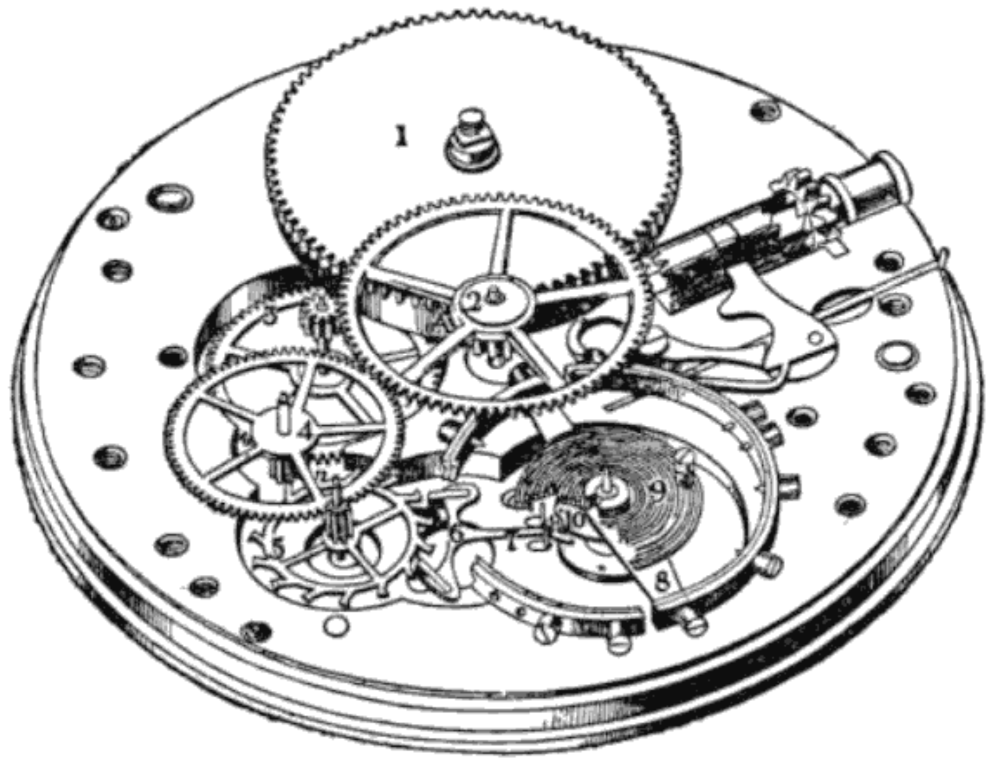
Synchronization

CS 241

March 2, 2012



Slides adapted in part from material accompanying Bryant & O'Hallaron, "Computer Systems: A Programmer's Perspective", 2/E

Announcements

MP4 due tonight

Midterm

- Next Tuesday, 7-9 p.m.
- Study guide and practice exam released Wednesday

PPT?

Do threads conflict in practice?

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <assert.h>

#define NUM_THREADS 2
#define ITERATIONS_PER_THREAD 5000000

int cnt = 0;

void * worker( void *ptr )
{
    int i;
    for (i = 0; i < ITERATIONS_PER_THREAD; i++)
        cnt++;
}
```

Do threads conflict in practice?

```
int main(void)
{
    pthread_t threads[NUM_THREADS];
    int i, result;

    /* Start threads */
    for (i = 0; i < NUM_THREADS; i++) {
        result = pthread_create(&threads[i], NULL, worker, NULL);
        assert(result == 0);
    }

    /* Wait for threads to finish */
    for (i = 0; i < NUM_THREADS; i++) {
        result = pthread_join(threads[i], NULL);
        assert(result == 0);
    }

    printf("Final value: %d (%.2f%%)\n", cnt,
        100.0 * cnt / (NUM_THREADS * (double)ITERATIONS_PER_THREAD));
}
```

Do threads conflict in practice?

If everything worked...

```
$ ./20-counter
Final value: 100000
```

Q: What are the minimum and maximum final value?

Q: What value do you expect in practice?

Assembly Code for Counter Loop

C code for counter loop for thread i

```
for (i=0; i < 50000; i++)
    cnt++;
```

Corresponding assembly code

```
        movl  (%rdi),%ecx
        movl  $0,%edx
        cmpl  %ecx,%edx
        jge   .L13
.L11:
        movl  cnt(%rip),%eax
        incl  %eax
        movl  %eax,cnt(%rip)
        incl  %edx
        cmpl  %ecx,%edx
        jl    .L11
.L13:
```

Head (H_i)

Load **cnt** (L_i)
Update **cnt** (U_i)
Store **cnt** (S_i)

Critical section: reading or writing shared variable

Tail (T_i)

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
- $\%eax_i$ is the content of %eax in thread i's context

Thread 1	Thread 2	$\%eax_1$	$\%eax_2$	cnt
H		-	-	0
L		0	-	0
U		1	-	0
S		1	-	1
	H	1	-	1
	L	1	1	1
	U	1	2	1
	S	1	2	2
	T	1	2	2
T		1	-	2

Thread 1 critical section

Thread 2 critical section

OK!

Concurrent execution (example 2)

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

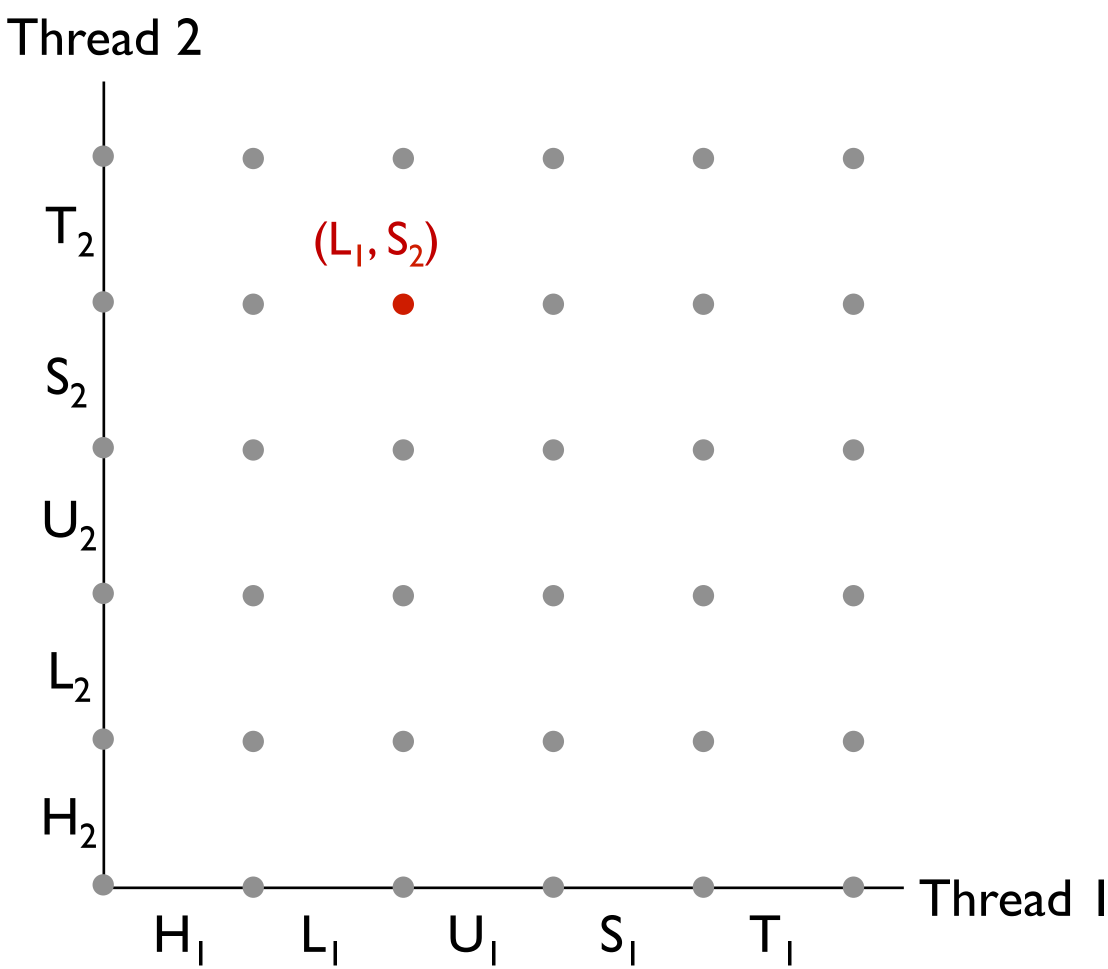
Thread 1	Thread 2	$\%eax_1$	$\%eax_2$	cnt
H		-	-	0
L		0	-	0
U		1	-	0
	H	1	-	0
	L	1	0	0
S		1	1	1
T		-	1	1
	U	-	1	1
	S	-	1	1
	T	-	-	1

Thread 1 critical section

Thread 2 critical section

Oops!

Progress Graphs



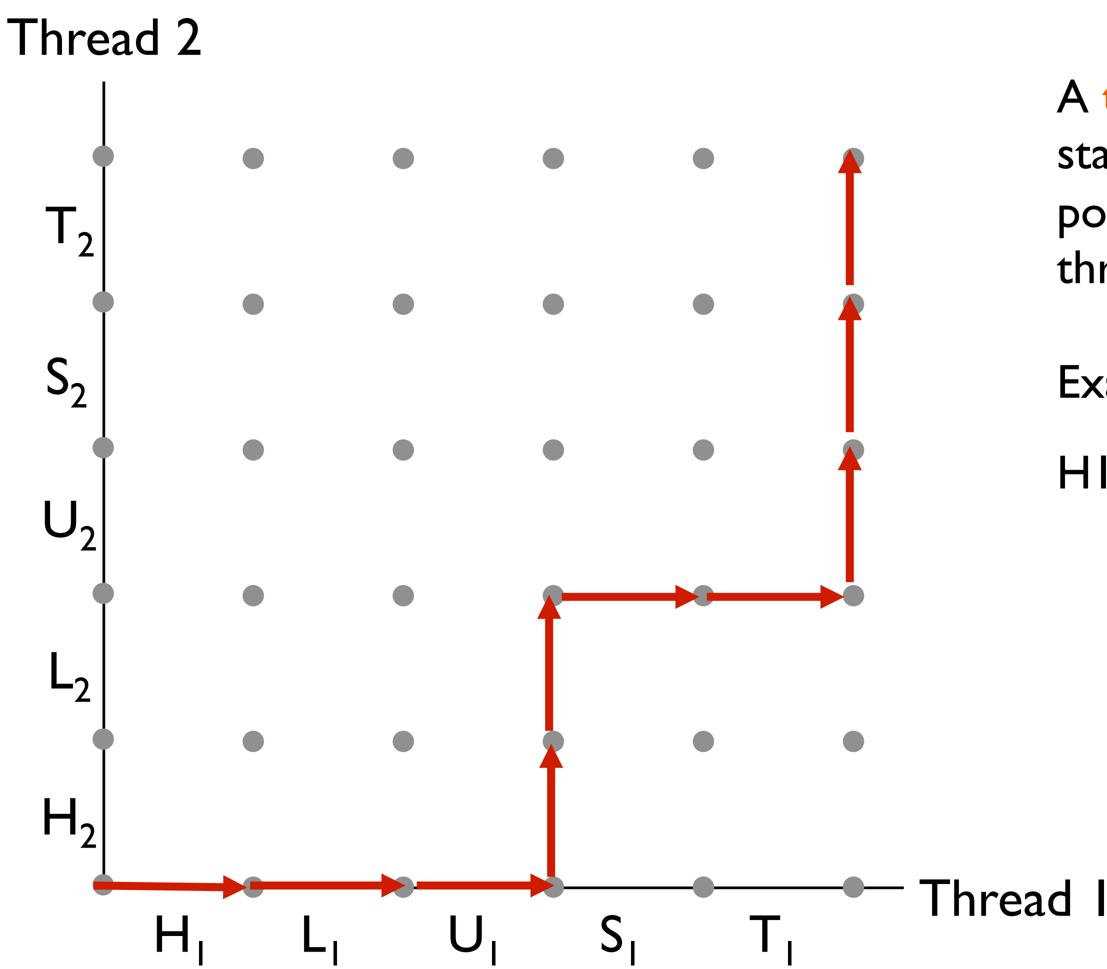
A **progress graph** depicts the discrete **execution state space** of concurrent threads.

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.

Progress Graphs

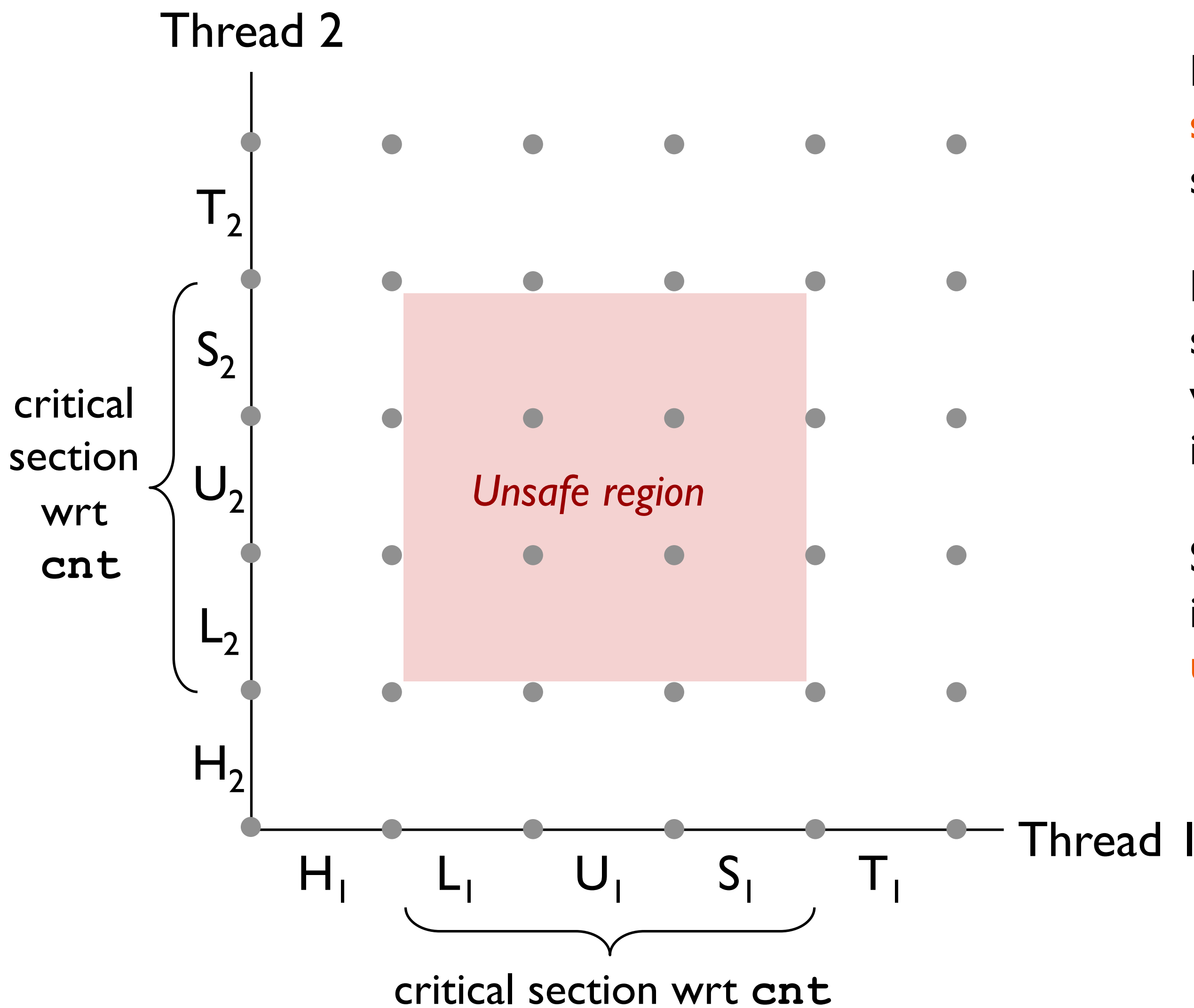


A **trajectory** is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

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

Critical Sections and Unsafe Regions

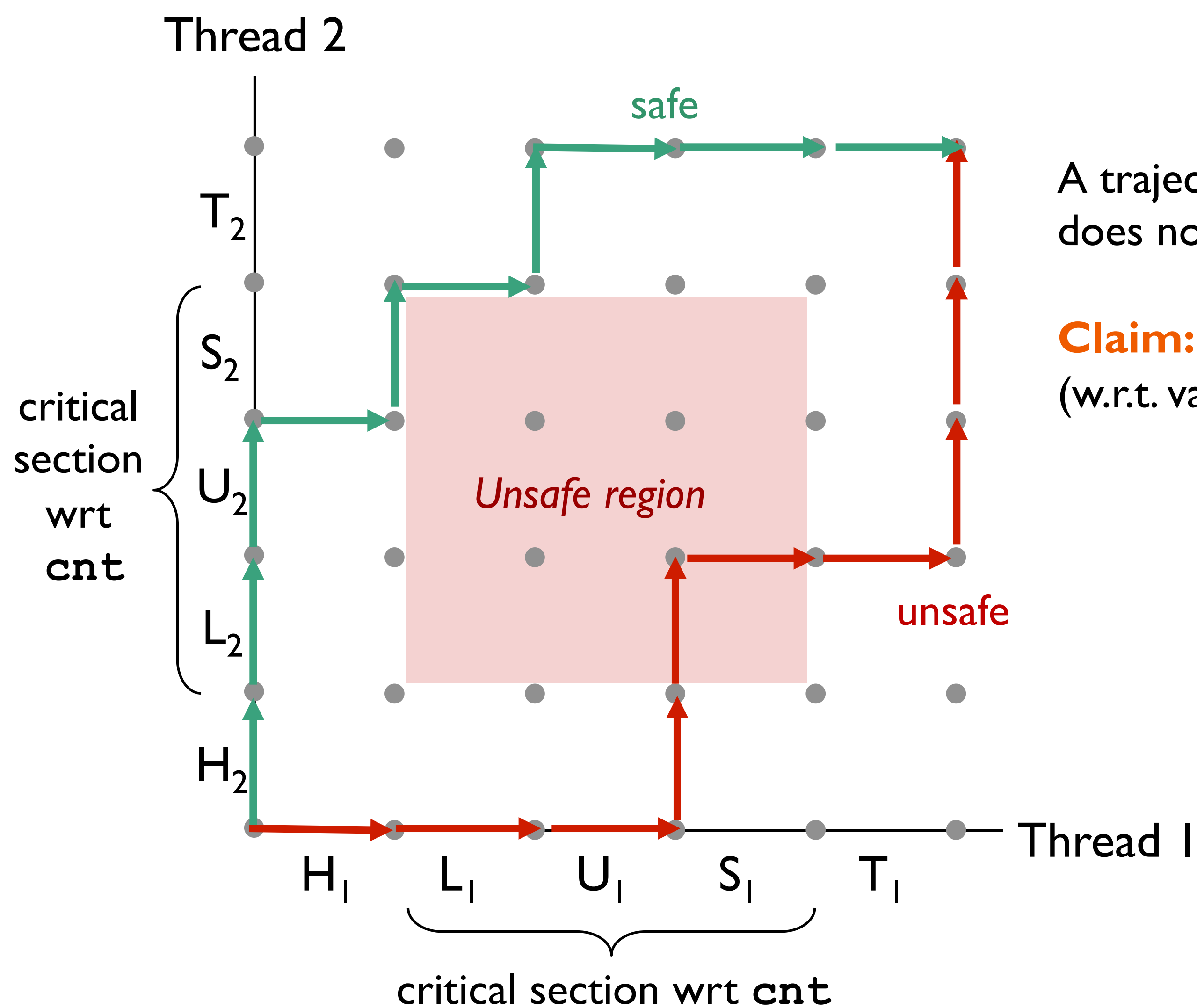


L, U, and S form a **critical section** with respect to the shared variable **`cnt`**

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

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

Critical Sections and Unsafe Regions



A trajectory is **safe** if and only if it does not enter any unsafe region

Claim: A trajectory is correct (w.r.t. variable `cnt`) iff it is safe

Enforcing mutual exclusion

How can we guarantee a safe trajectory?

Answer: We must **synchronize** the execution of the threads so that they never have an unsafe trajectory.

- i.e., need to guarantee **mutually exclusive access** to critical regions
- provides a sufficient condition for correctness

Classic solution

- Semaphores (Edsger Dijkstra) (pthreads)

Other approaches

- Mutexes, and condition variables (pthreads)
- Locks and rwlocks (pthreads)
- Monitors (Java)

photo: Les Meloures / wikimedia

Semaphores

Semaphores

A non-negative global integer synchronization variable

Manipulated by *wait* and *post* operations:

- *wait(s):* `[ while (s == 0) wait(); s--; ]`
  - Also *P*(s), Dutch for "Proberen" (test)
- *post(s):* `[ s++; ]`
  - Also *V*(s), Dutch for "Verhogen" (increment)

OS kernel guarantees that operations between brackets [ ] are executed indivisibly

- i.e., `s--` can't be broken into load/update/store
- Result: only one *wait* or *post* operation at a time can modify `s`
- When `while` loop in *wait* terminates, only that *wait* can decrement `s`

Semaphore invariant: *(s >= 0)*

C Semaphore Operations

pthreads functions:

```
#include <semaphore.h>

int sem_init(sem_t *sem, 0, unsigned int val);} /* s = val */

int sem_wait(sem_t *s);
int sem_post(sem_t *s);
```

Back to the counter...

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <assert.h>

#define NUM_THREADS 2
#define ITERATIONS_PER_THREAD 50000

int cnt = 0;

void * worker( void *ptr )
{
    int i;
    for (i = 0; i < ITERATIONS_PER_THREAD; i++)
        cnt++;
}
```

How can we fix this using semaphores?

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 *wait(mutex)* and *post(mutex)* operations.

Terminology

- **Binary semaphore**: semaphore whose value is always 0 or 1
- **Mutex:** binary semaphore used for mutual exclusion
  - *wait* operation: "locking" the mutex
  - *post* operation: "unlocking" or "releasing" the mutex
  - "Holding" a mutex: locked and not yet unlocked
- **Counting semaphore**: used to count a set of available resources

goodcounter.c: good synchronization

```
#include <semaphore.h>

...

int cnt = 0;
sem_t cnt_mutex;

int main(void)
{
    ...
    /* Initialize mutex */
    sem_init(&cnt_mutex, 0, 1);
    ...
}

void * worker( void *ptr )
{
    int i;
    for (i = 0; i < ITERATIONS_PER_THREAD; i++) {
        sem_wait(&cnt_mutex);
        cnt++;
        sem_post(&cnt_mutex);
    }
}
```

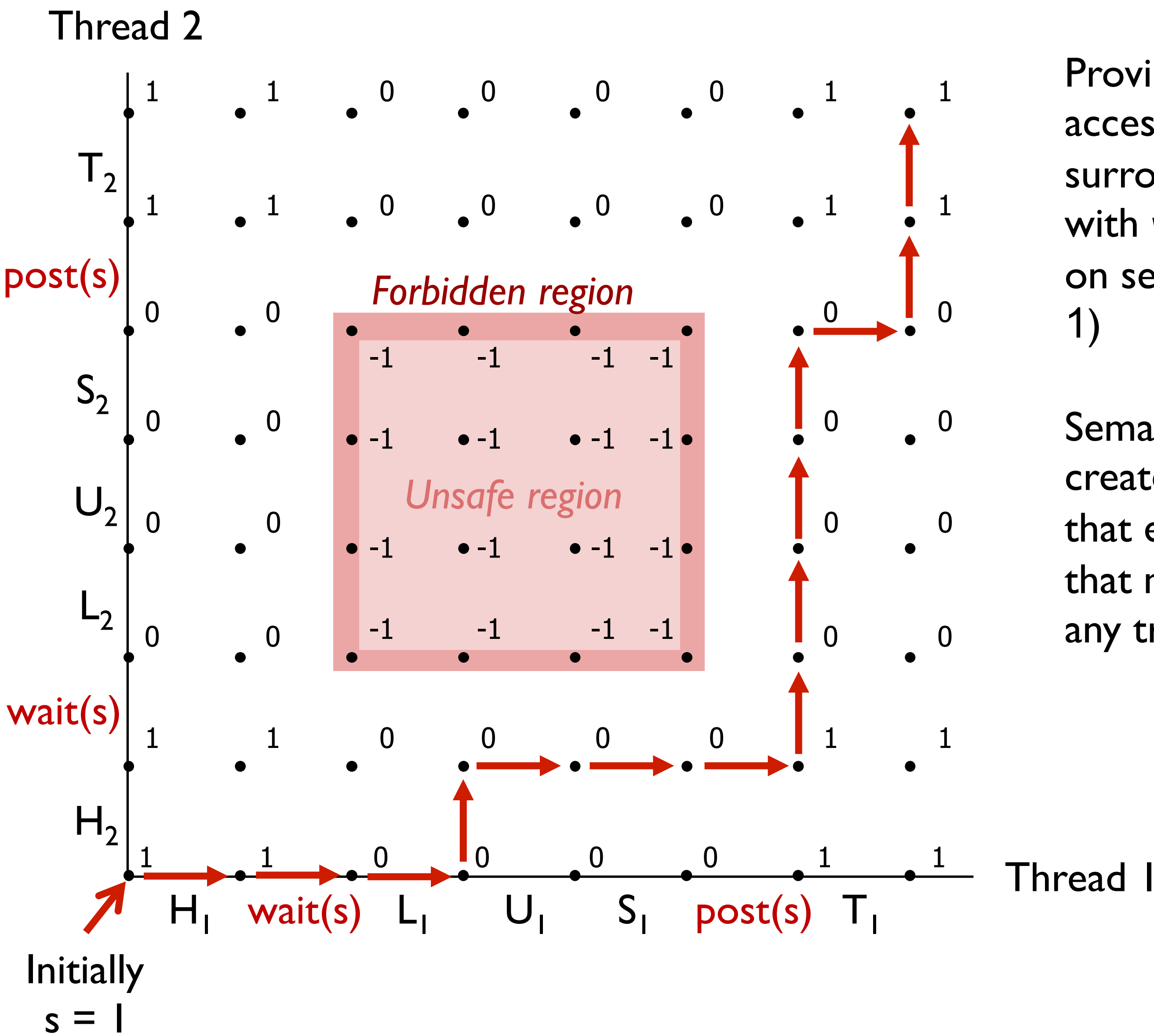
Necessary include

Declare mutex

Initialize to 1

Surround critical section

Why Mutexes Work



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

Semaphore invariant creates a **forbidden region** that encloses the unsafe region that must not be entered by any trajectory.

Discussion

Mutual exclusion changes scheduling between threads

- Previously: Schedule could be anything
- With mutual exclusion: Schedule is constrained

Q: Since scheduling is constrained, which thread goes first, Thread 1 or Thread 2?

A: We still have no clue

- mutex only ensures two threads aren't in critical section at one time
- otherwise scheduling is still arbitrary
- and that's fine with us

Better synchronization!

```
int main(void)
{
    ...
    /* Initialize mutex */
    result = sem_init(&cnt_mutex, 0, 1);
    if (result < 0)
        exit(-1);

    ...

    /* Clean up the semaphore that we're done with */
    result = sem_destroy(&cnt_mutex);
    assert(result == 0);
}
```

Check for errors on each call

Clean up resources

Why bother checking for errors?

Without error handling, your code might:

- Crash rather than exiting gracefully
- Keep working for a while, crash later
- Sometimes fail randomly, but usually work fine
  - Hard to reproduce: even harder to debug
- Fail when it might have recovered from the error cleanly!

At a minimum, error handling converts a messy failure into a clean failure

- Program terminates, but you know what caused it to terminate

Some errors are recoverable

```
void * worker( void *ptr )
{
    int i;
    for (i = 0; i < ITERATIONS_PER_THREAD; i++) {
        while (sem_wait(&cnt_mutex) < 0)
            if (errno != EINTR)
                exit(-1);
        cnt++;
        if (sem_post(&cnt_mutex) <  0)
            exit(-1);
    }
}
```

Much more in the Director's Cut

Options

- Named semaphores
- Semaphores shared between processes

Other functions / variants

- sem_trywait
- sem_timedwait
- semctl

Other mutual exclusion functions

- pthread_mutex_init
- PTHREAD_MUTEX_INITIALIZER
- pthread_mutex_lock / trylock / unlock
- pthread_mutex_destroy
- ...

Summary

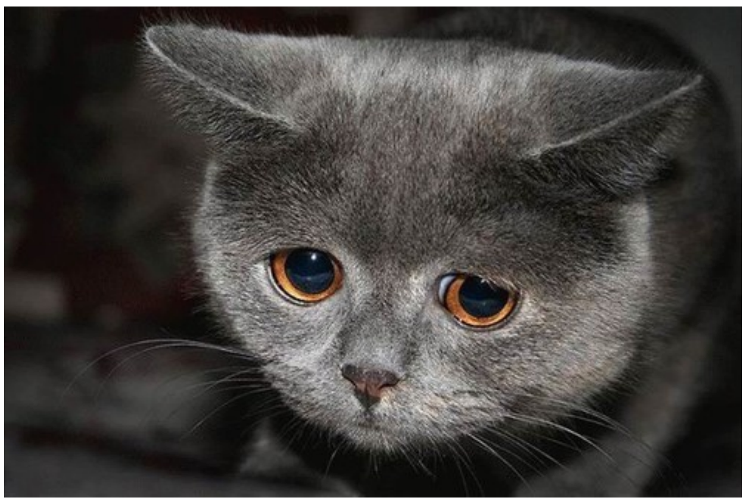
Programmers need a clear model of how variables are shared by threads

- Cannot reason about all possible interleavings of threads

Variables shared by multiple threads must be protected to ensure mutually exclusive access

Semaphores are a fundamental mechanism for enforcing mutual exclusion

Summary



This cat did not check for
exceptional cases

This cat did.