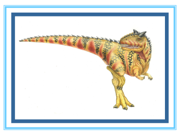
Chapter 6: Synchronization Tools



Chapter 6: Synchronization Tools

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Mutex Locks
- Semaphores

Objectives

- Describe the **critical-section problem** and illustrate the **race condition**
- Illustrate hardware solutions to the critical-section problem using compare-and-swap operations, and atomic variables
- Demonstrate how mutex locks, semaphores, and condition variables can be used to solve the critical section problem

Background

- Processes can execute concurrently
  - Processes may be interrupted at any time, partially completing execution, due to a variety of reasons.
- Concurrent access to any shared data may result in data inconsistency
- Maintaining data consistency requires mechanism(s) to ensure the orderly execution of cooperating processes

Illustration of the Problem

- Think about the Producer-Consumer problem
- An integer **`counter`** is used to keep track of the number of buffers occupied.
  - Initially, **`counter`** is set to 0
  - It is incremented each time by the producer after it produces an item and places in the buffer
  - It is decremented each time by the consumer after it consumes an item in the 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

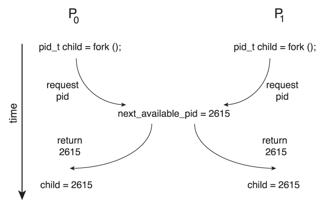
```
register2 = counter
register2 = register2 - 1
counter = register2
```

- 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 processes 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

- A Race Condition is an undesirable situation where several processes access and manipulate a shared data concurrently and the outcome of the executions depends on the particular order in which the accesses or executions take place
  - The results depend on the timing execution of programs. With some bad luck (i.e., context switches that occur at untimely points during execution), the result become **non-deterministic**
- Consider a system with *n* processes $\{P_0, P_1, \ldots P_{n-1}\}$
- A process has a Critical Section segment of code (can be short or long), during which
  - A process or thread may be changing shared variables, updating a table, writing a file, etc.
  - We need to ensure when one process is in Critical Section, no other can be in its critical section
  - In a way, **mutual exclusion** and **critical section** imply the same thing
- Critical section problem is to design a protocol to solve this
  - Specifically, each process must ask permissions before entering the critical section in entry section, may follow critical section with exit section, then remainder section

Critical Section

- The 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, 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 sections, the selection of a process that will enter the critical section next *cannot* be postponed *indefinitely* – selection of one process entering
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 – any waiting process

- Assume that each process executes at a nonzero speed, and there is no assumption concerning relative speed of the ***n*** processes

Critical-Section Problem in Kernel

- Kernel code - the code the operating system is running, is subject to several possible race conditions
  - A kernel data structure that maintains a list of all open files can be updated by multiple kernel processes, i.e., two processes were to open files simultaneously
  - Other kernel data structures such as the one maintaining memory allocation, process lists, interrupt handling and etc.
- Two general approaches are used to handle critical sections in operating system, depending on whether the kernel is preemptive or non-preemptive
  - Preemptive – allows preemption of process when running in the kernel mode, not free from the *race condition*, and increasingly more difficult in SMP architectures.
  - Non-preemptive – runs until exiting the kernel mode, blocks, or voluntarily yields CPU. This is essentially free of race conditions in the kernel mode, possibly used in single-processor system

Synchronization Tools

- Many systems provide hardware support for implementing the critical section code. On uniprocessor systems – it could simply disable interrupts, currently running code would execute without being pre-empted or interrupted. But this is generally too inefficient on multiprocessor systems
- Operating systems provide hardware and high level API support for critical section code

Programs	Share Programs
Hardware	Load/Store, Disable Interrupts, Test&Set, Compare&Swap
High level APIs	Locks, Semaphores

Synchronization Hardware

- Modern OS provides special atomic hardware instructions
  - Atomic = non-interruptible
- There are two commonly used hardware instructions
  - Either test a memory word and set a value – **`Test_and_Set()`**
  - Or swap contents of two memory words – **`Compare_and_Swap()`**

test_and_set Instruction

- Definition:

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

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;
}
```

Solution using compare_and_swap

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

```
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

```
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; /* no one is waiting, so release the lock */
   else
      waiting[j] = false; /* Unblock process j */
   /* remainder section */
} while (true);
```

Sketch Proof

- **Mutual-exclusion**: P_i enters its critical section only if either `waiting[i]==false` or `key==false`. The value of `key` can become `false` only if `test_and_set()` is executed. Only the first process to execute `test_and_set()` will find `key==false;` all others must wait. The variable `waiting[i]` can become `false` only if another process leaves its critical section; only one `waiting[i]` is set to `false`, thus maintaining the mutual-exclusion requirement.
- **Progress**: since a process existing its 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.
- **Bounded-waiting**; when a process leaves its critical section, it scans the array `waiting` in cyclic order {`i+1, i+2, …, n-1, 0, 1, …i-1`}. It designates the first process in this ordering that is in the entry section (`waiting[j]==true`) as the next one to enter the critical section. Any process waiting to enter its critical section will thus do so within `n-1` turns.

Atomic Variables

- Typically, instructions such as compare-and-swap are used as building blocks for other (more sophisticated) 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);`**
  - 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));
}
```

Mutex Locks

- OS builds software tools to solve the critical section problem
- The simplest tool that most OSes use is mutex lock
- To access the critical regions with it by first **`acquire()`** a lock then **`release()`** it afterwards
  - Boolean variable indicating if lock is available or not
- Calls to **`acquire()`** and **`release()`** must be **atomic** (non-interruptible)
  - Usually implemented via hardware atomic instructions
- But this solution requires busy waiting. This lock therefore called a **spinlock**
  - Spinlock wastes CPU cycles due to busy waiting, but it has one advantage in that no context switch is required when a process must wait on a lock, and a contest switch may take considerable time. Thus, when locks are expected to be held for short times, spinlock is useful
  - Spinlocks are often used in multiprocessor systems where one thread can "spin" on one processor while another thread performs its critical section on another processor

acquire() and release()

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

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

Solutions based on the idea of **lock** to protect critical section

- Operations are **atomic** (non-interruptible) – at most one thread acquires a lock at a time
- Lock before entering critical section for accessing share data
- Unlock upon departure after accessing shared data
- Wait if locked - all synchronization involves busy waiting, should "sleep" if waiting for a long time

Semaphore

- Semaphore ***S*** – non-negative integer variable, can be considered as a generalized lock
  - First defined by Dijkstra in late 1960s. It can behave similarly as mutex lock, but more sophisticated in its usage - the main synchronization primitive used in original UNIX
- Two standard operations modify ***S***: **`wait()`** and **`signal()`**
  - Originally called **`P()`** and **`V()`**, where **`P()`** stands for **"proberen"** (to test) and **`V()`** stands for **"verhogen"** (to increment) in Dutch
- It is critical that semaphore operations are executed atomically, which guarantees that no more than one process can execute **`wait()`** and **`signal()`** operations on the same semaphore at the same time.
- The semaphore can only be accessed via these two atomic operations except initialization

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

Semaphore Usage

- **Counting semaphore** – An integer value can range over an unrestricted domain
  - Counting semaphore can be used to control access to a given resource consisting of a finite number of instances; semaphore value is initialized to the number of resource available
- **Binary semaphore** – integer value can range only between `0` and `1`
  - This can behave similar to mutex locks, can also be used in different ways
- This can also be used to solve various synchronization problems
- Consider ***P_1*** and ***P_2*** that shares a common semaphore **`synch`**, initialized to `0`; it ensures that ***P1*** process executes ***S_1*** before ***P2*** process executes ***S_2***

```
P1:
   S1;
   signal(synch);
P2:
   wait(synch);
   S2;
```

Semaphore Implementation 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 on the queue
- 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 values may become negative, whereas this value can never be negative under the classical definition of semaphores with busy waiting.
- If a semaphore value is negative, its magnitude is the number of processes currently waiting on the semaphore.

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

Noticing that

- Increment and decrement are done before checking the semaphore value, unlike the busy waiting implementation
- The **`sleep()`** operation suspends the process that invokes it.
- The **`wakeup(P)`** operation resumes the execution of a suspended process P.

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 (details in Chapter 7)
- Let *S* and *Q* be two semaphores initialized to 1

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

- Consider if P0 executes wait(S) and P1 wait(Q). When P0 executes wait(Q), it must wait until P1 executes signal(Q), However, P1 is waiting until P0 execute signal(S). Since these signal() operations will never be executed, P0 and P1 are **deadlocked**, extremely difficult to debug
- **Starvation** – **indefinite blocking**
  - A process may never be removed from the semaphore queue, in which it is suspended. For instance, if we remove processes from the queue associated with a semaphore using LIFO (last-in, first-out) order or based on certain priorities.

End of Chapter 6