Operating Systems (A)
(Honor Track)

Lecture 16: Synchronization (III)

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This Lecture

Advanced Synchronization Topics

Messages and barriers

Concurrency mechanisms in Unix and Linux

Classic synchronization problems

Buzz Words

- Message
- Barrier
- Interprocess communication (IPC)
- Pipe
- Signal
- Memory barrier
- Interlock

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Messages

- Simple model of communication and synchronization based on atomic transfer of data across a channel
  - send(destination, &message);
  - receive(source, &message);
- Messages for synchronization are straightforward
- Issues
  - Message lost, ack lost
  - Order
  - Naming
  - Authentication
  - …

Producer-Consumer with Message Passing

```
#define N 100                                   /* number of slots in the buffer */

void producer(void)
{
     int item;
     message m;                                 /* message buffer */

     while (TRUE) {
          item = produce_item( );               /* generate something to put in buffer */
          receive(consumer, &m);                /* wait for an empty to arrive */
          build_message(&m, item);              /* construct a message to send */
          send(consumer, &m);                   /* send item to consumer */
     }
}
```

```
void consumer(void)
{
     int item, i;
     message m;

     for (i = 0; i < N; i++) send(producer, &m);  /* send N empties */
     while (TRUE) {
          receive(producer, &m);                  /* get message containing item */
          item = extract_item(&m);                /* extract item from message */
          send(producer, &m);                     /* send back empty reply */
          consume_item(item);                     /* do something with the item */
     }
}
```

Figure 2-36. The producer-consumer problem with N messages.

Barriers

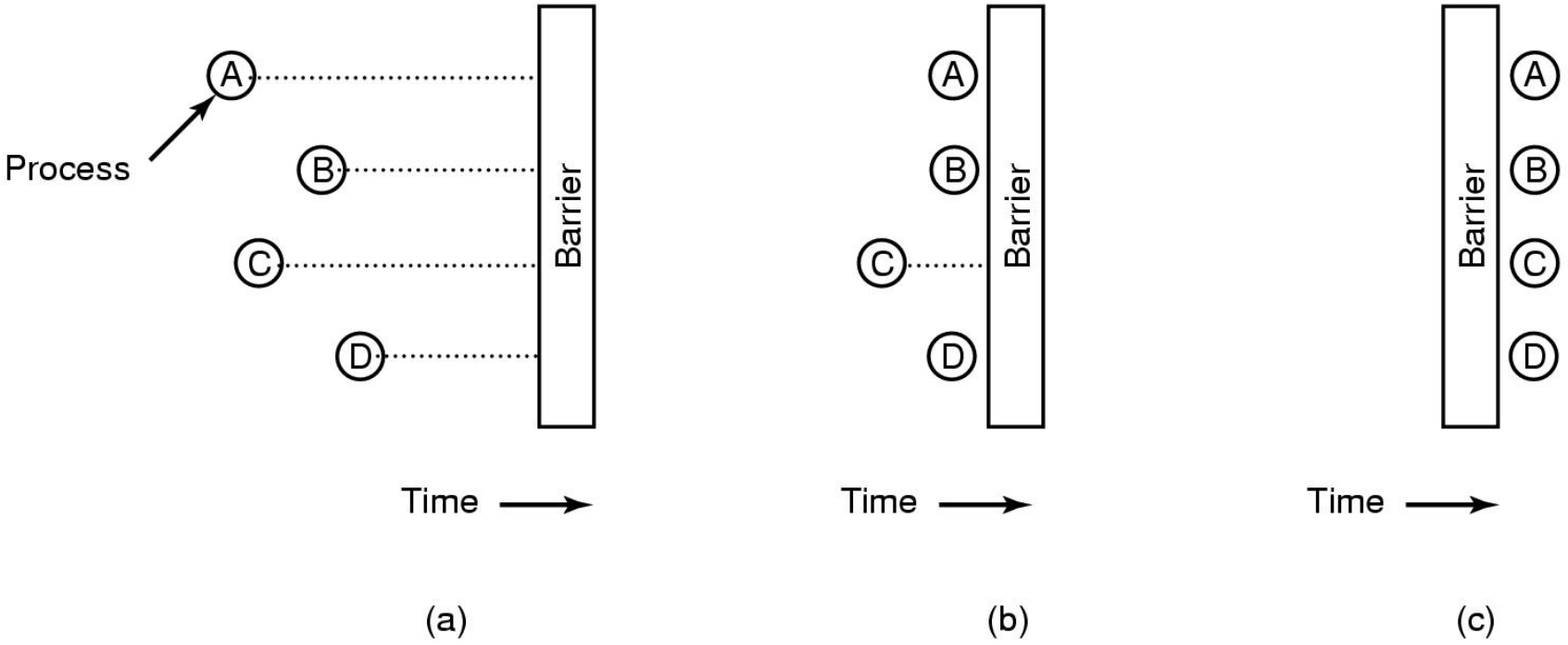

Figure 2-37. Use of a barrier. (a) Processes approaching a barrier. (b) All processes but one blocked at the barrier. (c) When the last process arrives at the barrier, all of them are let through.

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UNIX Concurrency Mechanisms

- UNIX provides a variety of mechanisms for interprocess communication (IPC) and synchronization including:
  - Pipes
  - Messages
  - Shared memory
  - Semaphores
  - Signals

Pipes

- A circular buffer allowing two processes to communicate on the producer-consumer model
  - first-in-first-out queue, written by one process and read by another.
- Two types:
  - Named: mkfifo my_pipe; rm my_pipe
  - Unnamed

Messages

- A block of bytes with an accompanying type
- UNIX provides ***msgsnd*** and ***msgrcv*** system calls for processes to engage in message passing
- Associated with each process is a message queue, which functions like a mailbox

Shared Memory

- A common block of virtual memory shared by multiple processes
- Permission is read-only or read-write for a process
  - determined on a per-process basis
- Mutual exclusion constraints are not part of the shared-memory facility but must be provided by the processes using the shared memory

Semaphores

- System V Release 4 (SVR4) uses a generalization of the ***semWait*** and ***semSignal*** primitives
- Associated with the semaphore are queues of processes blocked on that semaphore

Signals

- A software mechanism that informs a process of the occurrence of asynchronous events.
  - Similar to a hardware interrupt, without priorities
- A signal is delivered by updating a field in the process table for the process to which the signal is being sent

Signals Defined for UNIX SVR4

Value	Name	Description
01	SIGHUP	Hang up; sent to process when kernel assumes that the user of that process is doing no useful work
02	SIGINT	Interrupt
03	SIGQUIT	Quit; sent by user to induce halting of process and production of core dump
04	SIGILL	Illegal instruction
05	SIGTRAP	Trace trap; triggers the execution of code for process tracing
06	SIGIOT	IOT instruction
07	SIGEMT	EMT instruction
08	SIGFPE	Floating-point exception
09	SIGKILL	Kill; terminate process
10	SIGBUS	Bus error
11	SIGSEGV	Segmentation violation; process attempts to access location outside its virtual address space
12	SIGSYS	Bad argument to system call
13	SIGPIPE	Write on a pipe that has no readers attached to it
14	SIGALRM	Alarm clock; issued when a process wishes to receive a signal after a period of time
15	SIGTERM	Software termination
16	SIGUSR1	User-defined signal 1
17	SIGUSR2	User-defined signal 2
18	SIGCHLD	Death of a child
19	SIGPWR	Power failure

Linux Kernel Concurrency Mechanism

- Includes all the mechanisms found in UNIX plus
  - Atomic operations
  - Spinlocks
  - Semaphores (slightly different to SVR4)
  - Memory barriers

Atomic Operations

- Atomic operations execute without interruption and without interference
- Two types:
  - Integer operations – operating on an integer variable
  - Bitmap operations – operating on one bit in a bitmap

Linux Atomic Operations

Atomic Integer Operations	
`ATOMIC_INIT (int i)`	At declaration: initialize an atomic_t to i
`int atomic_read(atomic_t *v)`	Read integer value of v
`void atomic_set(atomic_t *v, int i)`	Set the value of v to integer i
`void atomic_add(int i, atomic_t *v)`	Add i to v
`void atomic_sub(int i, atomic_t *v)`	Subtract i from v
`void atomic_inc(atomic_t *v)`	Add 1 to v
`void atomic_dec(atomic_t *v)`	Subtract 1 from v
`int atomic_sub_and_test(int i, atomic_t *v)`	Subtract i from v; return 1 if the result is zero; return 0 otherwise
`int atomic_add_negative(int i, atomic_t *v)`	Add i to v; return 1 if the result is negative; return 0 otherwise (used for implementing semaphores)
`int atomic_dec_and_test(atomic_t *v)`	Subtract 1 from v; return 1 if the result is zero; return 0 otherwise
`int atomic_inc_and_test(atomic_t *v)`	Add 1 to v; return 1 if the result is zero; return 0 otherwise

Linux Atomic Operations

Atomic Bitmap Operations	
`void set_bit(int nr, void *addr)`	Set bit nr in the bitmap pointed to by addr
`void clear_bit(int nr, void *addr)`	Clear bit nr in the bitmap pointed to by addr
`void change_bit(int nr, void *addr)`	Invert bit nr in the bitmap pointed to by addr
`int test_and_set_bit(int nr, void *addr)`	Set bit nr in the bitmap pointed to by addr; return the old bit value
`int test_and_clear_bit(int nr, void *addr)`	Clear bit nr in the bitmap pointed to by addr; return the old bit value
`int test_and_change_bit(int nr, void *addr)`	Invert bit nr in the bitmap pointed to by addr; return the old bit value
`int test_bit(int nr, void *addr)`	Return the value of bit nr in the bitmap pointed to by addr

Spinlock

- Only one thread at a time can acquire a spinlock
  - Any other thread will keep trying (spinning) until it can acquire the lock
- A spinlock is an integer
  - If 0, the thread sets the value to 1 and enters its critical section
  - If the value is nonzero, the thread continually checks the value until it is zero

Linux Spinlocks

`void spin_lock(spinlock_t *lock)`	Acquires the specified lock, spinning if needed until it is available
`void spin_lock_irq(spinlock_t *lock)`	Like spin_lock, but also disables interrupts on the local processor
`void spin_lock_irqsave(spinlock_t *lock, unsigned long flags)`	Like spin_lock_irq, but also saves the current interrupt state in flags
`void spin_lock_bh(spinlock_t *lock)`	Like spin_lock, but also disables the execution of all bottom halves
`void spin_unlock(spinlock_t *lock)`	Releases given lock
`void spin_unlock_irq(spinlock_t *lock)`	Releases given lock and enables local interrupts
`void spin_unlock_irqrestore(spinlock_t *lock, unsigned long flags)`	Releases given lock and restores local interrupts to given previous state
`void spin_unlock_bh(spinlock_t *lock)`	Releases given lock and enables bottom halves
`void spin_lock_init(spinlock_t *lock)`	Initializes given spinlock
`int spin_trylock(spinlock_t *lock)`	Tries to acquire specified lock; returns nonzero if lock is currently held and zero otherwise
`int spin_is_locked(spinlock_t *lock)`	Returns nonzero if lock is currently held and zero otherwise

Semaphores

- Similar to UNIX SVR4 but also provides an implementation of semaphores for its own use
- Three types of kernel semaphores
  - Binary semaphores
  - Counting semaphores
  - Reader-writer semaphores
    - Allows multiple readers into the critical section but only one writer at any given time.
    - "struct rw_semaphore"

Linux Kernel Semaphores

Traditional Semaphores	
`void sema_init(struct semaphore *sem, int count)`	Initializes the dynamically created semaphore to the given count
`void init_MUTEX(struct semaphore *sem)`	Initializes the dynamically created semaphore with a count of 1 (initially unlocked)
`void init_MUTEX_LOCKED(struct semaphore *sem)`	Initializes the dynamically created semaphore with a count of 0 (initially locked)
`void down(struct semaphore *sem)`	Attempts to acquire the given semaphore, entering uninterruptible sleep if semaphore is unavailable
`int down_interruptible(struct semaphore *sem)`	Attempts to acquire the given semaphore, entering interruptible sleep if semaphore is unavailable; returns -EINTR value if a signal other than the result of an up operation is received.
`int down_trylock(struct semaphore *sem)`	Attempts to acquire the given semaphore, and returns a nonzero value if semaphore is unavailable
`void up(struct semaphore *sem)`	Releases the given semaphore
Reader-Writer Semaphores	
`void init_rwsem(struct rw_semaphore, *rwsem)`	Initalizes the dynamically created semaphore with a count of 1
`void down_read(struct rw_semaphore, *rwsem)`	Down operation for readers
`void up_read(struct rw_semaphore, *rwsem)`	Up operation for readers
`void down_write(struct rw_semaphore, *rwsem)`	Down operation for writers
`void up_write(struct rw_semaphore, *rwsem)`	Up operation for writers

Memory Barriers

- To enforce the order in which instructions are executed, Linux provides the memory barrier facility

Table 6.6 Linux Memory Barrier Operations

`rmb()`	Prevents loads from being reordered across the barrier
`wmb()`	Prevents stores from being reordered across the barrier
`mb()`	Prevents loads and stores from being reordered across the barrier
`Barrier()`	Prevents the compiler from reordering loads or stores across the barrier
`smp_rmb()`	On SMP, provides a `rmb()` and on UP provides a `barrier()`
`smp_wmb()`	On SMP, provides a `wmb()` and on UP provides a `barrier()`
`smp_mb()`	On SMP, provides a `mb()` and on UP provides a `barrier()`

SMP = symmetric multiprocessor
UP = uniprocessor

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Classic Synchronization Problems

- *Bounded Buffer* problem
- *Dining Philosophers* problem
- *Sleeping Barber* problem

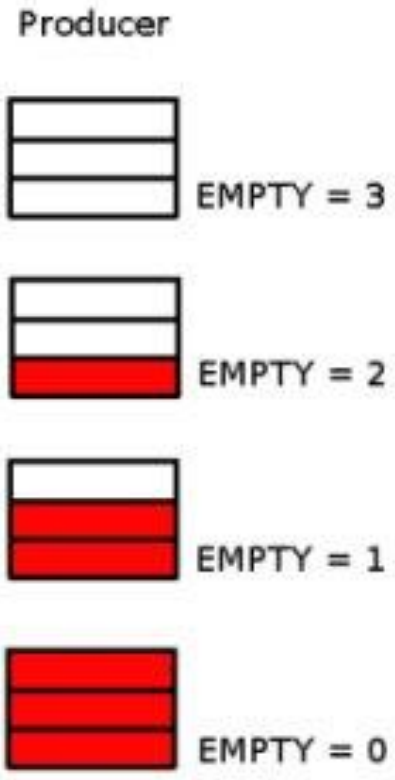
Bounded Buffer Problem (1/5)

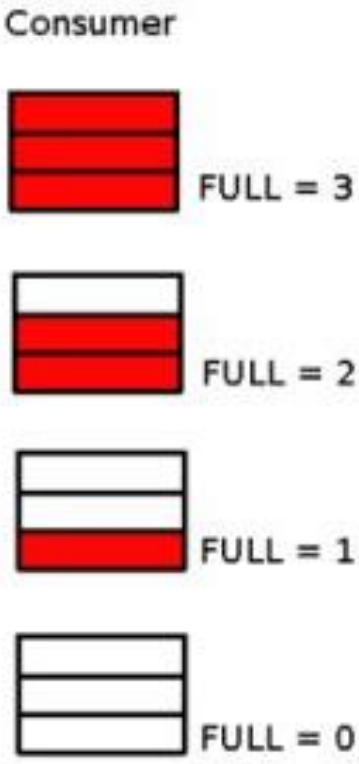
- Problem: there is a set of resource buffers shared by producer and consumer threads
  - Producer inserts resources into the buffer set
    - Output, disk blocks, memory pages, processes, etc.
  - Consumer removes resources from the buffer set
    - Whatever is generated by the producer
- Producer and consumer execute at different rates
  - No serialization of one behind the other
  - Tasks are independent (easier to think about)
  - The buffer set allows each to run without explicit handoff
- Safety:
  - If *nc* is number consumed, *np* number produced, and N the size of the buffer, then $0 \leq np - nc \leq N$

Bounded Buffer Problem (2/5)

- Use three semaphores:
  - empty – count of empty buffers
    - Counting semaphore
    - empty = N – (np-nc)
  - full – count of full buffers
    - Counting semaphore
    - *np* - *nc* = full
  - mutex – mutual exclusion to shared set of buffers
    - Binary semaphore

Bounded Buffer Problem (3/5)





Producer decrements EMPTY and blocks when buffer is full since the semaphore is at 0

Consumer decrements FULL and Blocks when buffer has no item Since the semaphore FULL is at 0

Bounded Buffer Problem (4/5)

```
Semaphore mutex = 1;   // mutual exclusion to shared set of buffers
Semaphore empty = N;   // count of empty buffers (all empty to start)
Semaphore full = 0;    // count of full buffers (none full to start)
```

```
producer {
  while (1) {
    Produce new resource;
    P(empty); // wait for empty buffer
    P(mutex); // lock buffer list
    Add resource to an empty buffer;
    V(mutex); // unlock buffer list
    V(full);  // note a full buffer
  }
}
```

```
consumer {
  while (1) {
    P(full);  // wait for a full buffer
    P(mutex); // lock buffer list
    Remove resource from a full buffer;
    V(mutex); // unlock buffer list
    V(empty); // note an empty buffer
    Consume resource;
  }
}
```

Bounded Buffer Problem (5/5)

- Why need the mutex at all?
- Where are the critical sections?

- What happens if operations on mutex and full/empty are switched around?
  - The pattern of P/V on full/empty is a common construct often called an interlock
- Why V(full) and V(empty)?

- Producer-Consumer and Bounded Buffer are classic examples of synchronization problems

Dining Philosophers: An Intellectual Game

- Philosophers eat/think
- Eating needs 2 forks
- Pick one fork at a time
- Possible deadlock?
- How to prevent deadlock?

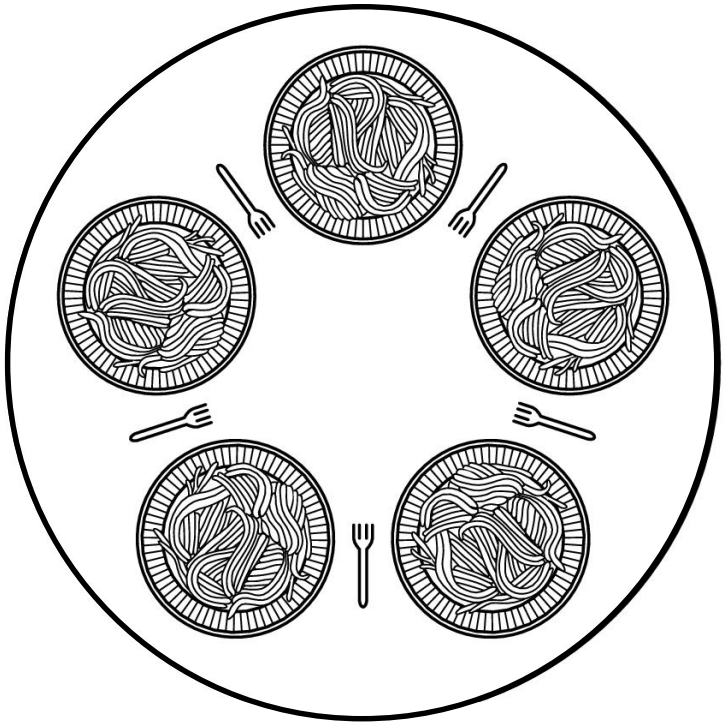


Figure 2-44. Lunch time in the Philosophy Department.

Does It Solve the Dining Philosophers Problem?


```
#define N 5                                   /* number of philosophers */

void philosopher(int i)                       /* i: philosopher number, from 0 to 4 */
{
        while (TRUE) {
                think( );                     /* philosopher is thinking */
                take_fork(i);                 /* take left fork */
                take_fork((i+1) % N);         /* take right fork; % is modulo operator */
                eat( );                       /* yum-yum, spaghetti */
                put_fork(i);                  /* put left fork back on the table */
                put_fork((i+1) % N);          /* put right fork back on the table */
        }
}
```

Figure 2-45. A nonsolution to the dining philosophers problem.

Dining Philosophers Solution (1/2)

```
#define N                5                  /* number of philosophers */
#define LEFT             (i+N−1)%N          /* number of i's left neighbor */
#define RIGHT            (i+1)%N            /* number of i's right neighbor */
#define THINKING         0                  /* philosopher is thinking */
#define HUNGRY           1                  /* philosopher is trying to get forks */
#define EATING           2                  /* philosopher is eating */
typedef int semaphore;                      /* semaphores are a special kind of int */
int state[N];                               /* array to keep track of everyone's state */
semaphore mutex = 1;                        /* mutual exclusion for critical regions */
semaphore s[N];                             /* one semaphore per philosopher */

void philosopher(int i)                     /* i: philosopher number, from 0 to N−1 */
{
    while (TRUE) {                          /* repeat forever */
        think( );                           /* philosopher is thinking */
        take_forks(i);                      /* acquire two forks or block */
        eat( );                             /* yum-yum, spaghetti */
        put_forks(i);                       /* put both forks back on table */
    }
}
```

Figure 2-46. A solution to the dining philosophers problem.

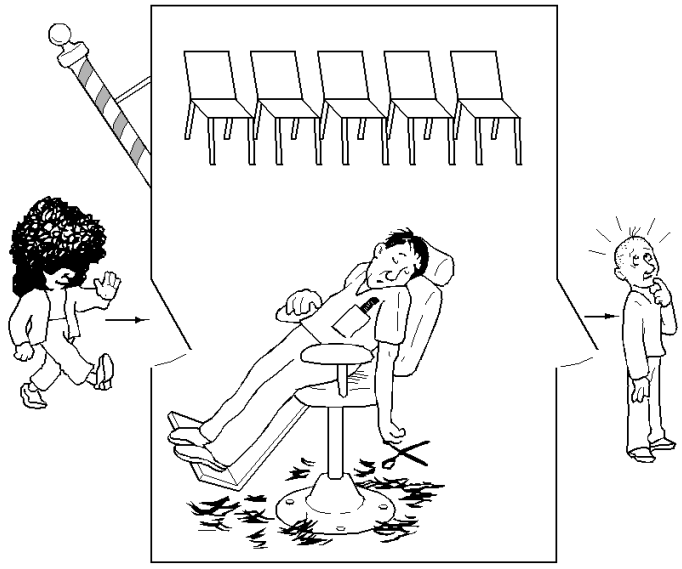
Dining Philosophers Solution (2/2)

```
void take_forks(int i)                    /* i: philosopher number, from 0 to N–1 */
{
      down(&mutex);                       /* enter critical region */
      state[i] = HUNGRY;                  /* record fact that philosopher i is hungry */
      test(i);                            /* try to acquire 2 forks */
      up(&mutex);                         /* exit critical region */
      down(&s[i]);                        /* block if forks were not acquired */
}

void put_forks(i)                         /* i: philosopher number, from 0 to N–1 */
{
      down(&mutex);                       /* enter critical region */
      state[i] = THINKING;                /* philosopher has finished eating */
      test(LEFT);                         /* see if left neighbor can now eat */
      test(RIGHT);                        /* see if right neighbor can now eat */
      up(&mutex);                         /* exit critical region */
}

void test(i)                              /* i: philosopher number, from 0 to N–1 */
{
      if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
            state[i] = EATING;
            up(&s[i]);
      }
}
```

Figure 2-46. A solution to the dining philosophers problem.

The Sleeping Barber Problem

- *N* customer chairs
  - Customer waiting if there is a free chair
  - Otherwise leave the shop
- One barber
  - can cut one customer's hair at any time
  - If no customer, goes to sleep



The Sleeping Barber Solution 1/3

```
#define CHAIRS 5                    /* # chairs for waiting customers */

typedef int semaphore;              /* use your imagination */

semaphore customers = 0;            /* # of customers waiting for service */
semaphore barbers = 0;              /* # of barbers waiting for customers */
semaphore mutex = 1;                /* for mutual exclusion */
int waiting = 0;                    /* customers are waiting (not being cut) */
```

The Sleeping Barber Solution 2/3

```
void barber(void)
{
    while (TRUE) {
        down(&customers);          /* go to sleep if # of customers is 0 */
        down(&mutex);              /* acquire access to 'waiting' */
        waiting = waiting – 1;     /* decrement count of waiting customers */
        up(&barbers);              /* one barber is now ready to cut hair */
        up(&mutex);                /* release 'waiting' */
        cut_hair( );               /* cut hair (outside critical region) */
    }
}
```

The Sleeping Barber Solution 3/3

```
void customer(void)
{
      down(&mutex);                    /* enter critical region */
      if (waiting < CHAIRS) {          /* if there are no free chairs, leave */
            waiting = waiting + 1;     /* increment count of waiting customers */
            up(&customers);            /* wake up barber if necessary */
            up(&mutex);                /* release access to 'waiting' */
            down(&barbers);            /* go to sleep if # of free barbers is 0 */
            get_haircut( );            /* be seated and be serviced */
      } else {
            up(&mutex);                /* shop is full; do not wait */
      }
}
```

Summary

- Messages and barriers
- Concurrency mechanisms in Unix and Linux
- Classic synchronization problems

- Next lecture: Deadlocks