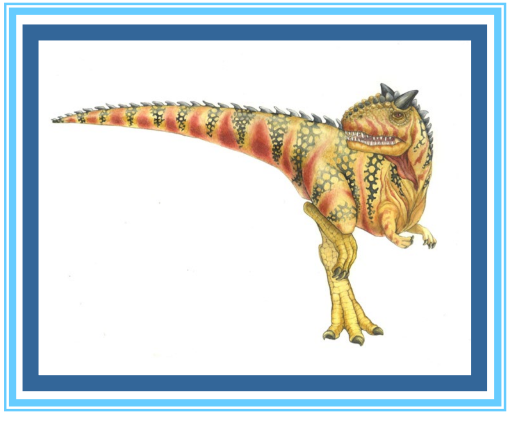
Chapter 6: Synchronization Tools



Chapter 6: Synchronization Tools

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

Objectives

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

Background

- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes

- 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

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

        while (counter == BUFFER_SIZE)
                ; /* do nothing */
        buffer[in] = next_produced;
        in = (in + 1) % BUFFER_SIZE;
        counter++;
}
```

Both update counter

```
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

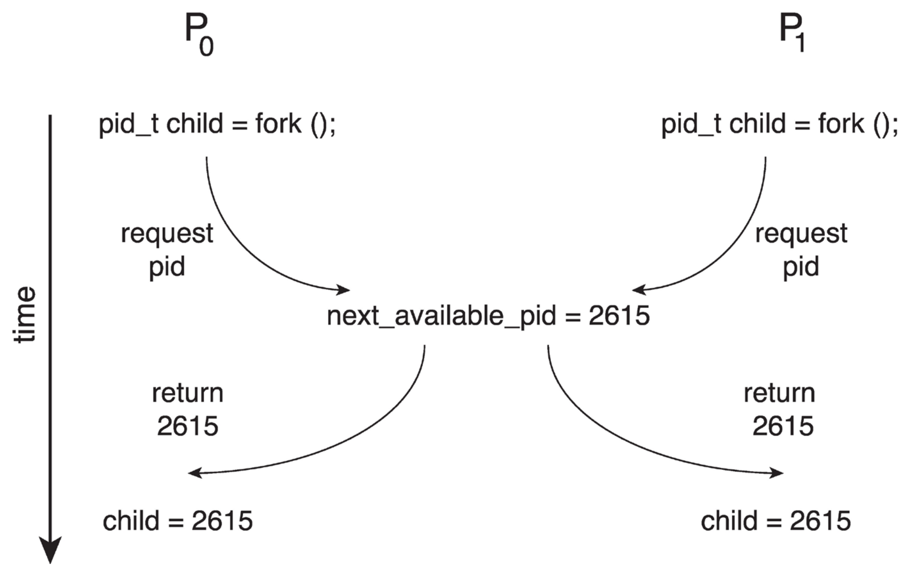
```
register2 = counter
register2 = register2 - 1
counter = register2
```

- 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}

Race Condition

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



- Unless there is mutual exclusion, the same pid could be assigned to two different processes!

Critical Section Problem

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

Critical Section

- General structure of process P_i

```
do {

    entry section

        critical section

    exit section

        remainder section

} while (true);
```

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

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

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Synchronization Hardware

- Many systems provide hardware support for implementing the critical section code.
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- We will look at three forms of hardware support:

1. Memory barriers

2. Hardware instructions

3. Atomic variables

test_and_set Instruction

Definition:

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

1. Executed atomically
2. Returns the original value of passed parameter
3. Set the new value of passed parameter to **`true`**

Solution using test_and_set()

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

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

            /* critical section */

     lock = false;
            /* remainder section */
 } while (true);
```

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;
}
```

1. Executed atomically
2. Returns the original value of passed parameter **`value`**
3. Set the variable **`value`** the value of the passed parameter **`new_value`** but only if **`*value == expected`** is true. That is, the swap takes place only under this condition.

Solution using compare_and_swap

- Shared integer **`lock`** initialized to 0;
- Solution:

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

    /* critical section */

    lock = 0;

    /* remainder section */
}
```

Atomic Variables

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

```
increment(&sequence);
```

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));
}
```

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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
- 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 such as compare-and-swap.
- But this solution requires **busy waiting**
  - This lock therefore called a **spinlock**

Solution to Critical-section Problem Using Locks

```
while (true) {
        acquire lock

        critical section

        release lock

        remainder section
}
```

Mutex Lock Definitions

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

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

These two functions must be implemented atomically.
Both test-and-set and compare-and-swap can be used to implement these functions.

Producer:

Let A be a **mutex**, initialized to T;

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

        while (counter == BUFFER_SIZE) ;
                /* do nothing */
        buffer[in] = next_produced;
        in = (in + 1) % BUFFER_SIZE;
        acquire(A);
        counter++;
        release(A);
}
```

entry code

exit code

What to do with Consumer?

Semaphore

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

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

- Definition of the **`signal() operation`**

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

Semaphore Usage

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

Semaphore Usage I

- **Binary semaphore** – integer value can range only between 0 and 1
  - Same as a **mutex lock**

The producer with counter:

Create a **semaphore *W*** initialized to 1;

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

Semaphore Usage II

- **Counting semaphore** – integer value can range over an unrestricted domain

- Semaphore **`empty`** initialized to the value n
  - Counting the number of empty buffers

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

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

Semaphore Usage III

- Other types of synchronization problems

- Generate an order:

  Consider P_1 and P_2 that require S_1 to happen before S_2:

Create a semaphore "`synch`" initialized to 0

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

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

Semaphore Usage IV (example of III)

- Can implement a counting semaphore ***S*** as a binary semaphore
- Semaphore **`empty`** initialized to the value n
  - Counting the number of empty buffers
- Consumer has waited on full, counting on filled buffers, initialzed to 0

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

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Problems when using Semaphores

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

Liveness

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

Liveness

- **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);`
`...`	`...`
`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 until P_1 executes signal(Q)
- However, P_1 is waiting until P_0 execute signal(S).
- Since these signal() operations will never be executed, P_0 and P_1 are **deadlocked**.

Liveness

- Other forms of deadlock:
- **Starvation** – indefinite blocking
  - A process may never be removed from the semaphore queue in which it is suspended
- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process
- Solved via **priority-inheritance protocol**

Priority Inheritance Protocol

- Consider the scenario with three processes **P1, P2**, and **P3**. **P1** has the highest priority, **P2** the next highest, and **P3** the lowest. Assume a resouce **P3** is assigned a resource **R** that **P1** wants. Thus, **P1** must wait for **P3** to finish using the resource. However, **P2** becomes runnable and preempts **P3**. What has happened is that **P2** - a process with a lower priority than **P1** - has indirectly prevented **P3** from gaining access to the resource.

- To prevent this from occurring, a **priority inheritance protocol** is used. This simply allows the priority of the highest thread waiting to access a shared resource to be assigned to the thread currently using the resource. Thus, the current owner of the resource is assigned the priority of the highest priority thread wishing to acquire the resource.

End of Chapter 6