# 15-213

***"The course that gives CMU its Zip!"***

# Programming with Threads
# Dec 6, 2001

**Topics**

- **Shared variables**
- **The need for synchronization**
- **Synchronizing with semaphores**
- **Synchronizing with mutex and condition variables**
- **Thread safety and reentrancy**
- **Races and deadlocks**

`class29.ppt`

# Shared variables in threaded C programs

## Question: Which variables in a threaded C program are *shared variables*?

- The answer is not as simple as "global variables are shared" and "stack variables are private".

## Requires answers to the following questions:

- What is the memory model for threads?
- How are variables mapped to memory instances?
- How many threads reference each of these instances?

# Threads memory model

## Conceptual model:

- **Each thread runs in the context of a process.**
- **Each thread has its own separate *thread context.***
  - Thread ID, stack, stack pointer, program counter, condition codes, and general purpose 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:

- **While register values are truly separate and protected....**
- **Any thread can read and write the stack of any other thread.**

## Mismatch between the conceptual and operation model is a source of confusion and errors.

# Example of threads accessing another thread's stack

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

int main()
{
    int i;
    pthread_t tid;
    char *msgs[N] = {
        "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 (cnt=%d)\n",
         myid, ptr[myid], ++cnt);
}
```

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

# Mapping variables to memory instances

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

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

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

int main()
{
    int i;
    pthread_t tid;
    char *msgs[N] = {
        "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 automatic 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 (cnt=%d)\n",
         myid, ptr[myid], ++cnt);
}
```

***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 |

**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.**

# `badcnt.c`: An improperly synchronized threaded program

```
unsigned int cnt = 0; /* shared */

int main() {
    pthread_t tid1, tid2;
    Pthread_create(&tid1, NULL,
                   count, NULL);
    Pthread_create(&tid2, NULL,
                   count, NULL);

    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    if (cnt != (unsigned)NITERS*2)
        printf("BOOM! cnt=%d\n",
               cnt);
    else
        printf("OK cnt=%d\n",
               cnt);
}
```

```
/* thread routine */
void *count(void *arg) {
    int i;
    for (i=0; i<NITERS; i++)
        cnt++;
    return NULL;
}
```

```
linux> badcnt
BOOM! ctr=198841183

linux> badcnt
BOOM! ctr=198261801

linux> badcnt
BOOM! ctr=198269672
```

**`ctr` should be equal to 200,000,000. What went wrong?!**

# Assembly code for counter loop

**C code for counter loop**

```
for (i=0; i<NITERS; i++)
    ctr++;
```

**Corresponding asm code (gcc -O0 -fforce-mem)**

Head ($H_i$)

```
.L9:
        movl -4(%ebp),%eax
        cmpl $99999999,%eax
        jle .L12
        jmp .L10
```

Load ctr ($L_i$)
Update ctr ($U_i$)
Store ctr ($S_i$)

```
.L12:
        movl ctr,%eax        # Load
        leal 1(%eax),%edx    # Update
        movl %edx,ctr        # Store
```

Tail ($T_i$)

```
.L11:
        movl -4(%ebp),%eax
        leal 1(%eax),%edx
        movl %edx,-4(%ebp)
        jmp .L9
.L10:
```

# Concurrent execution

**Key idea: In general, any sequentially consistent interleaving is possible, but some are incorrect!**

- $I_i$ denotes that thread i executes instruction I
- $\%eax_i$ is the contents of %eax in thread i's context

| i (thread) | $instr_i$ | $\%eax_1$ | $\%eax_2$ | ctr |
|---|---|---|---|---|
| 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 (cont)

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

| i (thread) | $instr_i$ | $\%eax_1$ | $\%eax_2$ | ctr |
|---|---|---|---|---|
| 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!**

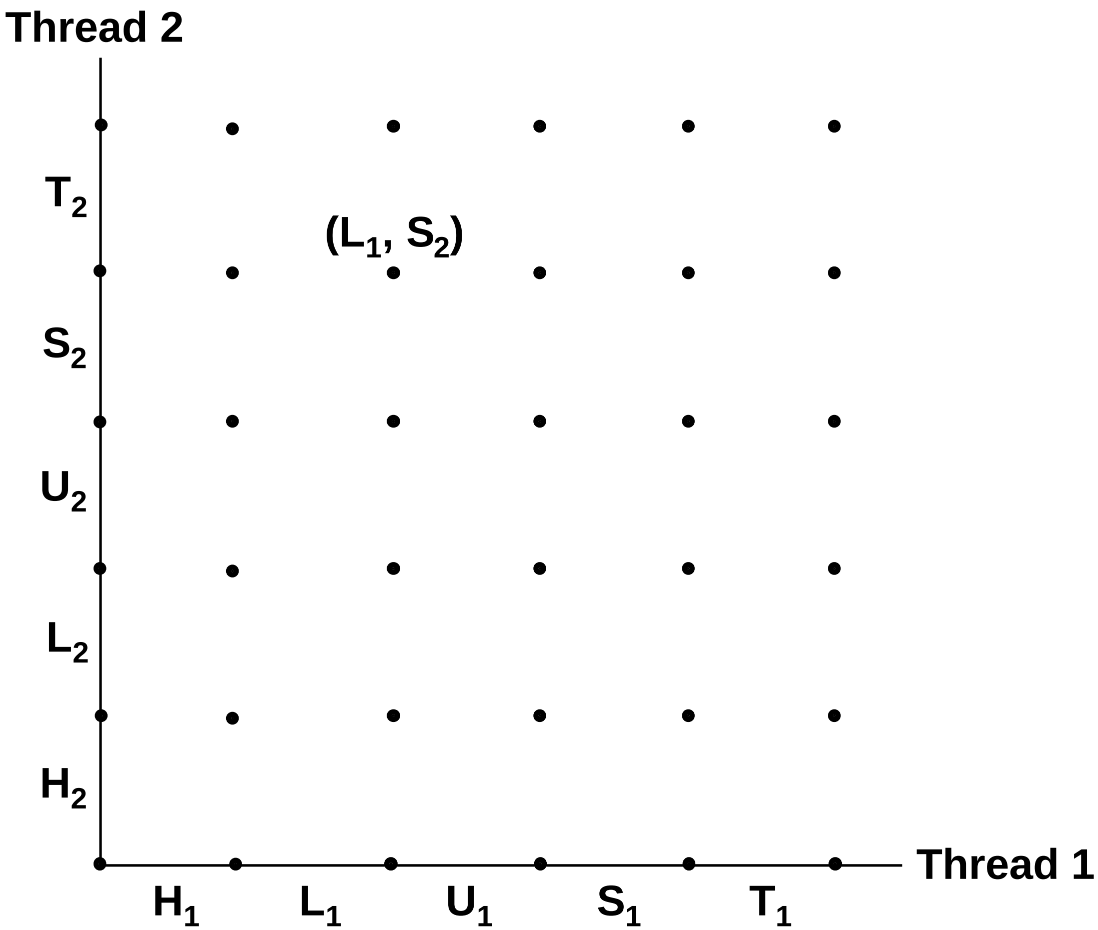
# Concurrent execution (cont)

## How about this ordering?

| i (thread) | $instr_i$ | $\%eax_1$ | $\%eax_2$ | ctr |
|---|---|---|---|---|
| 1 | $H_1$ | | | |
| 1 | $L_1$ | | | |
| 2 | $H_2$ | | | |
| 2 | $L_2$ | | | |
| 2 | $U_2$ | | | |
| 2 | $S_2$ | | | |
| 1 | $U_1$ | | | |
| 1 | $S_1$ | | | |
| 1 | $T_1$ | | | |
| 2 | $T_2$ | | | |

**We can clarify our understanding of concurrent execution with the help of the *progress graph***

# Progress graphs



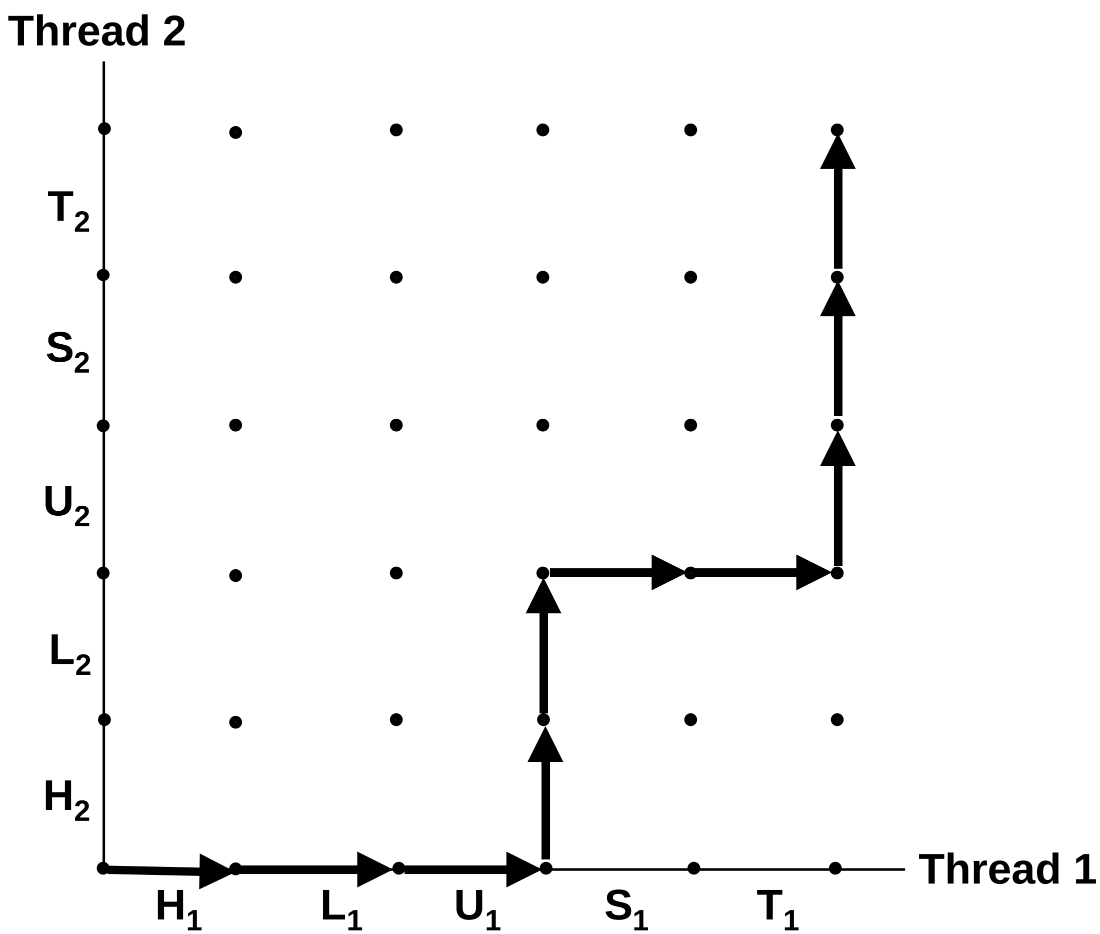

**A *progress graph* depicts the discrete *execution state space* of concurrent threads.**

**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

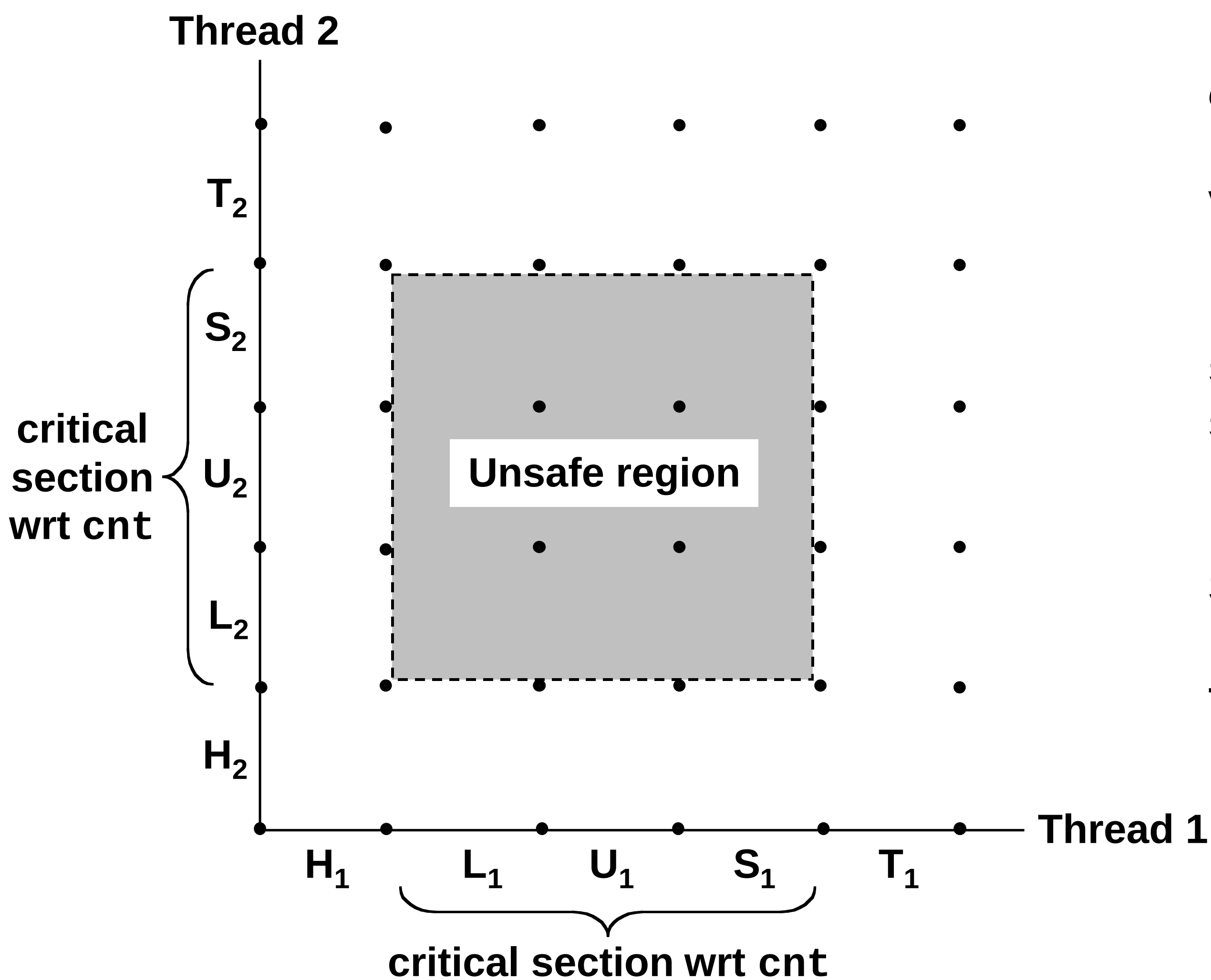



**A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.**

**Example:**

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

# Critical sections and unsafe regions

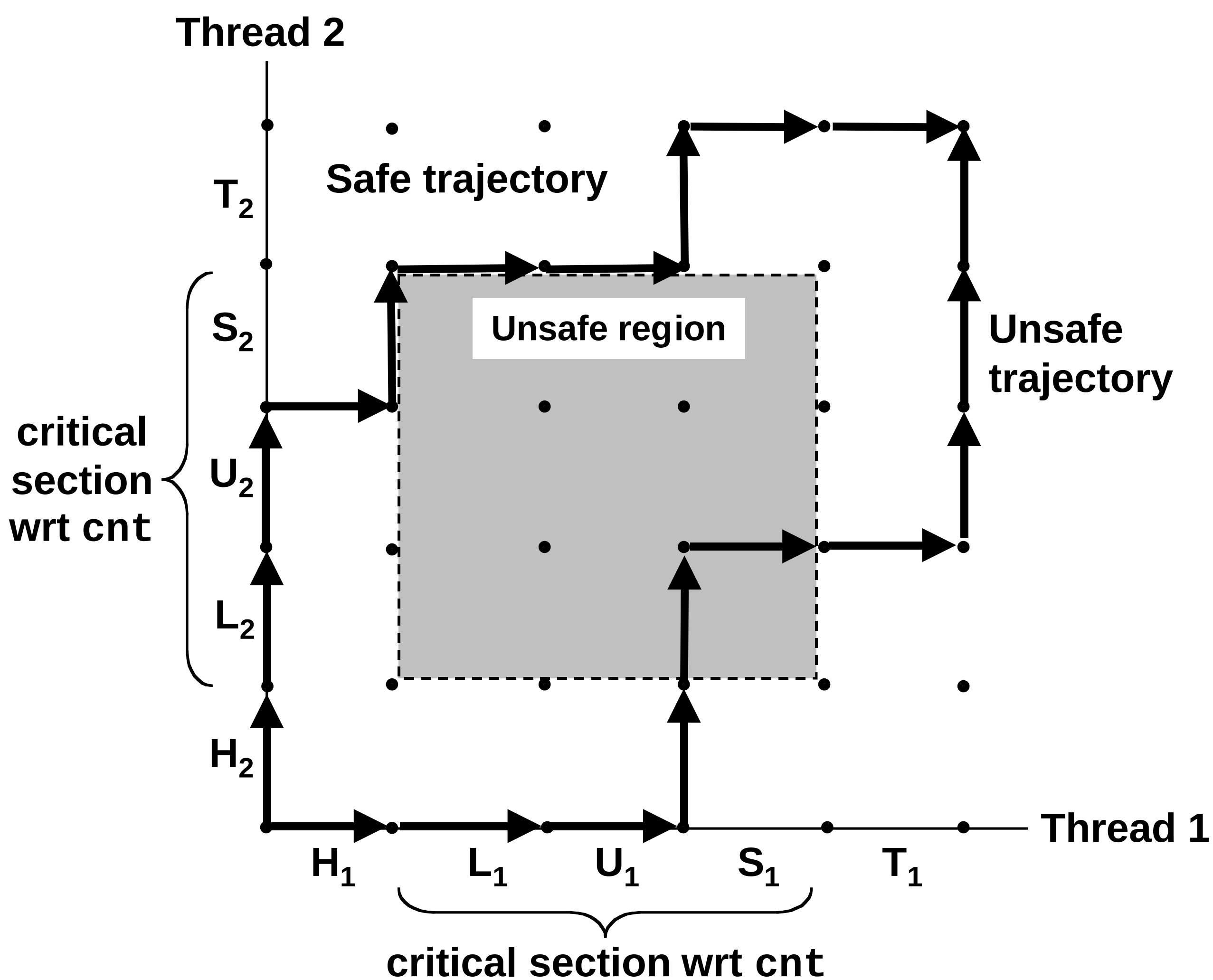



L, U, and S form a *critical section* with respect to the shared variable `cnt`.

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

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

# Safe and unsafe trajectories




***Def:*** **A trajectory is *safe* iff it doesn't touch any part of an unsafe region.**

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

# Synchronizing with semaphores

***Question:*** **How can we guarantee a safe trajectory?**

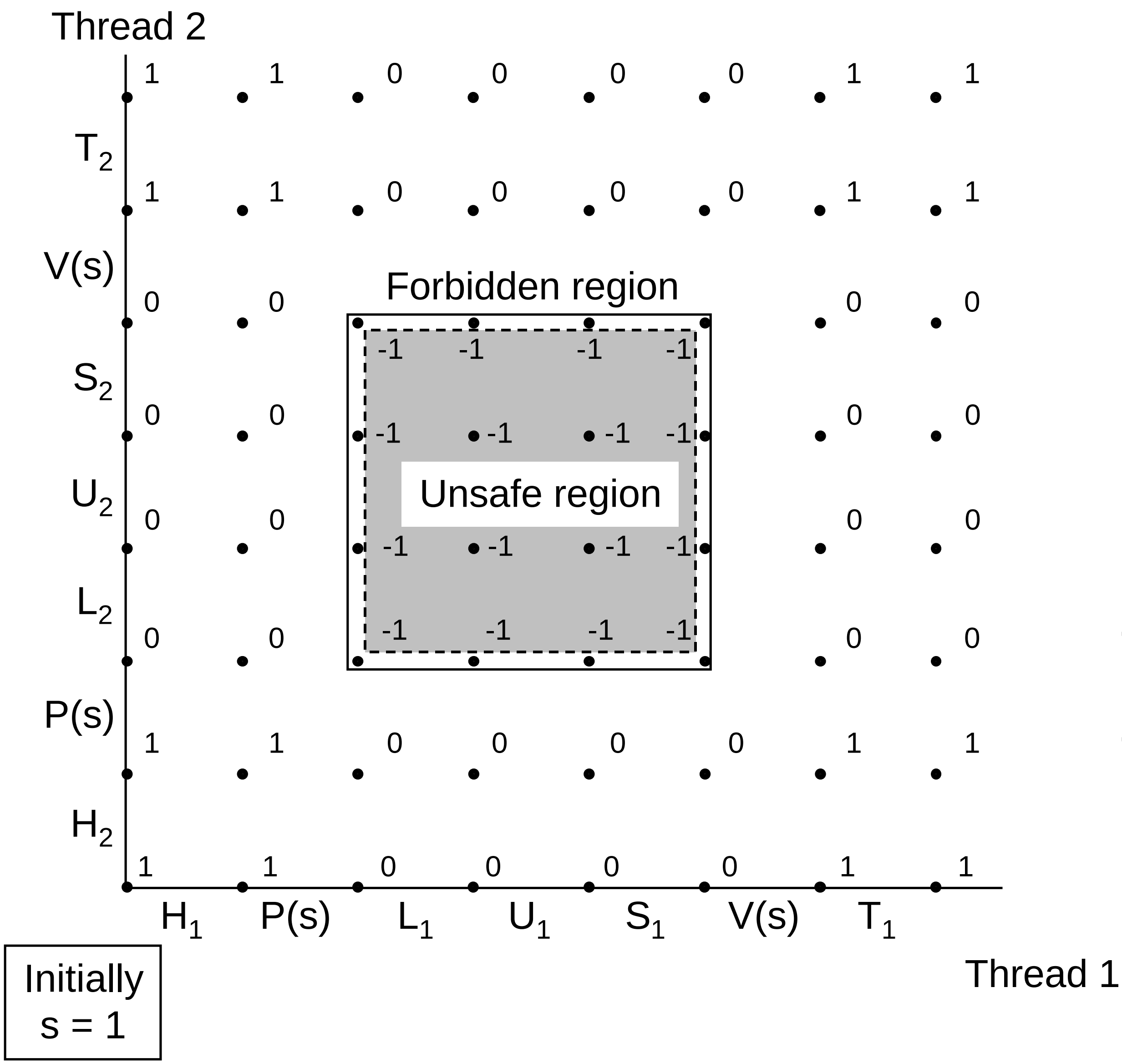
- **We must *synchronize* the threads so that they never enter an unsafe state.**

***Classic solution*****: Dijkstra's P and V operations on *semaphores.***

- ***semaphore:*** **non-negative integer synchronization variable.**
  - P(s): [ `while (s == 0) wait(); s--;` ]
    - » Dutch for "Proberen" (test)
  - V(s): [ `s++;` ]
    - » Dutch for "Verhogen" (increment)
- **OS 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)***

# Safe sharing with semaphores




**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 is never touched by any trajectory.**

# POSIX semaphores

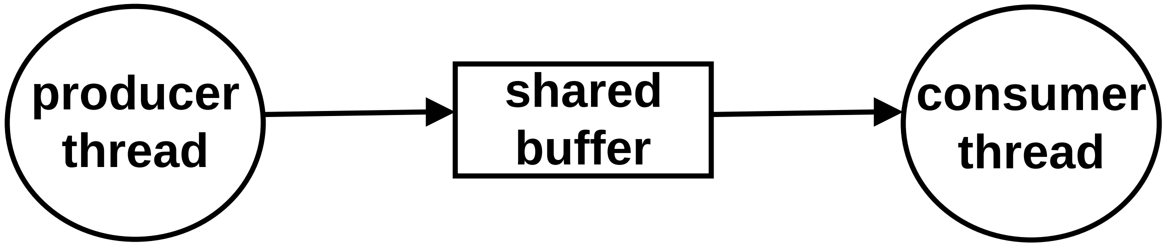
```
/* initialize semaphore sem to value */
/* pshared=0 if thread, pshared=1 if process */
void Sem_init(sem_t *sem, int pshared, unsigned int value) {
  if (sem_init(sem, pshared, value) < 0)
    unix_error("Sem_init");
}

/* P operation on semaphore sem */
void P(sem_t *sem) {
  if (sem_wait(sem))
    unix_error("P");
}

/* V operation on semaphore sem */
void V(sem_t *sem) {
  if (sem_post(sem))
    unix_error("V");
}
```

# Sharing with POSIX semaphores

```
/* goodcnt.c - properly sync'd
counter program */
#include "csapp.h"
#define NITERS 10000000

unsigned int cnt; /* counter */
sem_t sem;        /* semaphore */

int main() {
    pthread_t tid1, tid2;

    Sem_init(&sem, 0, 1);

    /* create 2 threads and wait */
    ...

   if (cnt != (unsigned)NITERS*2)
        printf("BOOM! cnt=%d\n", cnt);
    else
        printf("OK cnt=%d\n", cnt);
    exit(0);
}
```

```
/* thread routine */
void *count(void *arg)
{
    int i;

    for (i=0; i<NITERS; i++) {
        P(&sem);
        cnt++;
        V(&sem);
    }
    return NULL;
}
```

# Signaling with semaphores




## Common synchronization pattern:

- **Producer waits for slot, inserts item in buffer, and "*signals*" consumer.**
- **Consumer waits for item, removes it from buffer, and "signals" producer.**
  - "signals" in this context has nothing to do with Unix signals

## Examples

- **Multimedia processing:**
  - Producer creates MPEG video frames, consumer renders the frames
- **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 (1-buffer)

```c
/* buf1.c - producer-consumer
on 1-element buffer */
#include "csapp.h"

#define NITERS 5

void *producer(void *arg);
void *consumer(void *arg);

struct {
  int buf; /* shared var */
  sem_t full; /* sems */
  sem_t empty;
} shared;
```

```c
int main() {
  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);

  exit(0);
}
```

# Producer-consumer (cont)

**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;
}
```

# Limitations of semaphores

**Semaphores are sound and fundamental, but they have limitations.**

- **Difficult to broadcast a signal to a group of threads.**
  - e.g., *barrier synchronization:* no thread returns from the barrier function until every other thread has called the barrier function.
- **Impossible to do timeout waiting.**
  - e.g., wait for at most 1 second for a condition to become true.

**For these we must use Pthreads *mutex* and *condition variables.***

# Synchronizing with mutex and condition variables

**Semaphores can be used for two different kinds of synchronization:**

- **Safe sharing (e.g. `goodcnt.c`) and**
- **Signaling (e.g. `prodcons.c`).**

**Pthreads interface provides two different mechanisms for these functions:**

- **Safe sharing: operations on mutexes.**
- **Signaling: operations on condition variables**
  - discussed in text

# Basic operations on mutex variables

```
int pthread_mutex_init(pthread_mutex_t *mutex,
                       pthread_mutexattr_t *attr)
```

**Initializes a mutex variable (`mutex`) with some attributes (`attr`).**

- **attributes are usually NULL.**
- **like initializing a mutex semaphore to 1.**

```
int pthread_mutex_lock(pthread_mutex_t *mutex)
```

**Indivisibly waits for `mutex` to be unlocked and then locks it.**

- **like `P(mutex)`**

```
int pthread_mutex_unlock(pthread_mutex_t *mutex)
```

**Unlocks `mutex`.**

- **like `V(mutex)`**

# Thread-safe functions

Functions called from a thread must be ***thread-safe.***

**We identify four (non-disjoint) classes of thread-unsafe functions:**

- **Class 1: Failing to protect shared variables.**
- **Class 2: Relying on persistent state across invocations.**
- **Class 3: Returning a pointer to a static variable.**
- **Class 4: Calling thread-unsafe functions.**

# Thread-unsafe functions

## Class 1: Failing to protect shared variables.

- Fix: use Pthreads lock/unlock functions or P/V operations.
- Issue: synchronization operations will slow down code.
- Example: `goodcnt.c`

# Thread-safe functions (cont)

## Class 2: Relying on persistent state across multiple function invocations.

- The `my_read()` function called by `readline()` buffers input in a `static` array.

```
static ssize_t
my_read(int fd, char *ptr)
{
    static int read_cnt = 0;
    static char *read_ptr,
    static char *read_buf[MAXLINE];
    ...
}
```

- Fix: Rewrite function so that caller passes in all necessary state.

```
static ssize_t
my_read_r(Rline *rptr, char *ptr)
{
   ...
}
```

# Thread-safe functions (cont)

## Class 3: Returning a pointer to a `static` variable.

- **Fixes:**
  - **1. Rewrite so caller passes pointer to `struct`.**
    - » **Issue: Requires changes in caller and callee.**
  - **2. "Lock-and-copy"**
    - » **Issue: Requires only simple changes in caller (and none in callee)**
    - » **However, caller must free memory.**

```
struct hostent
*gethostbyname(char name)
{
  static struct hostent h;
  <contact DNS and fill in h>
  return &h;
}
```

```
hostp = Malloc(...));
gethostbyname1_r(name, hostp);
```

```
struct hostent
*gethostbyname_ts(char *name)
{
  struct hostent *q = Malloc(...);
  Pthread_mutex_lock(&mutex);
  p = gethostbyname(name);
  *q = *p;
  Pthread_mutex_unlock(&mutex);
  return q;
}
```

# Thread-safe functions

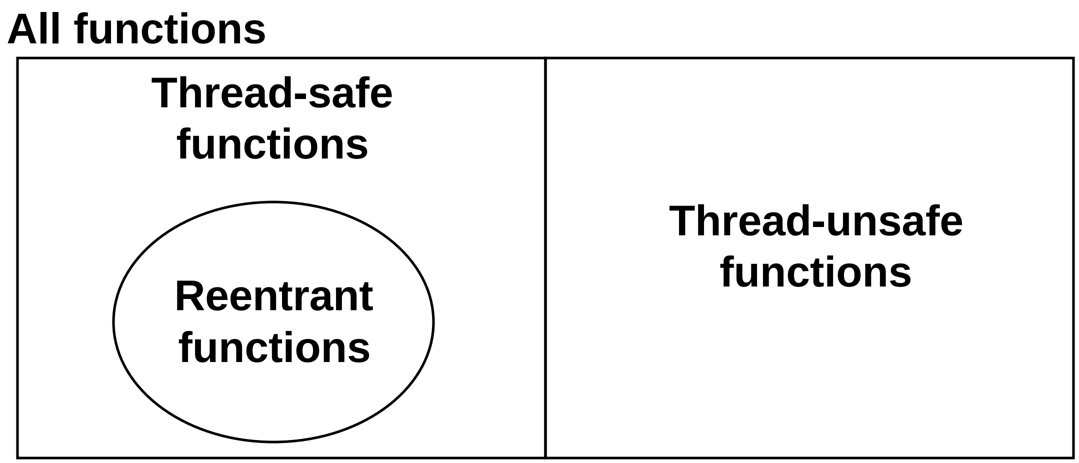
## Class 4: Calling thread-unsafe functions.

- Calling one thread-unsafe function makes an entire function thread-unsafe.
  - Since `readline()` calls the thread-unsafe `my_read()` function, it is also thread_unsafe.
- Fix: Modify the function so it calls only thread-safe functions
  - Example: `readline_r()` is a thread-safe version of `readline()` that calls the thread-safe `my_read_r()` function.

# Reentrant functions

## A function is *reentrant* iff it accesses NO shared variables when called from multiple threads.

- **Reentrant functions are a proper subset of the set of thread-safe functions.**




- **NOTE: The fixes to Class 2 and 3 thread-unsafe functions require modifying the function to make it reentrant.**

# Thread-safe library functions

All functions in the Standard C Library (at the back of your K&R text) are thread-safe.

Most Unix system calls are thread-safe, with a few exceptions:

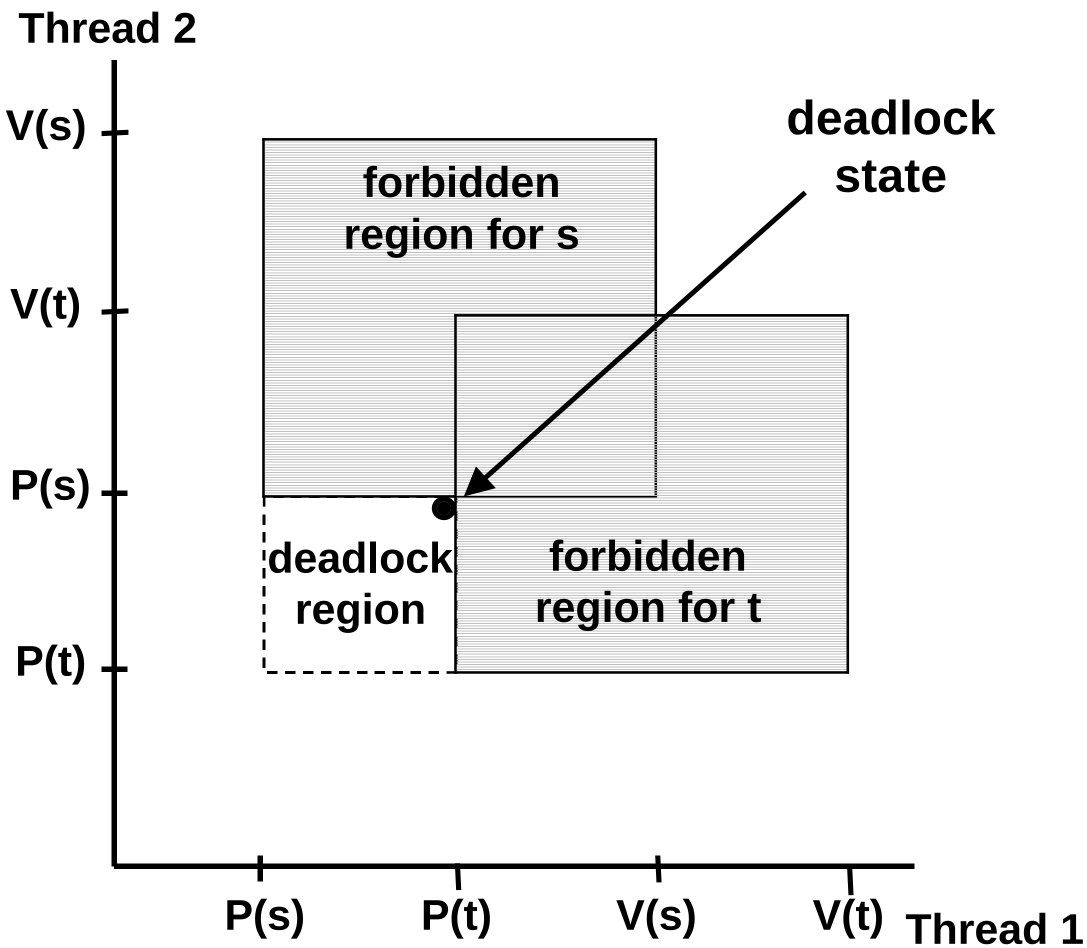
| Thread-unsafe function | Class | Reentrant version |
|---|---|---|
| `asctime` | 3 | `asctime_r` |
| `ctime` | 3 | `ctime_r` |
| `gethostbyaddr` | 3 | `gethostbyaddr_r` |
| `gethostbyname` | 3 | `gethostbyname_r` |
| `inet_ntoa` | 3 | `(none)` |
| `localtime` | 3 | `localtime_r` |
| `rand` | 2 | `rand_r` |

# Races

**A *race* occurs when the correctness of the program depends on one thread reaching point x before another thread reaches point y.**

```
/* a threaded program with a race */
int main() {
    pthread_t tid[N];
    int i;
    for (i = 0; i < N; i++)
        Pthread_create(&tid[i], NULL, thread, &i);
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    exit(0);
}

/* thread routine */
void *thread(void *vargp) {
    int myid = *((int *)vargp);
    printf("Hello from thread %d\n", myid);
    return NULL;
}
```

# Deadlock




**Initially, s=t=1**

**Locking introduces the potential for *deadlock:* waiting for a condition that will never be true.**

**Any trajectory that enters the *deadlock region* will eventually reach the *deadlock state*, waiting for either s or t to become nonzero.**

**Other trajectories luck out and skirt the deadlock region.**

***Unfortunate fact:* deadlock is often non-deterministic.**

# Threads summary

**Threads provide another mechanism for writing concurrent programs.**

**Threads are growing in popularity**

- **Somewhat cheaper than processes.**
- **Easy to share data between threads.**

**However, the ease of sharing has a cost:**

- **Easy to introduce subtle synchronization errors.**
- **Tread carefully with threads!**

**For more info:**

- **D. Butenhof, “Programming with Posix Threads”, Addison-Wesley, 1997.**