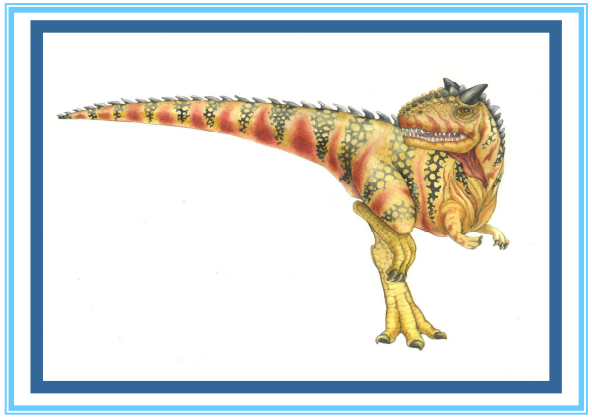
Chapter 6: Process Synchronization



Objectives

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

```
/* Producer */
while (true) {
        /* produce an item in next produced */

        while (counter == BUFFER_SIZE); /* Buffer is full, do nothing */

        buffer[in] = next_produced;
        in = (in + 1) % BUFFER_SIZE;
        counter++;
}
```

```
/* Consumer */
while (true) {
        while (counter == 0); /* Buffer is empty, do nothing */

        next_consumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        counter--;
        /* consume the item in next consumed */
}
```

Race Condition

Race condition is a situation where several processes access and manipulate the same data concurrently and the outcome of the execution depends on the particular order in which the access takes place.

`counter++` could be implemented as

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

`counter--` could be implemented as

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

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 {p_0, p_1, … 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 is

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

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 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-Section Handling in OS

Multiple processes may concurrently enter kernel mode and access kernel data structures for maintaining opened files, memory allocation, processes, interrupt handling, etc.

Two approaches depending on if kernel is preemptive or non-preemptive

Preemptive – allows preemption of process when running in kernel mode

Non-preemptive – runs until exits kernel mode, blocks, or voluntarily yields CPU

- Essentially free of race conditions in kernel mode

Synchronization Hardware

Many systems provide hardware support for implementing the 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
  - Operating systems using this not broadly scalable

Modern machines provide special atomic hardware instructions

- **Atomic** = non-interruptible
- Either test memory word and set value
- Or swap contents of two memory words

Mutex Locks

- Protect a critical section by first **`acquire()`** a lock then **`release()`** the lock
  - 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() and release()

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

release() {
    available = true;
}

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

Semaphore

Synchronization tool that does not require busy waiting

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
    S--;
}

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

Semaphore Usage

Counting semaphore – integer value can range over an unrestricted domain

Binary semaphore – integer value can range only between 0 and 1

Similar to a **mutex lock** (

Can implement a counting semaphore ***S*** as a binary semaphore

Can solve various synchronization problems

Consider P_1 and P_2 that require S_1 to happen before S_2

```
P1:
    S1;
    signal(synch);

P2:
    wait(synch);
    S2;
```

Semaphore Implementation

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

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

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);
    }
}
```

Semaphore Implementation

Must guarantee that no two processes can execute **`wait()`** and **`signal()`** on the same semaphore at the same time

Thus, 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
- 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

Deadlock and Starvation

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	P_1
`wait(S);`	`wait(Q);`
`wait(Q);`	`wait(S);` ← Deadlock here
.	.
`signal(S);`	`signal(Q);`
`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**

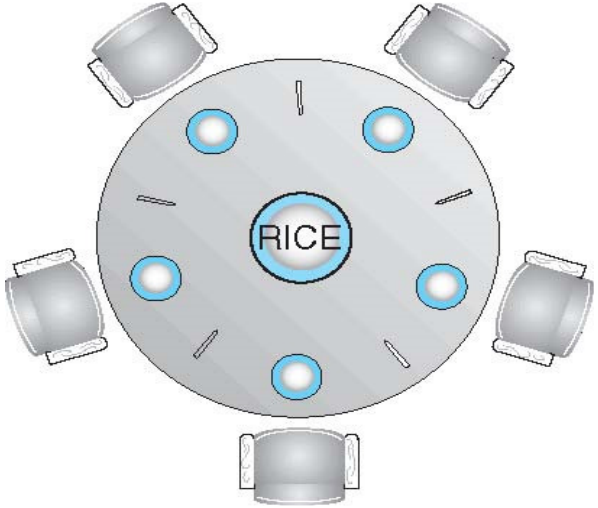
All processes that are accessing resources needed by a higher-priority process tempolarily inherit the higher priority until they are finished with the resources.

Classical Problems of Synchronization

Classical problems used to test newly-proposed synchronization schemes

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem

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

In the case of 5 philosophers

Shared data

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

Dining-Philosophers Problem Algorithm

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 (Cont.)

Deadlock handling

Allow at most 4 philosophers to be sitting simultaneously at the table.

Allow a philosopher to pick up the forks only if both are available (picking must be done in a critical section.

Use an asymmetric solution -- an odd-numbered philosopher picks up first the left chopstick and then the right chopstick. Even-numbered philosopher picks up first the right chopstick and then the left chopstick.

Problems with Semaphores

Incorrect use of semaphore operations:

signal (mutex) …. wait (mutex)

wait (mutex) … wait (mutex)

Omitting of wait (mutex) or signal (mutex) (or both)

Deadlock and starvation are possible.

Linux Synchronization

Linux provides:

- Atomic integers
- Mutex locks
- Semaphores
- Spinlocks

On single-cpu system, spinlocks replaced by enabling and disabling kernel preemption