Synchronization: Advanced

15-213/15-513/14-513: Introduction to Computer Systems
24th Lecture, November 26, 2024

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Announcements

- **SFSLab is available this morning**
  - Due Thursday, Dec 5^{th}
  - Only 1 grace / late day
- **All work with extended deadlines is due Friday, Dec 6^{th}**
  - Exceptional circumstances will result in an incomplete grade
- **Final exam Thursday December 12 at 8:30-11:30 am ET**
  - Location to be announced
  - Bring your **CMU ID** and up to two 8.5”x11” / A4 cheat sheets, written or printed
  - Look out for more details and accommodations information on Piazza : https://piazza.com/class/m0bs774647q5s2/post/1198

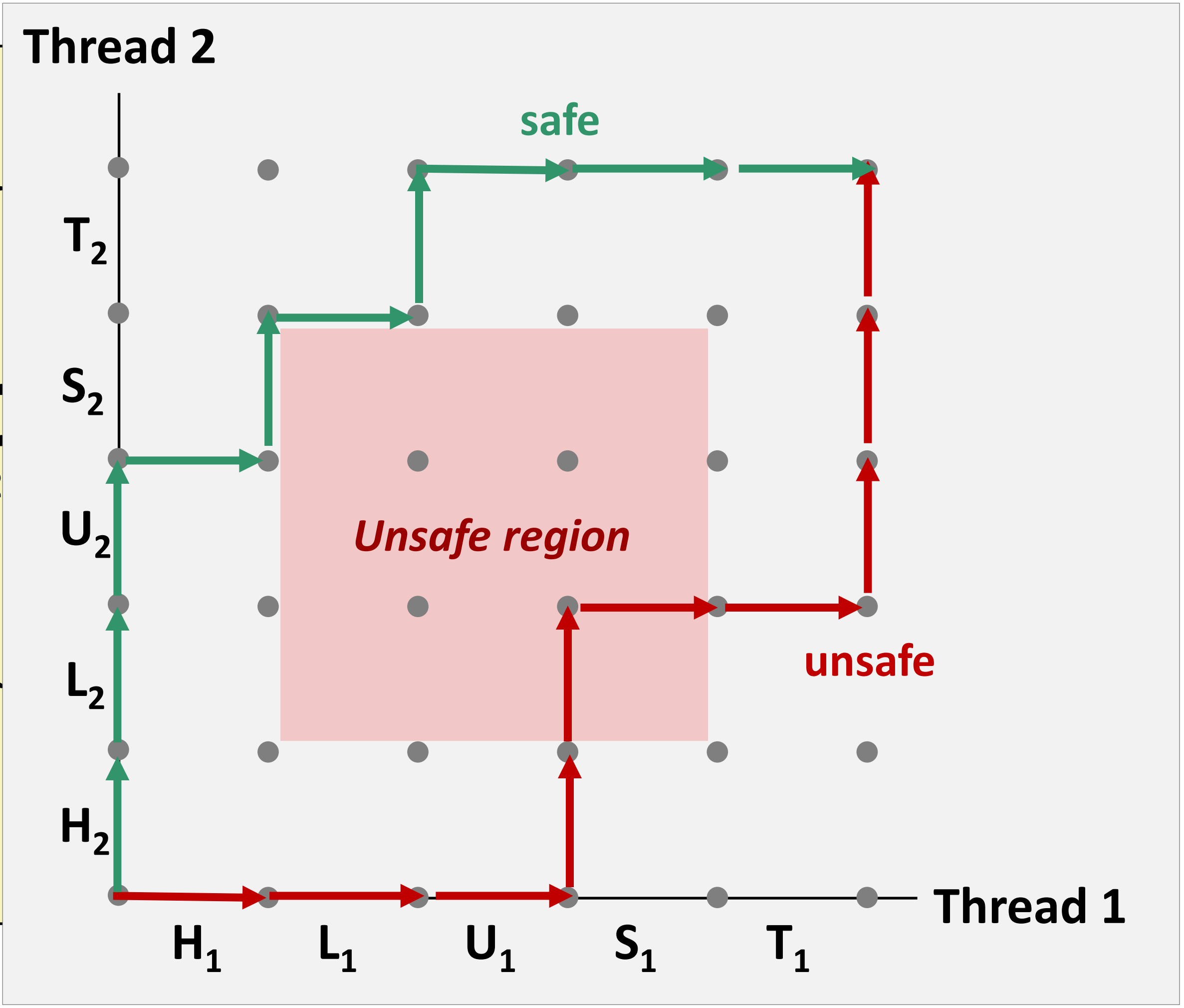
Today

- **Review: Races, Mutual Exclusion**
- Deadlock
- Semaphores, Events, and Queues
- Reader-Writer Locks and Starvation
- Thread-Safe API Design

Races

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

```
int cnt;

int main(int argc, cha
  pthread_t t1, t2;
  Pthread_create(&t1,
  Pthread_create(&t2,
  Pthread_join(t1, NUL
  Pthread_join(t2, NUL
  return (counter != 2
}

/* thread routine */
void *thread(void *var
  for (int i = 0; i <
    cnt++;
  return NULL;
}
```



Races

- Some races can be fixed with mutual exclusion

```
int cnt;
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
int main(int argc, char** argv) {
  pthread_t t1, t2;
  Pthread_create(&t1, NULL, thread, NULL);
  Pthread_create(&t2, NULL, thread, NULL);
  Pthread_join(t1, NULL);
  Pthread_join(t2, NULL);
  return (counter != 20000);
}

void *thread(void *vargp) {
  for (int i = 0; i < 10000; i++) {
    pthread_mutex_lock(&lock);
    cnt++;
    pthread_mutex_unlock(&lock);
  }
  return NULL;
}
```

Races

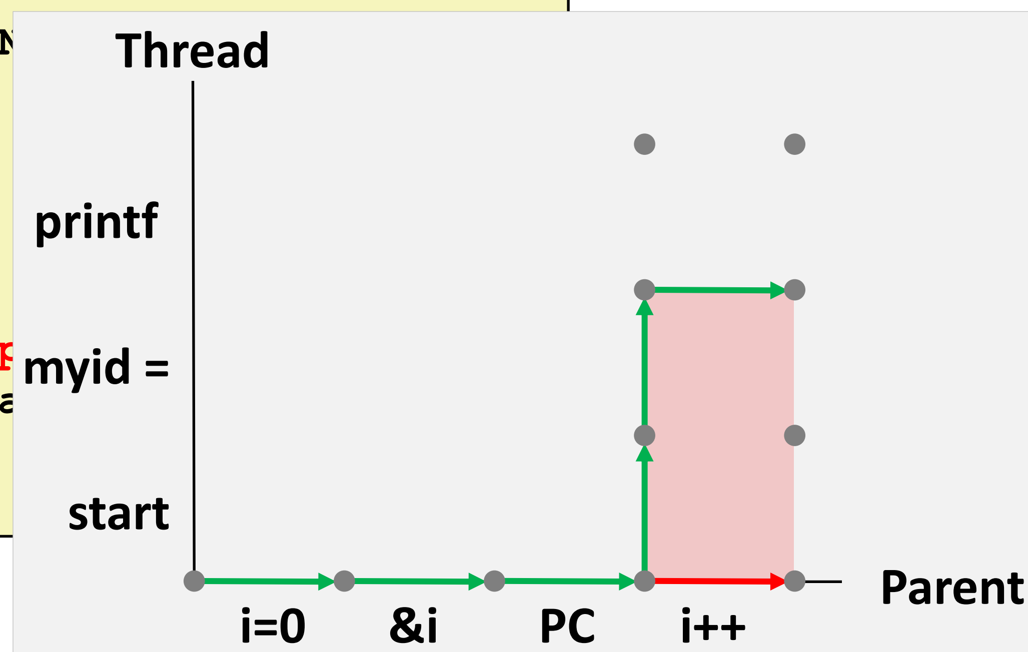
- **Not all races can be addressed with mutual exclusion**

```
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;
}
```

Races

- Not all races can be addressed with mutual exclusion

```
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], N
  return 0;
}

/* thread routine */
void *thread(void *vargp)
  int myid = *(int *)vargp
  printf("Hello from threa
  return NULL;
}
```



Races

- This race can be fixed by copying data

```
int main(int argc, char** argv) {
  pthread_t tid[N];
  int i;
  for (i = 0; i < N; i++)
    Pthread_create(&tid[i], NULL, thread, (void *)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;
}
```

Races

- This race can also be fixed with a semaphore

```
sem_t sem;
int main(int argc, char** argv) {
  pthread_t tid[N];
  int i;
  Sem_init(&sem, 0, 0); // initially closed
  for (i = 0; i < N; i++) {
    Pthread_create(&tid[i], NULL, thread, &i);
    sem_wait(&sem);
  }
  for (i = 0; i < N; i++)
    Pthread_join(tid[i], NULL);
  return 0;
}

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

Not all races involve *threads*

$ rm myfile.txt

- Time of check to time of use (TOCTOU)

```
if (access("myfile.txt", R_OK) == 0) {       ← Check
  FILE *fp = fopen("myfile.txt", "r");       ← Use
  while (fgets(fp, buf, sizeof buf) != NULL)
    process_line(buf);
  fclose(fp);
} else {
  fprintf(stderr, "myfile.txt not found\n");
}
```

- Fix: *Don't check*, just use (but be ready for failure)

```
FILE *fp = fopen("myfile.txt", "r");
if (fp) {
  while (fgets(fp, buf, sizeof buf) != NULL)
    process_line(buf);
  fclose(fp);
} else {
  fprintf(stderr, "myfile.txt: %s\n", strerror(errno));
}
```

Races involving signal handlers

- **Event happens earlier than anticipated**

```
void sigchld_handler(int unused) {
   int status;
   pid_t pid;
   while ((pid = waitpid(-1, &status, WNOHANG|WUNTRACED)) > 0)
     job_status_change(pid, status);
}

void start_fg_job(char **argv) {
  pid_t pid = fork();
  if (pid == -1) {
    perror("fork");
    return;
  } else if (pid == 0) {
    execve(argv[0], argv, environ);
    perror("execve");
    exit(127);
  } else {
    add_job(pid, argv);
  }
}
```

SIGCHLD delivered

Race Elimination

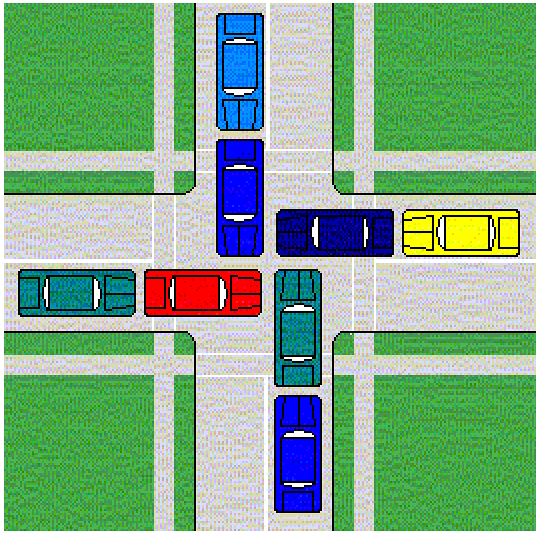
- **Don’t share state**
  - e.g. use malloc to generate separate copy of argument for each thread
- **Don’t check before using**
  - Attempt to use, see if it failed
- **Use synchronization primitives**
  - Which synchronization primitive? Depends on the situation

Today

- Review: Races, Mutual Exclusion
- **Deadlock**
- Semaphores, Events, and Queues
- Reader-Writer Locks and Starvation
- Thread-Safe API Design

Deadlock

- **A program is *deadlocked* when it is waiting for an event which *cannot* ever happen**
  - Mathematical impossibility, not just practical
- **Most common form:**
  - Thread A is waiting for thread B to do something
  - Thread B is waiting for thread A to do something
  - Neither can make forward progress



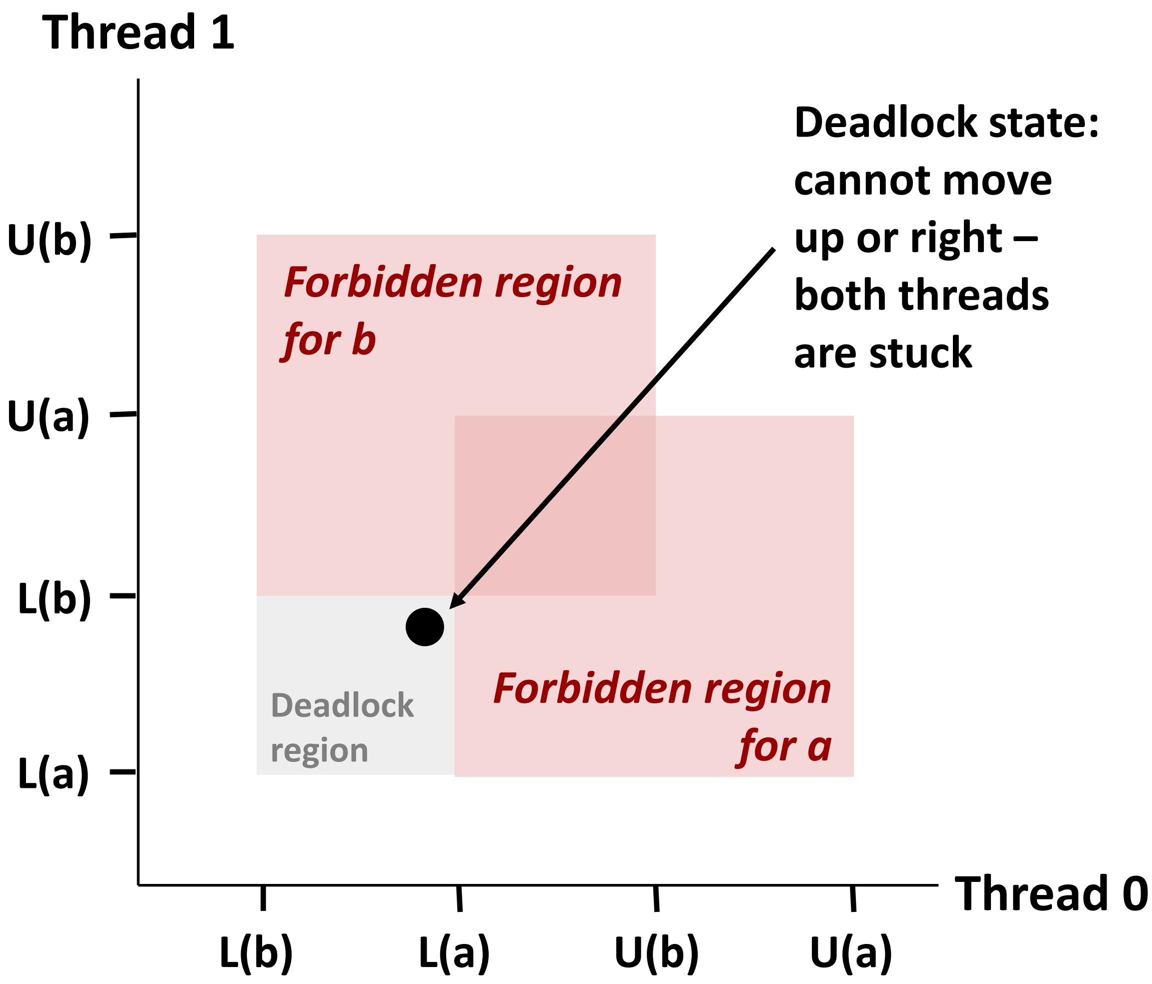
Deadlock caused by wrong locking order

```
void *thread_1(void *arg) {
  pthread_mutex_lock(&mA);
  pthread_mutex_lock(&mB);

  // do stuff ...

  pthread_mutex_unlock(&mA);
  pthread_mutex_unlock(&mB);
}
```

```
void *thread_2(void *arg) {
  pthread_mutex_lock(&mB);
  pthread_mutex_lock(&mA);

  // do stuff ...

  pthread_mutex_unlock(&mB);
  pthread_mutex_unlock(&mA);
}
```

Live coding demo: deadlocks

Deadlock Visualized in Progress Graph



Any trajectory that enters the ***deadlock region*** will eventually reach the ***deadlock state*** where each thread is waiting for the other to release a lock

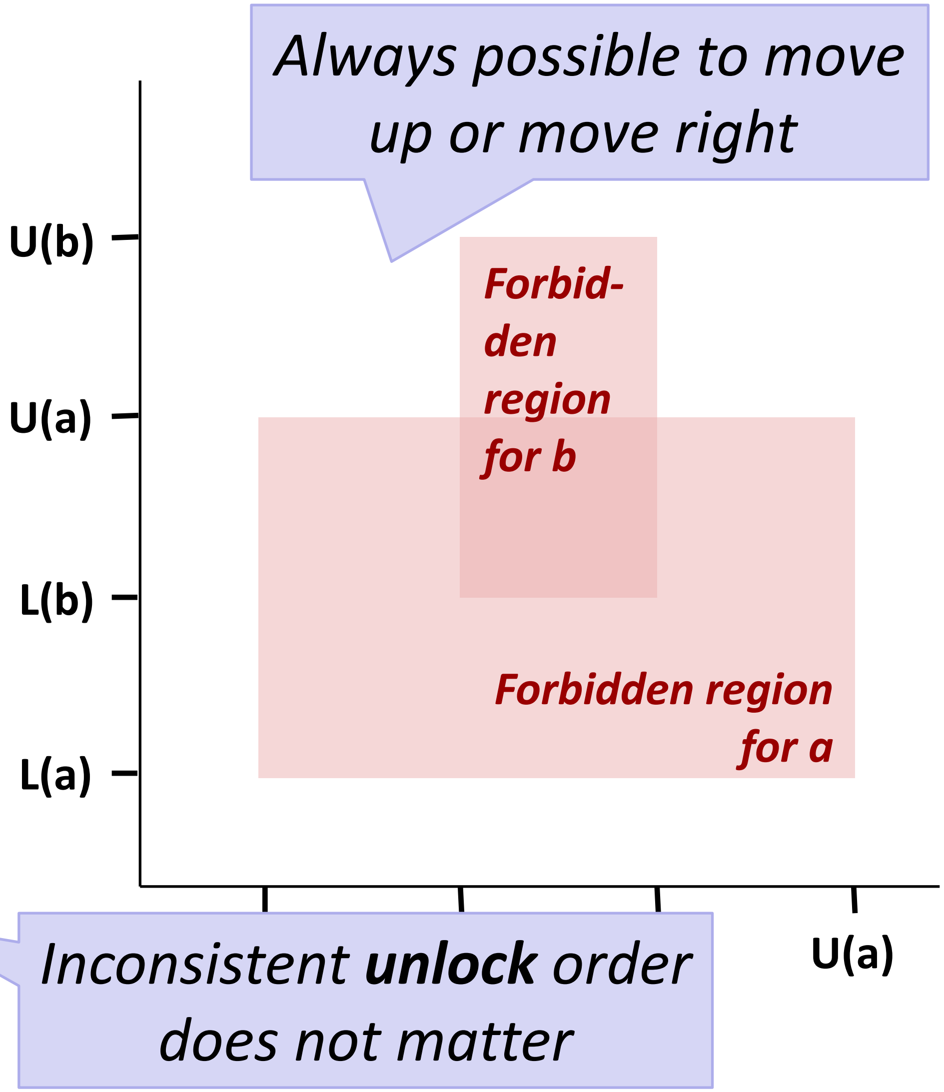
Other trajectories luck out and skirt the deadlock region

Unfortunate fact: trajectory variations may mean deadlock bugs are nondeterministic (don't always manifest, making them hard to debug)

Fix *this* deadlock with consistent ordering

```
void *thread_1(void *arg) {
  pthread_mutex_lock(&mA);
  pthread_mutex_lock(&mB);

  // do stuff ...

  pthread_mutex_unlock(&mA);
  pthread_mutex_unlock(&mB);
}
```

```
void *thread_2(void *arg) {
  pthread_mutex_lock(&mA);
  pthread_mutex_lock(&mB);

  // do stuff ...

  pthread_mutex_unlock(&mB);
  pthread_mutex_unlock(&mA);
}
```



Today

- Review: Races, Mutual Exclusion
- Deadlock
- **Semaphores, Events, and Queues**
- Reader-Writer Locks and Starvation
- Thread-Safe API Design

Recall: Semaphores

- **Integer value, always >= 0**
- **P(s) operation (aka `sem_wait`)**
  - If *s* is zero, wait for a *V* operation to happen.
  - Then subtract 1 from *s* and return.
- **V(s) operation (aka `sem_post`)**
  - Add 1 to *s*.
  - If there are any threads waiting inside a *P* operation, resume one of them
- **Any thread may call P; any thread may call V; no ordering requirements**
  - Key difference from mutexes

Semaphores for Events

- Remember this program from yesterday's quiz?

```
#define N 4
long *pointers[N];

void *thread(void *vargp) {
  long myid = (long) vargp;
  pointers[myid] = &myid;
  sleep(2);
  return NULL;
}
```

```
int main(void) {
  long i;
  pthread_t tids[N];

  for (i = 0; i < N; i++)
    Pthread_create(&tids[i], NULL,
          thread, (void *) i);
  sleep(1);
  for (i = 0; i < N; i++)
    printf("Thread #%ld has "
           "local value %ld\n",
           i, *pointers[i]);
  for (i = 0; i < N; i++)
    Pthread_join(tids[i], NULL);
  return 0;
}
```

- Let's fix it.
- With semaphores.

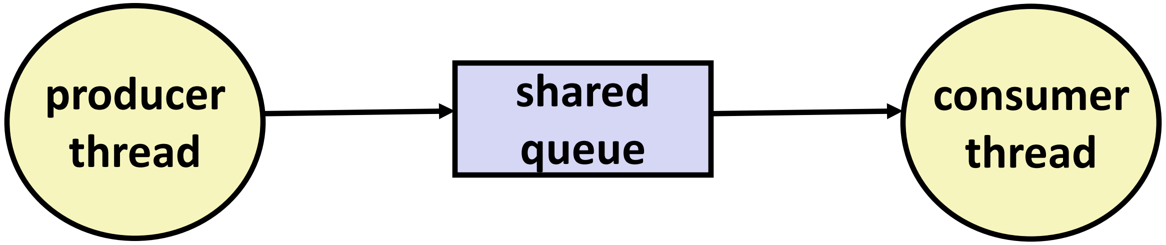
Live coding demo: event semaphores

Semaphores for Events

```
#define N 4
long *pointers[N];
sem_t ready[N];
sem_t finish;

void *thread(void *vargp) {
  long myid = (long) vargp;
  pointers[myid] = &myid;
  sem_post(&ready[myid]);
  sem_wait(&finish);
  return NULL;
}
```

```
int main(void) {
  long i;
  pthread_t tids[N];

  Sem_init(&finish, 0, 0);
  for (i = 0; i < N; i++) {
    Sem_init(&ready[i], 0, 0);
    Pthread_create(&tids[i], NULL,
        thread, (void *) i);
  }
  for (i = 0; i < N; i++) {
    sem_wait(&ready[i]);
    printf("Thread #%ld has "
           "local value %ld\n",
           i, *pointers[i]);
  }
  for (i = 0; i < N; i++)
    sem_post(&finish);
  for (i = 0; i < N; i++)
    Pthread_join(tids[i], NULL);
  return 0;
}
```

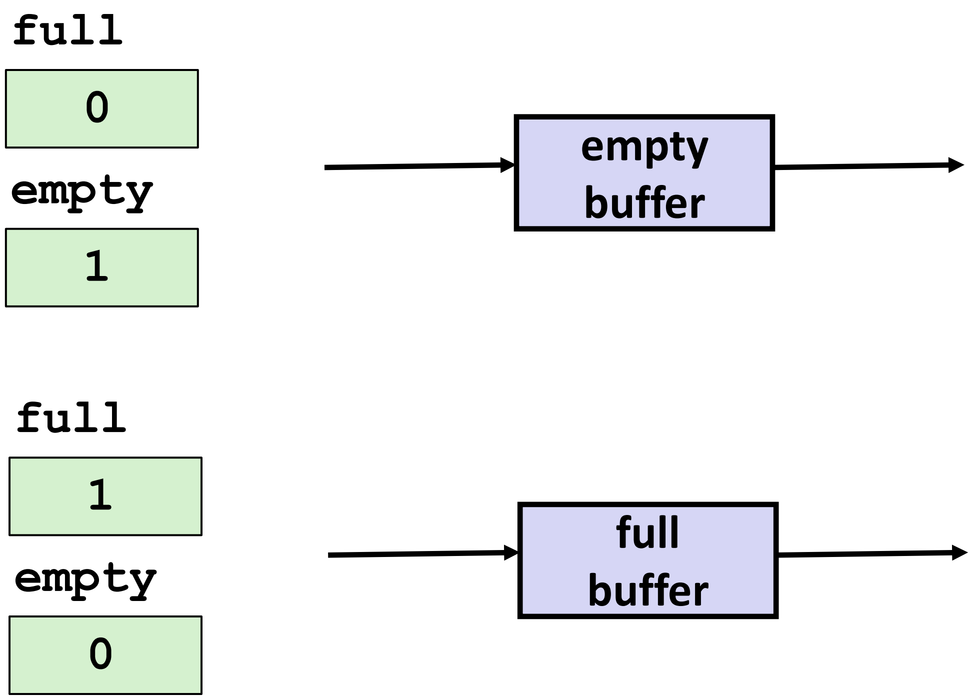
Queues, Producers, and Consumers



- **Common synchronization pattern:**
  - Producer waits for empty ***slot***, inserts item in queue, and notifies consumer
  - Consumer waits for ***item***, removes it from queue, 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 queue
    - Consumer retrieves events from queue and paints the display

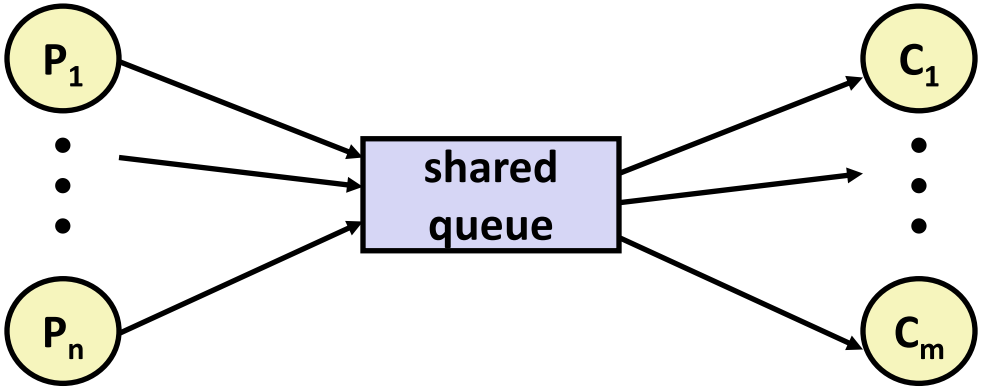
Producer-Consumer on 1-entry Queue

- Maintain two semaphores: `full` + `empty`



Why 2 Semaphores for 1-entry Queue?

- Consider multiple producers & multiple consumers



- Producers will contend with each to get `empty`
- Consumers will contend with each other to get `full`

Producers

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

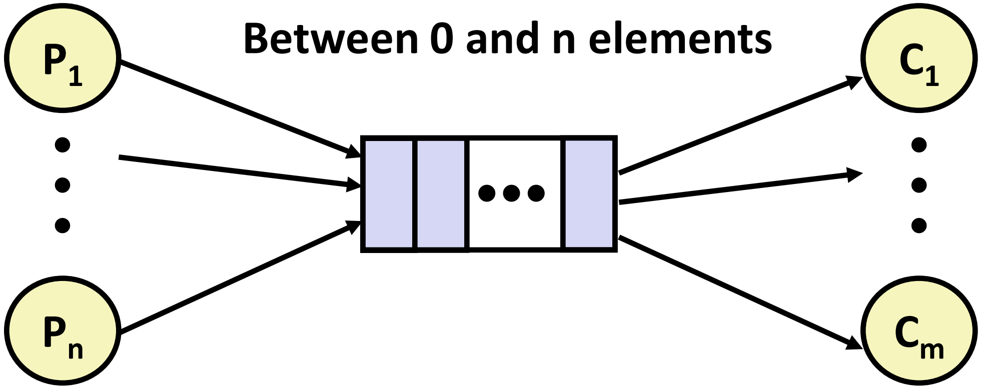
`empty`

`full`

Consumers

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

Producer-Consumer on *n*-element Queue



- **Requires a mutex and two counting semaphores:**
  - `mutex`: enforces mutually exclusive access to the queue's innards
  - `slots`: counts the available slots in the queue
  - `items`: counts the available items in the queue
- **Makes use of semaphore values > 1 (up to *n*)**

Today

- Review: Races, Mutual Exclusion
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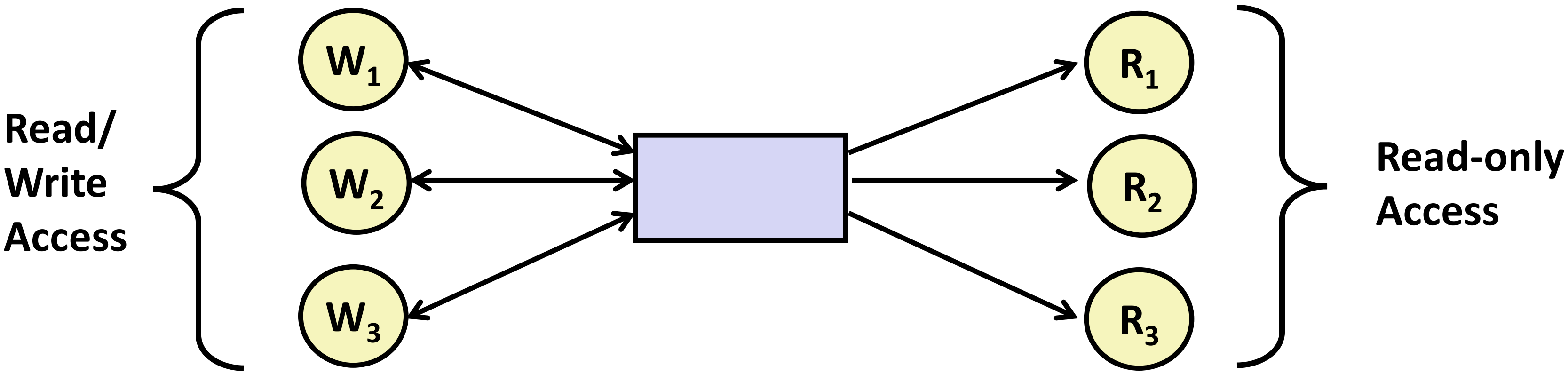
- Semaphores, Events, and Queues
- **Reader-Writer Locks and Starvation**
- Thread-Safe API Design

Readers-Writers Problem



- **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

Pthreads Reader/Writer Lock

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

```
pthread_rwlock_rdlock(pthread_rwlock_t *rwlock)
```

  - Acquire write lock

```
pthread_rwlock_wrlock(pthread_rwlock_t *rwlock)
```

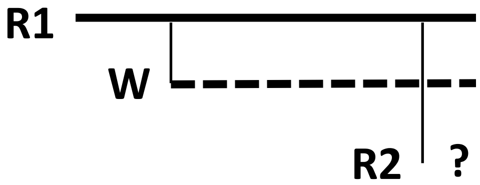
  - Release (either) lock

```
pthread_rwlock_unlock(pthread_rwlock_t *rwlock)
```

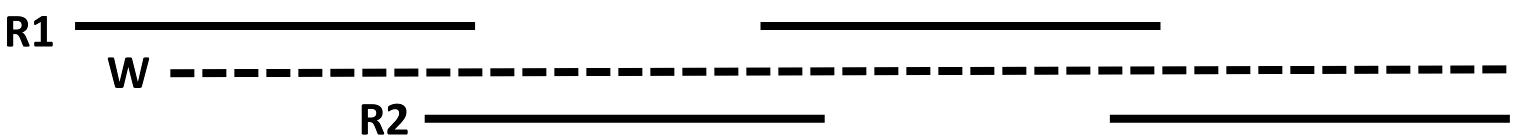
- **Must be used correctly!**
  - Up to programmer to decide what requires read access and what requires write access

Reader/Writer Starvation

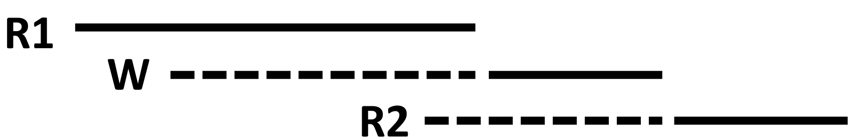
- **Thread 1 has a read lock. Thread 2 is waiting for a write lock. Thread 3 tries to take a read lock. What happens?**



- **Option 1: R2 gets read lock immediately**
  - Endless stream of overlapping readers → W waits forever



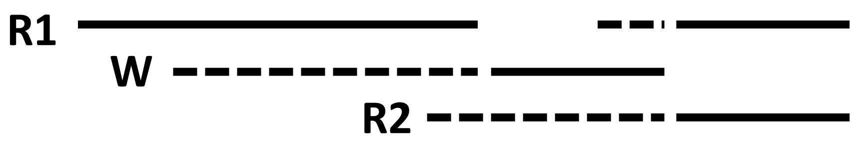
- **Option 2: Writer always gets lock as soon as possible**
  - Endless stream of overlapping writers → readers wait forever (not shown)



Starvation

- **A thread is *starved* when it makes no forward progress for an unacceptably long time**
  - Unlike deadlock, it's possible for it to get unstuck eventually
  - "Unacceptably long" depends on the application

- **Algorithms that guarantee no starvation are called *fair***
  - Fair R/W locks: every waiter receives the lock in first-come first-served order (several readers can receive the lock at the same time)



  - Fairness is more complicated to implement
  - Fairness can mean *all* threads are slower than they would be in an unfair system (e.g. "lock convoy problem")

Quiz

https://canvas.cmu.edu/courses/42532/quizzes/127188

Today

- Review: Races, Mutual Exclusion
- Deadlock
- Semaphores, Events, and Queues
- Reader-Writer Locks and Starvation
- **Thread-Safe API Design**

Thread-Safe APIs

- **A function is *thread-safe* if it always produces correct results when called repeatedly from multiple concurrent threads.**

- **Reasons for a function *not* to be thread-safe:**
  1. Internal shared state, no locking (e.g. your `malloc`)
  2. Internal state modified across multiple uses (e.g. `rand`)
  3. Returns a pointer to a static variable (e.g. `strtok`)
  4. Calls a function that does any of the above

Thread-Unsafe Functions (Class 1)

- **These functions *would* be thread-safe if they began with `pthread_mutex_lock(&l)` and ended with `pthread_mutex_unlock(&l)` for some lock L**

- **Good example: `malloc`, `realloc`, `free`**
  - Your implementation will crash if called from multiple concurrent threads
  - The C library's implementation won't; it has internal locks

- **Locking slows things down, of course**

Thread-Unsafe Functions (Class 2)

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

```
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;
}
```

- **Difference from class 1: locking would not fix the problem**
  - 2 threads call rand() simultaneously, both get different results than if only one made a sequence of calls to rand()

Fixing Class 2 Thread-Unsafe Functions

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

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

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

- **Requires API change**
- **Callers responsible for allocating space for state**

Thread-Unsafe Functions (Class 3)

- **Returning a pointer to a static variable**
- **Like class 2, locking inside function would not help**
  - Race between *use of result* and calls from another thread
- **Fix: make caller supply space for result**
  - Requires API change (also like class 2)
  - Can be awkward for caller: how much space is required?

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

```
/* Convert integer to string
   (thread-safe) */
void itoa_r(int x, char *buf,
            size_t bufsz)
{
    snprintf(buf, bufsz, "%d", x);
}
```

Thread-Unsafe Functions (Class 4)

- **Calling thread-unsafe functions**
  - Any function that uses a class 1, 2, or 3 function internally is just as thread-unsafe as that function itself
  - This applies transitively
- **Only fix is to modify the function to use only thread-safe functions**
  - This may or may not involve API changes

Thread-Safe Library Functions

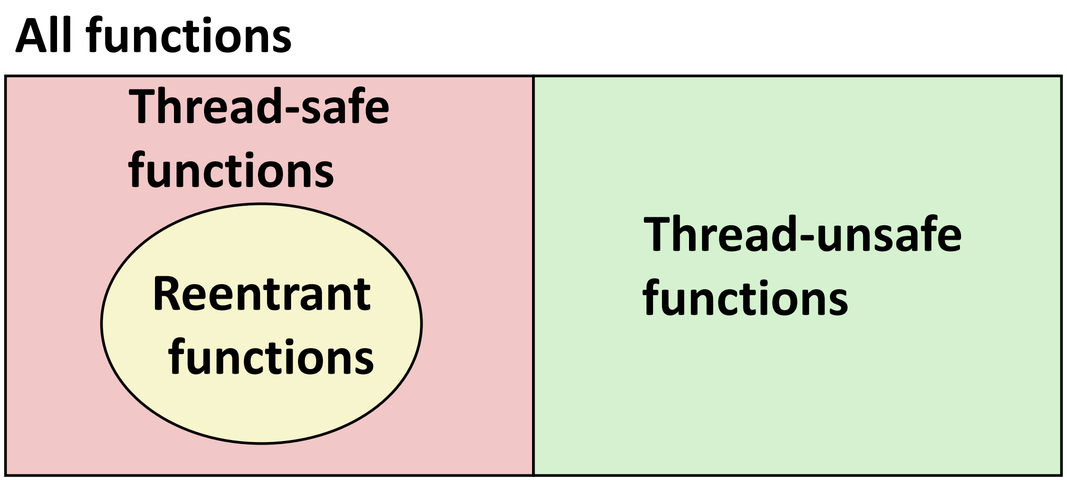
- **Most ISO C library functions are thread-safe**
  - Examples: **`malloc`**, **`free`**, **`printf`**, **`scanf`**
  - Exceptions: **`strtok`**, **`rand`**, **`asctime`**, …
- **Many older Unix C library functions are unsafe**
  - There is usually a safe replacement

Thread-unsafe function	Class	Reentrant version
`asctime`	3	`strftime`
`ctime`	3	`strftime`
`localtime`	3	`strftime`
`gethostbyname`	3	`getaddrinfo`
`gethostbyaddr`	3	`getnameinfo`
`inet_ntoa`	3	`getnameinfo`
`rand`	2	`rand_r*`

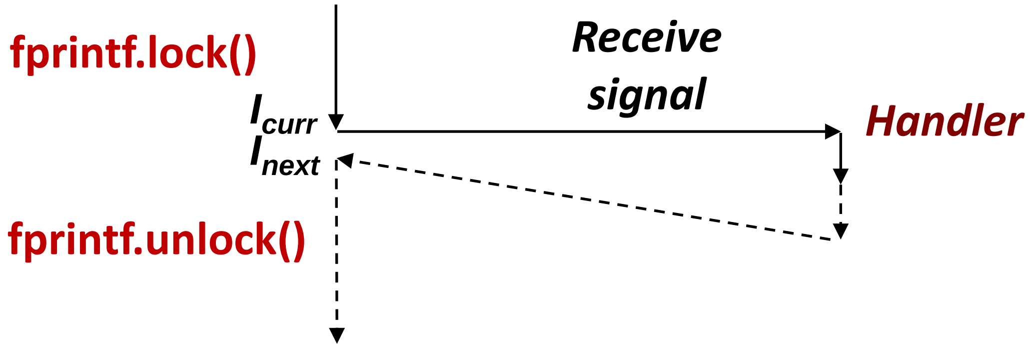
** The C library's random number generators are all old and not very "strong". Use a modern CSPRNG instead.*

Reentrant Functions

- **Def: A function is *reentrant* if 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 reentrant (e.g., `rand_r`)

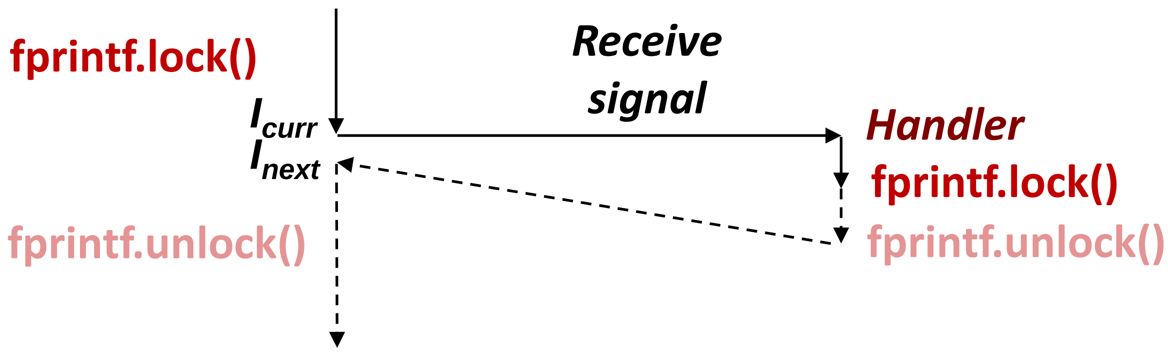


Threads / Signals Interactions



- **Many library functions use lock-and-copy for thread safety**
  - malloc
    - Free lists
  - fprintf, printf, puts
    - So that outputs from multiple threads don't interleave
  - snprintf
    - Calls malloc internally for scratch space
- **OK to interrupt them with locks held**
  - … as long as the handler doesn't use them itself!

Bad Thread / Signal Interactions



- **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