Chapter 6
Synchronization Tools

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Source: Abraham Silberschatz, Peter B. Galvin, and Greg Gagne, "Operating System Concepts", 10th Edition, Wiley.

Outline

Background

- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the **orderly execution** of cooperating processes
    - cooperating processes: processes that access the shared data
- Suppose that we wanted to provide a solution to the consumer-producer problem that fills all the buffers.
    - use an integer count
        - keeps track of the number of full buffers
        - Initially set to 0
        - Incremented by the producer after it produces a new buffer
        - Decremented by the consumer after it consumes a buffer

Producer

```
while (true)
{
            /* produce an item and put in nextProduced */
            while (count == BUFFER_SIZE)
                  ; // do nothing
            buffer [in] = nextProduced;
            in = (in + 1) % BUFFER_SIZE;
            count++;
}
```

Consumer

```
while (true)
{
        while (count == 0)
                ; // do nothing
        nextConsumed =  buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        count--;
        /*  consume the item in nextConsumed */
}
```

Race Condition

- count++ could be implemented as

  register1 = count
  register1 = register1 + 1
  count = register1

- count-- could be implemented as

  register2 = count
  register2 = register2 - 1
  count = register2

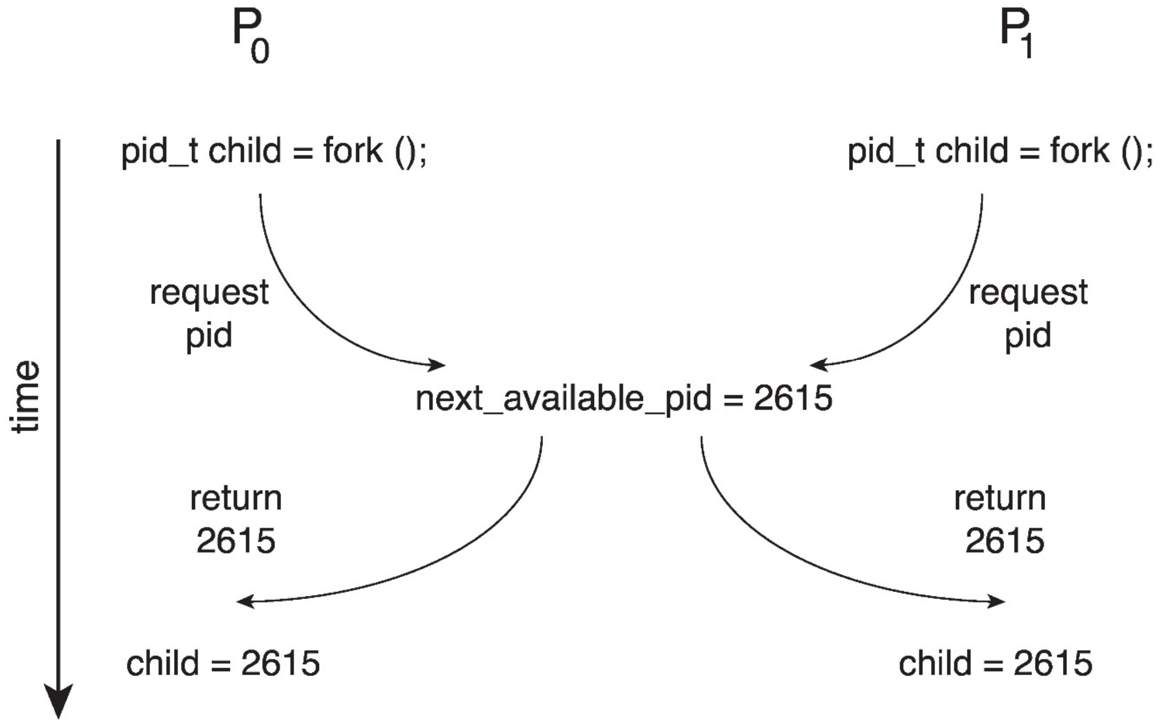
- Consider this execution interleaving with "count = 5" initially:

  S0: producer execute register1 = count {register1 = 5}
  S1: producer execute register1 = register1 + 1 {register1 = 6}
  S2: consumer execute register2 = count {register2 = 5}
  S3: consumer execute register2 = register2 - 1 {register2 = 4}
  S4: producer execute count = register1 {count = 6 }
  S5: consumer execute count = register2 {count = 4}

➔ ***Race condition***...

Race Condition – Another Example

- 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)



Critical Section

- Consider ***n*** cooperating processes $\{p_0, p_1, \ldots p_{n-1}\}$
- Each process has a **critical section**
  - A segment of code, in which the process may update shared data
- ***When a process is in the critical section, the others cannot enter their critical sections!***
  - no two processes in the same critical section at the same time

- Critical section problem
  - Design a protocol that processes can use to coordinate
    - Entry section: code to try/request to enter the critical section
    - Exit section: code that follows the critical section

Critical Section

```
do
{
    entry section
        critical section  //update shared data here…
    exit section
    remainder section
} while (TRUE)
```

Solution to Critical-Section Problem

A solution should satisfy the following requirements

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 processes 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 – guarantee a given process will finally be selected
   - Assume that each process executes at a nonzero speed
   - No assumption concerning relative speed of the N processes

Peterson’s Solution

- Two-process solution; a software based solution
- Assume that the LOAD and STORE 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 whether or not a process is ready to enter the critical section
  - flag[i] = TRUE implies that process P_i is ready!

Peterson's Solution

Algorithm for Process P_i

```
do {
    flag[i] = TRUE;
    turn = j;
    while ( flag[j] && turn == j);  // you first

        CRITICAL SECTION

    flag[i] = FALSE;                // exit

        REMAINDER SECTION

} while (TRUE);
```

Algorithm for Process P_j

```
do {
    flag[j] = TRUE;
    turn = i;
    while ( flag[i] && turn == i);  // you first

        CRITICAL SECTION

    flag[j] = FALSE;                // exit

        REMAINDER SECTION

} while (TRUE);
```

Peterson’s Solution

- Mutual exclusion is met
  - turn can either be i or j
- Progress and bounded-waiting are met
  - Once Pj exits, it sets flag[j] to false, allows Pi to enter
  - If Pj resets flag[j] to true, it must also set turn to i
    - Allow Pi to enter
  - Pi will enter critical section after at most one entry by Pj (bounded-waiting)
  - Selection will not be postponed forever (progress)

Peterson's Solution

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

Peterson's Solution

- Two threads share the data

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

- Thread 1 performs

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

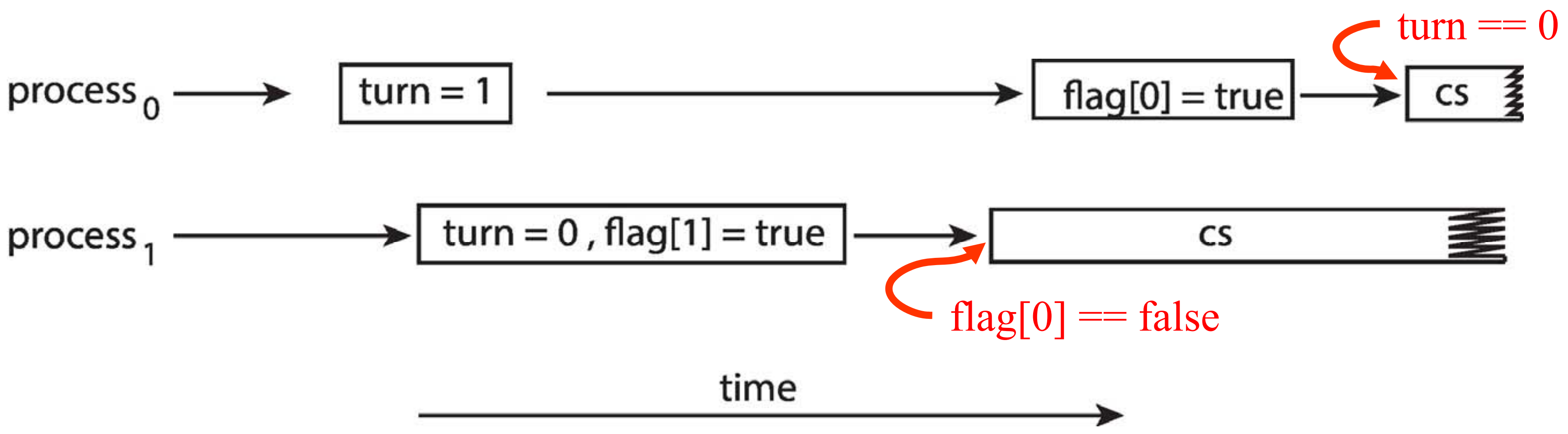
- Thread 2 performs

```
x = 100;
flag = true;
```

- What is the expected output?
  - 100? right?

Peterson's Solution

- However, the operations for Thread 2 may be reordered:
```
flag = true;
x = 100;
```
- If this occurs, the **output may be 0**!
- The effects of instruction reordering in Peterson's Solution



Both processes in their critical sections at the same time!

Hardware Support for Synchronization

- Many systems provide hardware support for synchronization
- Uniprocessor – could disable interrupts
  - Currently running code would execute without preemption
  - Common in embedded systems
  - However,
    - Not efficient on multiprocessor systems
      - Need to ask other processors to disable interrupts
      - Operating systems using this not broadly scalable
    - Clocks may stop in the critical section

Hardware Support for Synchronization

- We will look at three additional forms of hardware support

  1. Memory barriers

  2. Hardware instructions

  3. Atomic variables

Memory Barriers

- Memory models
  - **Strongly ordered:** a memory modification of one processor is immediately visible to all other processors.
  - **Weakly ordered:** a memory modification of one processor may not be immediately visible to all other processors.

- A ***memory barrier*** **(or memory fence)**
  - an instruction (e.g., mfence for x86) that forces any change in memory to be propagated (made visible) to all other processors.
  - ensure that all loads/stores are **finished** before any subsequent load/store operations are performed

Memory Barrier

- We could add a memory barrier to the following instructions to ensure Thread 1 outputs 100:
- Thread 1 now performs

```
while (!flag)
     memory_barrier(); //flag is loaded before x
print x;
```

- Thread 2 now performs

```
x = 100;
memory_barrier(); // x is assigned before flag
flag = true;
```

Using Memory Barriers for Peterson's Solution

- Place a memory barrier between the first two assignment statements

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

Critical Sections and Locks

```
do
{
        Acquire lock  // entry section
        Critical section…
        Release lock  // exit section
        Remainder section…
} while (TRUE)
```

Synchronization Hardware

- Modern machines provide special atomic hardware instructions for locks
    - Atomic = non-interruptable
- Test-and-Set instruction
- Compare-and-Swap instruction
- Swap instruction

test_and_set Instruction

Definition:

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

Done by a single instruction

- 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 here

        lock = FALSE;

        ….. remainder section here

} while (TRUE);
```

false→ true
true→ true

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;
}
```

Done by a single instruction

- Executed atomically
- Returns the original value of ***value**
- Set the ***value** to the **new_value** if ***value == expected**. 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) != 0)
         ; /* do nothing */

        ... critical section here...

        lock = 0;

        ... remainder section here ...
}
```

swap Instruction

- Definition

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

Done by a single instruction

Solution using swap

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

Used for swapping with *lock*

```
    do {
            key = TRUE;
            while (key == TRUE)    Swap ( &lock, &key );
            ….. critical section here
            lock = FALSE;
            ….. remainder section here
        } while (TRUE);
```

Lock: TRUE, key: FALSE

Synchronization Hardware

- The above examples
  - do not satisfy bounded waiting…
- The following code satisfy all the three requirements

```
Boolean waiting[n], lock=FALSE;
do {
        waiting[i] = TRUE;              // wish to acquire the lock
        key = TRUE;
        while (waiting[i] && key)   key = TestandSet(&lock);  // try to acquire the lock
        waiting[i] = FALSE;
        // ……critical section here…. //
        j = (i+1)%n;
        while ( (j!= i) && !waiting[j] )  j = (j+1)%n;  // keep locked and allow the
                                                        // next  to come in
        if ( j == i ) lock = FALSE;
        else waiting[j] = FALSE;
        // ……remainder section here…. //
} while (TRUE);
```

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 updates** on basic data types such as integers and booleans.
  - Useful when the critical section contains the update of a single shared variable
- For example, the **increment()** operation on the atomic variable *k* ensures *k* is incremented without interruption:

increment(&*k*);

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));
}
```

*v = 5

Thread 1	Thread 2
temp = *v = 5	---
---	**temp = *v = 5**
---	compare_and_swap(v, temp, temp+1); // *v = temp+1 = 6; return 5

compare_and_swap(v, temp, temp+1);
// *v != temp, v = 6, return 6;	

temp != 6; while(TRUE), next round	
temp = *v = 6	
	temp == 5; while (FALSE)
	increment() finishes Return to calling procedure

compare_and_swap(v, temp, temp+1);
// *v == temp+1=7, return 6;	

temp == 6; while (FALSE)	
increment() finishes Return to calling procedure	

Mutex Locks

- Previous solutions not target for application programmers
- A less complicated syn. interface to programmers - mutex lock
- Protect a critical section by first **acquire()** a lock then **release()** the lock
  - ensure mutual exclusion (see next slide)
- acquire()/release() must be atomic
  - Usually implemented via hardware atomic instructions such as compare-and-swap
- This solution requires **busy waiting**
  - a ***spinlock***

Critical Sections and Locks

```
do
{
        acquire()        // Acquire lock
        Critical section…
        release()        // Release lock
        Remainder section…
} while (TRUE)
```

Mutex Lock Definitions

```
acquire() {
        while (!available)
          ; /* busy wait */
        available = false;
}

release() {
        available = true;
}
```

- These two functions must be implemented atomically.
- Hardware instructions such as test-and-set/compare-and-swap can be used to implement these functions.

Semaphore

- More general than mutex locks
- Typical semaphore implementations do NOT require busy waiting
- Semaphore *S* – integer variable
- Two standard operations modify S: wait() and signal()
  - Originally called P() and V()
- Can only be accessed via two indivisible **(atomic)** operations

```
– wait (S) {
      while S <= 0                  // atomic for each iteration
          ; // no-op                // iteration: if S>0, S--; else, no-op and test again
      S--;
  }
– signal (S) {
      S++;                          // atomic
  }
```

Semaphore as General Synchronization Tool

- Counting semaphore – integer value can range over an unrestricted domain
- Binary semaphore – integer value can range only between 0 and 1; can be simpler to implement
  - Same as **mutex locks**
- A counting semaphore S can be used to implement a binary semaphore

Semaphore as General Synchronization Tool

- Provides mutual exclusion
  - Semaphore S;   // initialized to 1
  - wait (S);

              Critical Section

     signal (S);
- Other usages on semaphores
  - Control the usage of resources with N instances
    - S is initialized to N
  - Synchronization between processes
    - S is initialized to 0

Semaphore Implementation

- Previous semaphore definition requires busy waiting…
- Note that applications may spend lots of time in critical sections. In this case, busy waiting is not a good approach.
- Solution
  - Sleep/block instead of busy waiting

Semaphore Implementation WITHOUT Busy Waiting

- In addition to the semaphore value, each semaphore has an associated waiting queue

- Require blocking/waking-up a process
  - block
    - switch process state to "waiting"
    - remove the process from the ready queue
  - wakeup
    - switch process state to "ready"
    - place the process in the ready queue
- Both operations may lead to the invocation of the scheduler

Semaphore Implementation WITHOUT Busy waiting (Cont.)

- Implementation of wait:

```
wait (S){
        value--;
        if (value < 0) { // the value can be negative ➔ # of processes waiting
                add this process to the waiting queue
                 block();  /* suspend the process */ }
 }
```

- Implementation of signal:

```
signal (S){
           value++;
            if (value <= 0) {
                   remove a process P from the waiting queue
                    wakeup(P);  }
}
```

Semaphore Implementation

- The list of waiting processes?
  - A list of PCBs
  - FIFO ➔ ensure bounded waiting
- Must guarantee that no two processes can execute wait() and signal() on the same semaphore at the same time
  - The implementation in the previous slide should be **atomic**
- Thus, implementation becomes the critical section problem where the ***wait and signal code are placed in the critical section***.
  - For uniprocessor ➔ disable interrupt
  - For MP ➔ typically use a busy waiting approach., e.g. test_and_set
    - Acceptable for busy waiting in critical sections of the wait() and signal() operations since they are short…

Problems with Semaphores

- Using semaphores incorrectly can result in bugs that are hard to detect
- Incorrect use of semaphore operations:
  - signal (mutex) …. wait (mutex) ➔ race
  - wait (mutex) … wait (mutex) ➔ deadlock *(described later)*
  - Omitting of wait (mutex) or signal (mutex) (or both) ➔ race or deadlock
- The bugs are hard to detect
  - Faults don't always take place

Monitors

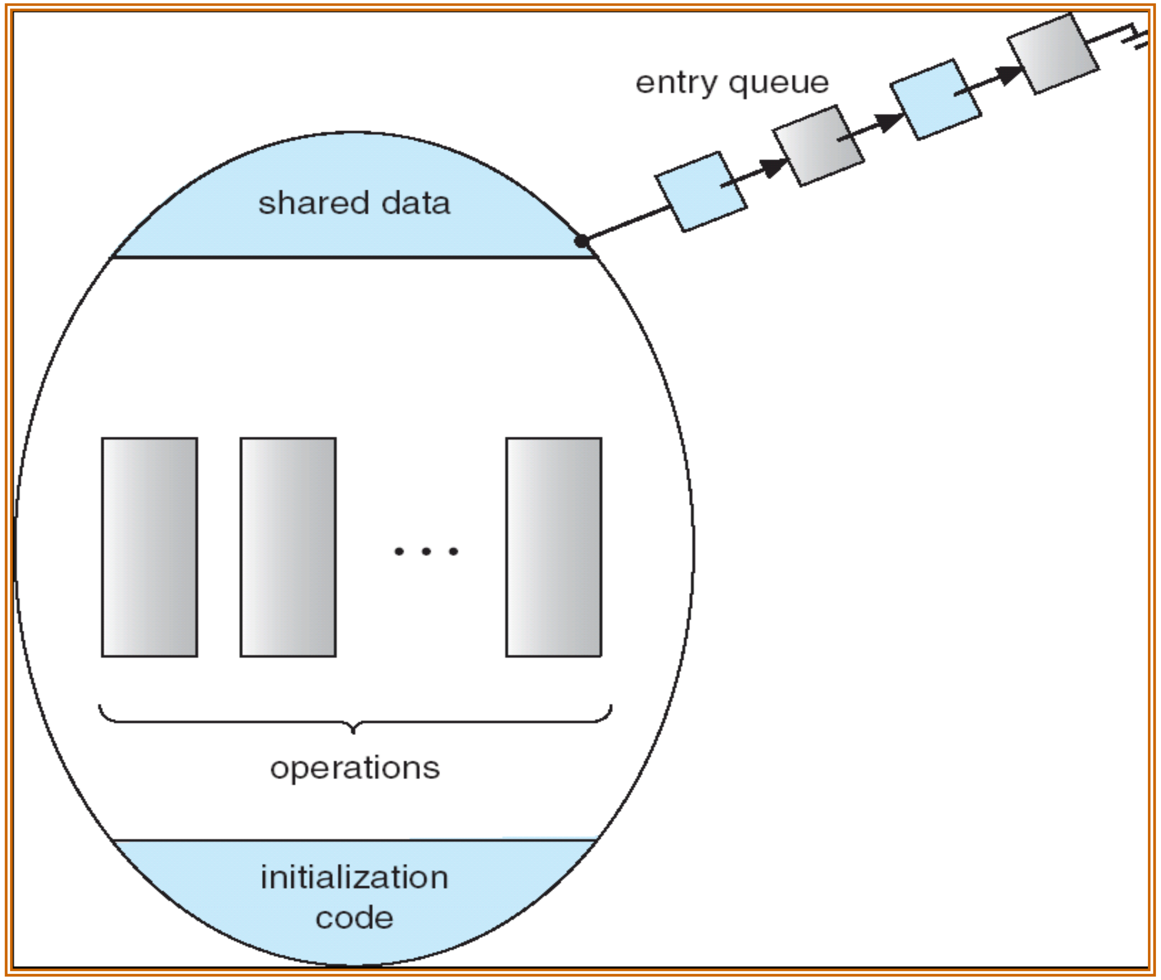
- A high-level abstraction that provides a convenient and effective mechanism for process synchronization

```
monitor monitor-name
{
        ... shared variable declarations

        procedure P1 (…) { …. }
        …
        procedure Pn (…) {……}
        Initialization code ( ….) { … }
        …
}
```

- **Programmers provide the operations**
- **Monitor makes sure only one process may be active within the monitor at a time**

Schematic View of a Monitor



A list of processes waiting for entering the monitor

Monitors

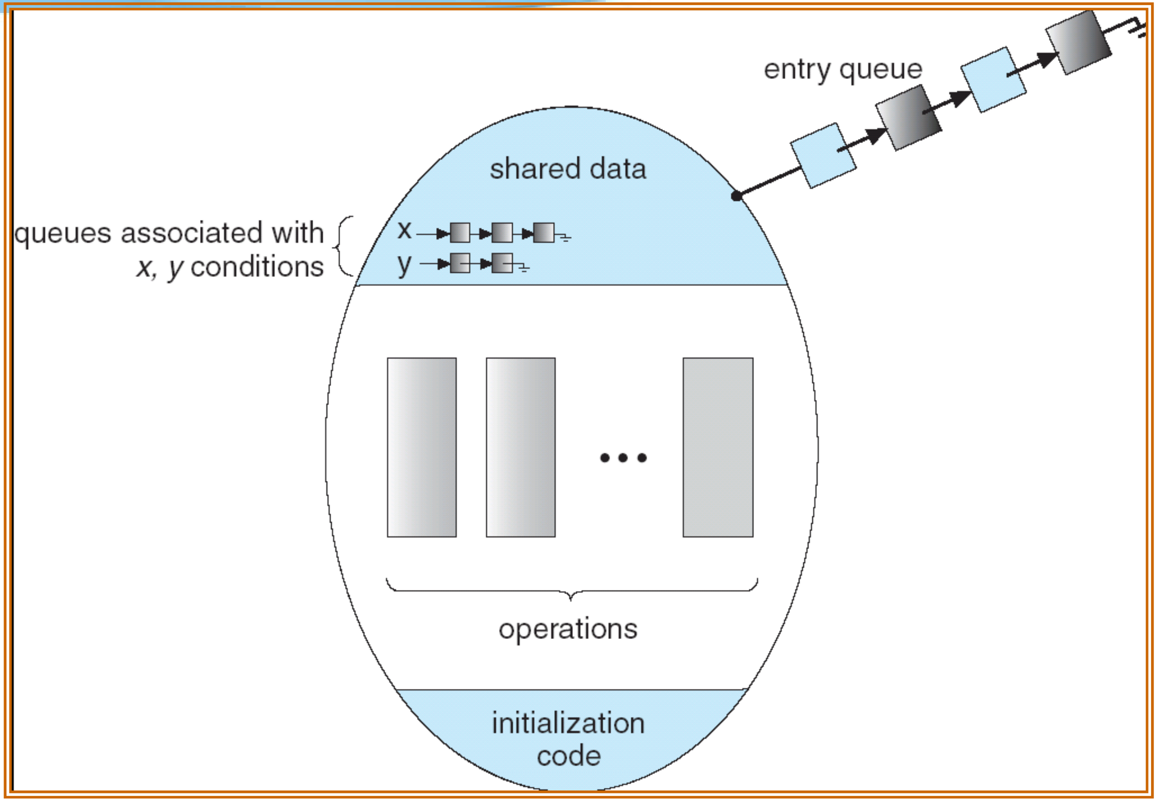
- With monitors, programmers do not need to code the synchronization constraint
- However, the function provided by monitors is limited
  - In many cases, programmers still need to define additional syn. mechanisms
    - Use condition variables

Condition Variables

- condition x, y;
- Two operations on a condition variable
  - x.wait()
    - a process that invokes the operation is suspended
  - x.signal()
    - resumes **one** of processes (if any) that invoked x.wait ()
    - No effect if no one is waiting
- No values, just suspend and resume
  - Different from semaphores

Using them incorrectly are still hard-to-be-detected bugs

Monitor with Condition Variables



If Q wait X and then P signal X

- P is now in monitor, but it will make Q become active in the monitor
- Two possibilities
  - A. **signal & wait** : Q becomes active immediately, P leaves
  - B. **signal & continue**: Q becomes active after P leaves

Implementing a Monitor Using Semaphores

- Use a semaphore **mutex** (init. as 1) for each monitor
  - wait(mutex) before entering the monitor
  - signal(mutex) after leaving the monitor

- A signaling process may wait until the resumed process to leave or wait
  - Use another semaphore **next** (init. as 0)
    - Signaling process can suspend on it
  - Next_count
    - Count the number of processes suspend on **next**

Implementing a Monitor Using Semaphores

- Each external procedure F is replaced by

```
wait (mutex);
    F
if (next_count >0 )       signal(next);     ⇐ Wakeup a signaling process
else                      signal(mutex);    ⇐ Allow another process to
                                              come in
```

- Each condition variable is implemented by using
  - x_sem : semaphore corresponds to x (init. as 0)
  - x_count: number of processes waiting on x_sem

Implementing a Monitor Using Semaphores

```
x.wait()
{
        x_count++;
        if (next_count >0 )     signal(next);
        else                    signal(mutex);
        wait(x_sem);            ← wait here....
        x_count--;              ← have been waken
}

x.signal()
{
        if (x_count >0 )
        {
                next_count++;
                signal(x_sem);
                wait(next);             ← wait here....
                next_count--;           ← have been waken
        }
}
```

Process Resuming Order

- Which process (waiting for the monitor) should be resumed first?
  - FCFS
  - Priority
    - Users can specify priority on suspension
      - x.wait(**priority**)
      - Process with the highest priority is scheduled next

Single Resource Allocation

- Allocate a single resource among competing processes using priority numbers that specify the maximum time a process plans to use the resource

```
R.acquire(t);
    ...
access the resource;
    ...
R.release();
```

- Where R is an instance of type **ResourceAllocator**
  - *See next slide*

A Monitor to Allocate Single Resource

```
monitor ResourceAllocator
{
    boolean busy;   //whether resource is busy or not
    condition x;    // wait on x if resource busy

    void acquire (int time) {
            if (busy)     x.wait(time);
            busy = true;
    }

    void release () {
            busy = FALSE;
            x.signal();
    }
    initialization code() {   busy = false;   }
}
```

Incorrect Use of Monitor

- Access a resource without being granted
- Never release the resource
- Release a resource that the process doesn’t have
  - Release the resource twice

- Monitors make sure only one process is in it at a time, but it can not solve all the problems related to resource allocation/deallocation

Liveness

- Processes may have to wait indefinitely while trying to acquire a lock
- 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.
- Examples of liveness failure
  - Deadlock
  - Starvation
  - Priority inversion

Liveness Failures

- Deadlock – two or more processes are waiting infinitely for an event that can be caused by only one of the waiting processes
- Let S and Q be two semaphores initialized to 1

```
        P0                          P1
    wait (S);                   wait (Q);
    wait (Q);                   wait (S);
        .                           .
        .                           .
        .                           .
    signal  (S);                signal (Q);
    signal (Q);                 signal (S);
```

  – Consider if P_0 executes wait(S) and P_1 wait(Q). When P_0 executes wait(Q), it must wait for P_1 . However, P_1 also waits for P_0 when it executes wait(S).

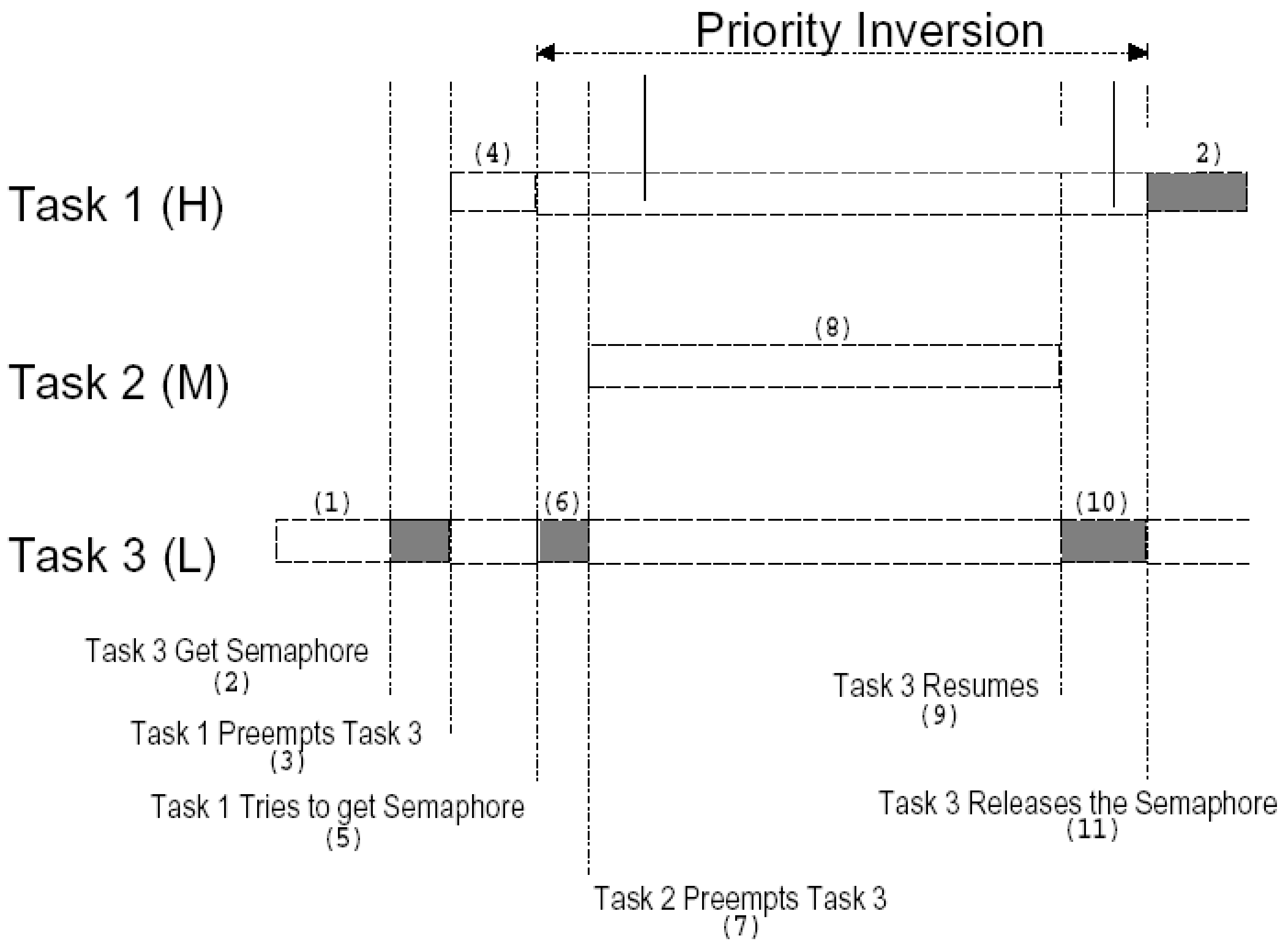
Liveness Failures

- Starvation – infinite 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
  - can be solved by priority-inheritance protocol

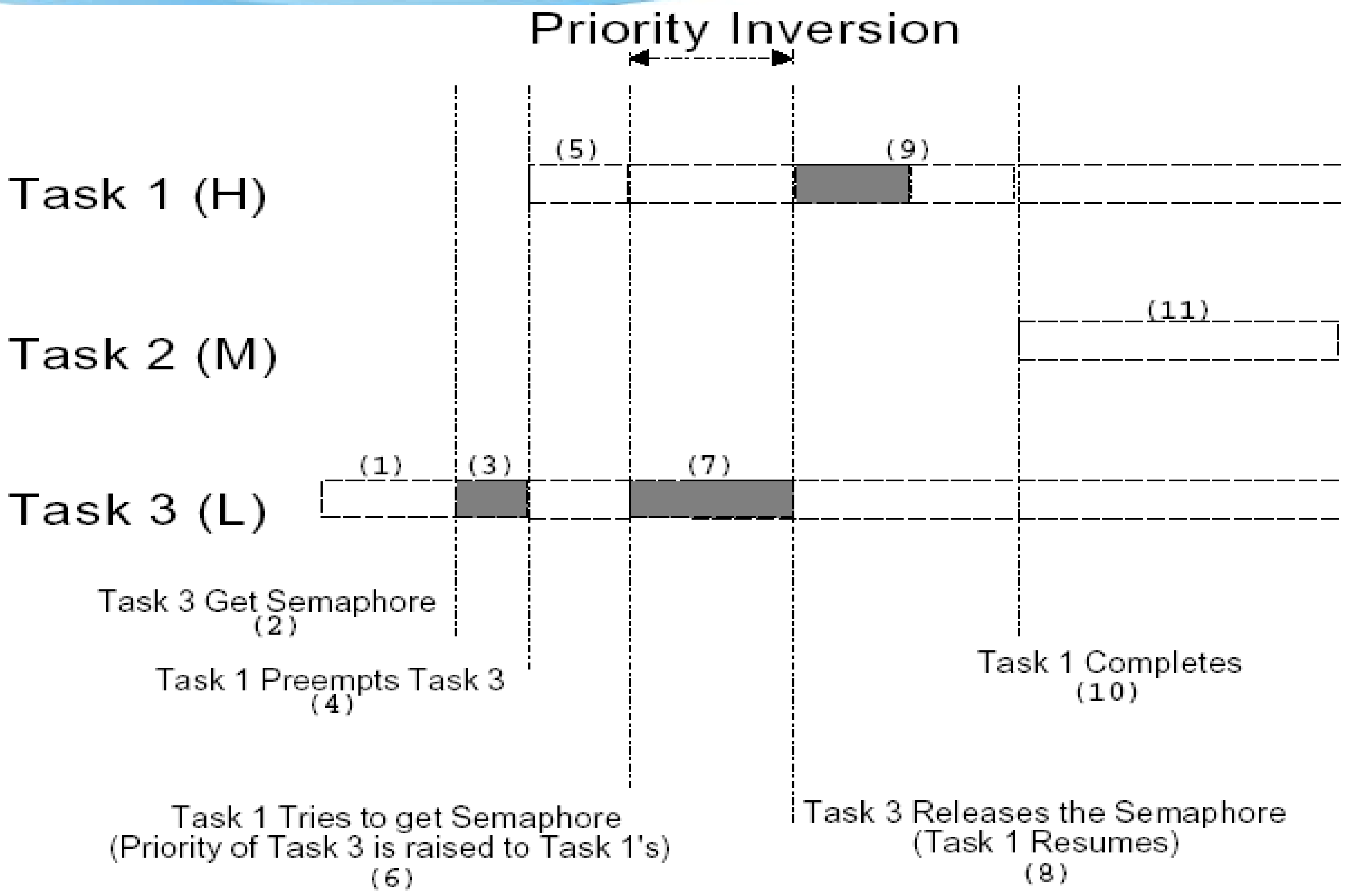
Priority Inversion

- A problem in real-time systems



Priority Inversion
Task 1 (H)
Task 2 (M)
Task 3 (L)
(1)
(4)
(6)
(8)
(10)
2)
Task 3 Get Semaphore (2)
Task 1 Preempts Task 3 (3)
Task 1 Tries to get Semaphore (5)
Task 2 Preempts Task 3 (7)
Task 3 Resumes (9)
Task 3 Releases the Semaphore (11)

Priority Inheritance Protocol (PIP)



Some level of priority inversion can not be avoided!!