15-213

"The course that gives CMU its Zip!"

Synchronization
April 29, 2008

Topics

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

class25.ppt

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`)

```
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);
}
```

Local automatic 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`: 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

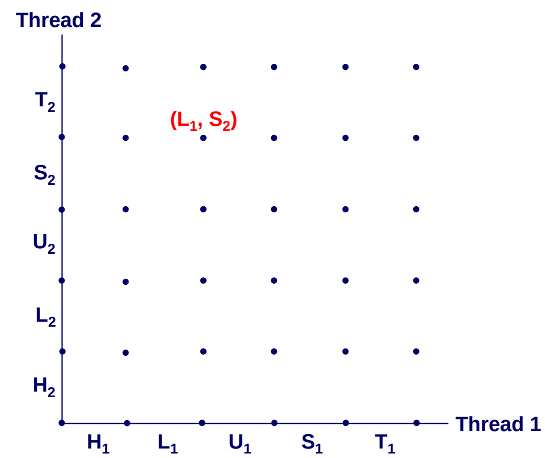
```
#define NITERS 100000000

/* 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



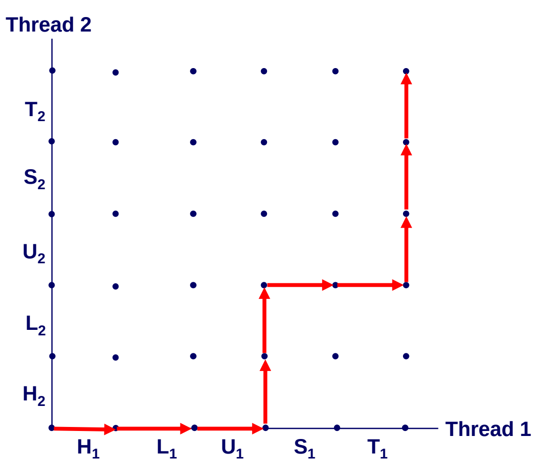
A ***progress graph*** depicts the discrete *execution state space* of concurrent threads.

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

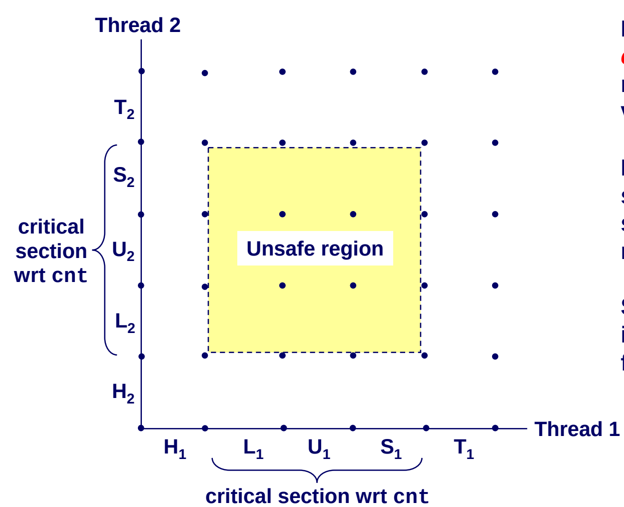


A ***trajectory*** is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Critical Sections and Unsafe Regions

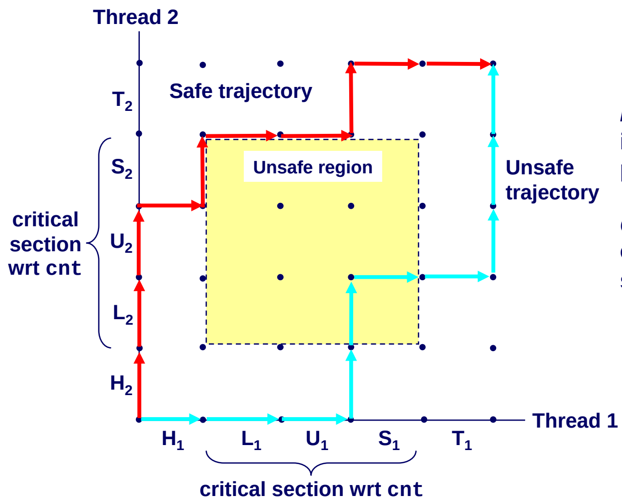


L, U, and S form a ***critical section*** with respect to the shared variable `cnt`.

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.**

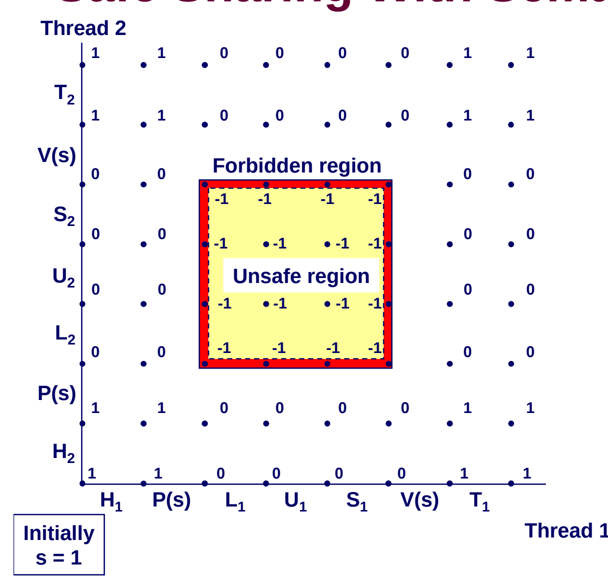
Semaphore invariant: *(s >= 0)*

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



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

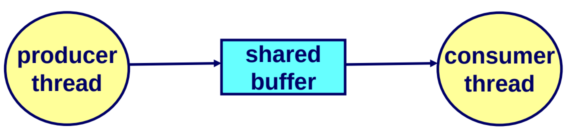
```
/* properly sync'd counter program */
#include "csapp.h"
#define NITERS 10000000

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;
}
```

Warning:

It's really slow!

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 */
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

Class 2: Pass state as part of argument

- Random number generator has no 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;
}
```

- User must maintain seed

Thread-Unsafe Functions (cont)

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

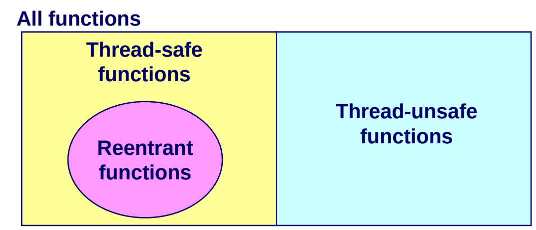
Class 4: Calling thread-unsafe functions.

- Calling one thread-unsafe function makes 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 (rand_r) and 3 (gethostbyname_r) are 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;
}
```

Where's the race?

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;
}
```


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

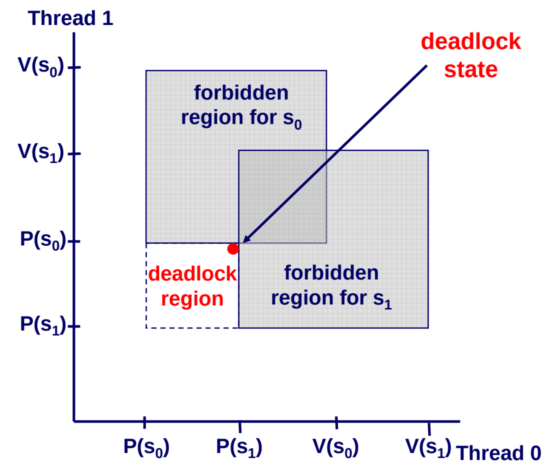
```
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], 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

Acquire shared resources in same order

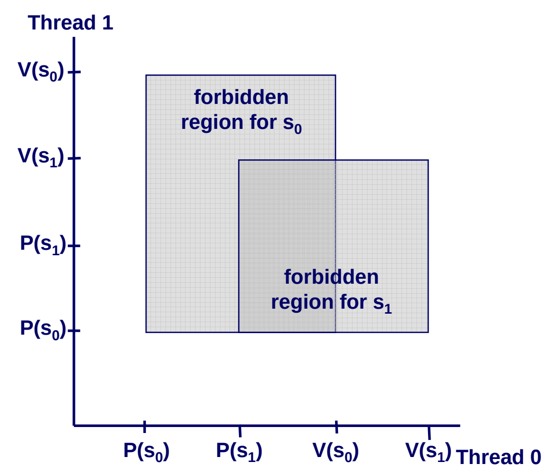
```
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], 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]:
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.