Chapter 6: Synchronization Tools

同步工具

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**
- Describe 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 execute concurrently
  - Processes may be interrupted at any time, partially completing execution, due to a variety of reasons.
- 并发访问 Concurrent access to any shared data may result in data inconsistency 数据不一致
- Maintaining data consistency requires OS mechanisms 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 争用条件

- `counter++` could be implemented as

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

- `counter--` could be implemented as

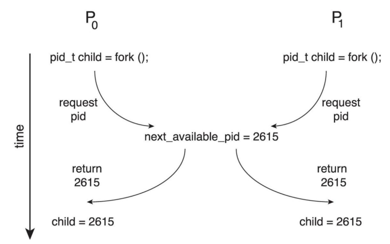
```
register2 = counter
register2 = register2 - 1
counter = register2
```

- 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! 互斥

※ Critical Section Problem 临界区问题

- A **Race Condition** is an undesirable (不良) situation where several processes access or/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 (临界区) 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 (协议) to solve this
  - Specifically, each process must ask permissions before entering a 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 {

$\boxed{\textit{entry section}}$

critical section

$\boxed{\textit{exit section}}$

remainder section

} while (true);

Solution to Critical-Section Problem

互斥
1. **Mutual exclusion** - If process P_i is executing in its critical section, no other processes can be executing in their critical sections

进度
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
不能 被 无限推迟

有界等待
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 each individual process

Critical-Section Problem in Kernel

- Kernel code (内核代码) - 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 (维护内存分配) memory allocation, process lists, interrupt handling etc.
- Two general approaches are used to handle critical sections in operating system, depending on whether the kernel is preemptive or non-preemptive
  抢占式 非抢占式
  - 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 同步工具

- 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 preempted or interrupted. But this is generally 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 禁用中断
High level APIs	Locks, Semaphores 锁 信号量

Synchronization Hardware 同步硬件.

- Modern OS provides special atomic 原子 hardware instructions
  - **Atomic** = non-interruptible （不可中断）
  - This ensures the execution of atomic instruction can not be interrupted, thus, no race condition can occur
  - The building block for more sophisticated synchronization mechanisms
- There are two commonly used atomic hardware instructions, which can be used to construct more sophisticated synchronization tools
  - Test a memory word and set a value – `Test_and_Set()`
  - Swap contents of two memory words – `Compare_and_Swap()`

test_and_set Instruction

通常用于实现锁机制

- Definition:

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


Solution using test_and_set()

利用它实现锁机制的方法：

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

```
do {
   while (test_and_set(&lock))
      ; /* do nothing */
   /* critical section */
   lock = false;
   /* remainder section */
} while (true);
```

① 如果 lock 为 false（未被占用），则 test_and_set() 将其设置为 true 并返回 false，表示成功获取锁

② 如果 lock 为 true（被占用），则 test_and_set() 将其设置为 true，表示获取锁失败，进程将继续在这个while循环中等待

4. **临界区**: `/* critical section */`
在成功获取锁后，进程进入临界区。在这个区域内，进程可以安全地访问共享资源，因为其他进程无法同时进入。

5. **释放锁**: `lock = false;`
一旦进程完成了对临界区的操作，它将 `lock` 设置回 `FALSE`，表示锁已被释放，其他进程可以尝试获取锁。

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);
```

3. **尝试获取锁**: `while (compare_and_swap(&lock, 0, 1) != 0)`
这行代码调用 `compare_and_swap()` 函数来尝试获取锁。`compare_and_swap(&lock, 0, 1)` 的作用是：
   - 检查 `lock` 的当前值是否为 `0`（表示未被占用）。
   - 如果是，则将 `lock` 设置为 `1`（表示已被占用），并返回 `0`。
   - 如果不是，则返回当前的 `lock` 值（即 `1`），表示获取锁失败，进程将继续在这个 `while` 循环中等待。

4. **临界区**: `/* critical section */`
在成功获取锁后，进程进入临界区。在这个区域内，进程可以安全地访问共享资源，因为其他进程无法同时进入。

5. **释放锁**: `lock = 0;`
一旦进程完成了对临界区的操作，它将 `lock` 设置回 `0`，表示锁已被释放，其他进程可以尝试获取锁。

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);
```



```c
do {
    waiting[i] = true; // 标记进程 i 正在等待
    key = true;        // 初始化 key 为 true
    while (waiting[i] && key) // 当进程 i 等待且 key 为 true 时循环
        key = test_and_set(&lock); // 尝试获取锁，更新 key 的值
    waiting[i] = false; // 退出等待状态，表示进程 i 已经获得锁
    /* critical section */ // 进入临界区，安全访问共享资源
    j = (i + 1) % n; // 设置 j 为下一个进程的索引
    while ((j != i) && !waiting[j]) // 检查是否有其他进程在等待
        j = (j + 1) % n; // 如果没有，继续检查下一个进程
    if (j == i) // 如果没有其他进程在等待
        lock = false; // 释放锁
    else
        waiting[j] = false; // 解除进程 j 的阻塞状态
    /* remainder section */ // 退出临界区，执行剩余部分
} while (true); // 无限循环
```

1. **等待标志**: `waiting[i] = true;`
   这行代码将当前进程 `i` 的等待状态设置为 `true`，表示它正在尝试获取锁。
2. **初始化 key**: `key = true;`
   初始化一个布尔变量 `key` 为 `true`，用于控制进程是否可以继续尝试获取锁。
3. **获取锁**: `while (waiting[i] && key)`
   这个循环会持续执行，直到进程 `i` 不再等待或 `key` 被设置为 `false`。在循环内部，调用 `test_and_set(&lock)` 尝试获取锁:
   - 如果成功获取锁，`key` 将被更新为 `false`，进程 `i` 将继续执行。
   - 如果锁已被其他进程占用，`key` 将保持为 `true`，进程 `i` 将继续等待。
4. **退出等待**: `waiting[i] = false;`
   一旦进程 `i` 成功获取锁，它将其等待状态设置为 `false`，表示不再等待。
5. **临界区**: `/* critical section */`
   在这一部分，进程 `i` 可以安全地访问共享资源，因为它已经获得了锁。
6. **检查其他进程**: `j = (i + 1) % n;`
   设置 `j` 为下一个进程的索引，以检查是否有其他进程在等待锁。
7. **寻找等待的进程**: `while ((j != i) && !waiting[j])`
   这个循环检查是否有其他进程在等待锁。如果没有，`j` 将继续指向下一个进程。
8. **释放锁**: `if (j == i)`
   如果 `j` 回到了 `i`，这意味着没有其他进程在等待，进程 `i` 可以释放锁。
9. **解除阻塞**: `else waiting[j] = false;`
   如果有其他进程在等待，解除进程 `j` 的阻塞状态，允许它继续执行。
10. **剩余部分**: `/* remainder section */`
    这部分代码表示进程在完成临界区操作后可以执行的其他任务。

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 原子变量

- 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 互斥锁

- OS builds a number of 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** 自旋锁
  - 缺点
    Spinlock wastes CPU cycles due to busy waiting, but it has one distinct advantage in that no
    优点 context switch is required when a process must wait on a lock, and a context 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()

当锁不可用时，忙等待

```
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 from critical section after accessing shared data
- Wait if locked - all synchronization involves busy waiting, should "sleep" or "block" if waiting for a long time

Semaphore 信号量

- **Semaphore *S*** – non-negative integer variable, can be considered as a generalized lock 广义锁
  - First defined by Dijkstra in late 1960s. It can behave similarly as mutex lock, but it has more sophisticated 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 essential 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 – serialization 序列化
- The semaphore can only be accessed via these two atomic operations except initialization

```
wait (S) {
    while (S <= 0)
       ; // busy wait
    S--;  表示成功获取了一个资源
}
signal (S) {
    S++;  表示释放了一个资源
}
```


Semaphore Usage

- **Counting semaphore** – An integer value can range over an unrestricted domain 不受限制的域
  - Counting semaphore can be used to control access to a given set of resources consisting of a finite number of instances; semaphore value is initialized to the number of resources available
- **Binary semaphore** – integer value can range only between `0` and `1`
  - This can behave like 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 P_1 process executes S_1 before P_2 process executes S_2

```
P1:
    S1;
    signal(synch);  // 释放信号量，表示S1操作已完成
P2:
    wait(synch);  // 等待信号量，直到S1操作完成
    S2;
```


Semaphore Implementation with no Busy waiting

- Each semaphore is associated with a 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 on the ready queue

在无忙等待的信号量实现中，信号量的值可以是负数，这表示有多个进程在等待获取资源

- 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 **`block()`** operation suspends 挂起 the process that invokes it.
- The **`wakeup(P)`** operation resumes the execution of a suspended process P.


```c
typedef struct {
    int value; // 信号量的值，表示可用资源的数量
    struct process *list; // 等待队列，存储等待该信号量的进程
} semaphore;

wait(semaphore *S) {
    S->value--; // 将信号量的值减 1
    if (S->value < 0) { // 如果信号量的值小于 0
        add this process to S->list; // 将当前进程添加到等待队列
        block(); // 阻塞当前进程，等待信号量可用
    }
}

signal(semaphore *S) {
    S->value++; // 将信号量的值加 1
    if (S->value <= 0) { // 如果信号量的值小于等于 0
        remove a process P from S->list; // 从等待队列中移除一个进程 P
        wakeup(P); // 唤醒进程 P，使其可以继续执行
    }
}
```

Deadlock and Starvation

死锁 饥饿

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes (to be examined in Chapter 8)
- 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 P_0 executes `wait(S)` and P_1 executes `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 executes `signal(S)`. Since these `signal()` operations will never be executed, P_0 and P_1 are **deadlocked**. This is extremely difficult to debug
- **Starvation – indefinite blocking** 无限期阻塞
  - 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