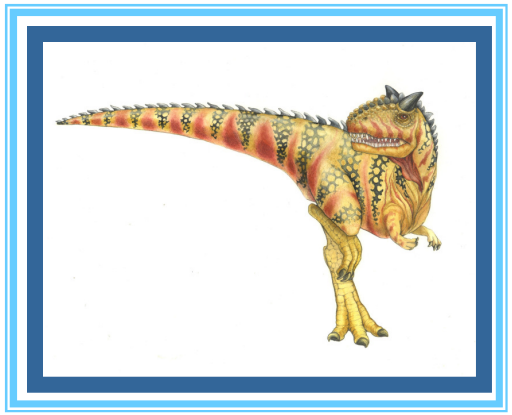
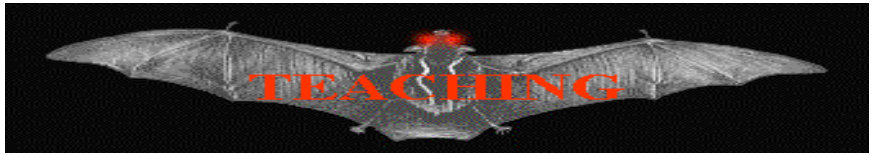
Chapter 6: Process Synchronization





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Outline

- Background.
- The Critical-Section Problem.
- Peterson's Solution.
- Synchronization Hardware.
- Semaphores.
- Classic Problems of Synchronization.
- Monitors.

Background (1/5)

- A ***cooperating process*** is one that can **affect** or **be affected** by other processes executing in the system.
  - Cooperating → **concurrent access to shared data**.
    - The data section of threads.
    - Shared memory among processes.
  - **May result in data inconsistency**.
- In this chapter, we discuss various mechanisms to ensure the orderly execution of cooperating processes.
  - Data consistency is maintained.

Background (2/5)

- In Ch. 3.4.1 (shared-memory systems), we present the concept of cooperating process by using the classical ***producer-consumer problem***.
  - ***Producer process*** produces items on a shared, bounded buffer.
  - ***Consumer process*** consumes the produced information from the buffer.

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

producer

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

consumer

Background (3/5)

- Although both the producer and consumer routines are correct separately, <u>they may not function correctly when executed concurrently</u>.
  - Suppose that the value of the variable `counter` is 5.
  - The producer and consumer processes execute the statements "`counter++`" and "`counter--`" concurrently.
  - Then the value of the variable of counter may be 4, 5, or 6!!
- Why?
  - The statement "`counter++` (or `counter--`)" may be implemented in machine language as:

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

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

Background (4/5)

- The **concurrent execution** of "`counter++`" and "`counter--`" is equivalent to a sequential execution where the lower-level statements presented previously are **interleaved in some arbitrary order**.

But the order within each high-level statement is preserved.

- For instance:

T_0: producer	execute	$register_1 = count$	$\{register_1 = 5\}$
T_1: producer	execute	$register_1 = register_1 + 1$	$\{register_1 = 6\}$
T_2: consumer	execute	$register_2 = count$	$\{register_2 = 5\}$
T_3: consumer	execute	$register_2 = register_2 - 1$	$\{register_2 = 4\}$
T_4: producer	execute	$count = register_1$	$\{count = 6\}$
T_5: consumer	execute	$count = register_2$	$\mathbf{\{count = 4\}}$

- We arrive at this incorrect state because we allowed both processes to manipulate the variable `counter` concurrently.

Background (5/5)

- ***Race condition***:
  - Several processes access and manipulate the same data concurrently.
  - The outcome of the execution depends on the particular order in which the access takes place.
- To guard against the race condition mentioned previously, we need to ensure that **only one process at a time** can be manipulating the variable `counter`.
- Race conditions occur frequently in operating systems.
  - Clearly, we want the resulting changes not to interfere with one another.
  - In this chapter, we talk about *process synchronization* and *coordination*.

The Critical-Section Problem (1/6)

- ***Critical section***:
  - A segment of code where a process may be changing common (shared) variables, updating a table, writing a file, and so on.
- Consider a system consisting of *n* processes:
  - Each process has a critical section.
  - Clearly, when one process is executing in its critical section, no other process is to be allowed to execute in its critical section.
- The critical-section problem is to design a ***protocol*** that the processes can use to cooperate.
  - That is, no two processes are executing in their critical sections at the same time.

The Critical-Section Problem (2/6)

- For a critical-section problem solution:
  - Each process <u>must request permission</u> to enter its critical section.
    - The section of code implementing this request is the ***entry section***.
  - The critical section may be followed by an ***exit section***.
  - The remainder code is the **remainder section**.

```
do {

   entry section

       critical section

   exit section

       remainder section

} while (TRUE);
```

The protocol

The Critical-Section Problem (3/6)

- A solution to the critical-section problem must satisfy the following three 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 only those processes that are not executing in their remainder sections can participate in the decision on which will enter its critical section.
   - The selection cannot be postponed indefinitely.

3. ***Bounded Waiting***:
   - A bound must exist on <u>the number of times that other processes are allowed to enter their critical sections</u> after a process has made a request to enter its critical section and before that request is granted.

The Critical-Section Problem (4/6)

- The code implementing an operating system (kernel code) is subject to several possible race conditions.
  - For instance:
    - A kernel data structure that maintains a list of all open files in the system.
    - If two processes were to open files simultaneously, the updates to this list could result in a race condition.
  - Other kernel data structures: structures for maintaining memory allocation, for maintaining process lists …
- The kernel developers have to ensure that the operating system is free from such race conditions.

The Critical-Section Problem (5/6)

- Two approaches, used to handle critical sections in operating systems:
  - ***Nonpreemptive kernels***:
    - Does not allow a process running in kernel mode to be preempted.
    - Is thus free from race conditions on kernel data structures, as only one process is active in the kernel at a time.
  - ***Preemptive kernels***:
    - Allow a process to be preempted while it is running in kernel mode.
    - The kernel must be carefully designed to ensure that shared kernel data are free from race conditions.

The Critical-Section Problem (6/6)

- Why prefer preemptive kernel?
  - Less risk that a kernel-mode process will run for an arbitrarily long period.
  - Allow a real-time process to preempt a process currently running in the kernel.

- Windows XP and Windows 2000 are nonpreemptive kernels.
- Several commercial versions of UNIX (including Solaris and IRIX) and Linux 2.6 kernel (and the later version) are preemptive.

Peterson's Solution (1/5)

- A **software-based** solution to the critical-section problem.
- Is restricted to **two processes** that alternate execution between their critical section and remainder sections.
  - The processes are numbered P_0 and P_1, or P_i and P_j.
- The method requires two data items to be shared between the two processes:

```
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!

Peterson's Solution (2/5)

- The Peterson's solution for process P_i. (j = 1 – i) (P_0 and P_1)

```
do {

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

  CRITICAL SECTION

  flag[i] = FALSE;

  REMAINDER SECTION

} while (TRUE);
```

If other process (P_j) wishes to enter the critical section, it can do so.

- If both processes try to enter at the same time …
  - `turn` will be set to both *i* and *j* at roughly the same time.
  - The eventual value of turn decides which can go.

Peterson's Solution (3/5)

- To prove the method is a solution for the critical-section problem, we need to show:

1. **Mutual exclusion is preserved**.
   - P_i enters its critical section only if either `flag[j]== false` or `turn==i`.
   - If both processes want to enter their critical sections at the same time, then `flag[i] == flag[j] == true`.
   - However, the value of `turn` can be either 0 or 1 **but cannot be both**.
   - Hence, one of the processes must have successfully executed the while statement (to enter its critical section), and the other process has to wait, till the process leaves its critical section. → *mutual exclusion is preserved*.

Peterson's Solution (3/5)

- To prove the method is a solution for the critical-section problem, we need to show:

1. **Mutual exclusion is preserved**.
   - 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 only those processes that are not executing in their remainder section can participate in the decision on which will enter its critical section next and this selection 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

Peterson's Solution (4/5)

2. **<u>The progress requirement is satisfied</u>**.
   - Case 1:
     - P_i is ready to enter its critical section.
     - If P_j is not ready to enter the critical section (it is in the remainder section).
     - Then `flag[j] == false`, and P_i can enter its critical section.
   - Case 2:
     - P_i and P_j are both ready to enter its critical section.
     - `flag[i] == flag[j] == true`.
     - Either `turn == i` or `turn == j`.
     - If `turn == i`, then P_i will enter the critical section.
     - If `turn == j`, then P_j will enter the critical section.

Peterson's Solution (5/5)

3. **<u>The bounded-waiting requirement is met</u>**.
   - Once P_j exits its critical section, it will reset `flag[j]` to `false`, allowing P_i to enter its critical section.
   - Even if P_j **immediately** resets `flag[j]` to `true`, it must also set `turn` to `i`.
   - Then, P_i will enter the critical section after at **<u>most one entry</u>** by P_j.

Synchronization Hardware (1/7)

- We can state that any solution to the critical-section problem requires a simple tool – a ***lock***.
  - A process must acquire a lock before entering a critical section.
  - It releases the lock when it exits the critical section.

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

- Here, we follow the above concept and explore solutions to the critical-section problem *using hardware techniques*.

Synchronization Hardware (2/7)

- Many systems provide hardware support for critical section code.
- Uniprocessors – could **disable interrupts**.
  - Currently running code would execute **without preemption**.
- Modern machines provide special **atomic hardware instructions**.
  - **Atomic → uninterruptible or indivisibly.**
  - ***Test and set*** the content of a word, atomically.
  - ***Swap*** the contents of two words, atomically.
  - Can be used to design solutions of the critical-section problem in a relatively simple manner.

Synchronization Hardware (3/7)

- The **atomic** ***TestAndSet()*** instruction:

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

- We can implement "*mutual exclusion*" by declaring a Boolean variable `lock`, initialized to `false`.

- Then the structure of process P_i is:

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

Synchronization Hardware (4/7)

- The **atomic** ***Swap()*** instruction.

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

- We can implement "*mutual exclusion*" by declaring a Boolean variable `lock`, initialized to `false`.

- Then the structure of process P_i is:

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

Synchronization Hardware (5/7)

- Do these algorithms (using `TestAndSet()` and `Swap()`) satisfy the bounded-waiting requirement? **NO!!**
  - But they do satisfy the mutual-exclusion requirement.
- An algorithm using the `TestAndSet()` instruction that satisfies all the critical-section requirements.
  - The method requires two data items to be shared between *n* processes:

```
Boolean waiting[n];
Boolean lock;
```

`waiting[i]` is true is P_i is waiting.

  - All initialized to false.

Synchronization Hardware (6/7)

```
do {
  waiting[i] = TRUE;
  key = TRUE;
  while (waiting[i] && key)
    key = TestAndSet(&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);
```

P_i can enter its critical section only if either `waiting[i] == false` or `key == false`.

The first process to execute the `TestAndSet()` will find `key == false`. All others must wait.

Find the next waiting process if any.

If no waiting process, release the lock.

Hold the lock, and P_j is granted to enter its critical section.

Synchronization Hardware (7/7)

- The mutual-exclusion requirement is met:
  - When a process leaves its critical section, only one `waiting[j]` is set to false.
- The progress requirement is met:
  - A process exiting the critical section either sets `lock` to `false` or sets `waiting[j]` to `false`.
  - Both allow a process that is waiting to enter its critical section to proceed.
- The bounded-waiting requirement is met:
  - When a process leaves its critical section, it scans the array `waiting` in the cyclic ordering.
  - Any waiting process will thus do so **within *n-1* turns**.

Semaphores (1/10)

- The hardware-based solutions are complicated for application programmers to use.
- ***Semaphore*** – a simple solution tool.
  - Is an integer.
  - Apart from initialization, is accessed only through two standard **atomic** operations: `wait()` and `signal()`.
  - When one process modifies the semaphore value, no other process can simultaneously modify the same semaphore value.

```
wait (S) {
    while S <= 0
        ; // no-op
    S--;
}
```

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

All the modifications (and testing) to the integer value of the semaphore must be executed **indivisibly**.

Semaphores – Usage (2/10)

- ***Binary semaphore***:
  - Also known as ***mutex*** locks (***mut***ual ***ex***clusion).
  - Range only between 0 and 1.
  - Used to deal with the critical-section problem for multiple processes.

Initialized to 1

```
do {

   wait(mutex);

   // critical section

   signal(mutex);

   // remainder section

}while (TRUE);
```

Semaphores – Usage (3/10)

- ***Counting semaphores***.
  - Range over an unrestricted domain.
  - Used to control access to a given resource consisting of a finite number of instances.
    - The semaphore is initialized to the number of resources available.
    - Each process that wishes to use a resource performs a wait() operation on the semaphore (thereby decrementing the count).
    - When a process releases a resource, it performs a signal() operation (incrementing the count).
    - When the count for the semaphore goes to 0, all resources are being used; processes that wish to use a resource will block until the count becomes greater than 0.

Semaphores – Usage (4/10)

- Semaphores can be used to solve synchronization problems.
  - 2 concurrently running processes: P_1 with a statement S_1 and P_2 with a statement S_2.
  - We require that S_2 be executed only after S_1 has completed.
  - A common semaphore `synch`, initialized to 0.

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

P_1

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

P_2

P_2 will execute S_2 only after P_1 has invoked `signal(sync)`.

Semaphores – Implementation (5/10)

- The main disadvantage of the semaphore definition is that it requires ***busy waiting***.
  - Also called a ***spinlock***; because the process spins while waiting for the lock.
  - A waiting process must loop continuously in the entry code.
  - Waste CPU cycles that some other process might be able to use productively.
  - However, spinlocks are useful on multiprocessor systems when locks are expected to be held for short times.
    - One thread can “spin” on one processor while another thread performs its critical section on another processor.

Semaphores – Implementation (6/10)

- To overcome the need for busy waiting.
  - In `wait()`:
    - When a process finds that the semaphore value is not positive, rather than engaging in busy waiting, **it blocks itself**.
    - The block operation places a process into a waiting queue (**waiting state**) associated with the semaphore.
    - The CPU scheduler then selects another process to execute.
  - In `signal()`:
    - When a process executes a `signal()` operation, a waiting process is restarted by a wakeup operation.
    - It changes the process from the **waiting state** to the **ready state** and place the process in the ready queue.
    - However, the CPU **may** or **may not** be switched to the newly ready process, depending on the CPU-scheduling algorithm.

Semaphores – Implementation (7/10)

- We define a semaphore as a "C" `struct`:

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

Each semaphore has an integer value and a list of processes list. When a process must wait on a semaphore, it is added to the list of processes.

Can be the link field in PCBs.

- The `wait()` semaphore operation:

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

The block() operation suspends the process that invokes it.

Semaphores – Implementation (8/10)

- The `signal()` semaphore operation:

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

The magnitude is the number of waiting process.

The wakeup() operation resumes the execution of a blocked process P.

- The list can use any queuing strategy, such as FIFO.

Semaphores – Implementation (9/10)

- We must guarantee that `wait()` and `signal()` are atomic.
  - No two processes can execute `wait()` and `signal()` operations on the same semaphore at the same time.
- In a single-processor environment, we can do it by **inhibiting interrupts** during the time of the operations are executing.
  - So that, instructions from different processes cannot be interleaved.
  - Until interrupts are reenabled and the scheduler can regain control.

Semaphores – Deadlocks and Starvation (10/10)

- ***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);
```

Suppose that P_0 executes wait(S) and then P_1 executes wait(Q). When P_0 executes wait(Q), it must wait until P_1 executes signal(Q).

Similarly, when P_1 executes wait(S), it must wait until P_0 executes signal(S). Since these signal() operations cannot be executed, P_0 and P_1 are deadlocked.

Semaphores – Deadlocks and Starvation (10/10)

- ***Starvation*** – indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended.
  - May occur with a semaphore in LIFO (last-in, first-out) order.

Classic Problems of Synchronization – The Bounded-Buffer Problem (1/16)

- Next, a number of synchronization problems as examples of a large class of concurrency-control problems will be presented.
- These problems are used for testing nearly every newly proposed synchronization scheme.
- In our solutions to the problems, semaphores will be used for synchronization.

Classic Problems of Synchronization – The Bounded-Buffer Problem (1/16)

- We assume that the pool consists of *n* buffers, each capable of holding one item.
- The `mutex` semaphore provides mutual exclusion for accesses to the buffer pool.
  - Initialized to the value 1.
- The `empty` and `full` semaphores count the number of empty and full buffers.
  - The semaphore `empty` is initialized to the value *n*.
  - The semaphore `full` is initialized to the value 0.

Classic Problems of Synchronization – The Bound-Buffer Problem (2/16)

- The structure of producer process:

```
do {
   ...
   // produce an item in nextp
   ...

   wait(empty);
   wait(mutex);

   // add nextp to buffer

   signal(mutex);
   signal(full);

} while (TRUE);
```

- The structure of the consumer process:

```
do {
   wait(full);
   wait(mutex);

   // remove an item from buffer
   // to nextc

   signal(mutex);
   signal(empty);

   // consume the item in nextc


} while (TRUE);
```

- Note the symmetry between the producer and consumer
- The producer is producing full buffers for the consumer and the consumer producing empty buffers for the producer.

Classic Problems of Synchronization – The Readers-Writers Problem (3/16)

- A database is to be shared among several concurrent processes.
  - Some processes may want only to read the database – **readers**.
  - Others may want to update (to read and write) – **writers**.
- If two readers access the shared data simultaneously, no adverse affects will result.
- However, if a writer and some other thread (either a reader or a writer) access the database simultaneously, chaos may ensue.
- We require that the writers have **exclusive access** to the shared database.

Classic Problems of Synchronization – The Readers-Writers Problem (9/16)

- The readers-writers problem has several variations, all involving priorities.
  - The *first* readers-writers problem:
    - No reader will be kept waiting unless a writer has already obtained permission to use the shared object.
    - Or, no reader should wait for other readers to finish.
    - Or readers have higher priorities.
  - The *second* readers-writers problem:
    - Once a writer is ready, the writer performs its write as soon as possible.
- Here, we present a solution to the first readers-writers problem.

Classic Problems of Synchronization – The Readers-Writers Problem (10/16)

- The **reader processes** share the following data structures:

```
semaphore mutex, wrt;
int readcount;
```

  - `readcount` is initialized to 0.
    - Keep track of how many processes are currently reading the database.
  - `mutex` and `wrt` are initialized to 1.
    - `mutex` is used to ensure mutual exclusion when the variable `readcount` is updated.
    - `wrt`, **shared with writers**, functions as a mutual-exclusion semaphore for the writers.

Classic Problems of Synchronization – The Readers-Writers Problem (11/16)

- The structure of a writer process:

```
do {
  wait(wrt);

  ...
  // writing is performed
  ...

  signal(wrt);

} while(TRUE);
```

Classic Problems of Synchronization – The Readers-Writers Problem (12/16)

- The structure of a reader process:

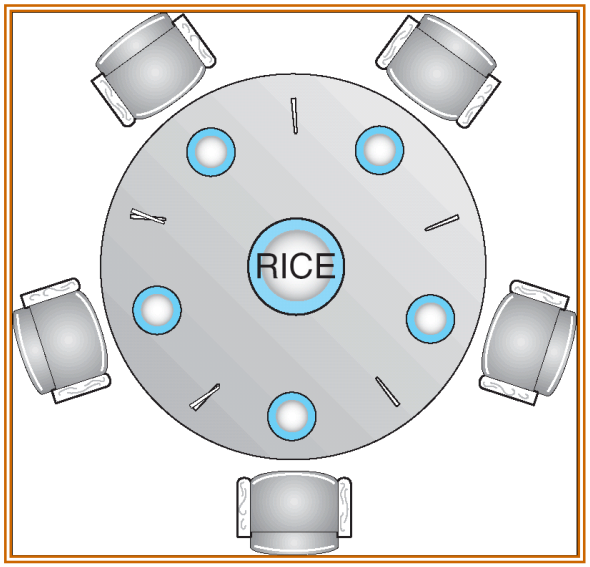
```
do {
  wait(mutex);
  readcount++;
  if (readcount == 1)
    wait(wrt);
  signal(mutex);

  ...
  // reading is performed
  ...

  wait(mutex);
  readcount--;
  if (readcount == 0)
    signal(wrt);
  signal(mutex);

} while(TRUE);
```

Note that if a writer is in the critical section and n readers are waiting, then one reader is queued on wrt, and n – 1 readers are queued on mutex.

Note that when a writer executes `signal(wrt)`, we may resume either the waiting reader**s** or a **single** waiting writer.

Classic Problems of Synchronization – The Dining-Philosopher Problem (13/16)

- Five philosophers spend their lives **thinking** and **eating**.
- The table is laid with five **single** chopsticks.
- When a philosopher gets hungry, she tries to pick up the two chopsticks that are closet to her.
  - Only one chopstick can be picked up at a time.
  - Obviously, she can not pick up a chopstick that is already in the hand of a neighbor.
- When a philosopher is finished eating, she puts down both of her chopsticks and starts thinking again.



Classic Problems of Synchronization – The Dining-Philosopher Problem (14/16)

- This problem is considered a classic synchronization problem.
  - It represents the need to allocate several resources among several processes in a deadlock-free and starvation-free manner.

- A plausible solution:
  - To represent each chopstick with a semaphore.

    ```
    semaphore chopstick[5];
    ```

    - All initialized to 1.
  - A philosopher tries to grab a chopstick by executing a `wait()` operation on that semaphore.
  - She releases her chopsticks by executing the `signal()`.

Classic Problems of Synchronization – The Dining-Philosopher Problem (15/16)

- 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);
```

Classic Problems of Synchronization – The Dining-Philosopher Problem (16/16)

- What is the problem with the last solution??
  - **DEADLOCK!!**
- Suppose that all five philosophers become hungry simultaneously and each grabs her left chopstick.
  - When each philosopher tries to grab her right chopstick, she will be delayed forever.
- Possible remedies:
  - At most four philosophers to be sitting simultaneously at the table.
  - Allow a philosopher to pick up her chopsticks only if both chopstick are available.
  - Asymmetric method – an odd philosopher picks up first her left chopstick, whereas an even philosopher picks up her right chopstick and then her left chopstick.

But … the deadlock-free solution does not Necessarily eliminate the possibility of starvation.

Monitors (1/18)

- Semaphores are effective, but <u>using them incorrectly</u> can result in timing errors that are **difficult to detect**.
  - These errors happen only if some particular execution sequences take place.
  - These sequences rarely occur.

Mutual-exclusion implementation with semaphores

```
do {
  waiting(mutex);

  // critical section

  signal(mutex);

  // remainder section

}while (TRUE);
```

Monitors (2/18)

- Suppose the sequence of `wait()` and `signal()` is reversed…
  - Several process may be executing in their critical sections simultaneously!!
  - The error can be discovered only if several processes are simultaneously active in their critical sections.

Mutual-exclusion implementation with semaphores

```
do {
   signal(mutex);

   // critical section

   wait(mutex);

   // remainder section

}while (TRUE);
```

Monitors (3/18)

- Suppose that a careless programmer replaces `signal()` with `wait()` ...
  - A deadlock will occur, even though there is a single process.

Mutual-exclusion implementation with semaphores

```
do {
   wait(mutex);

   // critical section

   wait(mutex);

   // remainder section

}while (TRUE);
```

Monitors – Usage (4/18)

- Synchronization models (such as semaphores) can easily produce errors when programmers use them incorrectly to solve the critical-section problem.
- Researchers have developed **high-level language constructs** – ***monitors*** – to make programming easier.
- A monitor type is an ADT which presents a set of programmer-defined operations that are provided mutual exclusion within the monitor.
  - An ADT (abstract data type) encapsulate private data with public methods to operate on that data.
- A monitor:
  - Is a collection of **procedures**, **variables**, and **data structures** that are all grouped together in a special kind of module or package.
  - Processes may call the procedures in a monitor whenever they want to.
  - But they **cannot** directly access the monitor's internal data structures outside the monitor.
  - Only one process at a time is active within the monitor.

Monitors – Usage (5/18)

```
Monitor monitor_name
{
  // shared variable declarations

  procedure P1 (...) {
    ...
  }

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

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

The **generic** syntax of a monitor

Many programming languages have Incorporated monitors.
Such as C# and Java.

Monitors – Usage (4/18)

- To make the monitor construct more powerful, we need to define additional synchronization mechanisms.
- These mechanisms are provided by the condition construct.
- You need to define one or more variables of type condition”
  - Condition x, y;
  - Only operations that can be invoked on a condition variables are wait() and signal().
  - x.wait() – the process invoking this operation is suspended until another process invokes x.signal().
  - x.signal() operation resumes exactly one suspended process.
  - If no process is suspended, then the signal() operation has no effect; i.e., the state of x is the same as if the operation has never executed.

Monitors – Usage (4/18)

- When the x.signal() operation is invoked by a process P, there exists a suspended process Q associated with condition x.
  - If Q is allowed to resume execution, P must wait.
- There are 2 possibilities
  - Signal and wait. P either waits until Q leaves the monitor or waits for another condition.
  - Signal and continue. Q either waits until P leaves the monitor or waits for another condition.
- Compromise
  - When P executes the signal operation, it immediately leaves the monitor. Hence, Q is immediately resumed.

Monitors – Usage (6/18)

- **Only one process can be active in a monitor at any instance.**
  - When a process calls a monitor procedure, the procedure will first check to see if any other process is currently active within the monitor.
  - If so, the calling process will be suspended until the other process has left the monitor.
  - If no other process is using the monitor, the calling process may enter.
- So, **by turning all the critical sections (of a problem) into monitor procedures**, no two processes will ever execute their critical sections at the same time.

Monitors – Usage (7/18)

- For instance, the monitor-based producer-consumer problem.

```
Monitor producer_consumer
{
  // shared variable declarations

  procedure Producer (...) {
     ...
  }

  procedure consumer (...) {
     ...
  }

  ...

}
```

Monitors – Usage (8/18)

- In the producer-consumer problem, we also need a way for processes to block when they cannot proceed.
  - we should block a producer process **when the buffer is full**.
- The blocking mechanism are provided by the ***condition*** construct.
  - Programmers can define one or more condition variables, along with two operations on them, `wait()` and `signal()`.
  - For instance, when the producer finds the buffer full, it does a `wait()` on some condition variable, say, *`full`*.
  - This action causes the calling process to block, and allows another process that had been previously prohibited from entering the monitor to enter now.

Monitors – Usage (9/18)

- Other process, for example, the consumer, can wake up its sleeping partner by doing a `signal()` on the condition variable that its partner is waiting on.
  - If a `signal()` is done on a condition variable on which several processes are waiting, **only one** of them is revived.

Monitors – Dining-Philosophers Solution (11/18)

- Using monitor concepts to present a deadlock-free solution to the dining-philosophers problem.

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

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

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

Philosoper *i* can delay herself when she is hungry but is unable to obtain the chopsticks.

Philosopher *i* can set `state[i]=eating` only if her two neighbors are not eating

Monitors –
Dining-Philosophers Solution (12/18)

```
  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);
  }

} // end of the monitor
```

Monitors – Dining-Philosophers Solution (13/18)

- Each philosopher (process), before starting to eat, must invoke the operation `pickup()`.
  - This **may** result in the suspension of the philosopher process.
- After the successful completion of the operation, the philosopher may eat.
- Following this, the philosopher invokes the `putdown()` operation.

```
dp.pickup(i);
...
eat
...
dp.putdown(i);
```

This solution is deadlock-free as no two Neighbors are eating simultaneously.

However, it is possible for a philosopher to starve to death.

Monitors – Implementation of a monitor using Semaphores (14/18)

- We shall now consider a possible implementation of the monitor mechanism using semaphores.
  - A common way is to use a binary semaphore (`mutex`) initialized to one.
  - The first few instructions of a procedure will check the semaphore (`wait(mutex)`) to see if any other process is currently active within the monitor.
    - If so, the calling process will be suspended until the other process has left the monitor.
- Each external procedure `F` is replaced by:

```
wait(mutex);
...
body of F
...
```

Monitors – Implementation Using Semaphores (14/18)

- It is the **compiler** of the high-level language <u>to implement the mutual exclusion on monitor entries</u>.
  - A common way is to use a binary semaphore (`mutex`) initialized to one.
  - The first few instructions of a procedure will check the semaphore (`wait(mutex)`) to see if any other process is currently active within the monitor.
    - If so, the calling process will be suspended until the other process has left the monitor.

- Each external procedure `F` is replaced by:

```
wait(mutex);
...
body of F
...
```

Monitors – Implementation Using Semaphores (15/18)

- For each condition variable `x`, we introduce a semaphore `x_sem` and an integer variable `x_count`, both initialized to 0.

- Here, we implement *the signal and wait monitor* that a signaling process must wait until the resumed process either leaves or wait.
  - Require an additional semaphore, `next`, initialized to 0.
    - On which the signaling processes may suspend themselves.
  - An integer variable `next_count` is provided to count the number of processes suspended on `next`.

Monitors – Implementation Using Semaphores (16/18)

- The operation `x.signal()`:

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

- The operation `x.wait()`:

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

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

Monitors – Resuming Processes (17/18)

- If several processes are suspended on condition `x`, then how do we determine which of the suspended processes should be resumed next?
  - One simple solution – FCFS ordering.
  - A flexible solution – ***conditional-wait***.

    ```
    x.wait(c);
    ```

    - Where `c` is an integer, called a **priority number**.
    - When `x.signal()` is executed, the process with the smallest associated priority number is resumed next.

Monitors – Resuming Processes (18/18)

- An example of conditional-wait:

```
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;
  }
}
```

When requesting an allocation of this resource, each process specifies the maximum time it plans to use the resource.

The monitor allocates the resource to the process that has the shortest time-allocation request.

End of Chapter 6