Synchronization: Basics

15-213: Introduction

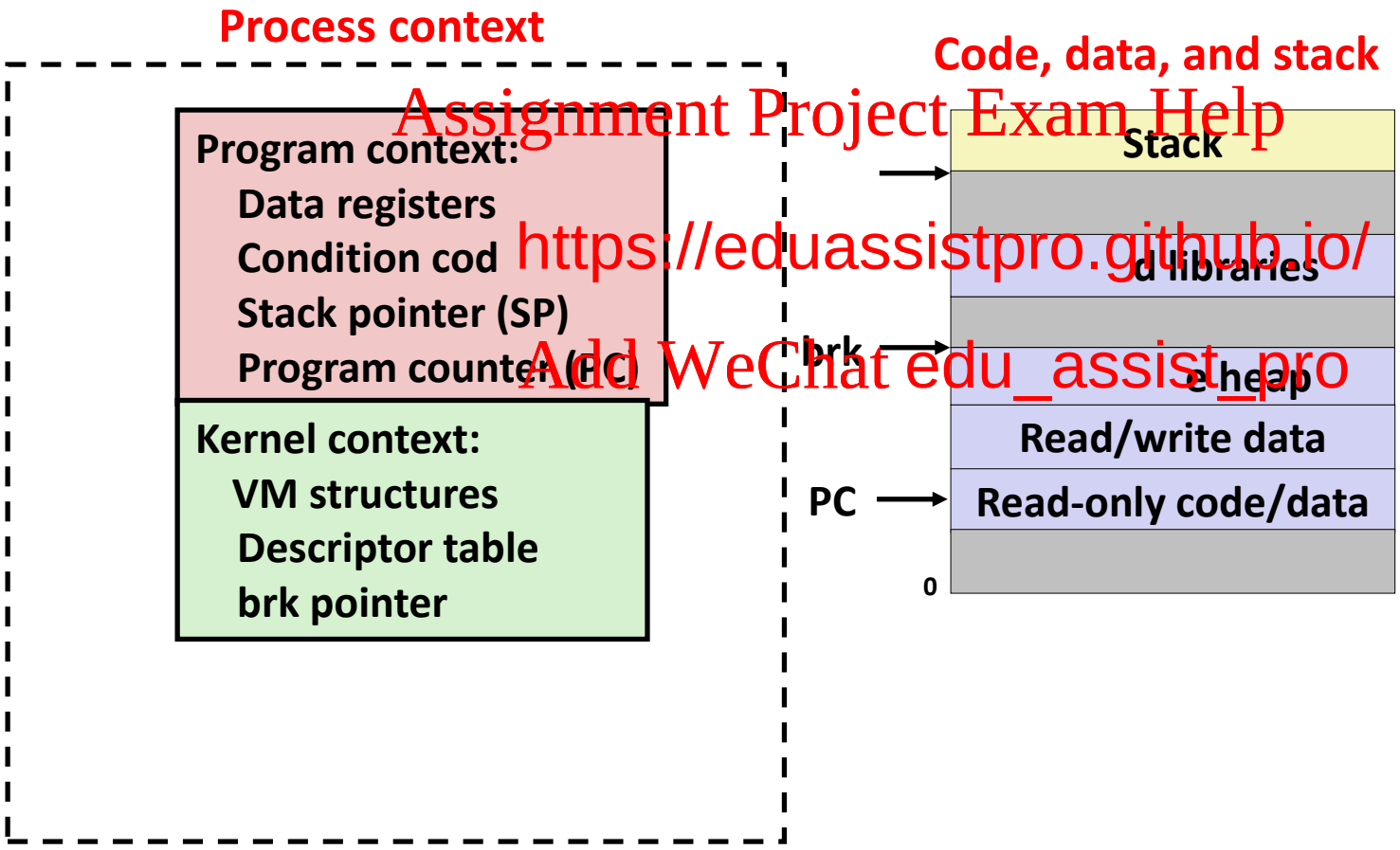
25th Lecture, April 1

Today

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

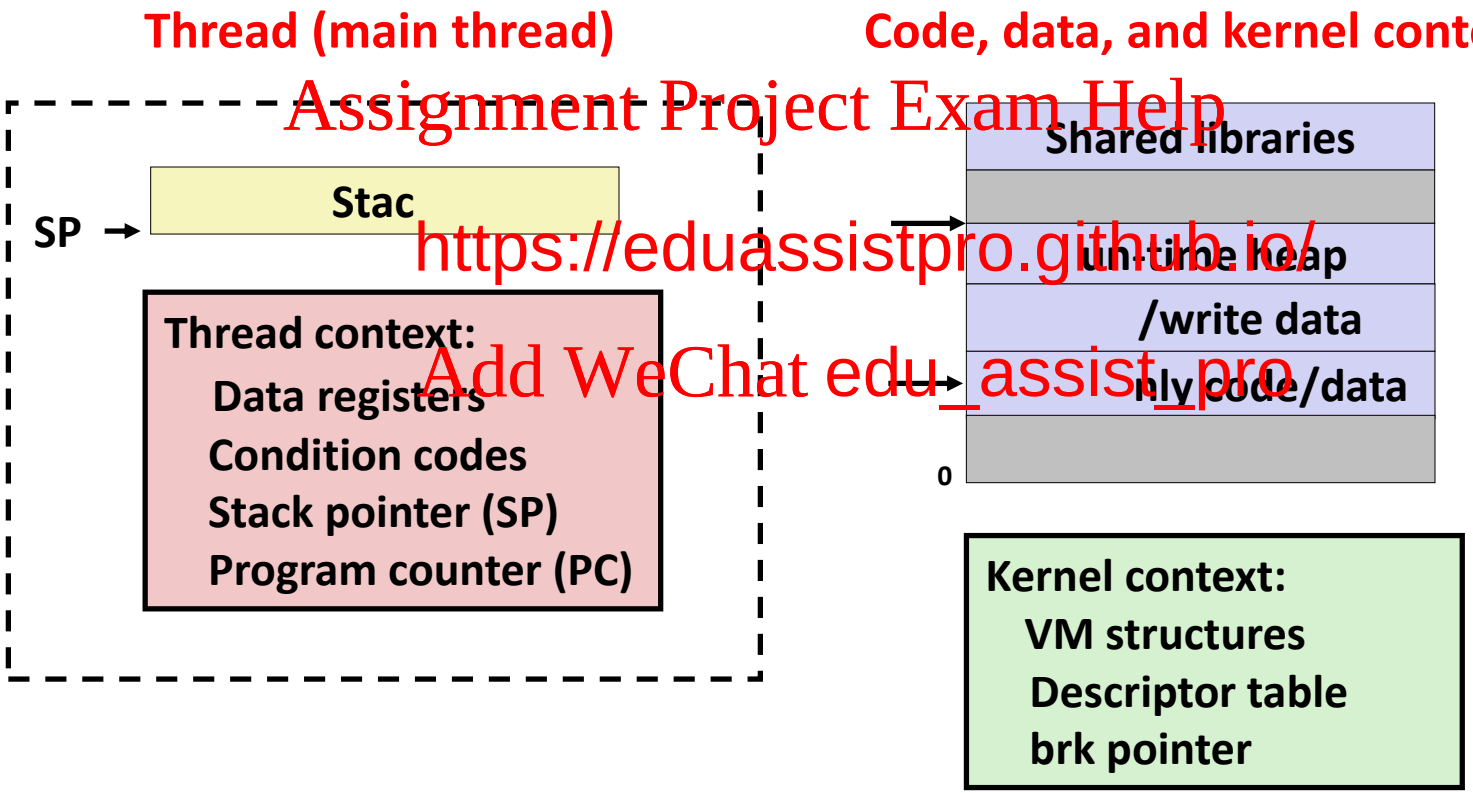
Traditional View of a Process

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



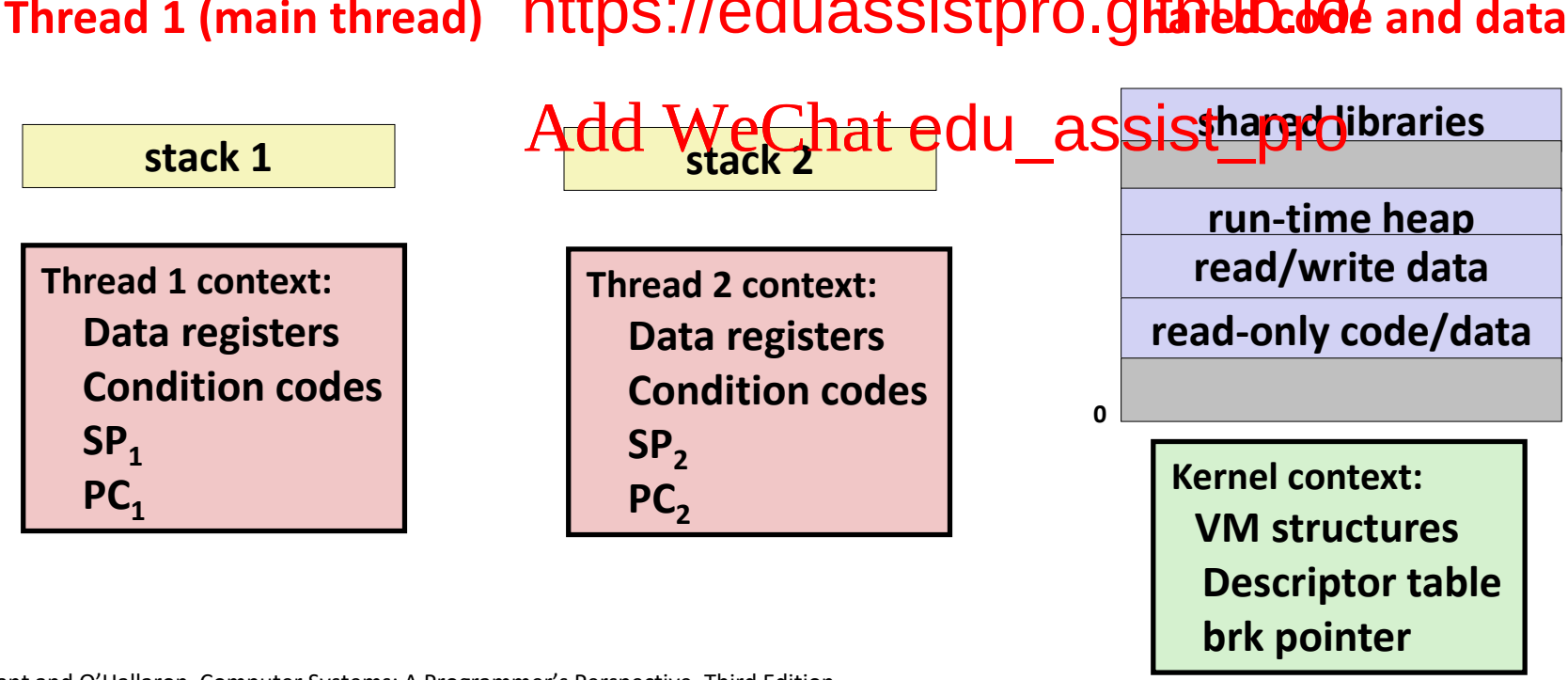
Alternate View of a Process

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

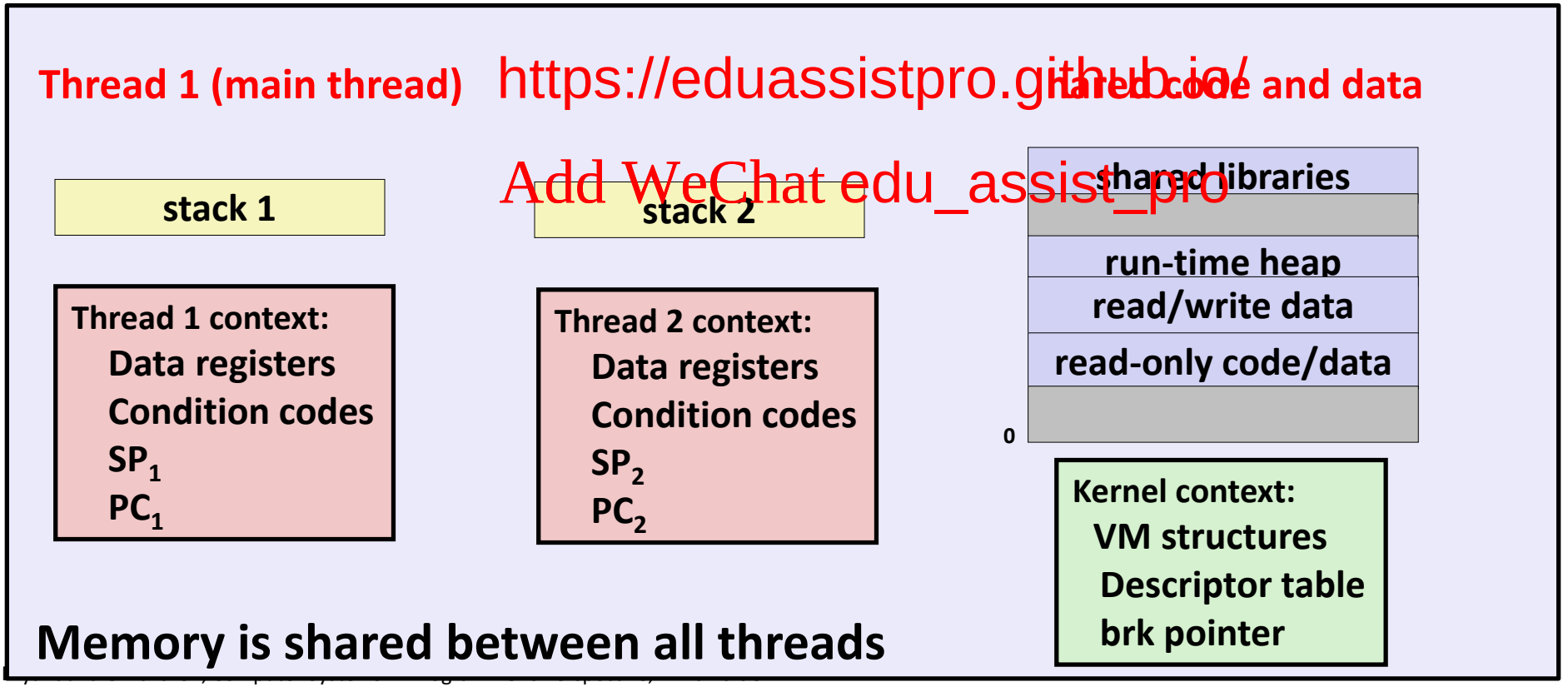


A Process With Multiple Threads

- **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!



Today

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

Shared Variables in Threaded C Programs

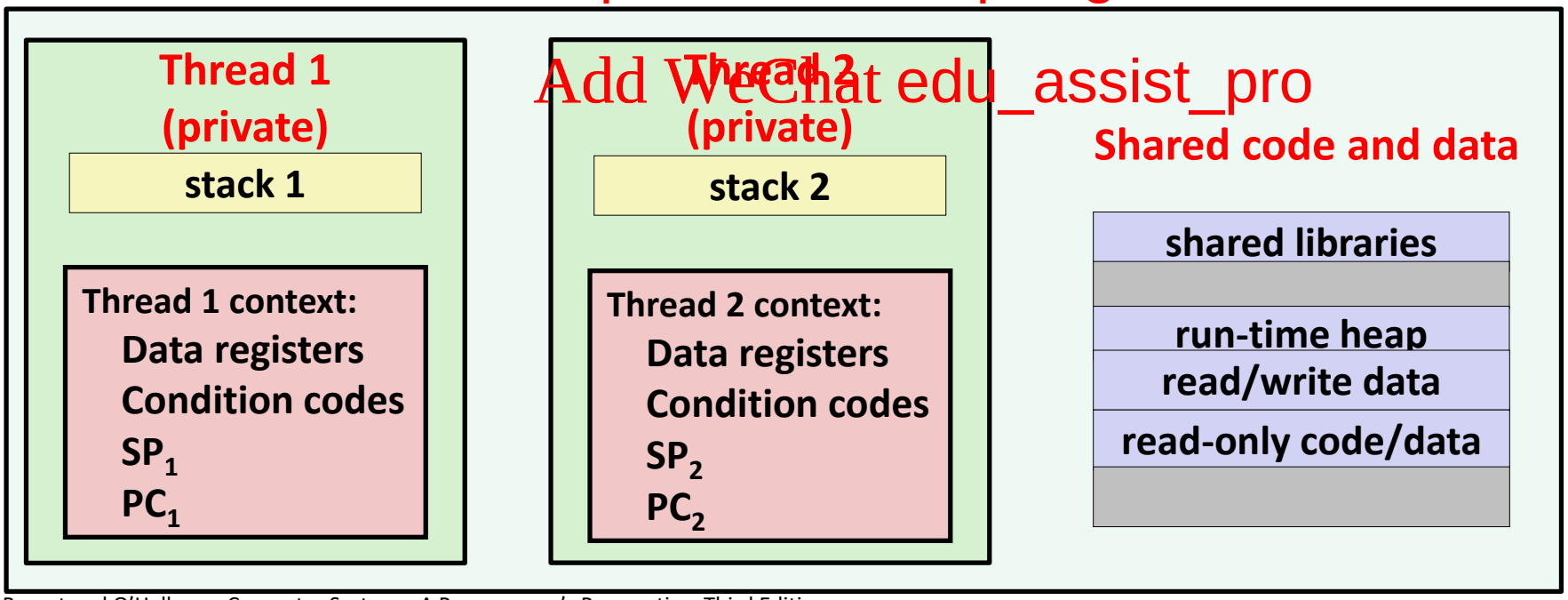
- **Question: Which variables in a threaded C program are shared?**
  - The answer is not as simple as "*global variables are shared*" and "*stack variables are private*"

- ***Def:*** **A variable `x` is shared if 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?

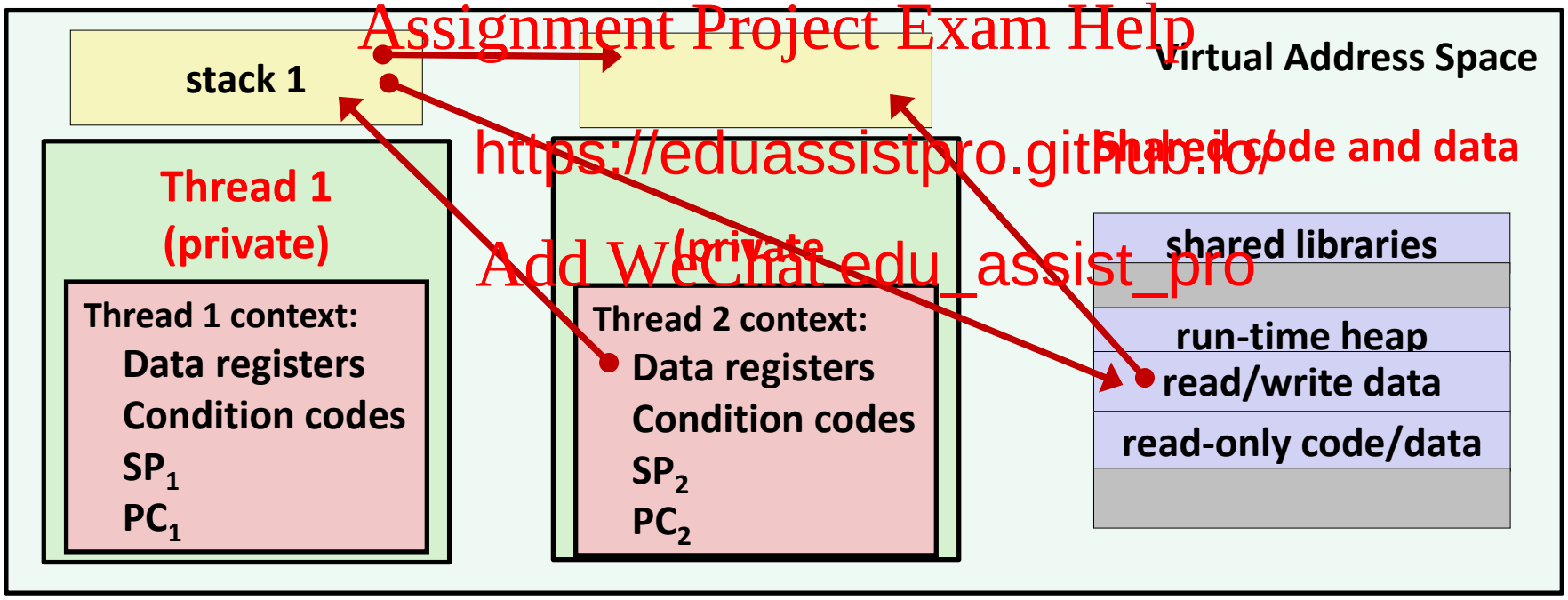
Threads Memory Model: Conceptual

- 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 handles



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 = Mallo
        *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;
}
```

```
voi                ) {
    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 = Mallo
        *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;
}
```


alloc to create a per
d 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(&
                     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;
}
```


se cast since
ong) <= 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(&
                     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;
}
```


ints to same location 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 pthread_create
  - Consumer deref
- **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 fo
        "Hello from ba
    };

    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",
           id, ptr[myid], ++cnt);
    NULL;
}
```

P erence 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 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 de `static` attribute
  - **Each thread stack contains one ins 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


```
vo                oid *vargp)
                = (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]
)


```
vo                oid *vargp)
                = (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		es
myid.p0	no		o
myid.p1	no	no	


```
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		o
`msgs.m`	yes		es
`myid.p0`	no	yes	
`myid.p1`	no	no	

- 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
        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++)
        nt++;

            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


```
    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:
```

: 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)	$instr_i$			
1	H_1			
1	L_1	0	-	
1	U_1	1	-	
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

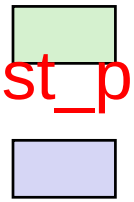
OK

****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)	$instr_i$			
1	H_1			
1	L_1	0	-	
1	U_1	1	-	
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			
1	U_1			
2	H_2			
2	L_2	-	0	
1	S_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)

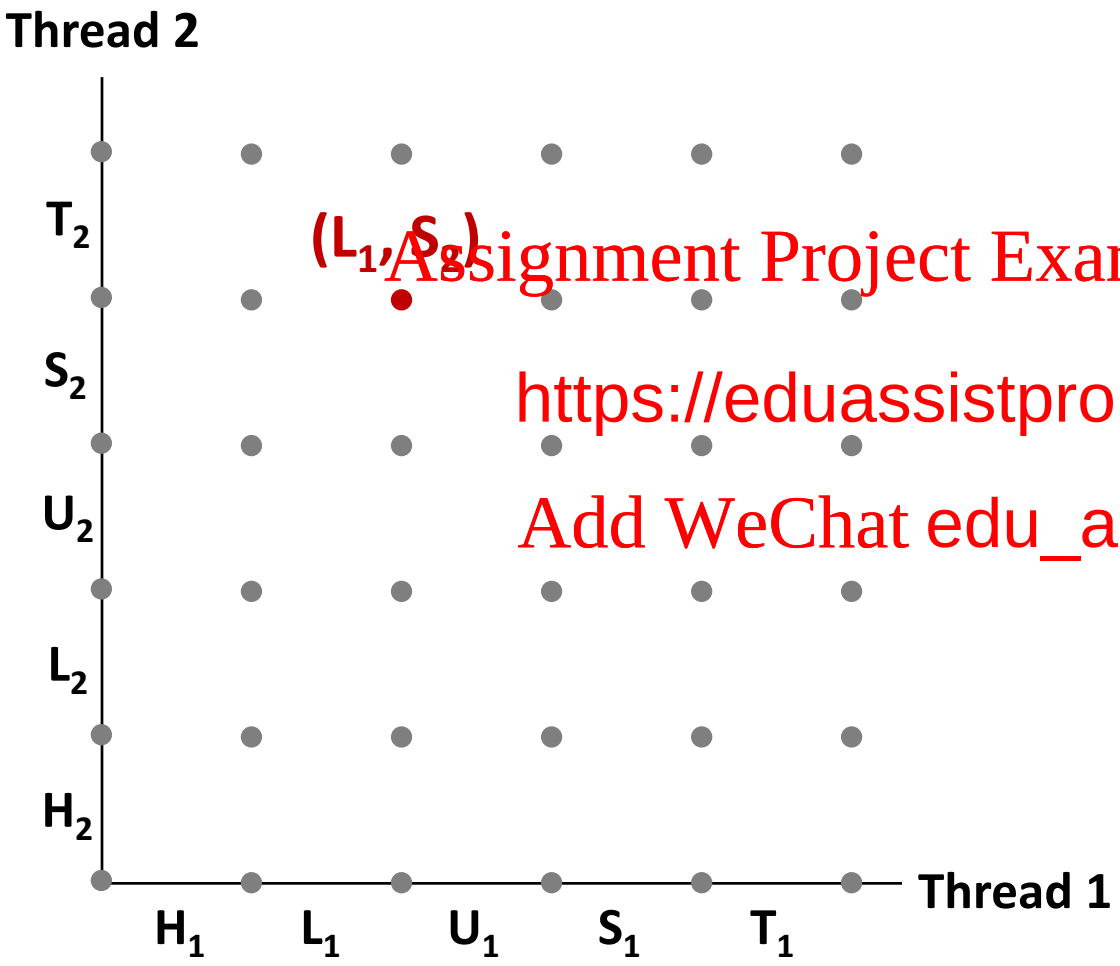
- How about this ordering?

i (thread)	$instr_i$	$\%rdx_1$	$\%rdx_2$	cnt
1	H_1			0
1	L_1	0		
2	H_2			
2	L_2			
2	U_2			
2	S_2		1	
1	U_1	1		
1	S_1	1		
1	T_1			1
2	T_2			1

Oops!

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

Progress Graphs



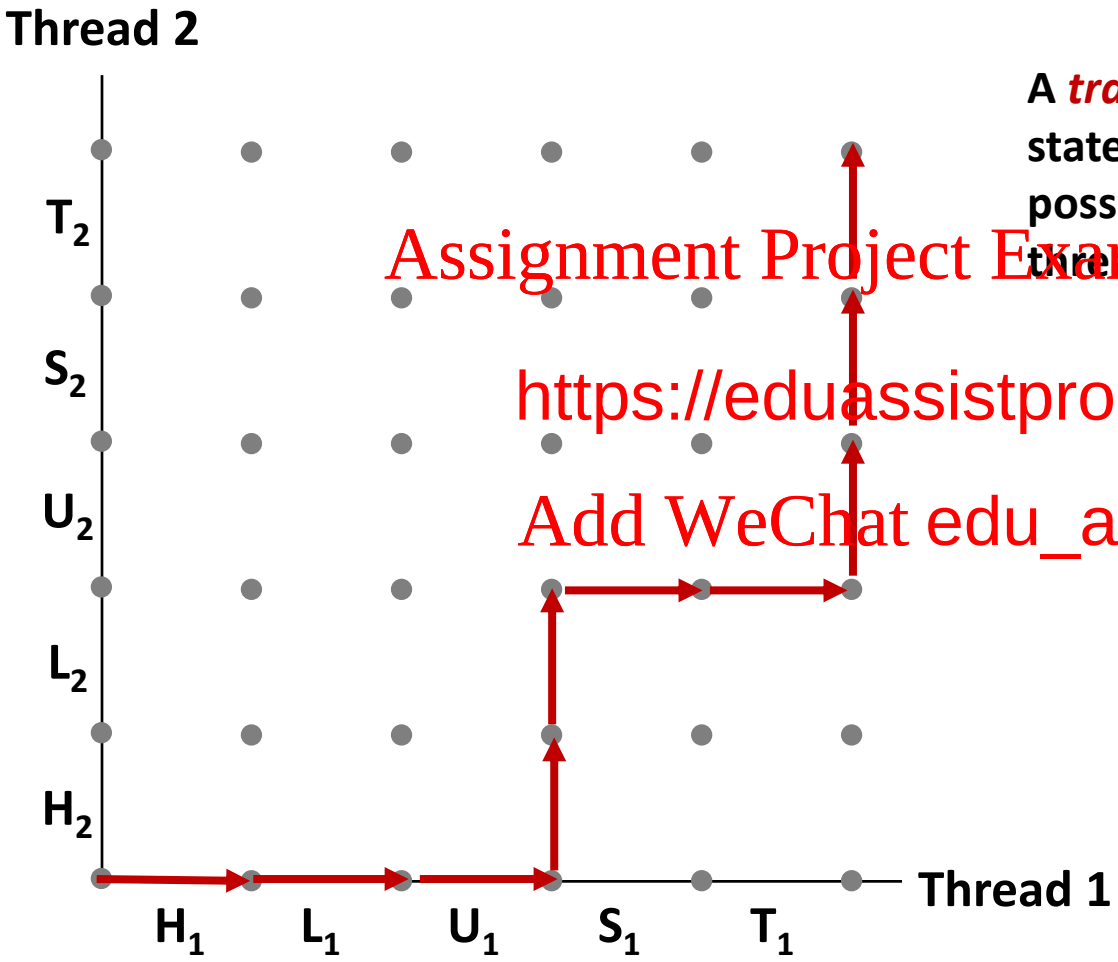
A *progress graph* depicts the discrete *execution state space* of concurrent threads.

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

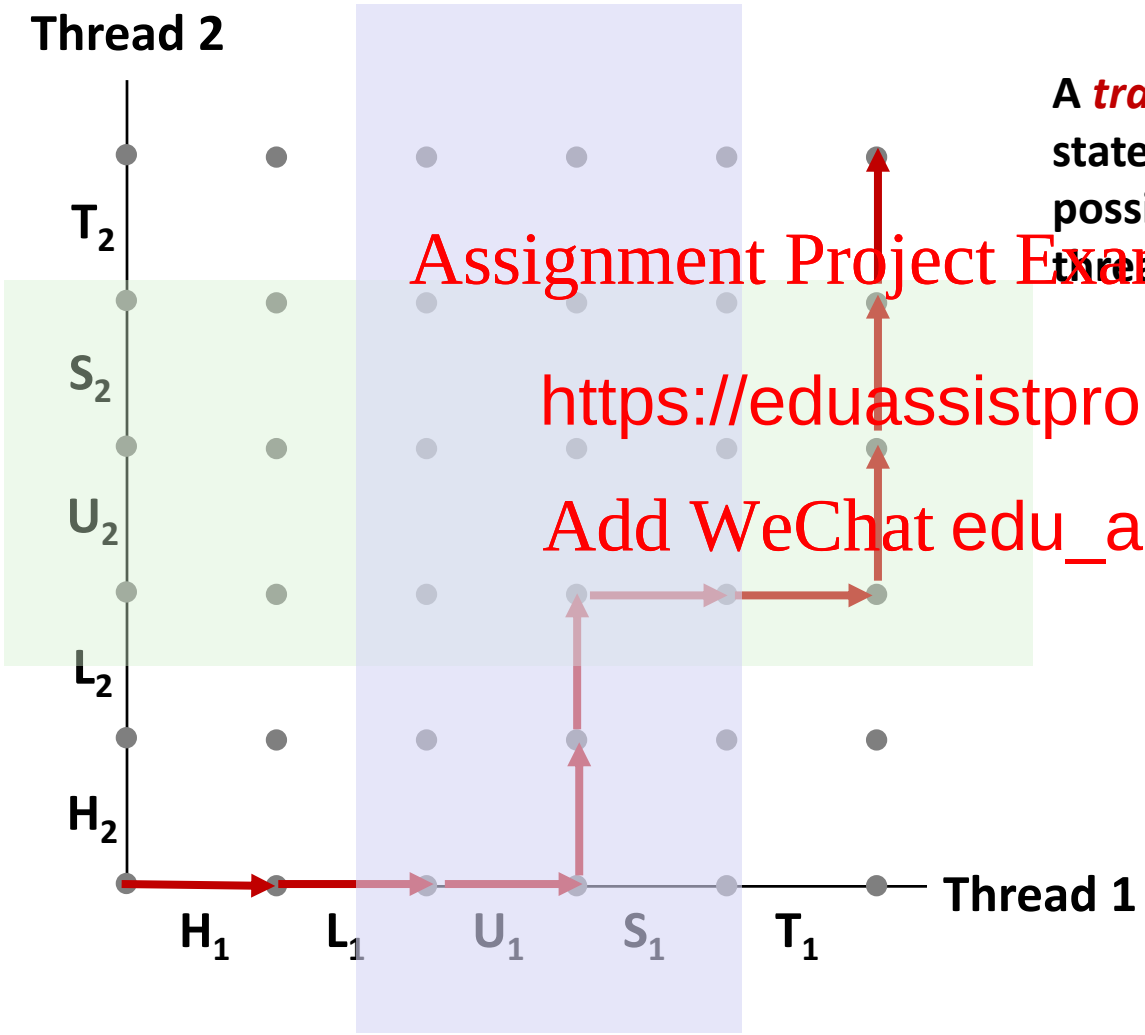


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

e.g.,

, H2, L2, S1, T1, U2, S2, T2

Trajectories in Progress Graphs

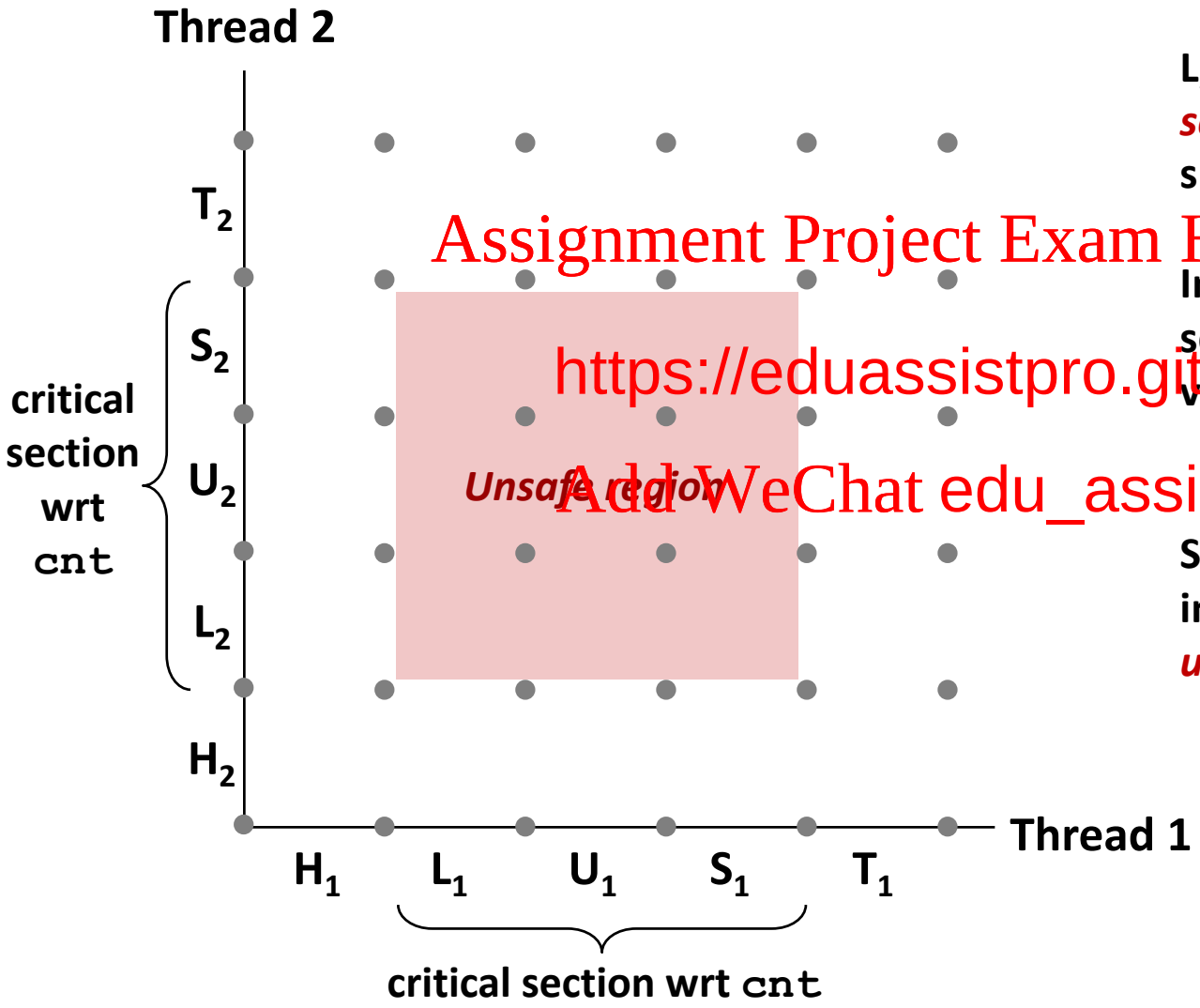


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

e:

, H2, L2, S1, T1, U2, S2, T2

Critical Sections and Unsafe Regions

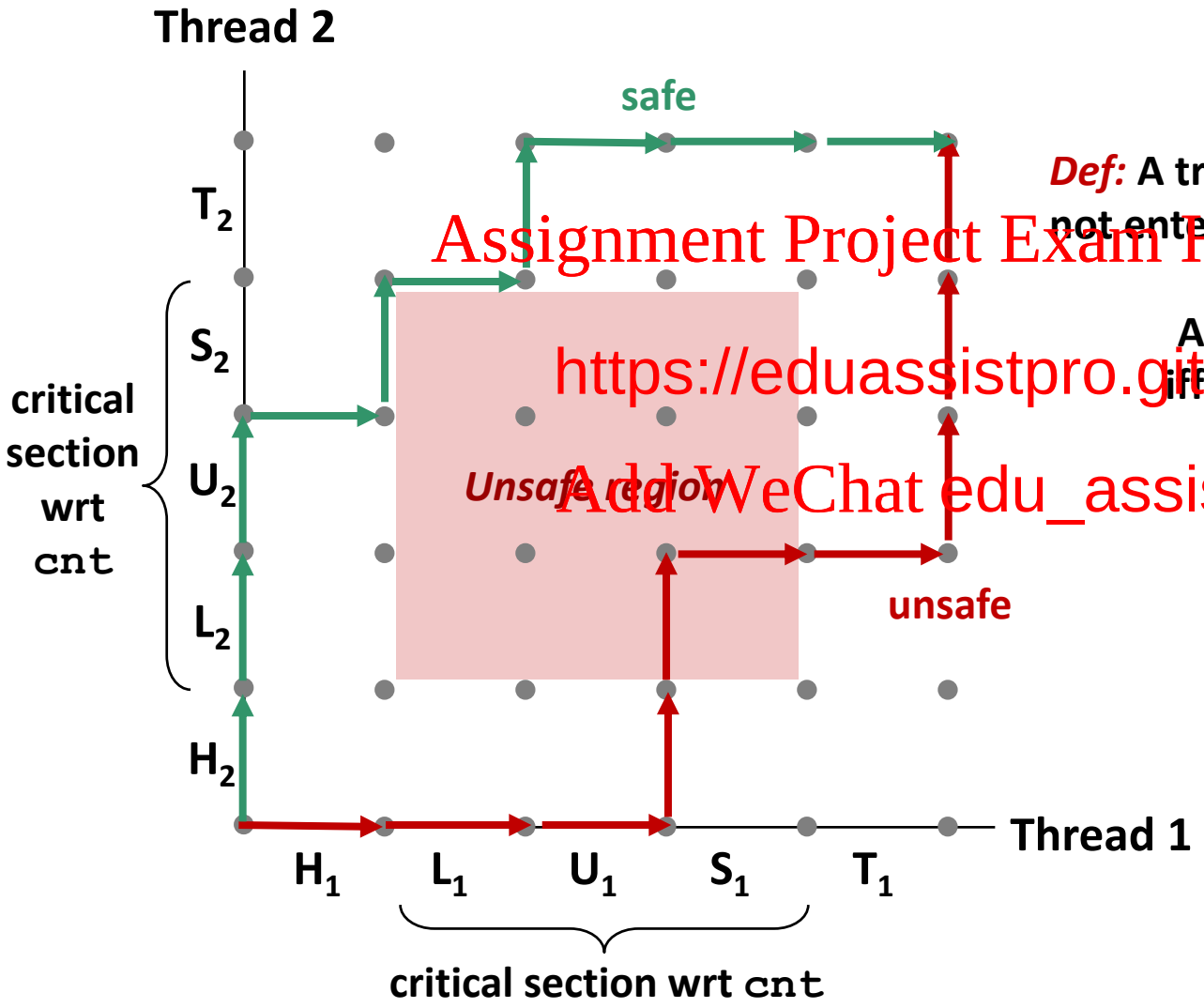


L, U, and S form a ***critical section*** with respect to the shared variable `cnt`

Instructions in critical sections (wrt some shared variable) should not be terleaved

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**

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
        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++)
        nt++;

                NULL;
```


	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
        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++)
        nt++;

                NULL;
```


	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 loca
              (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-Consu

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
  - After restarting, d 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 "P
  - *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
int sem_post(sem_t
```


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

```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
        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++;

                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)* operat

- **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

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

goodcnt.c

```
      > ./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 */
```

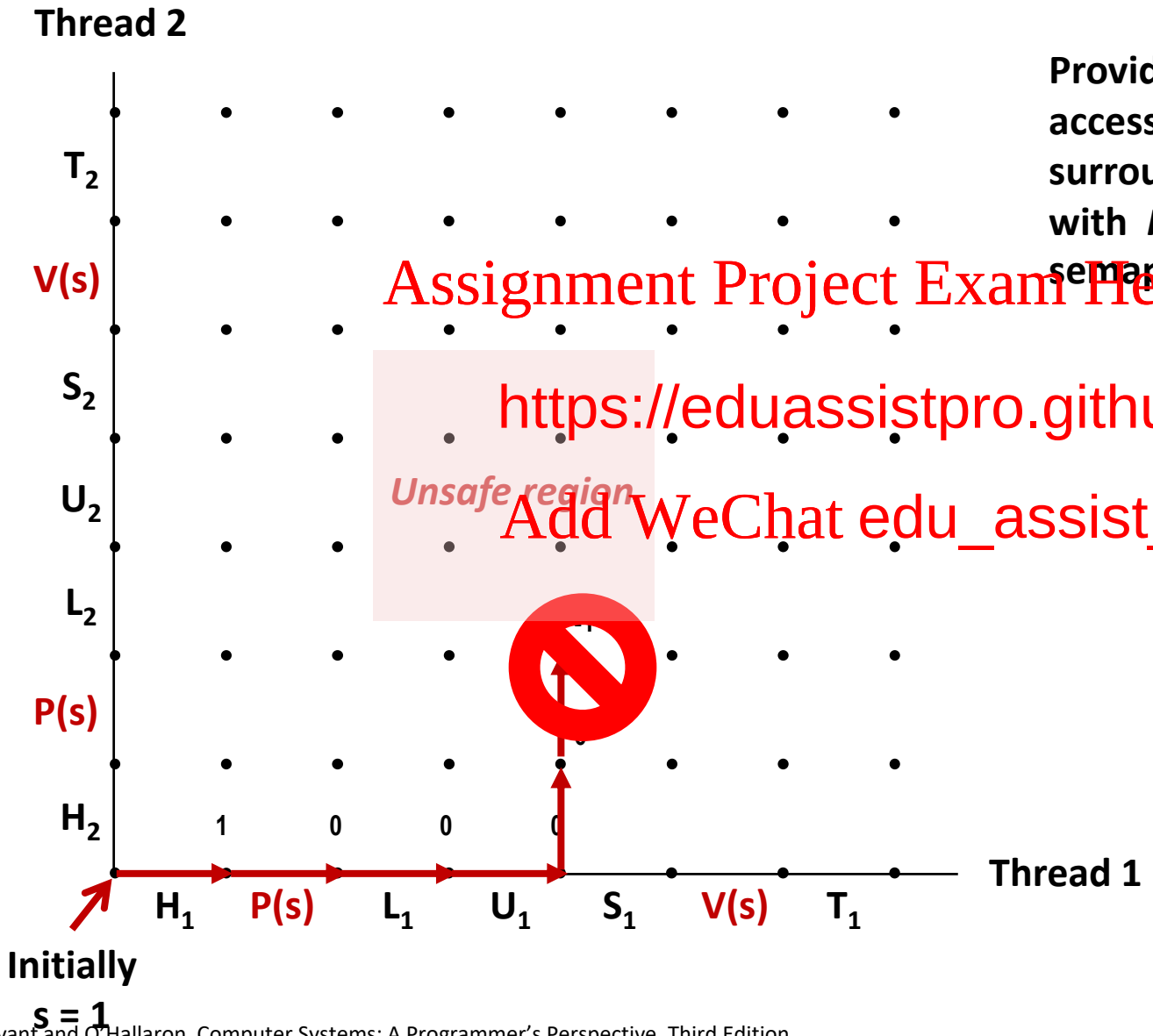

- Surround critical

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

Functi	cnt	goodcnt
Time (ms) niters = 10^6	12.0	450.0
Slowdown	1.0	**37.5**

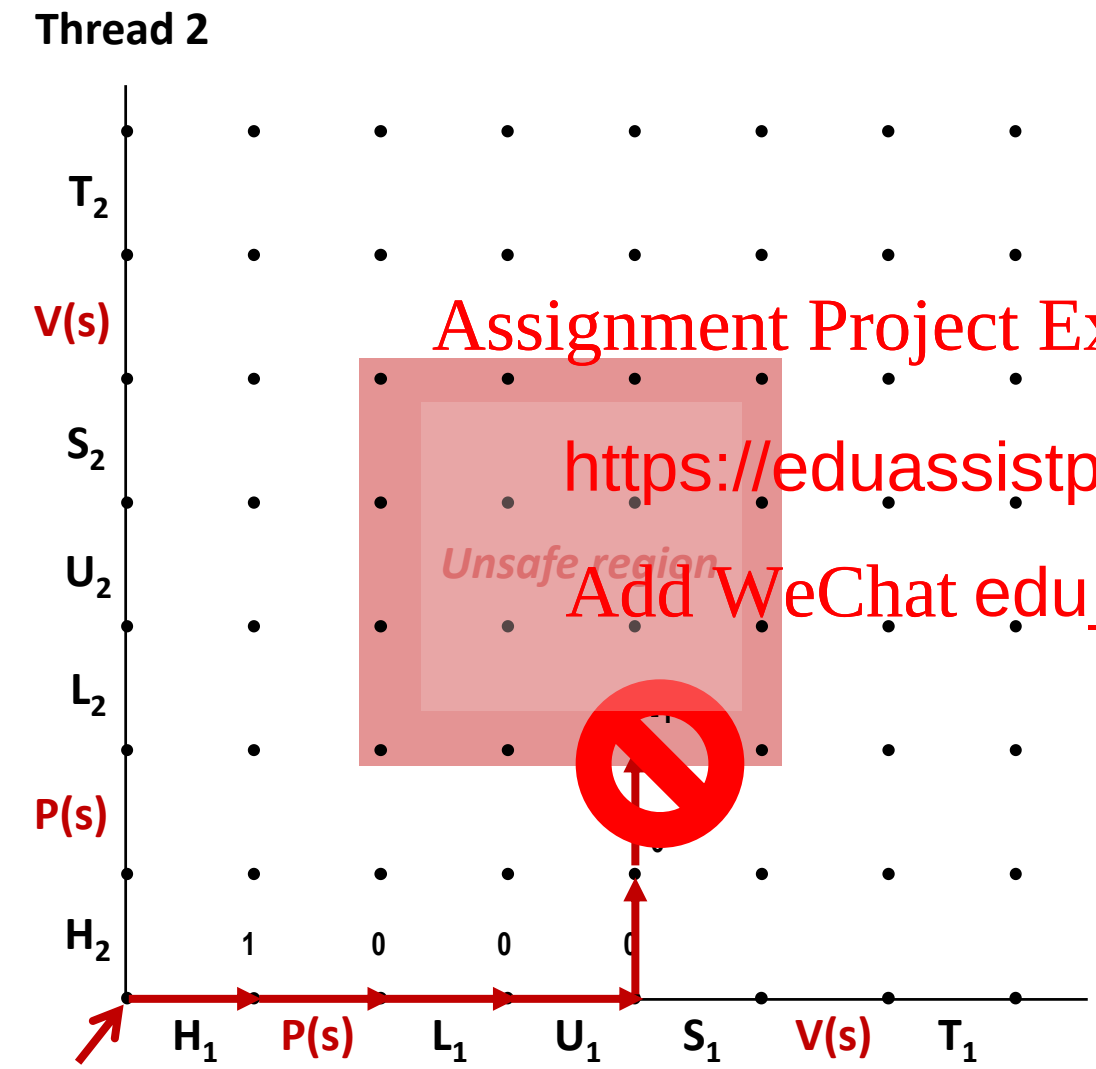
Warning: It's orders of magnitude slower than `badcnt.c`.

Why Mutexes Work



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

Why Mutexes Work

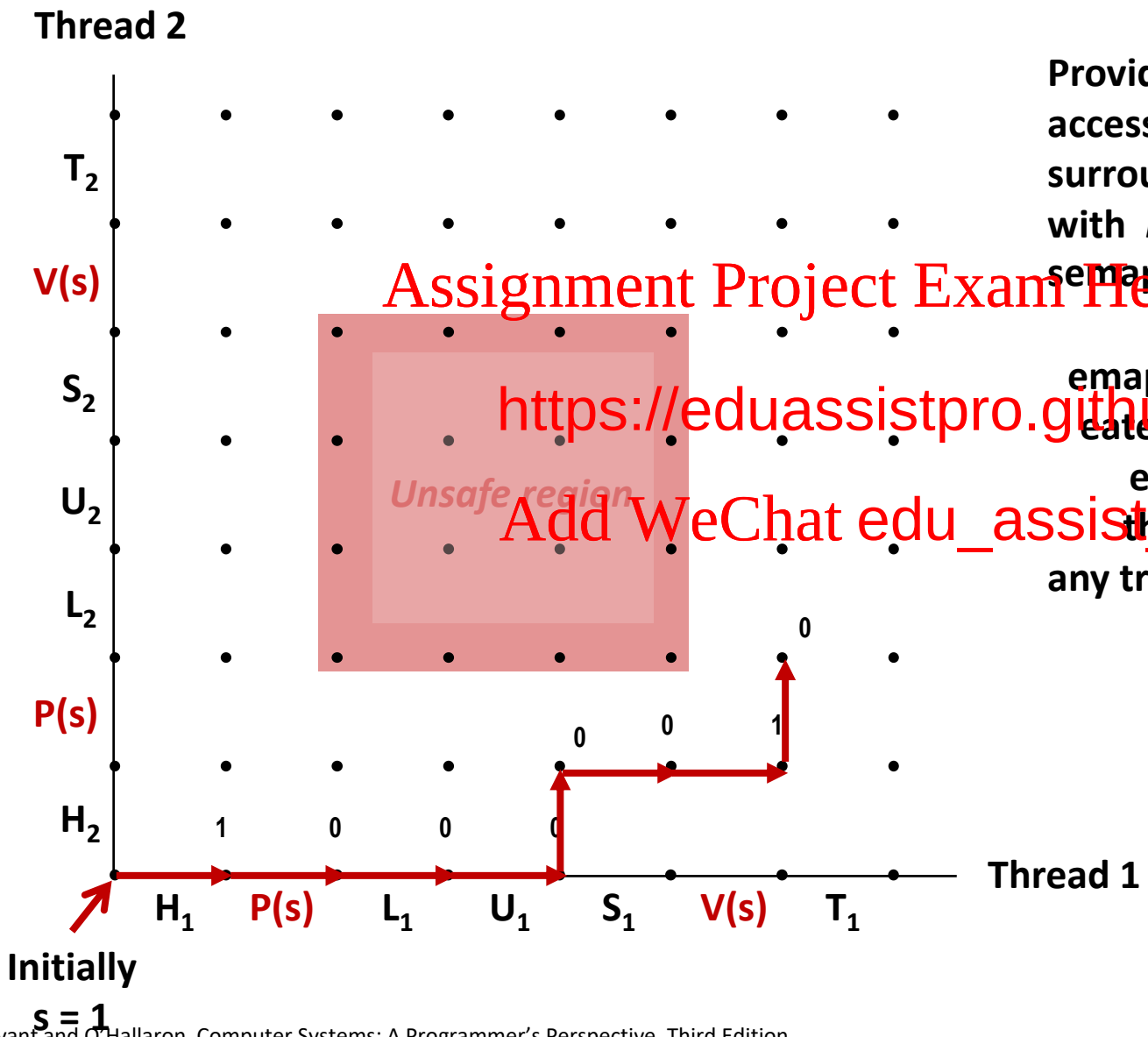


Provide mutually exclusive access to shared variable by surrounding critical section with *P* and *V* operations on semaphore s (initially set to 1)

emaphore invariant eates a *forbidden region*

encloses unsafe region that cannot be entered by any trajectory.

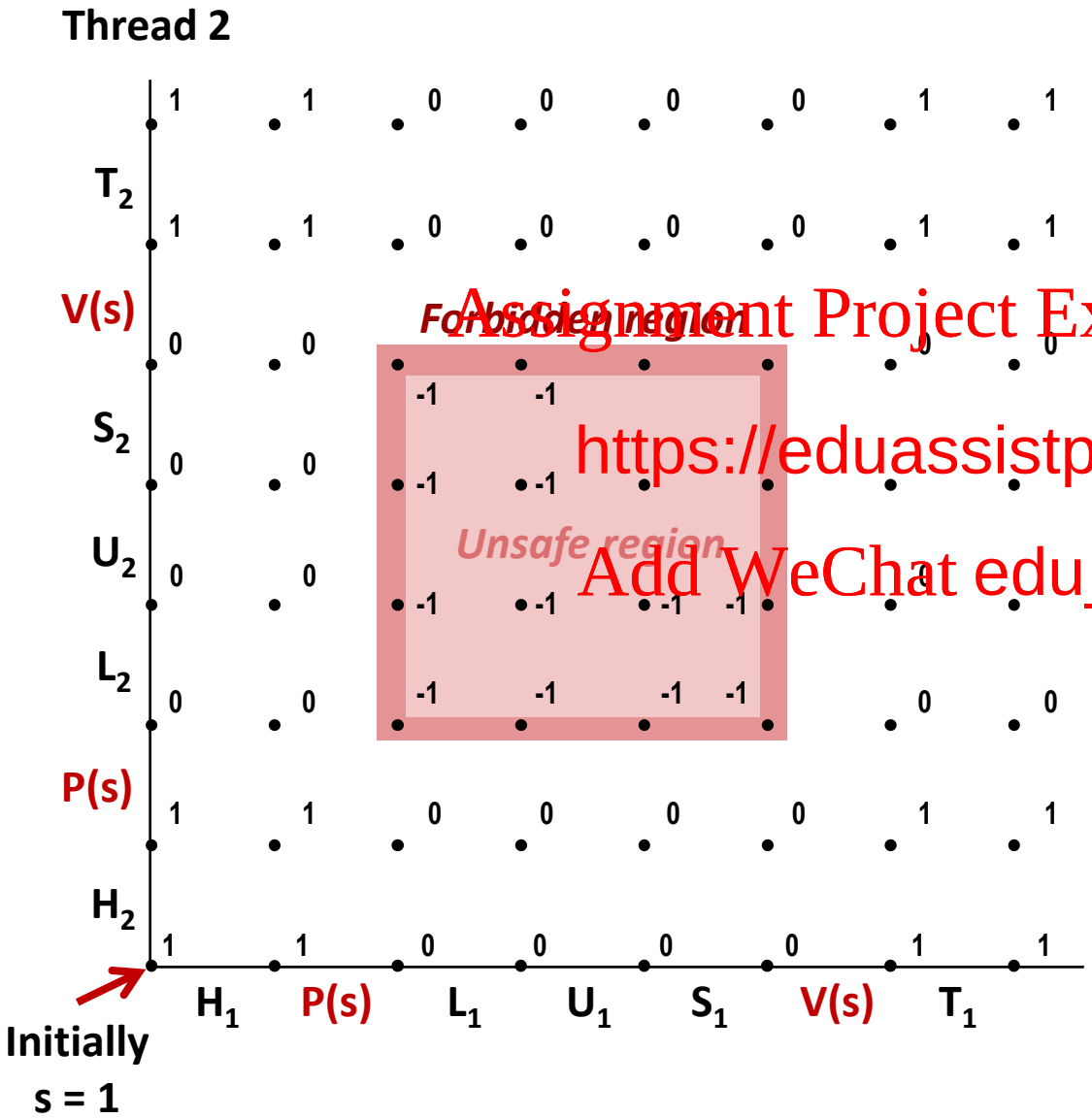
Why Mutexes Work



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

emaphore invariant eates a ***forbidden region*** encloses unsafe region that cannot be entered by any trajectory.

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)

emaphore invariant eates a *forbidden region* encloses unsafe region that cannot be entered by any trajectory.

Binary Semaphores – For Mutual Exlusion

- **Mutex is special case of semaphore**
  - Value either 0 or 1
- **Pthreads provides pthread_mutex_t**
  - Operations: lock, unlock
- **Recommended 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 :


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

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

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

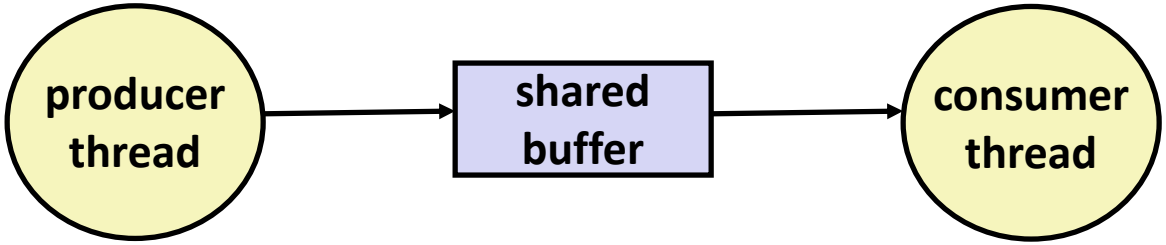
Today

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

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

Producer-Consumer Problem

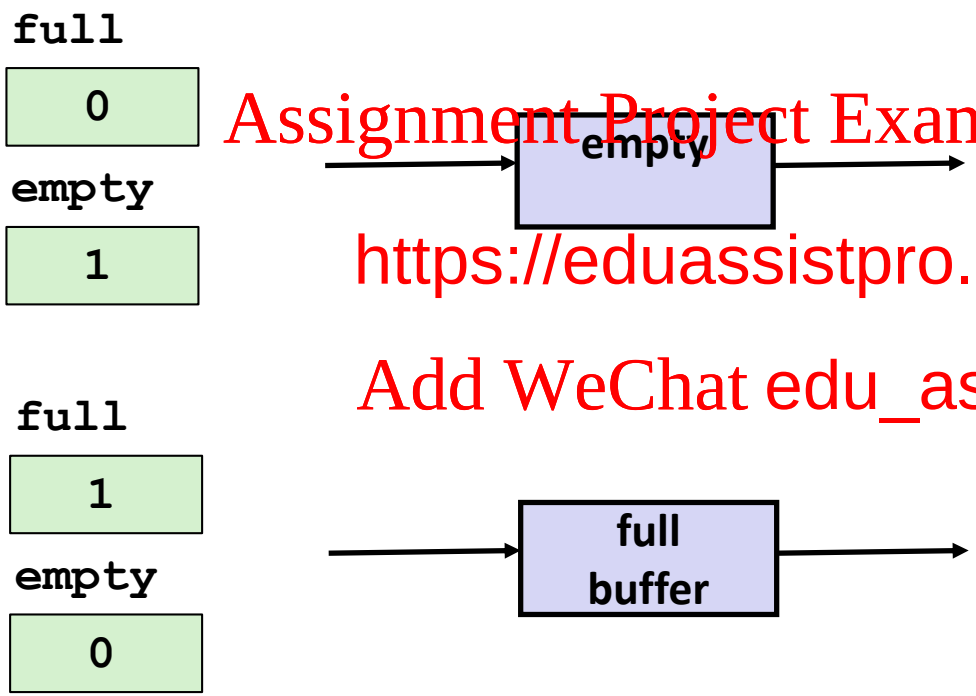


- **Common synchronization pattern:**
  - Producer waits fo ffer, and notifies consumer
  - Consumer waits f r, and notifies producer

- **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

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 */
                    red.empty, 0, 1);
                    red.full,  0, 0);

  /*                ds and wait */
  Pt                &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

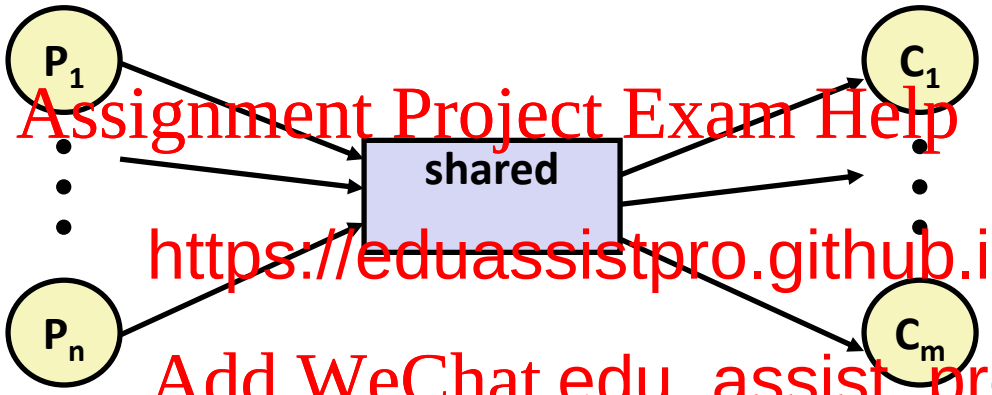
```
void *consumer(void *arg) {
  int i, item;

  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 eac pty
- Consumers will contend with each other to get `full`

Producers

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

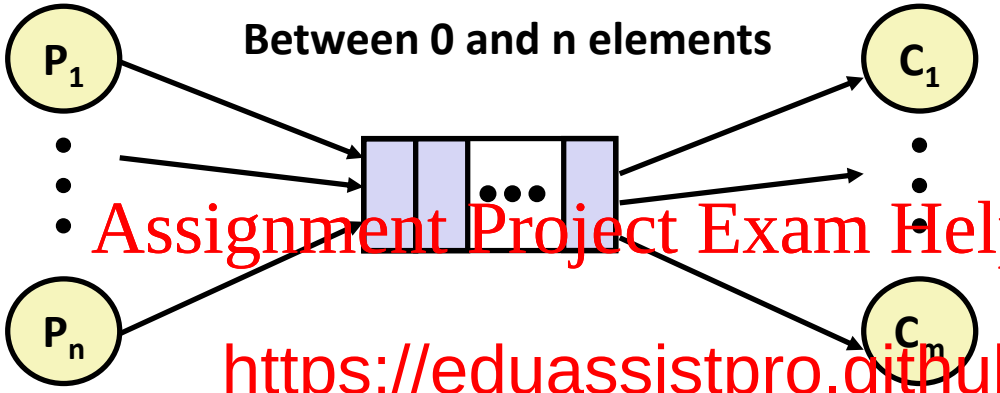
`empty`

`full`

Consumers

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

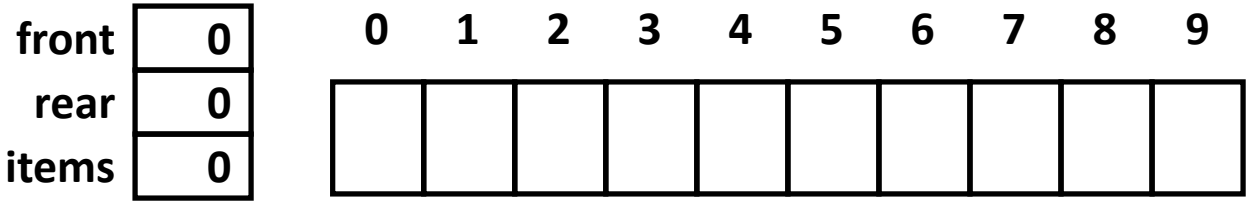
Producer-Consumer on an *n*-element Buffer



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

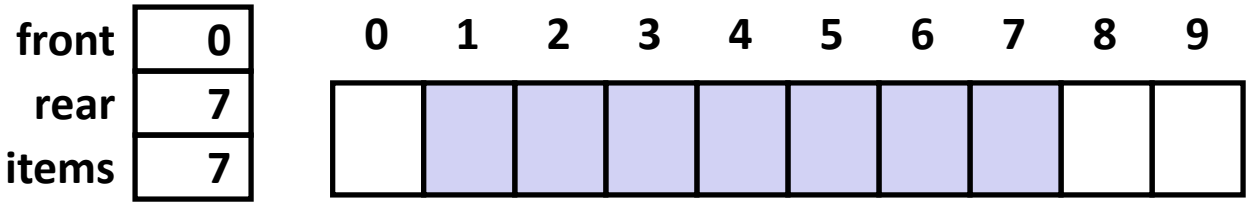
Circular Buffer (n = 10)

- Store elements in array of size n
- items: number of elements in buffer
- Empty buffer:
  - front = rear
- Nonempty buffe
  - rear: index of most recently inserte
  - front: (index of next element to re n
- Initially:

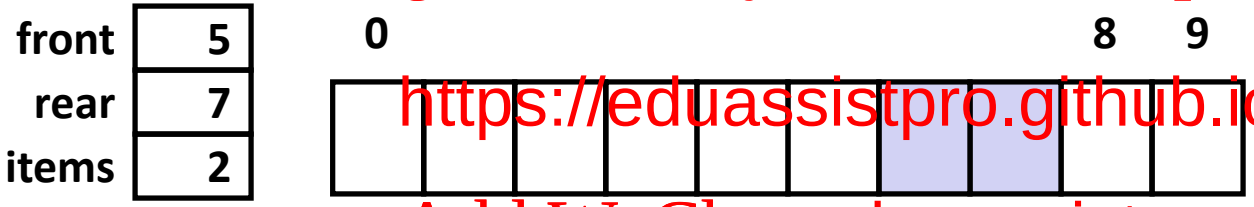


Circular Buffer Operation (n = 10)

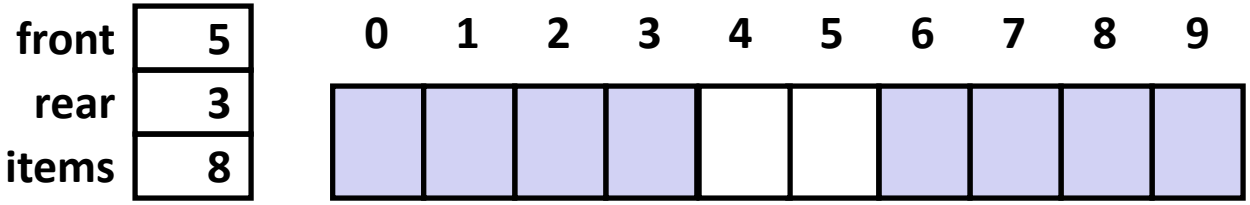
- Insert 7 elements



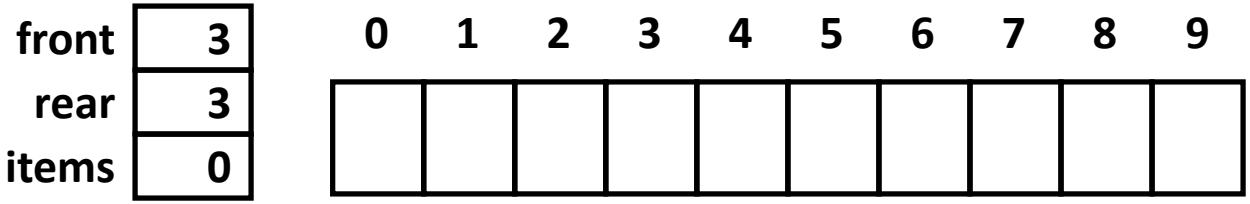
- Remove 5 elements



- Insert 6 elements



- Remove 8 elements



Sequential Circular Buffer Code

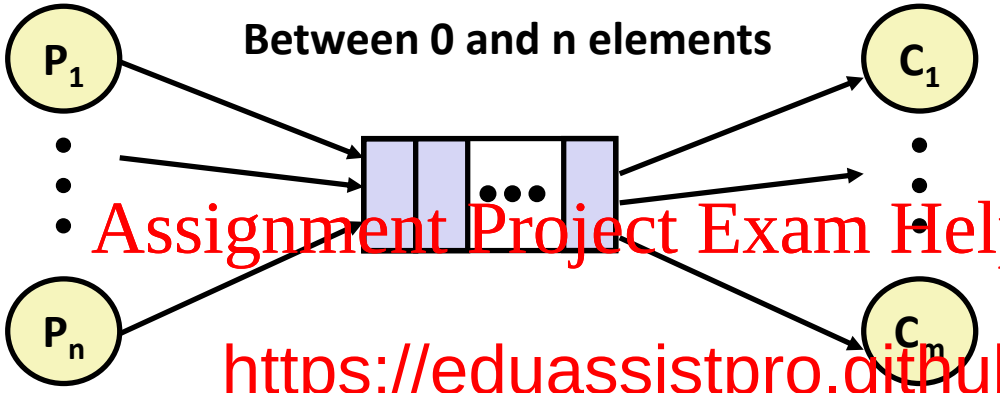
```
init(int v)
{
    items = front = rear = 0;
}
```

```
insert(int v)
{
    if (items >=
        error();
    if (++rear >=
    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;                                  is first item */
    int rear;                                   item          */
    sem_t mutex;       /* Protects ac                uf        */
    sem_t slots;       /* Counts avai                          */
    sem_t items;       /* Counts avai                          */
} 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;                       max of n items */
    sp->front = sp->r                if front == rear */
    Sem_init(&sp->mutex, 0, 1); /* Bin    e for locking */
    Sem_init(&sp->slots, 0, n); /* Ini    has n empty slots */
    Sem_init(&sp->items, 0, 0); /* Ini    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);                          ilable slot */
    P(&sp->mutex);                          fer         */
    if (++sp->rear >= sp->n)     /* In                 x (mod n) */
        sp->rear = 0;
    sp->buf[sp->rear] = item;    /* In                 m         */
    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);                          ilable item */
    P(&sp->mutex);                          fer         */
    if (++sp->front >=                      dex (mod n) */
        sp->front = 0;
    item = sp->buf[sp->front];  /* Re          m       */
    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 bu
- **5 consumers**
  - Each retrieves 20 elements from b
- **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 mutua
- Semaphores are a fundamental for enforcing mutual exclusion.