Synchronization: Advanced

15-213 / 18-213: Introduction to Computer Systems
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Reminder: Semaphores

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

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

- **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

```
mutex = 1

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

  - This case is so common, that pthreads provides mutex as primitive.

Today

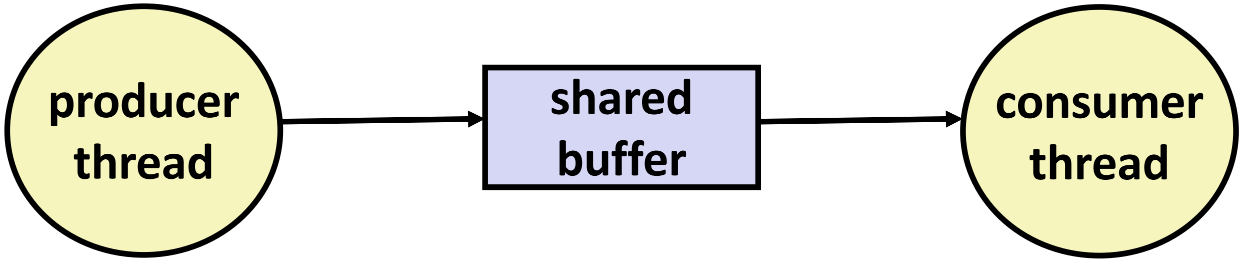
- **Using semaphores to schedule shared resources**
  - Producer-consumer problem
  - Readers-writers problem
- **Other concurrency issues**
  - Thread safety
  - Races
  - Deadlocks

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.

- **Two classic examples:**
  - The Producer-Consumer Problem
  - The Readers-Writers Problem

Producer-Consumer Problem

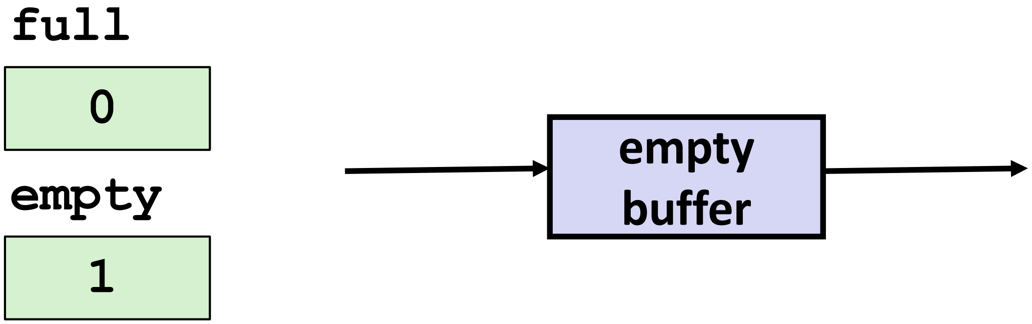


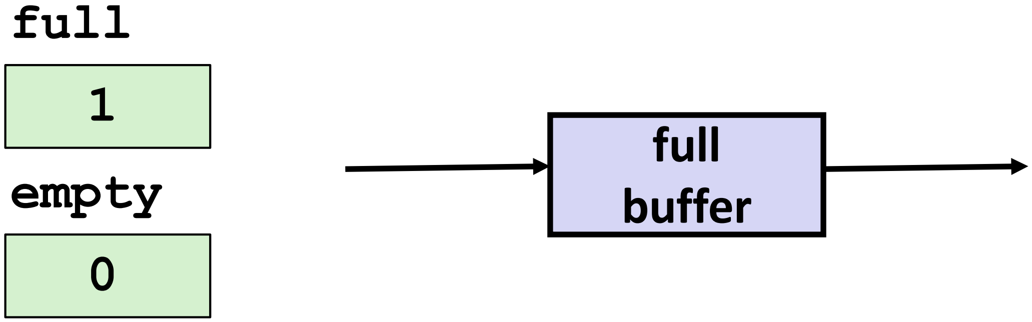
- **Common synchronization pattern:**
  - Producer waits for empty ***slot***, inserts item in buffer, and notifies consumer
  - Consumer waits for ***item***, removes it from buffer, and notifies producer

- **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

Producer-Consumer on 1-element Buffer

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





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;
```

```
int main(int argc, char** argv) {
  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);

  return 0;
}
```

Producer-Consumer on 1-element Buffer

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

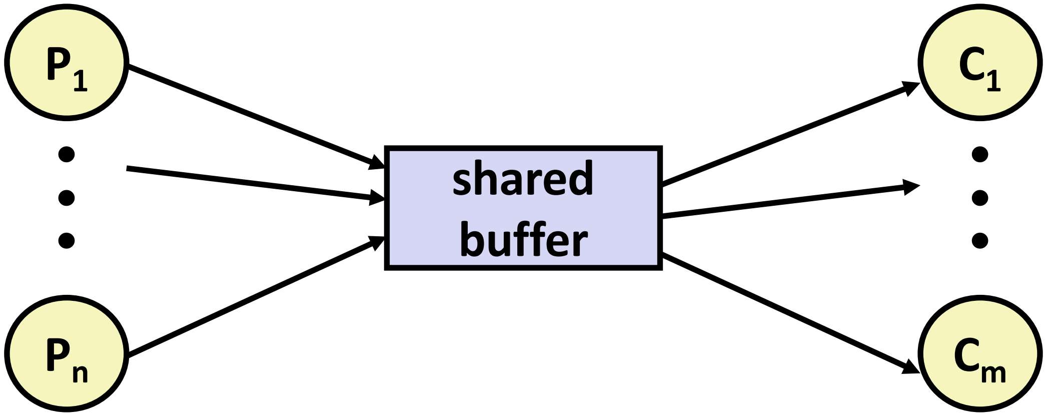
```
void *consumer(void *arg) {
  int i, item;

  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;
}
```

Why 2 Semaphores for 1-Entry Buffer?

- 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);
```

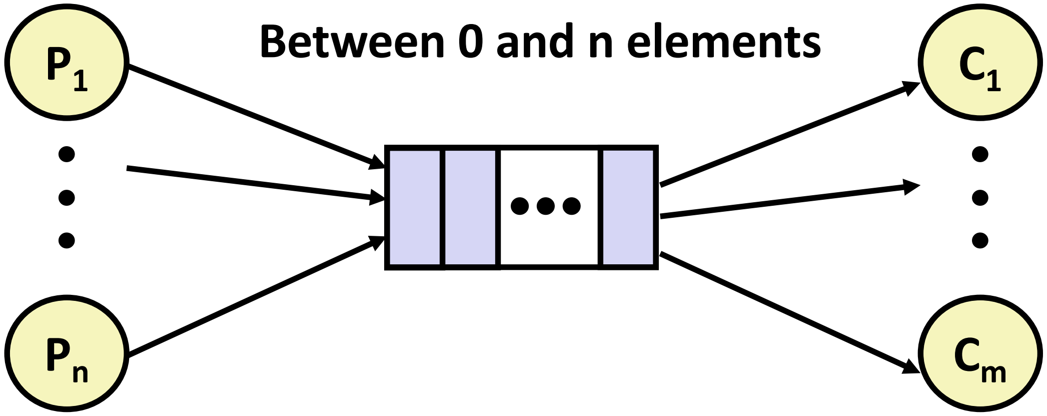
`empty`

`full`

Consumers

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

Producer-Consumer on an *n*-element Buffer



- Implemented using a shared buffer package called `sbuf`.

Circular Buffer (n = 10)

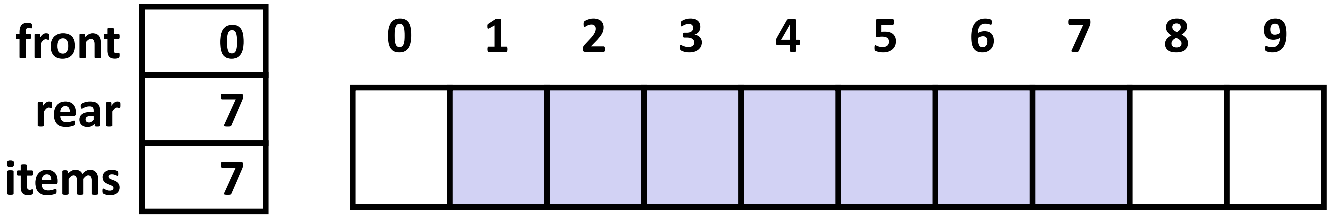
- Store elements in array of size n
- items: number of elements in buffer
- Empty buffer:
  - front = rear
- Nonempty buffer
  - rear: index of most recently inserted element
  - front: (index of next element to remove – 1) mod n
- Initially:

front	0
rear	0
items	0

0	1	2	3	4	5	6	7	8	9

Circular Buffer Operation (n = 10)

- Insert 7 elements

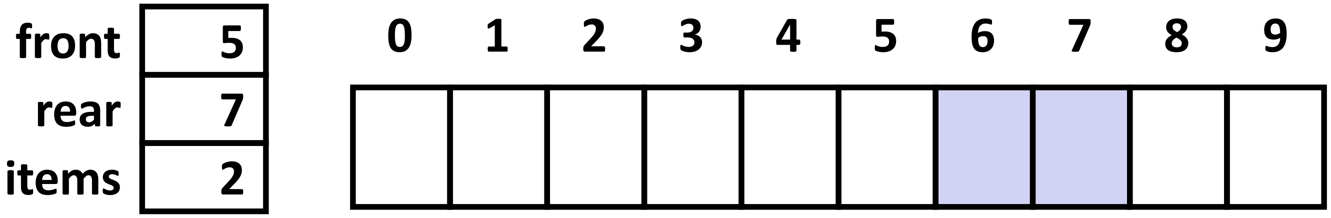


front 0

rear 7

items 7

- Remove 5 elements

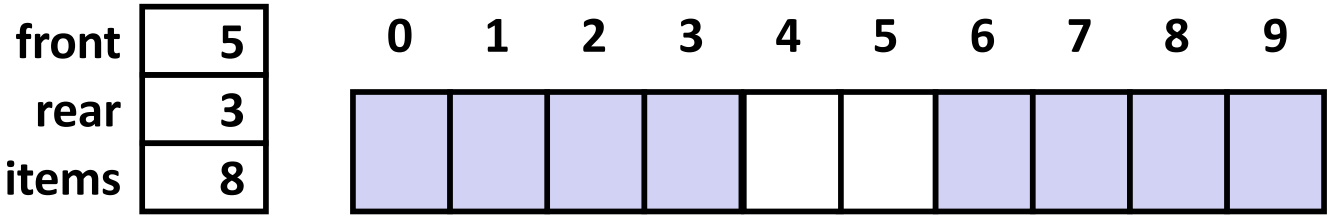


front 5

rear 7

items 2

- Insert 6 elements

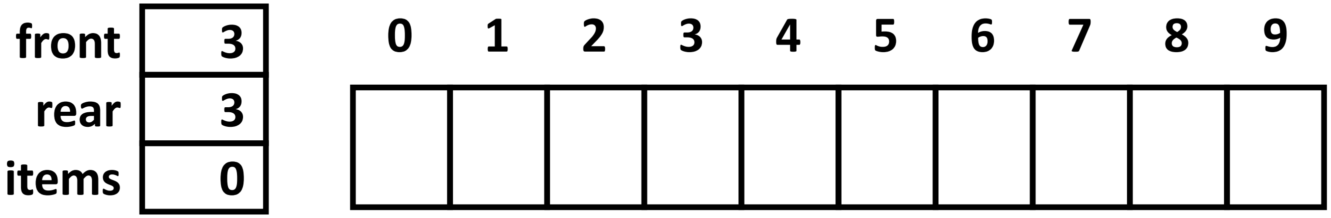


front 5

rear 3

items 8

- Remove 8 elements



front 3

rear 3

items 0

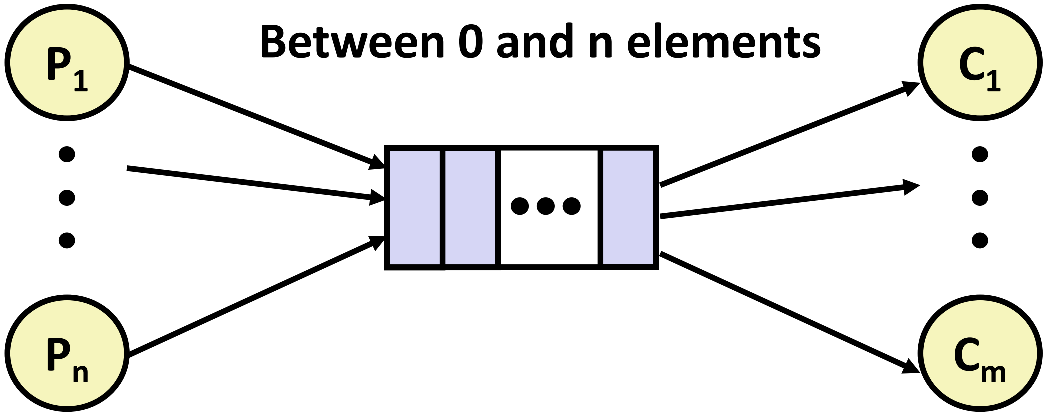
Sequential Circular Buffer Code

```
init(int v)
{
   items = front = rear = 0;
}
```

```
insert(int v)
{
   if (items >= n)
       error();
   if (++rear >= n) rear = 0;
   buf[rear] = v;
   items++;
}
```

```
int remove()
{
   if (items == 0)
       error();
   if (++front >= n) front = 0;
   int v = buf[front];
   items--;
   return v;
}
```

Producer-Consumer on an *n*-element Buffer



- **Requires a mutex and two counting semaphores:**
  - `mutex`: enforces mutually exclusive access to the buffer and counters
  - `slots`: counts the available slots in the buffer
  - `items`: counts the available items in the buffer
- **Makes use of general semaphores**
  - Will range in value from 0 to n

sbuf Package - Declarations

```
#include "csapp.h”

typedef struct {
    int *buf;      /* Buffer array                    */
    int n;         /* Maximum number of slots         */
    int front;     /* buf[front+1 (mod n)] is first item */
    int rear;      /* buf[rear]   is last item        */
    sem_t mutex;   /* Protects accesses to buf        */
    sem_t slots;   /* Counts available slots          */
    sem_t items;   /* Counts available items          */
} sbuf_t;

void sbuf_init(sbuf_t *sp, int n);
void sbuf_deinit(sbuf_t *sp);
void sbuf_insert(sbuf_t *sp, int item);
int sbuf_remove(sbuf_t *sp);
```

sbuf.h

sbuf Package - Implementation

Initializing and deinitializing a shared buffer:

```
/* Create an empty, bounded, shared FIFO buffer with n slots */
void sbuf_init(sbuf_t *sp, int n)
{
    sp->buf = Calloc(n, sizeof(int));
    sp->n = n;                       /* Buffer holds max of n items */
    sp->front = sp->rear = 0;        /* Empty buffer iff front == rear */
    Sem_init(&sp->mutex, 0, 1);      /* Binary semaphore for locking */
    Sem_init(&sp->slots, 0, n);      /* Initially, buf has n empty slots */
    Sem_init(&sp->items, 0, 0);      /* Initially, buf has zero items */
}

/* Clean up buffer sp */
void sbuf_deinit(sbuf_t *sp)
{
    Free(sp->buf);
}
```

sbuf.c

sbuf Package - Implementation

Inserting an item into a shared buffer:

```
/* Insert item onto the rear of shared buffer sp */
void sbuf_insert(sbuf_t *sp, int item)
{
    P(&sp->slots);               /* Wait for available slot */
    P(&sp->mutex);               /* Lock the buffer         */
    if (++sp->rear >= sp->n)     /* Increment index (mod n) */
        sp->rear = 0;
    sp->buf[sp->rear] = item;    /* Insert the item         */
    V(&sp->mutex);               /* Unlock the buffer       */
    V(&sp->items);               /* Announce available item */
}
```

sbuf.c

sbuf Package - Implementation

Removing an item from a shared buffer:

```
/* Remove and return the first item from buffer sp */
int sbuf_remove(sbuf_t *sp)
{
    int item;
    P(&sp->items);               /* Wait for available item */
    P(&sp->mutex);               /* Lock the buffer         */
    if (++sp->front >= sp->n)    /* Increment index (mod n) */
        sp->front = 0;
    item = sp->buf[sp->front];   /* Remove the item         */
    V(&sp->mutex);               /* Unlock the buffer       */
    V(&sp->slots);               /* Announce available slot */
    return item;
}
```

sbuf.c

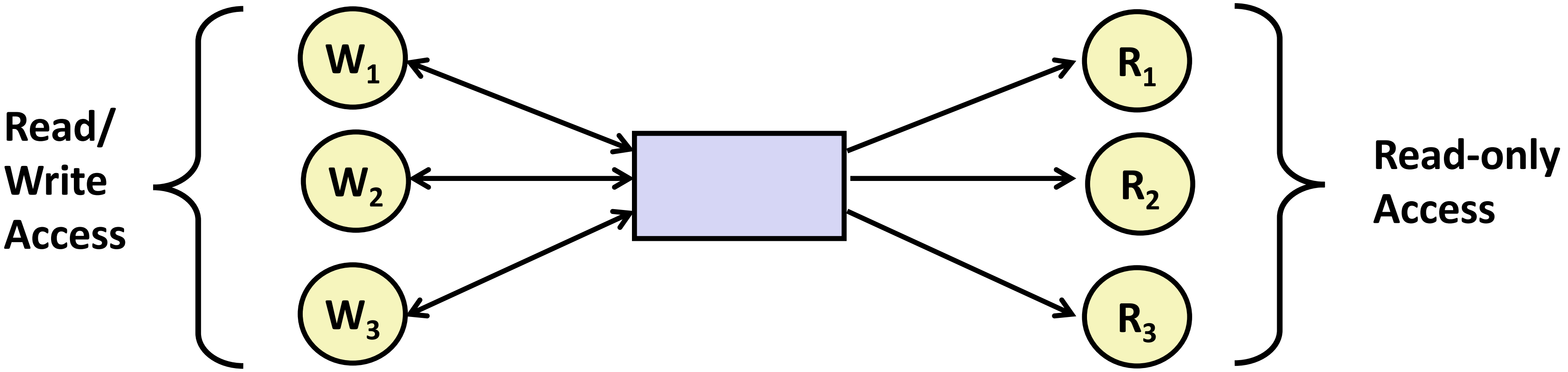
Demonstration

- **See program produce-consume.c in code directory**
- **10-entry shared circular buffer**
- **5 producers**
  - Agent i generates numbers from 20*i to 20*i – 1.
  - Puts them in buffer
- **5 consumers**
  - Each retrieves 20 elements from buffer
- **Main program**
  - Makes sure each value between 0 and 99 retrieved once

Today

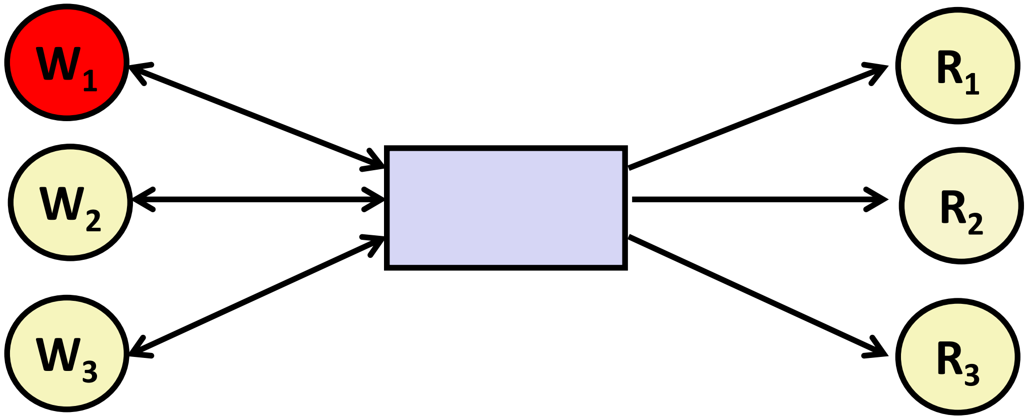
- **Using semaphores to schedule shared resources**
  - Producer-consumer problem
  - **Readers-writers problem**
- **Other concurrency issues**
  - Thread safety
  - Races
  - Deadlocks

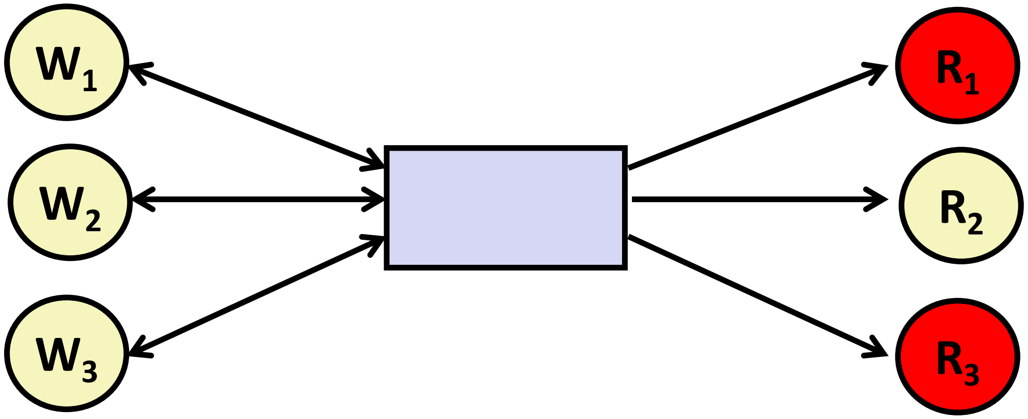
Readers-Writers Problem



- **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

Readers/Writers Examples





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.

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

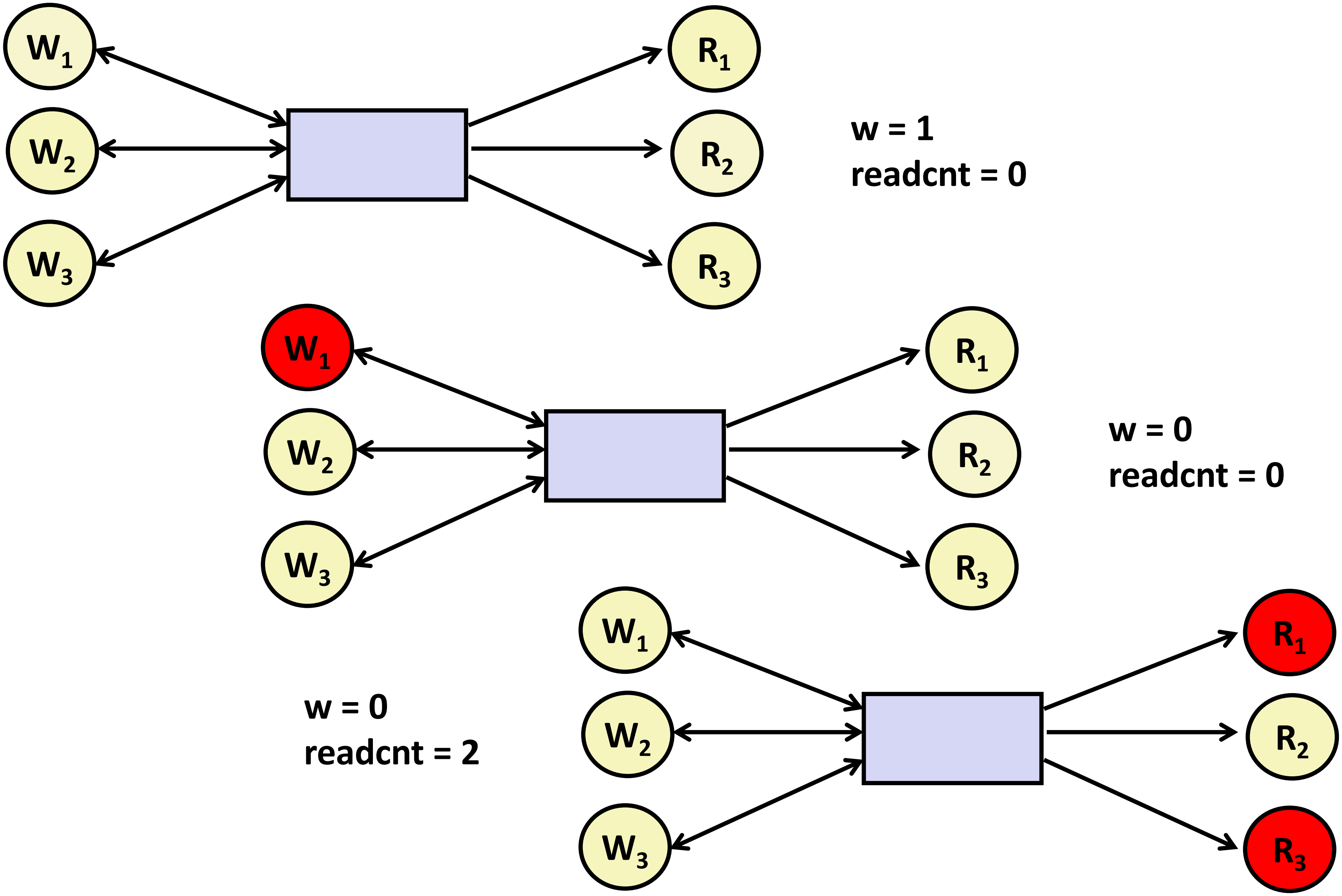
```
void writer(void)
{
  while (1) {
    P(&w);

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

Readers/Writers Examples



w = 1
readcnt = 0

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

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

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++;
R2 →    if (readcnt == 1) /* First in */
          P(&w);
        V(&mutex);

R1 →    /* 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

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);
R2 →
R1 →
    /* Reading happens here */

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

Writers:

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

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

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);

R2 →  /* Reading happens here */

    P(&mutex);
    readcnt--;
    if (readcnt == 0) /* Last out */
      V(&w);
    V(&mutex);
R1 → }
}
```

Writers:

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

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

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++;
R3 →     if (readcnt == 1) /* First in */
           P(&w);
         V(&mutex);

         /* Reading happens here */

R2 →
         P(&mutex);
         readcnt--;
         if (readcnt == 0) /* Last out */
           V(&w);
         V(&mutex);
R1 →   }
     }
```

Writers:

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

    /* Writing here */

    V(&w);
  }
}
```

rw1.c

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

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

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

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);
  }
}
```

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);
  }
}
```

Today

- Using semaphores to schedule shared resources
  - Producer-consumer problem
  - Readers-writers problem
- **Other concurrency issues**
  - **Races**
  - Deadlocks
  - Thread safety

One Worry: Races

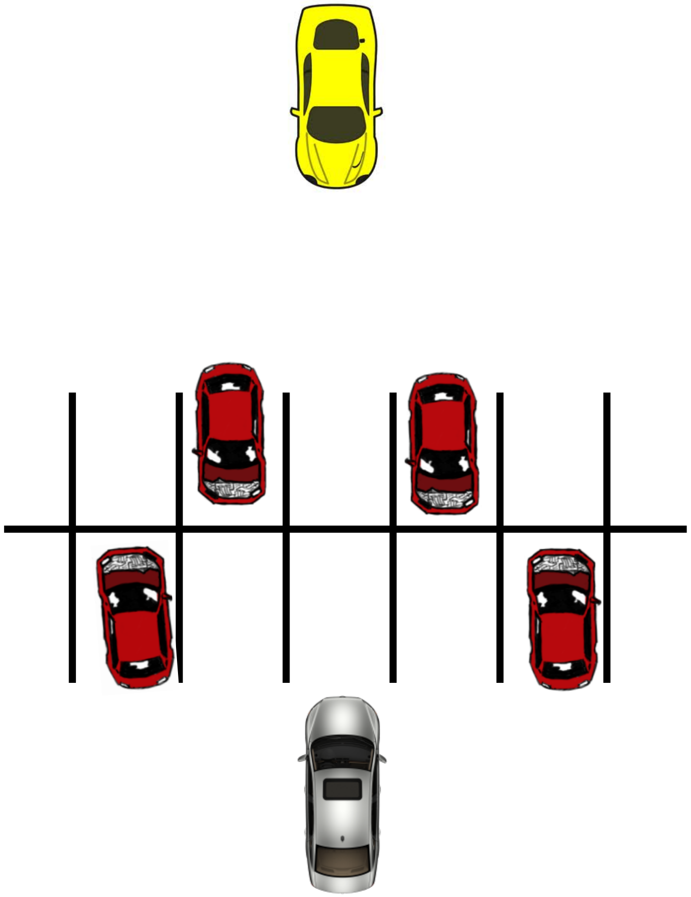
- A *race* occurs when correctness of the program depends on one thread reaching point x before another thread reaches point y

```
/* 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;
}
```

race.c

Data Race



Race Elimination

- Make sure don’t have unintended sharing of state

```c
/* a threaded program without the race */
int main(int argc, char** argv) {
    pthread_t tid[N];
    int i;
    for (i = 0; i < N; i++) {
        int *valp = Malloc(sizeof(int));
        *valp = i;
        Pthread_create(&tid[i], NULL, thread, valp);
    }
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    return 0;
}

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

norace.c

Today

- Using semaphores to schedule shared resources
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  - Readers-writers problem
- **Other concurrency issues**
  - Races
  - **Deadlocks**
  - Thread safety

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!

Deadlocking With Semaphores

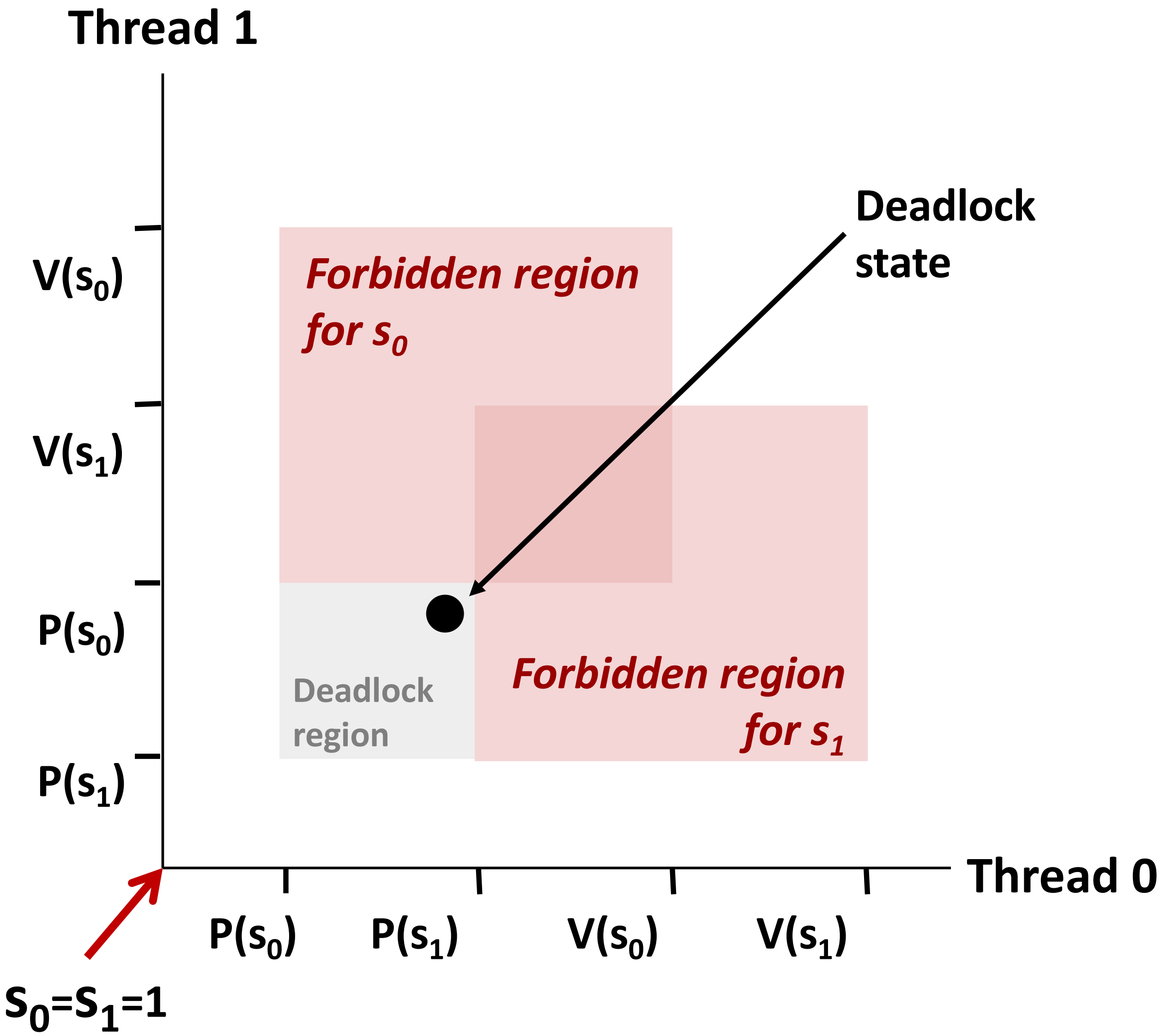
```
int main(int argc, char** argv)
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
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

```
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]:
P(s_0);
P(s_1);
cnt++;
V(s_0);
V(s_1);

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

Deadlock Visualized in Progress Graph



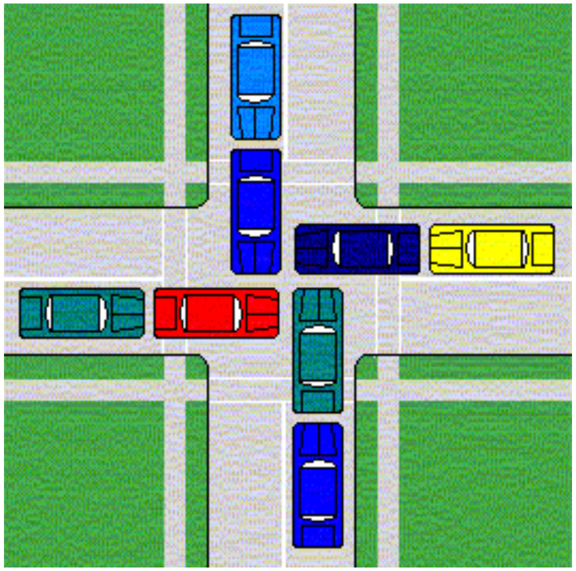
Locking introduces the potential for *deadlock:* waiting for a condition that will never be true

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



Avoiding Deadlock

Acquire shared resources in same order

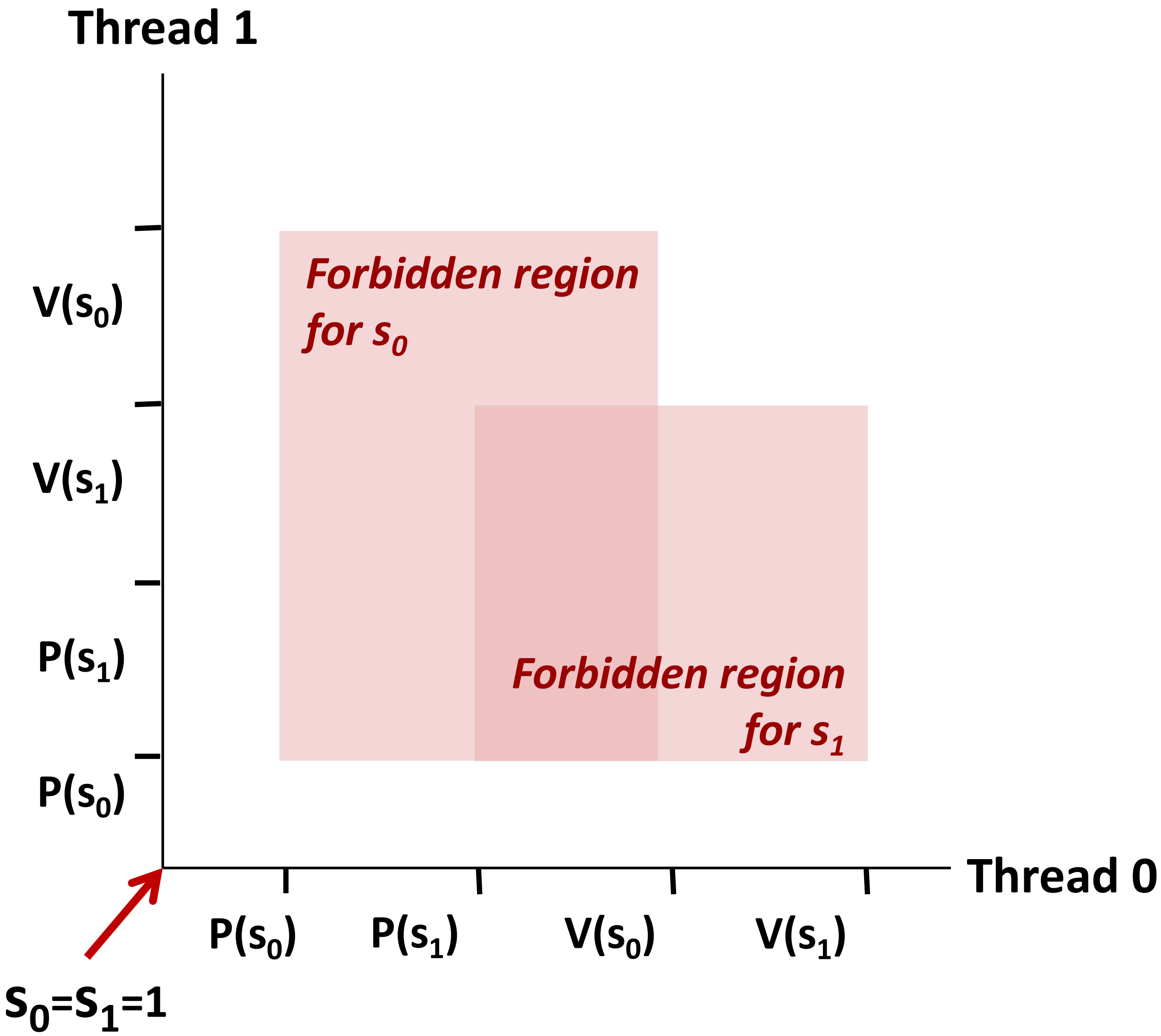
```
int main(int argc, char** argv)
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
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

```
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]:
$P(s_0)$;
$P(s_1)$;
cnt++;
$V(s_0)$;
$V(s_1)$;

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

Avoided Deadlock in Progress Graph



No way for trajectory to get stuck

Processes acquire locks in same order

Order in which locks released immaterial

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

Today

- Using semaphores to schedule shared resources
  - Producer-consumer problem
  - Readers-writers problem
- **Other concurrency issues**
  - Races
  - Deadlocks
  - **Thread safety**

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.**

- **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
  - Example: `goodcnt.c`
  - Issue: Synchronization operations will slow down code

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;
}
```

Thread-Safe Random Number Generator

- **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;
}
```

- **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;
}
```

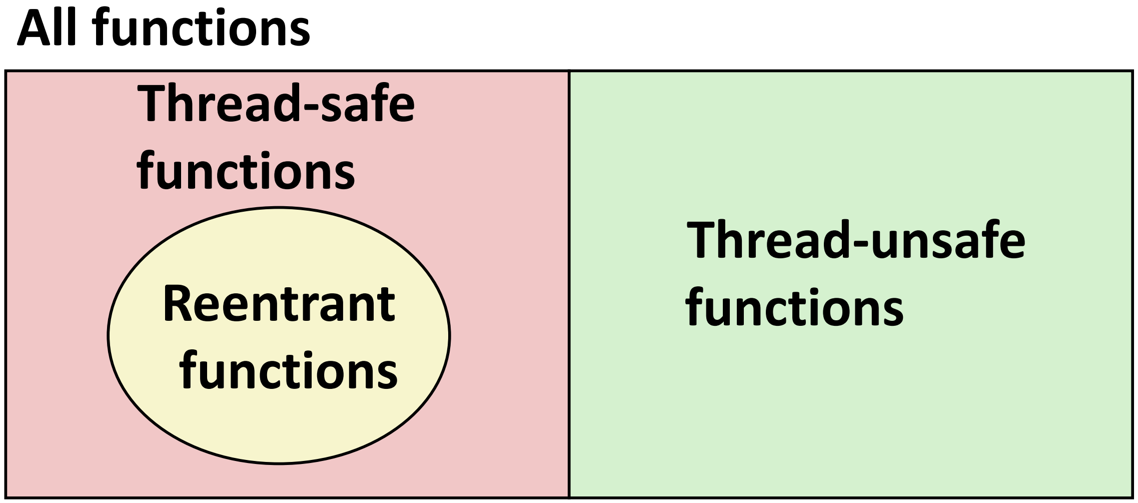
Warning: Some functions like `gethostbyname` require a *deep copy*. Use reentrant *`gethostbyname_r`* version instead.

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 ☺

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`)



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:**

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`

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