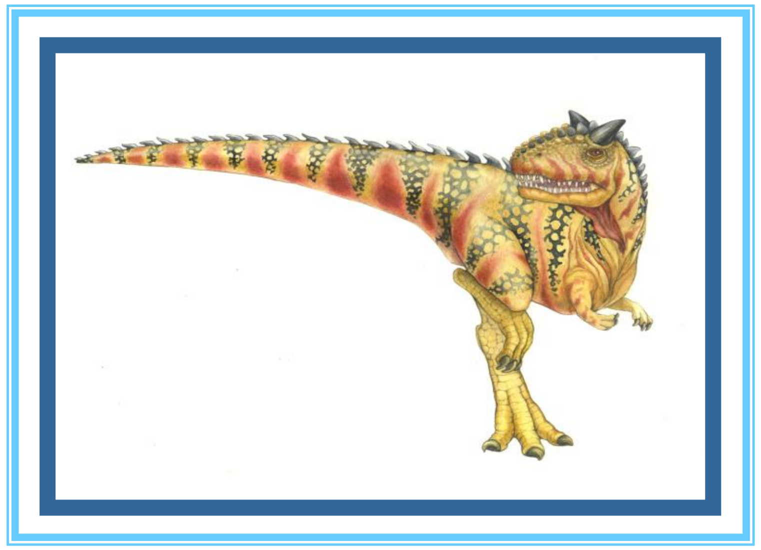
Chapter 6: Process Synchronization



Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Peterson’s Solution
- Synchronization Hardware
- Mutex Locks
- Semaphores
- Classic Problems of Synchronization
- Monitors
- Synchronization Examples
- **Objective**
  - To introduce the critical-section problem, whose solutions can be used to ensure the consistency of shared data
  - To present both software and hardware solutions of the critical-section problem
  - To examine several classical process-synchronization problems
  - To explore several tools that are used to solve process synchronization problems

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
- Illustration of the problem:
  Suppose that we wanted to provide a solution to the consumer-producer problem that fills ***all*** the buffers. We can do so by having an integer **`counter`** that keeps track of the number of full buffers. Initially, **`counter`** is set to 0. It is incremented by the producer after it produces a new buffer and is decremented by the consumer after it consumes a buffer.

Producer – Consumer Problem

Producer

```
while (true) {
      /* produce an item in next produced */
      while (counter == BUFFER SIZE) ;
            /* do nothing */
      buffer[in] = next_produced;
      in = (in + 1) % BUFFER SIZE;
      counter++;
}
```

Consumer

```
while (true) {
      while (counter == 0)
            ; /* do nothing */
      next_consumed = buffer[out];
      out = (out + 1) % BUFFER SIZE;
      counter--;
      /* consume the item in next consumed */
}
```

Race Condition

- `counter++` could be implemented as

```
register1 = counter
register1 = register1 + 1
counter = register1
```

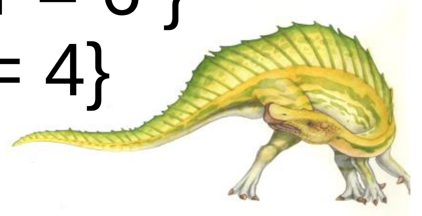
- `counter--` could be implemented as

```
register2 = counter
register2 = register2 - 1
counter = register2
```

Race condition: several processes access and manipulate the same data concurrently, and the outcome of the execution depends on the particular order where the access takes place.

- Consider this execution interleaving with “count = 5” initially:

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

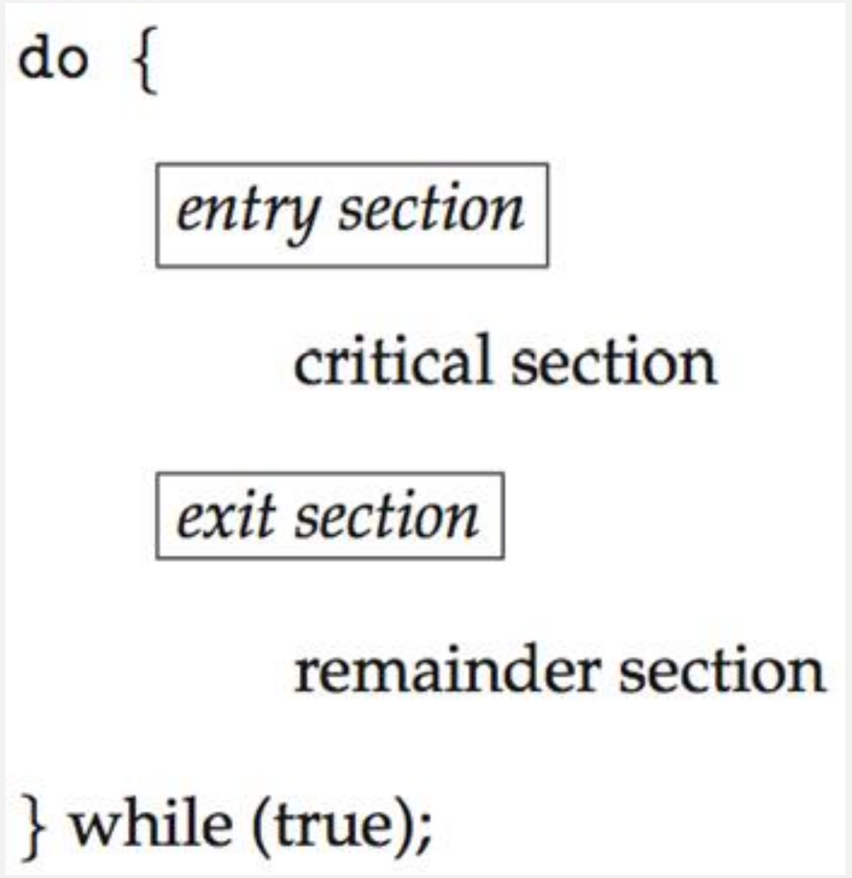


Critical Section Problem

- Consider system of ***n*** processes {$\boldsymbol{p_0, p_1, \ldots p_{n-1}}$}
- Each process has **critical section** 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**

General structure of process $\boldsymbol{p_i}$ is



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

Solution to Critical-Section Problem

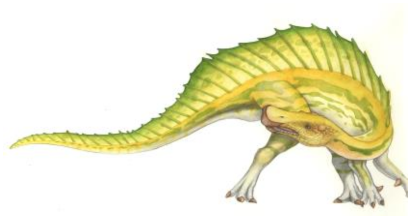
1. **Mutual Exclusion** - If process $\boldsymbol{P_i}$ is executing in its critical section, then no other processes can be executing in their critical sections
2. **Progress** - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, 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
   - Assume that each process executes at a nonzero speed
   - No assumption concerning **relative speed** of the ***n*** processes

- Critical sections in operating system:
  - **Preemptive kernel** – allows preemption of process when running in kernel mode
    - More responsive, good for real-time appl. ➔ prone to have race condition
  - **Non-preemptive kernel** – runs until exits kernel mode
    - Essentially free of race conditions in kernel mode

Peterson' s Solution

- Good algorithmic description of solving the problem
- Two-process solution
- The processes share two variables:
  - **`int turn;`**
  - **`Boolean flag[2]`**
    - **`turn:`** indicates whose turn it is to enter the critical section
    - **`flag[2]:`** indicates if a process is ready to enter the critical section.
    - **`flag[i] = true`** ➔ implies that process P_i is ready!
- Provable that

1. Mutual exclusion is preserved
2. Progress requirement is satisfied
3. Bounded-waiting requirement is met



Peterson’s Solution

Algorithm for Process P_i

```
do {
     flag[ i ] = true;
     turn = j;
     while( flag[ j ] && turn == j );
     critical section
     flag[ i ] = false;

     remainder section
} while (true);
```

Algorithm for Process P_j

```
do {
     flag[ j ] = true;
     turn = i;
     while( flag[ i ] && turn == i );
     critical section
     flag[ j ] = false;

     remainder section
} while (true);
```

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Synchronization Hardware

- Many systems provide hardware support for critical section code
- All solutions below based on idea of **locking**
  - Protecting critical regions via locks
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
- Modern machines provide special atomic hardware instructions
  - **Atomic** = non-interruptible
  - ***test_and_set instruction***
  - ***compare_and_swap instruction***

Solution to Critical-section Problem Using Locks

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

test_and_set Instruction

- **Definition:**

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

⇦ *atomic instruction*

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

```
do {
        while( test_and_set( &lock ) );    /* do nothing */

        /* critical section */
        lock = false;

        /* remainder section */
}  while (true);
```

Solution using compare_and_swap

- **Definition:**

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

atomic instruction

- **Solution:**

Shared Boolean variable ***lock*** initialized to FALSE;

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

    . . . .              /* remainder section */
} while (true);
```

Bounded-waiting Mutual Exclusion with test_and_set

```
boolean waiting[n];

boolean lock;
```

Both are initialized to **false**

Bounded waiting

```
do {
        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 );
```

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**
- Product critical regions with it by first **`acquire()`** a lock then **`release()`** it
  - **Boolean variable** indicating if lock is available or not
- Calls to **`acquire()`** and **`release()`** must be atomic
  - Usually implemented via hardware atomic instructions
- But this solution requires **busy waiting**
  - This lock therefore called a **spinlock**

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

do {
   acquire lock
      critical section
   release lock
      remainder section
} while (true);
```

Semaphore

- Semaphore ***S*** – **integer variable**
- Two standard operations modify ***S***: **`wait()`** and **`signal()`**
  - Originally called **`P()`** and **`V()`**
- Less complicated
- Can only be accessed via two indivisible (atomic) operations

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

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

Semaphore Usage

- **Counting semaphore** – integer value not only 0 or 1
  - Control access to a resource consisting of a finite number of instances
  - The semaphore is initialized to the number of resources available
  - wait( ) : decrements the count
  - signal() : increasess the count
  - count = 0 : all resources are being used and processes that wish to use a resource will block until the count becomes > 0.
- **Binary semaphore** – integer value can range only between 0 and 1
  - Then a **mutex lock**

Semaphore Usage

- Not only for resource mutual exclusive, but also for synchronization problems
- Consider ***P_1*** and ***P_2*** that require ***S_1*** to happen before ***S_2***
  - The common Semaphore ***synch*** is initialized to 0

P1:

```
        S1;
        signal( synch );
```

P2:

```
        wait( synch );
         S2;
```

  - Because synch is initialized to 0, P2 will execute S2 only after P1 has invoked signal(synch) which will increase synch to 1.

Semaphore Implementation with no Busy waiting

- The implementation in p14 still suffers from the problem of busy waiting. Since applications may spend lots of time in critical sections, this is not a good solution
- Solution 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

Semaphore Implementation with no Busy waiting (Cont.)

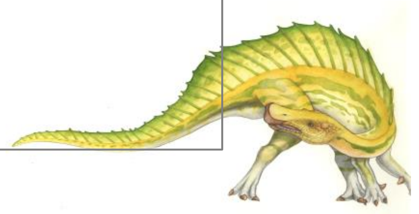
```
typedef struct{
   int value;
   struct process *list;
} semaphore;
```

```
wait( semaphore *S ) {
     S->value--;
     if ( S->value < 0 ) {
          add this process to S->list;
          block();
     }
}
```

- S->value <=0
  ➔ its magnitude is the number of processes waiting on that semaphore

- To ensure *bounded waiting* : use **FIFO** for the waiting list.

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



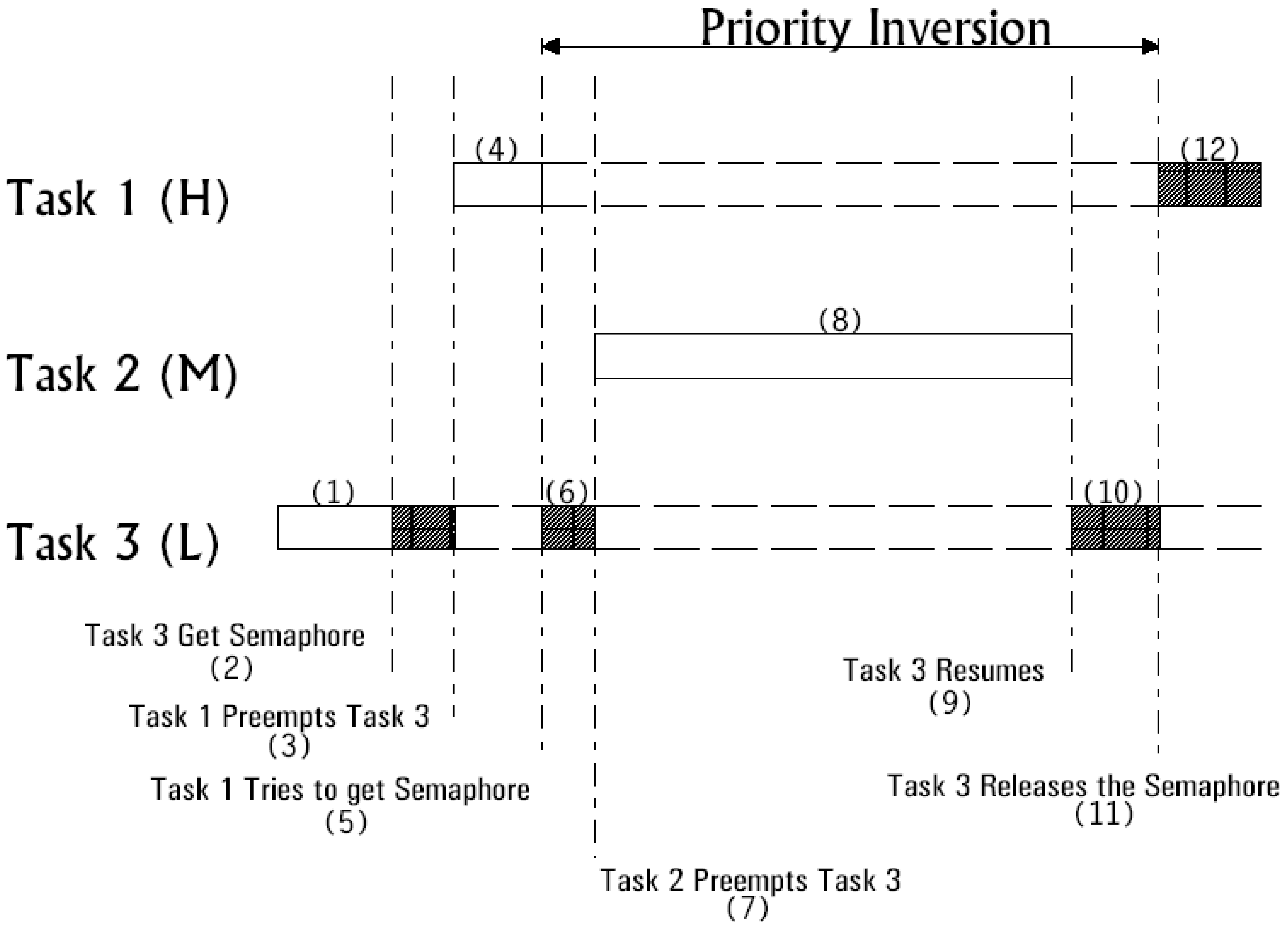
Deadlock, Starvation, Priority Inversion

- **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

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

- **Starvation** – **indefinite blocking**
  - A process may never be removed from the semaphore queue
  - It may occur if we remove processes from the list in LIFO order.
- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process
  - Solved via **priority-inheritance, or priority ceiling protocol**

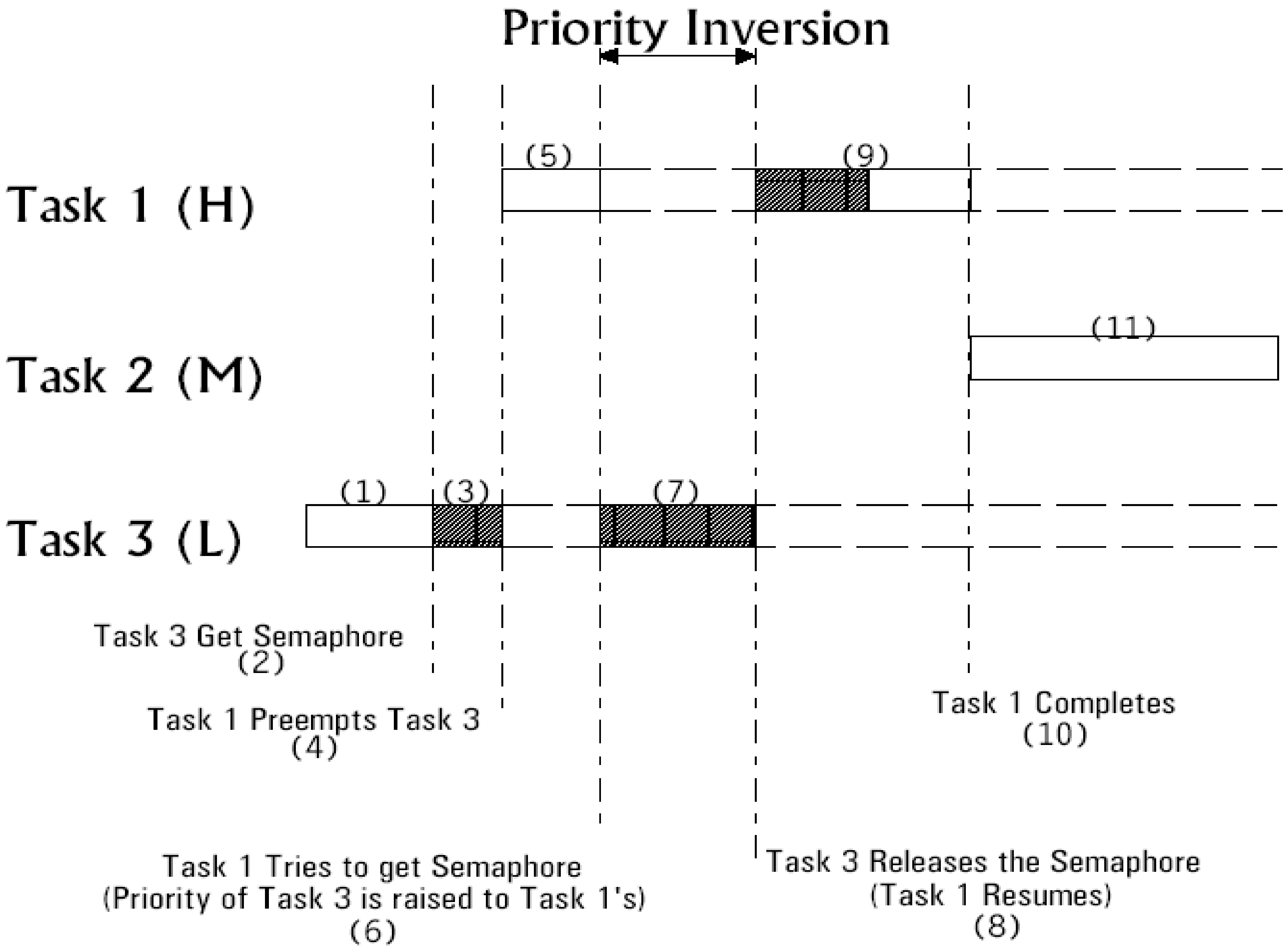
Priority Inversion Problem


Priority Inversion
Task 1 (H)
Task 2 (M)
Task 3 (L)
(1)
(4)
(6)
(8)
(10)
(12)
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)

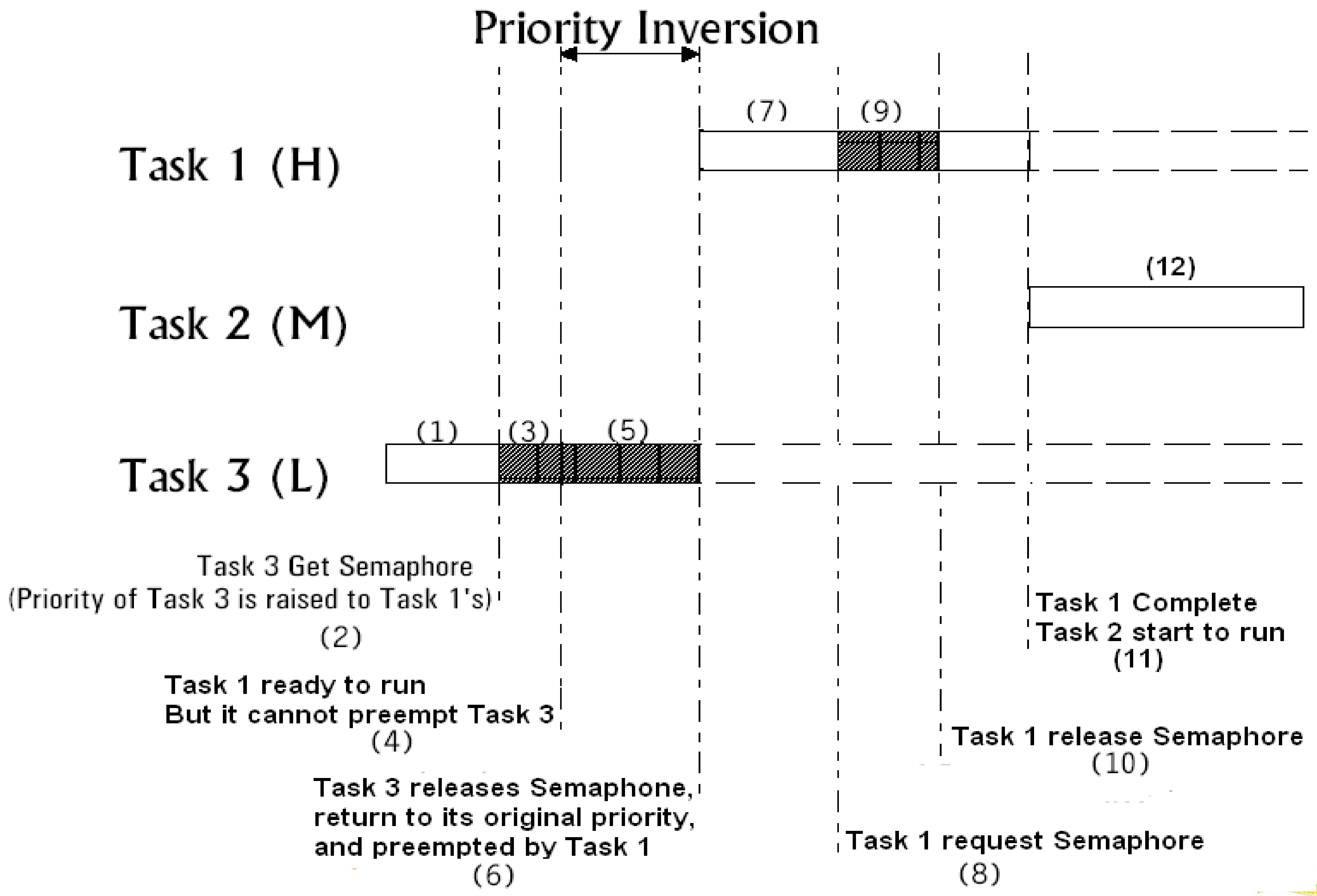
Priority Inversion Problem - Solution

- **Priority inheritance**
  - A low-priority task that holds the lock requested by a high-priority task temporarily "*inherits*" the priority of that high-priority task, *from the moment the high-priority task does the request*.
  - So, the L-task won't be preempted by the M-task, and can finish its critical section without holding up H-task any longer than needed.
  - When L-task releases the lock, its priority drops to its original level.
  - It generates *run-time* overhead, because the scheduler has to check the priorities of all tasks that access a lock.
- **Priority ceiling**
  - Every lock gets a priority level equal to the priority of the highest-priority task that *can* use the lock. This level is called *ceiling priority*.
  - when L-task enters the critical section, it *immediately* gets ceiling priority from the lock, so it will not be preempted by any M-task.
  - It generates compile-time overhead only.
    - The priority is changed *no matter* another task requests the lock or not.
    - That makes the L-task run at higher priority for longer time than needed.

Priority Inversion problem – Solved by Priority Inheritance


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

Priority Inversion problem – Solved by Priority Ceiling



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- **Classic Problems of Synchronization**
  - **Bounded-Buffer Problem**
  - **Readers and Writers Problem**
  - **Dining-Philosophers Problem**
- Monitors
- Synchronization Examples

Bounded Buffer Problem

```
there are n buffers
semaphore mutex  = 1 ;
semaphore full   = 0 ;
semaphore empty  = n ;
```

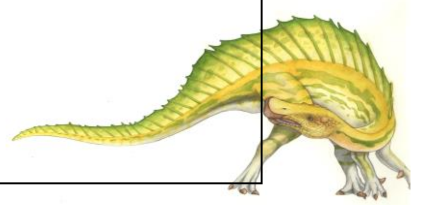
Shared data

- The producer process

```
do {
      . . .
     /* produce an item in
        next_produced */
      . . .
   wait(empty);
   wait(mutex);
    /* add next produced to
       the buffer */
   signal(mutex);
   signal(full);
      . . .
} while (true);
```

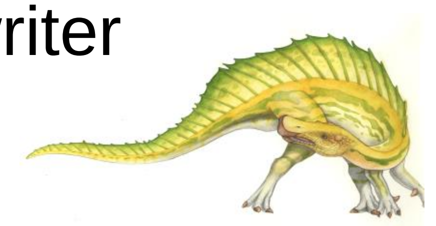
- The consumer process

```
do {
      . . .
   wait(full);
   wait(mutex);
   /* remove an item from
      buffer to next_consumed */
   signal(mutex);
   signal(empty);
      . . .
   /* consume the item in next
      consumed */
   } while (true);
```



Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do ***not*** perform any updates
  - Writers – can both read and write
- Problem – allow multiple readers to read at the same time
  - Only one single writer can access the shared data at the same time
- **Readers-Writers Problem Variations** - Several variations of how readers and writers are treated – all involve priorities
  - *First* variation – no reader kept waiting unless writer has permission to use shared object
  - *Second* variation – once writer is ready, it performs write asap
  - Both may have starvation leading to even more variations
  - Problem is solved on some systems by kernel providing reader-writer locks



Readers-Writers Problem (Cont.)

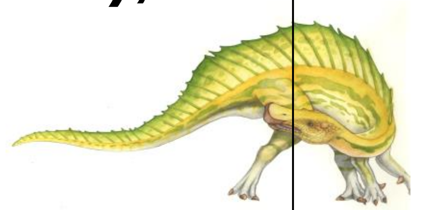
```
Shared Data
    data set
    semaphore rw_mutex = 1;
    semaphore mutex = 1;
    integer read_count = 0;
```

- **Writer process**

```
do {
     wait(rw_mutex);
    ...
     /* writing is performed */
    ...
  signal(rw_mutex);
} while (true);
```

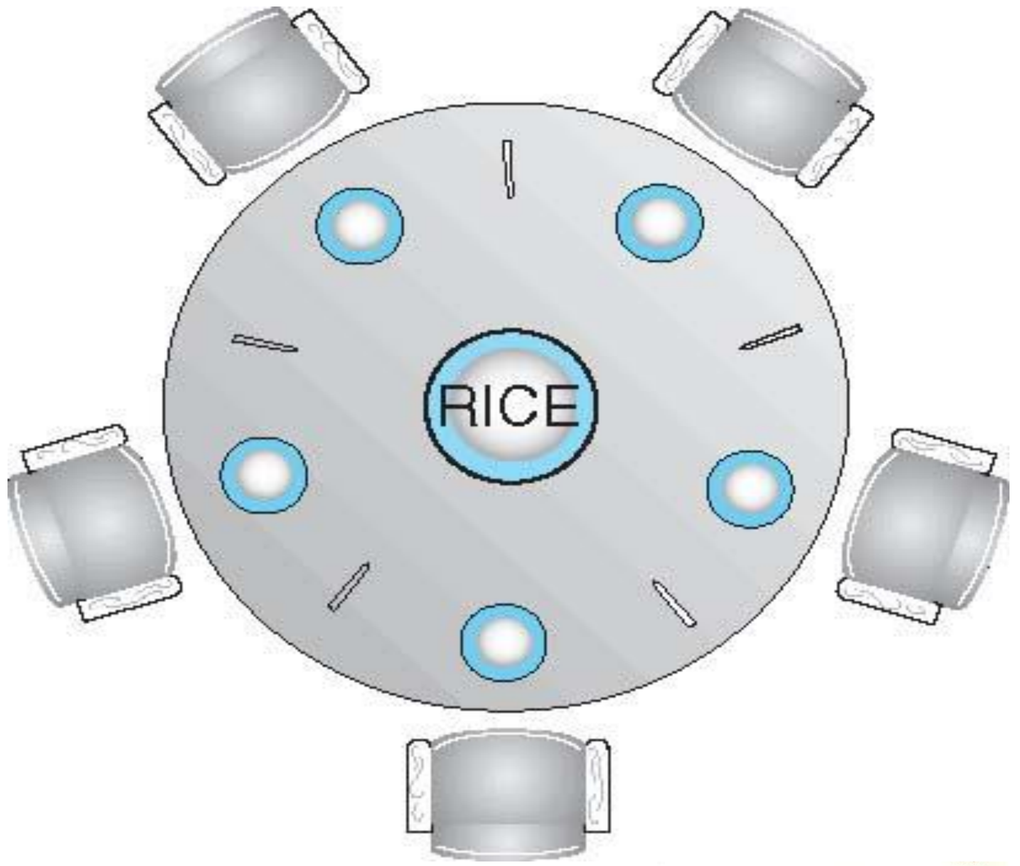
- **Reader process**

```
do {
      wait( mutex );
          read count++;
          if ( read_count == 1 )
              wait( rw_mutex );
     signal( mutex );
     ...
     /* reading is performed */
     ...
     wait( mutex );
         read count--;
         if ( read_count == 0 )
             signal( rw_mutex );
     signal( mutex );
} while (true);
```



Dining-Philosophers Problem

- Philosophers spend their lives thinking and eating
- Don't interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat, then release both when done
- It represent the need to allocate several resources among several processes in a deadlock-free and starvation-free manner.
- In the case of 5 philosophers
  - Shared data
    - Bowl of rice (data set)
    - Semaphore chopstick [5] initialized to 1



Dining-Philosophers Problem Algorithm

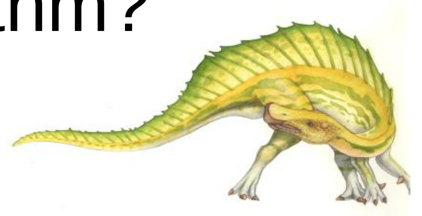
Shared data:

Bowl of rice (data set)
Semaphore chopstick [5];
  // initialized to 1

- The structure of Philosopher *i*:

```
do  {
        wait ( chopstick[i] );
        wait ( chopStick[ (i + 1) % 5] );

             //  eat

        signal ( chopstick[i] );
        signal (chopstick[ (i + 1) % 5] );

             //  think

} while (TRUE);
```

- What is the problem with this algorithm?



Dining-Philosophers Problem Algorithm

- What is the problem with the algorithm in P31 ?
  - Suppose all five philosophers become hungry at the same time and each grabs her left chopstick.

    ➔ deadline
- Several possible solutions
  1. Allow at most four philosophers to be sitting simultaneously at the table
  2. Allow philosopher to pick up her chopsticks only if both chopsticks are available (i.e., must pick them up in a critical section)
  3. Use an asymmetric solution –
     - odd-numbered philosophers: pick up left chopstick first and then right one
     - Even-number philosophers: pick up right chopstick first and then left one

Problems with Semaphores

- Incorrect use of semaphore operations:
  - **signal (mutex) …. wait (mutex)**

    $\rightarrow$ violate mutual-exclusion
  - **wait (mutex) … wait (mutex)** $\rightarrow$ deadlock
  - **Omitting of wait (mutex) or signal (mutex) (or both)**

    $\rightarrow$ either violate mutual-exclusion or deadlock
- Deadlock and starvation

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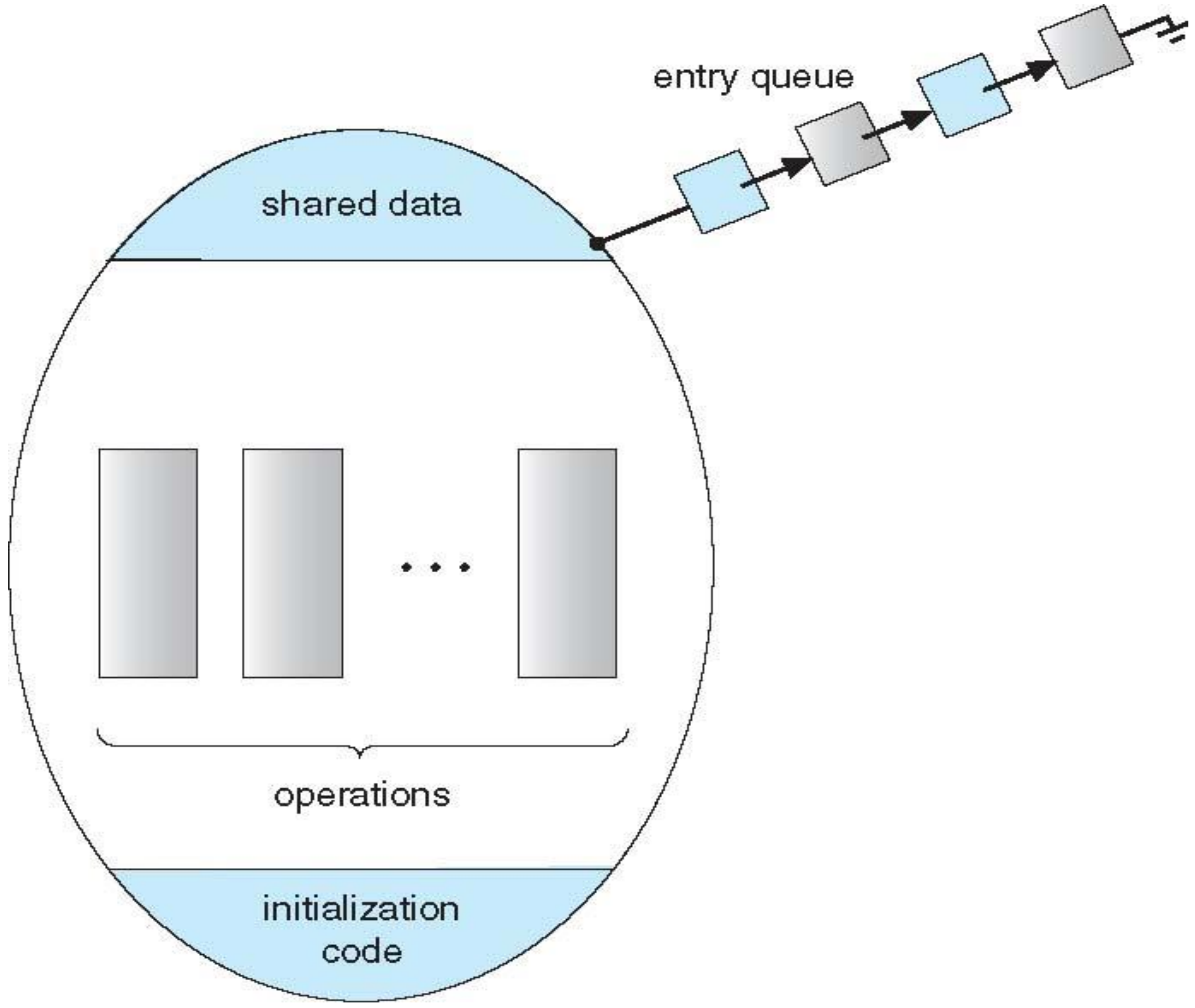
Monitors

- 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
  ➔ programmer does not need to code mutual exclusion explicitly
- But not powerful enough to model some synchronization schemes

```
monitor monitor-name
{
   // shared variable declarations
   procedure P1 (…) { …. }
   procedure Pn (…) {……}
    Initialization code (…) { … }
}
```

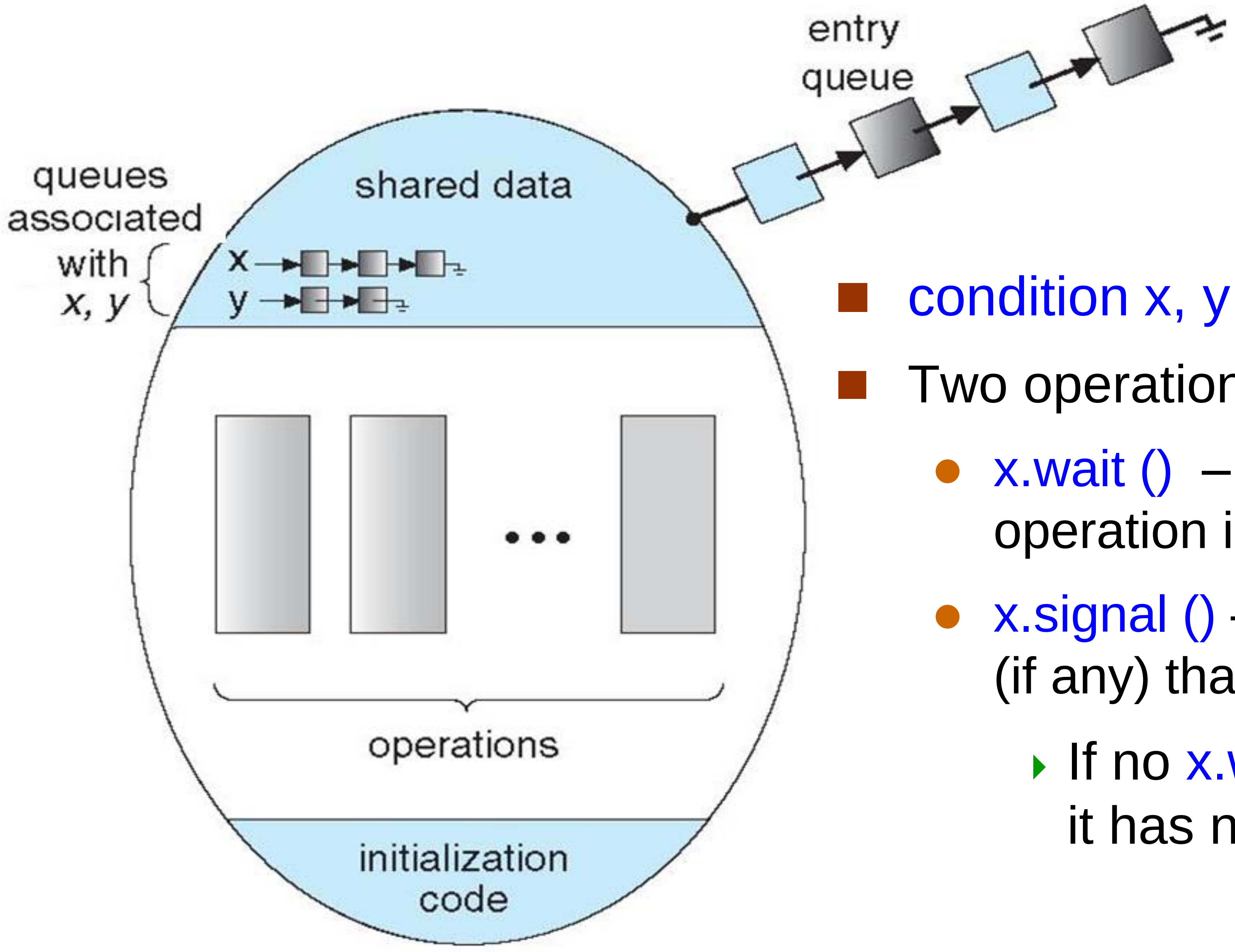
Schematic view of a Monitor



Condition Variables

- condition x, y;
- Two operations 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



- condition x, y;
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Solution to Dining Philosophers

```
monitor DiningPhilosophers
  {
    enum { THINKING; HUNGRY, EATING) state [5] ;
    condition self [5];

    void pickup (int i) {
          state[i] = HUNGRY;
          test(i);
          if (state[i] != EATING) self [i].wait;
    }

     void putdown (int i) {
          state[i] = THINKING;
            // test left and right neighbors
           test((i + 4) % 5);
           test((i + 1) % 5);
      }
```

To make sure two neighbors are not eating

```
      void test (int i) {
            if ( (state[(i + 4) % 5] != EATING) &&
                (state[i] == HUNGRY) &&
                (state[(i + 1) % 5] != EATING) ) {
                     state[i] = EATING ;
                     self[i].signal () ;
             }
       }

       initialization_code() {
            for (int i = 0; i < 5; i++)
            state[i] = THINKING;
      }
}
```

Solution to Dining Philosophers (Cont.)

- Each philosopher *i* invokes the operations pickup() and putdown() in the following sequence:

```
DiningPhilosophers.pickup (i);

   EAT

DiningPhilosophers.putdown (i);
```

- No deadlock, but starvation is possible
  - It is deadlock free because it imposes the restriction that a philosopher may pick up chopsticks only if both them are available.

Condition Variables Choices

- If process P invokes x.signal (), with Q in x.wait () state, what should happen next?
  - If Q is resumed, then P must wait
- Options include
  - **Signal and wait** – P waits until Q leaves monitor or waits for another condition
  - **Signal and continue** – Q waits until P leaves the monitor or waits for another condition
  - Both have pros and cons – language implementer can decide
  - Monitors implemented in Concurrent Pascal compromise
    - P executing signal immediately leaves the monitor, Q is resumed
  - Implemented in other languages including Mesa, C#, Java

Monitor Implementation Using Semaphores

- Variables

```
semaphore mutex;  // (initially  = 1)
semaphore next;     // (initially  = 0)
int next_count = 0;
```

- Each procedure ***F*** will be replaced by

```
wait( mutex );
        …
          body of F;
        …
if ( next_count > 0 )
    signal( next )
else
    signal(mutex);
```

- Mutual exclusion within a monitor is ensured

Monitor Implementation – Condition Variables

- For each condition variable ***x***, we have:

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

- The **x.wait** can be implemented as:

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

wake up others because the caller is going to wait

- The x.signal can be implemented as:

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

Since a signaling process must wait until the resumed process either leaves or waits, the "next" semaphore is used.

Resuming Processes within a Monitor

- If several processes queued on condition x, and x.signal() executed, which should be resumed?
- FCFS frequently not adequate
- **conditional-wait** construct of the form x.wait(c)
  - Where c is **priority number**
  - Process with lowest number (highest priority) is scheduled next

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;
    }
}
```

- A process that needs to access the resource must observe the following sequence
  - R is an instance of ResourceAllocator.
  - The process specifies the maximum time it plans to use the resource.
  - The process with the shortest time will get the resource first.

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

Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Peterson’s Solution
- Synchronization Hardware
- Mutex Locks
- Semaphores
- Classic Problems of Synchronization
- Monitors
- Synchronization Examples
  - **Solaris**
  - **Windows XP**
  - **Linux**
  - **Pthreads**

Solaris Synchronization

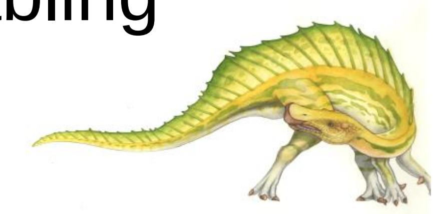
- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing
- Uses **adaptive mutexes** for efficiency when protecting data from short code segments
  - Starts as a standard semaphore spin-lock
  - If lock held, and by a thread running on another CPU, spins
  - If lock held by non-run-state thread, block and sleep waiting for signal of lock being released (i.e., always sleep waiting on a single-processor system)
- Uses **condition variables:** for long sections of code
- Uses **readers-writers:** for long sections of code
  - To protect data that are accessed frequently in a read-only manner.

Windows XP Synchronization

- Uses interrupt masks to protect access to global resources on uniprocessor systems
- Uses **spinlocks** on multiprocessor systems
  - Spinlocking-thread will never be preempted
- Also provides **dispatcher objects,** by which threads synchronize according to mechanisms like mutexes, semaphores, events, and timers
  - **Events**
    - An event acts much like a condition variable
  - **Timers** notify one or more thread when time expired
  - Dispatcher objects either in **signaled-state** (object available) or **non-signaled state** (object not available)
    - a thread will block when attempting to acquire the non-signaled object.

Linux Synchronization

- **Linux**:
  - Prior to kernel Version 2.6, where kernel is nonpreemptive, disables interrupts to implement short critical sections
  - Version 2.6 and later, kernel is fully preemptive (so a task can be preempted when it is running in the kernel)
- Linux provides:
  - semaphores
  - spinlocks
  - reader-writer versions of both
- On SMP, spinlock is used for short code protection.
- For a longer period, semaphores or mutex locks are appropriate to use.
- On single-cpu system, spinlocks replaced by enabling and disabling kernel preemption



Pthreads Synchronization

- Pthreads API is available at user level (OS-independent)
- It provides:
  - mutex locks
    - pthread_mutex_lock(), pthread_mutex_unlock();
  - condition variables
  - read-write locks
  - spinlocks

Lock

- ***Lock***:

  an object that can only be owned by a single thread at any given time.

  - acquire: mark the lock as owned by the current thread; if some other thread already held the lock, then first wait until the lock is free.
  - release: mark the lock as free

```
char buffer[SIZE];
int count=0, head=0, tail=0;
struct lock l;
lock_init(&l);

void producer(char c) {
  lock_acquire(&l);
  while (count == SIZE) {
    lock_release(&l);
    lock_acquire(&l);
  }

  count++;
  buffer[head] = c;
  head++;
  if(head == SIZE){head = 0;}

  lock_release(&l);
}
```

Condition Variables

- ***Condition Variable:***

  Synchronization mechanisms need more than just mutual exclusion; also need a way to wait for another thread to do something (e.g., wait for a character to be added to the buffer)

```
char buffer[SIZE];
int count = 0, head = 0, tail = 0;
struct lock l;
struct condition notEmpty, notFull;
lock_init(&l);
condition_init(&notEmpty);
condition_init(&notFull);

void producer(char c) {
     lock_acquire(&l);
    while (count == SIZE) {
            condition_wait(&notFull, &l);
    }

    count++;
    buffer[head] = c;
    head++;
    if (head == SIZE) { head = 0; }

    condition_signal(&notEmpty, &l);
     lock_release(&l);
}
```