Chapter 2

Processes and Threads

2.1 Processes

2.2 Threads

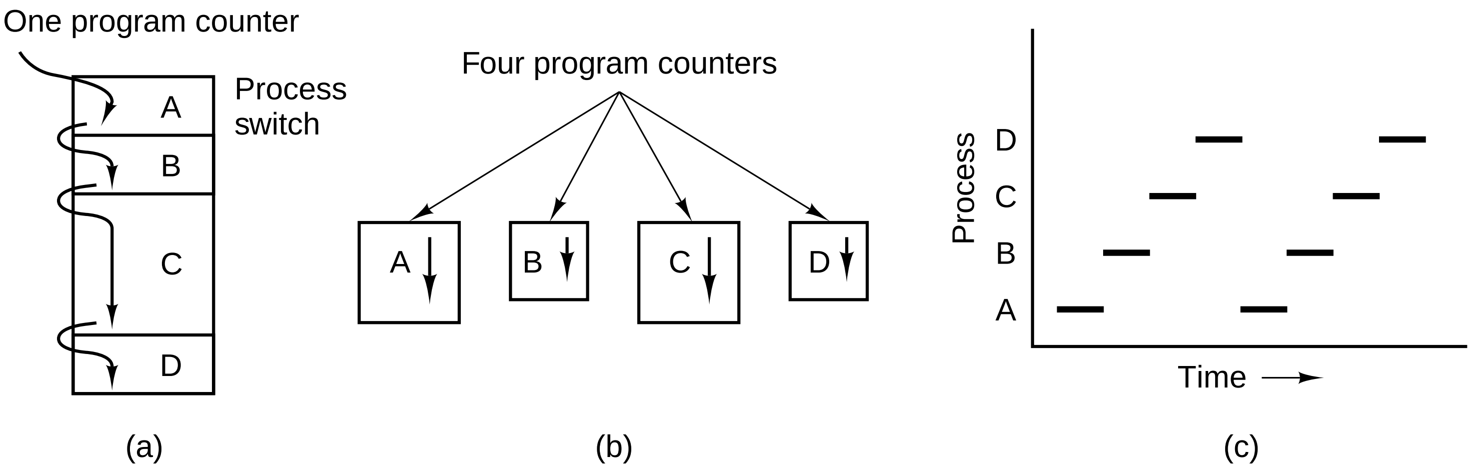
2.3 Interprocess communication

2.4 Classical IPC problems

2.5 Scheduling

Processes

The Process Model



(a) Multiprogramming of four programs

(b) Conceptual model of 4 independent, sequential processes

(c) Only one program active at any instant

Process Creation

Principal events that cause process creation

1. System initialization
2. Execution of a process creation system call by a running process
3. User request to create a new process
4. Initiation of a batch job

Parent and child processes do not share address space

Process Termination

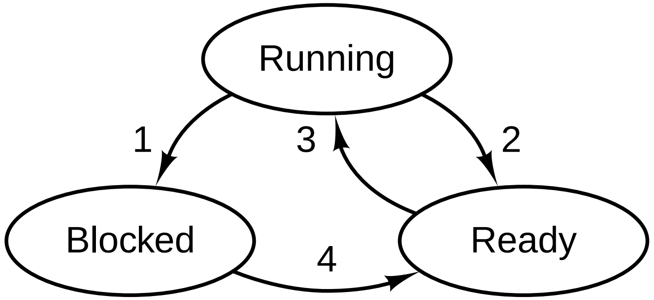
Conditions which terminate processes

1. Normal exit (voluntary)
2. Error exit (voluntary)
    - Error caused in the application
3. Fatal error (involuntary)
4. Killed by another process (involuntary)

Process Hierarchies

- Parent creates a child process, child processes can create its own process
- Forms a hierarchy
  - UNIX calls this a “process group”
- Windows has no concept of process hierarchy
  - all processes are created equal
- Init
  - 1st process created after boot

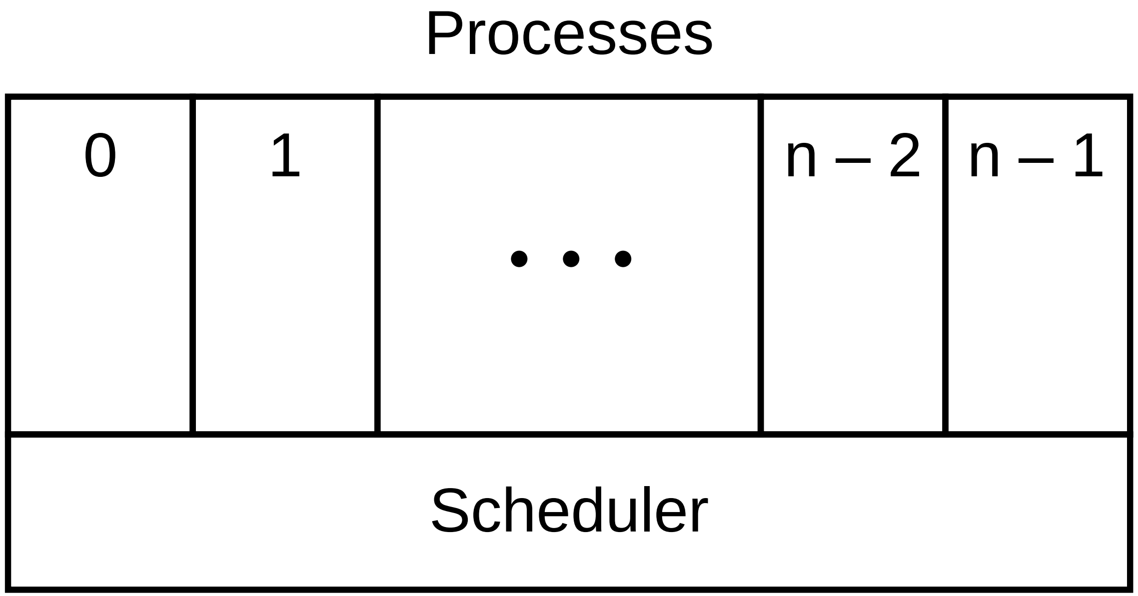
Process States (1)



1. Process blocks for input
2. Scheduler picks another process
3. Scheduler picks this process
4. Input becomes available

- Possible process states
  - running
  - blocked
  - ready
- Transitions between states shown

Process States (2)



Processes

0

1

. . .

n – 2

n – 1

Scheduler

- Lowest layer of process-structured OS
  - handles interrupts, scheduling
- Above that layer are sequential processes

Implementation of Processes (1)

Process management	**Memory management**	**File management**
Registers	Pointer to text segment	Root directory
Program counter	Pointer to data segment	Working directory
Program status word	Pointer to stack segment	File descriptors
Stack pointer		User ID
Process state		Group ID
Priority		
Scheduling parameters		
Process ID		
Parent process		
Process group		
Signals		
Time when process started		
CPU time used		
Children’s CPU time		
Time of next alarm		

Fields of a process table entry

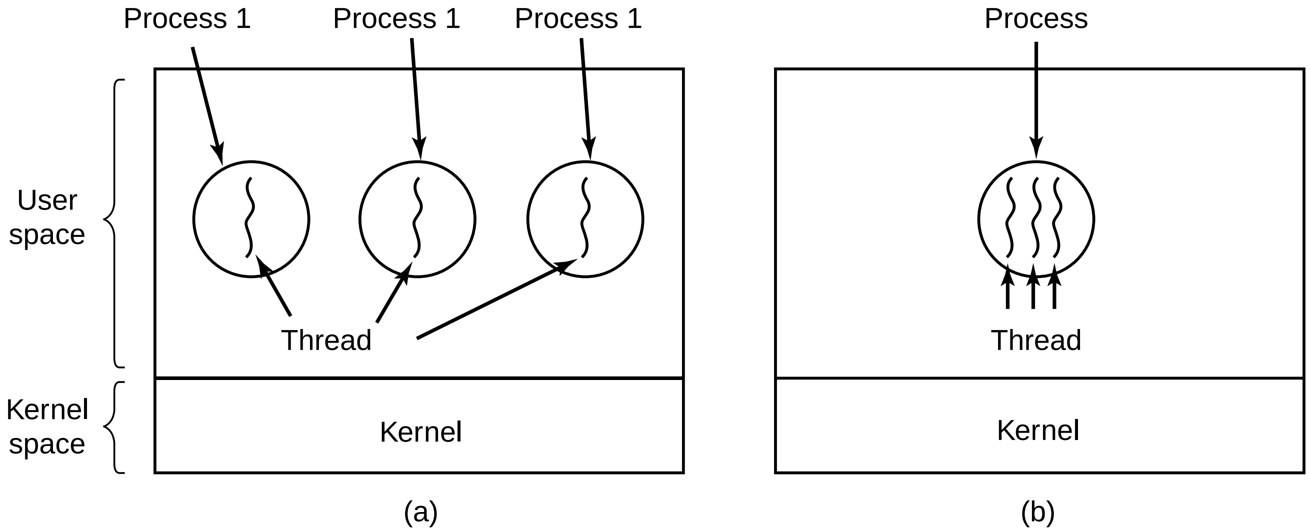
Implementation of Processes (2)

1. Hardware stacks program counter, etc.
2. Hardware loads new program counter from interrupt vector.
3. Assembly language procedure saves registers.
4. Assembly language procedure sets up new stack.
5. C interrupt service runs (typically reads and buffers input).
6. Scheduler decides which process is to run next.
7. C procedure returns to the assembly code.
8. Assembly language procedure starts up new current process.

Skeleton of what lowest level of OS does when an interrupt occurs (context switching)

Threads

The Thread Model (1)



(a) Three processes each with one thread

(b) One process with three threads

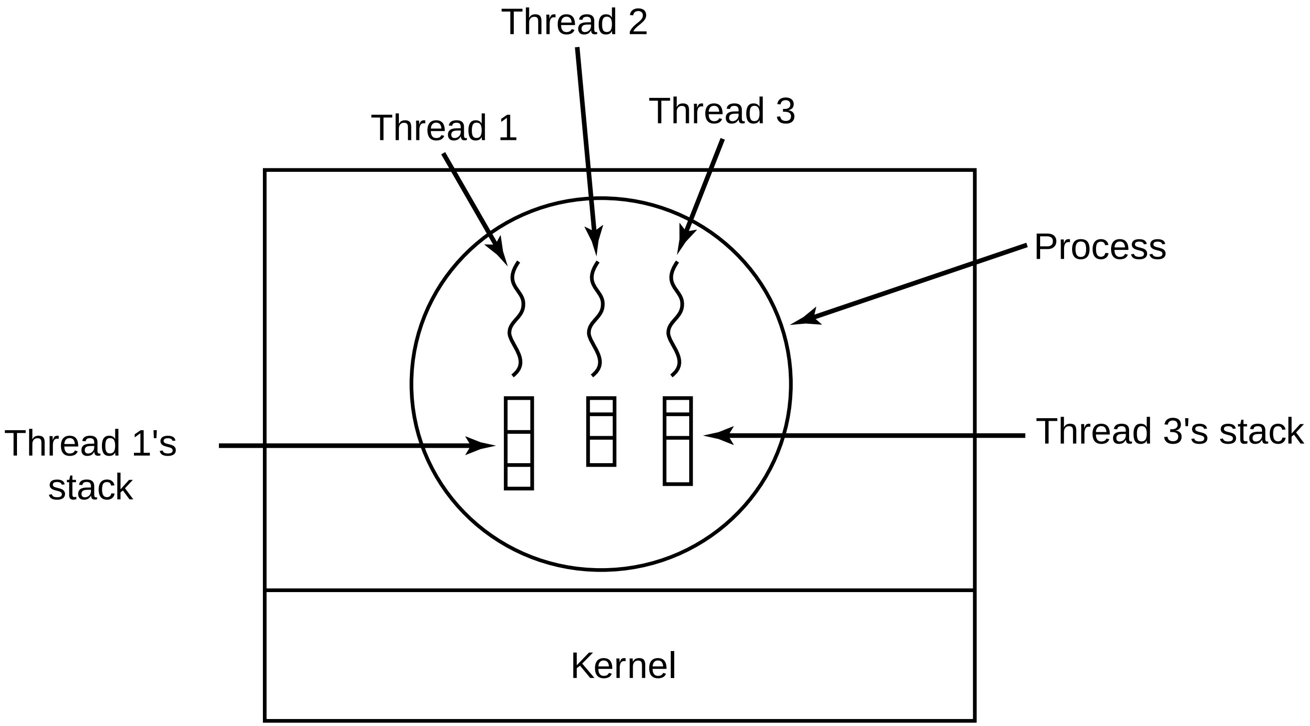
- Process
  - Resource grouping
  - Execution

The Thread Model (2)

Per process items	**Per thread items**
Address space	Program counter
Global variables	Registers
Open files	Stack
Child processes	State
Pending alarms	
Signals and signal handlers	
Accounting information	

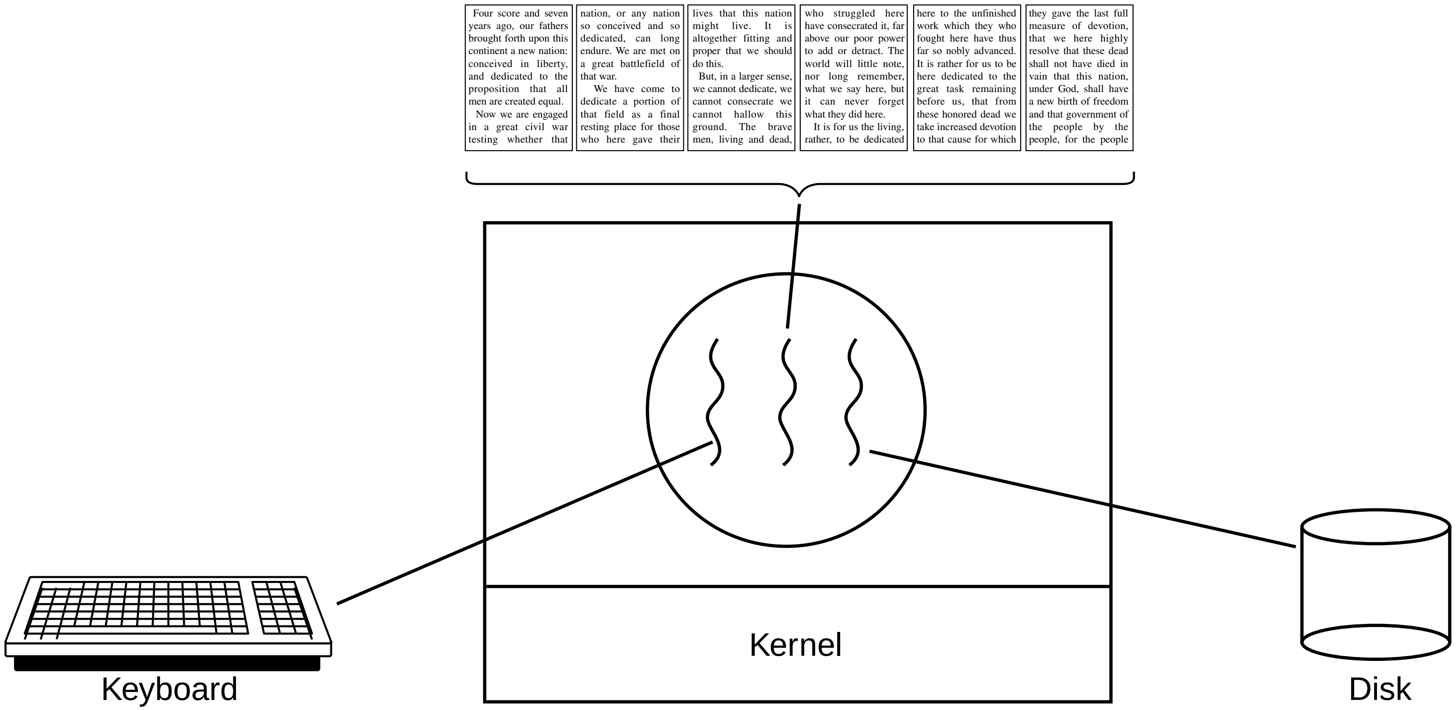
- Items shared by all threads in a process
- Items private to each thread

The Thread Model (3)



Each thread has its own stack

Thread Usage (1)



Four score and seven years ago, our fathers brought forth upon this continent a new nation: conceived in liberty, and dedicated to the proposition that all men are created equal.

Now we are engaged in a great civil war testing whether that nation, or any nation so conceived and so dedicated, can long endure. We are met on a great battlefield of that war.

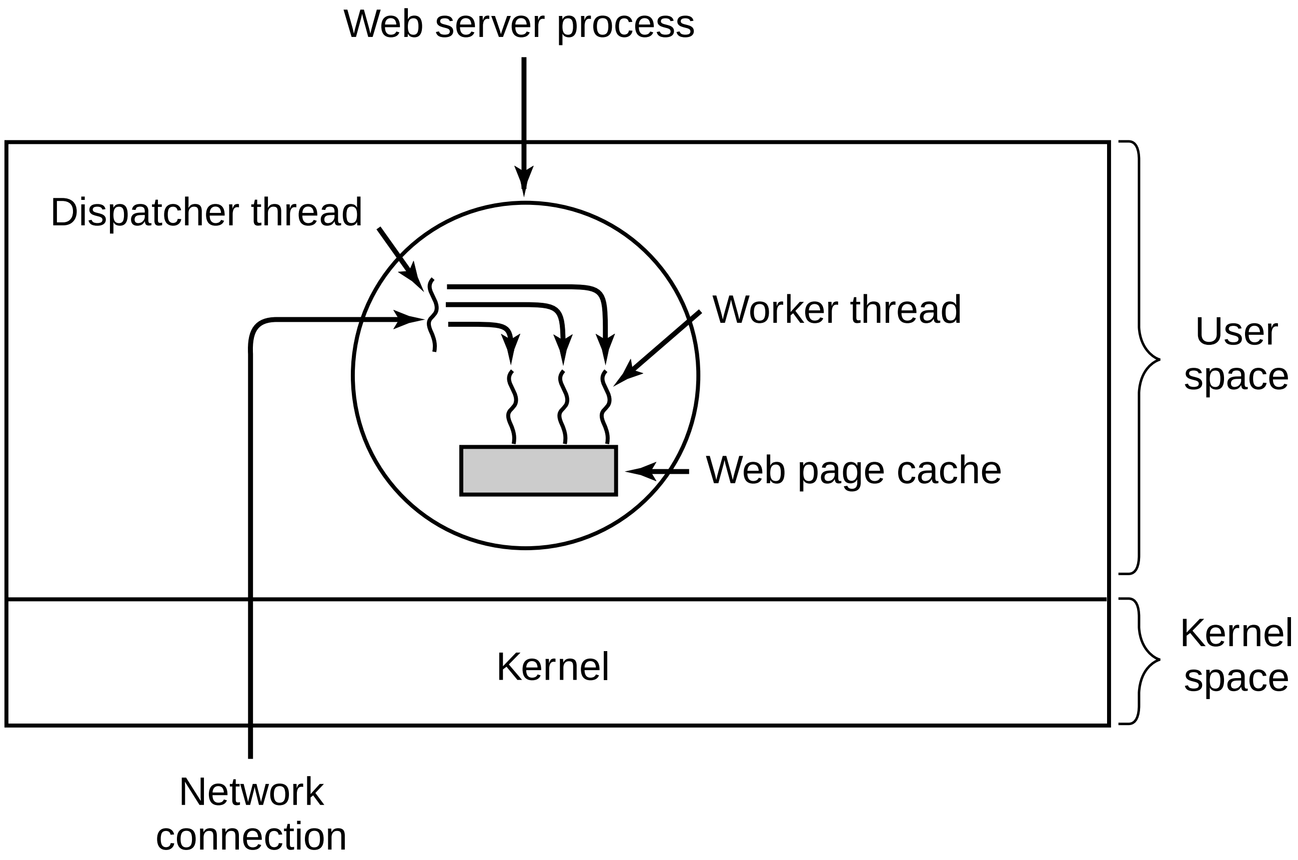
We have come to dedicate a portion of that field as a final resting place for those who here gave their lives that this nation might live. It is altogether fitting and proper that we should do this.

But, in a larger sense, we cannot dedicate, we cannot consecrate we cannot hallow this ground. The brave men, living and dead, who struggled here have consecrated it, far above our poor power to add or detract. The world will little note, nor long remember, what we say here, but it can never forget what they did here.

It is for us the living, rather, to be dedicated here to the unfinished work which they who fought here have thus far so nobly advanced. It is rather for us to be here dedicated to the great task remaining before us, that from these honored dead we take increased devotion to that cause for which they gave the last full measure of devotion, that we here highly resolve that these dead shall not have died in vain that this nation, under God, shall have a new birth of freedom and that government of the people by the people, for the people

A word processor with three threads

Thread Usage (2)



A multithreaded Web server

Thread Usage (3)

```
while (TRUE) {
    get_next_request(&buf);
    handoff_work(&buf);
}
```

(a)

```
while (TRUE) {
    wait_for_work(&buf)
    look_for_page_in_cache(&buf, &page);
    if (page_not_in_cache(&page))
        read_page_from_disk(&buf, &page);
    return_page(&page);
}
```

(b)

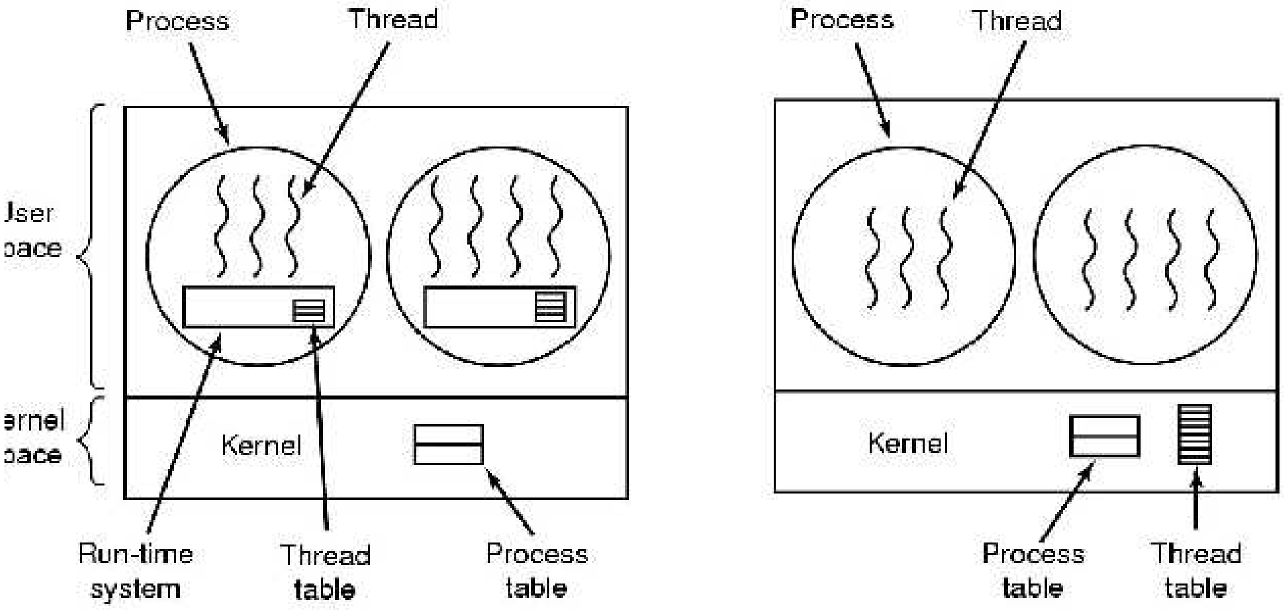
- Rough outline of code for previous slide
    - (a) Dispatcher thread
    - (b) Worker thread

Thread Usage (4)

Model	**Characteristics**
Threads	Parallelism, blocking system calls
Single-threaded process	No parallelism, blocking system calls
Finite-state machine	Parallelism, nonblocking system calls, interrupts

Three ways to construct a server

Implementing Threads(1)



- Implementing Threads in User Space
  - A user-level threads package
- Implementing Threads in the Kernel
  - A threads package managed by the kernel

Implementing Threads(2)

Implementing Threads in User Space

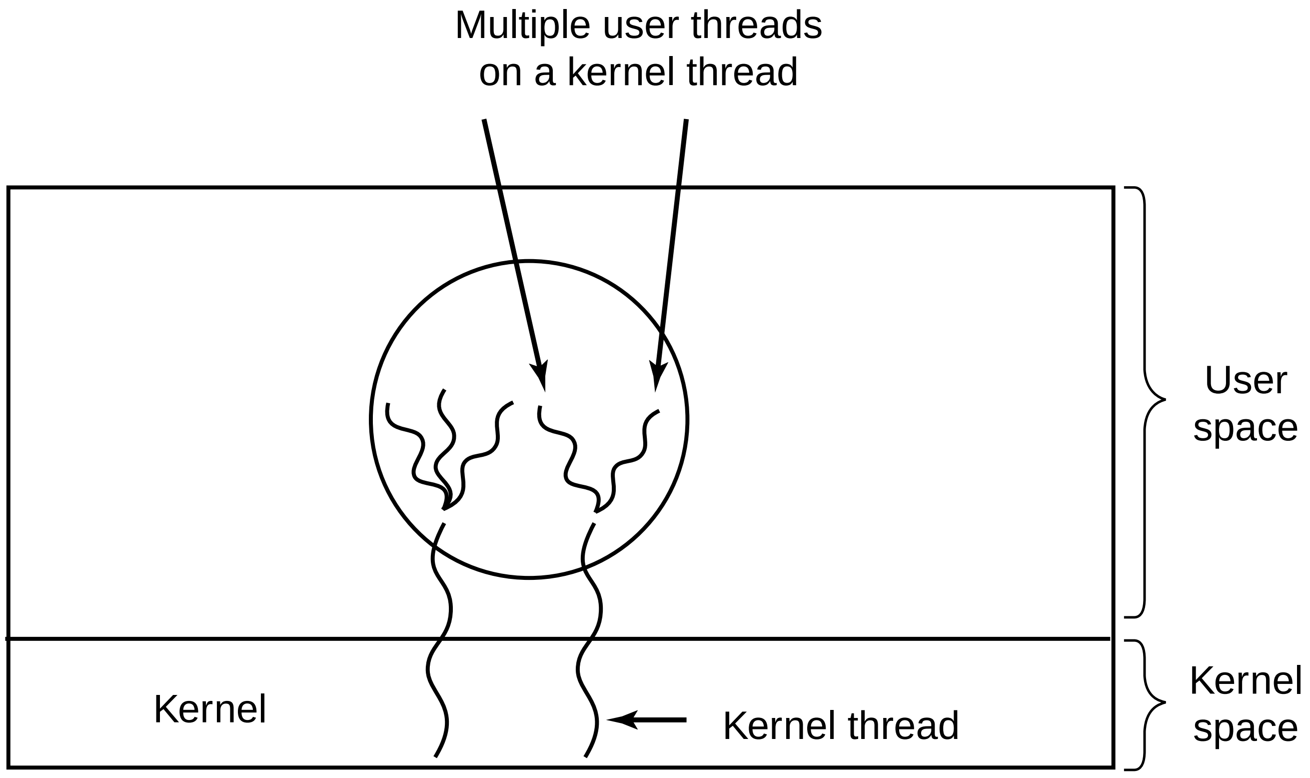
- Adv.
  - Thread scheduling and switching are fast (low overhead)
  - flexible scheduling algorithm
- Disadvantage
  - A system call blocks all threads in the same process
  - Page fault of a thread
  - No fairness granted in thread scheduling

Implementing Threads(3)

Implementing Threads in the Kernel

- Advantage
  - System call causes switching between thread
  - Kernel controls thread scheduling
    (e.g. thread from same or different process)
- Disadvantage
  - Higher overhead in thread switching

Hybrid Implementations

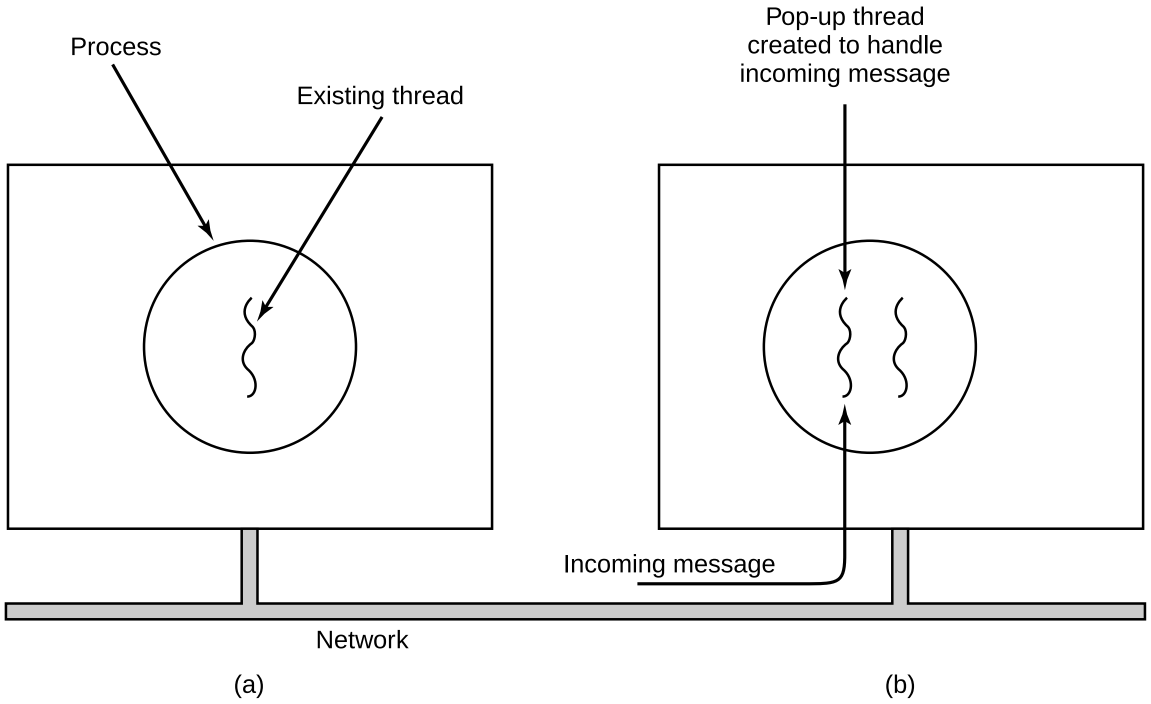


Multiplexing user-level threads onto kernel- level threads

Scheduler Activations

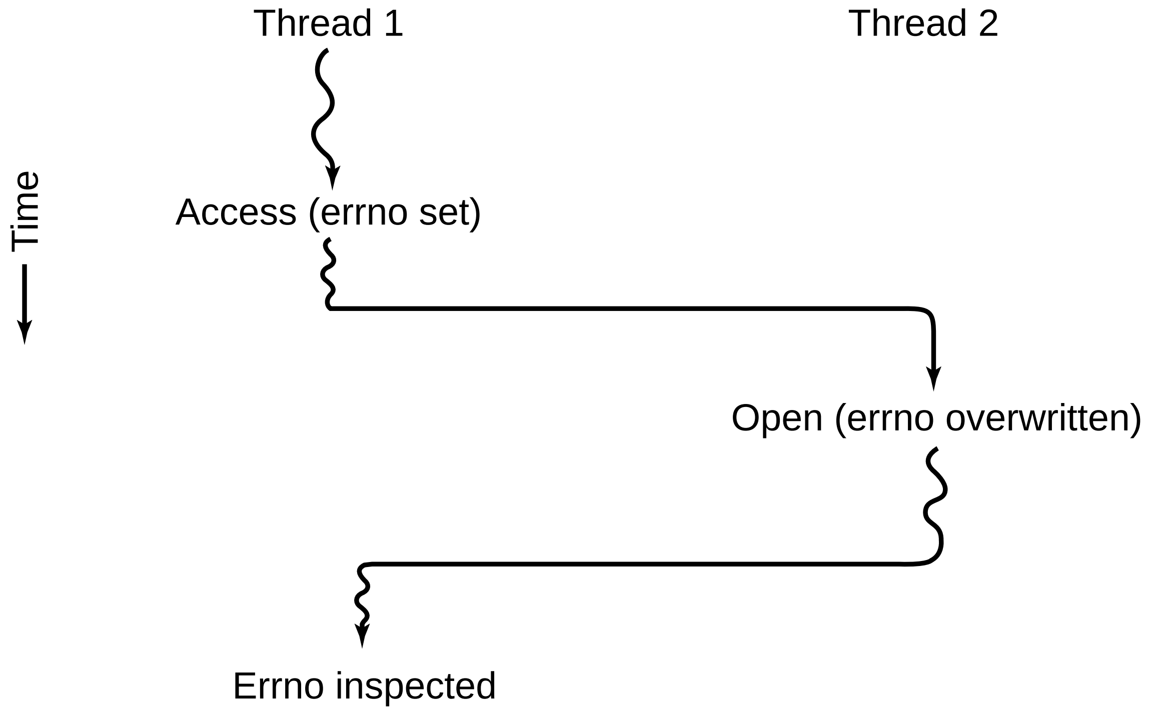
- Goal - mimic functionality of kernel threads
  - gain performance of user space threads
- Avoids unnecessary user/kernel transitions
- Kernel assigns virtual processors to each process
  - lets runtime system allocate threads to processors
- Problem:
  Fundamental reliance on kernel (lower layer)
  calling procedures in user space (higher layer)

Pop-Up Threads



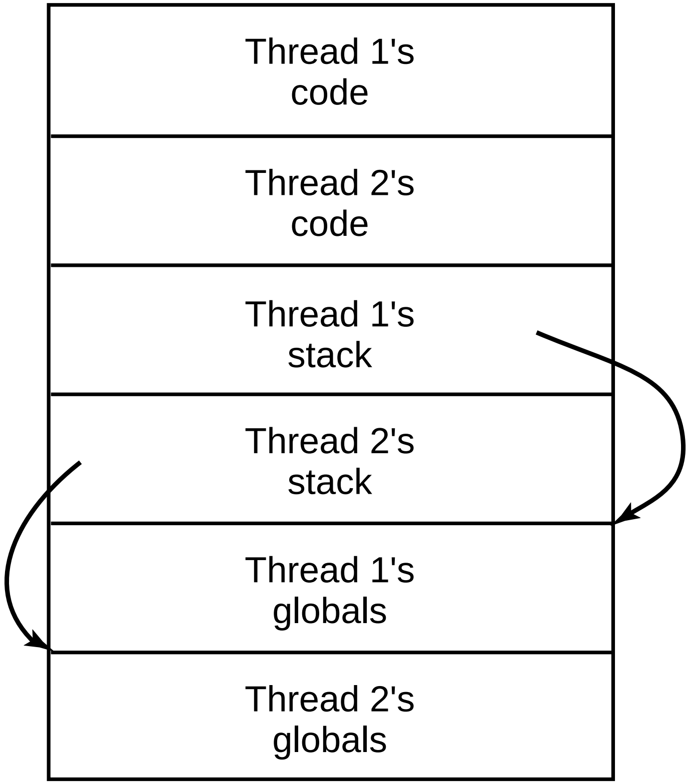
- Creation of a new thread when message arrives
  - (a) before message arrives
  - (b) after message arrives

Making Single-Threaded Code Multithreaded (1)



Conflicts between threads over the use of a global variable

Making Single-Threaded Code Multithreaded (2)



Thread 1's code

Thread 2's code

Thread 1's stack

Thread 2's stack

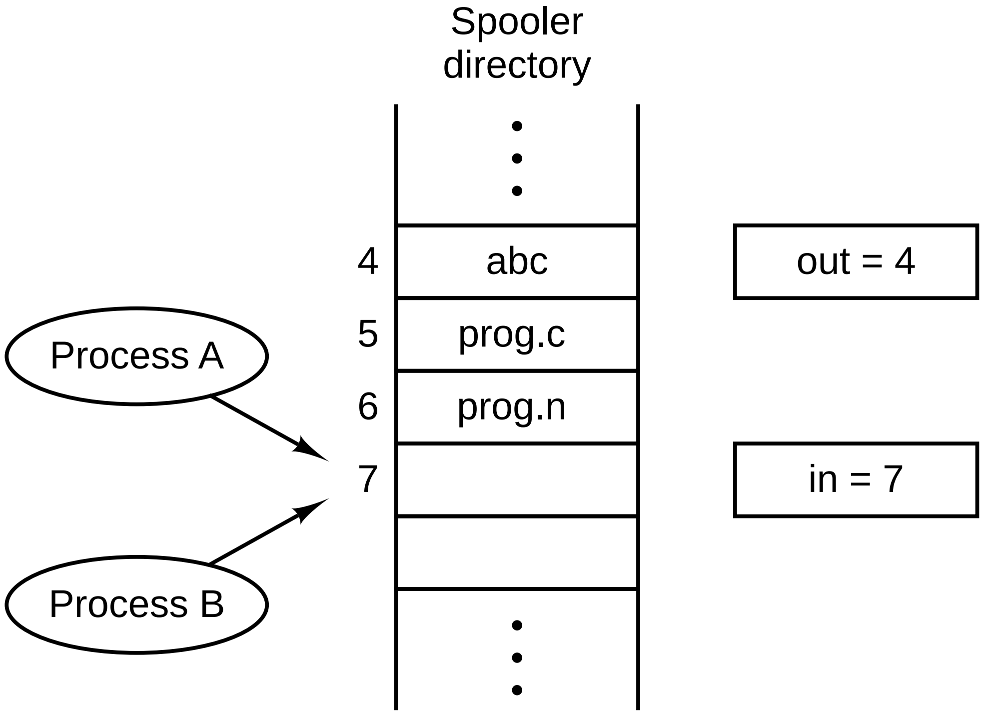
Thread 1's globals

Thread 2's globals

Threads can have private global variables

Interprocess Communication

Race Conditions (Def. on Page 102)



Spooler directory

4 abc

5 prog.c

6 prog.n

7

out = 4

in = 7

Process A

Process B

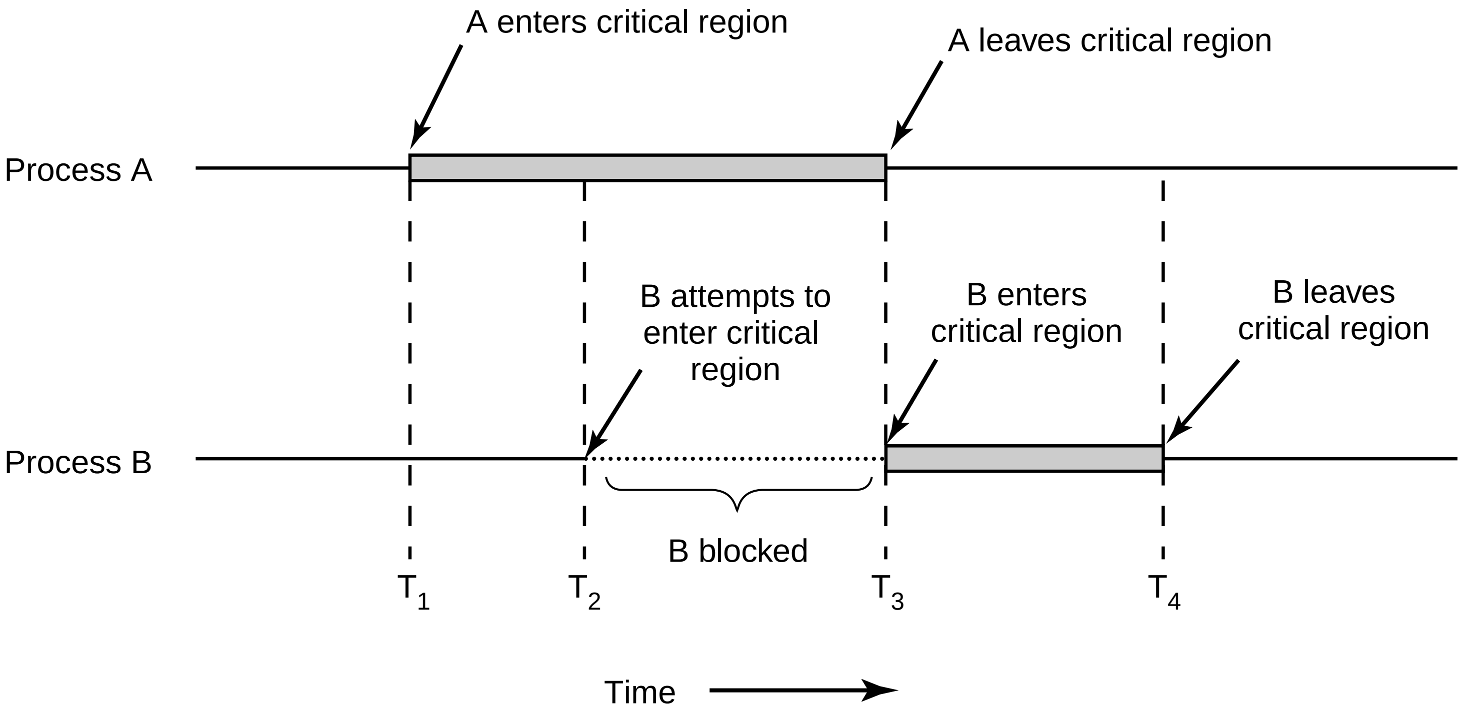
Two processes want to access shared memory at same time

Critical Regions (1)

Four conditions to provide mutual exclusion

1. No two processes simultaneously in critical region
2. No assumptions made about speeds or numbers of CPUs
3. No process running outside its critical region may block another process
4. No process must wait forever to enter its critical region

Critical Regions (2)



Mutual exclusion using critical regions

Mutual Exclusion with Busy Waiting (1)

```
while (TRUE) {
      while (turn != 0)          /* loop */ ;
      critical_region( );
      turn = 1;
      noncritical_region( );
}
```

(a)

```
while (TRUE) {
      while (turn != 1)          /* loop */ ;
      critical_region( );
      turn = 0;
      noncritical_region( );
}
```

(b)

Proposed solution to critical region problem
(Strict Alternation)

(a) Process 0. (b) Process 1.

Mutual Exclusion with Busy Waiting (2)

```
#define FALSE  0
#define TRUE   1
#define N      2                    /* number of processes */

int turn;                           /* whose turn is it? */
int interested[N];                  /* all values initially 0 (FALSE) */

void enter_region(int process);     /* process is 0 or 1 */
{
     int other;                     /* number of the other process */

     other = 1 – process;           /* the opposite of process */
     interested[process] = TRUE;    /* show that you are interested */
     turn = process;                /* set flag */
     while (turn == process && interested[other] == TRUE) /* null statement */ ;
}

void leave_region(int process)      /* process: who is leaving */
{
     interested[process] = FALSE;   /* indicate departure from critical region */
}
```

Peterson’s solution for achieving mutual exclusion

Mutual Exclusion with Busy Waiting (3)

```
enter_region:
      TSL REGISTER,LOCK                     | copy lock to register and set lock to 1
      CMP REGISTER,#0                       | was lock zero?
      JNE enter_region                      | if it was non zero, lock was set, so loop
      RET | return to caller; critical region entered


leave_region:
      MOVE LOCK,#0                          | store a 0 in lock
      RET | return to caller
```

Entering and leaving a critical region using the TSL instruction

TSL: Test and Set Lock Instruction.

Atomicity is guaranteed by hardware.

Sleep and Wakeup

```
#define N 100                               /* number of slots in the buffer */
int count = 0;                              /* number of items in the buffer */

void producer(void)
{
    int item;

    while (TRUE) {                          /* repeat forever */
        item = produce_item( );             /* generate next item */
        if (count == N) sleep( );           /* if buffer is full, go to sleep */
        insert_item(item);                  /* put item in buffer */
        count = count + 1;                  /* increment count of items in buffer */
        if (count == 1) wakeup(consumer);   /* was buffer empty? */
    }
}


void consumer(void)
{
    int item;

    while (TRUE) {                          /* repeat forever */
        if (count == 0) sleep( );           /* if buffer is empty, got to sleep */
        item = remove_item( );              /* take item out of buffer */
        count = count – 1;                  /* decrement count of items in buffer */
        if (count == N – 1) wakeup(producer); /* was buffer full? */
        consume_item(item);                 /* print item */
    }
}
```

Producer-consumer problem with fatal race condition

Semaphores

```
#define N 100                      /∗ number of slots in the buffer ∗/
typedef int semaphore;             /∗ semaphores are a special kind of int ∗/
semaphore mutex = 1;               /∗ controls access to critical region ∗/
semaphore empty = N;               /∗ counts empty buffer slots ∗/
semaphore full = 0;                /∗ counts full buffer slots ∗/

void producer(void)
{
     int item;

     while (TRUE) {                /∗ TRUE is the constant 1 ∗/
          item = produce_item( );  /∗ generate something to put in buffer ∗/
          down(&empty);            /∗ decrement empty count ∗/
          down(&mutex);            /∗ enter critical region ∗/
          insert_item(item);       /∗ put new item in buffer ∗/
          up(&mutex);              /∗ leave critical region ∗/
          up(&full);               /∗ increment count of full slots ∗/
     }
}


void consumer(void)
{
     int item;

     while (TRUE) {                /∗ infinite loop ∗/
          down(&full);             /∗ decrement full count ∗/
          down(&mutex);            /∗ enter critical region ∗/
          item = remove_item( );   /∗ take item from buffer ∗/
          up(&mutex);              /∗ leave critical region ∗/
          up(&empty);              /∗ increment count of empty slots ∗/
          consume_item(item);      /∗ do something with the item ∗/
     }
}
```

The producer-consumer problem using semaphores

Mutexes
(Binary Semaphore)

```
mutex_lock:
        TSL REGISTER,MUTEX              | copy mutex to register and set mutex to 1
        CMP REGISTER,#0                 | was mutex zero?
        JZE ok                          | if it was zero, mutex was unlocked, so return
        CALL thread_yield               | mutex is busy; schedule another thread
        JMP mutex_lock                  | try again later
ok:     RET | return to caller; critical region entered


mutex_unlock:
        MOVE MUTEX,#0                   | store a 0 in mutex
        RET | return to caller
```

Implementation of mutex_lock and mutex_unlock
with TSL Instruction

Monitors (1)

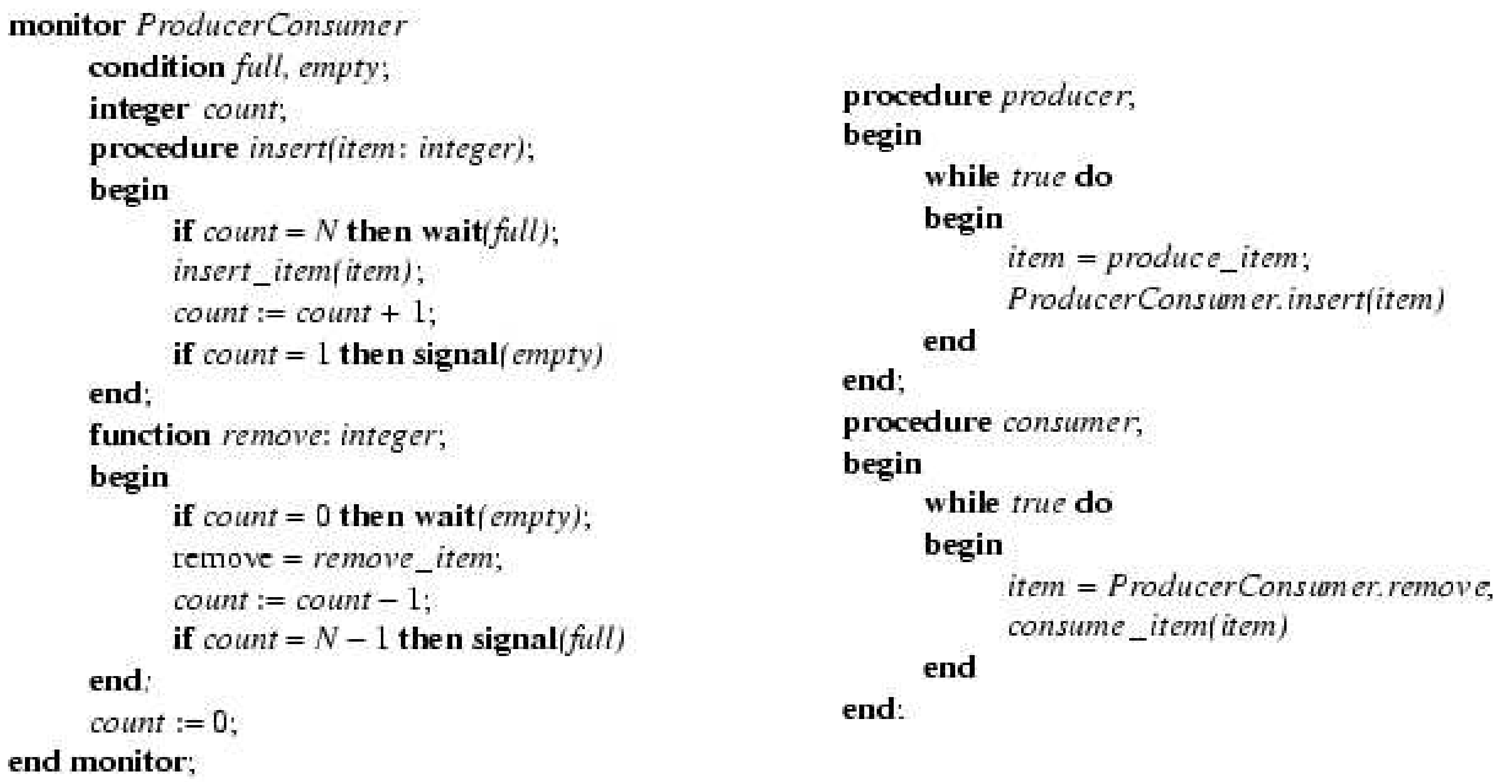
Example of a monitor

```
monitor example
    integer i;
    condition c;

    procedure producer( );
    .
    .
    .
    end;

    procedure consumer( );
    .
    .
    .
    end;
end monitor;
```

Monitor is a collection of

- procedures
- condition variables
- data structures

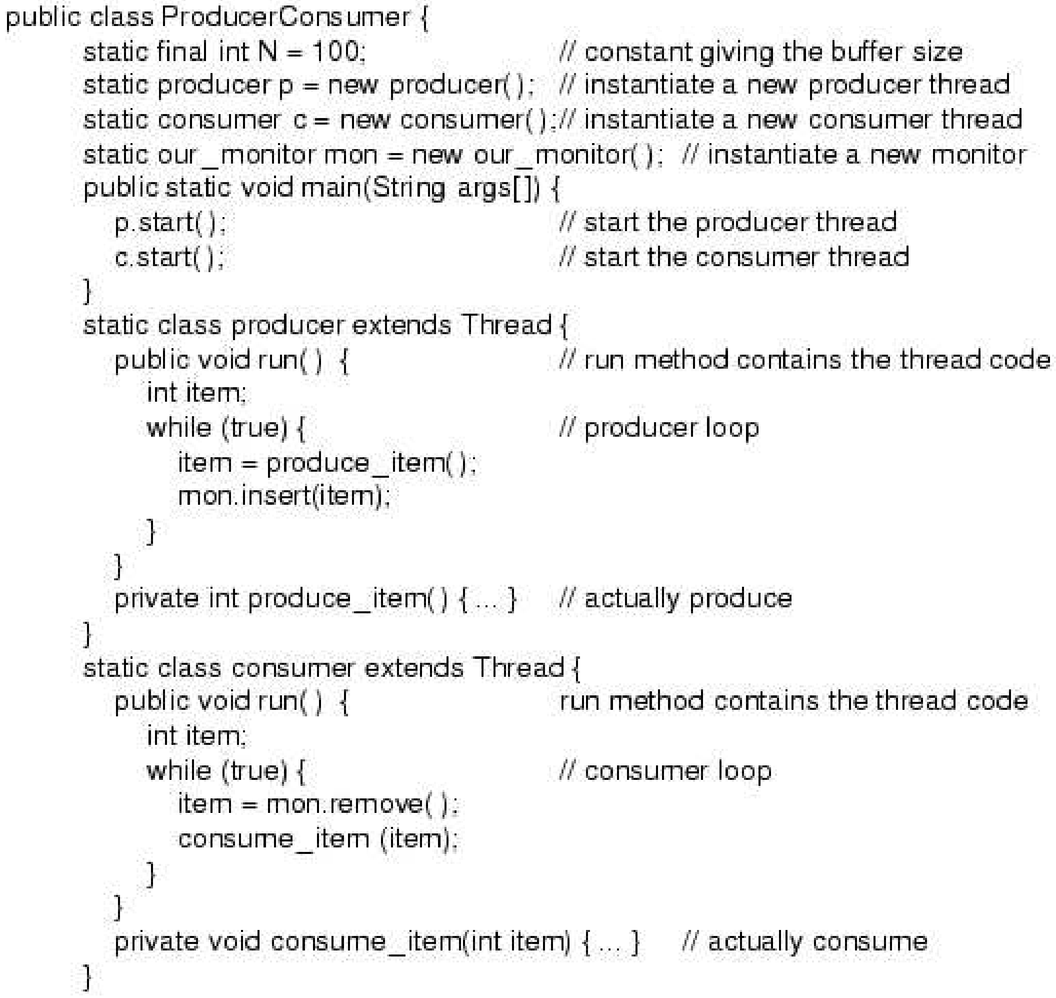
Monitors (2)



```
monitor ProducerConsumer
    condition full, empty;
    integer count;
    procedure insert(item: integer);
    begin
        if count = N then wait(full);
        insert_item(item);
        count := count + 1;
        if count = 1 then signal(empty)
    end;
    function remove: integer;
    begin
        if count = 0 then wait(empty);
        remove = remove_item;
        count := count − 1;
        if count = N − 1 then signal(full)
    end;
    count := 0;
end monitor;

procedure producer;
begin
    while true do
    begin
        item = produce_item;
        ProducerConsumer.insert(item)
    end
end;
procedure consumer;
begin
    while true do
    begin
        item = ProducerConsumer.remove;
        consume_item(item)
    end
end;
```

- Outline of producer-consumer problem with monitors
  - only one monitor procedure active at one time
  - buffer has N slots

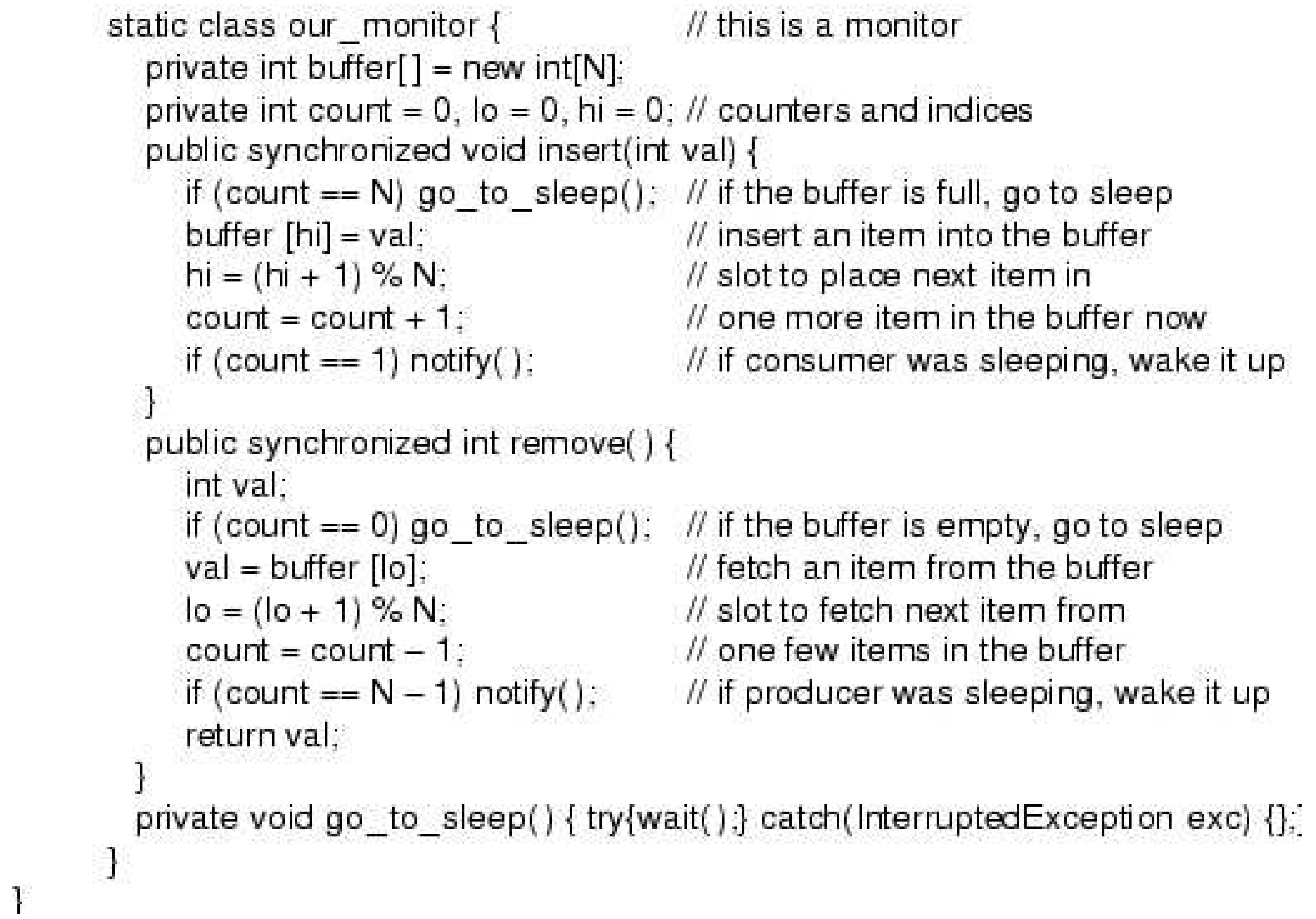
Monitors (3)



```
public class ProducerConsumer {
    static final int N = 100;                   // constant giving the buffer size
    static producer p = new producer( );   // instantiate a new producer thread
    static consumer  c = new consumer( );// instantiate a new consumer thread
    static our_monitor mon = new our_monitor( );  // instantiate a new monitor
    public static void main(String args[]) {
      p.start( );                               // start the producer thread
      c.start( );                               // start the consumer thread
    }
    static class producer extends Thread {
      public void run( )  {                     // run method contains the thread code
        int item;
        while (true) {                          // producer loop
          item = produce_item( );
          mon.insert(item);
        }
      }
      private int produce_item( ) { ... }       // actually produce
    }
    static class consumer extends Thread {
      public void run( )  {                     run method contains the thread code
        int item;
        while (true) {                          // consumer loop
          item = mon.remove( );
          consume_item (item);
        }
      }
      private void consume_item(int item) { ... }    // actually consume
    }
```

Solution to producer-consumer problem in Java (part 1)

Monitors (4)



```
        static class our_monitor {                    // this is a monitor
            private int buffer[] = new int[N];
            private int count = 0, lo = 0, hi = 0; // counters and indices
            public synchronized void insert(int val) {
                if (count == N) go_to_sleep();   // if the buffer is full, go to sleep
                buffer [hi] = val;               // insert an item into the buffer
                hi = (hi + 1) % N;               // slot to place next item in
                count = count + 1;               // one more item in the buffer now
                if (count == 1) notify( );       // if consumer was sleeping, wake it up
            }
            public synchronized int remove( ) {
                int val;
                if (count == 0) go_to_sleep();   // if the buffer is empty, go to sleep
                val = buffer [lo];               // fetch an item from the buffer
                lo = (lo + 1) % N;               // slot to fetch next item from
                count = count – 1;               // one few items in the buffer
                if (count == N – 1) notify( );   // if producer was sleeping, wake it up
                return val;
            }
            private void go_to_sleep( ) { try{wait( );} catch(InterruptedException exc) {};}
        }
}
```

Solution to producer-consumer problem in Java (part 2)

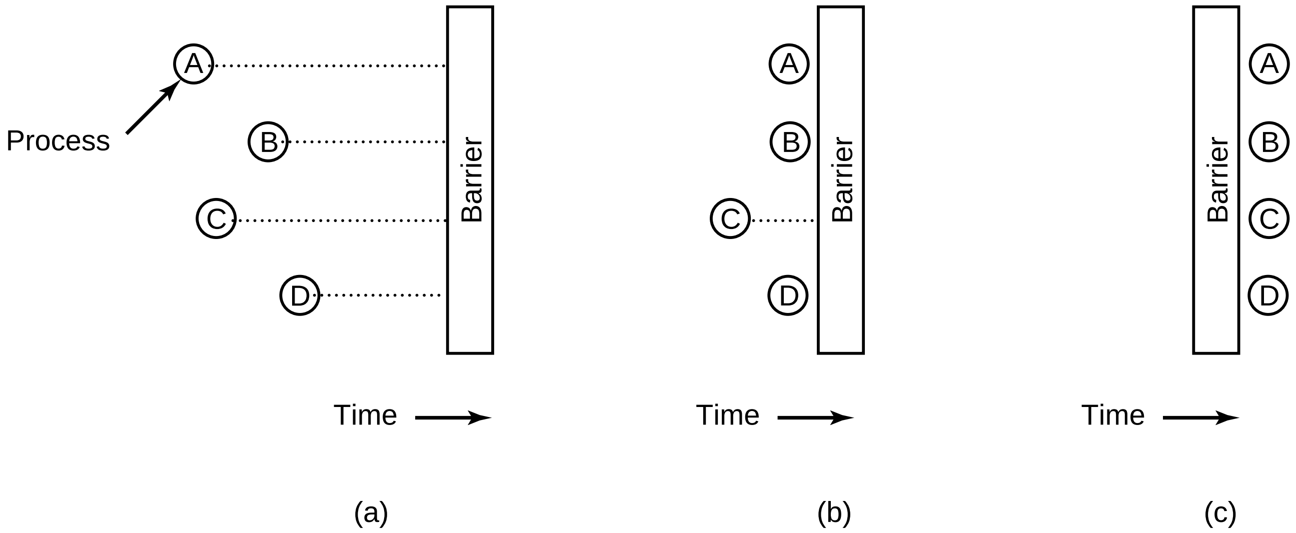
Message Passing

(applicable to distributed systems)

```
#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 */
     }
}
```

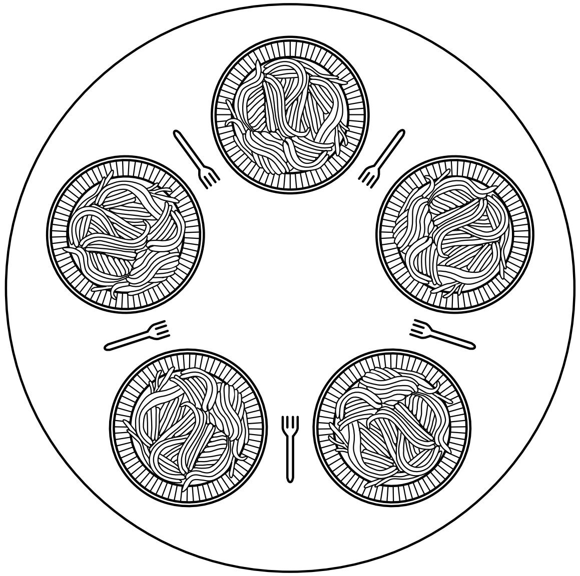
The producer-consumer problem with N messages

Barriers



- Use of a barrier
  - processes approaching a barrier
  - all processes but one blocked at barrier
  - last process arrives, all are let through

Dining Philosophers (1)



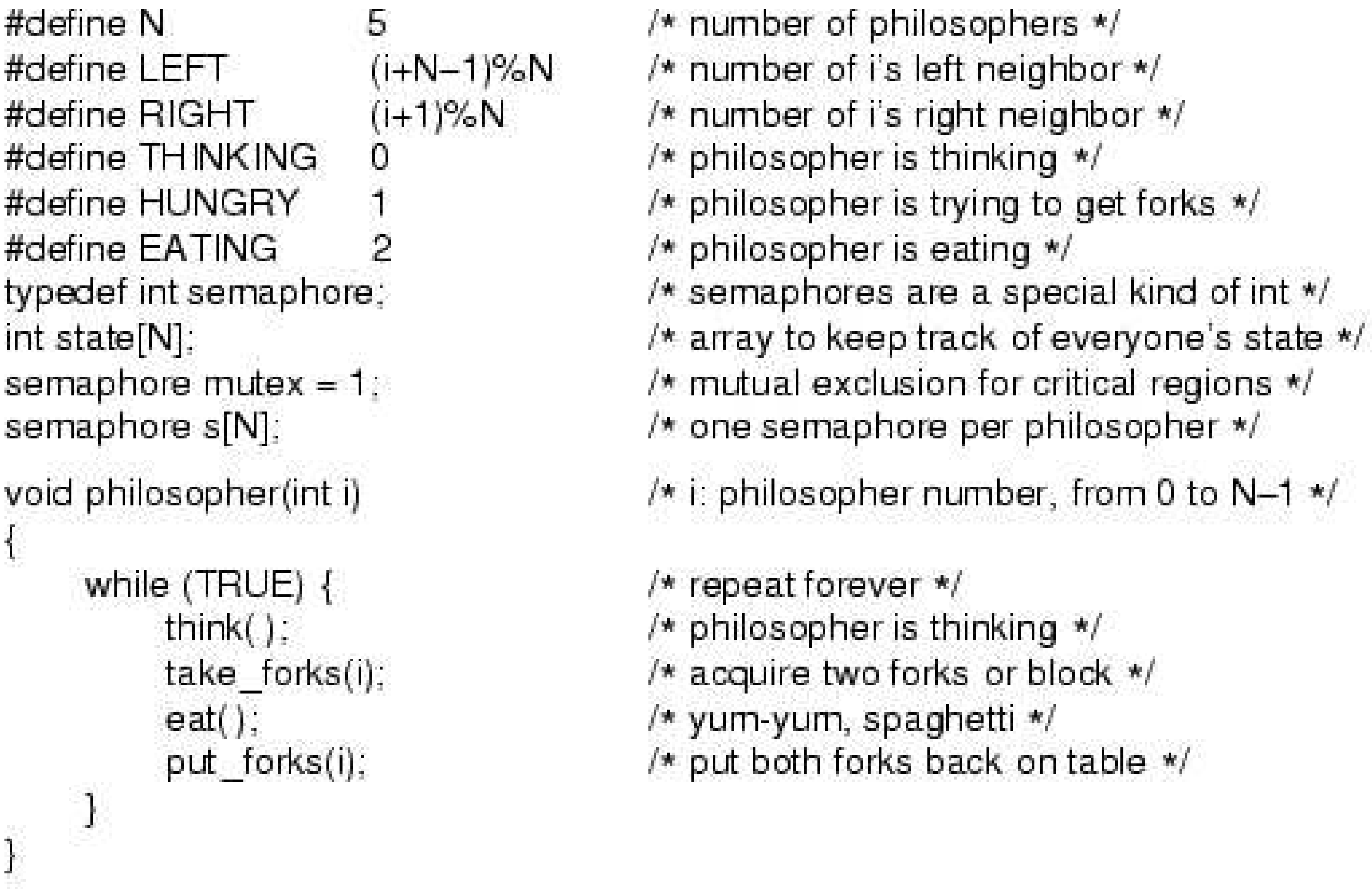
- Philosophers eat/think
- Eating needs 2 forks
- Pick one fork at a time
- How to prevent deadlock ?
  (Deadlock example:
  everyone takes left fork
  and wait for right one)

Dining Philosophers (2)

```
#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 */
      }
}
```

A nonsolution to the dining philosophers problem

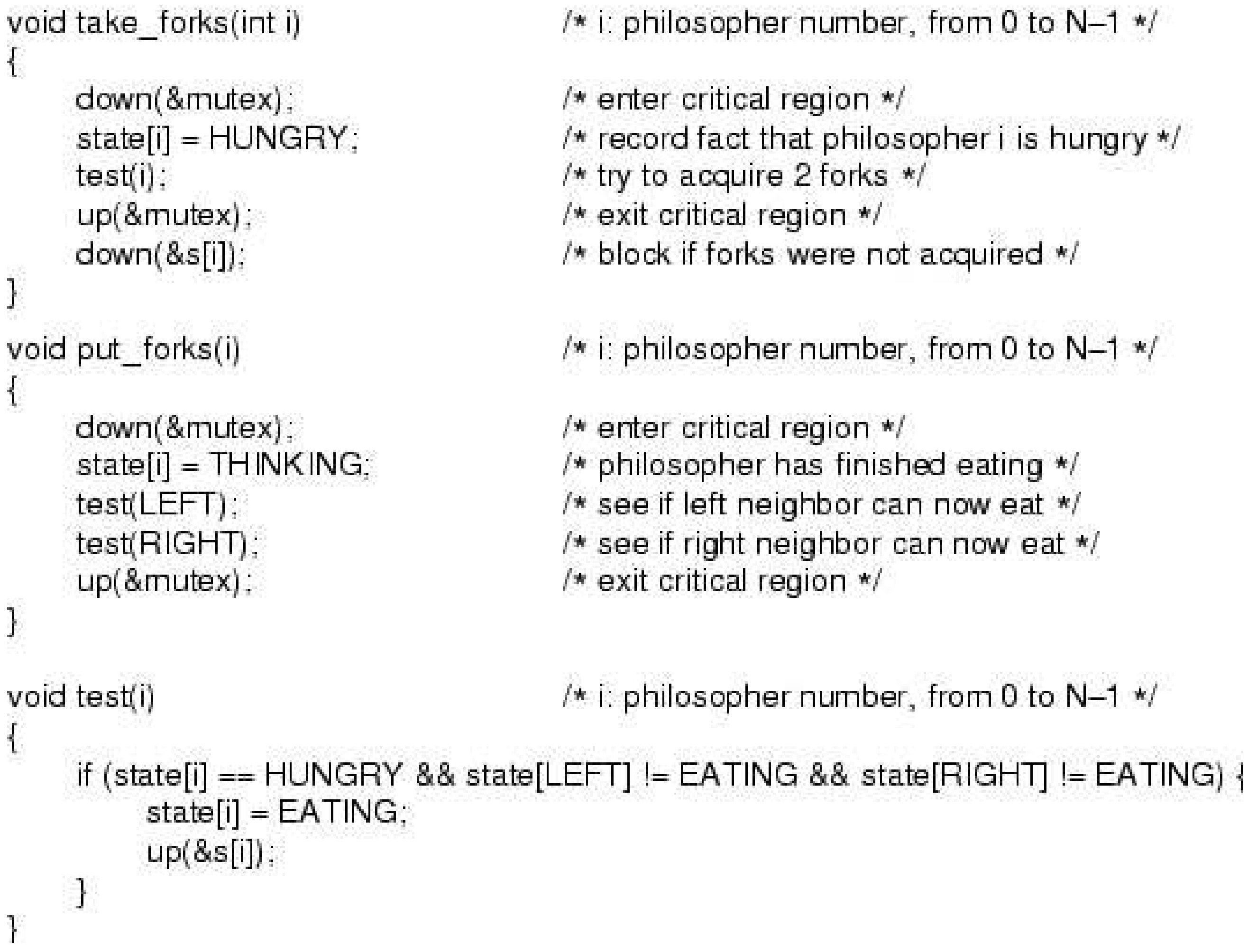
Dining Philosophers (3)



```
#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 */
     }
}
```

Solution to dining philosophers problem (part 1)

Dining Philosophers (4)



```
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]);
     }
}
```

Solution to dining philosophers problem (part 2)

The Readers and Writers Problem

```
typedef int semaphore;            /* use your imagination */
semaphore mutex = 1;              /* controls access to ’rc’ */
semaphore db = 1;                 /* controls access to the database */
int rc = 0;                       /* # of processes reading or wanting to */

void reader(void)
{
    while (TRUE) {                /* repeat forever */
        down(&mutex);             /* get exclusive access to ’rc’ */
        rc = rc + 1;              /* one reader more now */
        if (rc == 1) down(&db);   /* if this is the first reader ... */
        up(&mutex);               /* release exclusive access to ’rc’ */
        read_data_base( );        /* access the data */
        down(&mutex);             /* get exclusive access to ’rc’ */
        rc = rc – 1;              /* one reader fewer now */
        if (rc == 0) up(&db);     /* if this is the last reader ... */
        up(&mutex);               /* release exclusive access to ’rc’ */
        use_data_read( );         /* noncritical region */
    }
}


void writer(void)
{
    while (TRUE) {                /* repeat forever */
        think_up_data( );         /* noncritical region */
        down(&db);                /* get exclusive access */
        write_data_base( );       /* update the data */
        up(&db);                  /* release exclusive access */
    }
}
```

A solution to the (multiple) readers and writers problem

The Sleeping Barber Problem (1)

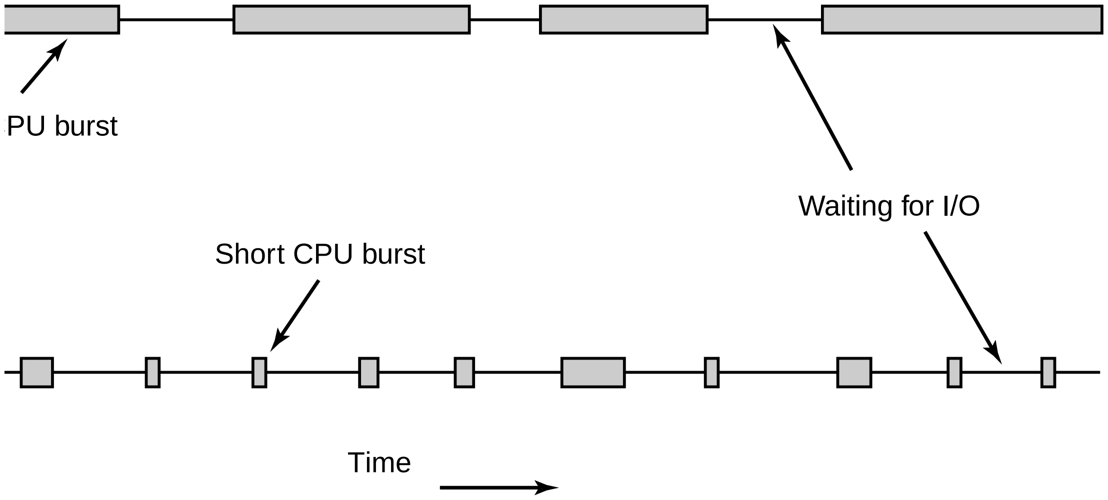
The Sleeping Barber Problem (2)

```
#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) ⋆/

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) ⋆/
    }
}


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 ⋆/
    }
}
```

Solution to sleeping barber problem.

Scheduling

Introduction to Scheduling (1)



- Bursts of CPU usage alternate with periods of I/O wait
  - a CPU-bound process
  - an I/O bound process
- Multiprograming environment (keep CPU busy)
  - Necessitates process scheduling

Introduction to Scheduling (2)

All systems

Fairness - giving each process a fair share of the CPU
Policy enforcement - seeing that stated policy is carried out
Balance - keeping all parts of the system busy

Batch systems

Throughput - maximize jobs per hour
Turnaround time - minimize time between submission and termination
CPU utilization - keep the CPU busy all the time

Interactive systems

Response time - respond to requests quickly
Proportionality - meet users' expectations

Real-time systems

Meeting deadlines - avoid losing data
Predictability - avoid quality degradation in multimedia systems

Scheduling Algorithm Goals

Scheduling in Batch Systems (1)

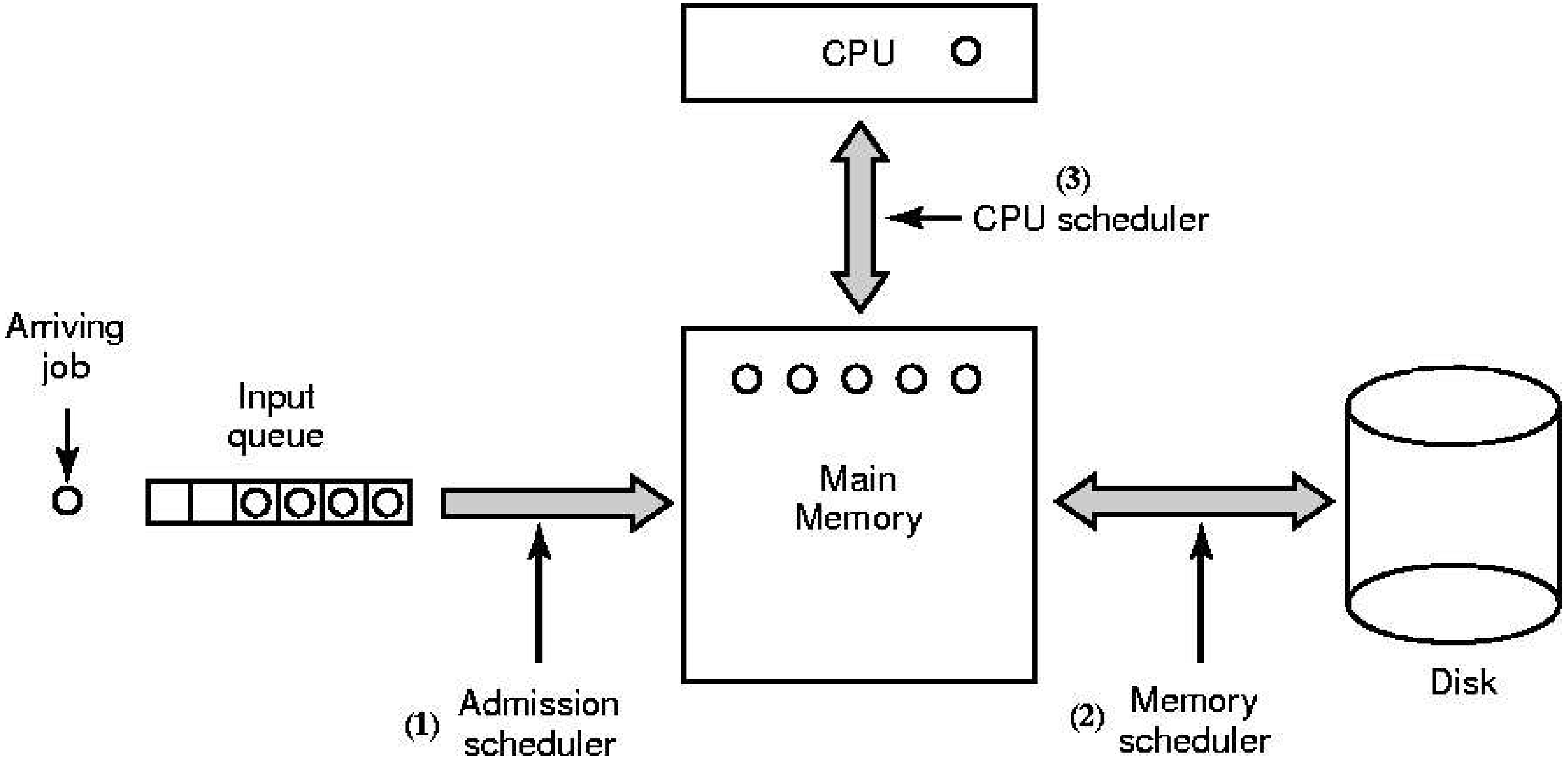
(a) (b)

(a) First come first served scheduling (FCFS)

(b) Shortest job first scheduling (SJF)

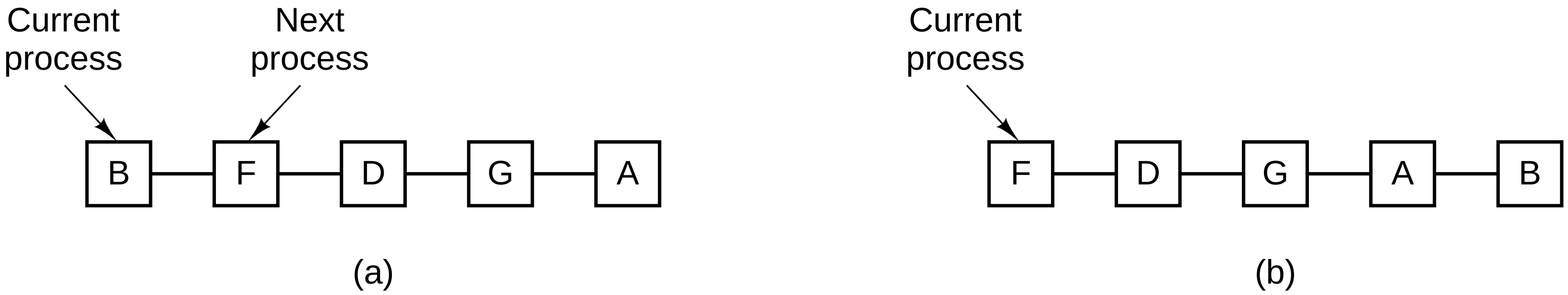
Average Turnaround Time: **FCFS** 14min, **SJF** 11min

Scheduling in Batch Systems (2)



Three level scheduling

Scheduling in Interactive Systems (1)



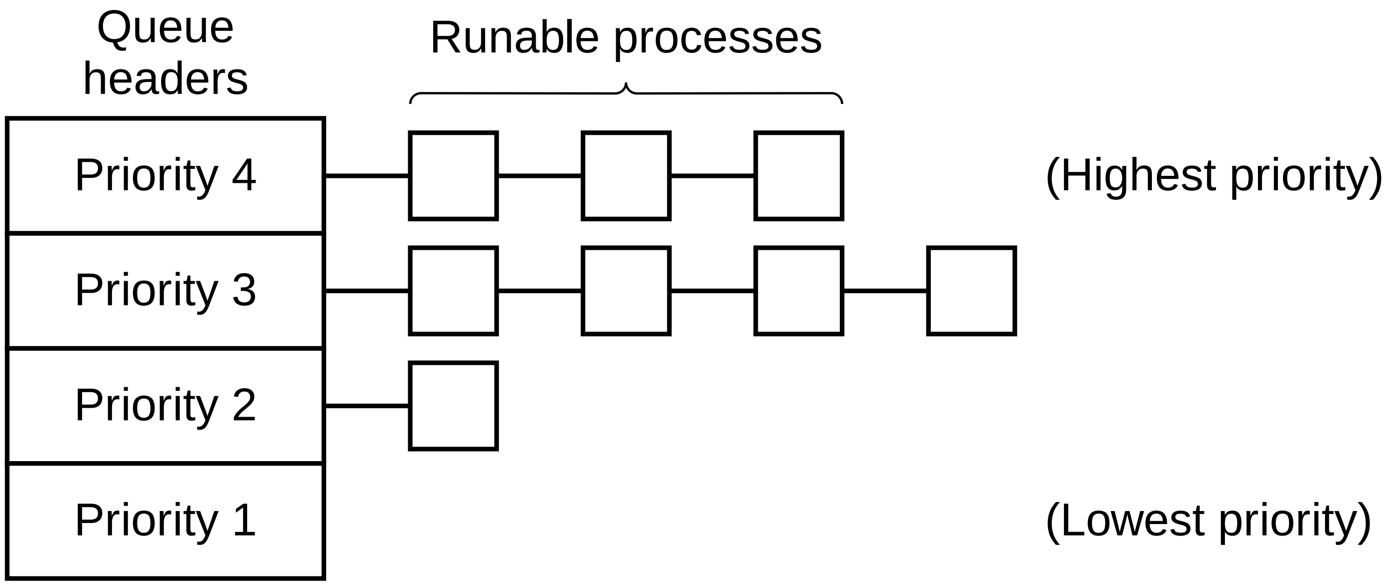
- Round Robin Scheduling

  (a) list of runnable processes

  (b) list of runnable processes after B uses up its quantum

- Quantum
  - A time interval assigned to each process to run
    Too long → slow response
    Too short → waste CPU time for switching

Scheduling in Interactive Systems (2)



A scheduling algorithm with four priority classes

No priority adjustment leads to starving of lower priority processes

Estimate execution time from past behavior (1/f)

Scheduling in Real-Time Systems

Schedulable real-time system

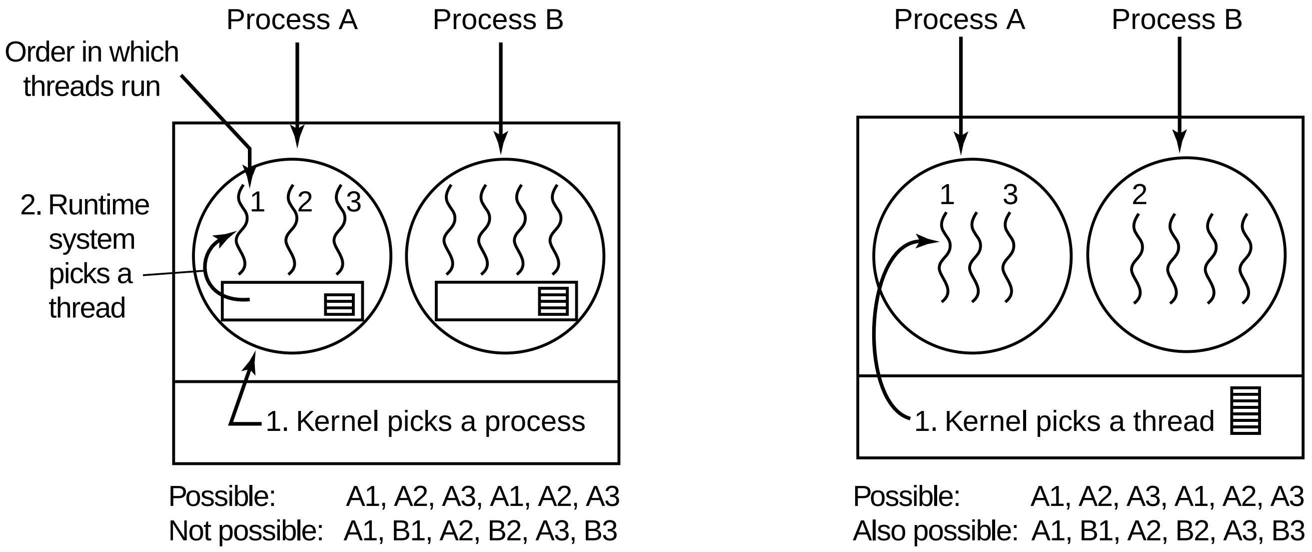
- Hard real time, Soft real time
  - Time constraint on program execution
  - Behavior is predictable and known in advance.
- Given
  - m periodic events
  - event i occurs within period Pi and requires Ci seconds
- Then the load can only be handled (= schedulable) if

$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

Policy versus Mechanism

- Separate what is allowed to be done with how it is done
  - a process knows which of its children threads are important and need priority
- Scheduling algorithm parameterized
  - mechanism in the kernel
    (e. g. priority scheduling)
- Parameters filled in by user processes
  - policy set by user process
    (e. g. how to set each process's priority)

Thread Scheduling(1)



(a) (b)

- Possible scheduling of user-level threads
  - 50-msec process quantum
  - threads run 5 msec/CPU burst
- Possible scheduling of kernel-level threads
  - 50-msec process quantum
  - threads run 5 msec/CPU burst

Thread Scheduling(2)

- Possible scheduling of user-level threads
  - Application specific scheduling possible (can be a disadvantage if one thread does not yield the CPU)
  - Thread switching is inexpensive
- Possible scheduling of kernel-level threads
  - Thread switching = full (process) context switching
  - Can switch to any thread irrespective of parent process