

# Chapter 6: Synchronization Tools

# Outline

- + Background
- + The Critical-Section Problem
- + Peterson's Solution
- + Hardware Support for Synchronization
- + Mutex Locks
- + Semaphores
- + Monitors
- + Liveness
- + Evaluation

# Objectives

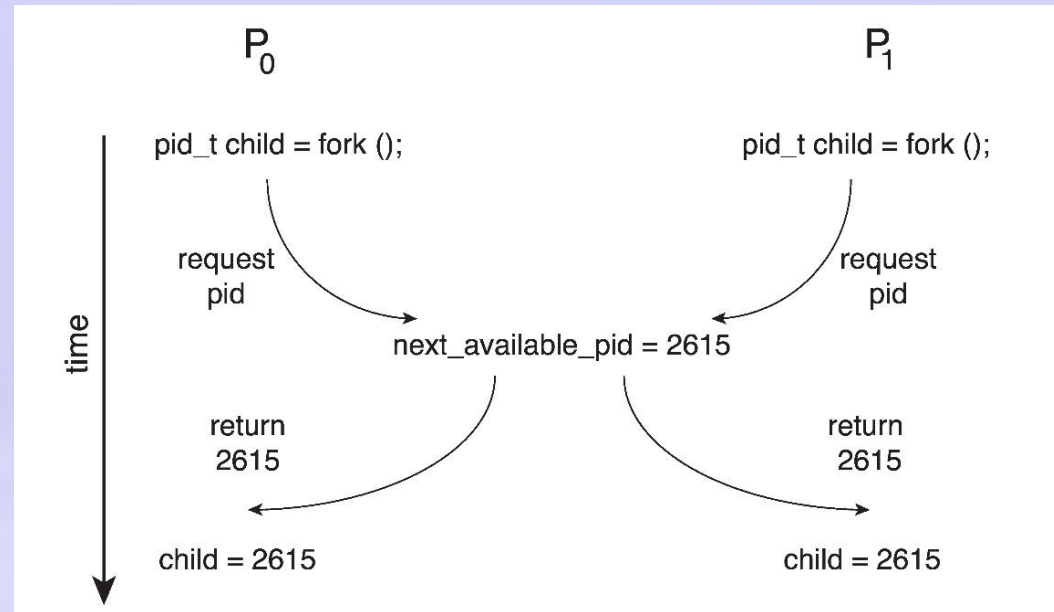
- # Describe the critical-section problem and illustrate a race condition
- # Illustrate hardware solutions to the critical-section problem using memory barriers, compare-and-swap operations, and atomic variables
- # Demonstrate how mutex locks, semaphores, monitors, and condition variables can be used to solve the critical section problem
- # Evaluate tools that solve the critical-section problem in low-, moderate-, and high-contention scenarios

# Background

- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes
- We illustrated in chapter 4 the problem when we considered the Bounded Buffer problem with use of a counter that is updated concurrently by the producer and consumer,. Which lead to race condition.

# Race Condition

- Processes  $P_0$  and  $P_1$  are creating child processes using the `fork()` system call
- Race condition on kernel variable `next_available_pid` which represents the next available process identifier (pid)



- Unless there is a mechanism to prevent  $P_0$  and  $P_1$  from accessing the variable `next_available_pid` the same pid could be assigned to two different processes!

# Critical Section Problem

- ✚ Consider system of  $n$  processes  $\{p_0, p_1, \dots, p_{n-1}\}$
- ✚ Each process has **critical section** segment of code
  - Process may be changing common variables, updating table, writing file, etc.
  - When one process in critical section, no other may be in its critical section
- ✚ **Critical section problem** is to design protocol to solve this
- ✚ Each process must ask permission to enter critical section in **entry section**, may follow critical section with **exit section**, then **remainder section**

# Critical Section

- General structure of process  $P_i$

```
do {  
    entry section  
    critical section  
    exit section  
    remainder section  
} while (true);
```



# Critical-Section Problem (Cont.)

Requirements for solution to critical-section problem

1. **Mutual Exclusion** - If process  $P_i$  is executing in its critical section, then no other processes can be executing in their critical sections
2. **Progress** - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the process that will enter the critical section next cannot be postponed indefinitely
3. **Bounded Waiting** - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
  - Assume that each process executes at a nonzero speed
  - No assumption concerning **relative speed** of the  $n$  processes



# Interrupt-based Solution

- + Entry section: disable interrupts
- + Exit section: enable interrupts
- + Will this solve the problem?
  - What if the critical section is code that runs for an hour?
  - Can some processes starve – never enter their critical section.
  - What if there are two CPUs?

# Software Solution 1

- ✦ Two process solution
- ✦ Assume that the **load** and **store** machine-language instructions are atomic; that is, cannot be interrupted
- ✦ The two processes share one variable:
  - `int turn;`
- ✦ The variable **turn** indicates whose turn it is to enter the critical section

# Algorithm (1) for Process $P_i P_j$

do {

**while** (turn  $\neq i$ ) ;

critical section

turn = j;

remainder section

} **while** (1);

do {

**while** (turn  $\neq j$ ) ;

critical section

turn = i;

remainder section

} **while** (1);

# Correctness of the Software Solution

- ✚ Mutual exclusion is preserved

$P_i$  enters critical section only if:

$$\text{turn} = i$$

and **turn** cannot be both 0 and 1 at the same time

- ✚ What about the Progress requirement?
- ✚ What about the Bounded-waiting requirement?

# Algorithm (2) for Process $P_i$ $P_j$

do {

flag[i] = TRUE;  
**while** (flag[j]) ;

critical section

flag[i] = FALSE;

remainder section

} **while** (1);

do {

flag[j] = TRUE;  
**while** (flag[i]) ;

critical section

flag[j] = FALSE;

remainder section

} **while** (1);

# Peterson's Solution

- + Two process solution
- + Assume that the **load** and **store** machine-language instructions are atomic; that is, cannot be interrupted
- + The two processes share two variables:
  - `int turn;`
  - `boolean flag[2]`
- + The variable **turn** indicates whose turn it is to enter the critical section
- + The **flag** array is used to indicate if a process is ready to enter the critical section.
  - `flag[i] = true` implies that process  $P_i$  is ready!

# Algorithm (3) for Process $P_i$ $P_j$

```
while (true) {
```

```
    flag[i] = TRUE;  
    turn = j;  
    while ( flag[j] && turn == j);
```

**CRITICAL SECTION**

```
    flag[i] = FALSE;
```

**REMAINDER SECTION**

```
}
```

```
while (true) {
```

```
    flag[j] = TRUE;  
    turn = i;  
    while ( flag[i] && turn == i);
```

**CRITICAL SECTION**

```
    flag[j] = FALSE;
```

**REMAINDER SECTION**

```
}
```



# Correctness of Peterson's Solution

✚ Provable that the three CS requirement are met:

1. Mutual exclusion is preserved

$P_i$  enters CS only if:

either `flag[j] = FALSE` or `turn = i`

2. Progress requirement is satisfied

3. Bounded-waiting requirement is met

# Peterson's Solution and Modern Architecture

- ✦ Although useful for demonstrating an algorithm, Peterson's Solution is not guaranteed to work on modern architectures.
  - To improve performance, processors and/or compilers may **reorder** operations that have no dependencies
- ✦ Understanding why it will not work is useful for better understanding race conditions.
- ✦ For single-threaded this is ok as the result will always be the same.
- ✦ For multithreaded the reordering may produce inconsistent or unexpected results!

# Modern Architecture Example

- Two threads share the data:

```
boolean flag = FALSE;  
int x = 0;
```

- Thread 1 performs

```
while (!flag)  
;  
print x
```

- What is the expected output?

100

- Thread 2 performs

```
x = 100;  
flag = TRUE
```

# Modern Architecture Example (Cont.)

- ✚ However, since the variables `flag` and `x` are independent of each other, the instructions:

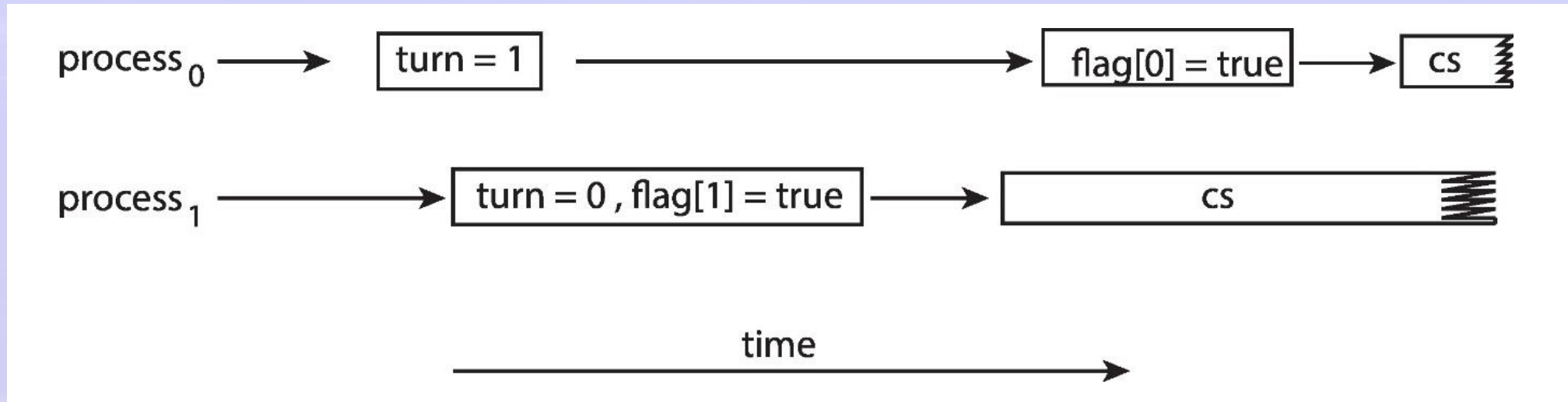
```
flag = TRUE;  
x = 100;
```

for Thread 2 may be reordered

- ✚ If this occurs, the output may be 0!

# Peterson's Solution Revisited

- ✚ The effects of instruction reordering in Peterson's Solution



- ✚ This allows both processes to be in their critical section at the same time!
- ✚ To ensure that Peterson's solution will work correctly on modern computer architecture we must use **Memory Barrier**.

# Synchronization Hardware

- + Many systems provide hardware support for implementing the critical section code.
- + Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - ▣ Operating systems using this not broadly scalable
- + We will look at three forms of hardware support:
  1. Memory Barriers/Fences
  2. Hardware instructions
  3. Atomic variables

# Memory Barrier

- ✚ **Memory model** are the memory guarantees a computer architecture makes to application programs.
- ✚ Memory models may be either:
  - **Strongly ordered** – where a memory modification of one processor is immediately visible to all other processors.
  - **Weakly ordered** – where a memory modification of one processor may not be immediately visible to all other processors.
- ✚ A **memory barrier** is an instruction that forces any change in memory to be propagated (made visible) to all other processors.



# Memory Barrier Instructions

- ✚ When a memory barrier instruction is performed, the system ensures that all loads and stores are completed before any subsequent load or store operations are performed.
- ✚ Therefore, even if instructions were reordered, the memory barrier ensures that the store operations are completed in memory and visible to other processors before **future** load or store operations are performed.

```
241 static __always_inline void __write_once_size(volatile void *p, void *res, int size)
242 {
243     switch (size) {
244         case 1: *(volatile __u8 *)p = *(__u8 *)res; break;
245         case 2: *(volatile __u16 *)p = *(__u16 *)res; break;
246         case 4: *(volatile __u32 *)p = *(__u32 *)res; break;
247         case 8: *(volatile __u64 *)p = *(__u64 *)res; break;
248         default:
249             barrier();
250             __builtin_memcpy((void *)p, (const void *)res, size);
251             barrier();
252     }
253 }
```

```
97 static inline void barrier(void)
98 {
99     asm volatile("" : : : "memory");
100 }
101
102 #endif /* _IO_H */
103
```

# Memory Barrier Example

- Returning to the example of slides 6.17 - 6.18
- We could add a memory barrier to the following instructions to ensure Thread 1 outputs 100:
- Thread 1 now performs
  - `while (!flag)`
  - `memory_barrier();`
  - `print x`
- Thread 2 now performs
  - `x = 100;`
  - `memory_barrier();`
  - `flag = TRUE`
- For Thread 1 we are guaranteed that the value of `flag` is loaded before the value of `x`.
- For Thread 2 we ensure that the assignment to `x` occurs before the assignment `flag`.

# Hardware Instructions

- + Special hardware instructions that allow us to either *test-and-modify* the content of a word, or two *swap* the contents of two words atomically (uninterruptedly.)
  - **Test-and-Set** instruction
  - **Compare-and-Swap** instruction
  - **Swap** instruction

# The test\_and\_set Instruction

## + Definition

```
boolean test_and_set (boolean *target)
{
    boolean rv = *target;
    *target = true;
    return rv;
}
```

## + Properties

- Executed atomically
- Returns the original value of passed parameter
- Set the new value of passed parameter to **TRUE**

# Solution Using test\_and\_set()

- Shared boolean variable **lock**, initialized to **FALSE**

- Solution:

```
do {  
    while (test_and_set(&lock))  
        ; /* do nothing */  
  
    /* critical section */  
  
    lock = FALSE;  
  
    /* remainder section */  
} while (TRUE);
```

- Does it solve the critical-section problem?

# The compare\_and\_swap Instruction

## + Definition

```
int compare_and_swap(int *value, int expected, int new_value)
{
    int temp = *value;
    if (*value == expected)
        *value = new_value;
    return temp;
}
```

## + Properties

- Executed atomically
- Returns the original value of passed parameter **value**
- Set the variable **value** the value of the passed parameter **new\_value** but only if **\*value == expected** is true. That is, the swap takes place only under this condition.

# Solution using compare\_and\_swap

- Shared integer `lock` initialized to 0;

- Solution:

```
while (TRUE) {  
    while (!compare_and_swap(&lock, 0, 1))  
        ; /* do nothing */  
  
    /* critical section */  
  
    lock = 0;  
  
    /* remainder section */  
}
```

- Does it solve the critical-section problem?



# The swap Instruction

Definition:

```
void swap (boolean *a, boolean *b)
{
    boolean temp = *a;
    *a = *b;
    *b = temp;
}
```

# Solution using swap

- Shared Boolean variable lock initialized to FALSE; Each process has a local Boolean variable key.

- Solution:

```
while (TRUE) {  
    key = TRUE;  
    while ( key == TRUE)  
        swap (&lock, &key );  
    //    critical section  
    lock = FALSE;  
    //    remainder section  
}
```

- Does it solve the critical-section problem?

# Bounded-waiting Mutual Exclusion

```
while (TRUE) {  
    waiting[i] = TRUE;  
    key = TRUE;  
    while (waiting[i] && key)  
        key = test_and_set(&lock);  
    waiting[i] = FALSE;  
    /* critical section */  
    j = (i + 1) % n;  
    while ((j != i) && !waiting[j])  
        j = (j + 1) % n;  
    if (j == i)  
        lock = FALSE;  
    else  
        waiting[j] = FALSE;  
    /* remainder section */  
}
```

```
while (TRUE) {  
    waiting[i] = TRUE;  
    key = 1;  
    while (waiting[i] && key == 1)  
        key = compare_and_swap(&lock, 0, 1);  
    waiting[i] = FALSE;  
    /* critical section */  
    j = (i + 1) % n;  
    while ((j != i) && !waiting[j])  
        j = (j + 1) % n;  
    if (j == i)  
        lock = 0;  
    else  
        waiting[j] = FALSE;  
    /* remainder section */  
}
```

# Atomic Variables

- ✦ Typically, instructions such as compare-and-swap are used as building blocks for other synchronization tools.
- ✦ One tool is an **atomic variable** that provides *atomic* (uninterruptible) updates on basic data types such as integers and booleans.
- ✦ For example:
  - Let **sequence** be an atomic variable
  - Let **increment()** be operation on the atomic variable **sequence**
  - The Command:  
**increment(&sequence) ;**  
ensures **sequence** is incremented without interruption:

# Atomic Variables

+ The `increment()` function can be implemented as follows:

```
void increment(atomic_int *v)
{
    int temp;
    do {
        temp = *v;
    }
    while (temp != (compare_and_swap(v, temp, temp+1)) );
}
```

# Mutex Locks

- + Previous solutions are complicated and generally inaccessible to application programmers
- + OS designers build software tools to solve critical section problem
- + Simplest is mutex lock
  - Boolean variable indicating if lock is available or not
- + Protect a critical section by
  - First **acquire()** a lock
  - Then **release()** the lock
- + Calls to **acquire()** and **release()** must be **atomic**
  - Usually implemented via hardware atomic instructions such as compare-and-swap.
- + But this solution requires **busy waiting**
  - This lock therefore called a **spinlock**

# Solution to CS Problem Using Mutex Locks

+ A variable **available**: indicate if the lock is available

```
● acquire(S) {  
    while (!available)  
        ; /* busy wait */  
    available = FALSE;  
}  
● release() {  
    available = TRUE;  
}
```

```
while (TRUE) {  
    acquire lock  
    critical section  
    release lock  
    remainder section  
}
```



# Semaphore

- ✚ Synchronization tool that provides more sophisticated ways (than Mutex locks) for processes to synchronize their activities.
- ✚ Semaphore **S** – integer variable
- ✚ Can only be accessed via two indivisible (atomic) operations
  - **wait()** and **signal()**
    - ▣ Originally called **P()** and **V()**

✚ Definition of the **wait()** operation

```
wait(S) {  
    while (S <= 0)  
        ; // busy wait  
    S--;  
}
```

✚ Definition of the **signal()** operation

```
signal(S) {  
    S++;  
}
```

# Semaphore (Cont.)

- + **Counting semaphore** – integer value can range over an unrestricted domain
- + **Binary semaphore** – integer value can range only between 0 and 1
  - Same as a **mutex lock**
- + Can implement a counting semaphore **S** as a binary semaphore
- + With semaphores we can solve various synchronization problems

```
typedef struct {  
    int value;  
    struct process *list;  
} semaphore;  
  
#define Semaphore(name, value) \  
semaphore _#name = {value, 0}, *name = &_#name
```

# Semaphore Usage Example

## + Solution to the CS Problem

- Create a semaphore “**mutex**” initialized to 1

```
wait(mutex) ;
```

```
CS
```

```
signal(mutex) ;
```

## + Consider $P_1$ and $P_2$ that with two statements $S_1$ and $S_2$ and the requirement that $S_1$ to happen before $S_2$

- Create a semaphore “**synch**” initialized to 0

P1 :

```
 $S_1$  ;
```

```
signal(synch) ;
```

P2 :

```
wait(synch) ;
```

```
 $S_2$  ;
```

# Semaphore Implementation

- + Must guarantee that no two processes can execute the `wait()` and `signal()` on the same semaphore at the same time
- + Thus, the implementation becomes the critical section problem where the `wait` and `signal` code are placed in the critical section
- + Could now have **busy waiting** in critical section implementation
  - But implementation code is short (  $< 2$  context switches )
  - Little busy waiting if critical section rarely occupied
- + Note that applications may spend lots of time in critical sections and therefore this is not a good solution

# Semaphore Implementation with no Busy waiting

- ✚ With each semaphore there is an associated waiting queue
- ✚ Each entry in a waiting queue has two data items:
  - Value (of type integer)
  - Pointer to next record in the list
- ✚ Two operations:
  - **block** – place the process invoking the operation on the appropriate waiting queue
  - **wakeup** – remove one of processes in the waiting queue and place it in the ready queue

# Implementation with no Busy waiting (Cont.)

## + Waiting queue

```
typedef struct {  
    int value;  
    struct process *list;  
} semaphore;
```

# Implementation with no Busy waiting (Cont.)

```
wait(semaphore *S) {  
    S->value--;  
    if (S->value < 0) {  
        add this process to S->list;  
        block();  
    }  
}  
  
signal(semaphore *S) {  
    S->value++;  
    if (S->value <= 0) {  
        remove a process P from S->list;  
        wakeup(P);  
    }  
}
```



# Problems with Semaphores

- + Incorrect use of semaphore operations:
  - `signal(mutex) ... wait(mutex)`
  - `wait(mutex) ... wait(mutex)`
  - Omitting of `wait(mutex)` and/or `signal(mutex)`
- + These – and others – are examples of what can occur when semaphores and other synchronization tools are used incorrectly.

# Monitors

- ✦ A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- ✦ *Abstract data type*, internal variables only accessible by code within the procedure
- ✦ Only one process may be active within the monitor at a time
- ✦ Pseudocode syntax of a monitor:

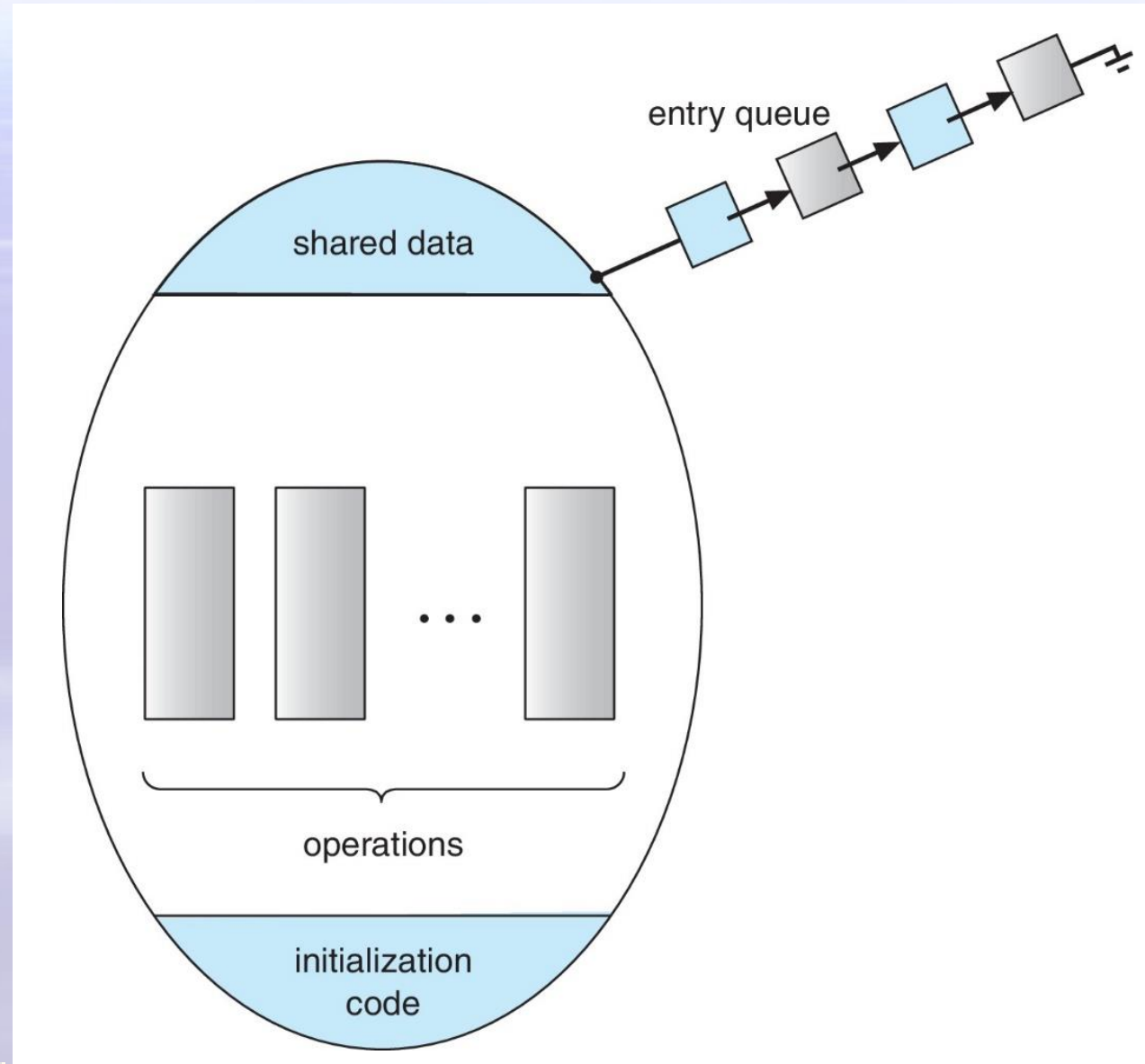
```
monitor monitor-name
{
    // shared variable declarations
    procedure P1 (...) { ... }

    procedure P2 (...) { ... }

    procedure Pn (...) {.....}

    initialization code (...) { ... }
}
```

# Schematic view of a Monitor



# Monitor Implementation Using Semaphores

- + Variables

```
semaphore mutex  
mutex = 1
```

- + Each procedure *P* is replaced by

```
wait(mutex) ;  
    ...  
    body of P ;  
    ...  
signal(mutex) ;
```

- + Mutual exclusion within a monitor is ensured

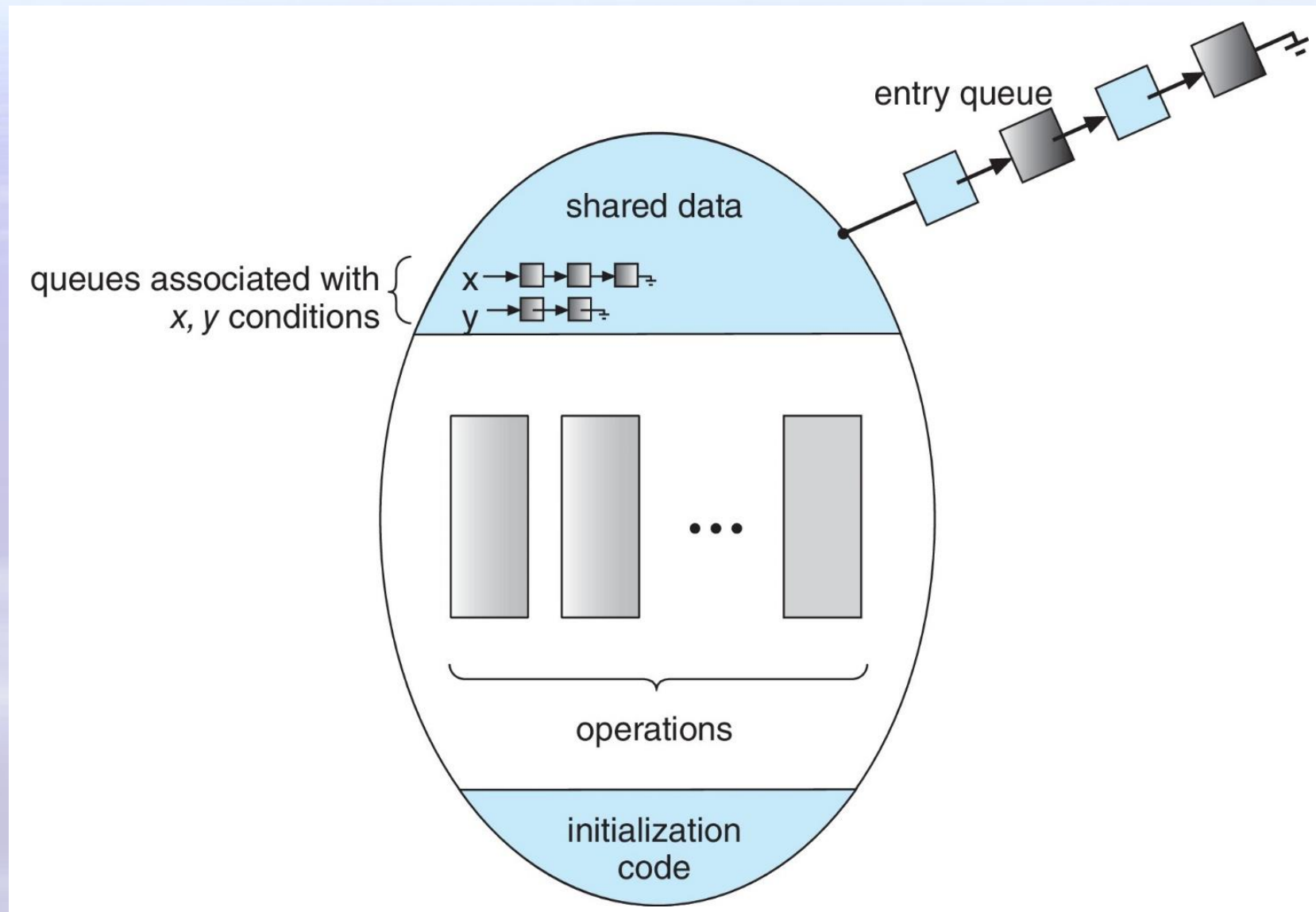
# Condition Variables

+ `condition x, y;`

+ Two operations are allowed on a condition variable:

- `x.wait()` – a process that invokes the operation is suspended until `x.signal()`
- `x.signal()` – resumes one of processes (if any) that invoked `x.wait()`
  - ▢ If no `x.wait()` on the variable, then it has no effect on the variable

# Monitor with Condition Variables



# Usage of Condition Variable Example

- ✦ Consider  $P_1$  and  $P_2$  that need to execute two statements  $S_1$  and  $S_2$  and the requirement that  $S_1$  to happen before  $S_2$ 
  - Create a monitor with two procedures  $F_1$  and  $F_2$  that are invoked by  $P_1$  and  $P_2$  respectively
  - One condition variable “x” initialized to 0
  - One Boolean variable “done”
  - $F_1$ :

```
S1;  
done = TRUE;  
x.signal();
```
  - $F_2$ :

```
if done = FALSE  
    x.wait()  
S2;
```



# Monitor Implementation Using Semaphores

## + Variables

```
semaphore mutex;  // (initially = 1)
semaphore next;   // (initially = 0)
int next_count = 0; // number of processes waiting
                    // inside the monitor
```

## + Each function $P$ will be replaced by

```
wait(mutex);
...
body of P;
...
if (next_count > 0)
    signal(next)
else
    signal(mutex);
```

## + Mutual exclusion within a monitor is ensured

# Implementation – Condition Variables

- ✚ For each condition variable  $x$ , we have:

```
semaphore x_sem; // (initially = 0)
int x_count = 0;
```

- ✚ The operation  $x.\text{wait}()$  can be implemented as:

```
x_count++;
if (next_count > 0)
    signal(next);
else
    signal(mutex);
wait(x_sem);
x_count--;
```

# Implementation (Cont.)

- The operation `x.signal()` can be implemented as:

```
if (x_count > 0) {  
    next_count++;  
    signal(x_sem);  
    wait(next);  
    next_count--;  
}
```

```
semaphore mutex; // (initially = 1)
semaphore next;  // (initially = 0)
int next-count = 0;
semaphore x-sem; // (initially = 0)
int x-count = 0;
```

```
wait(mutex);
...
body of  $F$ ;
...
if (next-count > 0)
    signal(next)
else
    signal(mutex);
```

x.wait()

x.signal()

```
x-count++;
if (next-count > 0)
    signal(next);
else
    signal(mutex);
wait(x-sem);
x-count--;
```

```
if (x-count > 0) {
    next-count++;
    signal(x-sem);
    wait(next);
    next-count--;
}
```

# Resuming Processes within a Monitor

- + If several processes queued on condition variable **x**, and **x.signal()** is executed, which process should be resumed?
- + FCFS frequently not adequate
- + Use the **conditional-wait** construct of the form  
`x.wait(c)`

where:

- **c** is an integer (called the priority number)
- The process with lowest number (highest priority) is scheduled next

# Single Resource allocation

- ✦ Allocate a single resource among competing processes using priority numbers that specifies the maximum time a process plans to use the resource
- ✦ The process with the shortest time is allocated the resource first
- ✦ Let  $R$  is an instance of type **ResourceAllocator** (next slide)
- ✦ Access to **ResourceAllocator** is done via:

```
R.acquire( $\tau$ ) ;  
    ...  
    access the resource ;  
    ...  
R.release ;
```

- ✦ Where  $\tau$  is the maximum time a process plans to use the resource

# A Monitor to Allocate Single Resource

```
monitor ResourceAllocator
{
    boolean busy;
    condition x;
    void acquire(int time) {
        if (busy)
            x.wait(time);
        busy = TRUE;
    }
    void release() {
        busy = FALSE;
        x.signal();
    }
    initialization code() {
        busy = FALSE;
    }
}
```



# Single Resource Monitor (Cont.)

## + Usage:

**acquire**

**...**

**release**

## + Incorrect use of monitor operations

- **release()** ... **acquire()**
- **acquire()** ... **acquire()**
- Omitting of **acquire()** and/or **release()**

# Liveness

- Processes may have to wait indefinitely while trying to acquire a synchronization tool such as a mutex lock or semaphore.
- Waiting indefinitely violates the progress and bounded-waiting criteria discussed at the beginning of this chapter.
- Liveness** refers to a set of properties that a system must satisfy to ensure processes make progress.
- Indefinite waiting is an example of a liveness failure.

# Liveness (Cont.)

- ✦ **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes

- ✦ Let **S** and **Q** be two semaphores initialized to 1

$P_0$   
wait (S);  
wait (Q);  
...  
signal (S);  
signal (Q);

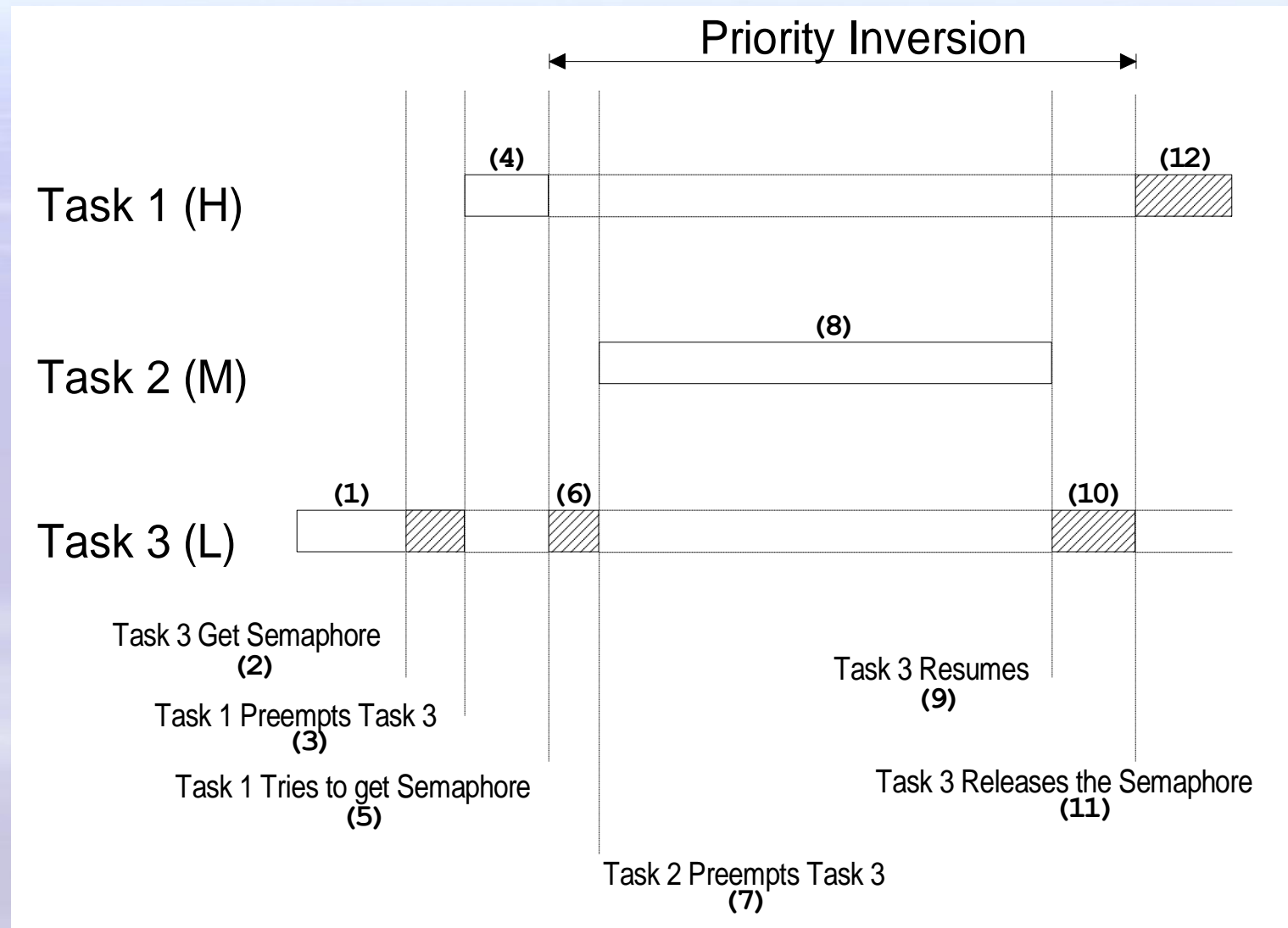
$P_1$   
wait (Q);  
wait (S);  
...  
signal (Q);  
signal (S);

- ✦ **Starvation** – indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended.

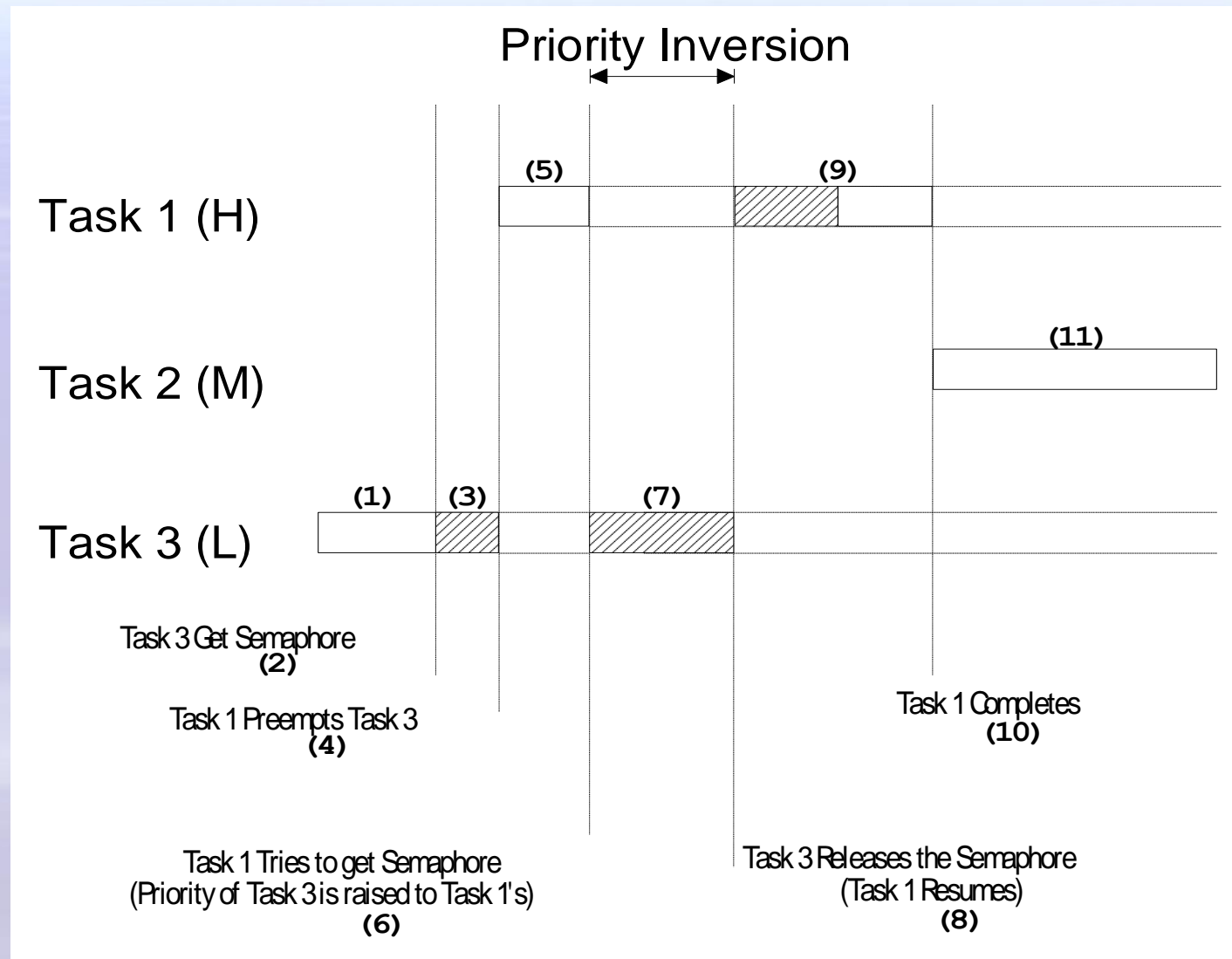
- ✦ **Priority Inversion** - Scheduling problem when lower-priority process holds a lock needed by higher-priority process

- Solved via **priority-inheritance protocol**

# Priority Inversion



# Priority Inheritance



# End of Chapter 6

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