

Synchronization: Basics

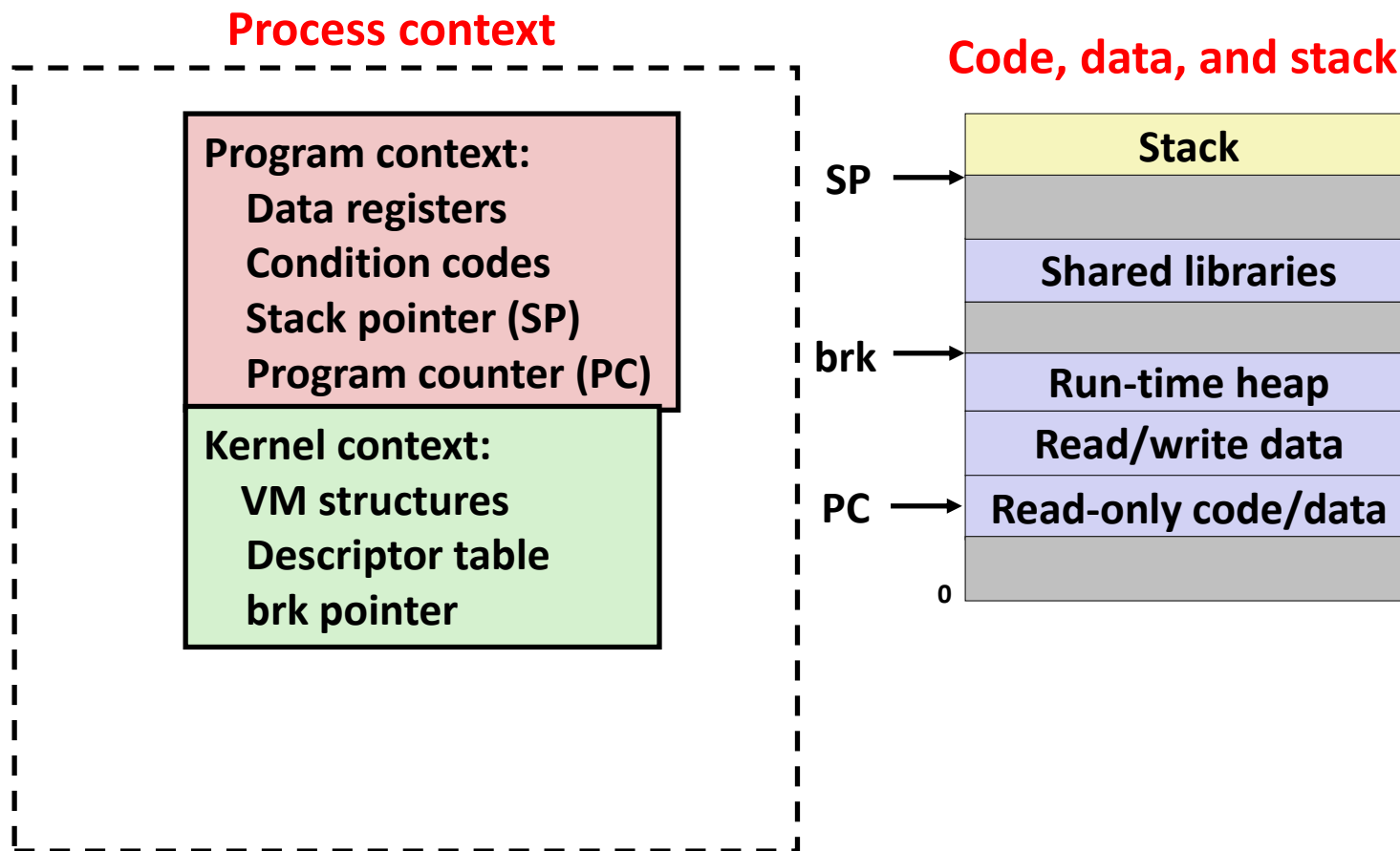
15-213: Introduction to Computer Systems
25th Lecture, April 16, 2020

Today

- **Threads review**
- Sharing
- Mutual exclusion
- Semaphores

Traditional View of a Process

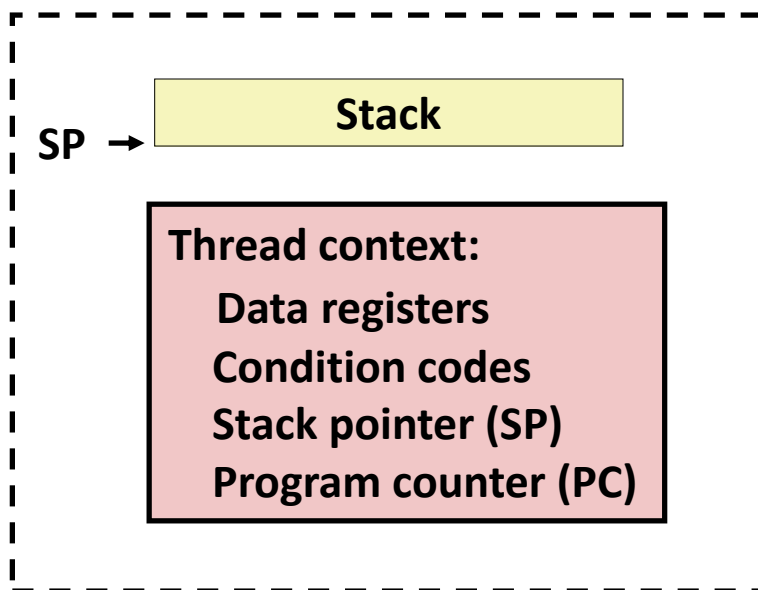
- Process = process context + code, data, and stack



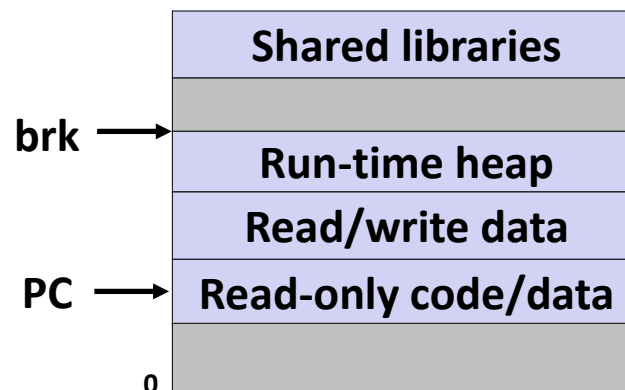
Alternate View of a Process

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

Thread (main thread)



Code, data, and kernel context



Kernel context:

- VM structures
- Descriptor table
- brk pointer

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
 - Each thread has its own stack for local variables
 - but not protected from other threads
 - Each thread has its own thread id (TID)

Thread 1 (main thread) Thread 2 (peer thread)

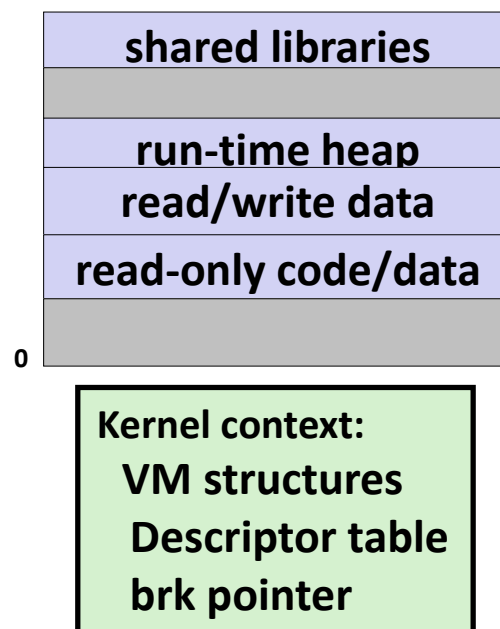
stack 1

stack 2

Thread 1 context:
Data registers
Condition codes
 SP_1
 PC_1

Thread 2 context:
Data registers
Condition codes
 SP_2
 PC_2

Shared code and data



Don't let picture confuse you!

Thread 1 (main thread) Thread 2 (peer thread)

stack 1

stack 2

Thread 1 context:
Data registers
Condition codes
 SP_1
 PC_1

Thread 2 context:
Data registers
Condition codes
 SP_2
 PC_2

Shared code and data

shared libraries

**run-time heap
read/write data**

read-only code/data

0

Kernel context:
VM structures
Descriptor table
brk pointer

Memory is shared between all threads

Today

- Threads review
- **Sharing**
- Mutual exclusion
- Semaphores
- **Producer-Consumer Synchronization**

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*”

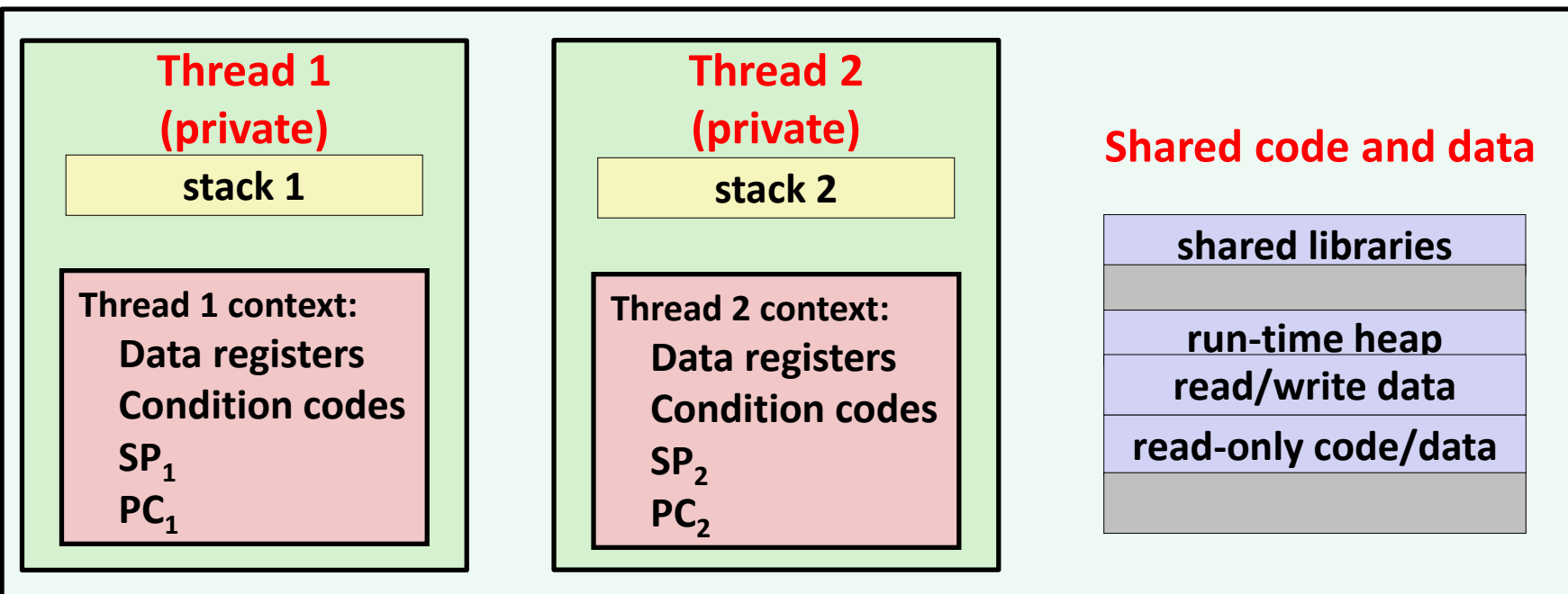
- **Def: A variable x is *shared* if and only if multiple threads reference some instance of x .**

- **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?

Threads Memory Model: Conceptual

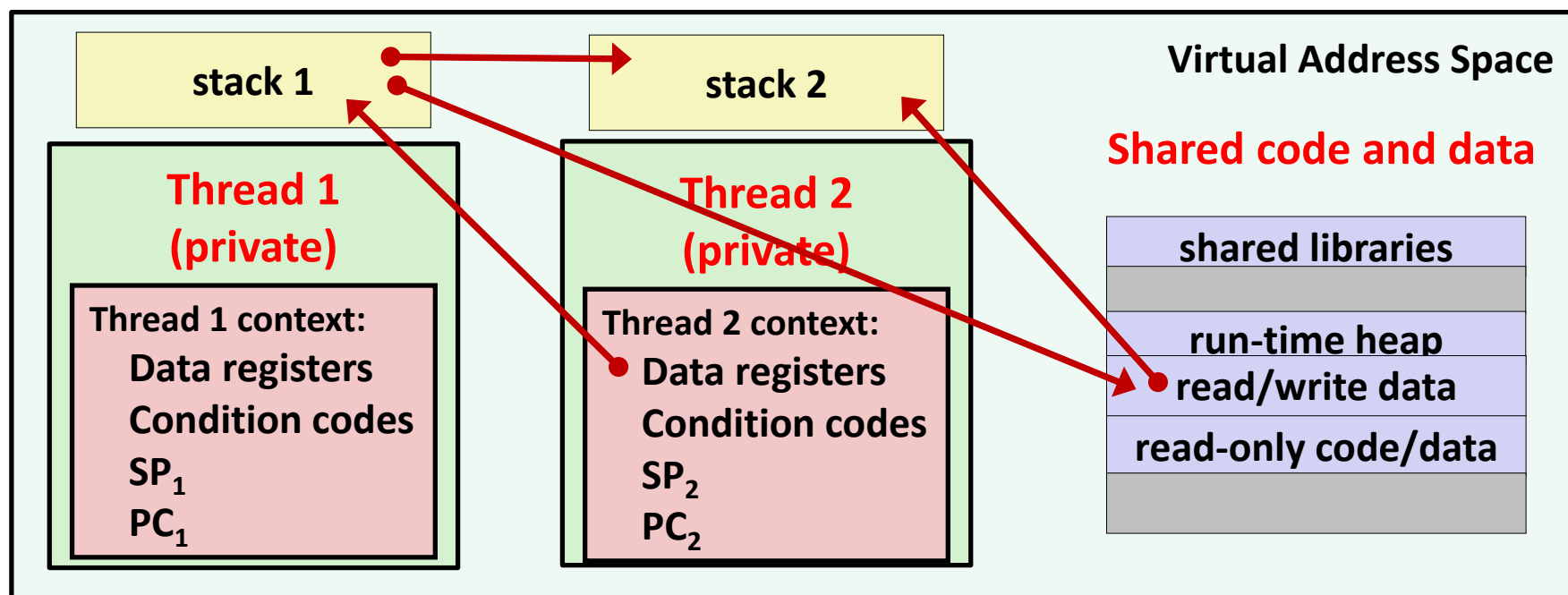
- Multiple threads run within the context of a single process
- Each thread has its own separate thread context
 - Thread ID, stack, stack pointer, PC, condition codes, and GP registers
- All threads share the remaining process context
 - Code, data, heap, and shared library segments of the process virtual address space
 - Open files and installed handlers



Threads Memory Model: Actual

■ Separation of data 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*

Passing an argument to a thread - Pedantic

```
int hist[N] = {0};

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++) {
        long* p = Malloc(sizeof(long));
        *p = i;
        Pthread_create(&tids[i],
                       NULL,
                       thread,
                       (void *)p);
    }
    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    check();
}
```

```
void *thread(void *vargp)
{
    hist[*(long *)vargp] += 1;
    Free(vargp);
    return NULL;
}
```

```
void check(void) {
    for (int i=0; i<N; i++) {
        if (hist[i] != 1) {
            printf("Failed at %d\n", i);
            exit(-1);
        }
    }
    printf("OK\n");
}
```

Passing an argument to a thread - Pedantic

```
int hist[N] = {0};

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++) {
        long* p = Malloc(sizeof(long));
        *p = i;
        Pthread_create(&tids[i],
                       NULL,
                       thread,
                       (void *)p);
    }
    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    check();
}
```

```
void *thread(void *vargp)
{
    hist[* (long *)vargp] += 1;
    Free(vargp);
    return NULL;
}
```

- Use malloc to create a per thread heap allocated place in memory for the argument
- Remember to free in thread!
- Producer-consumer pattern

Passing an argument to a thread – Also OK!

```
int hist[N] = {0};

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++)
        Pthread_create(&tids[i],
                       NULL,
                       thread,
                       (void *)i);

    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    check();
}
```

```
void *thread(void *vargp)
{
    hist[(long)vargp] += 1;
    return NULL;
}
```

- Ok to Use cast since $\text{sizeof}(\text{long}) \leq \text{sizeof}(\text{void}^*)$
- Cast does NOT change bits

Passing an argument to a thread – **WRONG!**

```
int hist[N] = {0};

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++)
        Pthread_create(&tids[i],
                       NULL,
                       thread,
                       (void *)&i);

    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    check();
}
```

```
void *thread(void *vargp)
{
    hist[*(long*)vargp] += 1;
    return NULL;
}
```

- **&i** points to same location for all threads!
- **Creates a data race!**

Three Ways to Pass Thread Arg

■ Malloc/free

- Producer malloc's space, passes pointer to pthread_create
- Consumer dereferences pointer

■ Ptr to stack slot

- Producer passes address to producer's stack in pthread_create
- Consumer dereferences pointer

■ Cast of int

- Producer casts an int/long to address in pthread_create
- Consumer casts void* argument back to int/long

Example Program to Illustrate Sharing

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

int main(int argc, char *argv[])
{
    long 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);
}
```

sharing.c

```
void *thread(void *vargp)
{
    long myid = (long)vargp;
    static int cnt = 0;

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

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

A common way to pass a single argument to a thread routine

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*”

- **Def: A variable x is *shared* if and only if multiple threads reference some instance of x .**

- **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?

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

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

int main(int main, char *argv[])
{
    long 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);
}
```

sharing.c

```
void *thread(void *vargp)
{
    long myid = (long)vargp;
    static int cnt = 0;

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

Mapping Variable Instances to Memory

Global var: 1 instance (ptr [data])

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

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

int main(int main, char *argv[])
{
    long 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);
}
```

sharing.c

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

```
void *thread(void *vargp)
{
    long myid = (long)vargp;
    static int cnt = 0;

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

Local static var: 1 instance (cnt [data])

Shared Variable Analysis

■ Which variables are shared?

<i>Variable instance</i>	<i>Referenced by main thread?</i>	<i>Referenced by peer thread 0?</i>	<i>Referenced by peer thread 1?</i>
<code>ptr</code>	yes	yes	yes
<code>cnt</code>	no	yes	yes
<code>i.m</code>	yes	no	no
<code>msgs.m</code>	yes	yes	yes
<code>myid.p0</code>	no	yes	no
<code>myid.p1</code>	no	no	yes

```
char **ptr; /* global var */
int main(int main, char *argv[]) {
    long 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);
}
```

```
void *thread(void *vargp)
{
    long myid = (long)vargp;
    static int cnt = 0;

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

Shared Variable Analysis

■ Which variables are shared?

<i>Variable instance</i>	<i>Referenced by main thread?</i>	<i>Referenced by peer thread 0?</i>	<i>Referenced by peer thread 1?</i>
<code>ptr</code>	yes	yes	yes
<code>cnt</code>	no	yes	yes
<code>i.m</code>	yes	no	no
<code>msgs.m</code>	yes	yes	yes
<code>myid.p0</code>	no	yes	no
<code>myid.p1</code>	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

Synchronizing Threads

- Shared variables are handy...
- ...but introduce the possibility of nasty *synchronization* errors.

badcnt.c: Improper Synchronization

```

/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    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=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}

```

badcnt.c

```

/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
        *((long *)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++;
```

Asm code for thread i

<pre> movq (%rdi), %rcx testq %rcx,%rcx jle .L2 movl \$0, %eax </pre>	<pre> } H_i : Head </pre>
<pre> .L3: movq cnt(%rip), %rdx addq \$1, %rdx movq %rdx, cnt(%rip) </pre>	<pre> } L_i : Load cnt U_i : Update cnt S_i : Store cnt </pre>
<pre> addq \$1, %rax cmpq %rcx, %rax jne .L3 .L2: </pre>	<pre> } T_i : Tail </pre>

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
 - $\%rdx_i$ is the content of $\%rdx$ in thread i 's context

i (thread)	$instr_i$	$\%rdx_1$	$\%rdx_2$	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

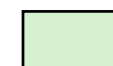
**For now. In reality, on x86 even non-sequentially consistent interleavings are possible*

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
- $\%rdx_i$ is the content of $\%rdx$ in thread i 's context

i (thread)	$instr_i$	$\%rdx_1$	$\%rdx_2$	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	%rdx ₁	%rdx 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?

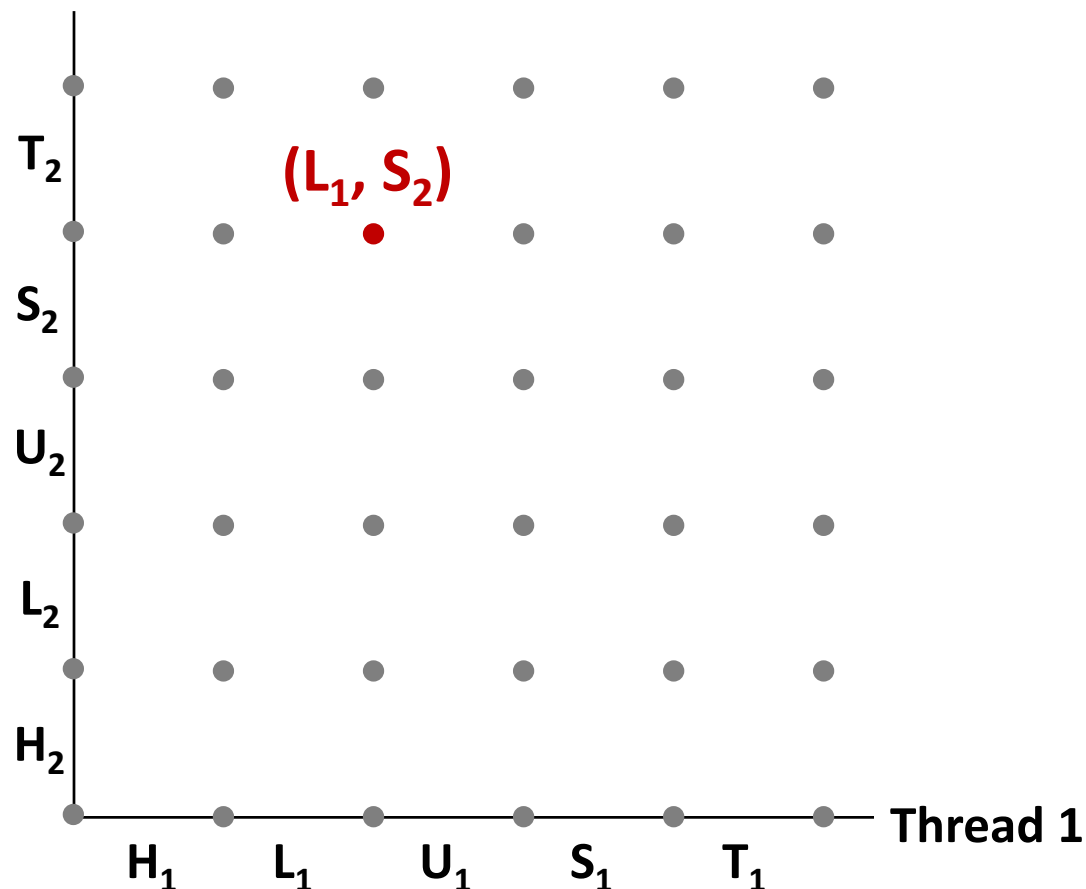
i (thread)	instr _i	%rdx ₁	%rdx ₂	cnt
1	H ₁			0
1	L ₁	0		
2	H ₂			
2	L ₂		0	
2	U ₂		1	
2	S ₂		1	1
1	U ₁	1		
1	S ₁	1		1
1	T ₁			1
2	T ₂			1

Oops!

■ We can analyze the behavior using a *progress graph*

Progress Graphs

Thread 2



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

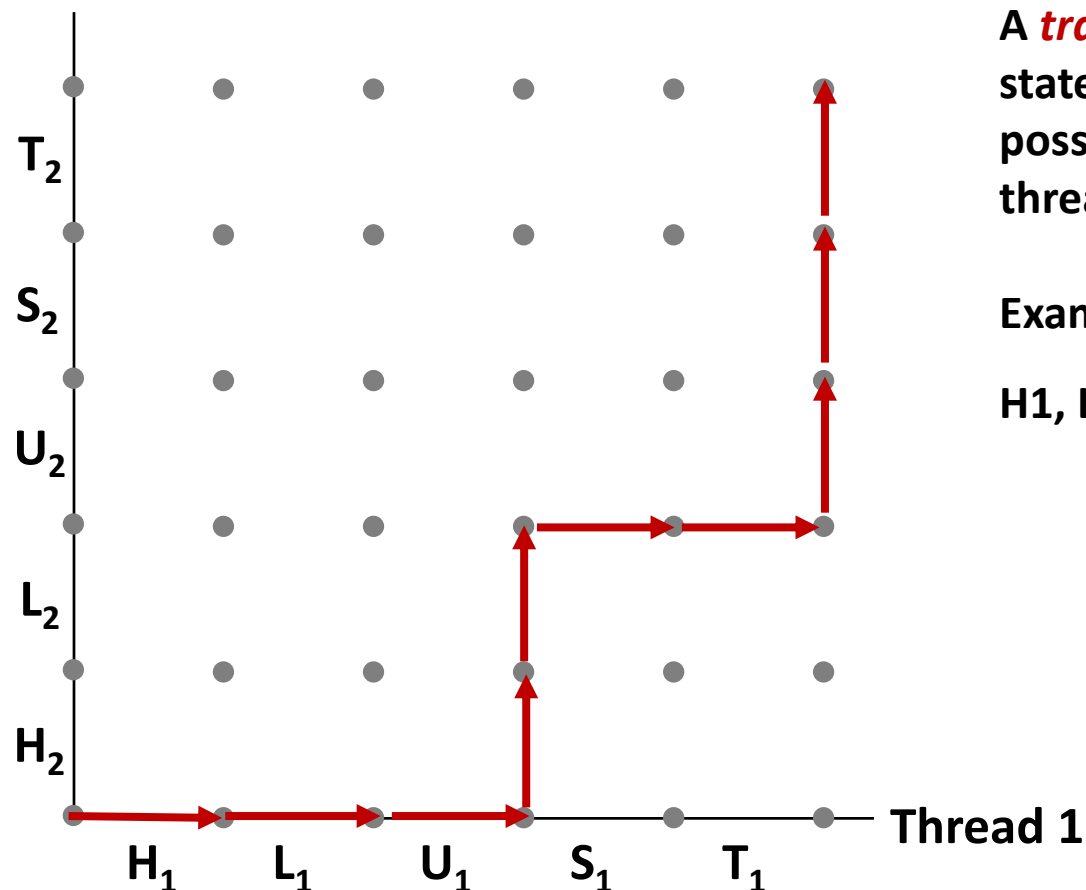
Each axis corresponds to the sequential order of instructions in a thread.

Each point corresponds to a possible **execution state** (Inst₁, Inst₂).

E.g., (L_1, S_2) denotes state where thread 1 has completed L₁ and thread 2 has completed S₂.

Trajectories in Progress Graphs

Thread 2

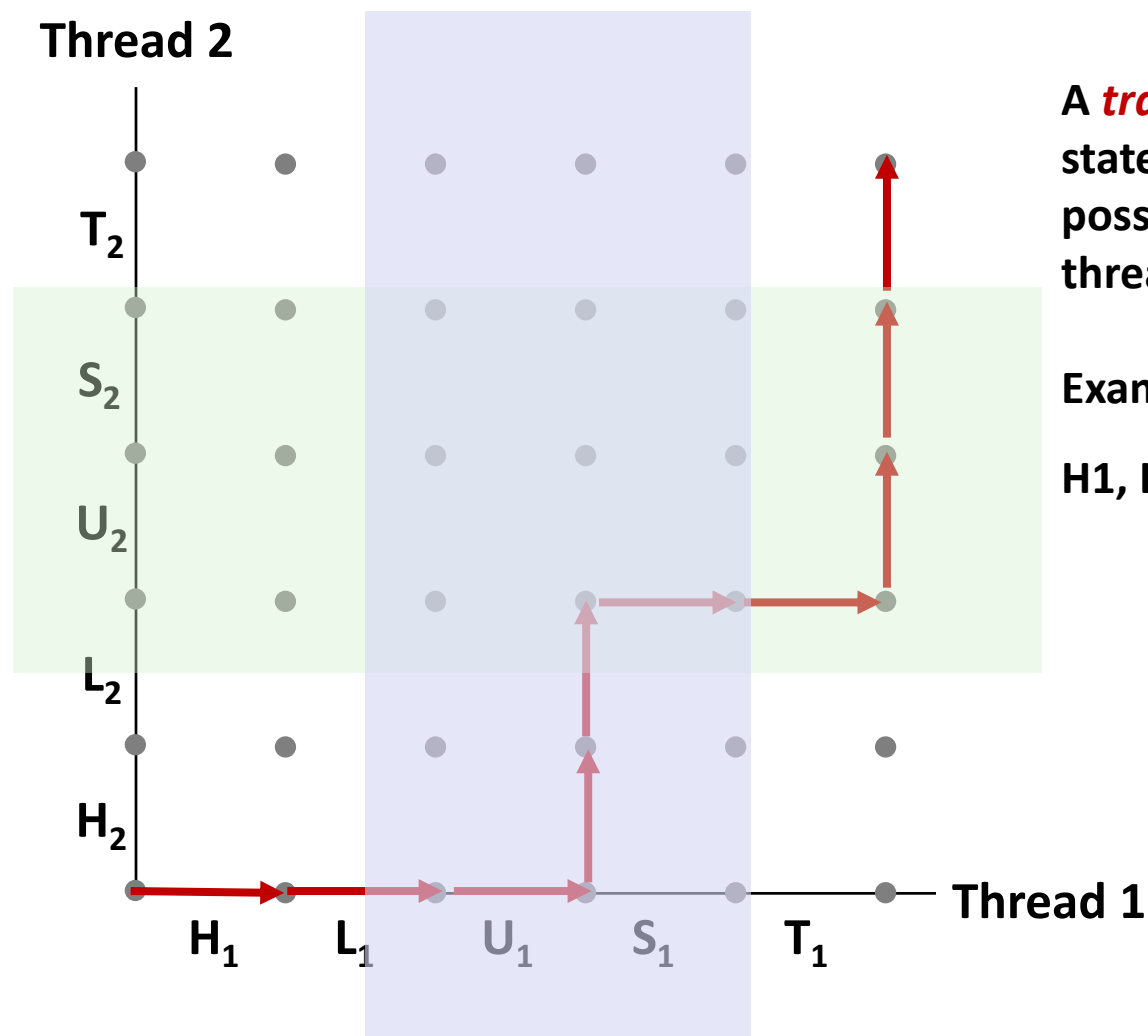


A **trajectory** is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Trajectories in Progress Graphs

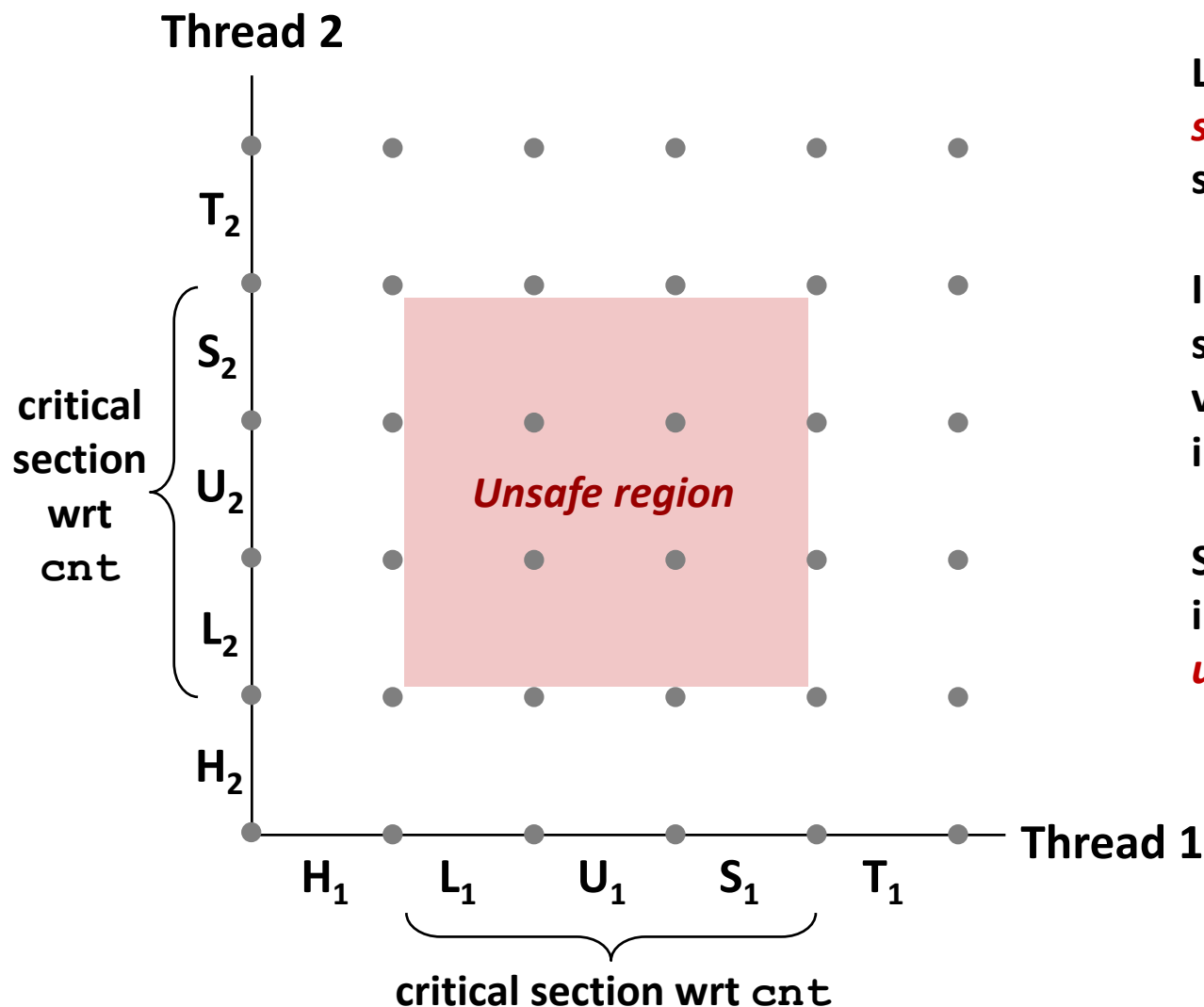


A **trajectory** is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Critical Sections and Unsafe Regions

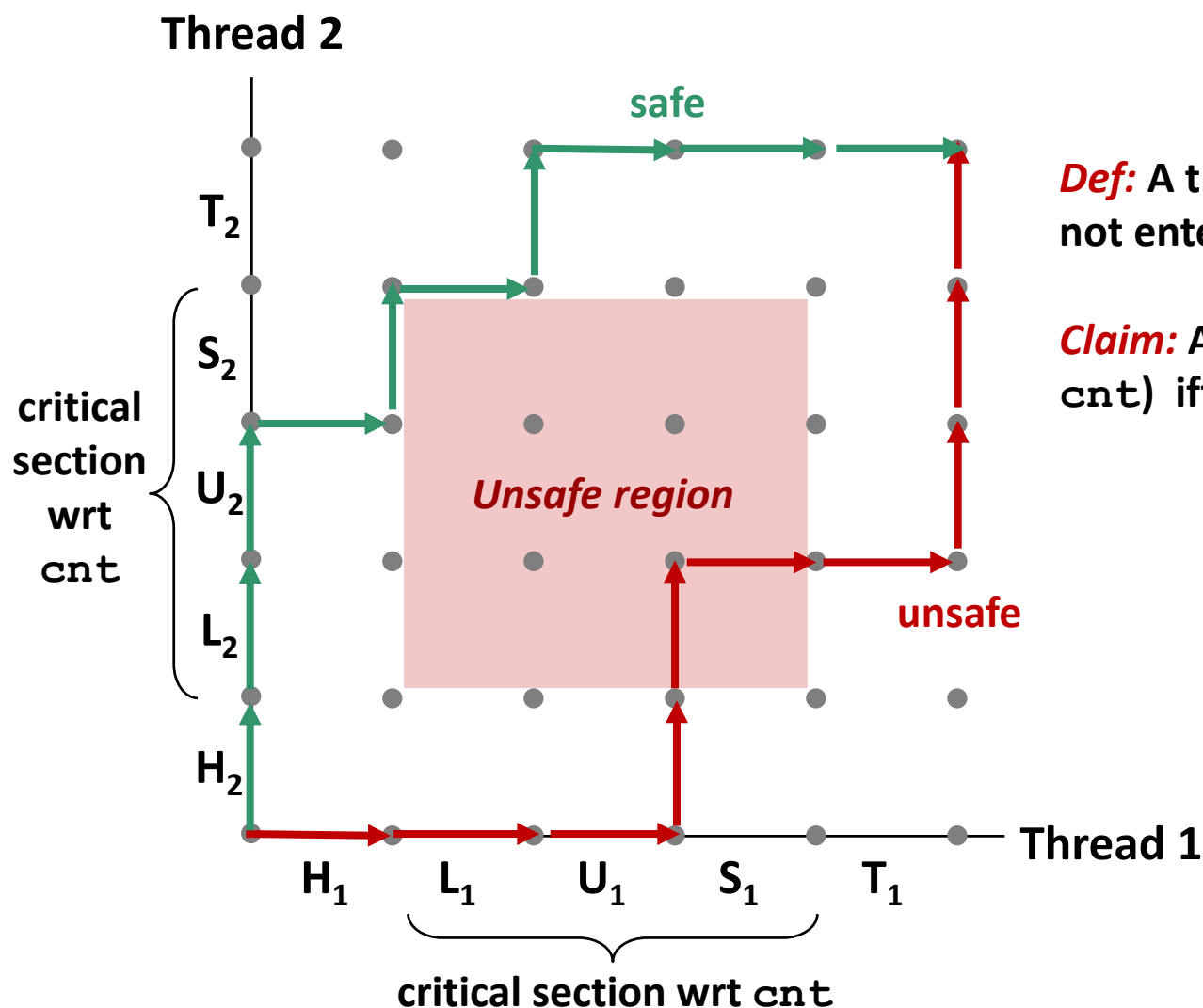


L , U , and S form a **critical section** with respect to the shared variable `cnt`

Instructions in critical sections (wrt 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

badcnt.c: Improper Synchronization

```

/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    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=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}

```

badcnt.c

```

/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
        *((long *)vargp);

    for (i = 0; i < niters; i++)
        cnt++;

    return NULL;
}

```

Variable	main	thread1	thread2
cnt			
niters.m			
tid1.m			
i.1			
i.2			
niters.1			
niters.2			

badcnt.c: Improper Synchronization

```

/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    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=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}

```

badcnt.c

```

/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
        *((long *)vargp);

    for (i = 0; i < niters; i++)
        cnt++;

    return NULL;
}

```

Variable	main	thread1	thread2
cnt	yes*	yes	yes
niters.m	yes	no	no
tid1.m	yes	no	no
i.1	no	yes	no
i.2	no	no	yes
niters.1	no	yes	no
niters.2	no	no	yes

Break Time!

Check out:

Quiz: day 25: Synchronization Basic

<https://canvas.cmu.edu/courses/31656>

Bonus Quiz Question 6:

```
#include "csapp.h"
#define N 2
void *thread(void *vargp);
long *pointers[N];

int main(int argc, char *argv[]) {
    long i;
    pthread_t tids[N];

    for (i = 0; i < N; i++)
        Pthread_create(&tids[i], NULL, thread, (void *) i);
    sleep(1);    // Sleep-#1
    for (i = 0; i < N; i++)
        printf("Thread id %u has local value %ld\n",
            (int) tids[i], *pointers[i]);
    for (i = 0; i < N; i++)
        Pthread_join(tids[i], NULL);
    return 0;
}

void *thread(void *vargp) {
    long myid = (long) vargp;
    pointers[myid] = &myid;
    sleep(2);    // Sleep-2
    return NULL;
}
```

If the statement labeled "Sleep #1" is kept, the main thread might have a segmentation fault when referencing "pointers"?

- True?
- False?

Today

- Threads review
- Sharing
- **Mutual exclusion**
- **Semaphores**
- Producer-Consumer Synchronization

Enforcing Mutual Exclusion

- **Question:** How can we guarantee a safe trajectory?
- **Answer:** We must *synchronize* the execution of the threads so that they can never have an unsafe trajectory.
 - i.e., need to guarantee *mutually exclusive access* for each critical section.
- **Classic solution:**
 - Semaphores (Edsger Dijkstra)
- **Other approaches (out of our scope)**
 - Mutex and condition variables (Pthreads)
 - Monitors (Java)

Semaphores

- ***Semaphore***: non-negative global integer synchronization variable. Manipulated by *P* and *V* operations.
- ***P(s)***
 - If *s* is nonzero, then decrement *s* by 1 and return immediately.
 - Test and decrement operations occur atomically (indivisibly)
 - If *s* is zero, then suspend thread until *s* becomes nonzero and the thread is restarted by a *V* operation.
 - After restarting, the *P* operation decrements *s* and returns control to the caller.
- ***V(s)***:
 - Increment *s* by 1.
 - Increment operation occurs atomically
 - If there are any threads blocked in a *P* operation waiting for *s* to become non-zero, then restart exactly one of those threads, which then completes its *P* operation by decrementing *s*.
- **Semaphore invariant: ($s \geq 0$)**

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: ($s \geq 0$)**

C Semaphore Operations

Pthreads functions:

```
#include <semaphore.h>

int sem_init(sem_t *s, 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:

```
#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

```
/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    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=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}
```

badcnt.c

```
/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
        *((long *)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 long 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++) {
    P(&mutex);
    cnt++;
    V(&mutex);
}
```

goodcnt.c

```
linux> ./goodcnt 10000
OK cnt=20000
linux> ./goodcnt 10000
OK cnt=20000
linux>
```

Warning: It's orders of magnitude slower than badcnt.c.

goodcnt.c: Proper Synchronization

- Define and initialize a mutex for the shared variable `cnt`:

```
volatile long cnt = 0; /* Counter */
sem_t mutex;          /* Semaphore that protects cnt */

sem_init(&mutex, 0, 1); /* mutex = 1 */
```

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

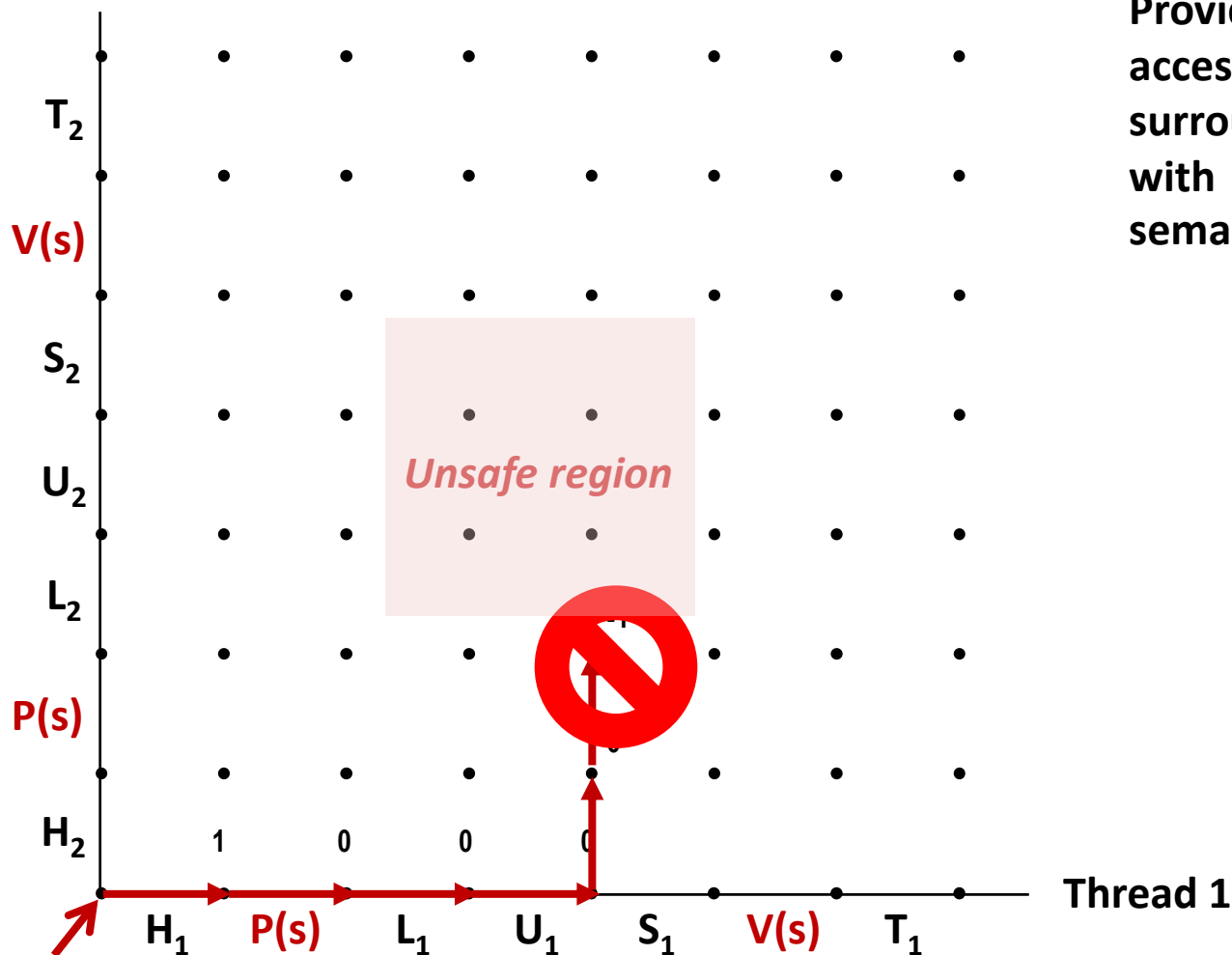
```
for (i = 0; i < niters; i++) {
    P(&mutex);
    cnt++;
    V(&mutex);
}
```

Function	badcnt	goodcnt
Time (ms) niters = 10 ⁶	12.0	450.0
Slowdown	1.0	37.5

Warning: It's orders of magnitude slower than `badcnt.c`.

Why Mutexes Work

Thread 2



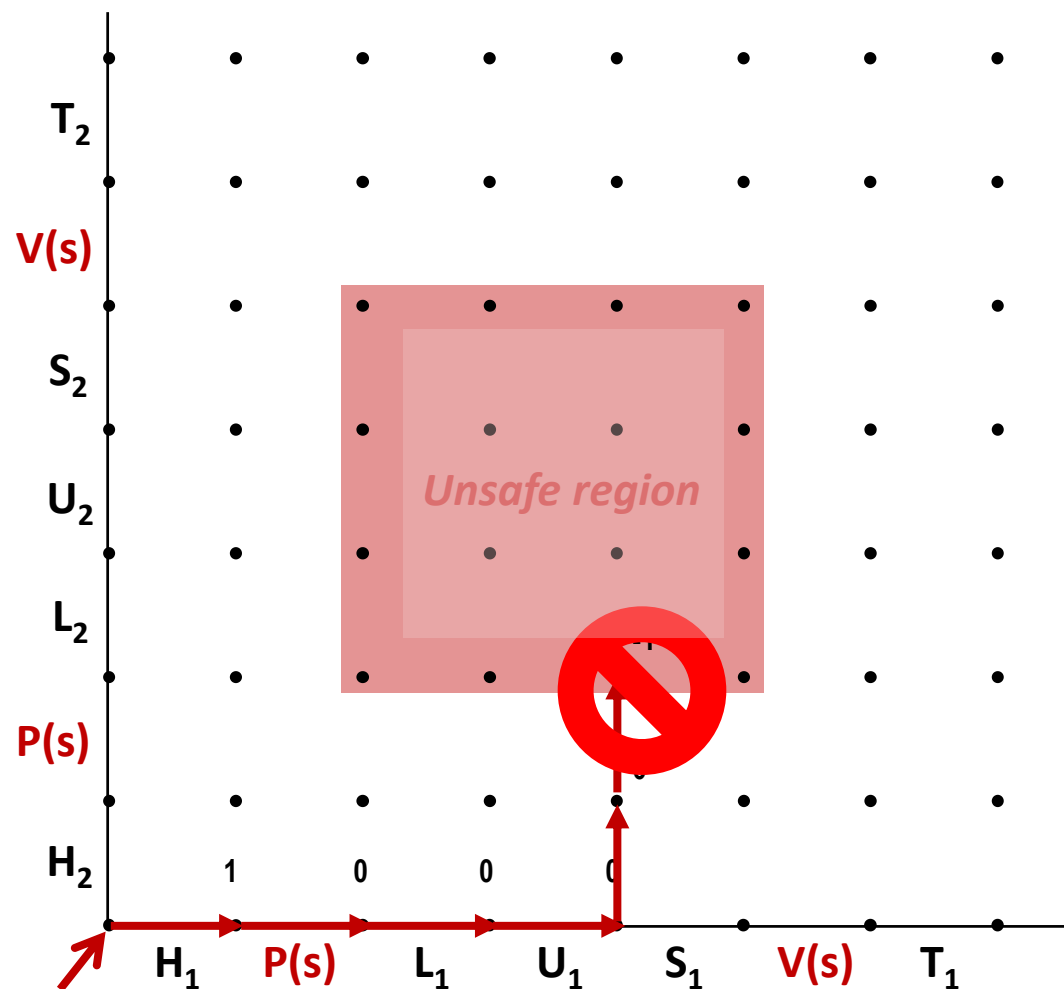
Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore s (initially set to 1)

Initially

$s = 1$

Why Mutexes Work

Thread 2



Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore s (initially set to 1)

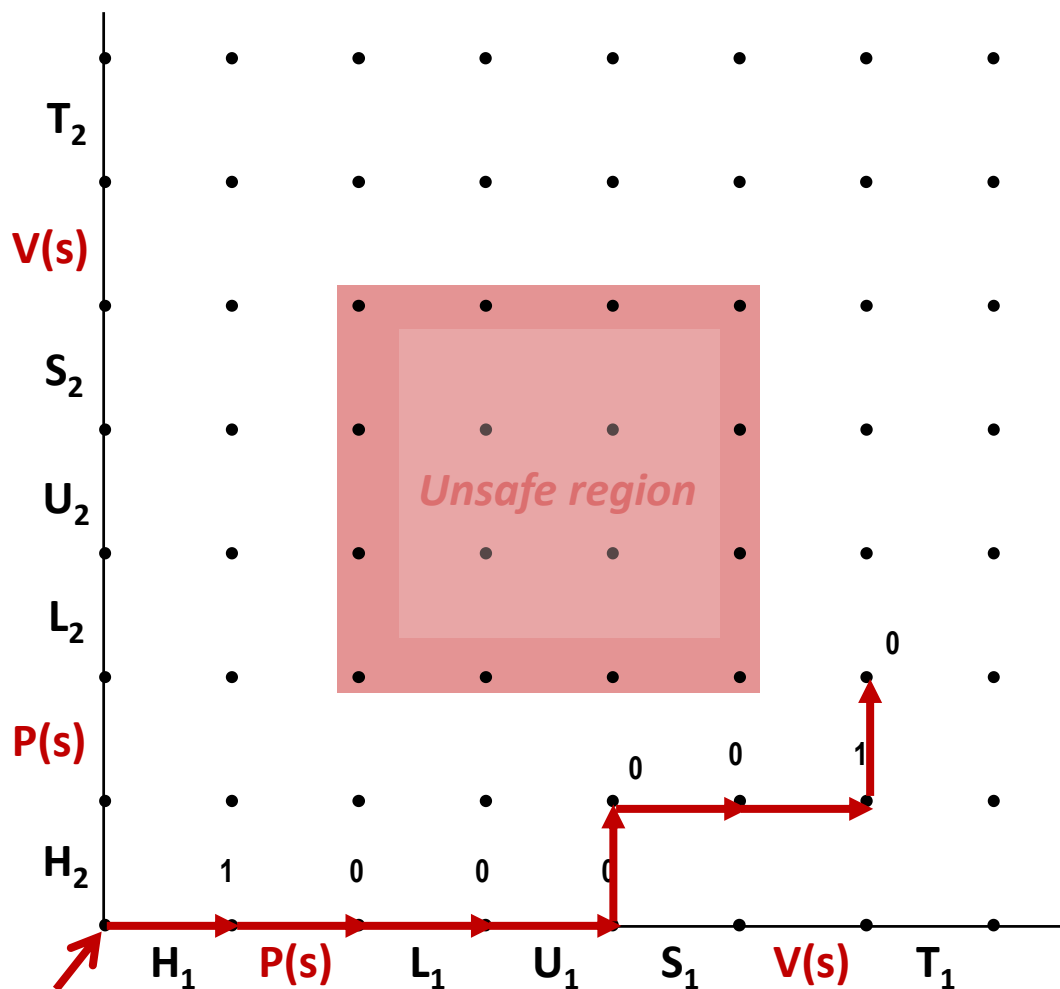
Semaphore invariant creates a *forbidden region* that encloses unsafe region and that cannot be entered by any trajectory.

Initially

$s = 1$

Why Mutexes Work

Thread 2

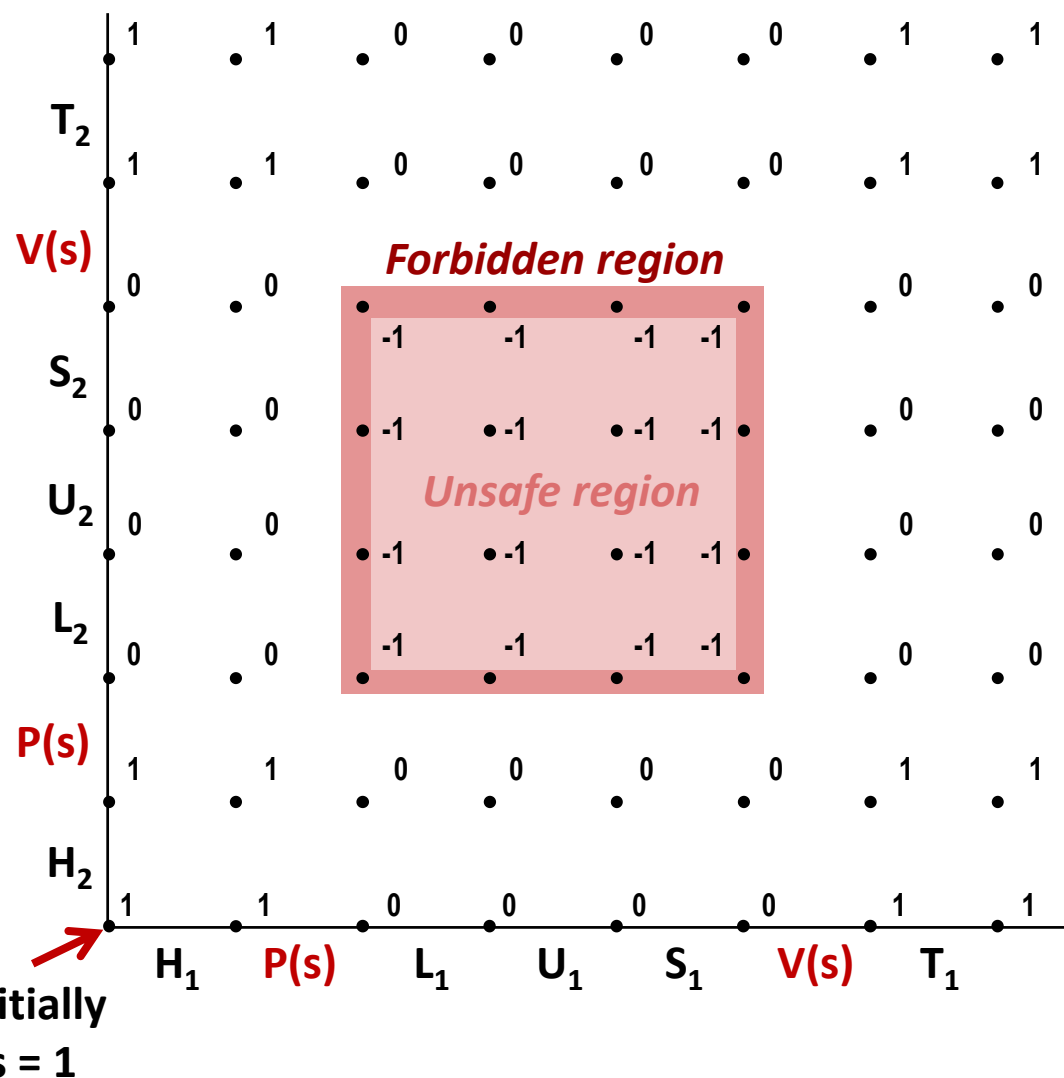


Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore s (initially set to 1)

Semaphore invariant creates a *forbidden region* that encloses unsafe region and that cannot be entered by any trajectory.

Why Mutexes Work

Thread 2



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 that cannot be entered by any trajectory.

Thread 1

Binary Semaphores – For Mutual Exclusion

- **Mutex is special case of semaphore**
 - Value either 0 or 1
- **Pthreads provides `pthread_mutex_t`**
 - Operations: lock, unlock
- **Recommended over general semaphores when appropriate**

goodmcent.c: Mutex Synchronization

- Define and initialize a mutex for the shared variable `cnt`:

```
volatile long cnt = 0; /* Counter */
pthread_mutex_t mutex;
pthread_mutex_init(&mutex, NULL); // No special attributes
```

- Surround critical section with *lock* and *unlock*:

```
for (i = 0; i < niters; i++) {
    pthread_mutex_lock(&mutex);
    cnt++;
    pthread_mutex_unlock(&mutex);
}
```

```
linux> ./goodmcent 10000
OK cnt=20000
linux> ./goodmcent 10000
OK cnt=20000
```

Function	badcnt	goodcnt	goodmcent
Time (ms) niters = 10^6	12.0	450.0	214.0
Slowdown	1.0	37.5	17.8

Today

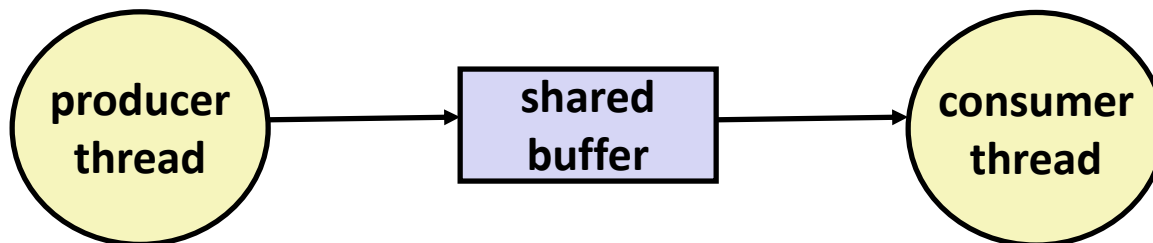
- Threads review
- Sharing
- Mutual exclusion
- Semaphores
- **Producer-Consumer Synchronization**

Using Semaphores to Coordinate Access to Shared Resources

- **Basic idea: Thread uses a semaphore operation to notify another thread that some condition has become true**
 - Use counting semaphores to keep track of resource state.
 - Use binary semaphores to notify other threads.

- **The Producer-Consumer Problem**
 - Mediating interactions between processes that generate information and that then make use of that information

Producer-Consumer Problem



■ Common synchronization pattern:

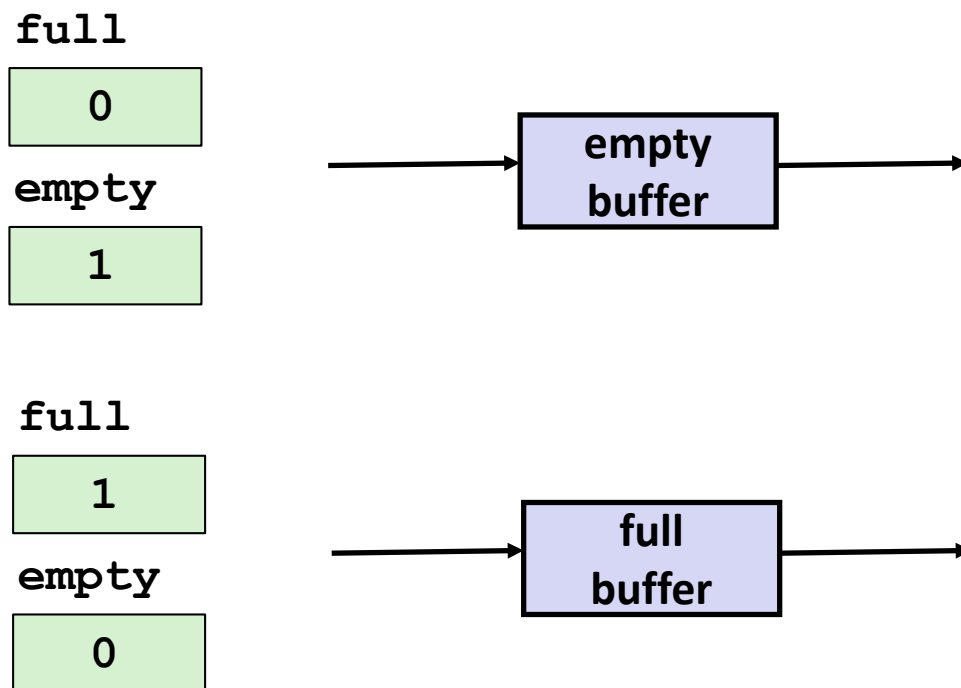
- Producer waits for empty *slot*, inserts item in buffer, and notifies consumer
- Consumer waits for *item*, removes it from buffer, and notifies producer

■ Examples

- Multimedia processing:
 - Producer creates 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 1-element Buffer

- Maintain two semaphores: `full` + `empty`



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(int argc, char** argv) {
    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);

    return 0;
}
```

Producer-Consumer on 1-element Buffer

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

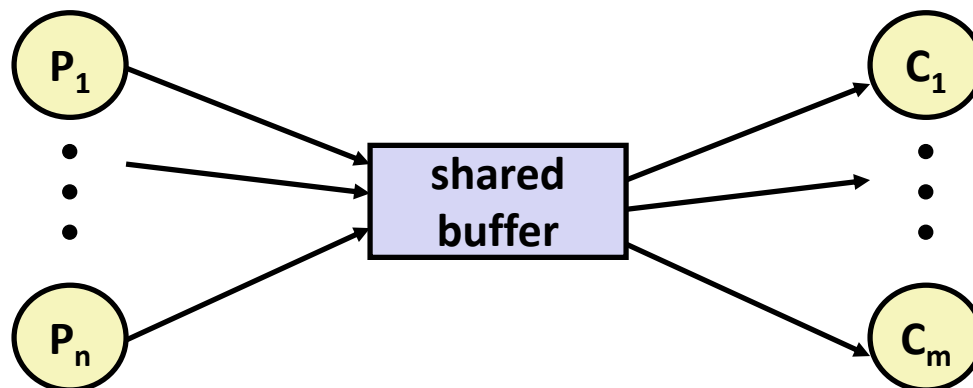
```
void *consumer(void *arg) {
    int i, item;

    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;
}
```

Why 2 Semaphores for 1-Entry Buffer?

- Consider multiple producers & multiple consumers

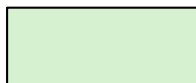


- Producers will contend with each to get **empty**
- Consumers will contend with each other to get **full**

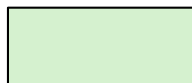
Producers

```
P(&shared.empty);  
shared.buf = item;  
V(&shared.full);
```

empty



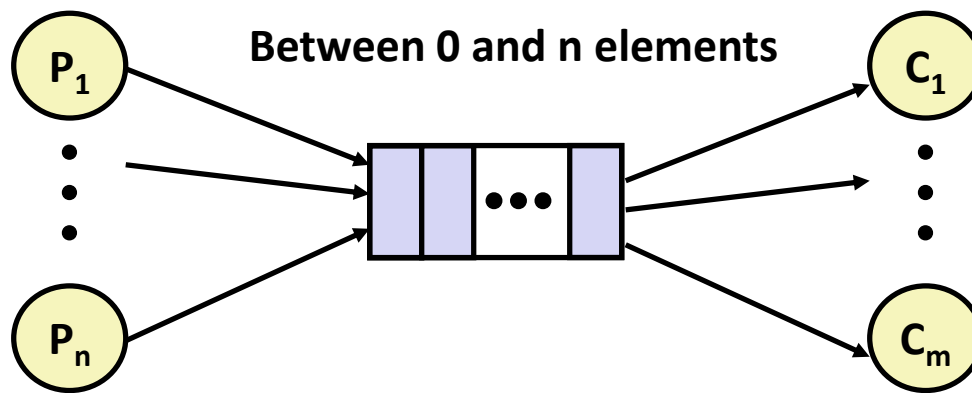
full



Consumers

```
P(&shared.full);  
item = shared.buf;  
V(&shared.empty);
```

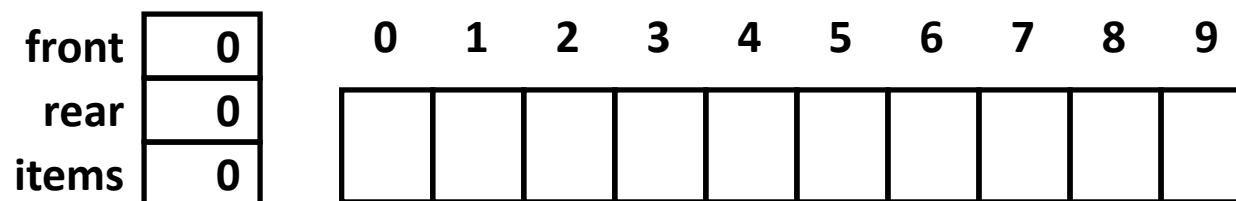
Producer-Consumer on an n -element Buffer



- Implemented using a shared buffer package called `sbuf`.

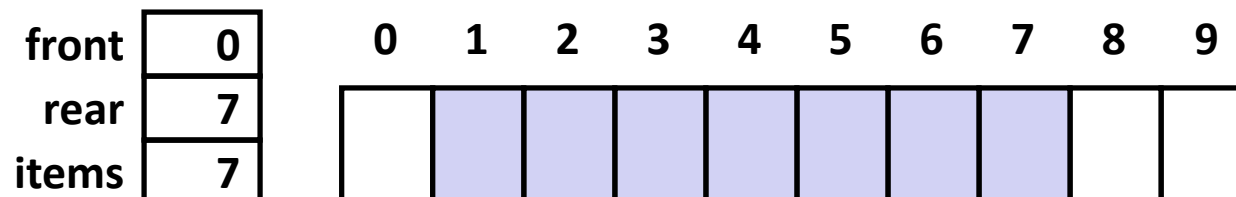
Circular Buffer (n = 10)

- Store elements in array of size n
- items: number of elements in buffer
- Empty buffer:
 - front = rear
- Nonempty buffer
 - rear: index of most recently inserted element
 - front: (index of next element to remove – 1) mod n
- Initially:

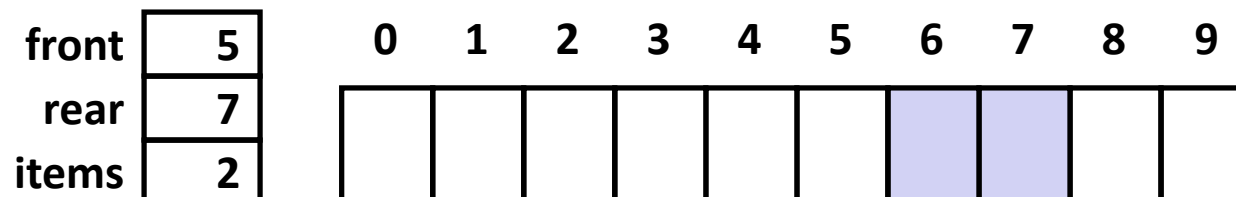


Circular Buffer Operation (n = 10)

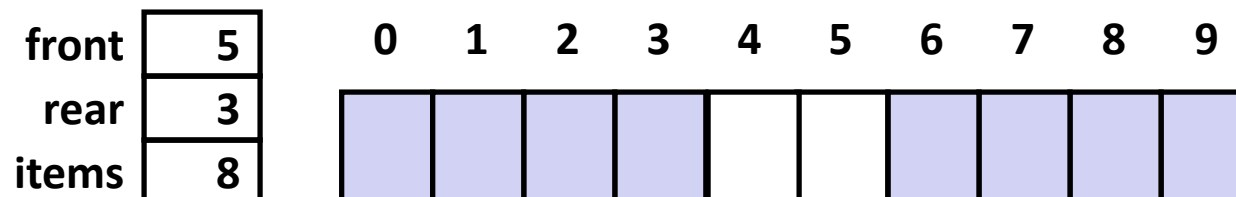
■ Insert 7 elements



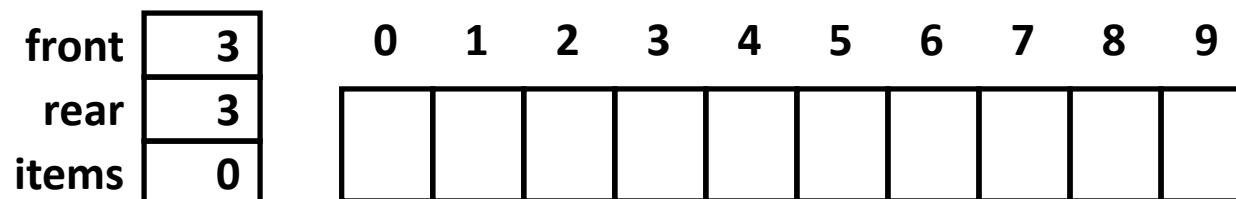
■ Remove 5 elements



■ Insert 6 elements



■ Remove 8 elements



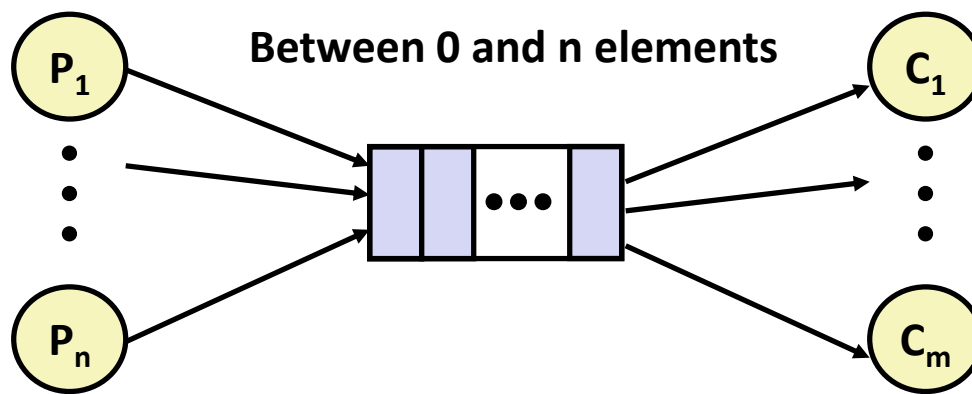
Sequential Circular Buffer Code

```
init(int v)
{
    items = front = rear = 0;
}
```

```
insert(int v)
{
    if (items >= n)
        error();
    if (++rear >= n) rear = 0;
    buf[rear] = v;
    items++;
}
```

```
int remove()
{
    if (items == 0)
        error();
    if (++front >= n) front = 0;
    int v = buf[front];
    items--;
    return v;
}
```


Producer-Consumer on an n -element Buffer



- **Requires a mutex and two counting semaphores:**
 - `mutex`: enforces mutually exclusive access to the buffer and counters
 - `slots`: counts the available slots in the buffer
 - `items`: counts the available items in the buffer
- **Makes use of general semaphores**
 - Will range in value from 0 to n

sbuf Package - Declarations

```
#include "csapp.h"

typedef struct {
    int *buf;          /* Buffer array */
    int n;             /* Maximum number of slots */
    int front;         /* buf[front+1 (mod n)] is first item */
    int rear;          /* buf[rear] is last item */
    sem_t mutex;       /* Protects accesses to buf */
    sem_t slots;       /* Counts available slots */
    sem_t items;       /* Counts available items */
} sbuf_t;

void sbuf_init(sbuf_t *sp, int n);
void sbuf_deinit(sbuf_t *sp);
void sbuf_insert(sbuf_t *sp, int item);
int sbuf_remove(sbuf_t *sp);
```

sbuf.h

sbuf Package - Implementation

Initializing and deinitializing a shared buffer:

```
/* Create an empty, bounded, shared FIFO buffer with n slots */
void sbuf_init(sbuf_t *sp, int n)
{
    sp->buf = Calloc(n, sizeof(int));
    sp->n = n; /* Buffer holds max of n items */
    sp->front = sp->rear = 0; /* Empty buffer iff front == rear */
    Sem_init(&sp->mux, 0, 1); /* Binary semaphore for locking */
    Sem_init(&sp->slots, 0, n); /* Initially, buf has n empty slots */
    Sem_init(&sp->items, 0, 0); /* Initially, buf has zero items */
}

/* Clean up buffer sp */
void sbuf_deinit(sbuf_t *sp)
{
    Free(sp->buf);
}
```

sbuf.c

sbuf Package - Implementation

Inserting an item into a shared buffer:

```
/* Insert item onto the rear of shared buffer sp */
void sbuf_insert(sbuf_t *sp, int item)
{
    P(&sp->slots);          /* Wait for available slot */
    P(&sp->mutex);           /* Lock the buffer          */
    if (++sp->rear >= sp->n)  /* Increment index (mod n) */
        sp->rear = 0;
    sp->buf[sp->rear] = item; /* Insert the item          */
    V(&sp->mutex);           /* Unlock the buffer        */
    V(&sp->items);           /* Announce available item  */
}
```

sbuf.c

sbuf Package - Implementation

Removing an item from a shared buffer:

```
/* Remove and return the first item from buffer sp */
int sbuf_remove(sbuf_t *sp)
{
    int item;
    P(&sp->items);          /* Wait for available item */
    P(&sp->mutex);           /* Lock the buffer */
    if (++sp->front >= sp->n) /* Increment index (mod n) */
        sp->front = 0;
    item = sp->buf[sp->front]; /* Remove the item */
    V(&sp->mutex);           /* Unlock the buffer */
    V(&sp->slots);           /* Announce available slot */
    return item;
}
```

sbuf.c

Demonstration

- See program `produce-consume.c` in code directory
- 10-entry shared circular buffer
- 5 producers
 - Agent i generates numbers from $20*i$ to $20*i - 1$.
 - Puts them in buffer
- 5 consumers
 - Each retrieves 20 elements from buffer
- Main program
 - Makes sure each value between 0 and 99 retrieved once

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.**