# 15-213 Lectures 22 and 23: Synchronization

## Introduction to Computer Systems

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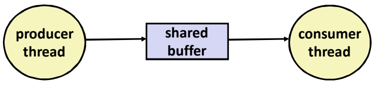
## Introduction

- **Last Time:**
  - Threads
  - Concepts
  - Synchronization with Semaphores
- **Today: Synchronization in Greater Depth**
  - Producer Consumer
  - Buffer Pools and Condition Variables
  - Message Queues
  - Message Passing

## Notifying With Semaphores



- **Common synchronization pattern:**
  - Producer waits for 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 a Buffer That Holds One Item

```
/* buf1.c - 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 (cont)

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, Circular Buffer

```
/* bufn.c - producer-consumer
on n-element buffer */
#include “csapp.h”

#define NITERS 100
#define N 20 /* buffer size */

void *producer(void *arg);
void *consumer(void *arg);

struct {
  int buf[N]; /* 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, N);
  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, Circular Buffer (cont)

Initially, shared.full = 0, shared.empty = N

```
/* 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[i%N] = 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[i%N];
    V(&shared.empty);

    /* consume item */
    printf("consumed %d\n“, item);
  }
  return NULL;
}
```

## Do You Need Semaphores?

```
/* data structure */
int shared;

/* initially */
shared = 0;
```

```
/* producer */
while (shared != 0) ;
shared = any_non_zero_data;


/* consumer */
while (shared == 0) ;
data_to_consume = shared;
shared = 0;
```

- **Notes:**
  - Producer notifies Consumer by writing non-zero
  - Consumer notifies Producer by writing zero
  - Don’t try this at home! (loops, hot-spot)
  - This is just a mental warm-up

## Do You Need Semaphores? (cont)

```
/* data structure */
#define N 20
struct {
  int head;
  int tail;
  int buf[N];
} shared;

/* initiallize */
shared.head = 0;
Shared.tail = 0;
```

```
/* producer */
int i = (shared.tail + 1) % N;
if (i == shared.head) return FAIL;
shared.buf[i] = produced_data;
tail = i; /* atomic update */

/* consumer */
if (shared.tail == shared.head)
    return FAIL;
data_to_consume = shared.buf[shared.head];
/* atomic update: */
shared.head = (shared.head + 1) % N;
```

- **Notes:**
  - Producer notifies Consumer by updating tail
  - Consumer notifies Producer by updating head
  - Data copied in *before* notifying consumer
  - Data copied out *before* notifying producer
  - **What about out-of-order writes?**

## Sharing With Dependencies

- **Threads interact through a resource manager**
- **(Standard terminology: *monitor*)**
- **One thread may need to wait for something another thread provides**
- **Example 1: previous circular buffer**
  - But that had a simple semaphore solution
- **Example 2: memory buffer pool**
  - Multiple threads checking out and returning buffers
  - Might have to wait for buffer of the right size to show up
- **Ultimately, our solution will be: *mutex* and *condition variable***

## Naïve Solution

```
/* protected access to buffer structures */
mutex_t mutex;
Mutex_init(&mutex);

/* get a buffer */
Mutex_lock(&mutex);
Find a suitable buffer
Mutex_unlock(&mutex);

/* return a buffer */
Mutex_lock(&mutex);
Return buffer to pool
Mutex_unlock(&mutex);
```

- **Notes:**
  - mutex_lock is functionally similar to P()
  - mutex_unlock is similar to V()
  - Analog of Mutex_init() is initializing semaphore to 1

---

## What If Resource Is Unavailable?

```
/* protected access to buffer structures */
mutex_t mutex;
Mutex_init(&mutex);

/* get a buffer */
Mutex_lock(&mutex);
while (!Find_a_suitable_buffer()) {
  Mutex_unlock(); Mutex_lock();
}
Reserve the suitable buffer
Mutex_unlock(&mutex);

/* return a buffer */
Mutex_lock(&mutex);
Return buffer to pool
Mutex_unlock(&mutex);
```

- **Bad: spins rather than yielding processor to threads holding the very resources we are waiting for!**

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## What If Resource Is Unavailable? (cont)

```
/* protected access to buffer structures */
mutex_t mutex;
Mutex_init(&mutex);

/* get a buffer */
Mutex_lock(&mutex);
while (!Find_a_suitable_buffer()) {
  Mutex_unlock(); Yield(); Mutex_lock();
}
Reserve the suitable buffer
Mutex_unlock(&mutex);

/* return a buffer */
Mutex_lock(&mutex);
Return buffer to pool
Mutex_unlock(&mutex);
```

- **Better, but not really acceptable. Polls until buffer is available.**

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## How About Waiting for a Notification?

```
/* protected access to buffer structures */
mutex_t mutex;
Mutex_init(&mutex);
int waiting = FALSE;
sem_t rsrc;
Sem_init(&rsrc, 0, 0);

/* get a buffer */
Mutex_lock(&mutex);
while (!Find_a_suitable_buffer()) {
  waiting = TRUE;
  Mutex_unlock(&mutex); P(&rsrc); Mutex_lock(&mutex);
}
Reserve the suitable buffer
Mutex_unlock(&mutex);

/* return a buffer */
Mutex_lock(&mutex);
Return buffer to pool
if (waiting) { waiting = FALSE; V(&rsrc); }
Mutex_unlock(&mutex);
```

---

## How About Waiting for a Notification?

```
/* protected access to buffer structures */
mutex_t mutex;
Mutex_init(&mutex);
```

**Problems:**

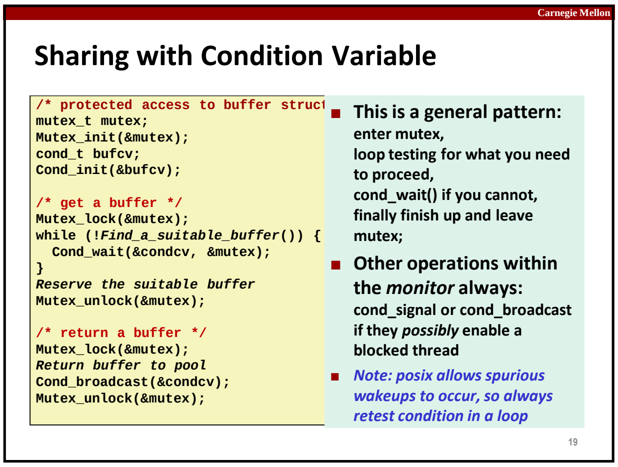
- This will not work with multiple waiting threads
  - `waiting` is only a Boolean
- Hard to analyze
  - Need a more general approach
  - Special-case “hacks” invite obscure bugs

```
/* return a buffer */
Mutex_lock(&mutex);
Return buffer to pool
if (waiting) { waiting = FALSE; V(&rsrc); }
Mutex_unlock(&mutex);
```

---

## Condition Variable

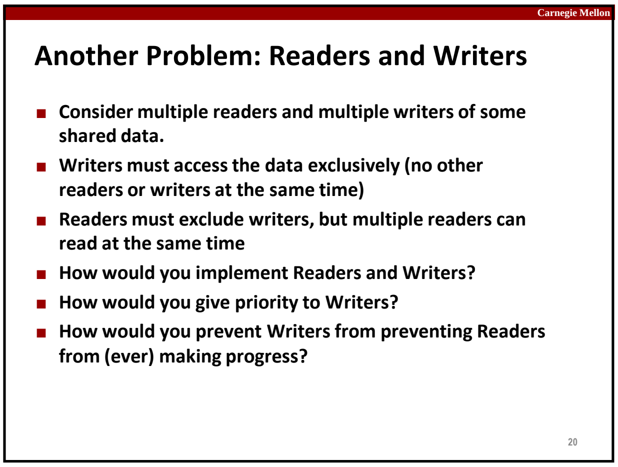
- **Yet another synchronization mechanism**
  - Not a semaphore, not a mutex
  - Not really a “variable”
- **Essentially a queue of waiting/sleeping/suspended threads**
- **Operations:**
  - Cond_wait puts thread on the queue
  - Cond_signal wakes up one thread on the queue (if any)
  - Cond_broadcast wakes up all threads on the queue
- **Special feature of Condition Variables:**
  - Cond_wait atomically puts thread on queue *and* releases a mutex lock
  - Waking up automatically reacquires the lock (!)



## Sharing with Condition Variable

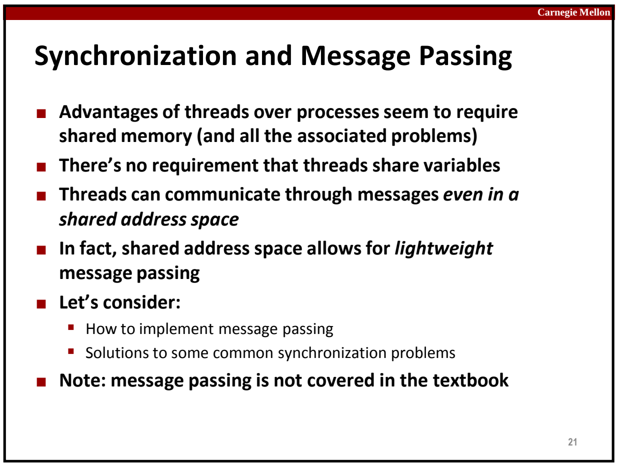
```
/* protected access to buffer struct
mutex_t mutex;
Mutex_init(&mutex);
cond_t bufcv;
Cond_init(&bufcv);

/* get a buffer */
Mutex_lock(&mutex);
while (!Find_a_suitable_buffer()) {
  Cond_wait(&condcv, &mutex);
}
Reserve the suitable buffer
Mutex_unlock(&mutex);

/* return a buffer */
Mutex_lock(&mutex);
Return buffer to pool
Cond_broadcast(&condcv);
Mutex_unlock(&mutex);
```

- This is a general pattern:
  enter mutex,
  loop testing for what you need to proceed,
  cond_wait() if you cannot,
  finally finish up and leave mutex;
- Other operations within the *monitor* always:
  cond_signal or cond_broadcast if they *possibly* enable a blocked thread
- *Note: posix allows spurious wakeups to occur, so always retest condition in a loop*



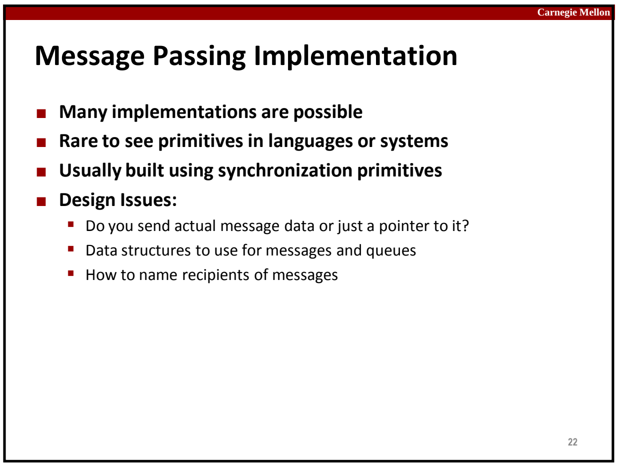
## Another Problem: Readers and Writers

- Consider multiple readers and multiple writers of some shared data.
- Writers must access the data exclusively (no other readers or writers at the same time)
- Readers must exclude writers, but multiple readers can read at the same time
- How would you implement Readers and Writers?
- How would you give priority to Writers?
- How would you prevent Writers from preventing Readers from (ever) making progress?



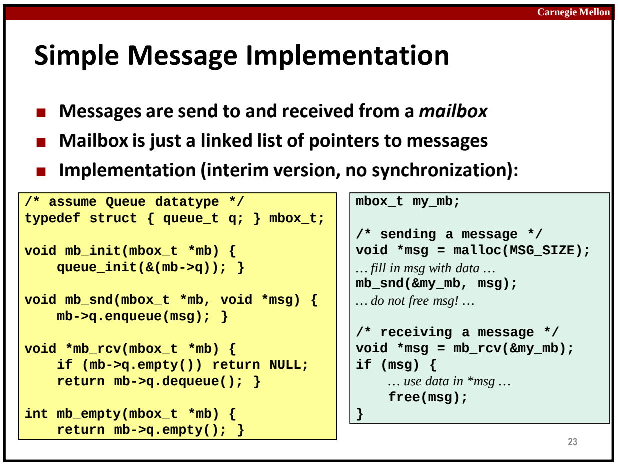
## Synchronization and Message Passing

- Advantages of threads over processes seem to require shared memory (and all the associated problems)
- There's no requirement that threads share variables
- Threads can communicate through messages *even in a shared address space*
- In fact, shared address space allows for *lightweight* message passing
- Let's consider:
  - How to implement message passing
  - Solutions to some common synchronization problems
- Note: message passing is not covered in the textbook



## Message Passing Implementation

- Many implementations are possible
- Rare to see primitives in languages or systems
- Usually built using synchronization primitives
- Design Issues:
  - Do you send actual message data or just a pointer to it?
  - Data structures to use for messages and queues
  - How to name recipients of messages

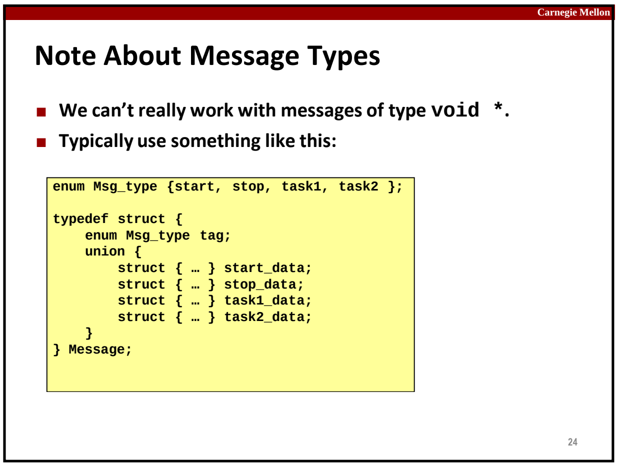


## Simple Message Implementation

- Messages are send to and received from a *mailbox*
- Mailbox is just a linked list of pointers to messages
- Implementation (interim version, no synchronization):

```
/* assume Queue datatype */
typedef struct { queue_t q; } mbox_t;

void mb_init(mbox_t *mb) {
    queue_init(&(mb->q)); }

void mb_snd(mbox_t *mb, void *msg) {
    mb->q.enqueue(msg); }

void *mb_rcv(mbox_t *mb) {
    if (mb->q.empty()) return NULL;
    return mb->q.dequeue(); }

int mb_empty(mbox_t *mb) {
    return mb->q.empty(); }
```

```
mbox_t my_mb;

/* sending a message */
void *msg = malloc(MSG_SIZE);
… fill in msg with data …
mb_snd(&my_mb, msg);
… do not free msg! …

/* receiving a message */
void *msg = mb_rcv(&my_mb);
if (msg) {
    … use data in *msg …
    free(msg);
}
```



## Note About Message Types

- We can't really work with messages of type `void *`.
- Typically use something like this:

```
enum Msg_type {start, stop, task1, task2 };

typedef struct {
    enum Msg_type tag;
    union {
        struct { … } start_data;
        struct { … } stop_data;
        struct { … } task1_data;
        struct { … } task2_data;
    }
} Message;
```

# Synchronization

- **Problem 1: Shared access to Mailboxes (and Queues)**

```
/* assume Queue datatype */
typedef struct { Queue q;
                 sem_t s; } mbox_t;


void mb_init(mbox_t *mb) {
    queue_init(&(mb->q));
    Sem_init(&(mb->s, 0, 1));  }


void mb_snd(mbox_t *mb, void *msg) {
    P(&(mb->s));
    mb->q.enqueue(msg);
    V(&(mb->s)); }
```

```

void *mb_rcv(mbox_t *mb) {
    void *m;
    P(&(mb->s));
    if (mb->q.empty()) {
        V(&(mb->s));
        return NULL;
    }
    m = mb->q.dequeue();
    V(&(mb->s));
}

int mb_empty(mbox_t *mb) {
    int empty;
    P(&(mb->s));
    empty = mb->q.empty();
    V(&(mb->s));
    return empty; }
```

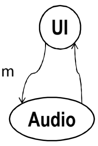
# Synchronization (cont)

- **Problem 2: Waiting for a message: rewrite with condition var**

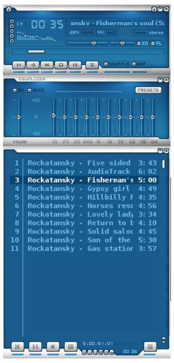
```
/* assume Queue datatype */
typedef struct { Queue q;
                 mutex_t s;
                 cond_t rdy;} mbox_t;


void mb_init(mbox_t *mb) {
    queue_init(&(mb->q));
    Mutex_init(&(mb->s));
    Cond_init(&(mb->rdy));  }


void mb_snd(mbox_t *mb, void *msg) {
    mutex_lock(&(mb->s));
    mb->q.enqueue(msg);
    cond_signal(&(mb->rdy));
    mutex_unlock(&(mb->s)); }
```

```

void *mb_rcv(mbox_t *mb) {
    void *m;
    mutex_lock(&(mb->s));
    while (mb->q.empty()) {
        cond_wait(&(mb->rdy),
                  &(mb->s));
    }
    m = mb->q.dequeue();
    mutex_unlock(&(mb->s));
}

int mb_empty(mbox_t *mb) {
    int empty;
    mutex_lock(&(mb->s));
    empty = mb->q.empty();
    mutex_unlock(&(mb->s));
    return empty; }
```

# Example Message Passing Application



- **Consider an Audio Player**
  - User interface
    - sends filename, EQ, volume, position to audio thread
    - displays song pos. and spectrum
  - Audio thread
    - reads, decodes, plays audio
    - computes spectrum data
- **Possible implementation**
  - 2 mailboxes: one for UI, one for Audio thread
  - Each thread: check for msgs, do work, repeat
  - No shared variables except for mailboxes:
    - No shared access to screen
    - Display updates unlikely to block time-critical audio thread



# Beware of Optimizing Compilers!

**Code From Book**

```
#define NITERS 100000000

/* shared counter variable */
unsigned int cnt = 0;

/* thread routine */
void *count(void *arg)
{
    int i;
    for (i = 0; i < NITERS; i++)
        cnt++;
    return NULL;
}
```

- Global variable `cnt` shared between threads
- Multiple threads could be trying to update within their iterations

**Generated Code**

```
movl     cnt, %ecx
movl     $99999999, %eax
.L6:
   leal  1(%ecx), %edx
   decl  %eax
   movl  %edx, %ecx
   jns   .L6
   movl  %edx, cnt
```

- Compiler moved access to `cnt` out of loop
- Only shared accesses to `cnt` occur before loop (read) or after (write)
- What are possible program outcomes?

# Controlling Optimizing Compilers!

**Revised Book Code**

```
#define NITERS 100000000

/* shared counter variable */
volatile unsigned int cnt = 0;

/* thread routine */
void *count(void *arg)
{
    int i;
    for (i = 0; i < NITERS; i++)
        cnt++;
    return NULL;
}
```

- Declaring variable as volatile forces it to be kept in memory

**Generated Code**

```
   movl $99999999, %edx
.L15:
   movl cnt, %eax
   incl %eax
   decl %edx
   movl %eax, cnt
   jns  .L15
```

- Shared variable read and written each iteration

# Threads Summary

- **Threads provide another mechanism for writing concurrent programs**
- **Threads are very popular**
  - Somewhat cheaper than processes
  - Easy to share data between threads
  - Make use of multiple cores for parallel algorithms
- **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