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Synchronization: Advanced

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15-213/18-213/14-513/15-513/18-613:

Introduction to Computer Systems

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26th Lecture, Nov. 21, 2019

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Reminder: Semaphores

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

- **Manipulated by *P* and *V* operations:**
  - *P(s):* [`while (s == 0); s--;`]
    - Dutch for "Proberen" (test)
  - *V(s):* [`s++;`]
    - Dutch for "Verhogen" (increment)

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- **OS kernel guarantees that operations between brackets [ ] are executed atomically**
    - 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)***

Review: Using semaphores to protect shared resources via mutual exclusion

- **Basic idea:**
  - Associate a unique semaphore *mutex*, initially 1, with each shared variable (or related set of shared variables)
  - Surround each access to the shared variable(s) with *P(mutex)* and *V(mutex)* operations

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```
mutex = 1

P(mutex)
cnt++
V(mutex)
```

Review: Using Lock for Mutual Exclusion

- **Basic idea:**
  - Mutex is special case of semaphore that only has value 0 (locked) or 1 (unlocked)
  - *Lock(m):* [`while (m == 0); m=0;`]
  - *Unlock(m):* [`m=1`]
- **~2x faster than using semaphore for this purpose**
  - And, more clearly indicates programmer's intention

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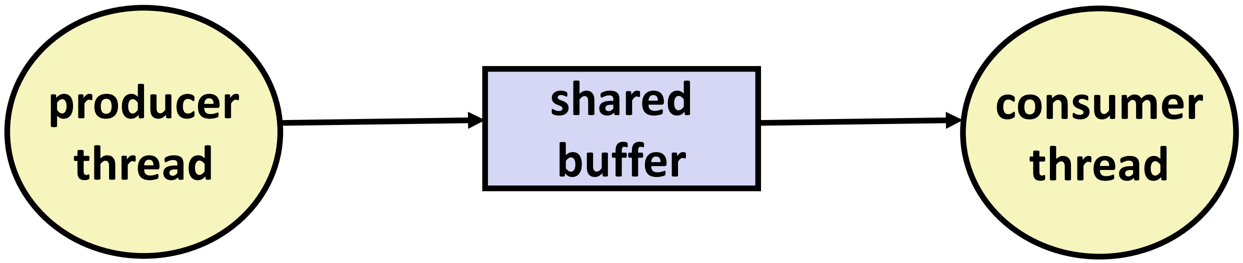
```
mutex = 1

lock(mutex)
cnt++
unlock(mutex)
```

Review: Producer-Consumer Problem



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- **Common synchronization pattern:**
  - Producer waits for empty *slot*, inserts item in buffer, and notifies consumer
  - Consumer waits for ***item***, removes it from buffer, and notifies producer
- **Examples**
  - Multimedia processing:
    - Producer creates video frames, consumer renders them
  - Event-driven graphical user interfaces
    - Producer detects mouse clicks, mouse movements, and keyboard hits and inserts corresponding events in buffer
    - Consumer retrieves events from buffer and paints the display

Review: Using Semaphores to Coordinate Access to Shared Resources

- **Basic idea: Thread uses a semaphore operation to notify another thread that some condition has become true**
  - Use counting semaphores to keep track of resource state.
  - Use binary semaphores to notify other threads.

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- **The Producer-Consumer Problem**
  - Mediating interactions between processes that generate information and that then make use of that information
  - Single entry buffer implemented with two binary semaphores
    - One to control access by producer(s)
    - One to control access by consumer(s)
  - N-entry implemented with semaphores + circular buffer

Today

- **Using semaphores to schedule shared resources**
  - **Readers-writers problem**
- **Other concurrency issues**
  - Thread safety
  - Races
  - Deadlocks
  - Interactions between threads and signal handling

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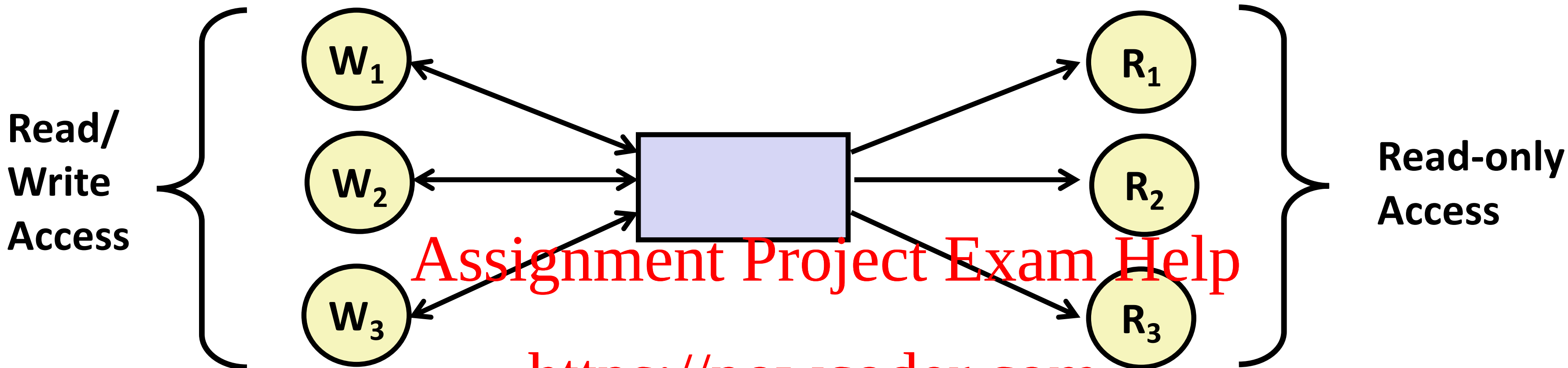
Readers-Writers Problem



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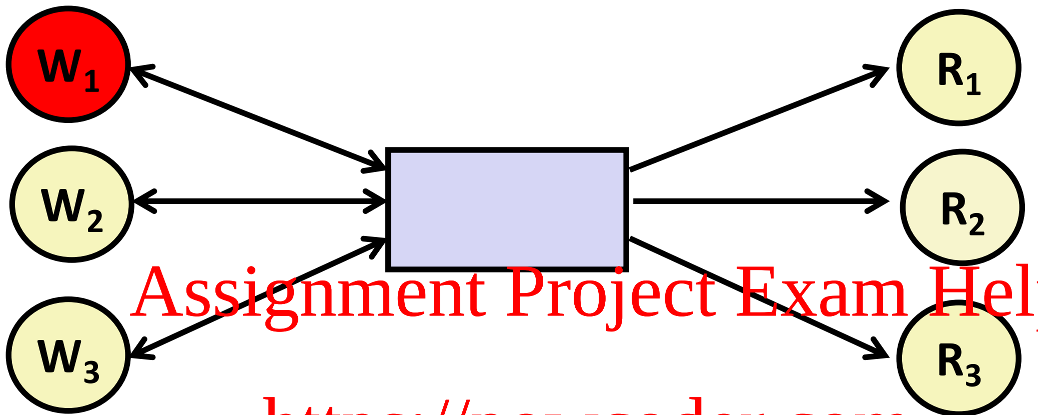
- **Problem statement:**
  - *Reader* threads only read the object
  - *Writer* threads modify the object (read/write access)
  - Writers must have exclusive access to the object
  - Unlimited number of readers can access the object
- **Occurs frequently in real systems, e.g.,**
  - Online airline reservation system
  - Multithreaded caching Web proxy

Readers/Writers Examples



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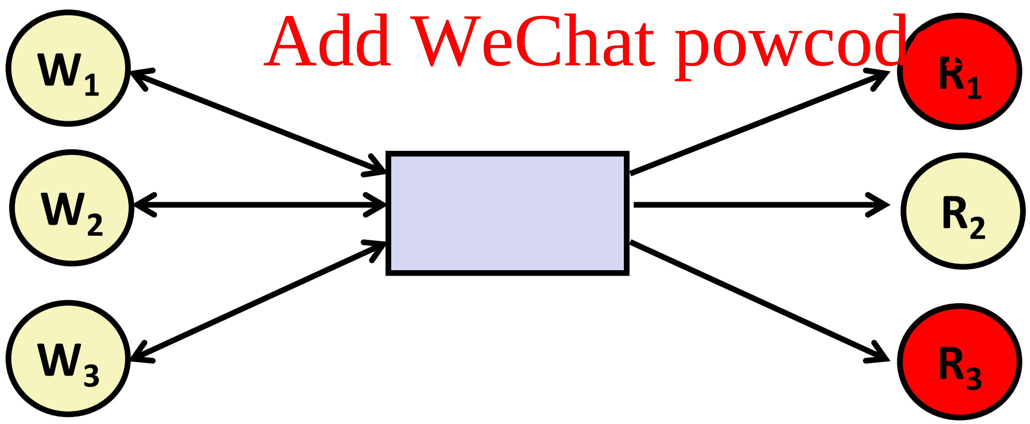

Variants of Readers-Writers

- ***First readers-writers problem*** **(favors readers)**
  - No reader should be kept waiting unless a writer has already been granted permission to use the object.
  - A reader that arrives after a waiting writer gets priority over the writer.

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- ***Second readers-writers problem*** **(favors writers)**

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  - Once a writer is ready to write, it performs its write as soon as possible
  - A reader that arrives after a writer must wait, even if the writer is also waiting.

- ***Starvation*** **(where a thread waits indefinitely) is possible in both cases.**

Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

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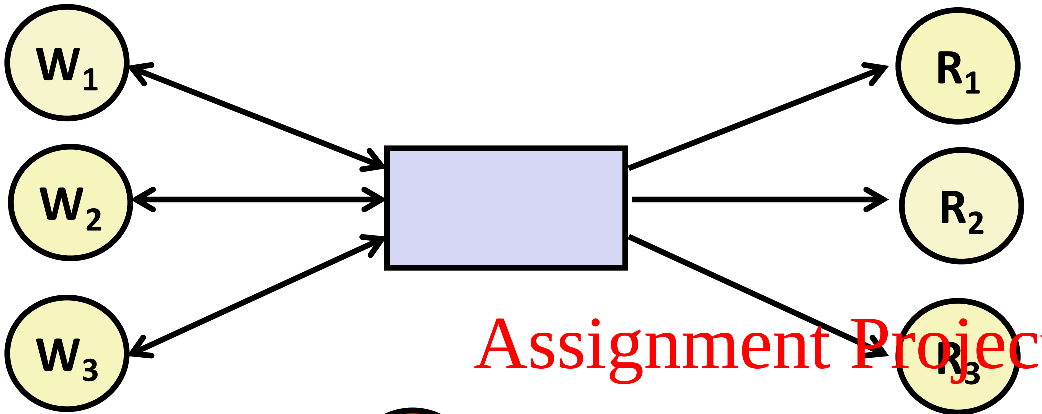
Readers/Writers Examples



w = 1
readcnt = 0

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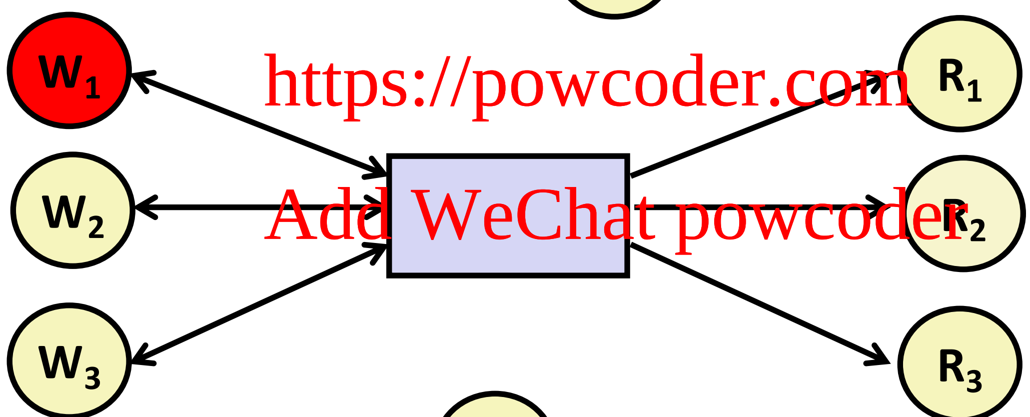
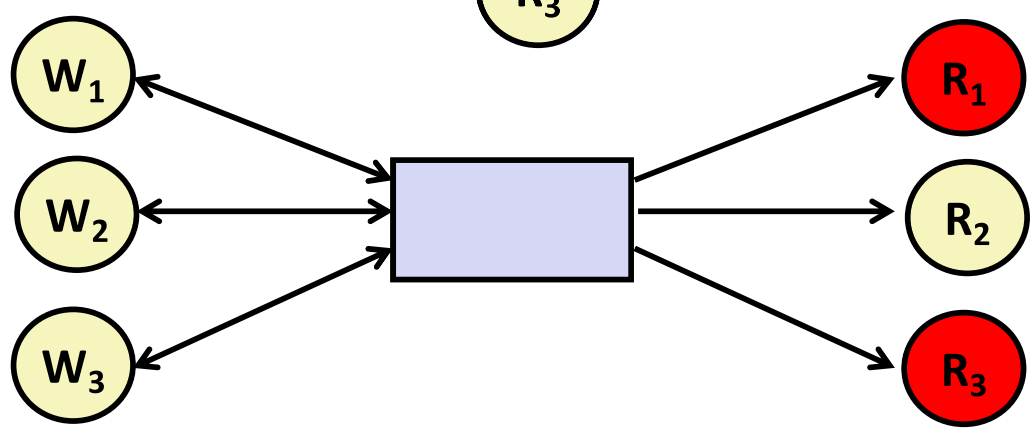


w = 0
readcnt = 0

w = 0
readcnt = 2



Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

Arrivals: R1 R2 W1 R3

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Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

R1

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

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Arrivals: R1 R2 W1 R3

Readcnt == 1
W == 0

Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

R2 → `if (readcnt == 1)`

R1 → `/* Reading happens here */`

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

Arrivals: R1 R2 W1 R3

Readcnt == 2
W == 0

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Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

R2

R1

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

W1

rw1.c

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Arrivals: R1 R2 W1 R3

Readcnt == 2
W == 0

Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

R2

R1

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

W1

rw1.c

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Arrivals: R1 R2 W1 R3

Readcnt == 1
W == 0

Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

R3

R2

R1

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

W1

rw1.c

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Arrivals: R1 R2 W1 R3

Readcnt == 2
W == 0

Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

R3 ->
    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
R2 ->
    V(&mutex);
  }
}
```

Writers:

```
void writer(void)
{
  while (1) {    <- W1
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

Arrivals: R1 R2 W1 R3

Readcnt == 1
W == 0

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Solution to First Readers-Writers Problem

Readers:

```
int readcnt;    /* Initially 0 */
sem_t mutex, w; /* Both initially 1 */

void reader(void)
{
  while (1) {
    P(&mutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&mutex);

    /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
  }
}
```

R3

Writers:

```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

W1

rw1.c

Arrivals: R1 R2 W1 R3

Readcnt == 0
W == 1

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Other Versions of Readers-Writers

- **Shortcoming of first solution**
  - Continuous stream of readers will block writers indefinitely
- **Second version**
  - Once writer comes along, blocks access to later readers
  - Series of writes could block all reads
- **FIFO implementation**
  - See rwqueue code in code directory
  - Service requests in order received
  - Threads kept in FIFO
  - Each has semaphore that enables its access to critical section

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Solution to Second Readers-Writers Problem

```
int readcnt, writecnt;      // Initially 0
sem_t rmutex, wmutex, r, w; // Initially 1
void reader(void)
{
  while (1) {
    P(&r);
    P(&rmutex);
    readcnt++;
    if (readcnt == 1) /* First in */
      P(&w);
    V(&rmutex);
    V(&r)

    /* Reading happens here */

    P(&rmutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&rmutex);
  }
}
```

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Solution to Second Readers-Writers Problem

```
void writer(void)
{
  while (1) {
    P(&wmutex);
    writecnt++;
    if (writecnt == 1)
        P(&r);
    V(&wmutex);

    P(&w);
    /* Writing here */
    V(&w);

    P(&wmutex);
    writecnt--;
    if (writecnt == 0);
        V(&r);
    V(&wmutex);
  }
}
```

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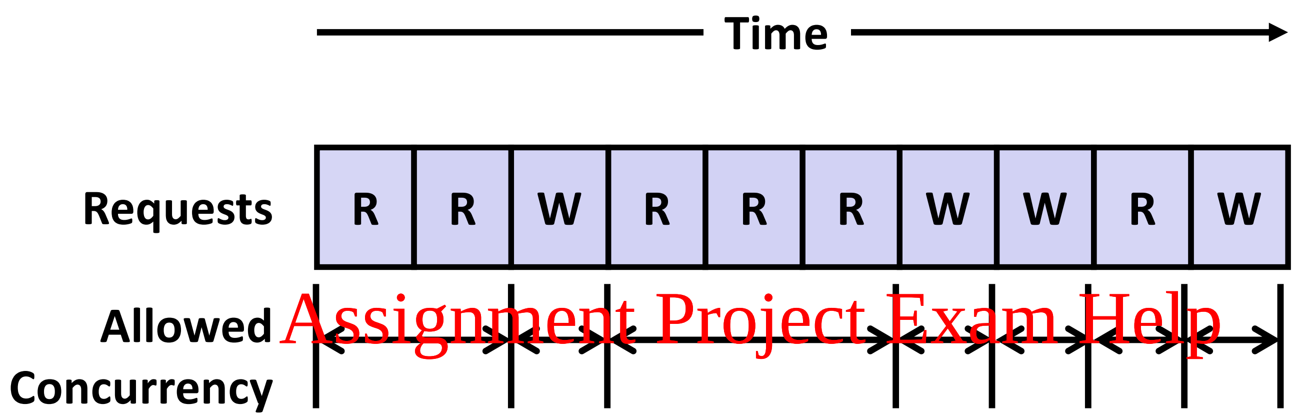
Managing Readers/Writers with FIFO



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- **Idea**
  - Read & Write requests are inserted into FIFO
  - Requests handled as remove from FIFO
    - Read allowed to proceed if currently idle or processing read
    - Write allowed to proceed only when idle
  - Requests inform controller when they have completed
- **Fairness**
  - Guarantee very request is eventually handled

Readers Writers FIFO Implementation

- Full code in rwqueue.{h,c}

```
/* Queue data structure */
typedef struct {
    sem_t mutex;     // Mutual exclusion
    int reading_count;    // Number of active readers
    int writing_count;    // Number of active writers
    // FIFO queue implemented as linked list with tail
    rw_token_t *head;
    rw_token_t *tail;
} rw_queue_t;
```

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```
/* Represents individual thread's position in queue */
typedef struct TOK {
    bool is_reader;
    sem_t enable;        // Enables access
    struct TOK *next;    // Allows chaining as linked list
} rw_token_t;
```

Readers Writers FIFO Use

- In rwqueue-test.c

```
/* Get write access to data and write */
void iwriter(int *buf, int v)
{
    rw_token_t tok;
    rw_queue_request_write(&q, &tok);
    /* Critical section */
    *buf = v;
    /* End of Critical Section  */
    rw_queue_release(&q);
}
```

```
/* Get read access to data and read */
int ireader(int *buf)
{
    rw_token_t tok;
    rw_queue_request_read(&q, &tok);
    /* Critical section */
    int v = *buf;
    /* End of Critical section */
    rw_queue_release(&q);
    return v;
}
```

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Library Reader/Writer Lock

- **Data type `pthread_rwlock_t`**
- **Operations**
  - Acquire read lock

```
Pthread_rwlock_rdlock(pthread_rw_lock_t *rwlock)
```

  - Acquire write lock

```
Pthread_rwlock_wrlock(pthread_rw_lock_t *rwlock)
```

  - Release (either) lock

```
Pthread_rwlock_unlock(pthread_rw_lock_t *rwlock)
```

- **Observation**
  - Library must be used correctly!
    - Up to programmer to decide what requires read access and what requires write access

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Today

- **Using semaphores to schedule shared resources**
  - Readers-writers problem
- **Other concurrency issues**
  - **Races**
  - Deadlocks
  - Thread safety
  - Interactions between threads and signal handling

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One Worry: Races

- A *race* occurs when 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(int argc, char** argv) {
    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);
    return 0;
}

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

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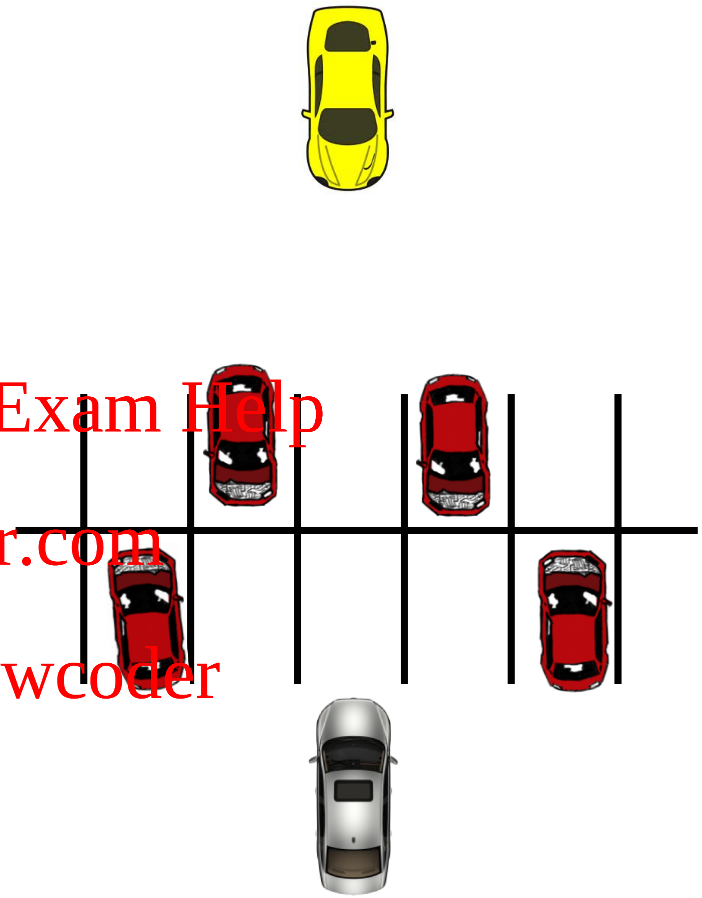
race.c

Data Race



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Race Elimination

- **Don't share state**
  - E.g., use malloc to generate separate copy of argument for each thread
- **Use synchronization primitives to control access to shared state**

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norace.c

Today

- **Using semaphores to schedule shared resources**
  - Producer-consumer problem
- **Other concurrency issues**
  - **Races**
  - **Deadlocks**
  - Thread safety
  - Interactions between threads and signal handling

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A Worry: Deadlock

- **Def: A process is *deadlocked* iff it is waiting for a condition that will never be true.**

- **Typical Scenario**
  - Processes 1 and 2 needs two resources (A and B) to proceed
  - Process 1 acquires A, waits for B
  - Process 2 acquires B, waits for A
  - Both will wait forever!

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Deadlocking With Semaphores

```
int main(int argc, char** argv)
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    return 0;
}
```

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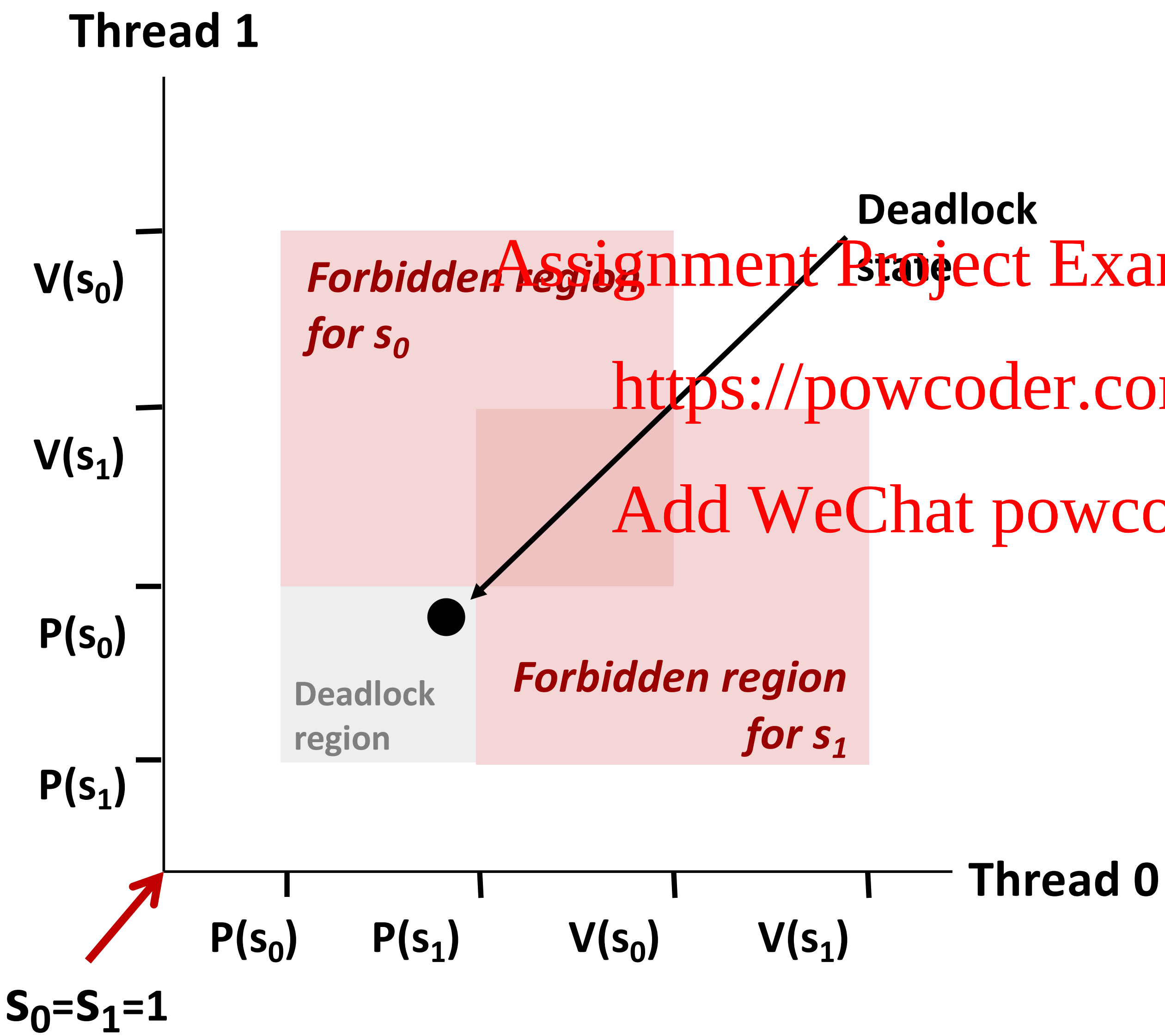
```
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[id]); P(&mutex[1-id]);
        cnt++;
        V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

Tid[0]:	Tid[1]:
P(s_0);	P(s_1);
P(s_1);	P(s_0);
cnt++;	cnt++;
V(s_0);	V(s_1);
V(s_1);	V(s_0);

Deadlock Visualized in Progress Graph



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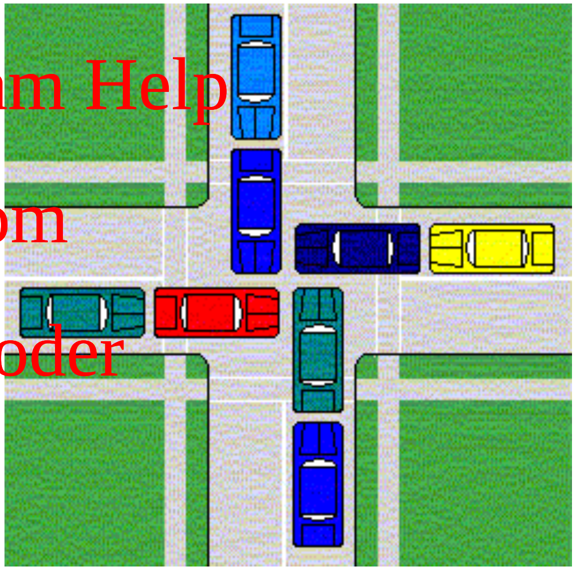
Locking introduces the potential for ***deadlock:*** waiting for a condition that will never be true

Any trajectory that enters the ***deadlock region*** will eventually reach the ***deadlock state***, waiting for either S_0 or S_1 to become nonzero

Other trajectories luck out and skirt the deadlock region

Unfortunate fact: deadlock is often nondeterministic (race)

Deadlock



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Avoiding Deadlock

Acquire shared resources in same order

```
int main(int argc, char** argv)
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    return 0;
}
```

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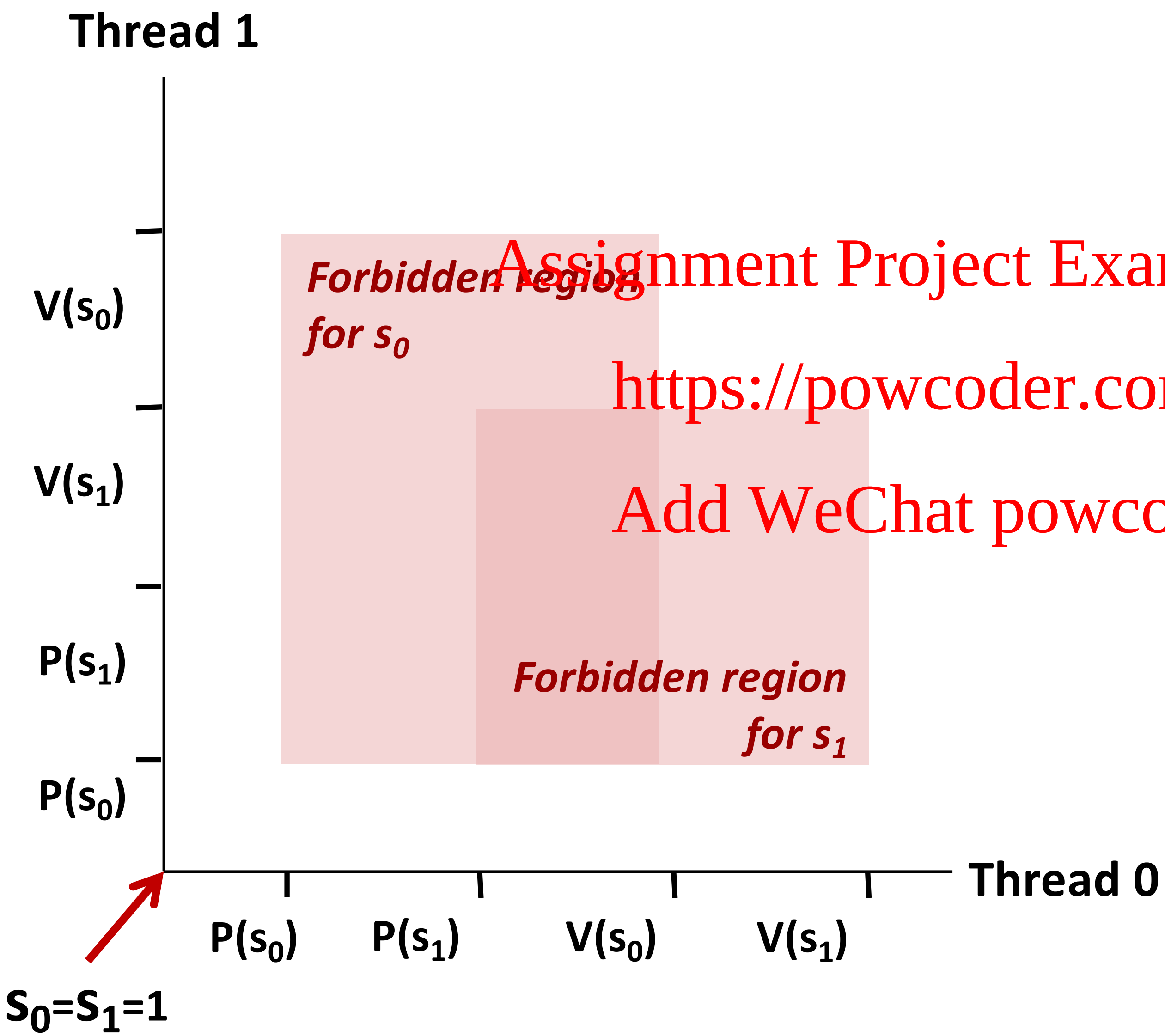
```
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[0]); P(&mutex[1]);
        cnt++;
        V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

Tid[0]:	Tid[1]:
$P(s_0)$;	$P(s_0)$;
$P(s_1)$;	$P(s_1)$;
cnt++;	cnt++;
$V(s_0)$;	$V(s_1)$;
$V(s_1)$;	$V(s_0)$;

Avoided Deadlock in Progress Graph



No way for trajectory to get stuck

Processes acquire locks in same order

Order in which locks released immaterial

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Demonstration

- **See program deadlock.c**
- **100 threads, each acquiring same two locks**
- **Risky mode**
  - Even numbered threads request locks in opposite order of odd-numbered ones

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- **Safe mode**
  - All threads acquire locks in same order

Quiz Time!

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Check out:

https://canvas.cmu.edu/courses/10968

Today

- **Using semaphores to schedule shared resources**
  - Readers-writers problem
- **Other concurrency issues**
  - **Races**
  - **Deadlocks**
  - **Thread safety**
  - Interactions between threads and signal handling

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Crucial concept: Thread Safety

- **Functions called from a thread must be *thread-safe***
- ***Def:* A function is *thread-safe* iff it will always produce correct results when called repeatedly from multiple concurrent threads.**

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- **Classes of thread-unsafe functions:**
  - Class 1: Functions that do not protect shared variables
  - Class 2: Functions that keep state across multiple invocations
  - Class 3: Functions that return a pointer to a static variable
  - Class 4: Functions that call thread-unsafe functions

Thread-Unsafe Functions (Class 1)

- **Failing to protect shared variables**
  - Fix: Use *P* and *V* semaphore operations (or mutex)
  - Example: `goodcnt.c`
  - Issue: Synchronization operations will slow down code

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Thread-Unsafe Functions (Class 2)

- **Relying on persistent state across multiple function invocations**
  - Example: Random number generator that relies on static state

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```
static unsigned int next = 1;

/* rand: return pseudo-random integer on 0..32767 */
int rand(void)
{
    next = next*1103515245 + 12345;
    return (unsigned int)(next/65536) % 32768;
}

/* srand: set seed for rand() */
void srand(unsigned int seed)
{
    next = seed;
}
```

Thread-Safe Random Number Generator

- **Pass state as part of argument**
  - and, thereby, eliminate static state

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```
/* rand_r - return pseudo-random integer on 0..32767 */

int rand_r(int *nextp)
{
    *nextp = *nextp*1103515245 + 12345;
    return (unsigned int)(*nextp/65536) % 32768;
}
```

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- **Consequence: programmer using `rand_r` must maintain seed**

Thread-Unsafe Functions (Class 3)

- **Returning a pointer to a static variable**
- **Fix 1. Rewrite function so caller passes address of variable to store result**
  - Requires changes in caller and callee
- **Fix 2. Lock-and-copy**
  - Requires simple changes in caller (and none in callee)
  - However, caller must free memory.

```
/* Convert integer to string */
char *itoa(int x)
{
    static char buf[11];
    sprintf(buf, "%d", x);
    return buf;
}
```

```
char *lc_itoa(int x, char *dest)
{
    P(&mutex);
    strcpy(dest, itoa(x));
    V(&mutex);
    return dest;
}
```

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Thread-Unsafe Functions (Class 4)

- **Calling thread-unsafe functions**
  - Calling one thread-unsafe function makes the entire function that calls it thread-unsafe
  - Fix: Modify the function so it calls only thread-safe functions ☺

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Reentrant Functions

- **Def: A function is *reentrant* iff it accesses no shared variables when called by multiple threads.**
  - Important subset of thread-safe functions
    - Require no synchronization operations
    - Only way to make a Class 2 function thread-safe is to make it reetnrant (e.g., `rand_r`)

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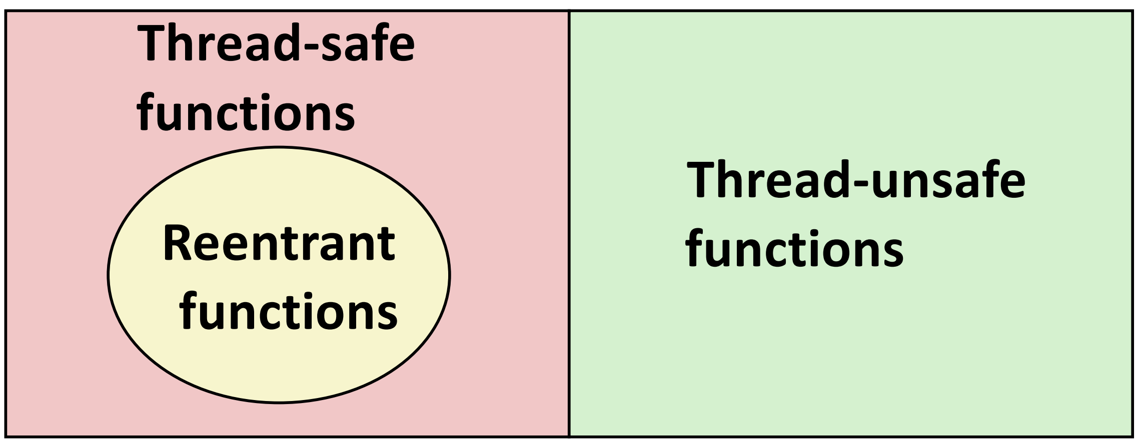
All functions



Thread-Safe Library Functions

- **All functions in the Standard C Library (at the back of your K&R text) are thread-safe**
  - Examples: `malloc`, `free`, `printf`, `scanf`
- **Most Unix system calls are thread-safe, with a few exceptions:**

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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`

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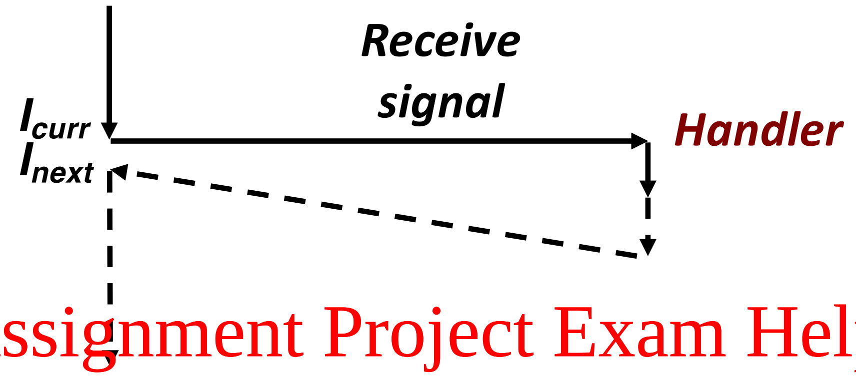
Signal Handling Review



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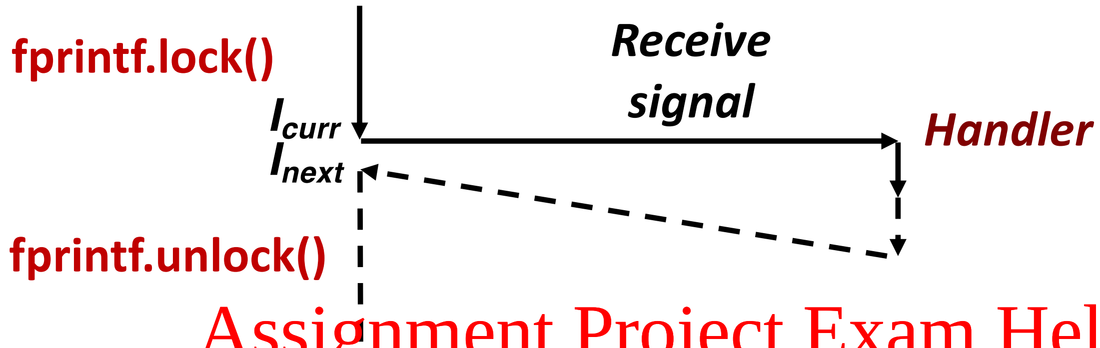
- **Action**
  - Signal can occur at any point in program execution
    - Unless signal is blocked
  - Signal handler runs within same thread
  - Must run to completion and then return to regular program execution

Threads / Signals Interactions



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- **Many library functions use lock-and-copy for thread safety**
  - Because they have hidden state
  - malloc
    - Free lists
  - fprintf, printf, puts
    - So that outputs from multiple threads don't interleave
  - sprintf
    - Not officially asynch-signal-safe, but seems to be OK
- **OK for handler that doesn't use these library functions**

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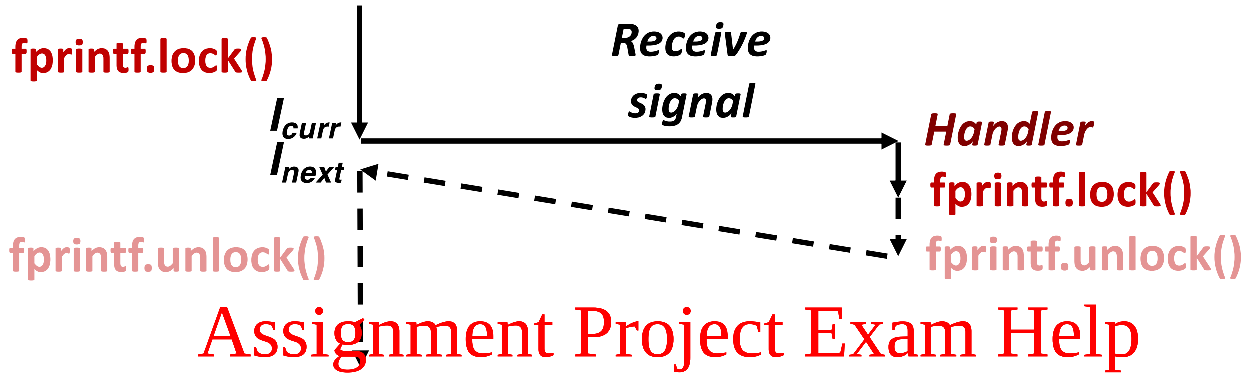
Bad Thread / Signal Interactions



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- **What if:**
  - Signal received while library function holds lock
  - Handler calls same (or related) library function
- **Deadlock!**
  - Signal handler cannot proceed until it gets lock
  - Main program cannot proceed until handler completes
- **Key Point**
  - Threads employ symmetric concurrency
  - Signal handling is asymmetric

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

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