Concurrency and Synchronization

CMPSCI 230: Computer Systems Principles

```
int pthread_join (pthread_t thread, void **value_ptr) {
    int result;
    ptw32_thread_t * tp = (ptw32_thread_t *) thread.p;
    …
    if (NULL == tp
      || thread.x != tp->ptHandle.x){
      result = ESRCH;
    }
    else if (PTHREAD_CREATE_DETACHED == tp->detachState){
      result = EINVAL;
    }
    else {
      result = 0;
    }
    if (result == 0) {
        result = pthreadCancelableWait (tp->threadH);
        …
        *value_ptr = tp->exitStatus;
        result = pthread_detach (thread);
    }
    return (result);
}
```

Typical way a function return two values

```
int pthread_join (pthread_t thread, void **value_ptr) {
    int result;
    ptw32_thread_t * tp = (ptw32_thread_t *) thread.p;
    …
    if (NULL == tp
      || thread.x != tp->ptHandle.x){
      result = ESRCH;
    }
    else if (PTHREAD_CREATE_DETACHED == tp->detachState){
      result = EINVAL;
    }
    else {
      result = 0;
    }
    if (result == 0) {
        result = pthreadCancelableWait (tp->threadH);
        …
        *value_ptr = tp->exitStatus;
        result = pthread_detach (thread);
    }
    return (result);
}
```

Typical way a function return two values

```
int pthread_join (pthread_t thread, void **value_ptr) {
    int result;
    ptw32_thread_t * tp = (ptw32_thread_t *) thread.p;
    …
    if (NULL == tp
      || thread.x != tp->ptHand
      result = ESRCH;
    }
    else if (PTHREAD_CREAT
      result = EINVAL;
    }
    else {
      result = 0;
    }
    if (result == 0) {
        result = pthreadCancelableWait (tp->threadH);
        …
        *value_ptr = tp->exitStatus;
        result = pthread_detach (thread);
    }
    return (result);
}
```

To change a pointer even outside of a function, you need to use double pointer.

Concurrency and Synchronization

CMPSCI 230: Computer Systems Principles

Today

- Sharing
- Mutual exclusion
- Semaphores

Shared Variables in Threaded C Programs

- **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 model:**
  - 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

- **Conceptual model:**
  - Multiple threads run within the **context of a single process**
  - Each thread has its own **separate thread context**
    - Thread ID, stack, stack pointer, 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
- **Operationally, this model 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

Example Program to Illustrate Sharing

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

int main()
{
    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);
}
```

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

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

Example Program to Illustrate Sharing

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

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

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

pthread_exit
vs
pthread_join:
Do you need further
processing in main thread?

Example Program to Illustrate Sharing

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

int main()
{
    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);
}
```

```
/* thread routine */
void *thread(void *vargp)
{
    long myid = (long)(vargp);
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    printf("[%d]: %s (svar=%d)\n",
        myid, ptr[myid], ++cnt);
}
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Example Program to Illustrate Sharing

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int main()
{
    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);
}
```

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

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

static acts to extend the lifetime of a variable to the lifetime of the process

Example Program to Illustrate Sharing

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

int main()
{
    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);
}
```

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

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

Example Program to Illustrate Sharing

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

int main()
{
    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);
}
```

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

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

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

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])

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

int main()
{
    int 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);
}
```

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

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

`sharing.c`

Mapping Variable Instances to Memory

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

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

int main()
{
    int 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);
}
```

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

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

`sharing.c`

Mapping Variable Instances to Memory

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

int main()
{
    int 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);
}
```

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

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

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

`sharing.c`

Mapping Variable Instances to Memory

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

int main()
{
```

What if declare myid static?

```
        "Hello from bar"
    };
    ptr = msgs;

    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
            NULL,
            thread,
            (void *)i);
    Pthread_exit(NULL);
}
```

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

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

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

`sharing.c`

Mapping Variable Instances to Memory

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

int main()
{
    int i;
    pthread_t tid;
    char *msgs[2] = {
        "Hello from foo",
        "Hello from bar"
    };
    ptr = msgs;

    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
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            thread,
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}
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```
/* thread routine */
void *thread(void *vargp)
{
    int myid = (int)vargp;
    static int cnt = 0;

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

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

sharing.c

Mapping Variable Instances to Memory

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

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

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

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

int main()
{
    int i;
    pthread_t tid;
    char *msgs[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);
}
```

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

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

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

`sharing.c`

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

- **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;
}
```

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);
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    /* 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);

    < niters; i++)
```

This guarantees the read/write actually happens

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```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);
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    /* Check result */
    if (cnt != (2 * niters))
        printf("BOOM! cnt=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
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}
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```c
/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
                *((long *)vargp);

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

    return NULL;
}
```

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int main(int argc, char **argv)
{
    long niters;
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    niters = atoi(argv[1]);
    Pthread_create(&tid1, NULL,
        thread, &niters);
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    Pthread_join(tid1, NULL);
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    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}
```

badcnt.c

```
int main (int argc, char *argv[]) {
  pthread_t tid;
  for(int i=0; i<10; i++) {
        pthread_create(&tid, NULL, thread, &i);
  }
  pthread_exit(NULL);
  return 0;
}
```

race.c

Race

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);
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    if (cnt != (2 * niters))
        printf("BOOM! cnt=%ld\n", cnt);
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badcnt.c

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race.c

Race

No Race

badcnt.c: Improper Synchronization

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volatile long cnt = 0; /* Counter */

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

    niters = atoi(argv[1]);
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badcnt.c

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

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

    return NULL;
}
```

badcnt.c: Improper Synchronization

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int main(int argc, char **argv)
{
    long niters;
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    niters = atoi(argv[1]);
    Pthread_create(&tid1, NULL,
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void *thread(void *vargp)
{
    long i, niters =
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```

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 1000000
OK cnt=2000000
linux> ./badcnt 1000000
BOOM! cnt=1332062
```

cnt should equal 2,000,000.

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:
```

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    movq   %rdx, cnt(%rip)
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    cmpq   %rcx, %rax
    jne    .L3
.L2:
```

H_i : Head

Assembly Code for Counter Loop

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```
for (i = 0; i < niters; i++)
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Asm code for thread i

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    movq   (%rdi), %rcx
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    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`

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

iClicker question

Suppose that cnt starts with value 0, and that two threads each execute the code below once. What are the possible values for cnt afterward?

A) Only 2

B) 1 or 2

C) 0 or 1 or 2

D) None of the above

```
movq  cnt(%rip),%rdx
addq  $1, %rdx
movq  %rdx, cnt(%rip)
```

iClicker question solution

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Concurrent Execution

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1	H_1	-	-	**0**

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2	H_2	-	-	1

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2	U_2	-	2	1
2	S_2	-	2	2

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2	U_2	-	2	1
2	S_2	-	2	2
2	T_2	-	2	2

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2	T_2	-	2	2
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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

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1	U_1	1	-	0
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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

Thread 1 critical section

Thread 2 critical section

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

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2	L_2	-	0	0
1	S_1	1	-	1

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2	L_2	-	0	0
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Concurrent Execution (cont)

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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
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2	U_2	-	1	1
2	S_2	-	1	1
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Oops!

Concurrent Execution (cont)

- **Incorrect ordering: two threads increment the counter, but the result is 1 instead of 2**

i (thread)	instr_i	$\%\text{rdx}_1$	$\%\text{rdx}_2$	cnt
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1	L1	0	-	0
1	U1	1	-	0
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2	L_2	-	0	0
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Oops!

Thread 1 critical section

Thread 2 critical section

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2	U_2	-	2	1
2	S_2	-	2	2
2	T_2	-	2	2
1	T_1	1	-	2

OK

Thread 1 critical section

Thread 2 critical section

Concurrent Execution (cont)

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Oops!

Thread 1 critical section

Thread 2 critical section

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!

Concurrent Execution (cont)

- **How about this ordering?**

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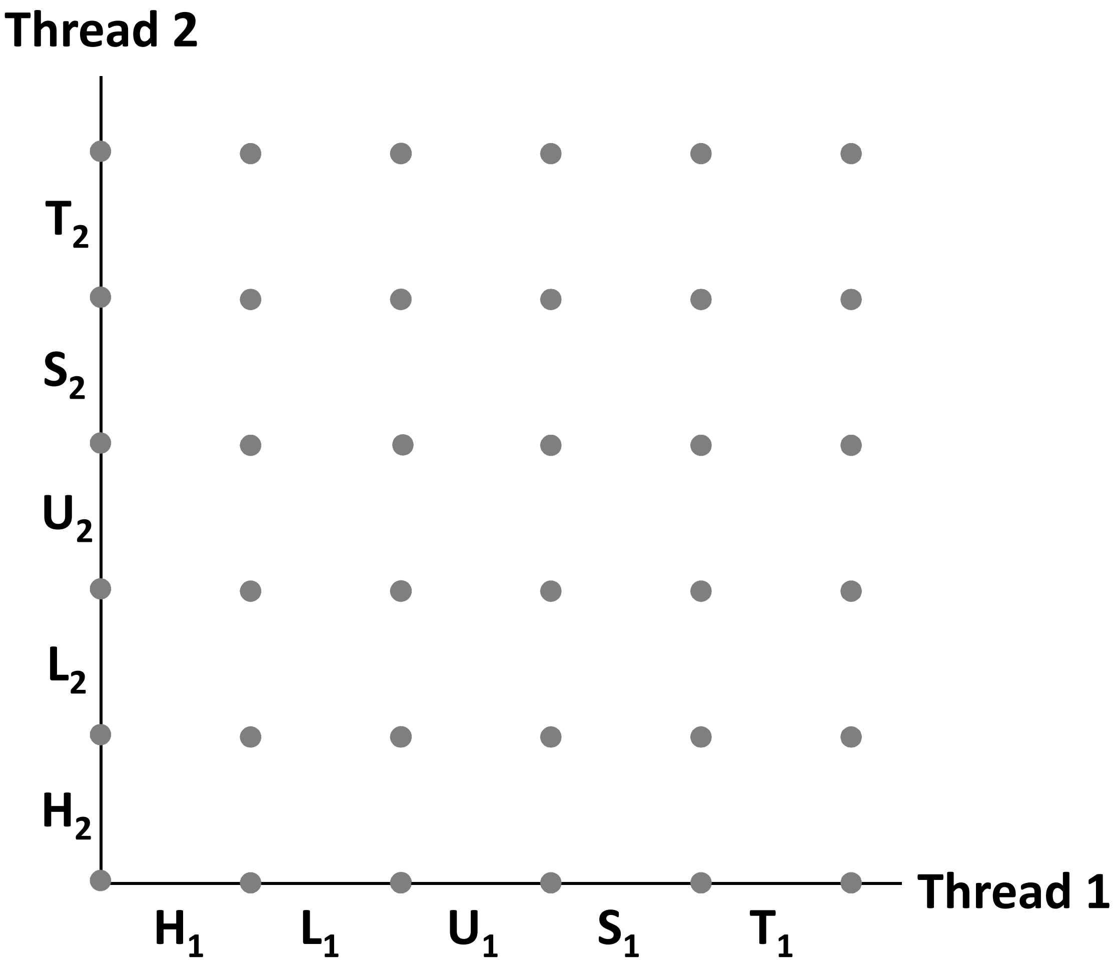
2	H_2			
2	L_2		0	
2	U_2		1	
2	S_2		1	1
1	U_1	1		
1	S_1	1		1
1	T_1			1
2	T_2			1

Oops!

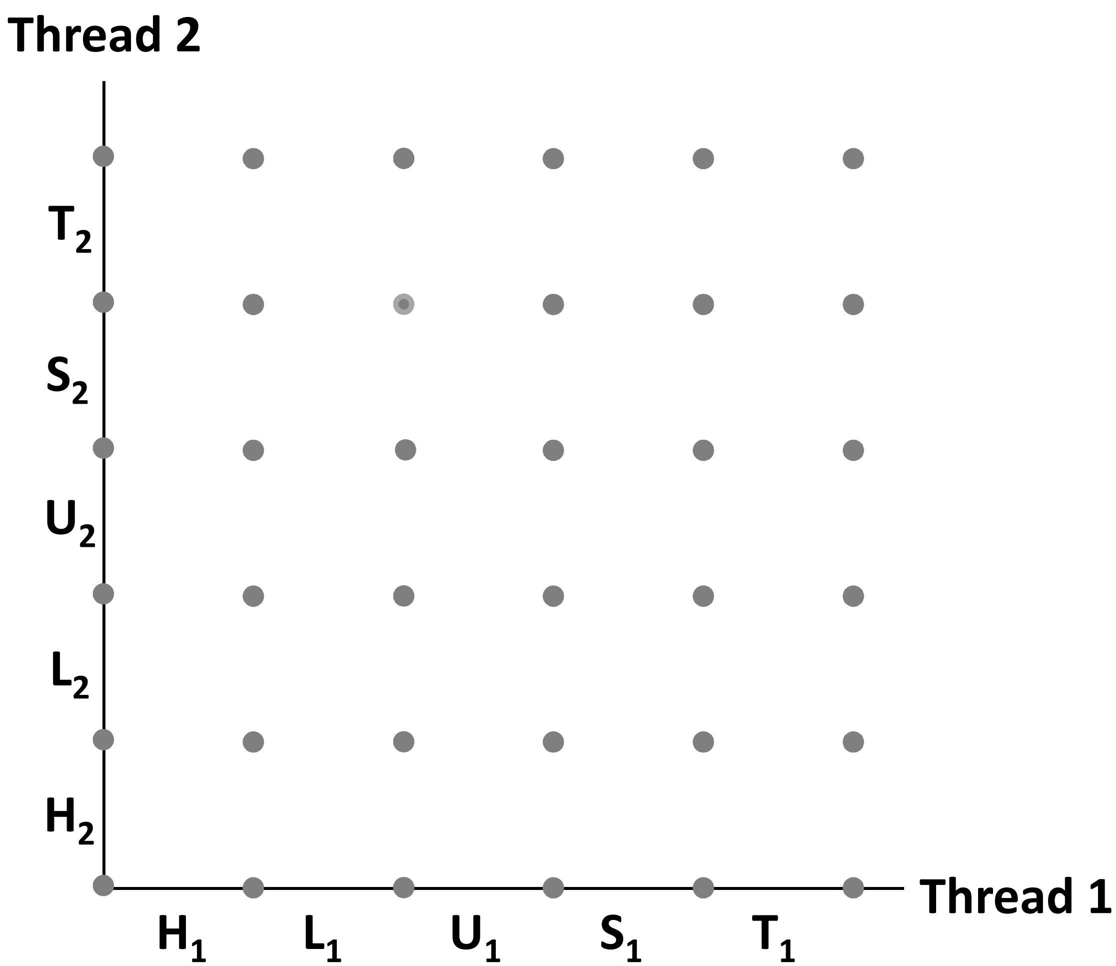
We can analyze the behavior using a *progress graph*

Progress Graphs



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

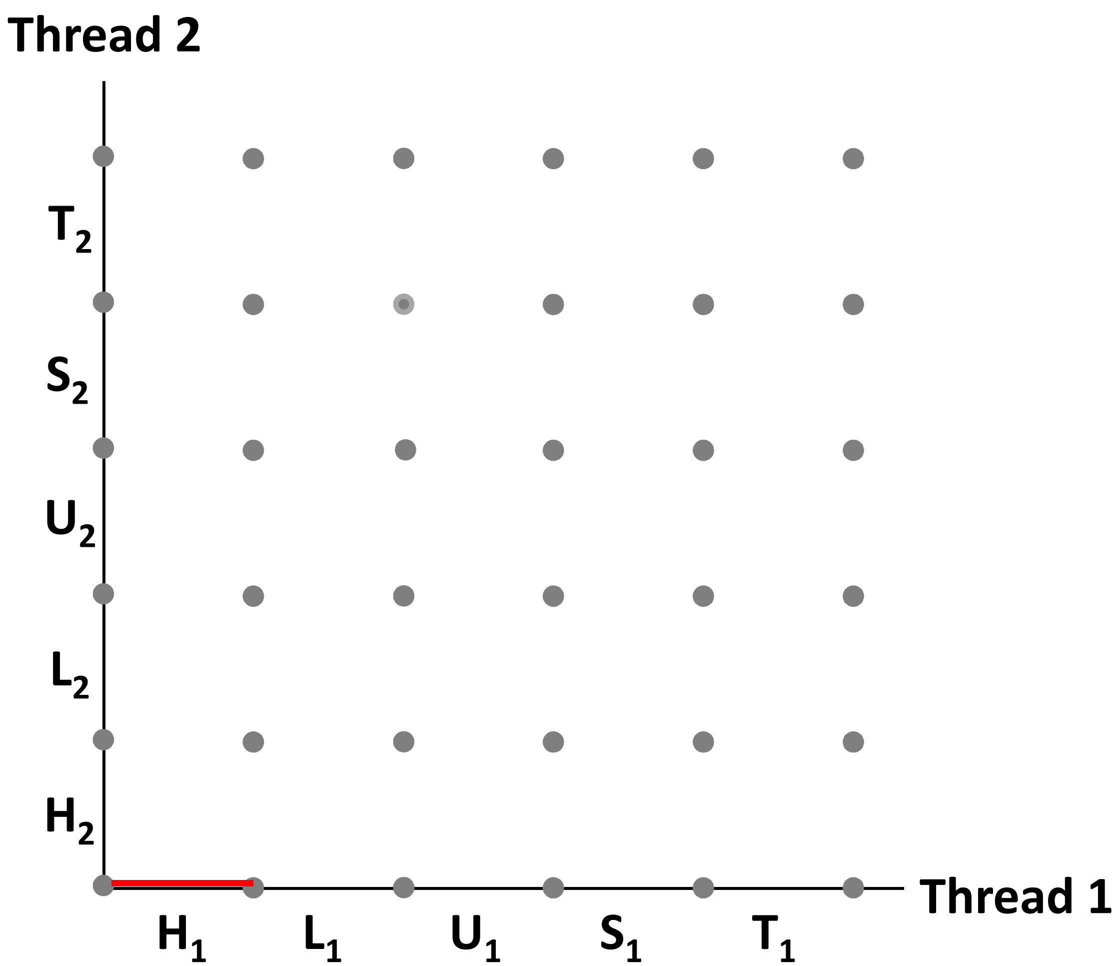
Progress Graphs



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

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

Progress Graphs



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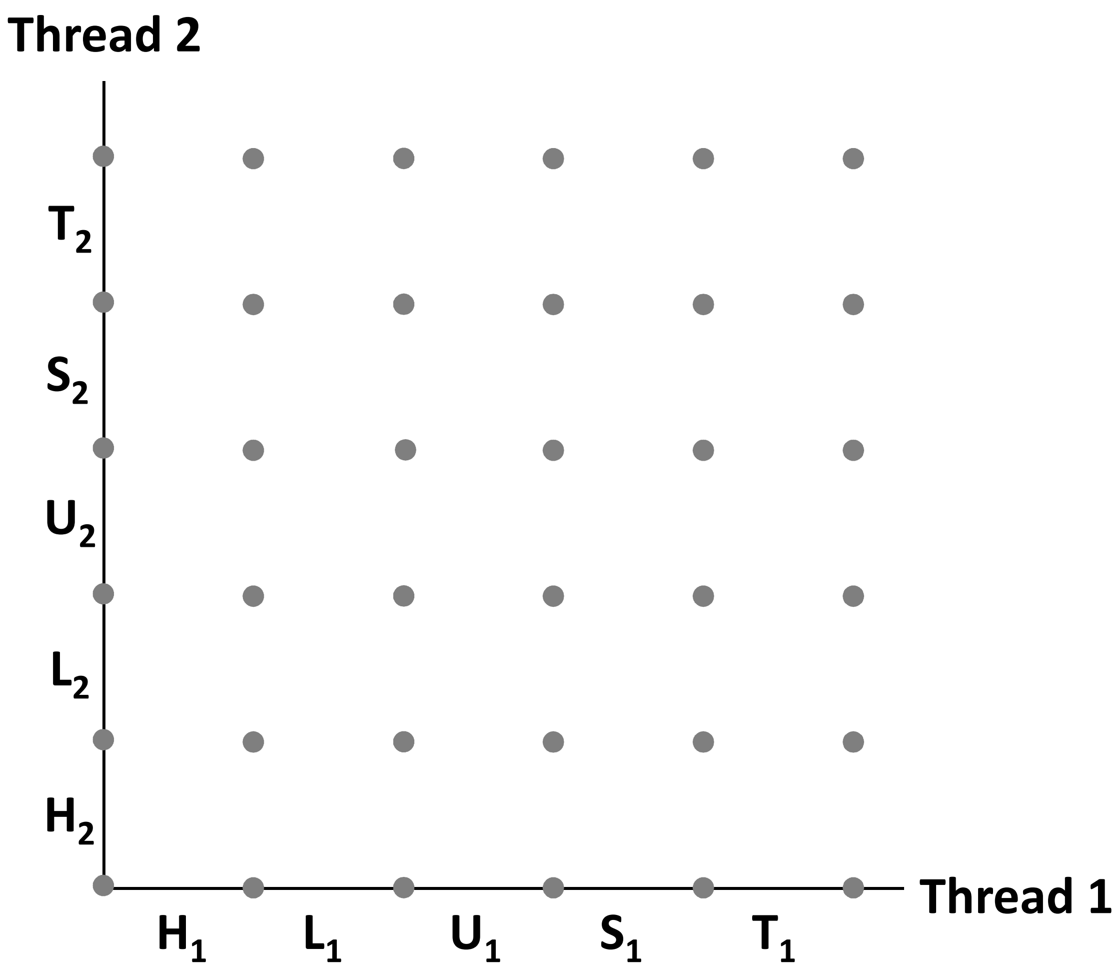

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Each point corresponds to a possible ***execution state*** ($Inst_1$, $Inst_2$).

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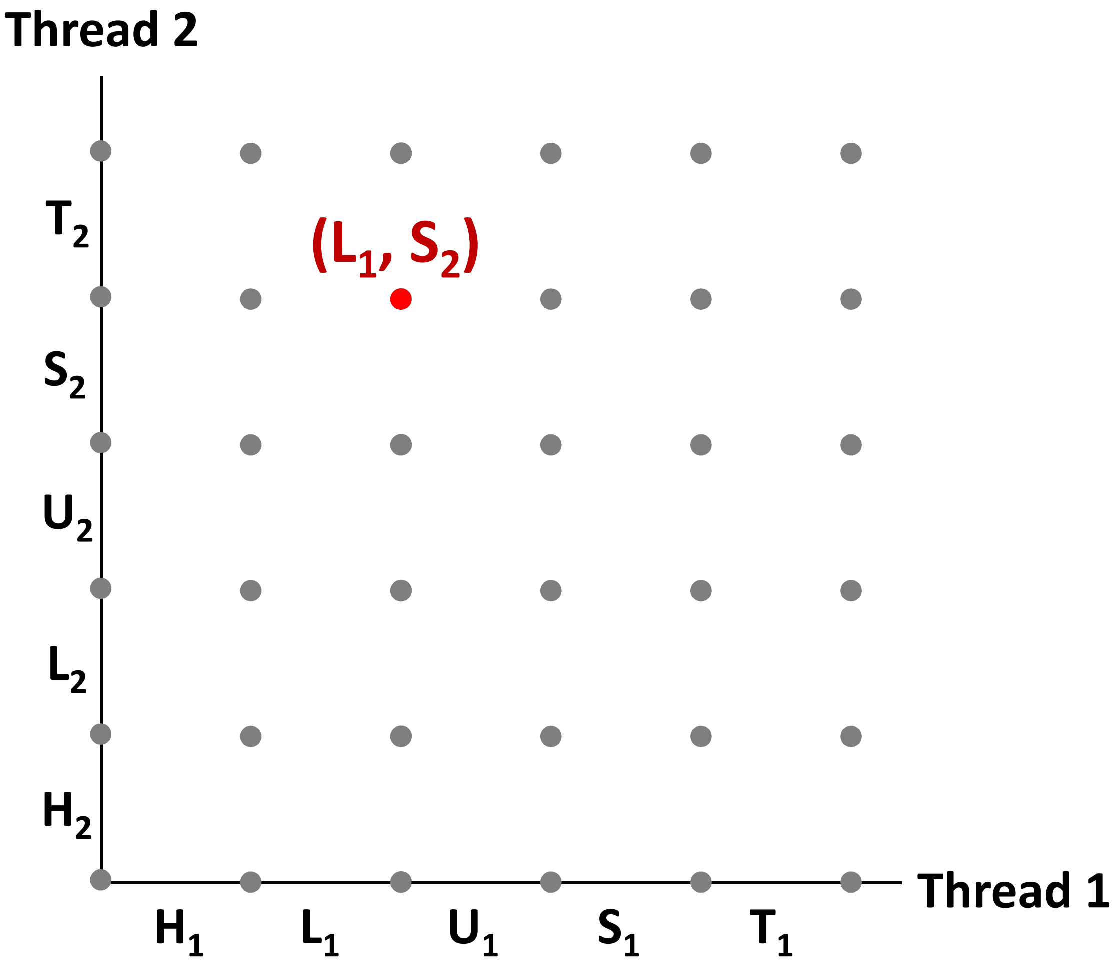


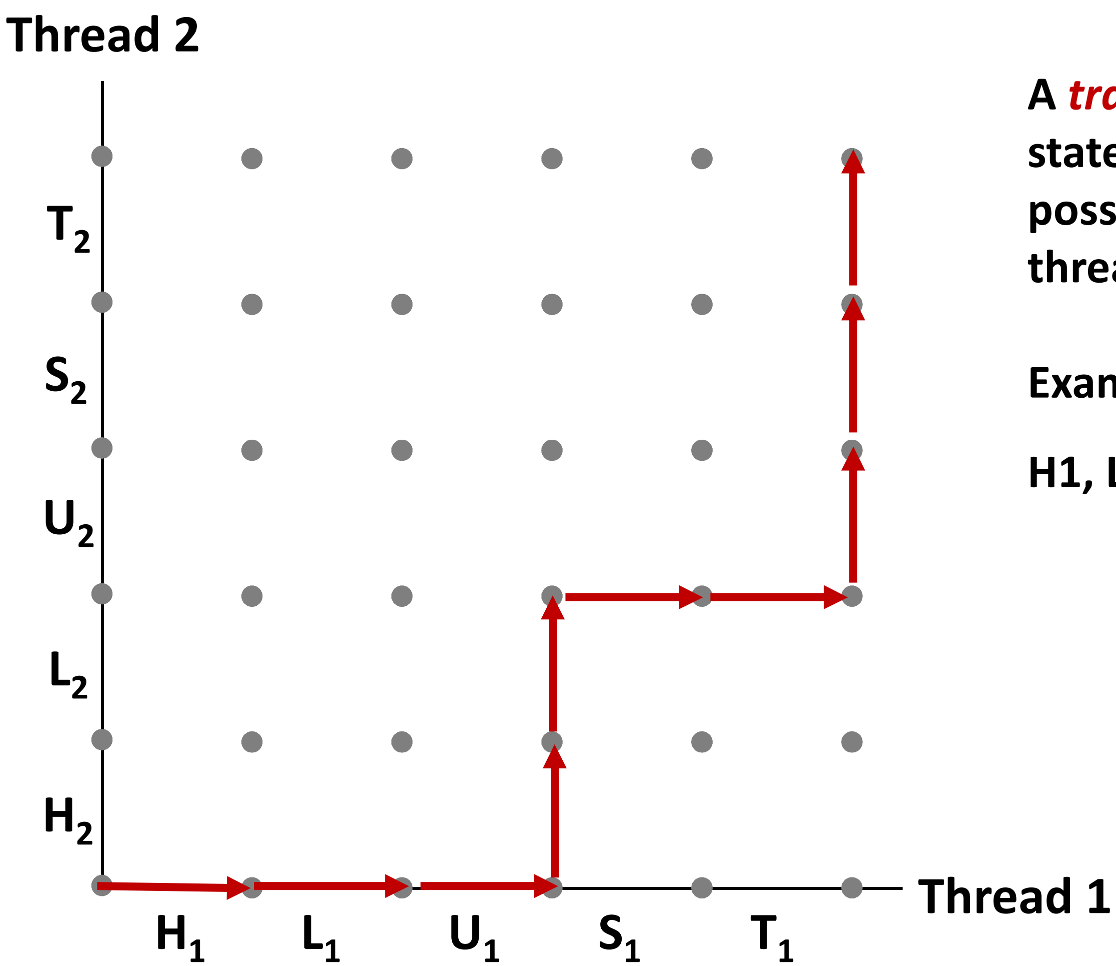
A ***progress graph*** depicts the discrete ***execution state space*** of concurrent threads.

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

Each point corresponds to a possible ***execution state*** ($Inst_1$, $Inst_2$).

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

Trajectories in Progress Graphs

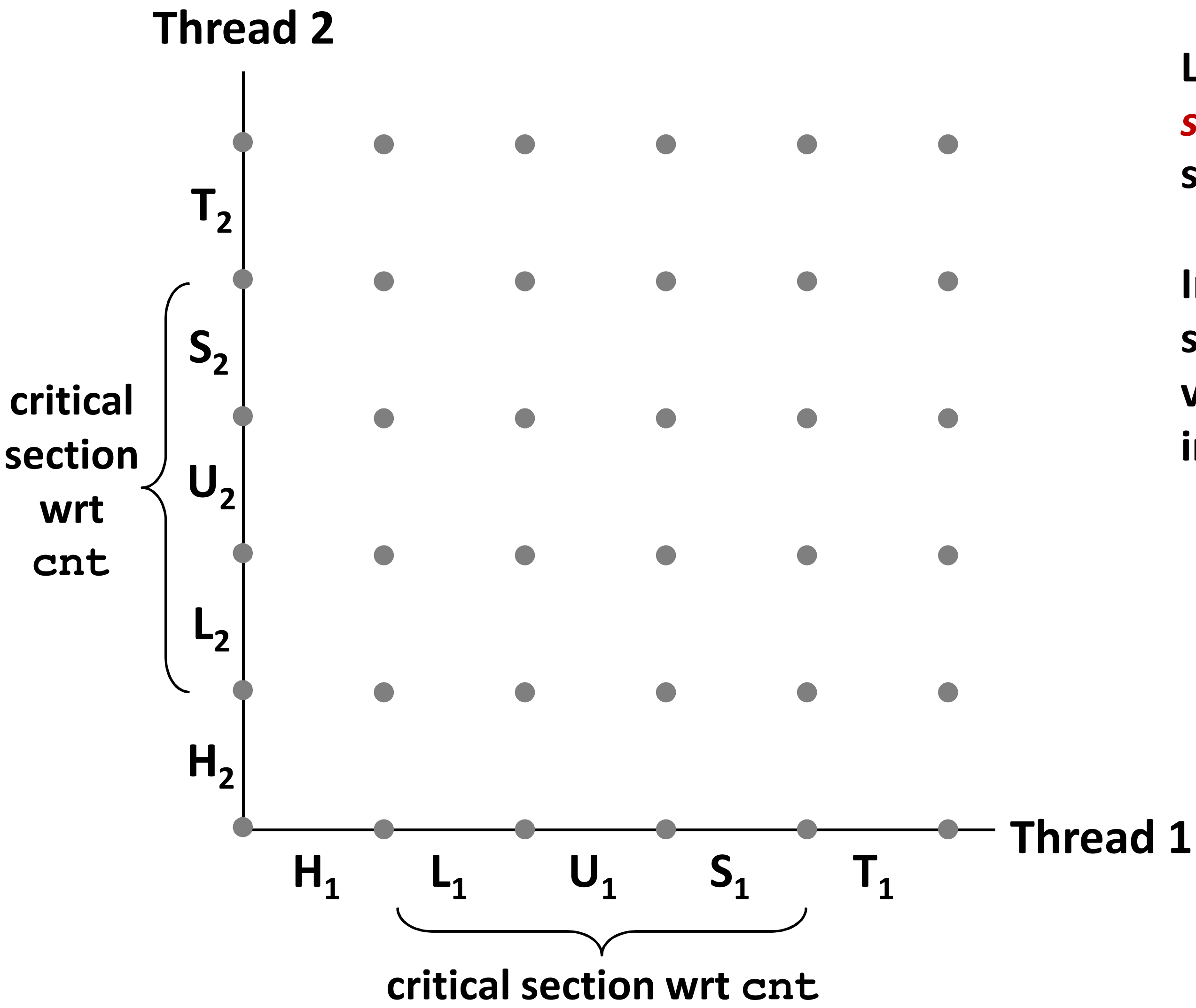


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

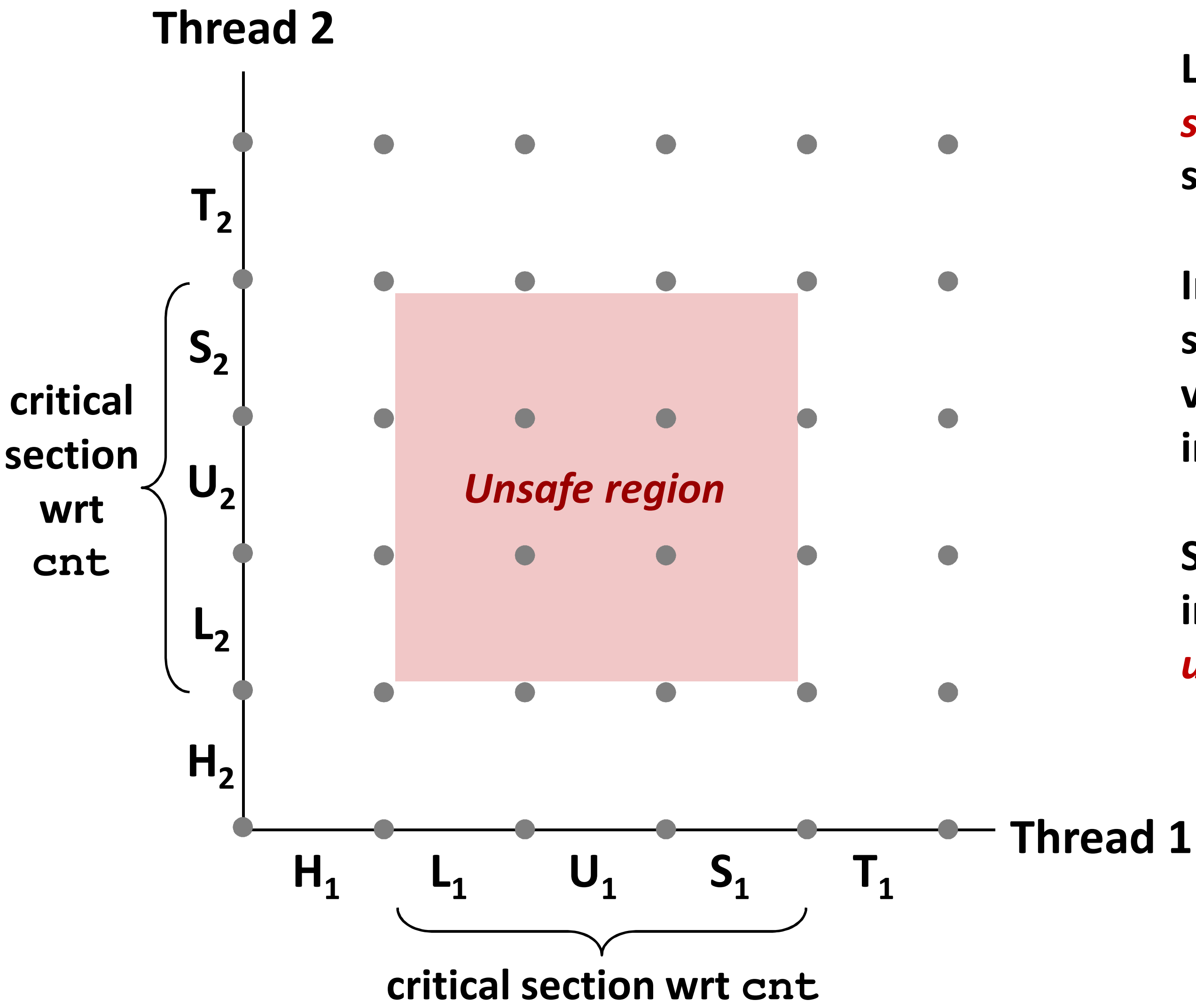
Critical Sections and Unsafe Regions



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

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

Critical Sections and Unsafe Regions

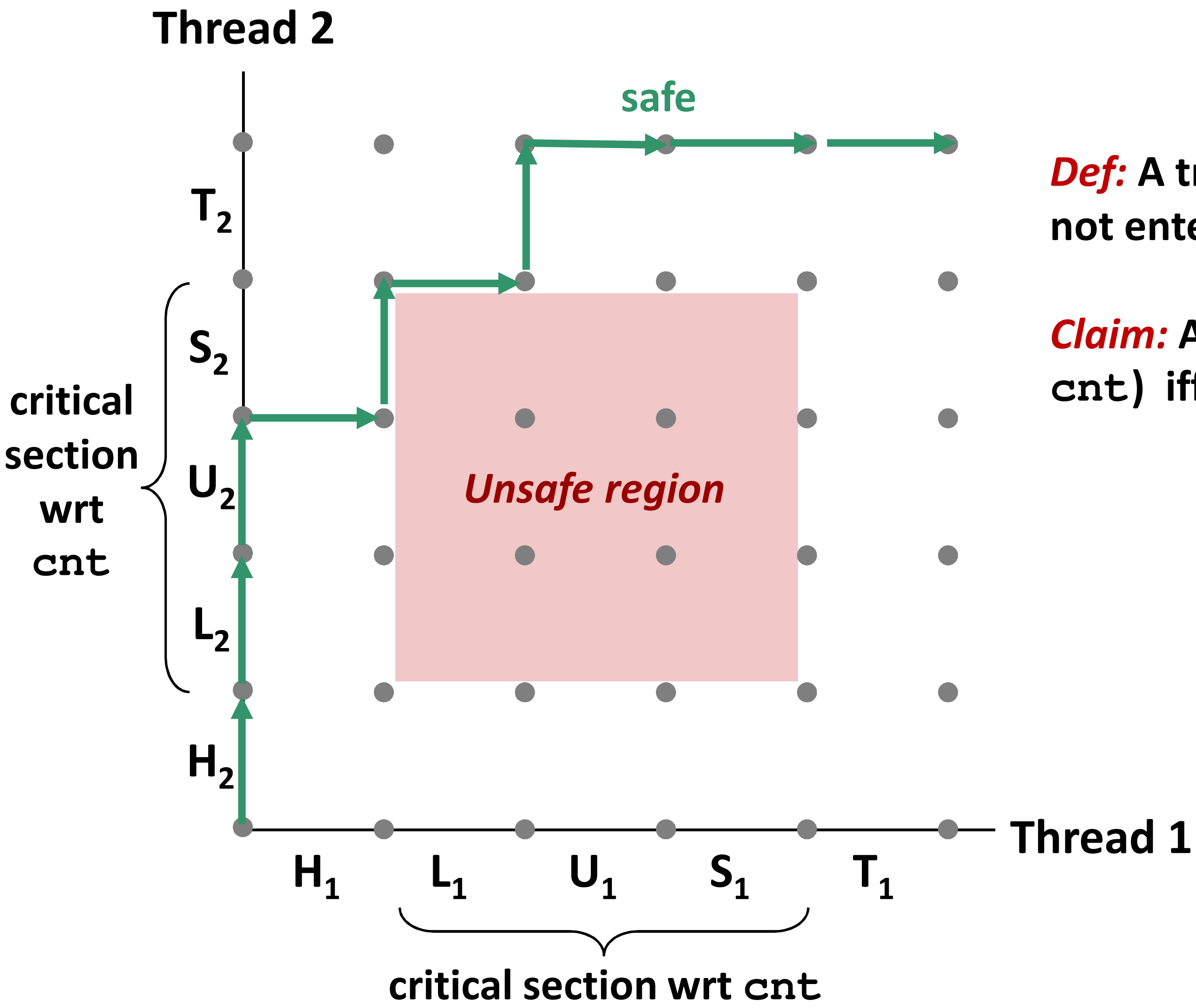


L, U, and S form a *critical section* with respect to the shared variable `cnt`

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

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

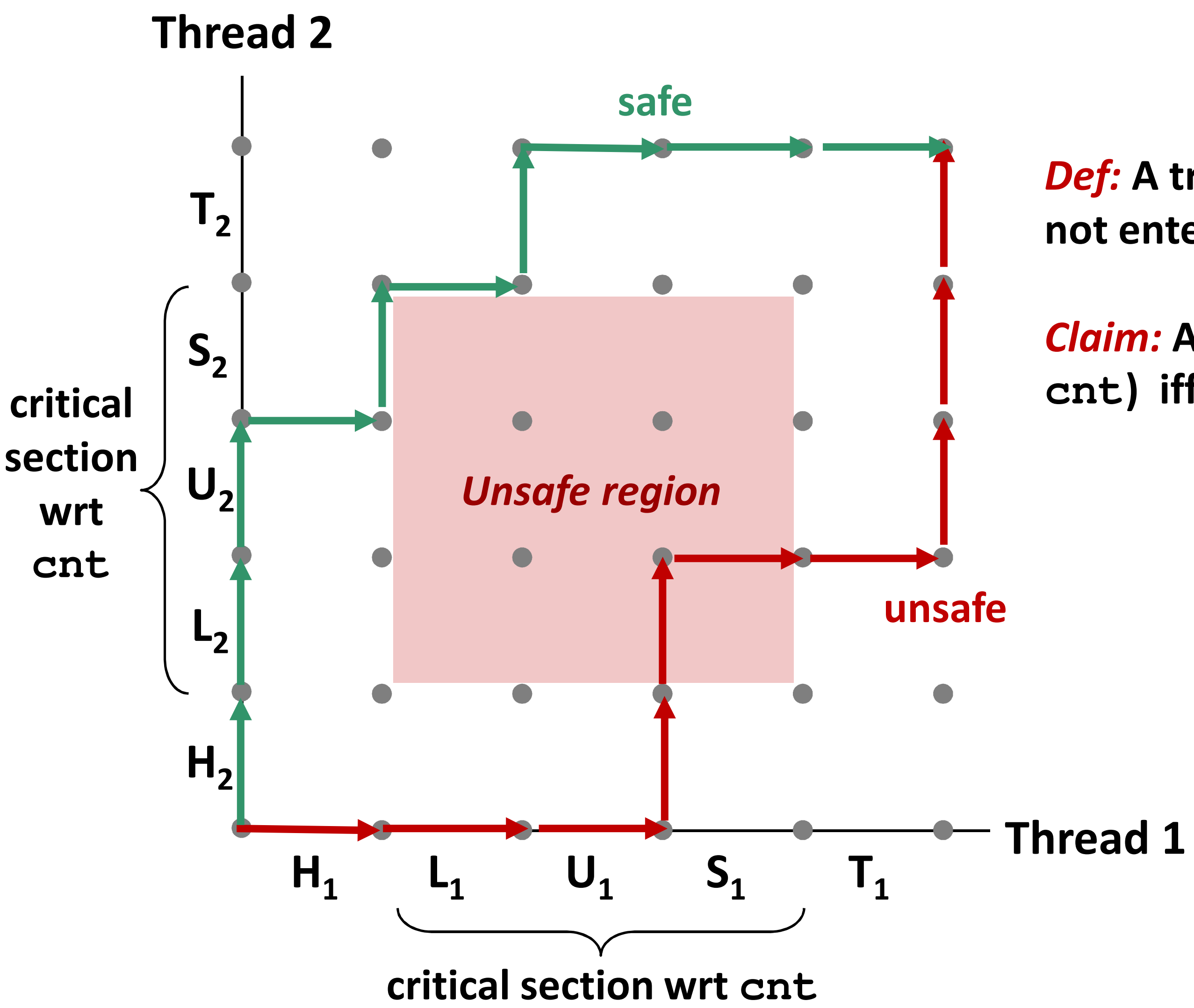
Critical Sections and Unsafe Regions



Def: A trajectory is ***safe*** iff it does not enter any unsafe region

Claim: A trajectory is correct (wrt `cnt`) iff it is safe

Critical Sections and Unsafe Regions



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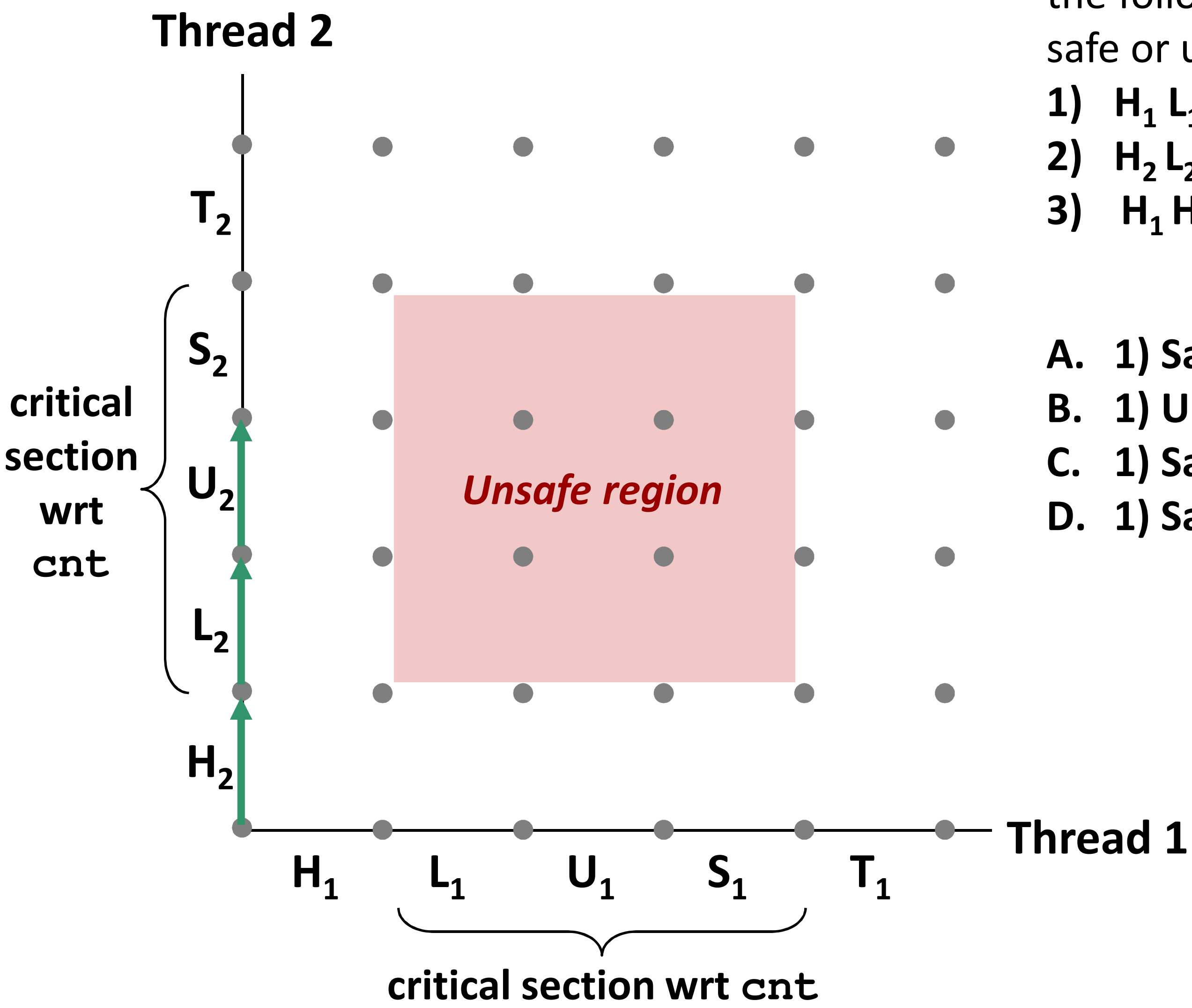
i-clicker question

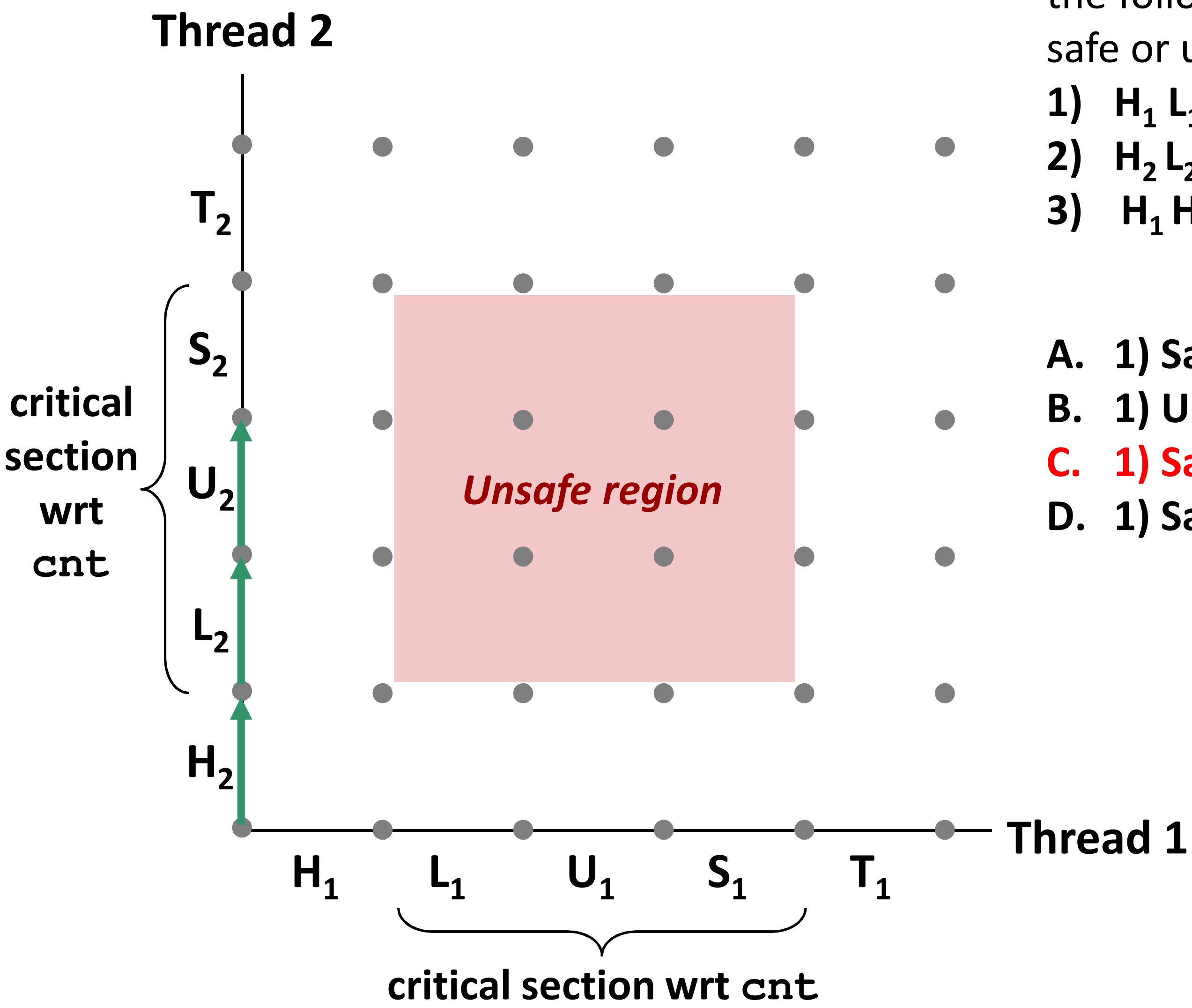


Using the program graph, classify the following trajectories as either safe or unsafe.

1) $H_1\ L_1\ U_1\ S_1\ H_2\ L_2\ U_2\ S_2\ T_2\ T_1$
2) $H_2\ L_2\ H_1\ L_1\ U_1\ S_1\ T_1\ U_2\ S_2\ T_2$
3) $H_1\ H_2\ L_2\ U_2\ S_2\ L_1\ U_1\ S_1\ T_1\ T_2$

A. 1) Safe 2) Safe 3) Safe
B. 1) Unsafe 2) Unsafe 3) Unsafe
C. 1) Safe 2) Unsafe 3) Safe
D. 1) Safe 2) Unsafe 3) Unsafe

i-clicker question solution



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3) $H_1\ H_2\ L_2\ U_2\ S_2\ L_1\ U_1\ S_1\ T_1\ T_2$

A. 1) Safe 2) Safe 3) Safe
B. 1) Unsafe 2) Unsafe 3) Unsafe
C. 1) Safe 2) Unsafe 3) Safe
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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.

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 1000000
OK cnt=2000000
linux> ./badcnt 1000000
BOOM! cnt=1332062
```

cnt should equal 2,000,000.

What went wrong?

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.**

Semaphores

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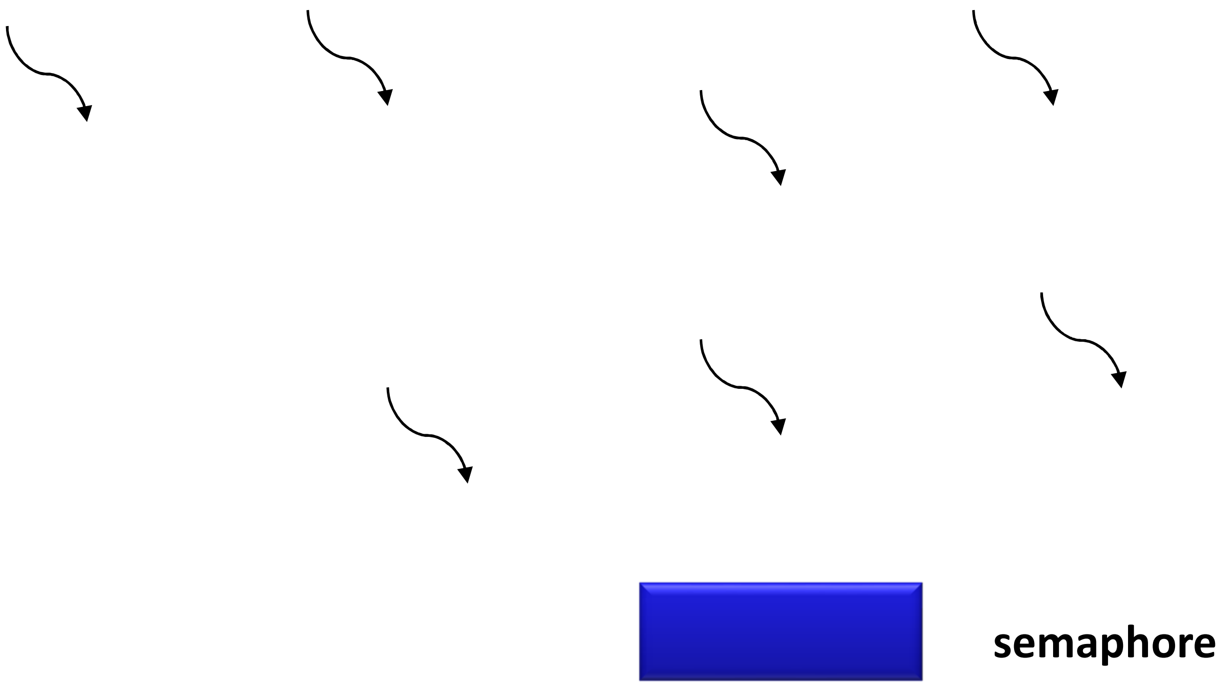
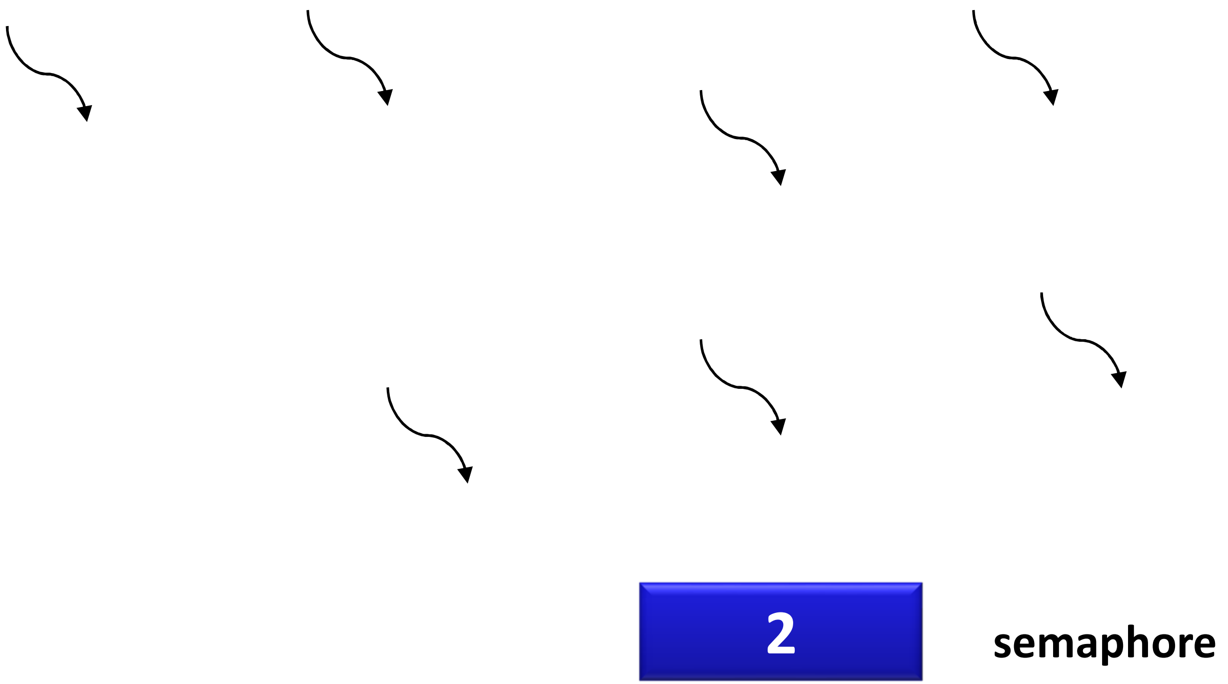


Semaphores

- ***Semaphore:*** **non-negative global integer synchronization variable.**



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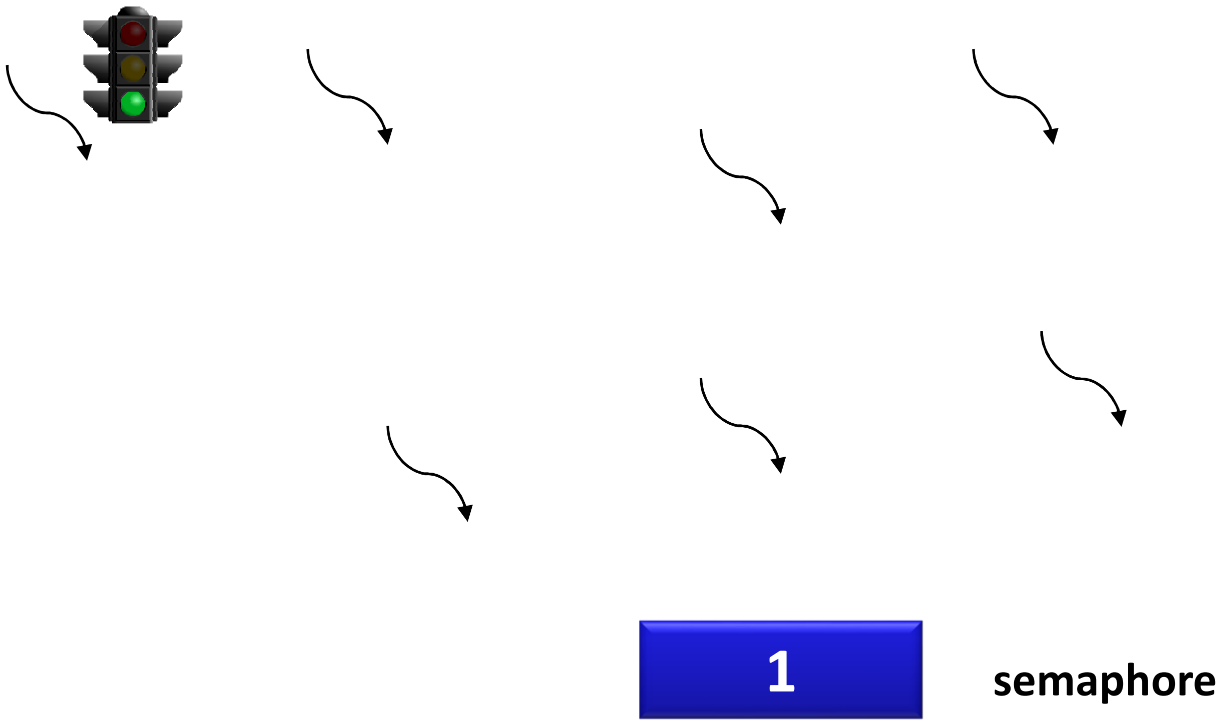

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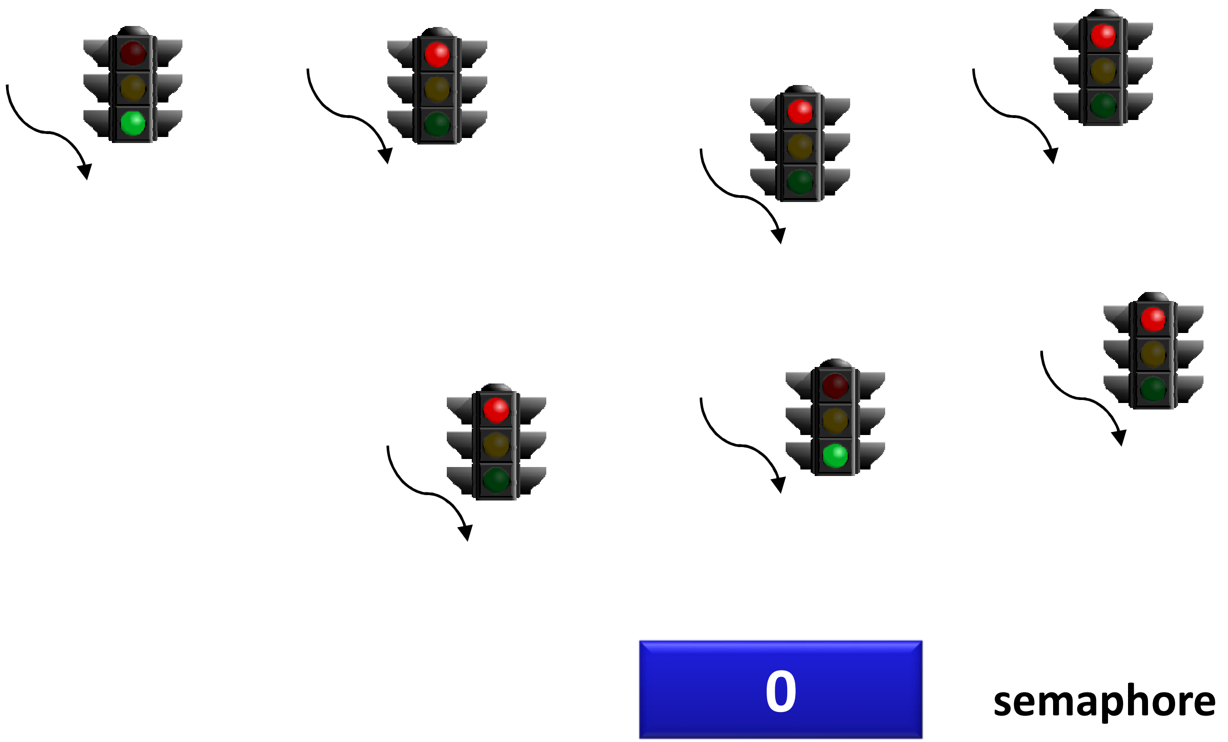

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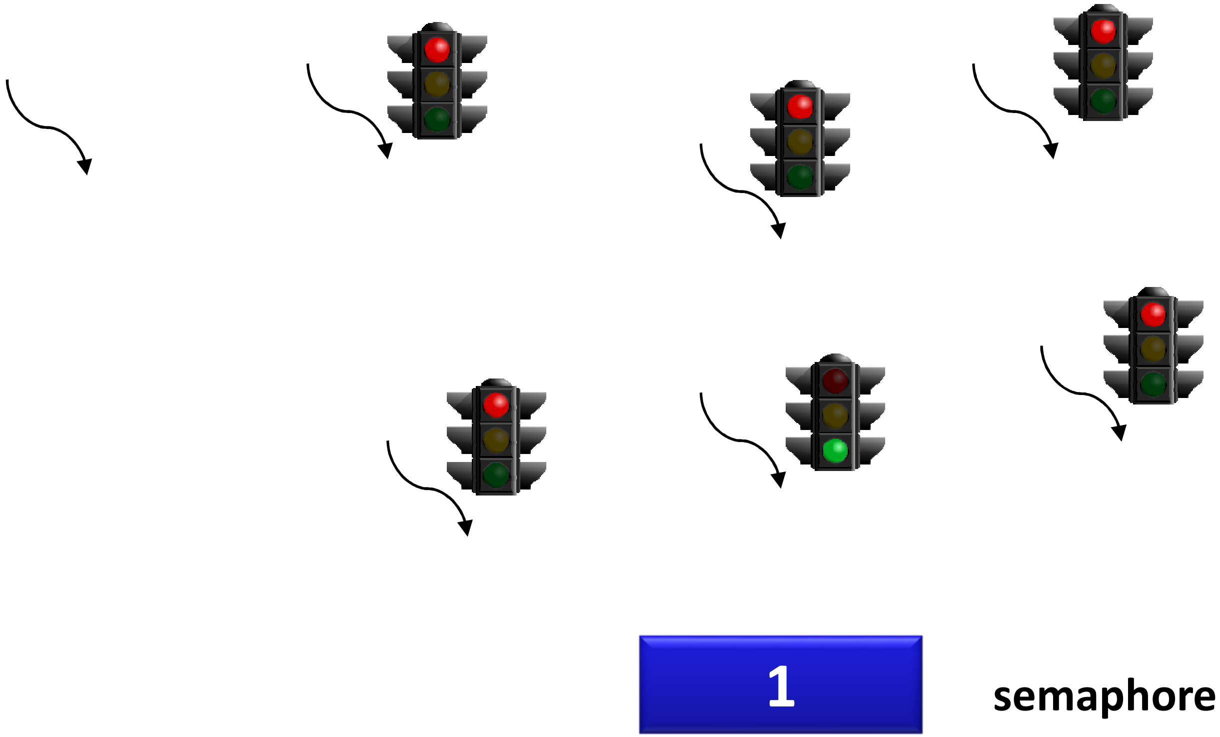

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- **P(s)**
  - If *s* is nonzero, then decrement *s* by 1 and return immediately.
    - Test and decrement operations occur atomically (indivisibly)
  - If *s* is zero, then suspend thread until *s* becomes nonzero and the thread is restarted by a 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*.

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- **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) */
```

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.

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- **Basic idea:**
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  - 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++) {
    sem_wait(&mutex);
    cnt++;
    sem_post(&mutex);
}
```

goodcnt.c

```
linux> ./goodcnt 1000000
OK cnt=1000000
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goodcnt.c

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OK cnt=1000000
linux> ./goodcnt 1000000
OK cnt=1000000
```
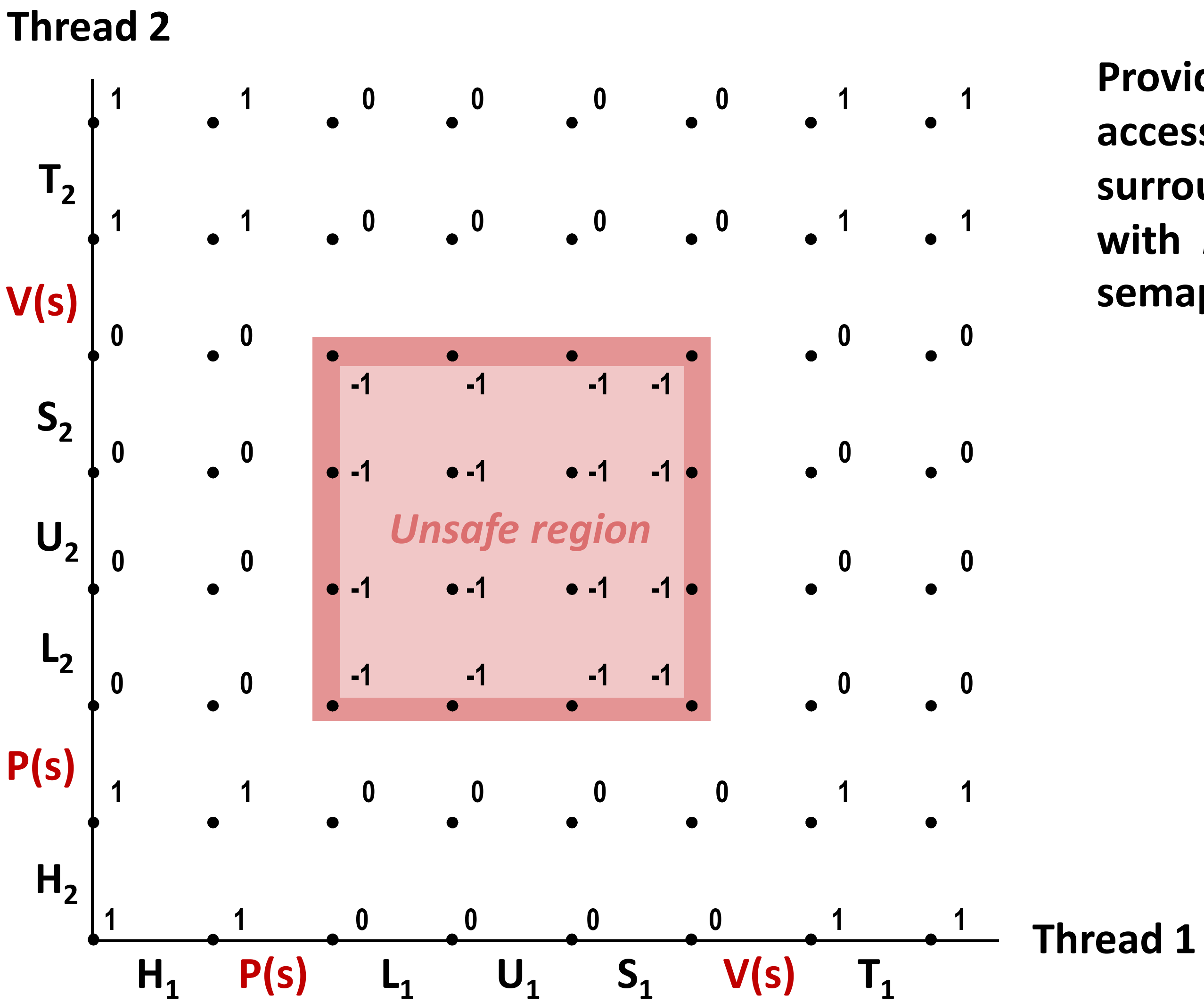

Warning: It's orders of magnitude slower than badcnt.c.

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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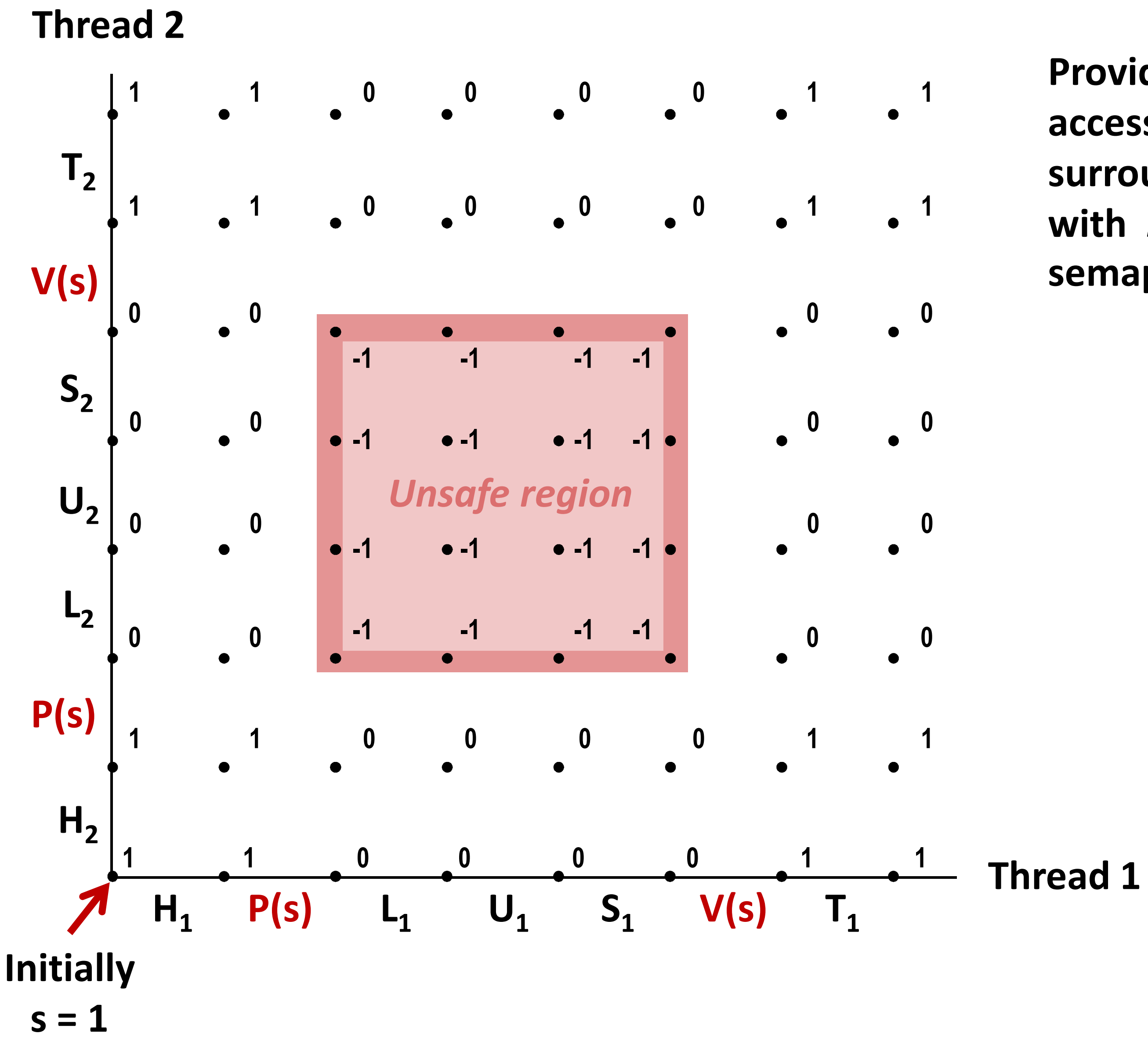

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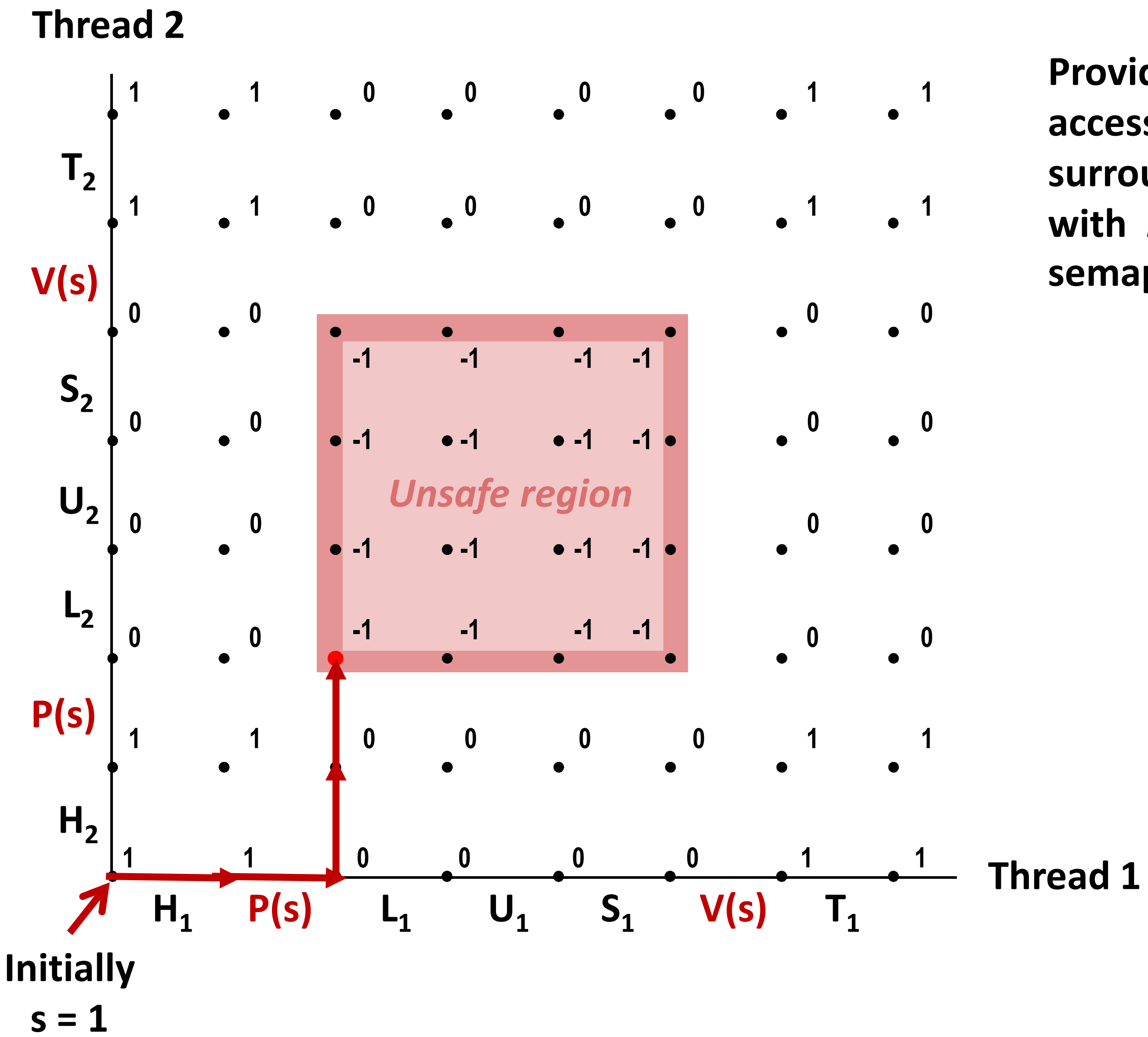

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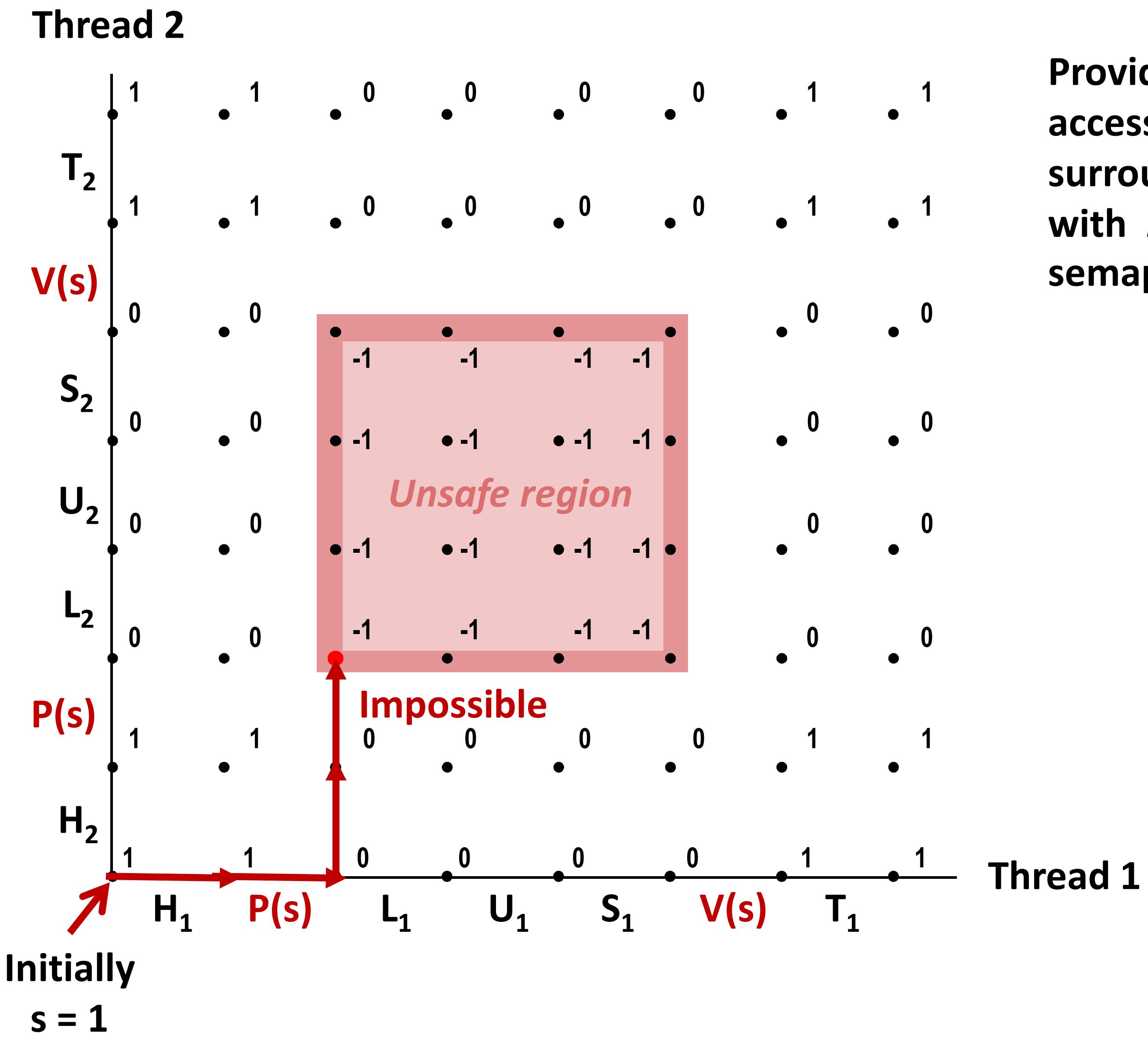

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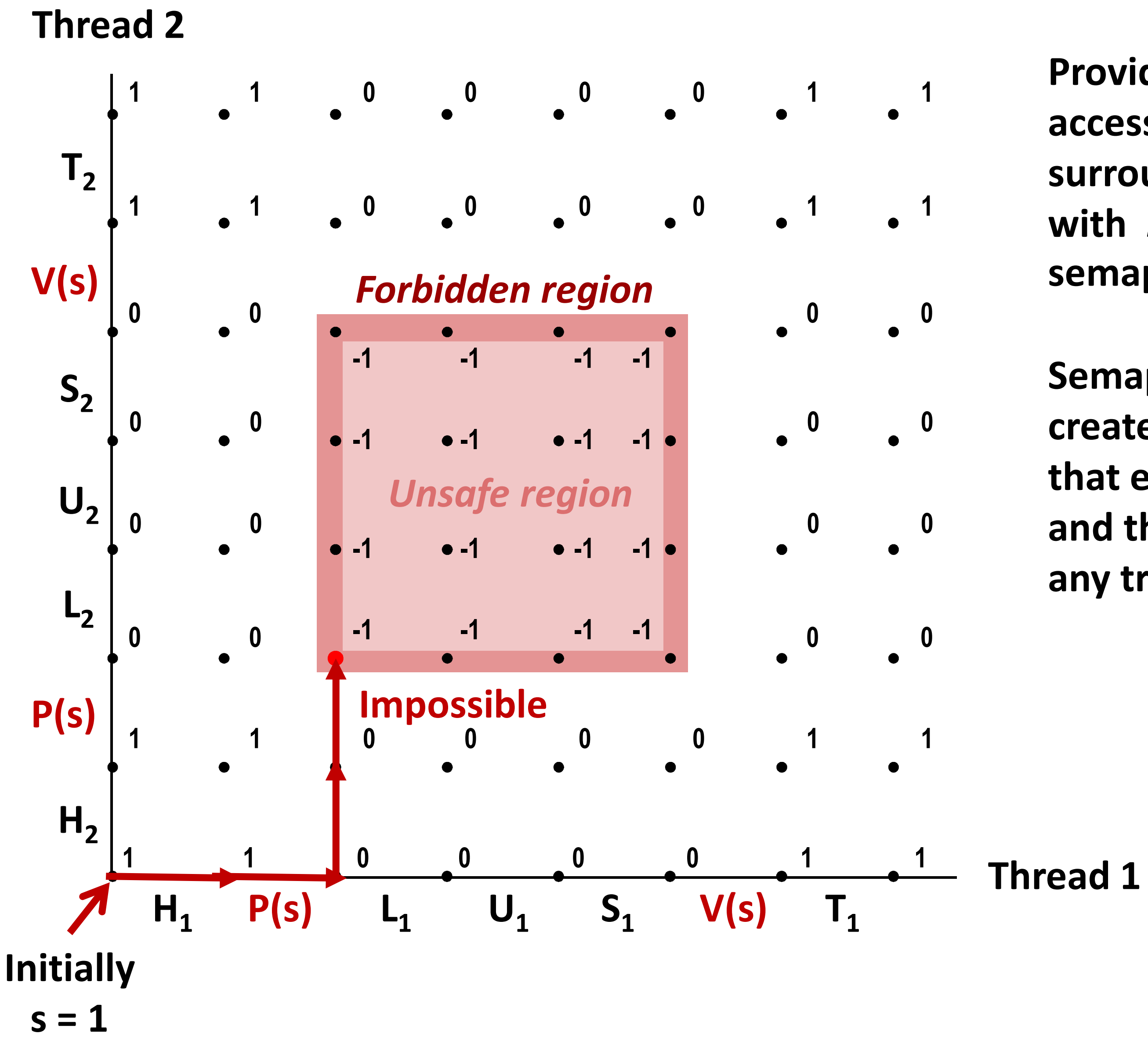

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Semaphore invariant creates a ***forbidden region*** that encloses unsafe region and that cannot be entered by any trajectory.

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.**