15-213

"The course that gives CMU its Zip!"

Programming with Threads
December 7, 2004

Topics

- Shared variables
- The need for synchronization
- Synchronizing with semaphores
- Thread safety and reentrancy
- Races and deadlocks

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 memory instances?
- How many threads 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:

- **While register values are truly separate and protected....**
- **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.

Example of Threads Accessing Another Thread's Stack

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

int main()
{
    int i;
    pthread_t tid;
    char *msgs[N] = {
        "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 Mem. Instances

Global var: 1 instance (`ptr` [data])

Local automatic vars: 1 instance (`i.m, msgs.m`)

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

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

int main()
{
    int i;
    pthread_t tid;
    char *msgs[N] = {
        "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);
}
```

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: An Improperly Synchronized Threaded Program

```
/* 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

```
for (i=0; i<NITERS; i++)
    cnt++;
```

Corresponding asm 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 are incorrect!

- I_i denotes that thread i executes instruction I
- $\%eax_i$ is the contents 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 clarify our understanding of concurrent execution with the help of the *progress graph*

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;
}
```

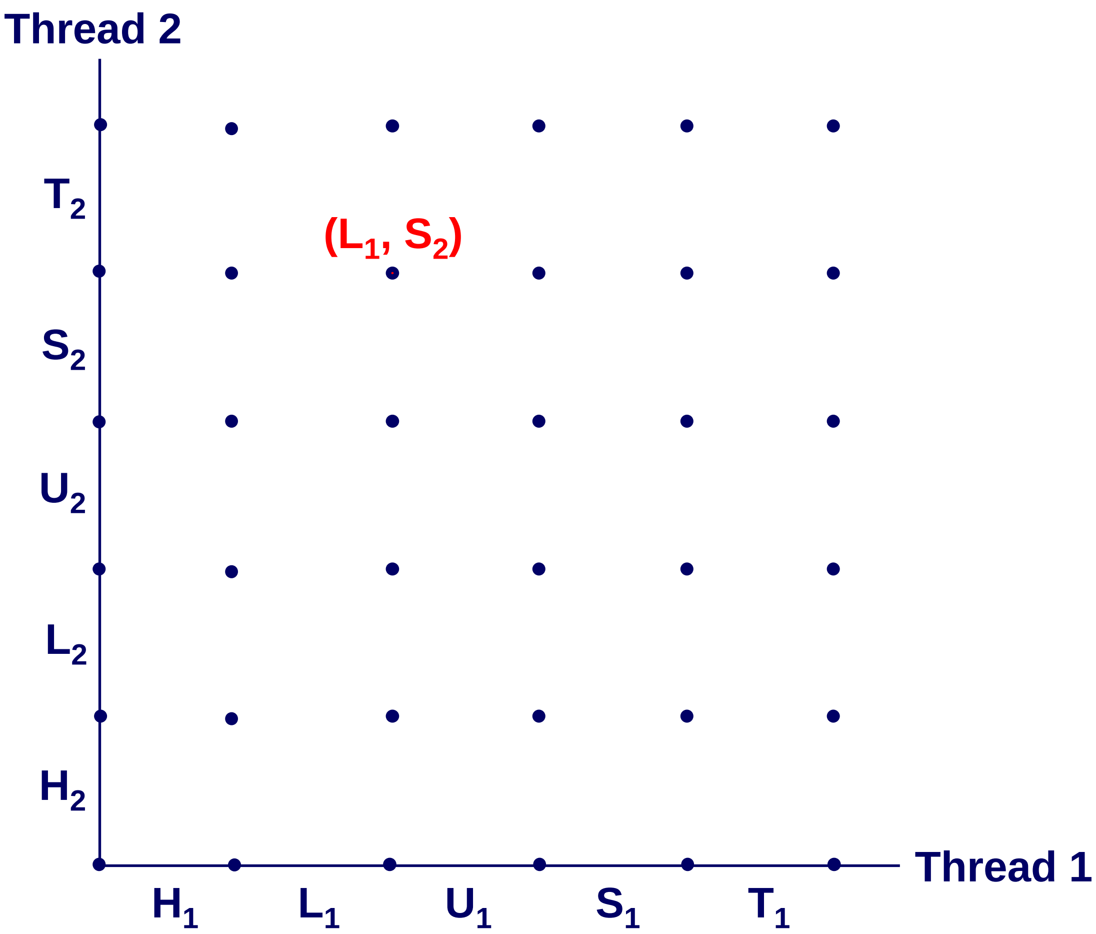
Generated Code

```
        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

Progress Graphs



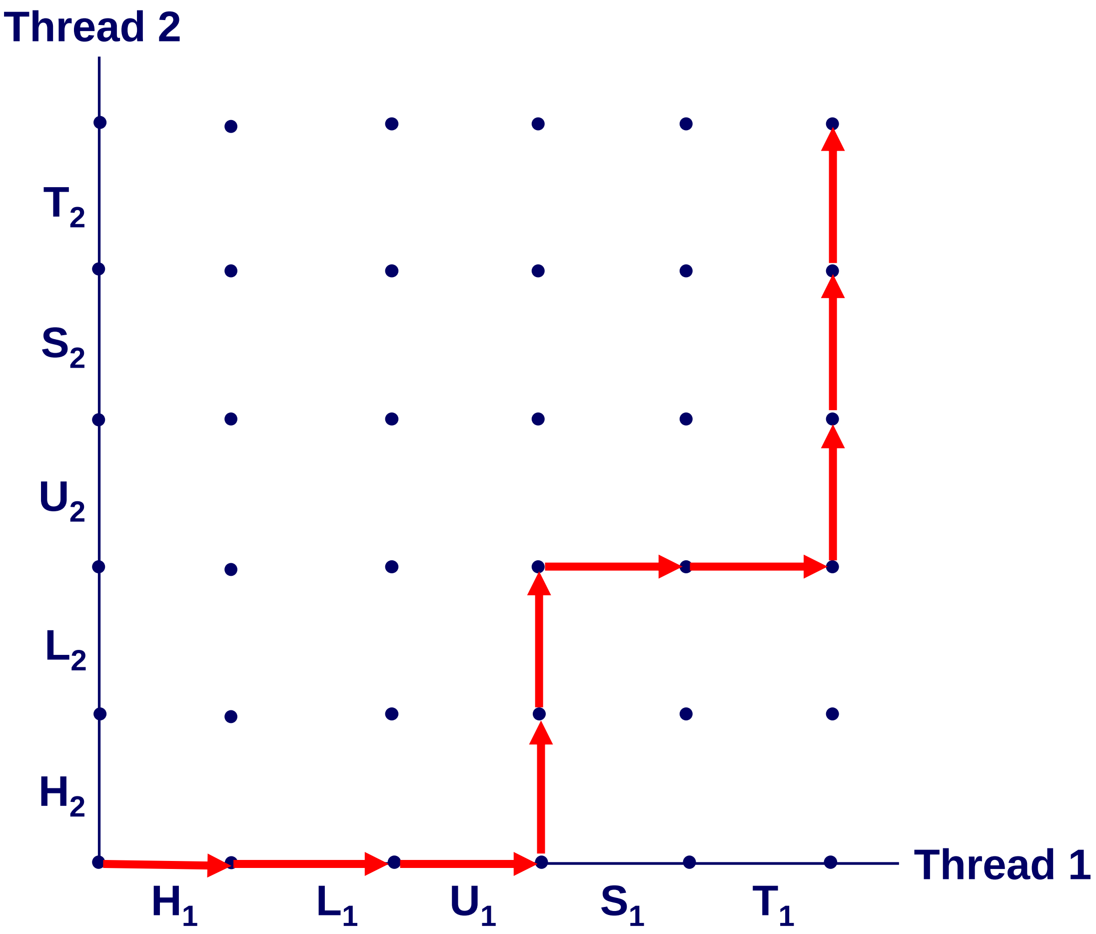
A *progress graph* depicts the discrete *execution state space* of concurrent threads.

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

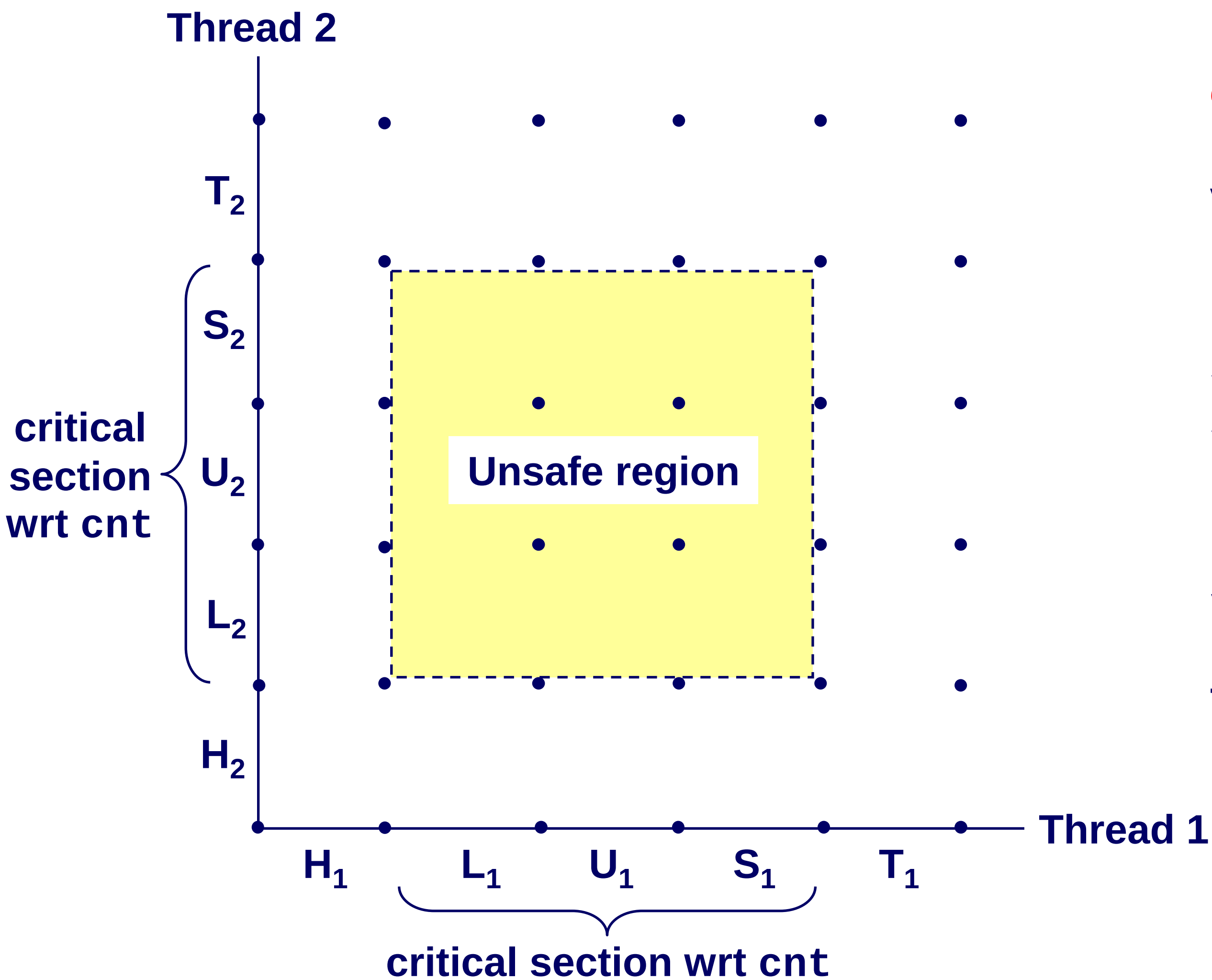


A ***trajectory*** **is a sequence of legal state transitions that describes one possible concurrent execution of the threads.**

Example:

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

Critical Sections and Unsafe Regions

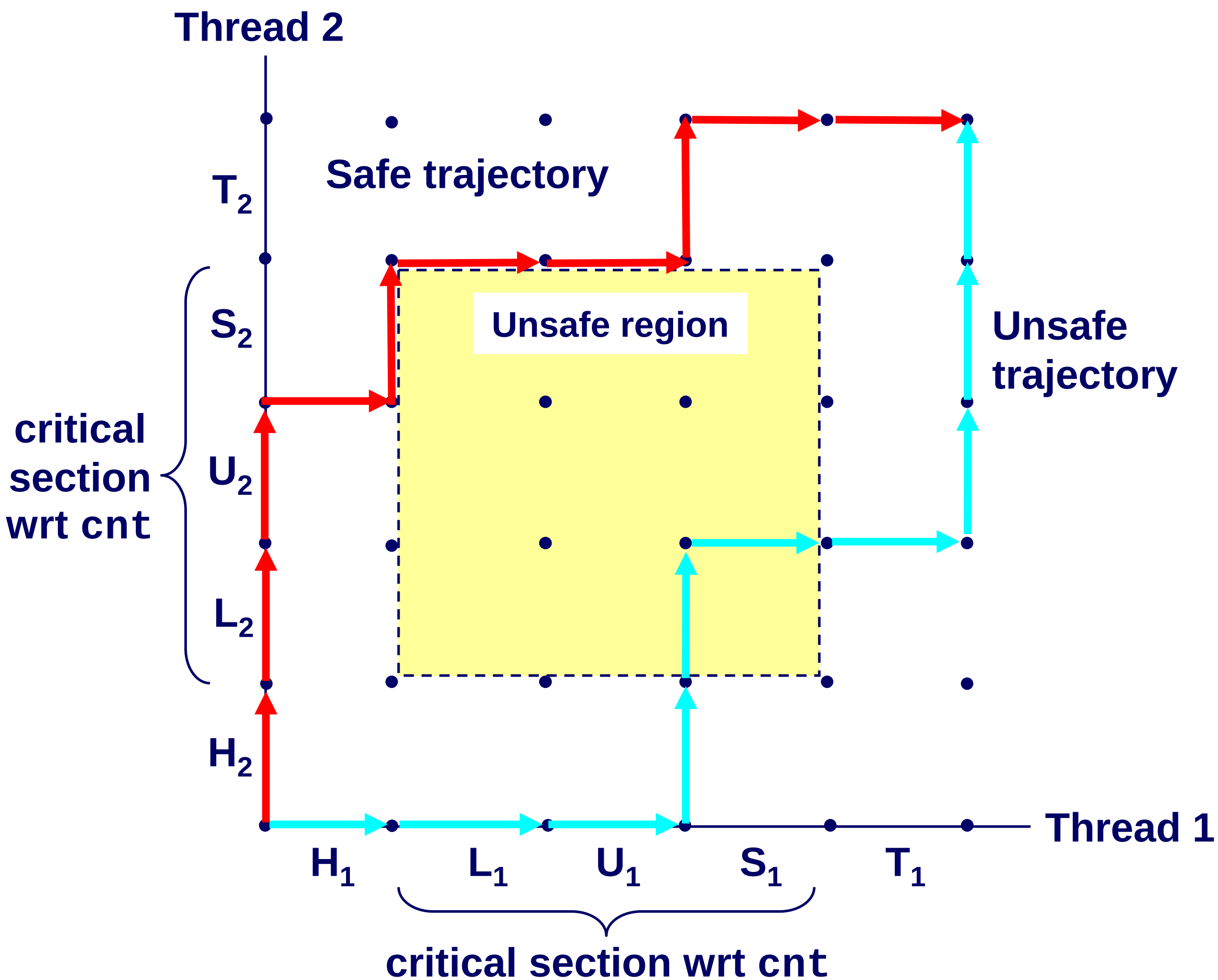


L, U, and S form a *critical section* with respect to the shared variable `cnt` .

Instructions in critical sections (wrt to some shared variable) should not be interleaved.

Sets of states where such interleaving occurs form *unsafe regions*.

Safe and Unsafe Trajectories



Def: **A trajectory is *safe* iff it doesn't touch any part of an 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 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.**

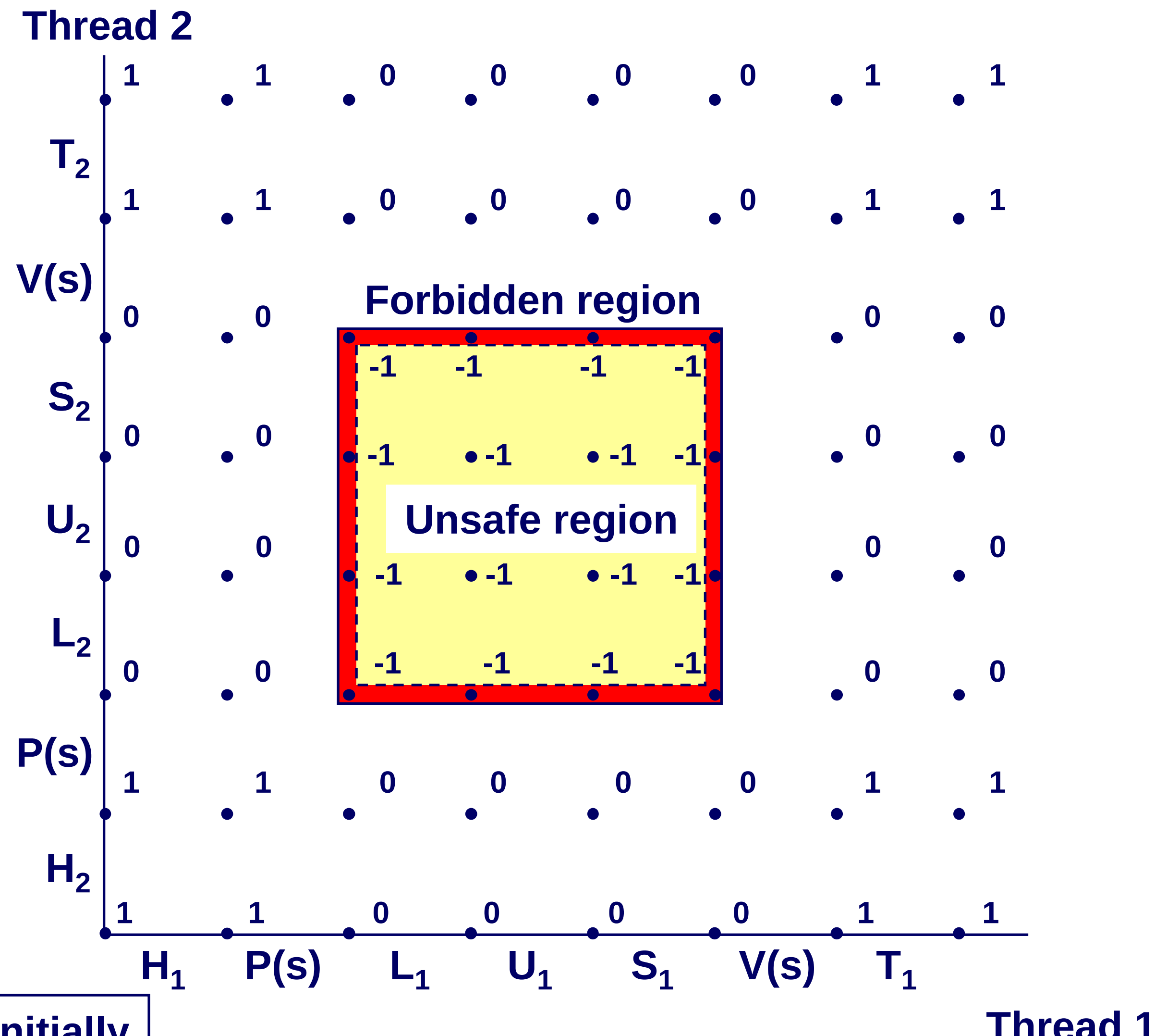
Semaphore invariant: *(s >= 0)*

Safe Sharing with Semaphores

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



Initially
s = 1

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 never touched by any trajectory.

Wrappers on POSIX Semaphores

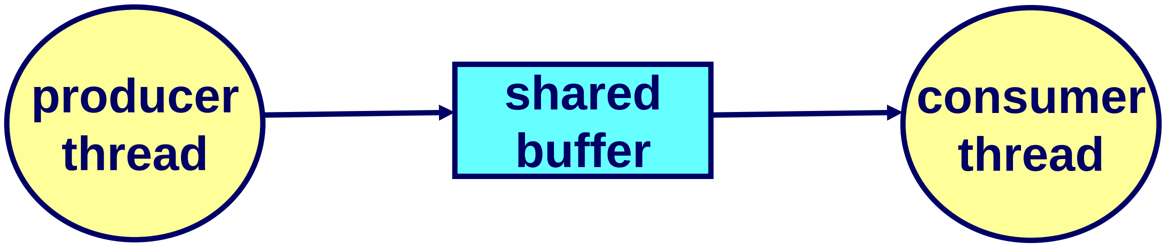
```
/* Initialize semaphore sem to value */
/* pshared=0 if thread, pshared=1 if process */
void Sem_init(sem_t *sem, int pshared, unsigned int value) {
  if (sem_init(sem, pshared, value) < 0)
    unix_error("Sem_init");
}

/* 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;
}
```

Signaling With Semaphores



Common synchronization pattern:

- Producer waits for slot, inserts item in buffer, and "*signals*" consumer.
- Consumer waits for item, removes it from buffer, and "signals" producer.
  - "signals" in this context has nothing to do with Unix signals

Examples

- Multimedia processing:
  - Producer creates MPEG video frames, consumer renders the frames
- 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;
}
```

Thread Safety

Functions called from a thread must be *thread-safe*.

We identify four (non-disjoint) classes of thread-unsafe functions:

- **Class 1: Failing to protect shared variables.**
- **Class 2: Relying on persistent state across invocations.**
- **Class 3: Returning a pointer to a static variable.**
- **Class 4: 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 (cont)

Class 2: Relying on persistent state across multiple function invocations.

- Random number generator relies on static state

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

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

- Fix: Rewrite function so that caller passes in all necessary state.

Thread-Unsafe Functions (cont)

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

Class 3: Returning a ptr to a `static` variable.

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

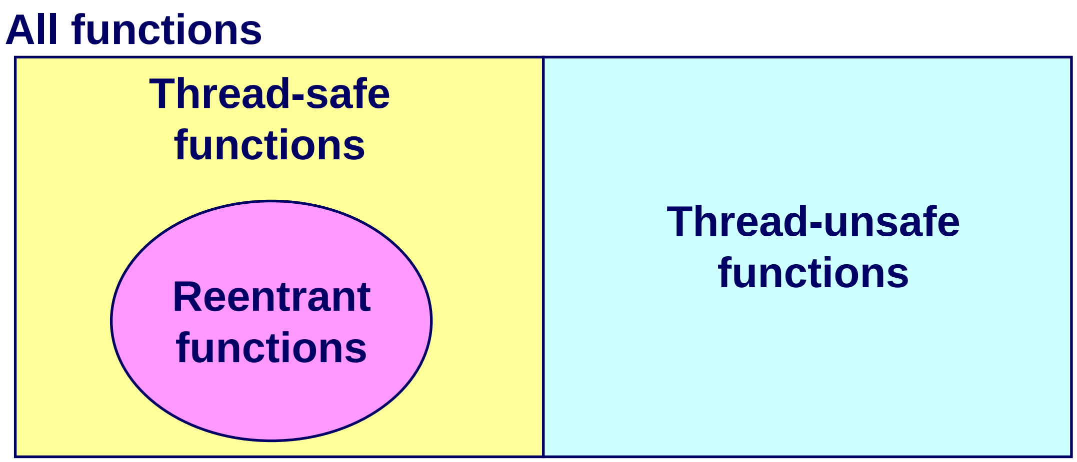
Class 4: Calling thread-unsafe functions.

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

Reentrant Functions

A function is *reentrant* iff it accesses NO shared variables when called from multiple threads.

- **Reentrant functions are a proper subset of the set of thread-safe functions.**



- **NOTE: The fixes to Class 2 and 3 thread-unsafe functions require modifying the function to make it reentrant.**

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`

Races

- A ***race*** occurs when the 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;
}
```

Deadlock

- Processes wait for condition that will never be true

Typical Scenario

- Processes 1 and 2 needs 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

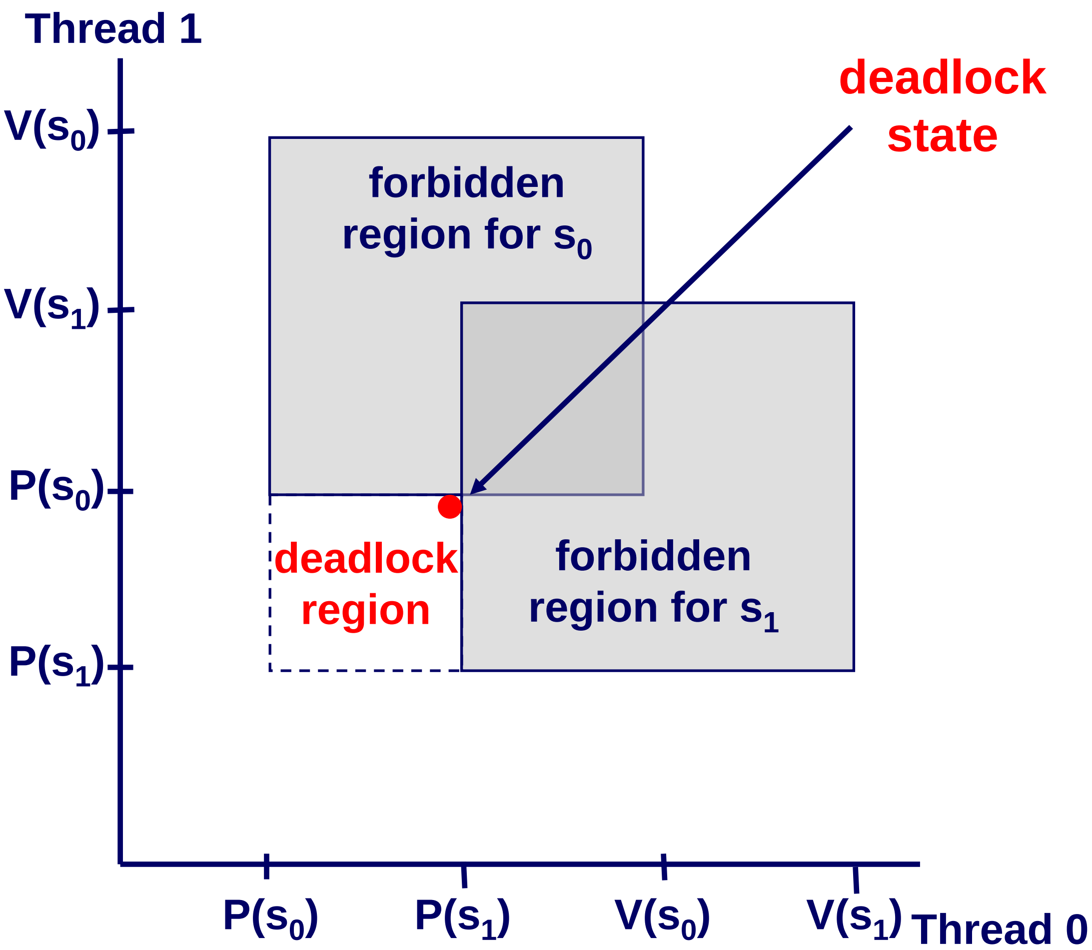
```
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], 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]:
P(s_0);
P(s_1);
cnt++;
V(s_0);
V(s_1);

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

Deadlock



Initially, $s_0=s_1=1$

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

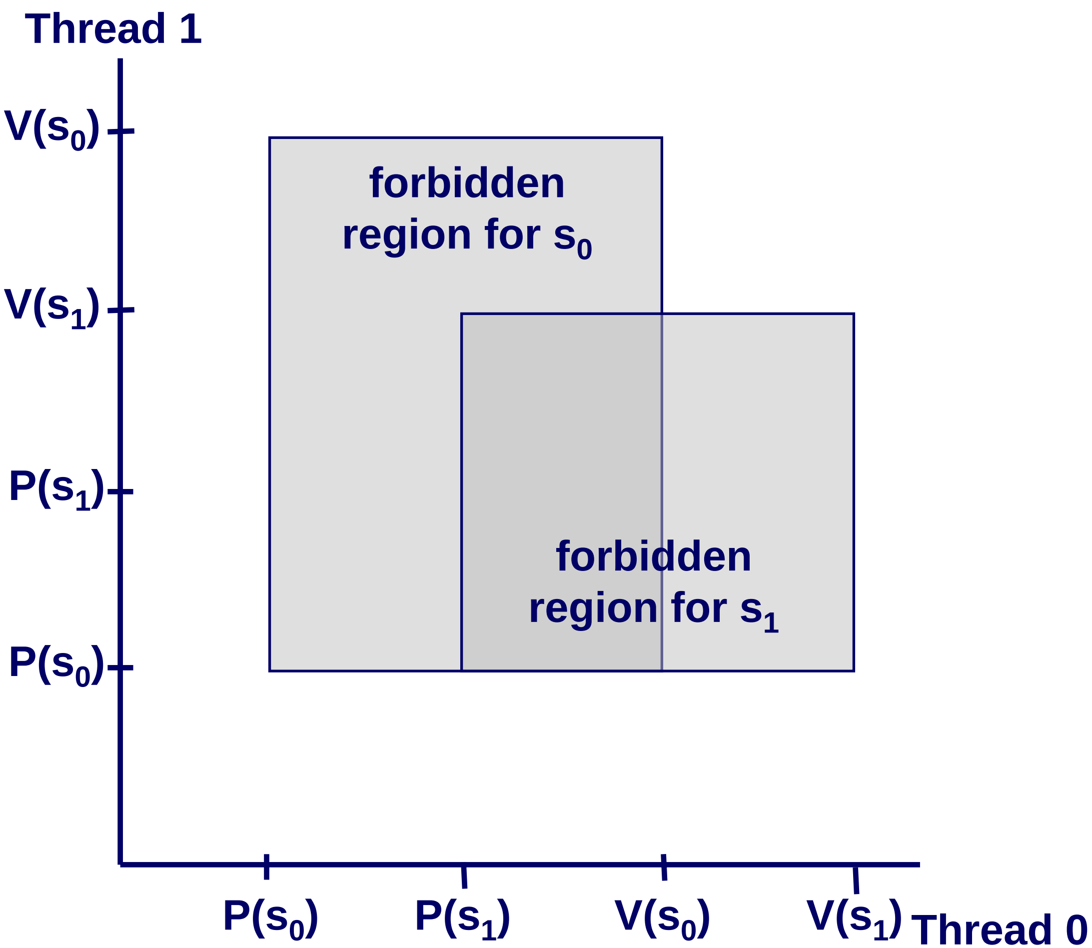
```
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], 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]:
$P(s_0)$;
$P(s_1)$;
cnt++;
$V(s_0)$;
$V(s_1)$;

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

Removed Deadlock



Initially, s_0=s_1=1

- No way for trajectory to get stuck
- Processes acquire locks in same order
- Order in which locks released immaterial

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.