Synchronization: Advanced

15-213 / 18-213: Introduction to Computer Systems
25th Lecture, July 31, 2018

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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

\[
\text{mutex} = 1 \\
P(mutex) \\
cnt++ \\
V(mutex)
\]
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

```
<table>
<thead>
<tr>
<th>full</th>
<th>empty</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
```

```
<table>
<thead>
<tr>
<th>full</th>
<th>empty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
```
# Producer-Consumer on 1-element Buffer

```c
#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

```c
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

```c
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

\[ P(\&\text{shared.empty}); \]
\[ \text{shared.buf} = \text{item}; \]
\[ V(\&\text{shared.full}); \]

Consumers

\[ P(\&\text{shared.full}); \]
\[ \text{item} = \text{shared.buf}; \]
\[ V(\&\text{shared.empty}); \]

Producers will contend with each to get empty
Consumers will contend with each other to get full
Producer-Consumer on an $n$-element Buffer

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

Between 0 and $n$ elements
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:

<table>
<thead>
<tr>
<th>front</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>rear</td>
<td>0</td>
</tr>
<tr>
<td>items</td>
<td>0</td>
</tr>
</tbody>
</table>

```plaintext
  0 9 8 7 6 5 4 3 2 1
```

Circular Buffer Operation (n = 10)

- Insert 7 elements

  - front: 0
  - rear: 7
  - items: 7

- Remove 5 elements

- Insert 6 elements

- Remove 8 elements
Circular Buffer Operation (n = 10)

- Insert 7 elements

<table>
<thead>
<tr>
<th>front</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>rear</td>
<td>7</td>
</tr>
<tr>
<td>items</td>
<td>7</td>
</tr>
</tbody>
</table>

- Remove 5 elements

<table>
<thead>
<tr>
<th>front</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>rear</td>
<td>7</td>
</tr>
<tr>
<td>items</td>
<td>2</td>
</tr>
</tbody>
</table>

- Insert 6 elements

- Remove 8 elements
Circular Buffer Operation (n = 10)

- **Insert 7 elements**
  - front: 0
  - rear: 7
  - items: 7
  - Diagram: 0 9 8 7 6 5 4 3 2 1

- **Remove 5 elements**
  - front: 5
  - rear: 7
  - items: 2
  - Diagram: 0 9 8 7 6 5 4 3 2 1

- **Insert 6 elements**
  - front: 5
  - rear: 3
  - items: 8
  - Diagram: 0 9 8 7 6 5 4 3 2 1

- **Remove 8 elements**
  - front: 3
  - rear: 3
  - items: 0
  - Diagram: 0 9 8 7 6 5 4 3 2 1
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

\begin{array}{l}
\text{init}(\text{int } v) \\
\{ \\
\quad \text{items} = \text{front} = \text{rear} = 0; \\
\}
\\
\text{insert}(\text{int } v) \\
\{ \\
\quad \text{if (items} \geq \text{n)} \quad \text{error();} \\
\qquad \text{if (++rear} \geq \text{n)} \quad \text{rear} = 0; \\
\qquad \text{buf[rear]} = v; \\
\qquad \text{items++;} \\
\}
\\
\text{int remove()} \\
\{ \\
\quad \text{if (items} = 0) \quad \text{error();} \\
\qquad \text{if (++front} \geq \text{n)} \quad \text{front} = 0; \\
\qquad \text{int } v = \text{buf[front];} \\
\qquad \text{items--;} \\
\qquad \text{return } v; \\
\}
\end{array}
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

```c
#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:

```c
/* 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:

```c
/* 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 */
}
```

```c
insert(int v)
{
    if (items >= n)
        error();
    if (++rear >= n) rear = 0;
    buf[rear] = v;
    items++;
}
```
Removing an item from a shared buffer:

```c
/* 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;
}
```

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

```c
void *
producer(void *vargp)
{
    int cnt = 0;
    while (maxcnt > 0) {
        sbuf_insert(&sbuf, cnt);
        cnt++;
        maxcnt--;
    }
    sbuf_insert(&sbuf, -1);
    pthread_exit(0);
}

void *
consumer(void *vargp)
{
    int sum = 0;
    while (1) {
        int val = sbuf_remove(&sbuf);
        if (val < 0) break;
        sum += val;
    }
    total = sum;
    pthread_exit(0);
}
```
Is there another way?

■ One producer and one consumer

```c
/* 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 */
    sp->buf[(++sp->rear)%(sp->n)] = item; /* Insert the item */
    V(&sp->mutex);                /* Unlock the buffer */
    V(&sp->items);                /* Announce available item */
}

/* 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 */
    item = sp->buf[(++sp->front)%(sp->n)]; /* Remove the item */
    V(&sp->mutex);                /* Unlock the buffer */
    V(&sp->slots);                /* Announce available slot */
    return item;
}
```
### Shared variable analysis

<table>
<thead>
<tr>
<th>variable</th>
<th>prod</th>
<th>cons$_0$</th>
<th>cons$_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>buf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buf[k]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Items</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slots</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Is there another way?

- **One** producer and one consumer

```c
/* 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 */
    sp->buf[(++sp->rear)%(sp->n)] = item; /* Insert the item */
    V(&sp->mutex);                        /* Unlock the buffer */
    V(&sp->items);                        /* Announce available item */
}

/* 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 */
    item = sp->buf[(++sp->front)%(sp->n)]; /* Remove the item */
    V(&sp->mutex);                         /* Unlock the buffer */
    V(&sp->slots);                         /* Announce available slot */
    return item;
}
```
### Do we need semaphores at all?

/* Insert item onto the rear of shared buffer sp */
void sbuf_insert(sbuf_t *sp, int item)
{
    P(&sp->slots); /* Wait for available slot */

    sp->buf[(++sp->rear)%(sp->n)] = item; /* Insert the item */

    V(&sp->items); /* Announce available item */
}

/* Remove and return the first item from buffer sp */
int sbuf_remove(sbuf_t *sp)
{
    int item;

    P(&sp->items); /* Wait for available item */

    item = sp->buf[(++sp->front)%(sp->n)]; /* Remove the item */

    V(&sp->slots); /* Announce available slot */
    return item;
}
Are Front and rear (really) shared?

typedef struct {
    int *buf;
    int n;
    int front;
    int rear;
    int cnt;
} sbuf_t;

global void
sbuf_init(sbuf_t *sp, int n) {
    sp->n = n;
    sp->buf = calloc(sizeof(int), n);
    sp->front = 0;
    sp->rear = 0;
    sp->cnt = 0;
}
Are Front and rear (really) shared?

```c
void
sbuf_insert(sbuf_t* sp, int v)
{
    int next = sp->rear+1;
    if (next == sp->n)
        next = 0;
    while (next == sp->front)
        pthread_yield();
    sp->buf[sp->rear] = v;
    sp->rear = next;
}

int
sbuf_remove(sbuf_t* sp)
{
    while (sp->front == sp->rear)
        pthread_yield();
    int next = sp->front+1;
    if (next == sp->n) next = 0;
    int val = sp->buf[sp->front];
    sp->front = next;
    return val;
}
```
Are Front and rear (really) shared?

```c
void
sbuf_insert(sbuf_t* sp, int v)
{
    int next = sp->rear+1;
    if (next == sp->n)
        next = 0;
    while (next == sp->front)
        pthread_yield();
    sp->buf[sp->rear] = v;
    sp->rear = next;
}

int
sbuf_remove(sbuf_t* sp)
{
    while (sp->front == sp->rear)
        pthread_yield();
    int next = sp->front+1;
    if (next == sp->n) next = 0;
    int val = sp->buf[sp->front];
    sp->front = next;
    return val;
}
```
void
sbuf_insert(sbuf_t* sp, int v)
{
    int next = sp->rear+1;
    if (next == sp->n)
        next = 0;
    while (next == sp->front)
        pthread_yield();
    sp->buf[sp->rear] = v;
    sp->rear = next;
}

int
sbuf_remove(sbuf_t* sp)
{
    while (sp->front == sp->rear)
        pthread_yield();
    int next = sp->front+1;
    if (next == sp->n) next = 0;
    int val = sp->buf[sp->front];
    sp->front = next;
    return val;
}

Why does this work for ONLY 1 producer and 1 consumer?
Front and rear are **really** shared!

```c
void
sbuf_insert(sbuf_t* sp, int v)
{
    int next = sp->rear+1;
    if (next == sp->n)
        next = 0;
    while (next == sp->front)
        pthread_yield();
    sp->buf[sp->rear] = v;
    sp->rear = next;
}
```

```c
int
sbuf_remove(sbuf_t* sp)
{
    while (sp->front == sp->rear)
        pthread_yield();
    int next = sp->front+1;
    if (next == sp->n) next = 0;
    int val = sp->buf[sp->front];
    sp->front = next;
    return val;
}
```

Why does this work for ONLY 1 producer and 1 consumer?
Timing

Where are the overheads? How important are the overheads? Choose your package carefully.

Original sbuf w/3 semaphores

Original sbuf w/2 semaphores

No locks!

User-level threads

Size of Queue

2 4 8 16 32 64 128

Seconds

Carnegie Mellon
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:

```c
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:

```c
void writer(void)
{
    while (1) {
        P(&w);
        /* Writing here */
        V(&w);
    }
}
```

rw1.c
Readers/Writers Examples

w = 0
readcnt = 0

w = 1
readcnt = 0

w = 0
readcnt = 2
Solution to First Readers-Writers Problem

Readers:

```c
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:

```c
void writer(void)
{
    while (1) {
        P(&w);
        /* Writing here */
        V(&w);
    }
}
```

Arrivals: R1 R2 W1 R3
Solution to First Readers-Writers Problem

Readers:

```c
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:

```c
void writer(void)
{
    while (1) {
        P(&w);
        /* Writing here */
        V(&w);
    }
}
```

Arrivals: R1 R2 W1 R3

Readcnt == 1
W == 0
Solution to First Readers-Writers Problem

Readers:

```c
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:

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

        /* Writing here */
        V(&w);
    }
}
```

Arrivals: R1 R2 W1 R3

Readcnt == 2
W == 0
Solution to First Readers-Writers Problem

Readers:

```c
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:

```c
void writer(void)
{
    while (1) {
        P(&w);
        /* Writing here */
        V(&w);
    }
}
```

Arrivals: R1 R2 W1 R3

Readcnt == 2
W == 0
Solution to First Readers-Writers Problem

Readers:

```c
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:

```c
void writer(void)
{
    while (1) {
        P(&w);
        /* Writing here */
        V(&w);
    }
}
```

Arrivals: R1 R2 W1 R3

Readcnt == 1
W == 0
Solution to First Readers-Writers Problem

Readers:

```c
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:

```c
void writer(void)
{
    while (1) {
        P(&w);
        /* Writing here */
        V(&w);
    }
}
```

Arrivals: R1 R2 W1 R3

- R1: Readcnt == 2
- W1: W == 0
Solution to First Readers-Writers Problem

Readers:

```c
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:

```c
void writer(void)
{
    while (1) {
        P(&w);
        /* Writing here */
        V(&w);
    }
}
```

Arrivals: R1 R2 W1 R3

Readcnt == 1
W == 0
Solution to First Readers-Writers Problem

Readers:

```c
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);
        /* Reading happens here */
    }
}
```

Writers:

```c
void writer(void)
{
    while (1) {
        P(&w);
        /* Writing here */
        V(&w);
    }
}
```

Arrivals: R1 R2 W1 R3

Readcnt == 0
W == 1
Demonstration

- See program read-write.c
- 100 agents
  - ~20% are writers. They write their ID to global variable
  - Rest are readers. They read the global variable
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.

```c
/* 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
  - Producer-consumer problem
  - 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

```c
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

```c
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

Thread 1

Forbidden region for $s_0$

Forbidden region for $s_1$

$S_0 = S_1 = 1$
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

```c
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

```c
/* 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.

```c
/* 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 reentrant (e.g., `rand_r`)

### All functions

<table>
<thead>
<tr>
<th>Thread-safe functions</th>
<th>Thread-unsafe functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reentrant function</td>
<td></td>
</tr>
</tbody>
</table>


---

The diagram shows the classification of functions into thread-safe and thread-unsafe categories. Reentrant functions are marked as a subset of thread-safe functions, while thread-unsafe functions do not access shared variables.
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:

<table>
<thead>
<tr>
<th>Thread-unsafe function</th>
<th>Class</th>
<th>Reentrant version</th>
</tr>
</thead>
<tbody>
<tr>
<td>asctime</td>
<td>3</td>
<td>asctime_r</td>
</tr>
<tr>
<td>ctime</td>
<td>3</td>
<td>ctime_r</td>
</tr>
<tr>
<td>gethostbyaddr</td>
<td>3</td>
<td>gethostbyaddr_r</td>
</tr>
<tr>
<td>gethostbyname</td>
<td>3</td>
<td>gethostbyname_r</td>
</tr>
<tr>
<td>inet_ntoa</td>
<td>3</td>
<td>(none)</td>
</tr>
<tr>
<td>localtime</td>
<td>3</td>
<td>localtime_r</td>
</tr>
<tr>
<td>rand</td>
<td>2</td>
<td>rand_r</td>
</tr>
</tbody>
</table>
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