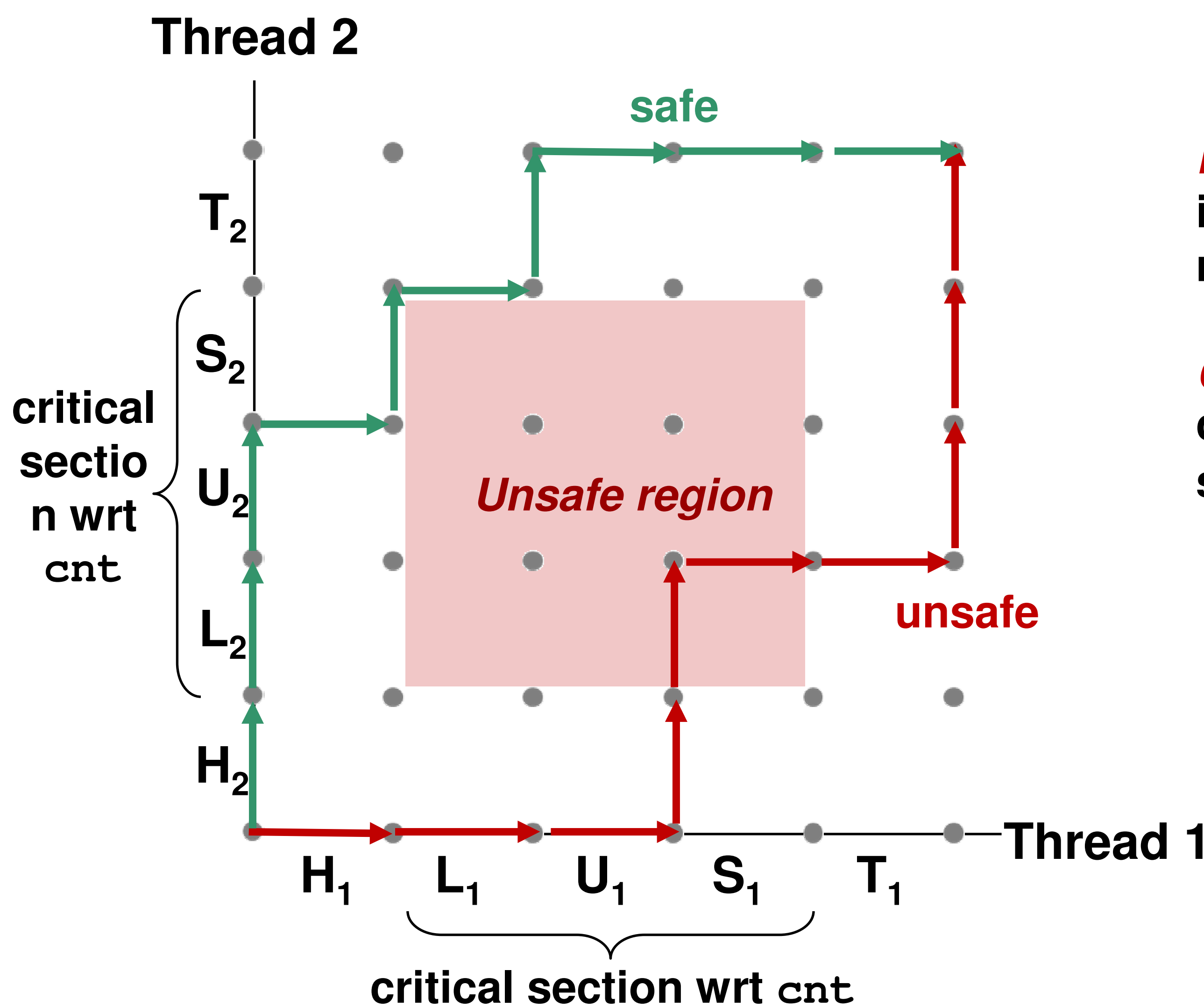


L, U, and S form a *critical section* with respect to the shared variable `cnt`

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



Definition: A trajectory is *sa*
iff it does not enter any uns
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`

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

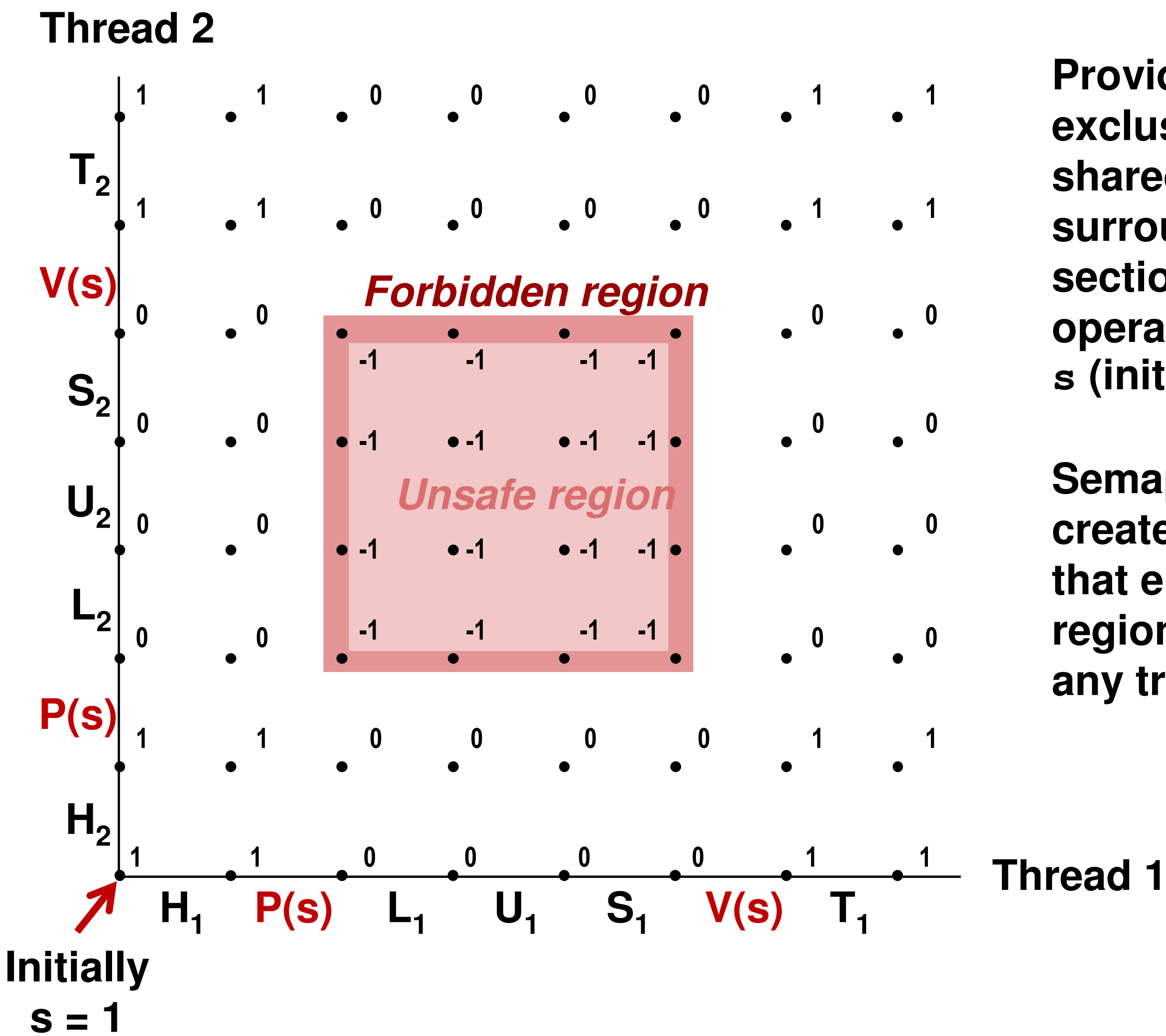
- One semaphore per shared variable
- Initially set to 1
- Here is how we would use P and V operations to synchronize the threads that update `cnt`

```
/* 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;
}
```

Warning:

It's really slow!

Today

- Threads: basics
- Synchronization
- **Races, deadlocks, thread safety**

One worry: races

- A ***race*** **occurs when correctness of the program depends on one 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 don't have unintended sharing of state**

```
/* a threaded program with a race */
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!

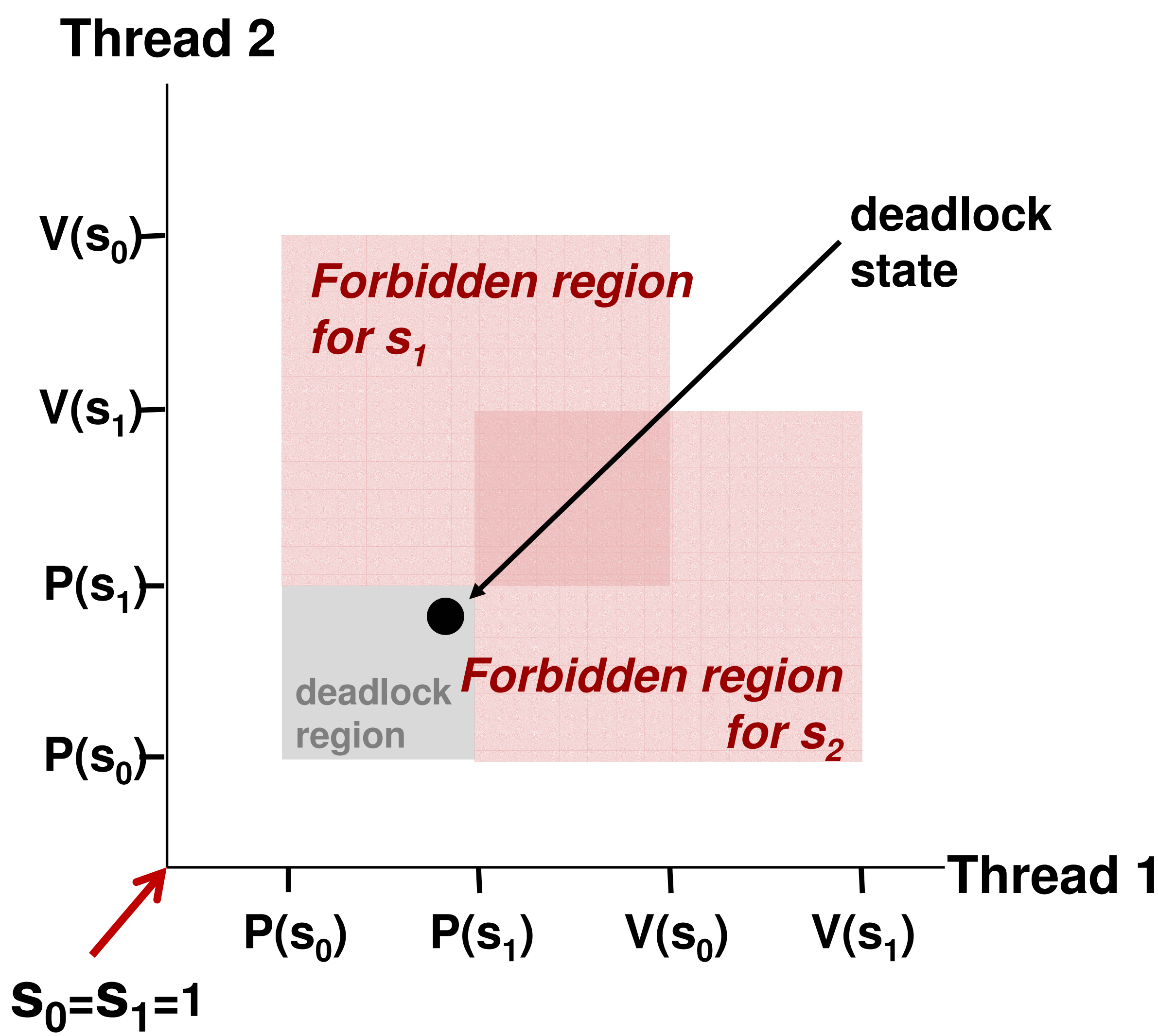
Deadlocking With POSIX Semaphores

```
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

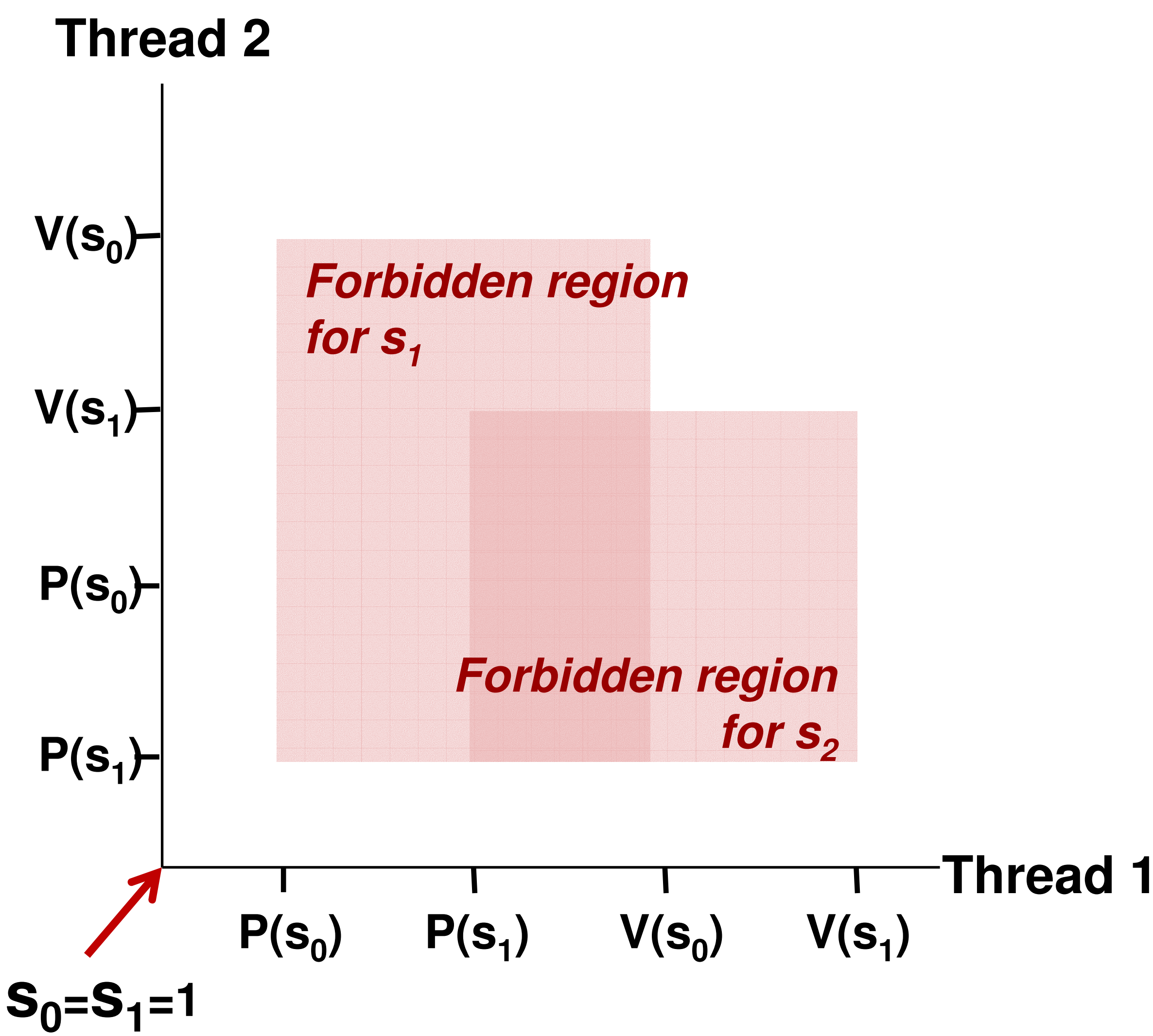
Acquire shared resources in same order

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

Avoided Deadlock in Progress Graph



No way for trajectory to get stuck

Processes acquire locks in same order

Order in which locks released 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 functions:**
  - Failing to protect shared variables
  - Relying on persistent state across invocations
  - Returning a pointer to a static variable
  - Calling 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

```
/* 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 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)

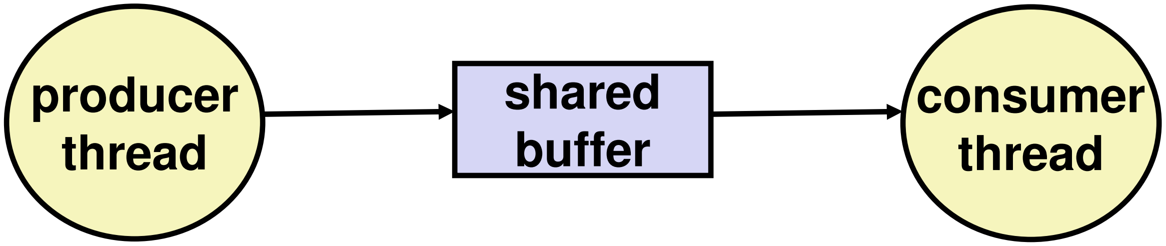
- **Calling thread-unsafe functions**
  - Calling one thread-unsafe function makes the entire function that calls it thread-unsafe
  - Fix: Modify the function so it calls only thread-safe functions ☺

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`

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;
}
```

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

Beware of Optimizing Compilers!

Code From Book

```
#define NITERS 100000000

/* shared counter variable */
unsigned int cnt = 0;

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

- Global variable `cnt` shared between threads
- Multiple threads could be trying to update within their iterations

Generated Code

```
movl    cnt, %ecx
movl    $99999999, %eax
.L6:
   leal   1(%ecx), %edx
   decl   %eax
   movl   %edx, %ecx
   jns    .L6
   movl   %edx, cnt
```

- Compiler moved access to `cnt` out of loop
- Only shared accesses to `cnt` occur before loop (read) or after (write)
- What are possible program outcomes?

Controlling Optimizing Compilers!

Revised Book Code

```
#define NITERS 100000000

/* shared counter variable */
volatile unsigned int cnt = 0;

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

Generated Code

```
    movl $99999999, %edx
.L15:
    movl cnt,  %eax
    incl %eax
    decl %edx
    movl %eax,  cnt
    jns  .L15
```

- Declaring variable as volatile forces it to be kept in memory
- Shared variable read and written each iteration