Synchronization: Advanced

15-213 / 18-213: Introduction to Computer Systems
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Today

- **Races**
- Locking and Deadlocks
- Producer-consumer problem
- Readers-writers problem
- 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() {
    pthread_t tid[N];
    int i;
    for (i = 0; i < N; i++)
        Pthread_create(&tid[i], NULL, thread, &i);
    for (i = 0; i < N; i++)
       Pthread_join(tid[i], NULL);
    exit(0);
}

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

race.c

Race Elimination

- **Make sure don't have unintended sharing of state**

```
/* a threaded program without the race */
int main() {
    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);
    exit(0);
}

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

norace.c

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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 indivisibly**
    - Only one *P* or *V* operation at a time can modify s.
    - When `while` loop in *P* terminates, only that *P* can decrement `s`
- **Semaphore invariant: *(s >= 0)***

Reminder: Mutual exclusion via Semaphores

- **Basic idea:**
  - Associate a unique semaphore *mutex*, initially 1, with each shared variable (or related set of shared variables)
  - Surround corresponding critical sections with *P(mutex)* and *V(mutex)* operations
- **Terminology:**
  - *Binary semaphore*: semaphore whose value is always 0 or 1
  - *Mutex:* binary semaphore used for mutual exclusion
    - P operation: "locking" the mutex
    - V operation: "unlocking" or "releasing" the mutex
    - *"Holding"* a mutex: locked and not yet unlocked
  - *Counting semaphore*: used as a counter for set of available resources

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!

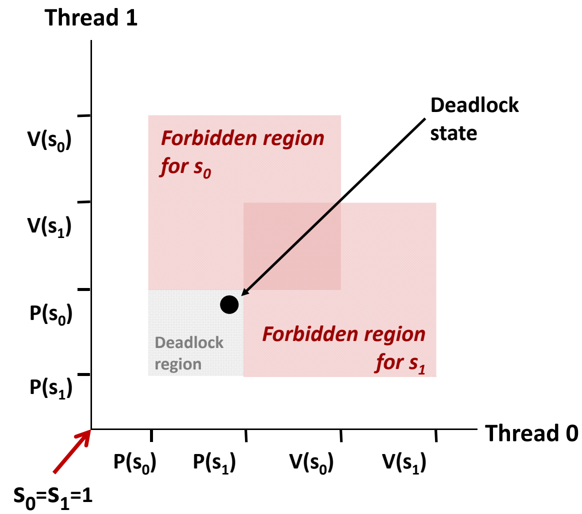
Deadlocking With Semaphores

```
int main()
{
    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);
    exit(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]:	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



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)

Avoiding Deadlock

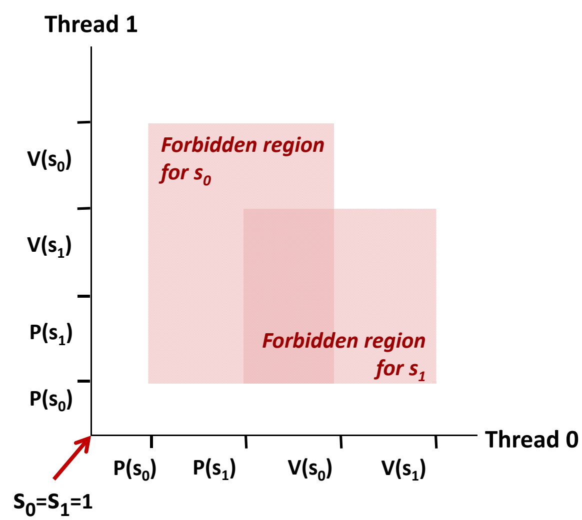
Acquire shared resources in same order

```
int main()
{
    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);
    exit(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]:	Tid[1]:
P(s0);	P(s0);
P(s1);	P(s1);
cnt++;	cnt++;
V(s0);	V(s1);
V(s1);	V(s0);

Avoided Deadlock in Progress Graph



No way for trajectory to get stuck

Processes acquire locks in same order

Order in which locks released immaterial

Today

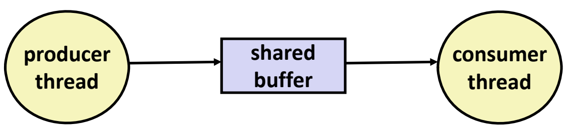
- Races
- Deadlocks
- **Producer-consumer problem**
- Readers-writers problem
- Thread safety

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 MPEG 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

```
#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() {
  pthread_t tid_producer;
  pthread_t tid_consumer;

  /* Initialize the semaphores */
  Sem_init(&shared.empty, 0, 1);
  Sem_init(&shared.full,  0, 0);

  /* Create threads and wait */
  Pthread_create(&tid_producer, NULL,
                 producer, NULL);
  Pthread_create(&tid_consumer, NULL,
                 consumer, NULL);
  Pthread_join(tid_producer, NULL);
  Pthread_join(tid_consumer, NULL);

  exit(0);
}
```

Producer-Consumer 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;
}
```


Counting with Semaphores

- **Remember, it's a non-negative integer**
  - So, values greater than 1 are legal
- **Lets repeat thing_5() 5 times for every 3 of thing_3()**

```
/* thing_5 and thing_3 */
#include "csapp.h"

sem_t five;
sem_t three;

void *five_times(void *arg);
void *three_times(void *arg);
```

```
int main() {
  pthread_t tid_five, tid_three;

  /* initialize the semaphores */
  Sem_init(&five, 0, 5);
  Sem_init(&three,  0, 3);

  /* create threads and wait */
  Pthread_create(&tid_five, NULL,
               five_times, NULL);
  Pthread_create(&tid_three, NULL,
               three_times, NULL);
  .
  .
  .
}
```


Counting with semaphores (cont)

Initially: five = 5, three = 3

```
/* thing_5() thread */
void *five_times(void *arg) {
  int i;

  while (1) {
    for (i=0; i<5; i++) {
      /* wait & thing_5() */
      P(&five);
      thing_5();
    }
    V(&three);
    V(&three);
    V(&three);
  }
  return NULL;
}
```

```
/* thing_3() thread */
void *three_times(void *arg) {
  int i;

  while (1) {
    for (i=0; i<3; i++) {
      /* wait & thing_3() */
      P(&three);
      thing_3();
    }
    V(&five);
    V(&five);
    V(&five);
    V(&five);
    V(&five);
  }
  return NULL;
}
```


Producer-Consumer on an *n*-element Buffer

- **Requires a mutex and two counting semaphores:**
  - `mutex`: enforces mutually exclusive access to the the buffer
  - `slots`: counts the available slots in the buffer
  - `items`: counts the available items in the buffer
- **Implemented using a shared buffer package called `sbuf`.**

sbuf Package - Declarations

```
#include "csapp.h"

typedef struct {
    int *buf;          /* Buffer array */
    int n;             /* Maximum number of slots */
    int front;         /* buf[(front+1)%n] is first item */
    int rear;          /* buf[rear%n] 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 */
    sp->buf[(++sp->rear)%(sp->n)] = 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 */
    item = sp->buf[(++sp->front)%(sp->n)];   /* Remove the item */
    V(&sp->mutex);                           /* Unlock the buffer */
    V(&sp->slots);                           /* Announce available slot */
    return item;
}
```

sbuf.c

Sample program using sbuf

```
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

```
/* 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 locks 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;
}
```


Front and rear are not (really) shared!

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

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;
}
```

Front and rear are not (really) shared!

```
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;
}
```


Front and rear are not (really) shared!

```
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;
}
```


Front and rear are not (really) shared!

```
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?

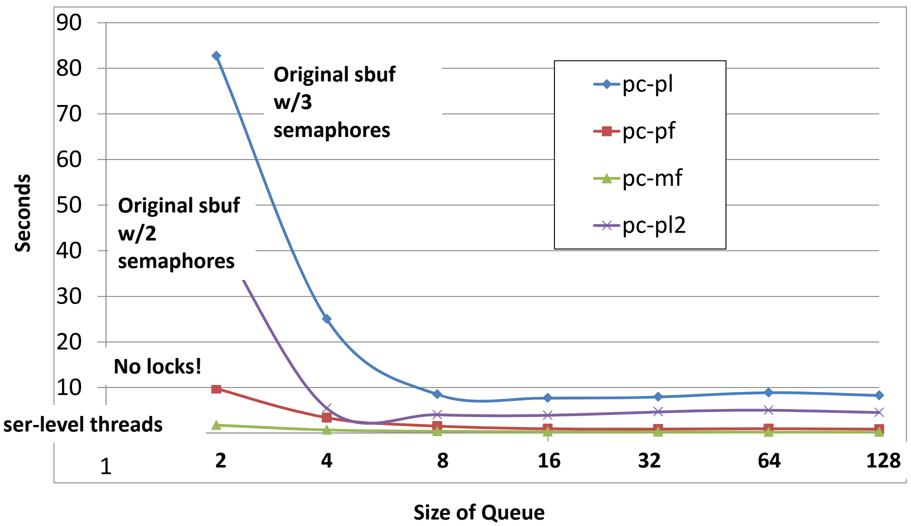
Front and rear are really shared!

```
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?

Timing



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- **Readers-writers problem**
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Readers-Writers Problem

- **Generalization of the mutual exclusion problem**
- **Problem statement:**
  - *Reader* threads only read the object
  - *Writer* threads modify the object
  - 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

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

Today

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- Readers-writers problem
- **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.

```
/* lock-and-copy version */
char *ctime_ts(const time_t *timep,
               char *privatep)
{
    char *sharedp;

    P(&mutex);
    sharedp = ctime(timep);
    strcpy(privatep, sharedp);
    V(&mutex);
    return privatep;
}
```

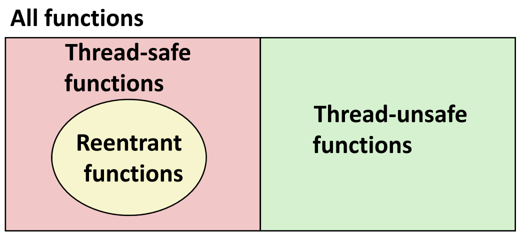
Warning: Some functions like `gethostbyname` require a *deep copy.* Use reentrant *`gethostbyname_r`* version instead.

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

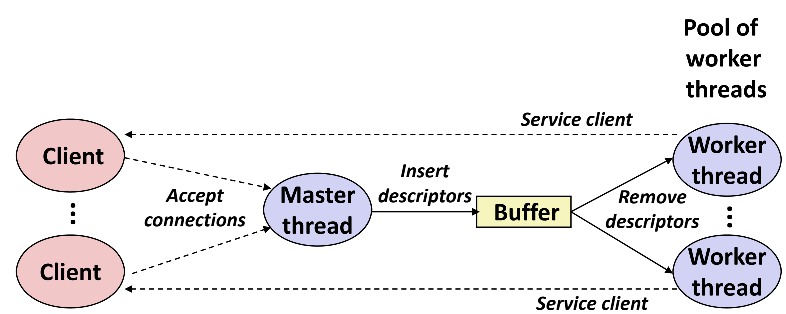
- **All functions in the Standard C Library (at the back of your K&R text) are thread-safe**
  - Examples: `malloc`, `free`, `printf`, `scanf`
- **Most Unix system calls are thread-safe, with a few exceptions:**

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

Case Study: Prethreaded Concurrent Server



Prethreaded Concurrent Server

```
sbuf_t sbuf; /* Shared buffer of connected descriptors */

int main(int argc, char **argv)
{
    int i, listenfd, connfd, port;
    socklen_t clientlen=sizeof(struct sockaddr_in);
    struct sockaddr_in clientaddr;
    pthread_t tid;

    port = atoi(argv[1]);
    sbuf_init(&sbuf, SBUFSIZE);
    listenfd = Open_listenfd(port);

    for (i = 0; i < NTHREADS; i++)  /* Create worker threads */
        Pthread_create(&tid, NULL, thread, NULL);

    while (1) {
        connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
        sbuf_insert(&sbuf, connfd); /* Insert connfd in buffer */
    }
}
```

echoservert_pre.c

Prethreaded Concurrent Server

Worker thread routine:

```
void *thread(void *vargp)
{
    Pthread_detach(pthread_self());
    while (1) {
        int connfd = sbuf_remove(&sbuf); /* Remove connfd from
                                            buffer */
        echo_cnt(connfd);                /* Service client */
        Close(connfd);
    }
}
```

echoservert_pre.c

Prethreaded Concurrent Server

`echo_cnt` initialization routine:

```
static int byte_cnt;  /* Byte counter */
static sem_t mutex;   /* and the mutex that protects it */

static void init_echo_cnt(void)
{
    Sem_init(&mutex, 0, 1);
    byte_cnt = 0;
}
```

echo_cnt.c

Prethreaded Concurrent Server

Worker thread service routine:

```
void echo_cnt(int connfd)
{
    int n;
    char buf[MAXLINE];
    rio_t rio;
    static pthread_once_t once = PTHREAD_ONCE_INIT;

    Pthread_once(&once, init_echo_cnt);
    Rio_readinitb(&rio, connfd);
    while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        P(&mutex);
        byte_cnt += n;
        printf("thread %d received %d (%d total) bytes on fd
%d\n”,
               (int) pthread_self(), n, byte_cnt, connfd);
        V(&mutex);
        Rio_writen(connfd, buf, n);
    }
}
```

echo_cnt.c