Synchronization: Basics

Introduction to Computer Systems
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Today

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

Traditional View of a Process

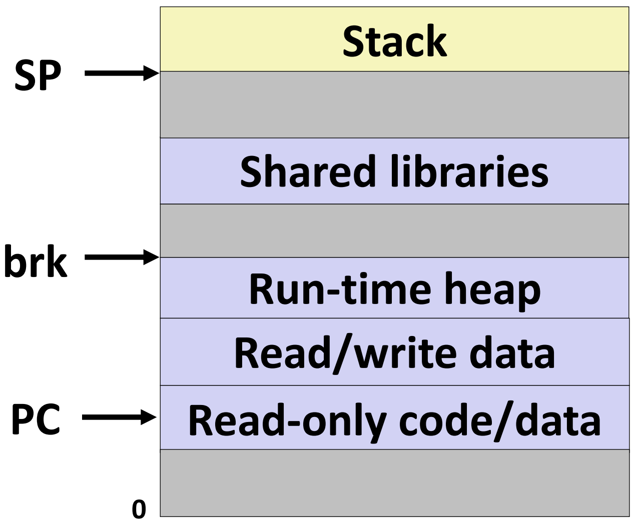
- Process = process context + code, data, and stack

Process context

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

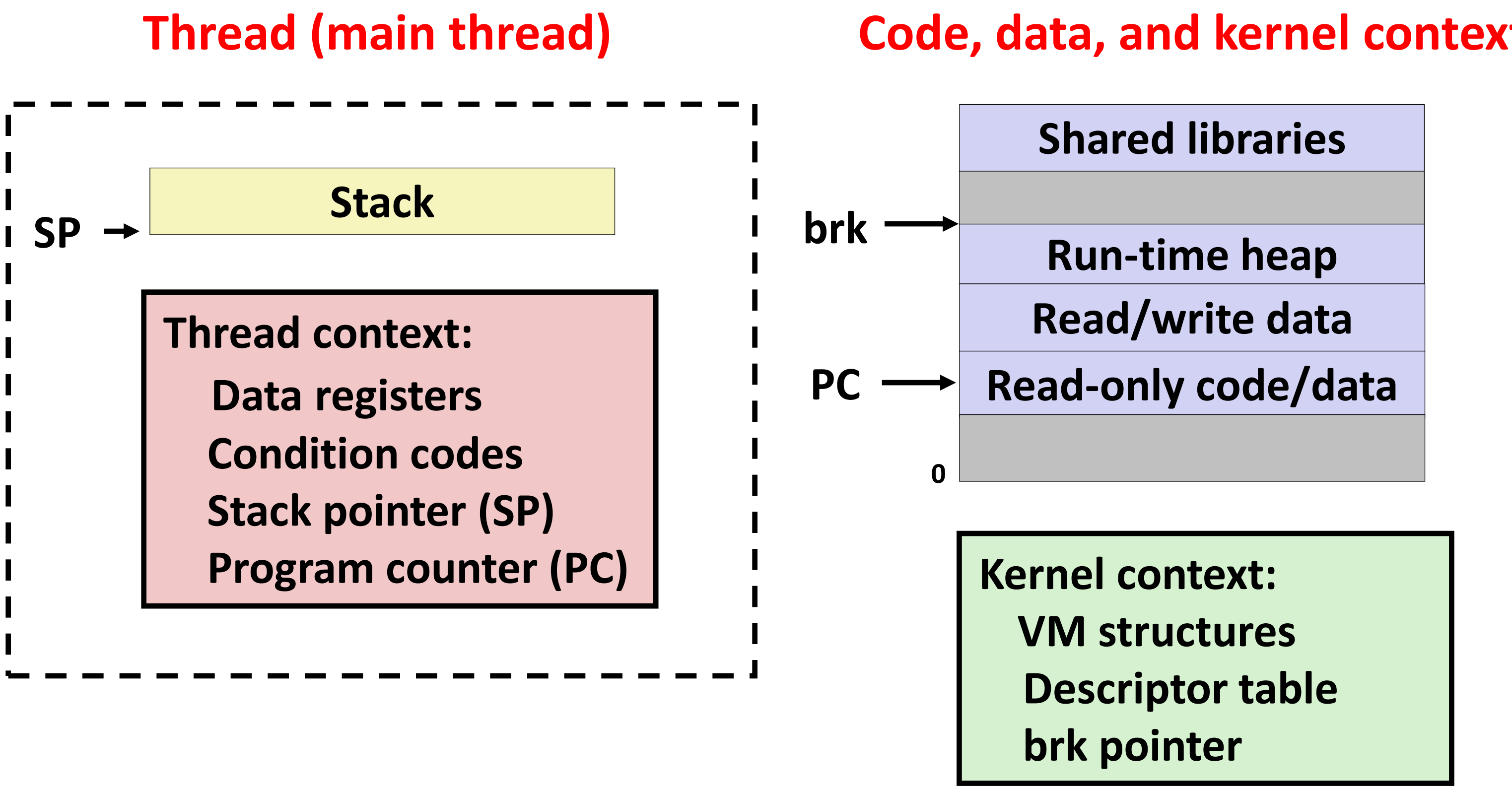
Kernel context:
- VM structures
- Descriptor table
- brk pointer

Code, data, and stack



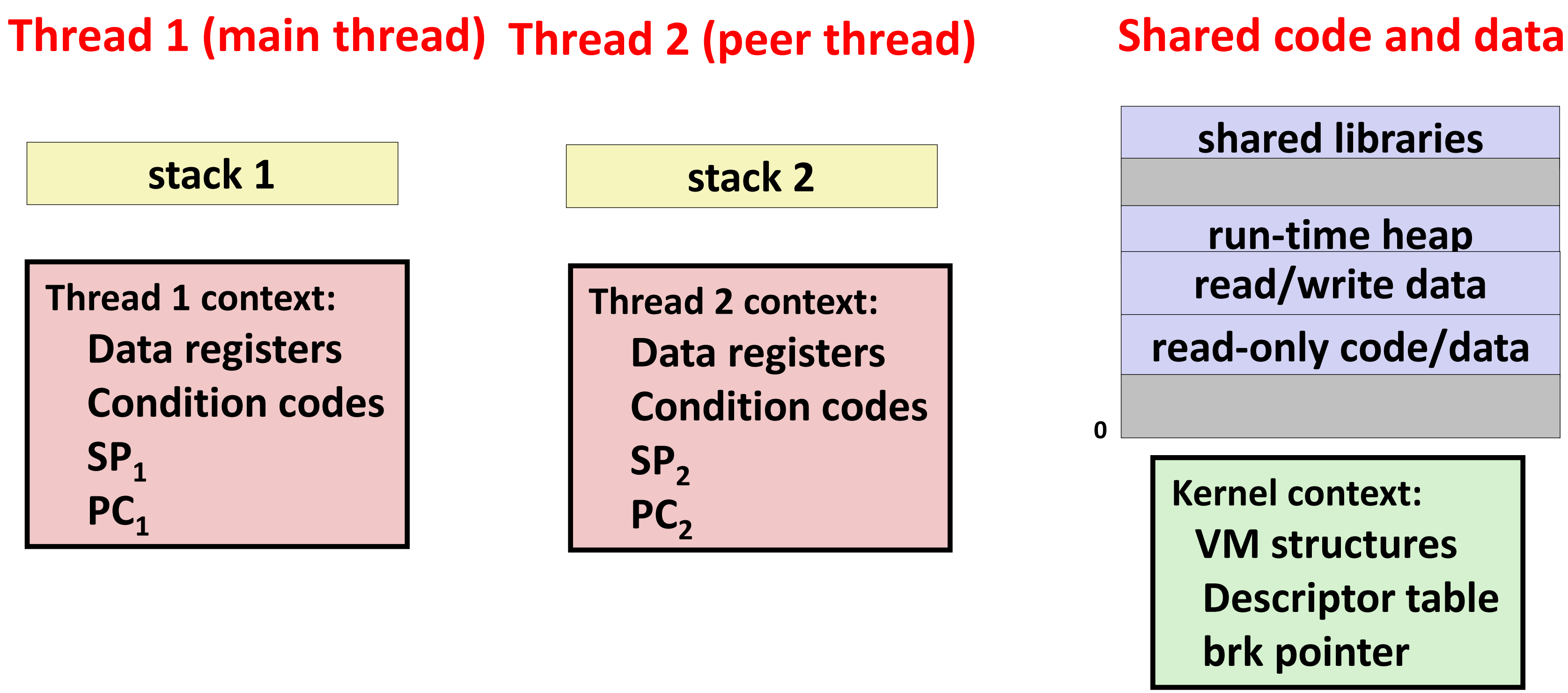
Alternate View of a Process

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

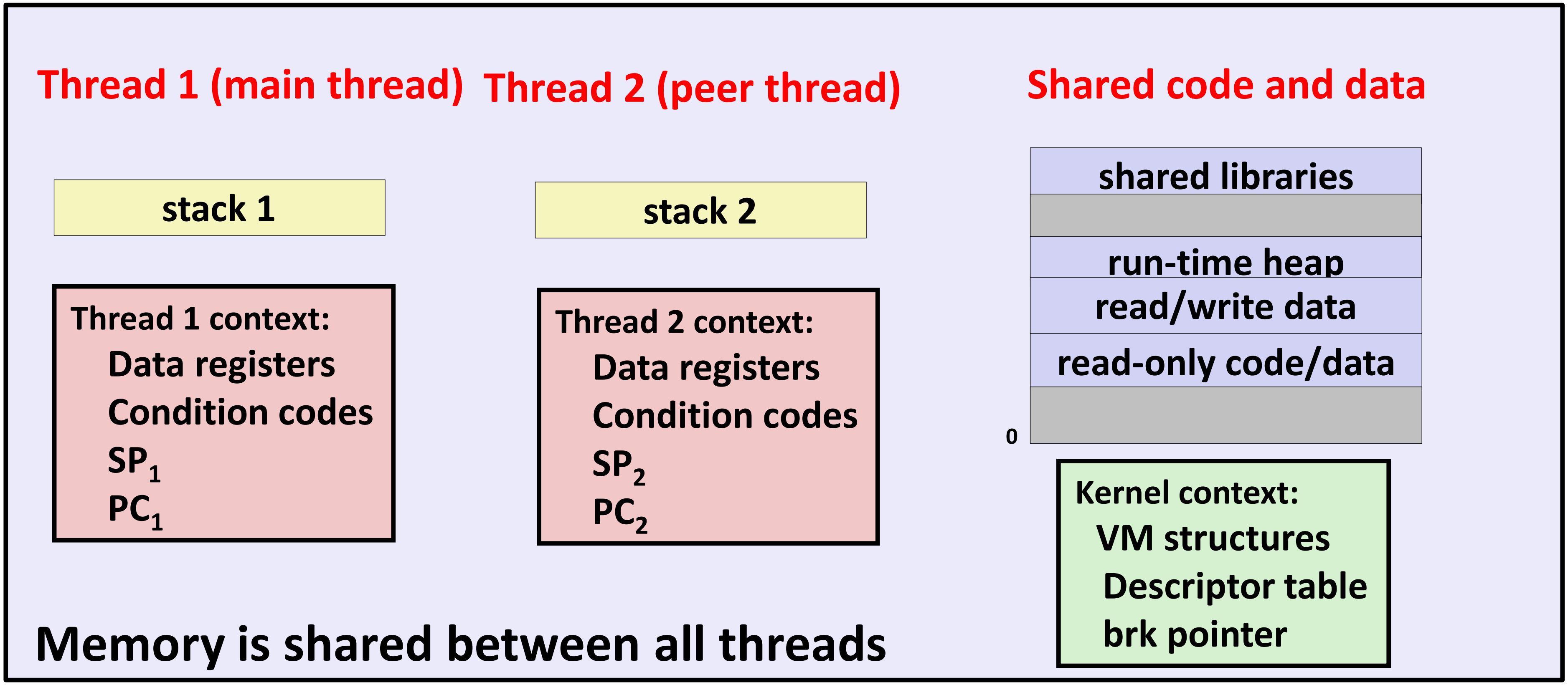


A Process With Multiple Threads

- **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)



Don’t let picture confuse you!



Threads vs. Processes

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

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

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!

Today

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

Shared Variables in Threaded C Programs

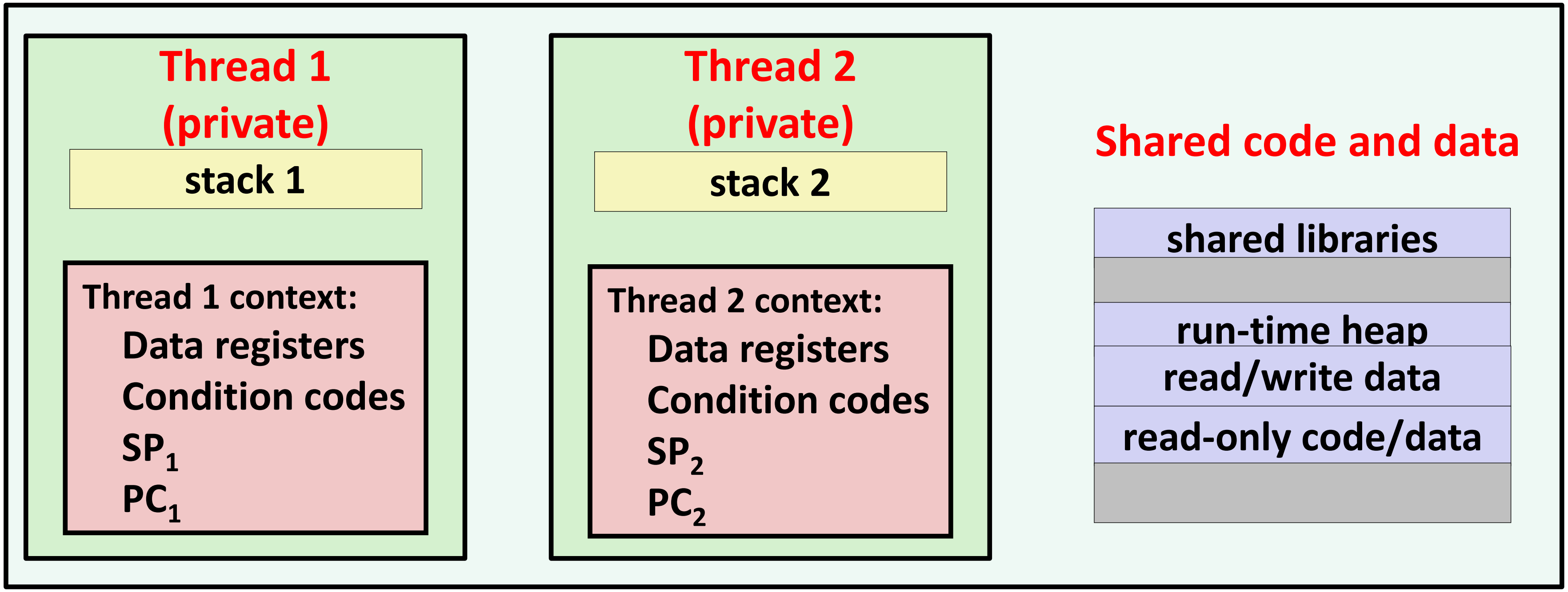
- **Question: Which variables in a threaded C program are shared?**
  - The answer is not as simple as "*global variables are shared*" and "*stack variables are private*"

- ***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?

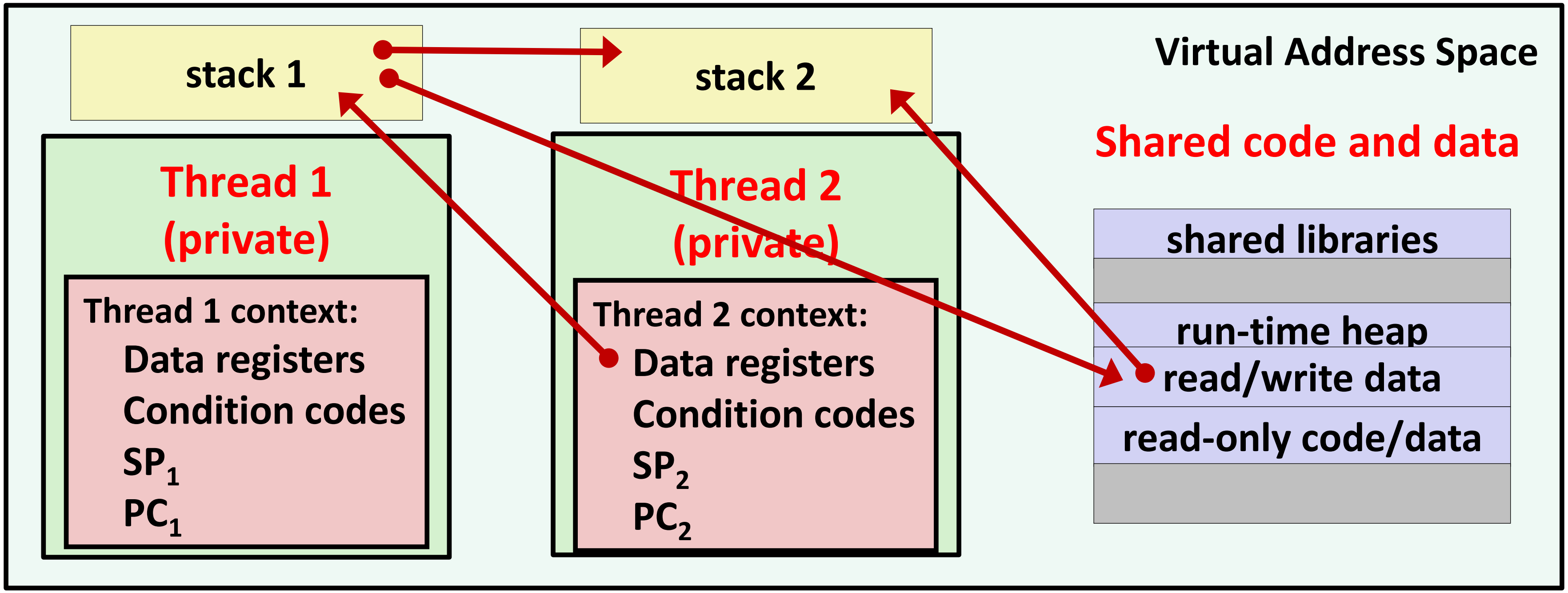
Threads Memory Model: Conceptual

- **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 sizeof(long) <= sizeof(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, but inelegant way to pass a single argument to a thread routine

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

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

Local vars: 1 instance (`i.m`, `msgs.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?**

Variable instance	*Referenced by main thread?*	*Referenced by peer thread 0?*	*Referenced by peer thread 1?*
`ptr`	yes	yes	yes
`cnt`	no	yes	yes
`i.m`	yes	no	no
`msgs.m`	yes	yes	yes
`myid.p0`	no	yes	no
`myid.p1`	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?

Variable instance	*Referenced by main thread?*	*Referenced by peer thread 0?*	*Referenced by peer thread 1?*
`ptr`	yes	yes	yes
`cnt`	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`, `cnt`, and `msgs` are shared
  - `i` and `myid` are *not* shared

Today

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

Synchronizing Threads

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

`badcnt.c`: Improper Synchronization

```c
/* 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

```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

```
    movq   (%rdi), %rcx
    testq  %rcx,%rcx
    jle    .L2
    movl   $0, %eax
.L3:
    movq   cnt(%rip),%rdx
    addq   $1, %rdx
    movq   %rdx, cnt(%rip)
    addq   $1, %rax
    cmpq   %rcx, %rax
    jne    .L3
.L2:
```

H_i : Head

L_i : Load cnt
U_i : Update cnt
S_i : Store cnt

T_i : Tail

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

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)

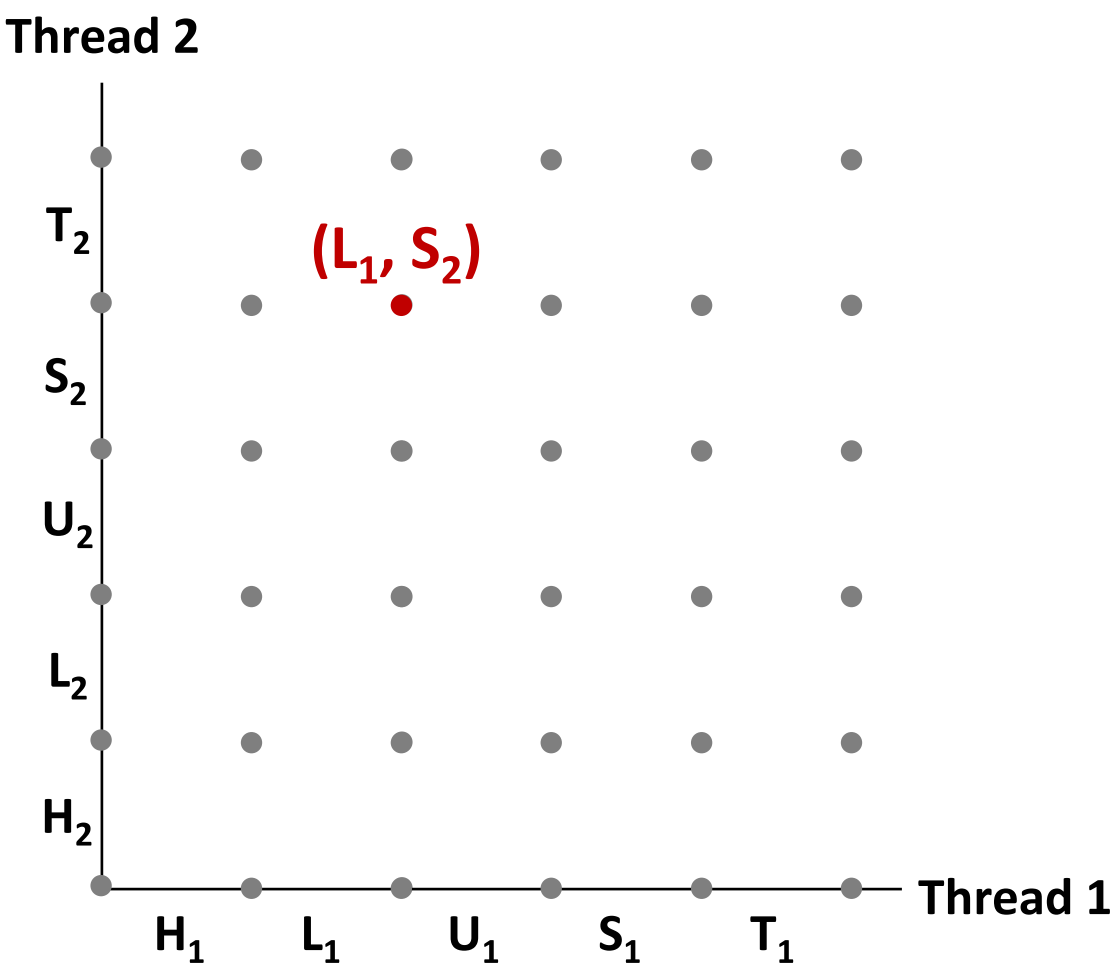
- How about this ordering?

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



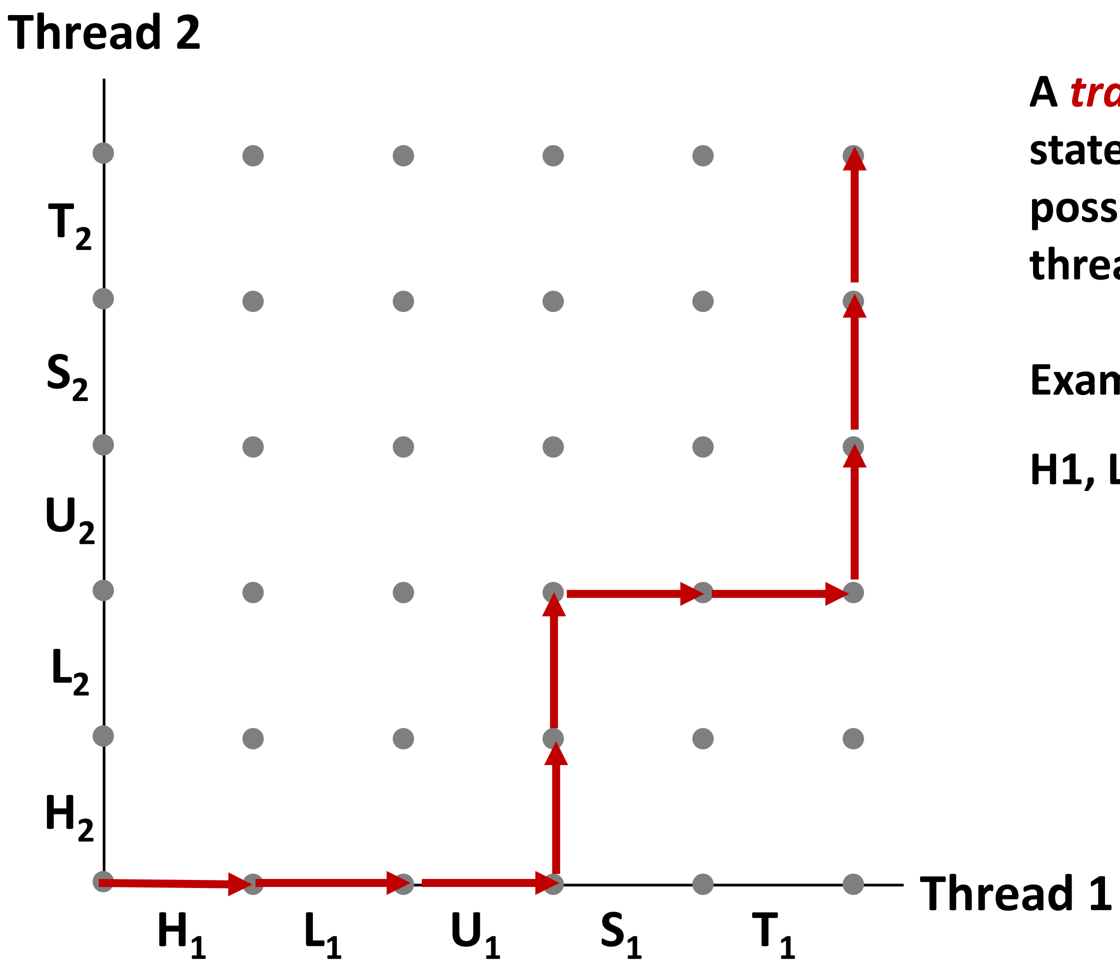
A ***progress graph*** depicts the discrete ***execution state space*** of concurrent threads.

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

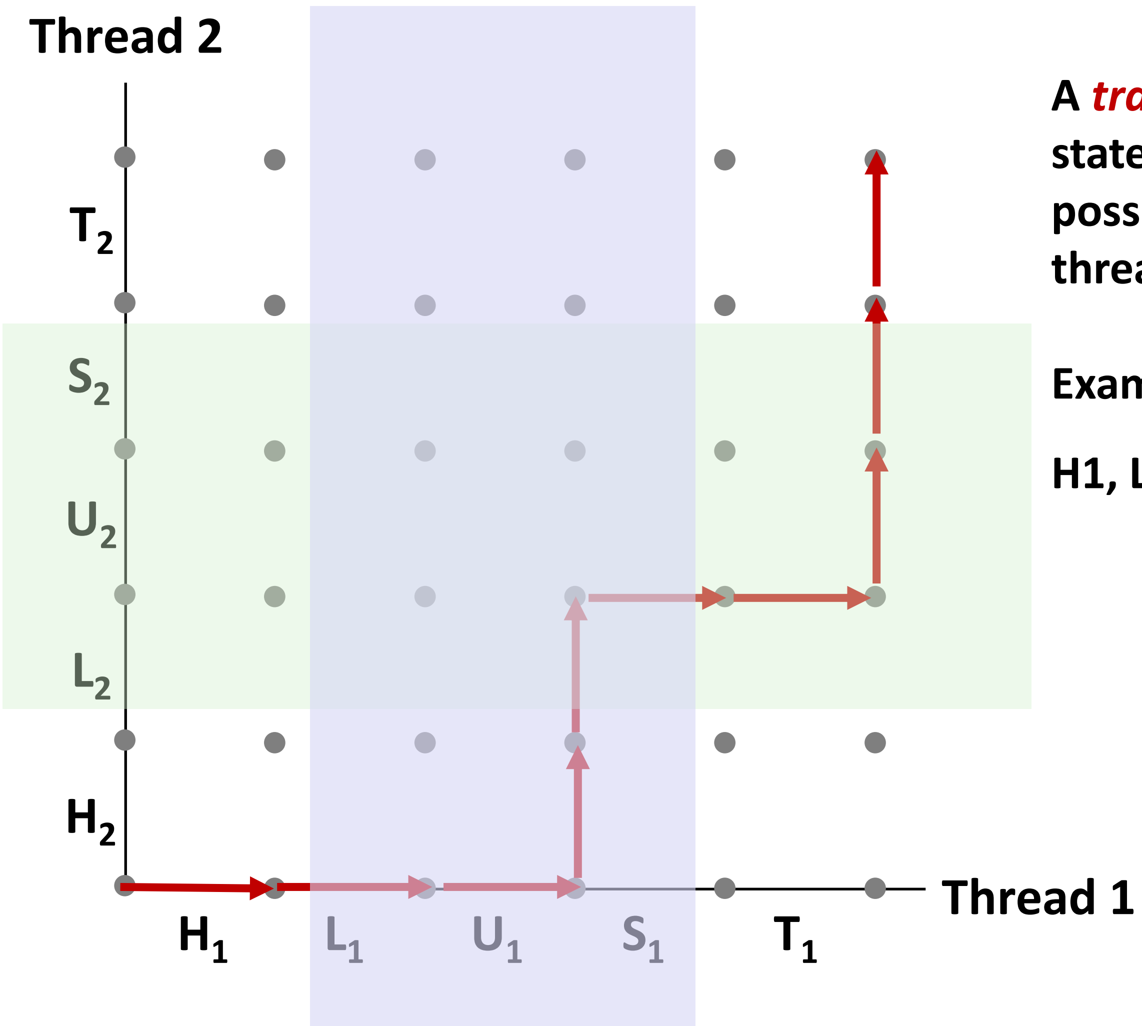


A ***trajectory*** **is a sequence of legal state transitions that describes one possible concurrent execution of the threads.**

Example:

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

Trajectories in Progress Graphs

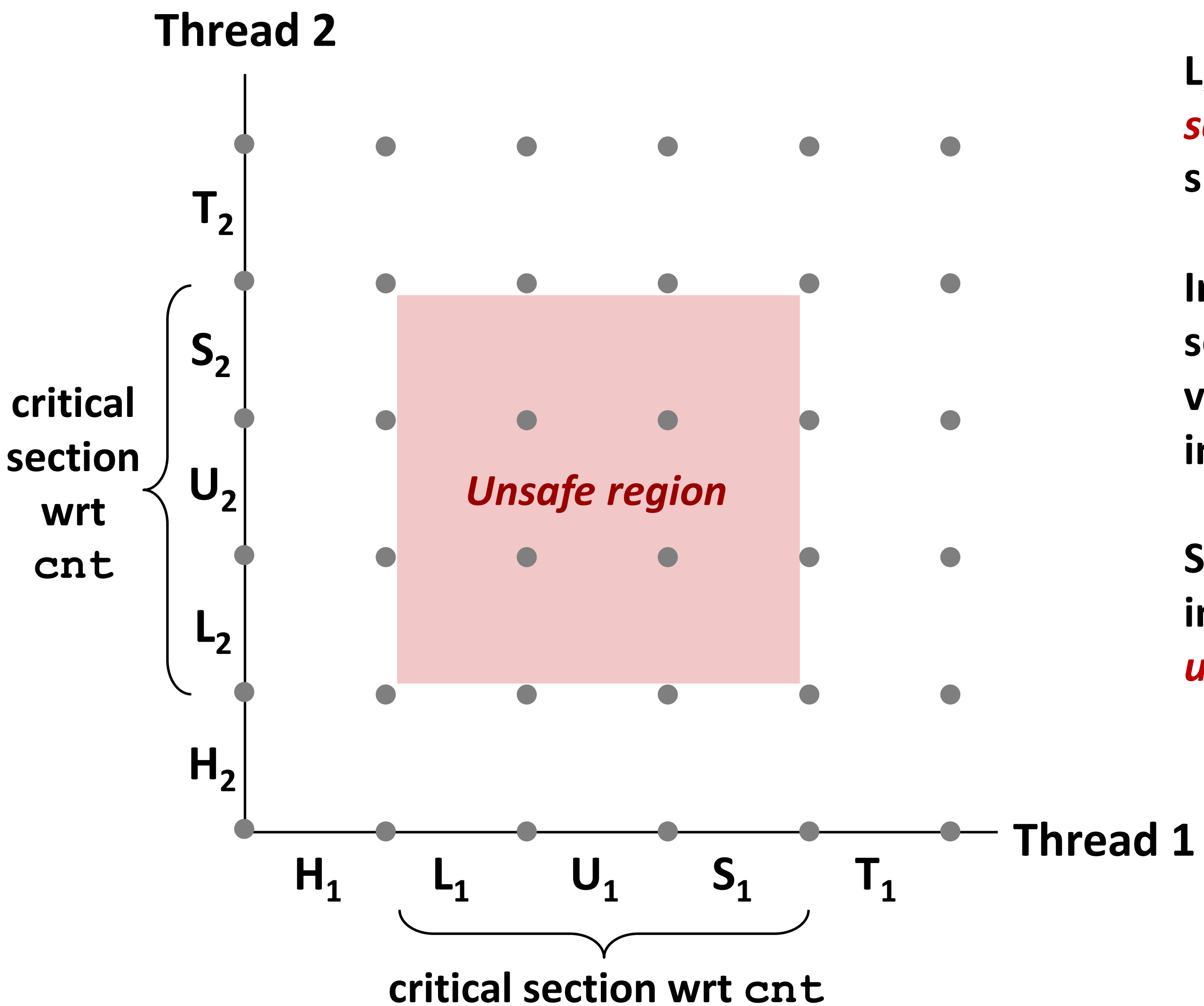


A ***trajectory*** is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Critical Sections and Unsafe Regions

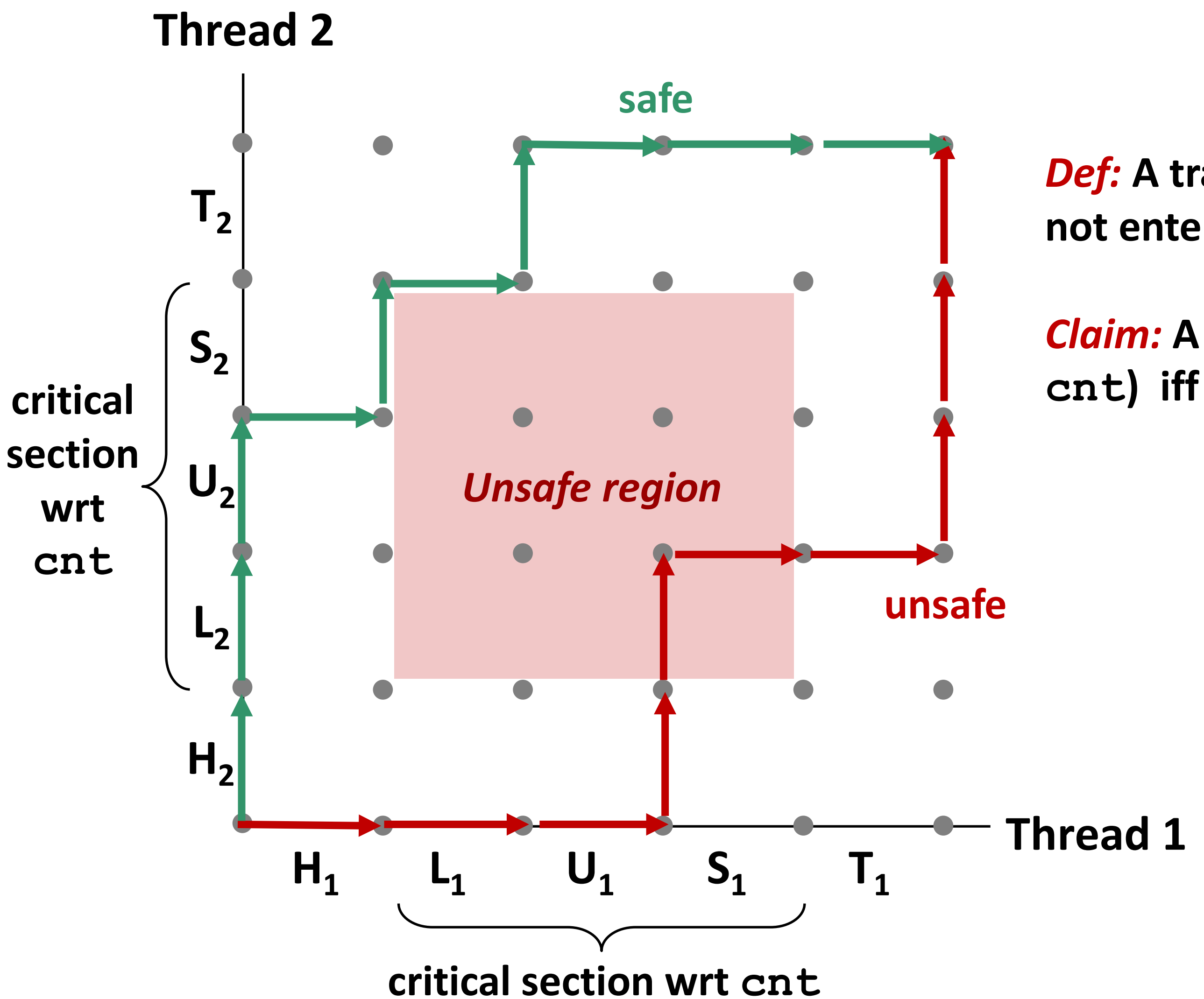


L, U, and S form a ***critical section*** with respect to the shared variable `cnt`

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

```c
/* 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

```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

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)

Today

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

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 >= 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 >= 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);
}
```

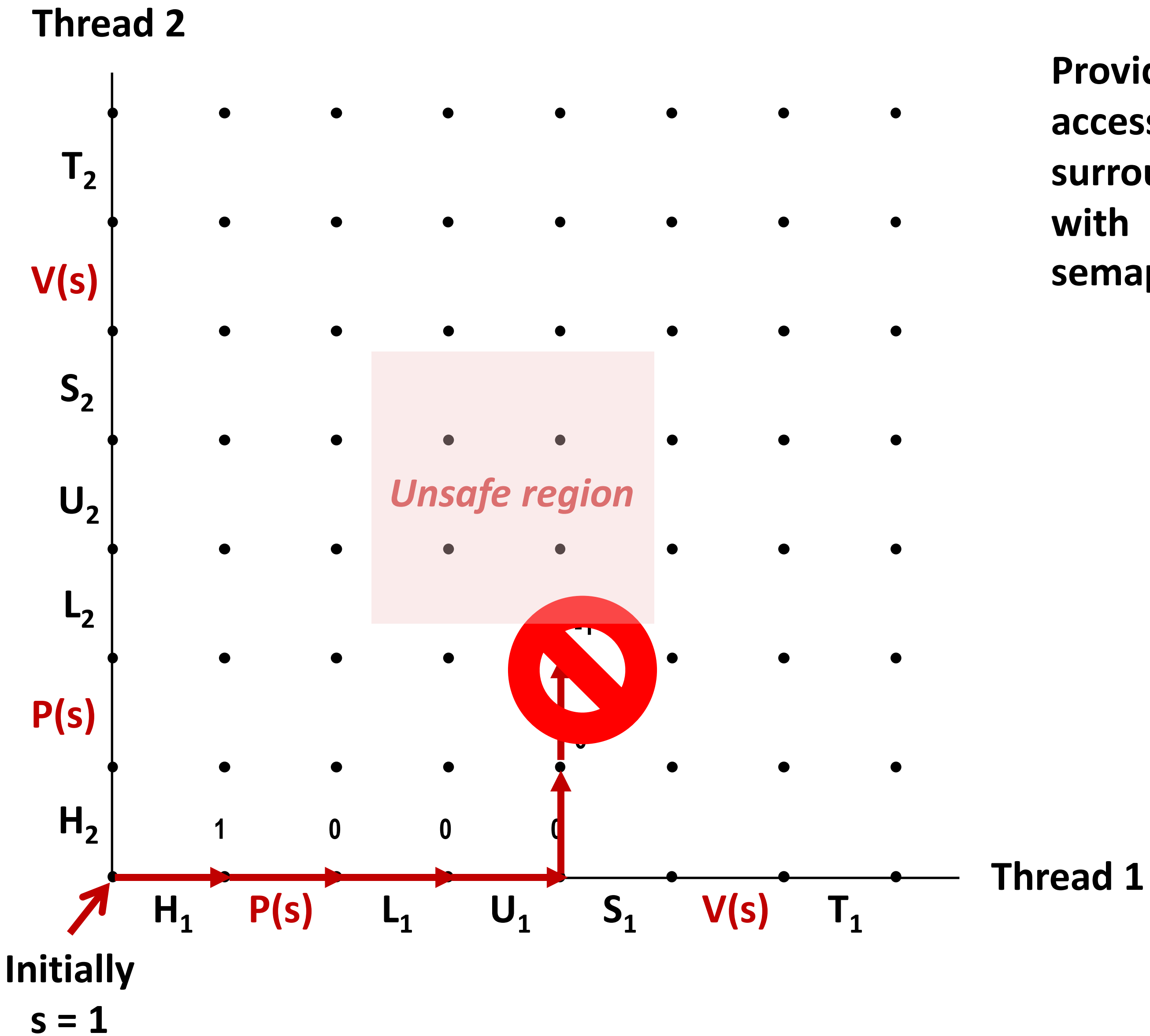
goodcnt.c

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

Function	badcnt	goodcnt
Time (ms) niters = 10^6	12	450
Slowdown	1.0	37.5

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

Why Mutexes Work



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

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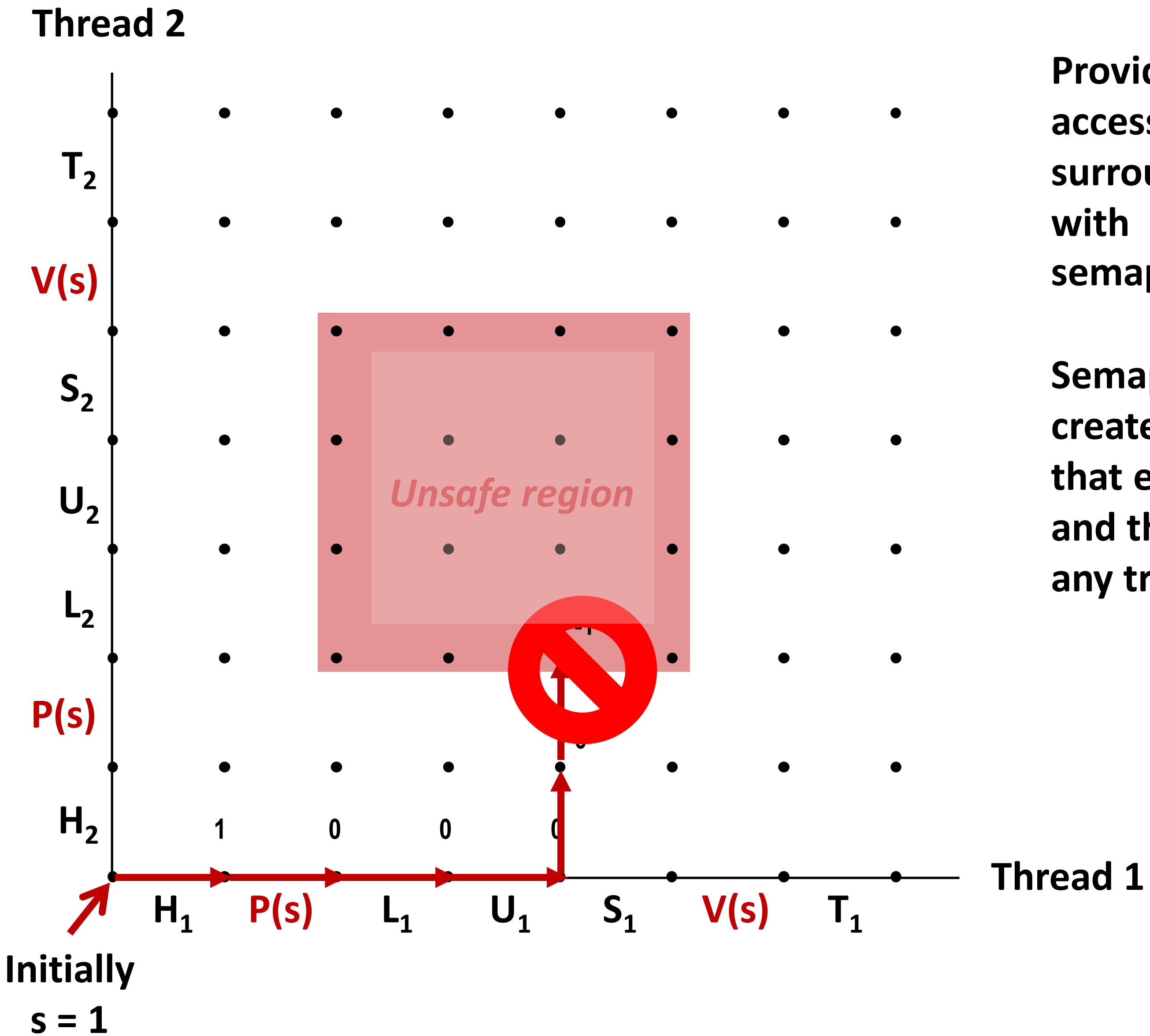

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Semaphore invariant creates a ***forbidden region*** that encloses unsafe region and that cannot be entered by any trajectory.

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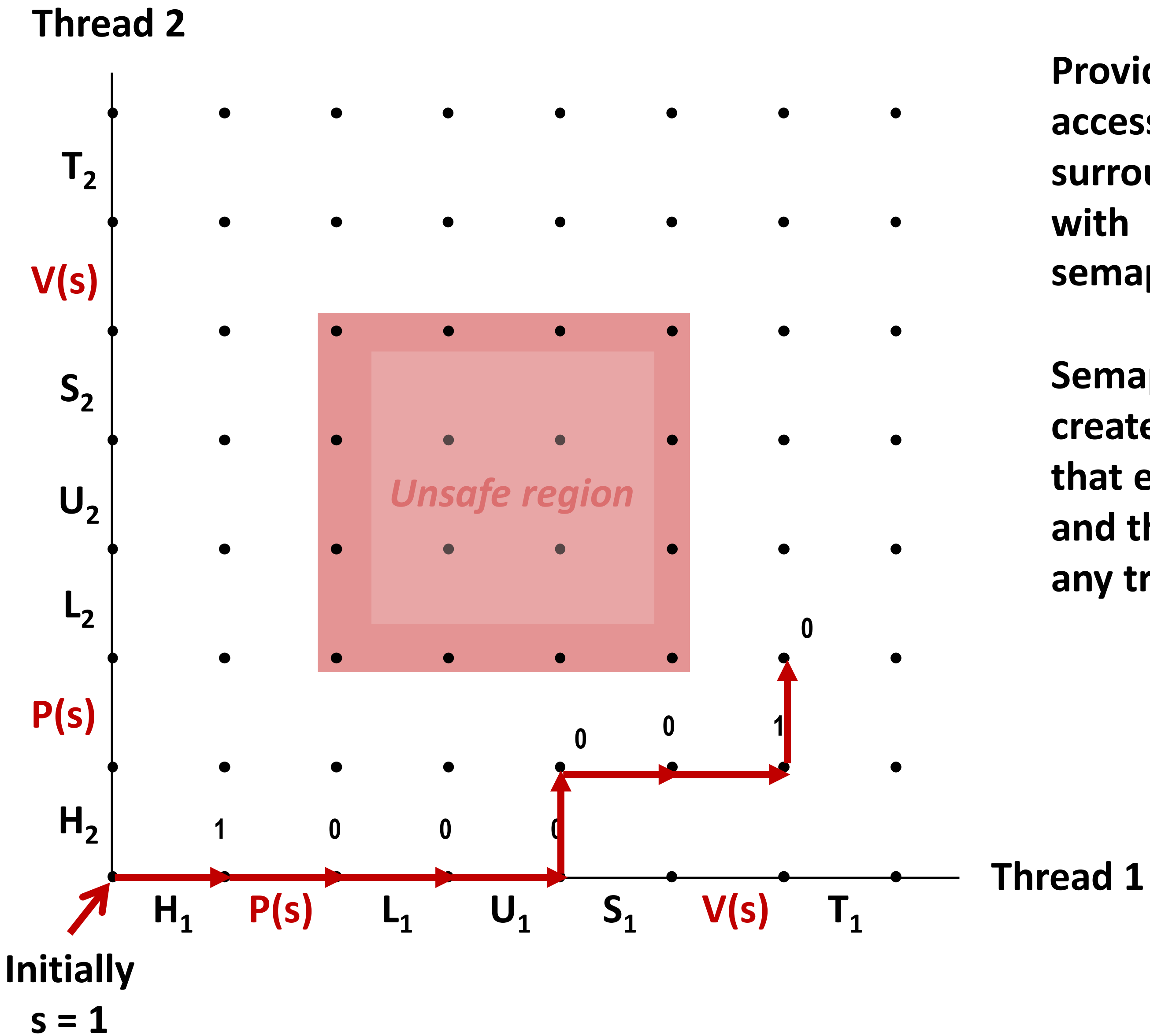

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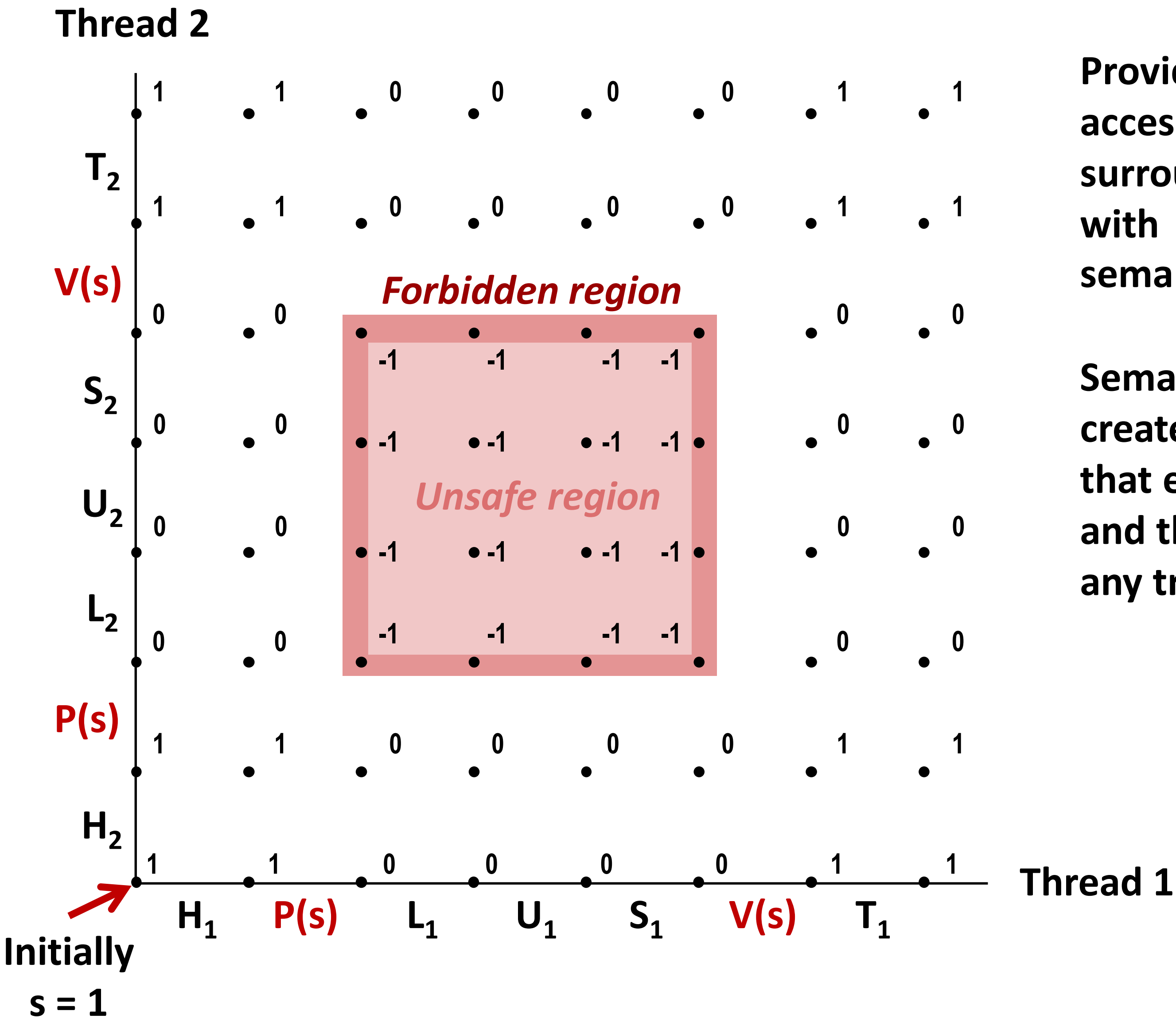


Provide mutually exclusive access to shared variable by surrounding critical section with *P* and *V* operations on semaphore s (initially set to 1)

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

Enforcing 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**

goodmcnt.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);
}
```

goodcnt.c

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

Function	badcnt	goodcnt	goodmcnt
Time (ms) niters = 10^6	12	450	214
Slowdown	1.0	37.5	17.8

Today

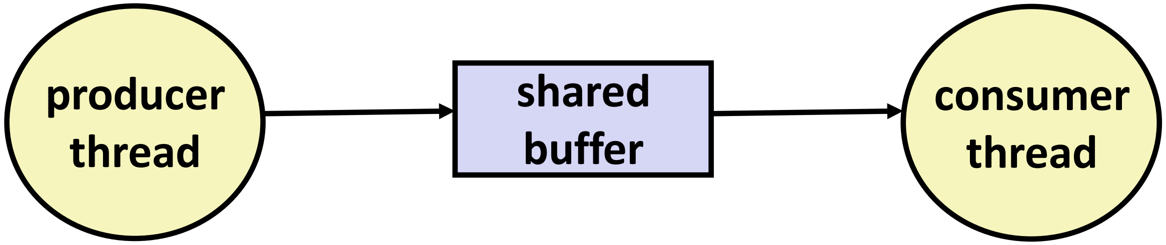
- Threads review
- Sharing
- Mutual exclusion
- Semaphores
- **Producer-Consumer Synchronization**

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

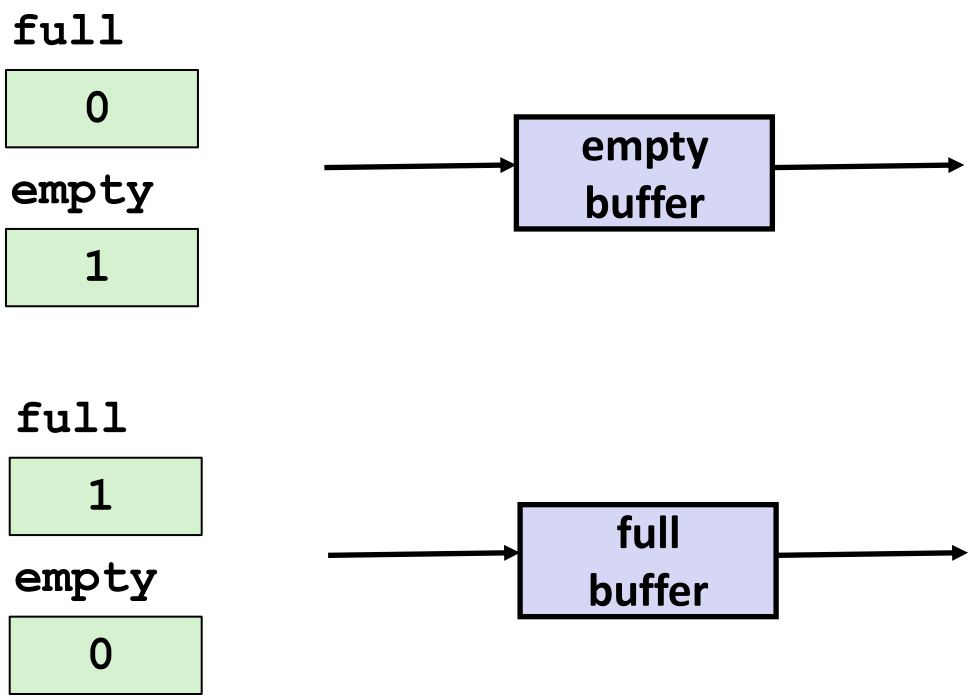


- **Common synchronization pattern:**
  - Producer waits for empty ***slot***, inserts item in buffer, and notifies consumer
  - Consumer waits for ***item***, removes it from buffer, and notifies producer

- **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

```c
#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;
```

```c
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

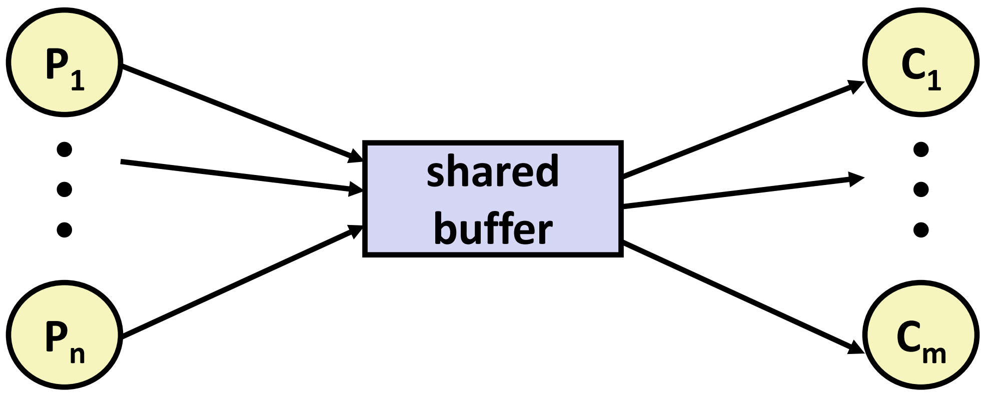
```
void *consumer(void *arg) {
  int i, item;

  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);
```

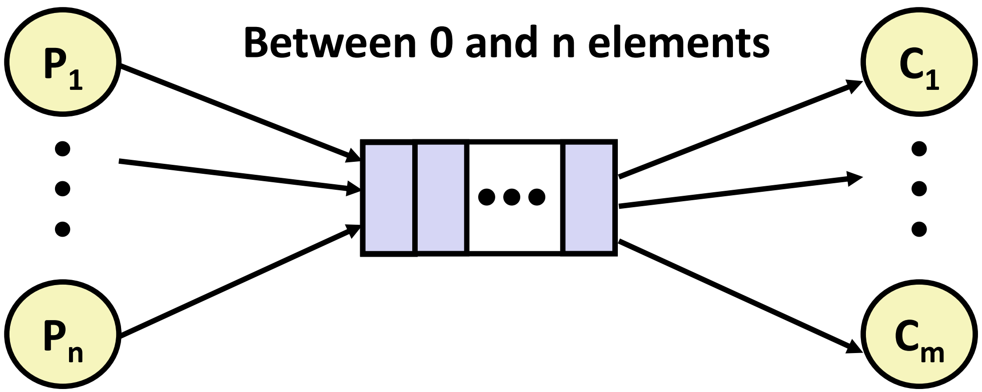
empty

full

Consumers

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

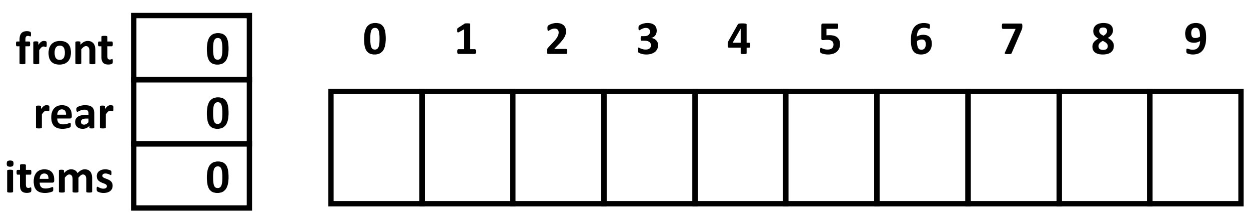
Producer-Consumer on an *n*-element Buffer



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

Circular Buffer (n = 10)

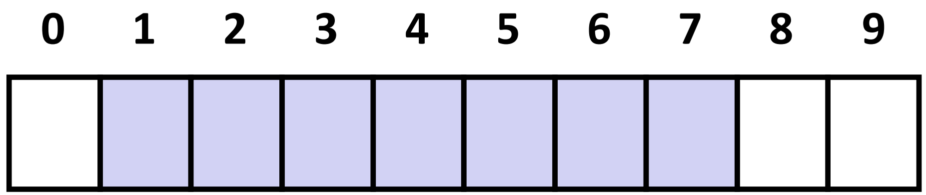
- **Store elements in array of size n**
- **items: number of elements in buffer**
- **Empty buffer:**
  - front = rear
- **Nonempty buffer**
  - rear: index of most recently inserted element
  - front: (index of next element to remove – 1) mod n
- **Initially:**



Circular Buffer Operation (n = 10)

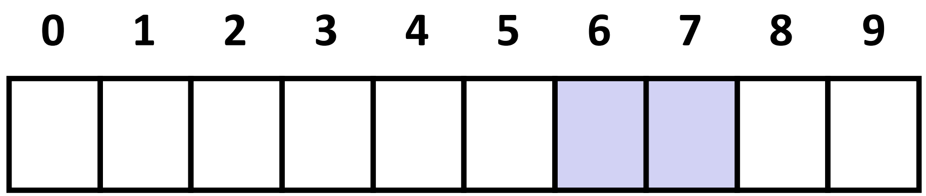
- **Insert 7 elements**

front	0
rear	7
items	7



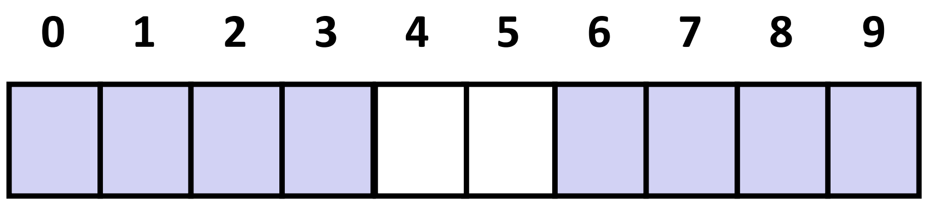
- **Remove 5 elements**

front	5
rear	7
items	2



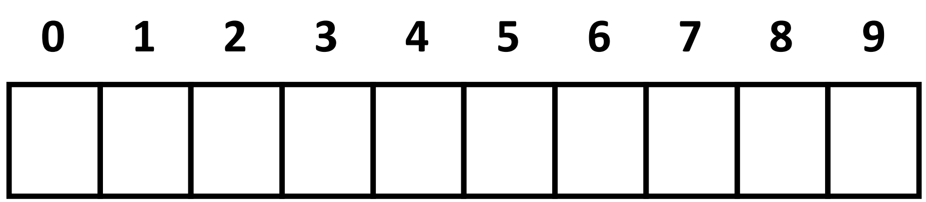
- **Insert 6 elements**

front	5
rear	3
items	8



- **Remove 8 elements**

front	3
rear	3
items	0



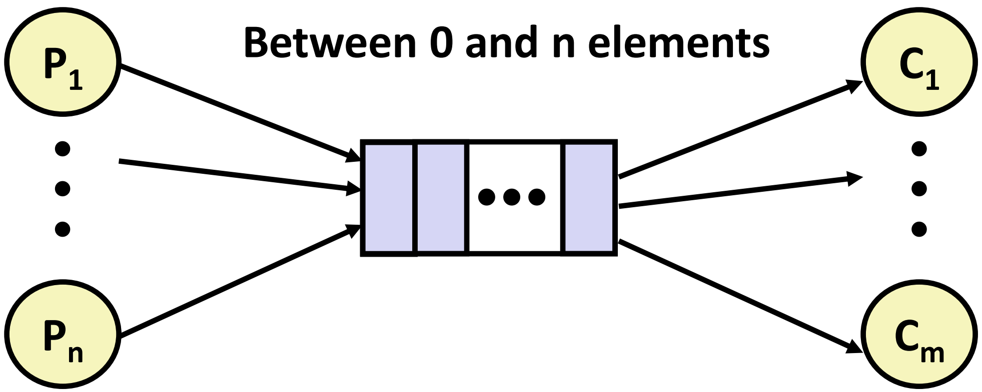
Sequential Circular Buffer Code

```
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->mutex, 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**
  - And can also support producer-consumer synchronization