

Synchronization: Advanced

15-213 / 18-213: Introduction to Computer Systems
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1

Today

- Races
- Locking and Deadlocks
- Producer-consumer problem
- Readers-writers problem
- Thread safety

2

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

3

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

4

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5

Dining Philosopher's Problem

5 Philosophers sitting at a table
with 5 forks

- 1) Eating (requires two chopsticks)
- 2) Thinking (no chopsticks)
- 3) No thinking + eating

Deadlock and Starvation



Reminder: Semaphores

- **Semaphore:** non-negative global integer synchronization variable
- **Manipulated by P and V operations:**
 - $P(s): [\text{while } (s == 0) \text{ wait}(); s--;]$
 - 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: $(s \geq 0)$**

7

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

8

Test and Set Instruction

- Special Supervisory mode instruction to facilitate Atomic actions
- Can not be interrupted in the middle
 - No need to disable interrupts

```
boolean Test_and_Set( boolean memory[m] )
{
  [
    if( memory[m] )
      return True;
    else {
      memory[m] = True;
      return False;
    }
  ]
}
```

x86 Examples
 xchg
 Cmpxchg
 Xadd
 (use LOCK prefix)

9

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!

10

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);
}
```

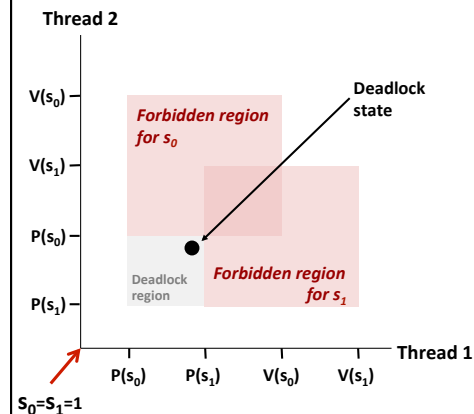
```
void *count(void *vargp)
{
  int i;
  int id = (int) vargp;
  for (i = 0; i < NITERS; i++) {
    P(&mutex[id]); P(&mutex[1-id]);
    cnt++;
    V(&mutex[id]); V(&mutex[1-id]);
  }
  return NULL;
}
```

Tid[0]:
 P(s₀);
 P(s₁);
 cnt++;
 V(s₀);
 V(s₁);

Tid[1]:
 P(s₁);
 P(s₀);
 cnt++;
 V(s₁);
 V(s₀);

11

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 s₀ or s₁ to become nonzero

Other trajectories luck out and skirt the deadlock region

Unfortunate fact: deadlock is often nondeterministic (race)

12

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);
}
```

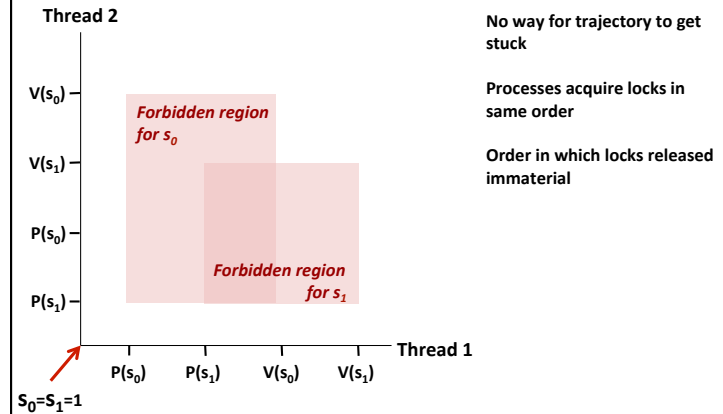
```
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[id]); P(&mutex[1-id]);
        cnt++;
        V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

```
Tid[0]:
P(s0);
P(s1);
cnt++;
V(s0);
V(s1);
```

```
Tid[1]:
P(s0);
P(s1);
cnt++;
V(s1);
V(s0);
```

13

Avoided Deadlock in Progress Graph



14

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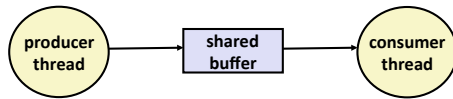
15

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

16

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

17

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);
}
  
```

18

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;
}
  
```

19

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);
    .
    .
    .
}
  
```

20

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;
}
```

21

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`.

22

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

23

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

24

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

25

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

26

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27

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

28

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.**

29

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

30

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31

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

32

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

33

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;
}
```

34

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**

35

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.

36

Thread-Unsafe Functions (Class 4)

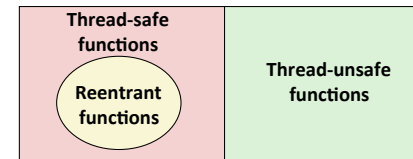
- **Calling thread-unsafe functions**
 - Calling one thread-unsafe function makes the entire function that calls it thread-unsafe
 - Fix: Modify the function so it calls only thread-safe functions ☺

37

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



38

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
<code>asctime</code>	3	<code>asctime_r</code>
<code>ctime</code>	3	<code>ctime_r</code>
<code>gethostbyaddr</code>	3	<code>gethostbyaddr_r</code>
<code>gethostbyname</code>	3	<code>gethostbyname_r</code>
<code>inet_ntoa</code>	3	(none)
<code>localtime</code>	3	<code>localtime_r</code>
<code>rand</code>	2	<code>rand_r</code>

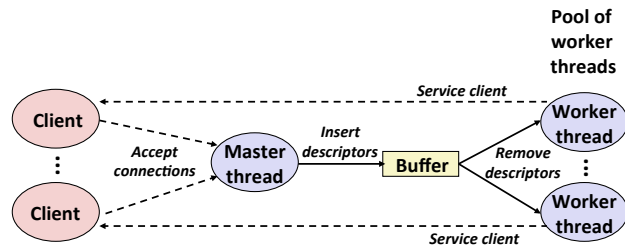
39

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

40

Case Study: Prethreaded Concurrent Server



41

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, SBUF_SIZE);
    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 */
    }
}
  
```

echoserv_pre.c 42

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);
    }
}
  
```

echoserv_pre.c

43

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

44

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

45