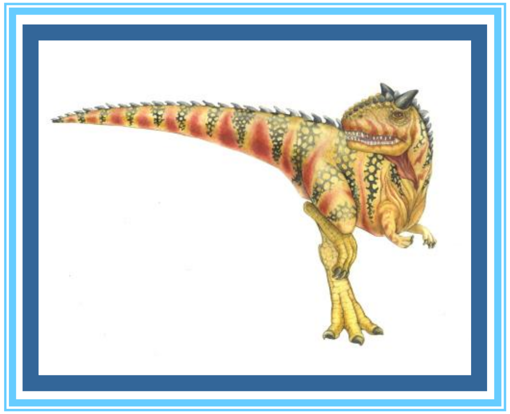
Chapter 5: Process Synchronization



Chapter 5: Process Synchronization

- Background
- The Critical-Section Problem
- Peterson's Solution
- Synchronization Hardware
- Mutex Locks
- Semaphores
- Classic Problems of Synchronization
- Monitors
- Synchronization Examples
- Alternative Approaches

Objectives

To present the concept of process synchronization.

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

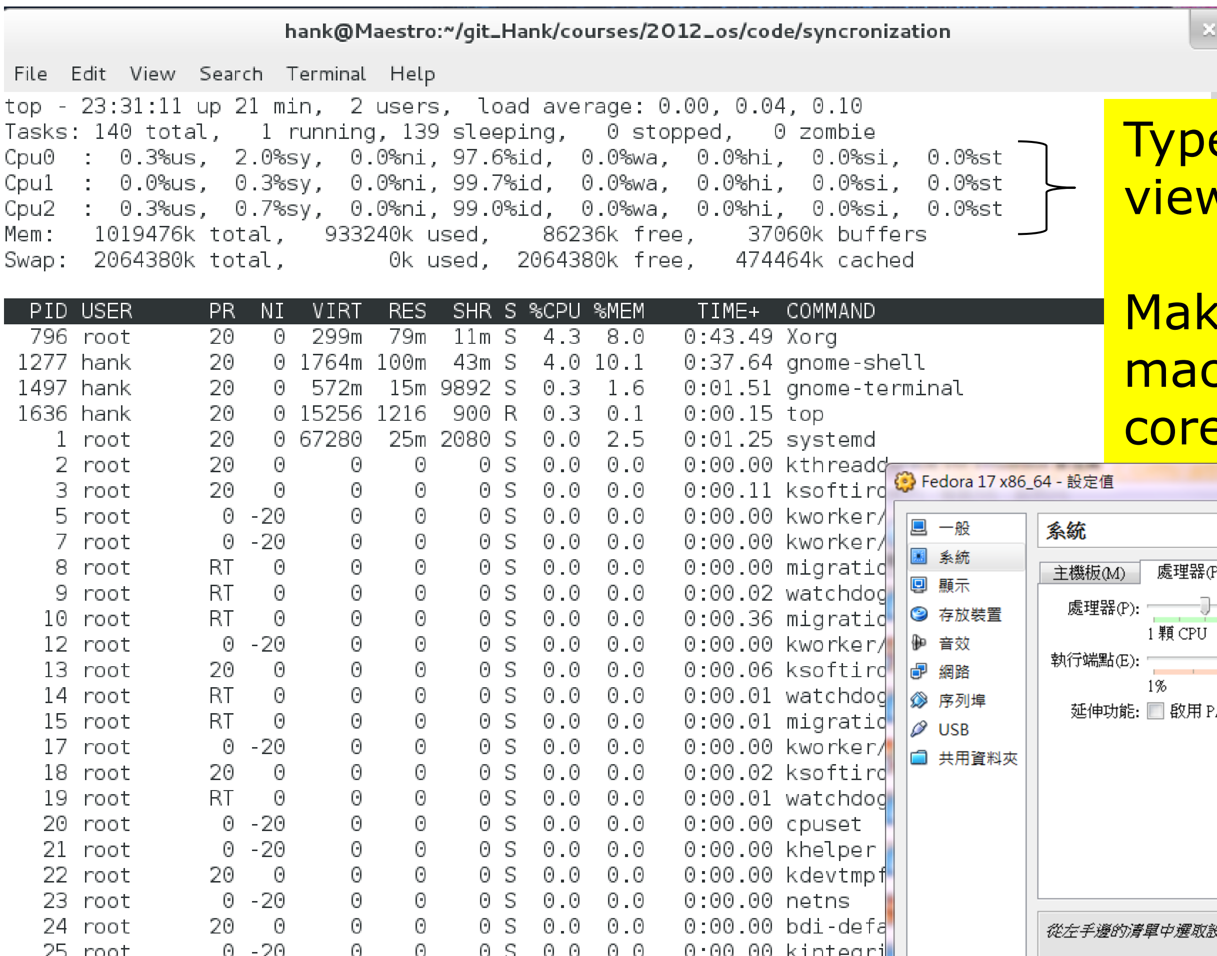
To examine several classical process-synchronization problems

To explore several tools that are used to solve process synchronization problems

Background

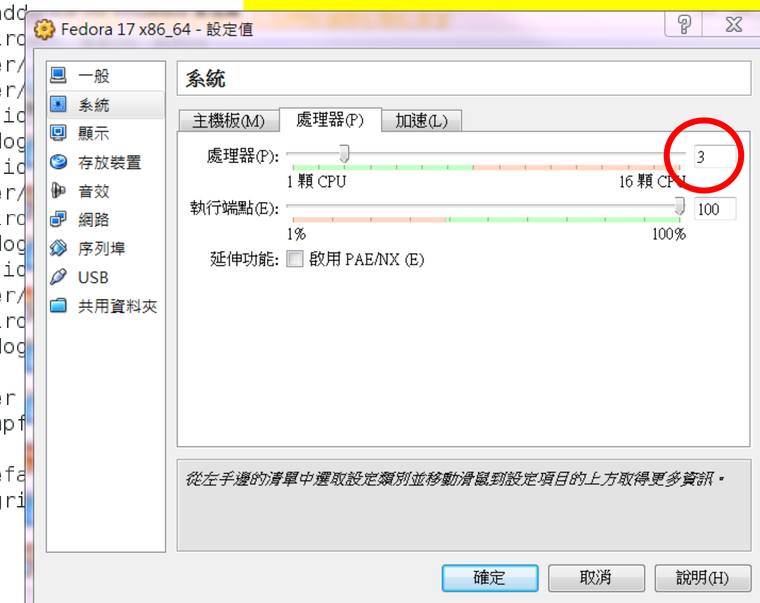
- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes
- Illustration of the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

Synchronization



Type ‘1’ to toggle SMP view

Make sure your machine has multiple cores



Single thread addition

```
unsigned long long int cnt;

void* AdditionX(void* pParam);
void* AdditionY(void* pParam);


int main() {

    timespec start_realtime, end_realtime;
    const unsigned long long int limit = 100000000;
    cnt = 0;


    clock_gettime(CLOCK_REALTIME, &start_realtime );
    printf("start running...\n");

    AdditionX((void*)&limit);
    AdditionY((void*)&limit);

    printf("cnt = %llu\n", cnt);

    clock_gettime(CLOCK_REALTIME, &end_realtime );

    printf("duration = %d nanoseconds\n", (end_realtime.tv_sec - start_realtime.tv_sec)*1000000000 +
                                          (end_realtime.tv_nsec - start_realtime.tv_nsec));

    return 0;
}
```

Single thread addition

```c
void* AdditionX(void* pParam)
{
    unsigned long long int limit = *((const unsigned long long int*)pParam);

    printf("thread X  limit = %d\n", limit);

    while(limit-- > 0) {
        cnt++;
    }

    return 0;
}

void* AdditionY(void* pParam)
{
    unsigned long long int limit = *((const unsigned long long int*)pParam);

    printf("thread Y limit = %d\n", limit);

    while(limit-- > 0 ) {
        cnt++;
    }

    return 0;
}
```

Single thread addition

```
hank@Maestro:~/git_Hank/courses/2012_os/code/syncronization
File  Edit  View  Search  Terminal  Help
remote: Counting objects: 11, done.
remote: Compressing objects: 100% (4/4), done.
remote: Total 6 (delta 2), reused 0 (delta 0)
Jnpacking objects: 100% (6/6), done.
=rom ssh://code.cs.nctu.edu.tw/var/git/person/Hank
   dbddac1..464d0c1  master     -> origin/master
Jpdating dbddac1..464d0c1
=ast-forward
 courses/2012_os/code/syncronization/complex.cpp | 80 --------------------------------
 1 file changed, 80 deletions(-)
 delete mode 100644 courses/2012_os/code/syncronization/complex.cpp
[hank@Maestro syncronization]$ ls -al
total 20
drwxrwxr-x. 2 hank hank 4096 Oct 31 23:45 .
drwxrwxr-x. 6 hank hank 4096 Oct 31 21:21 ..
-rw-rw-r--. 1 hank hank 1399 Oct 31 22:27 multiple_thread_add.cpp
-rw-rw-r--. 1 hank hank 1502 Oct 31 22:30 multiple_thread_inc.cpp
-rw-rw-r--. 1 hank hank 1100 Oct 31 21:47 single_thread_add.cpp
[hank@Maestro syncronization]$
[hank@Maestro syncronization]$ g++ -g ./single_thread_add.cpp -lrt -lpthread
[hank@Maestro syncronization]$ ./a.out
start running...
thread X  limit = 100000000
thread Y limit = 100000000
cnt = 200000000
duration = 456750331 nanoseconds
[hank@Maestro syncronization]$
```

Multithread addition

```c
unsigned long long int cnt;

void* AdditionX(void* pParam);
void* AdditionY(void* pParam);

int main() {

    pthread_t tidX, tidY;
    pthread_attr_t thread_attr;
    timespec start_realtime, end_realtime;

    const unsigned long long int limit = 100000000;

    cnt = 0;

    pthread_attr_init(&thread_attr);
    pthread_attr_setdetachstate(&thread_attr, PTHREAD_CREATE_JOINABLE);


    clock_gettime(CLOCK_REALTIME, &start_realtime );
    printf("start running...\n");


    pthread_create(&tidX, &thread_attr, AdditionX, (void*)&limit );
    pthread_create(&tidY, &thread_attr, AdditionY, (void*)&limit );


    pthread_join(tidX,0);
    pthread_join(tidY,0);

    printf("cnt = %llu\n", cnt);

    clock_gettime(CLOCK_REALTIME, &end_realtime );

    printf("duration = %d nanoseconds\n", (end_realtime.tv_sec - start_realtime.tv_sec)*1000000000 +
                                          (end_realtime.tv_nsec - start_realtime.tv_nsec));

    return 0;
}
```

Multithread Addition

```
[hank@Maestro syncronization]$
[hank@Maestro syncronization]$ g++ -g ./multiple_thread_add.cpp -lrt -lpthread
[hank@Maestro syncronization]$ ./a.out
start running...
thread X  limit = 100000000
thread Y limit = 100000000
cnt = 112770930
duration = 733176733 nanoseconds
[hank@Maestro syncronization]$
```

Multithread Addition

```
void* AdditionX(void* pParam)
{
    unsigned long long int limit =
        *((const unsigned long long int*)pParam);

    printf("thread X  limit = %d\n", limit);

    while(limit-- > 0) {
        cnt++;
    }

    return 0;
}
```

```
void* AdditionY(void* pParam)
{
    unsigned long long int limit =
        *((const unsigned long long int*)pParam);

    printf("thread Y limit = %d\n", limit);

    while(limit-- > 0 ) {
        cnt++;
    }

    return 0;
}
```

The code of AdditionX and the code of AdditionY may interleave

Any problem?

The code of AdditionX and the code of AdditionY may overlap

Any problem?

Multithread Addition

```
e for function AdditionX(void*):
<+0>:     push   %rbp
<+1>:     mov    %rsp,%rbp
<+4>:     sub    $0x20,%rsp
<+8>:     mov    %rdi,-0x18(%rbp)
<+12>:    mov    -0x18(%rbp),%rax
<+16>:    mov    (%rax),%rax
<+19>:    mov    %rax,-0x8(%rbp)
<+23>:    mov    -0x8(%rbp),%rax
<+27>:    mov    %rax,%rsi
<+30>:    mov    $0x400bb8,%edi
<+35>:    mov    $0x0,%eax
<+40>:    callq  0x400740 <printf@plt>
<+45>:    jmp    0x400a59 <AdditionX(void*)+65>
<+47>:    mov    0x2005aa(%rip),%rax        # 0x600ff8 <cnt>
<+54>:    add    $0x1,%rax
<+58>:    mov    %rax,0x20059f(%rip)        # 0x600ff8 <cnt>
<+65>:    cmpq   $0x0,-0x8(%rbp)
<+70>:    setne  %al
<+73>:    subq   $0x1,-0x8(%rbp)
<+78>:    test   %al,%al
<+80>:    jne    0x400a47 <AdditionX(void*)+47>
<+82>:    mov    $0x0,%eax
<+87>:    leaveq
<+88>:    retq
```

```
e for function AdditionY(void*):
<+0>:     push   %rbp
<+1>:     mov    %rsp,%rbp
<+4>:     sub    $0x20,%rsp
<+8>:     mov    %rdi,-0x18(%rbp)
<+12>:    mov    -0x18(%rbp),%rax
<+16>:    mov    (%rax),%rax
<+19>:    mov    %rax,-0x8(%rbp)
<+23>:    mov    -0x8(%rbp),%rax
<+27>:    mov    %rax,%rsi
<+30>:    mov    $0x400bce,%edi
<+35>:    mov    $0x0,%eax
<+40>:    callq  0x400740 <printf@plt>
<+45>:    jmp    0x400ab2 <AdditionY(void*)+65>
<+47>:    mov    0x200551(%rip),%rax        # 0x600ff8 <cnt>
<+54>:    add    $0x1,%rax
<+58>:    mov    %rax,0x200546(%rip)        # 0x600ff8 <cnt>
<+65>:    cmpq   $0x0,-0x8(%rbp)
<+70>:    setne  %al
<+73>:    subq   $0x1,-0x8(%rbp)
<+78>:    test   %al,%al
<+80>:    jne    0x400aa0 <AdditionY(void*)+47>
<+82>:    mov    $0x0,%eax
<+87>:    leaveq
<+88>:    retq
```

‘cnt++’ is compiled into multiple instructions

Multithread Inc

```
void* AdditionX(void* pParam)
{
    unsigned long long int limit = *((const unsigned long long int*)pParam);

    printf("thread X  limit = %d\n", limit);

    while(limit-- > 0) {
        asm  ("incq %0": "=m" (cnt));
    }

    return 0;
}
```

A single line of assembly

Will this version run correctly on a uniprocessor?

```
void* AdditionY(void* pParam)
{
    unsigned long long int limit = *((const unsigned long long int*)pParam);

    printf("thread Y limit = %d\n", limit);

    while(limit-- > 0 ) {
        asm  ("incq %0": "=m" (cnt));
    }

    return 0;
}
```

Will this version run correctly on a multiprocessor?

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}

Critical Section

Producer thread

```
while (true) {

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

Consumer thread

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

Code in this "critical section" should not be interleaved or overlapped

Critical Section - How

CriticalSection cs;

Producer thread

```
while (true) {

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

Consumer thread

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

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);
```

Algorithm for Process P_i

```
do {

      while (turn == j);
            critical section
      turn = j;
            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 (**Freedom from Deadlock **)** - 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 (**Freedom from Starvation**)** - 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

"Freedom from starvation" implies "freedom from deadlock"

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

1st attempt on the design of a Critical Section Lock

```
class CriticalSectionLockOne
{
        bool flag[2];

public:
        void lock()
        {
                int i = ThreadID.get();
                int j = 1-i;
                flag[i] = true;
                while(flag[j]) ;  // wait
        }

        void unlock()
        {
                int i = ThreadID.get();
                flag[i] = false;
        }
};
```

Assume that the LOAD and STORE instructions are atomic; that is, cannot be interrupted.

1st attempt on the design of a Critical Section Lock

Does CriticalSectionLockOne satisfy

- mutual exclusion?
- freedom from deadlock?
- freedom from starvation?

1st attempt on the design of a Critical Section Lock

Does CriticalSectionLockOne satisfy

- mutual exclusion?
- freedom from deadlock?
- freedom from starvation?

1^{st} attempt on the design of a Critical Section Lock

Proof of that CriticalSectionLockOne satisfies mutual exclusion

Assume thread *A* and *B*.

Let CS_A^j be the interval during which *A* executes the critical section for the *j*-th time.

Let CS_B^k be the interval during which *B* executes the critical section for the *k*-th time.

$\text{write}_A(x{=}v)$ denotes the event in which *A* assigns value *v* to field *x*.
$\text{read}_A(v{==}x)$ denotes the event in which *A* reads *v* from field *x*.

Suppose CriticalSectionLockOne does not satisfy mutual exclusion. Then there exist integers *j* and *k* such that $CS_A^j \nrightarrow CS_B^k$ and $CS_B^k \nrightarrow CS_A^j$. Consider each thread's last execution of the lock() method before entering its *k*-th (*j*-th) critical section.

Inspecting the code, we see that

$\text{write}_A(\text{flag}[A]{=}\text{true}) \rightarrow \text{read}_A(\text{flag}[B]{==}\text{false}) \rightarrow CS_A$ (1)
$\text{write}_B(\text{flag}[B]{=}\text{true}) \rightarrow \text{read}_B(\text{flag}[A]{==}\text{false}) \rightarrow CS_B$ (2)
$\text{read}_A(\text{flag}[B]{==}\text{false}) \rightarrow \text{write}_B(\text{flag}[B]{=}\text{true})$ (3)

By transitivity of the precedence order, we have

$$\text{write}_A(\text{flag}[A]{=}\text{true}) \rightarrow \text{read}_A(\text{flag}[B]{==}\text{false}) \rightarrow \text{write}_B(\text{flag}[B]{=}\text{true}) \rightarrow \text{read}_B(\text{flag}[A]{==}\text{false})$$

It follows that $\text{write}_A(\text{flag}[A]{=}\text{true}) \rightarrow \text{read}_B(\text{flag}[A]{==}\text{false})$ without an intervening write to the flag[] array, a contradiction. □

1^{st} attempt on the design of a Critical Section Lock

CriticalSectionLockOne deadlocks if $write_A(flag[A]=true)$ and $write_B(flag[B]=true)$ events occur before $read_A(flag[B])$ and $read_B(flag[A])$ events, then both threads wait forever.

2nd attempt on the design of a Critical Section Lock

```
class CriticalSectionLockTwo
{
          int victim;

public:
          void lock()
          {
                    int i = ThreadID.get();
                    victim = i;  // let the other go first
                    while(victim ==i) ;       // wait
          }

           void unlock() {}
};
```

Exercise: prove that CriticalSectionLockTwo satisfies
             mutual exclusion.

But CriticalSectionLockTwo deadlocks if one thread runs completely before the other

Peterson's Solution

Two process solution

Assume that the LOAD and STORE instructions are atomic; that is, cannot be interrupted.

The two processes share two variables:

int victim;

Boolean flag[2]

The variable victim indicates whose turn it is to wait.

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 Lock

```
class CriticalSection_PetersonLock
{
        bool flag[2];
        int victim;
public:
        void lock()
        {
                int i = ThreadID.get();
                int j = 1-i;
                flag[i] = true;  // I'm ready
                victim = i;  // you go first
                while(flag[j] && victim==i) ; // wait
        }

        void unlock()
        {
                int i = ThreadID.get();
                flag[i] = false;  // I'm not ready
        }
};
```

PetersonLock satisfies mutual exclusion

Suppose not. Consider the last execution of the lock method() by threads *A* and *B*. Inspecting the code, we see that

$$\text{write}_A(\text{flag}[A]=\text{true}) \rightarrow \text{write}_A(\text{victim}=A) \rightarrow \text{read}_A(\text{flag}[B]) \rightarrow \text{read}_A(\text{victim}) \rightarrow CS_A \qquad (1)$$

$$\text{write}_B(\text{flag}[B]=\text{true}) \rightarrow \text{write}_B(\text{victim}=B) \rightarrow \text{read}_B(\text{flag}[A]) \rightarrow \text{read}_B(\text{victim}) \rightarrow CS_B \qquad (2)$$

WLOG, assume that *A* was the last thread to write to the victim field

$$\text{write}_B(\text{victim}=B) \rightarrow \text{write}_A(\text{victim}=A) \qquad (3)$$

Eq.(3) implies that *A* observed victim to be *A* in Eq. (1). Since *A* nevertheless entered its critical section, it must have observed flag[*B*] to be *false*, so we have

$$\text{write}_A(\text{victim}=A) \rightarrow \text{read}_A(\text{flag}[B]==\text{false}) \qquad (4)$$

Eq.(2) ~ Eq.(4), together with the transitivity of precedence order, imply

$$\text{write}_B(\text{flag}[B]=\text{true}) \rightarrow \text{write}_B(\text{victim}=B) \rightarrow \text{write}_A(\text{victim}=A) \rightarrow \text{read}_A(\text{flag}[B]==\textit{false})$$

It follows that $\text{write}_B(\text{flag}[B]=\text{true}) \rightarrow \text{read}_A(\text{flag}[B]==\textit{false})$.
This is a contradiction because no other write to flag[*B*] was performed before the critical section executions. □

PetersonLock is starvation-free

Suppose not. WLOG, suppose that *A* runs forever in the lock() method. It must be executing the **while** statement, waiting until either flag[*B*] becomes *false* or victim is set to *B.*

What is *B* doing while *A* fails to make progress?

> Perhaps B is repeatedly entering and leaving its critical section. If so, however, then *B* sets victim to *B* as soon as it reenters the critical section. Once victim is set to *B,* it does not change, and A must eventually return from the lock() method(), a contradiction.
>
> So it must be that *B* is also stuck in the lock() method call, waiting until either flag[*A*] becomes false or victim is set to *A*. But victim cannot be both A and B, a contradiction. □

x86 Guaranteed Atomic Operations

[Intel® 64 and IA-32 Architectures Software Developer's Manual Volume 3A: System Programming Guide, Part 1]

8.1.1 Guaranteed Atomic Operations

The Intel486 processor (and newer processors since) guarantees that the following basic memory operations will always be carried out atomically:

- Reading or writing a byte
- Reading or writing a word aligned on a 16-bit boundary
- Reading or writing a doubleword aligned on a 32-bit boundary

The Pentium processor (and newer processors since) guarantees that the following additional memory operations will always be carried out atomically:

- Reading or writing a quadword aligned on a 64-bit boundary
- 16-bit accesses to uncached memory locations that fit within a 32-bit data bus

The P6 family processors (and newer processors since) guarantee that the following additional memory operation will always be carried out atomically:

- Unaligned 16-, 32-, and 64-bit accesses to cached memory that fit within a cache line

Accesses to cacheable memory that are split across cache lines and page boundaries are not guaranteed to be atomic by the Intel Core 2 Duo, Intel® Atom™, Intel Core Duo, Pentium M, Pentium 4, Intel Xeon, P6 family, Pentium, and Intel486 processors. The Intel Core 2 Duo, Intel Atom, Intel Core Duo, Pentium M, Pentium 4, Intel Xeon, and P6 family processors provide bus control signals that permit external memory subsystems to make split accesses atomic; however, nonaligned data accesses will seriously impact the performance of the processor and should be avoided.

x86 memory ordering guarantees

[Intel® 64 and IA-32 Architectures Software Developer's Manual Volume 3A: System Programming Guide, Part 1]

CHAPTER 8
MULTIPLE-PROCESSOR MANAGEMENT

Peterson Lock in action

multithread_add_peterson.html

```
class Peterson
{
    volatile bool X,Y;
    volatile pthread_t victim;

public:

    Peterson()
    {
        X = Y = false;
        victim = -1;
    }

    void lock()
    {
        if ( pthread_self()==tidX) { // thread X wanna to acquire lock
            X = true;
            victim = tidX;
            asm volatile("mfence" :::  "memory");
            while(Y && victim==tidX) ;  // spin
        }
        else {  //thread Y wanna acquire lock
            Y = true;
            victim = tidY;
            asm volatile("mfence" :::  "memory");
            while(X && victim==tidY); // spin
        }
    }
```

Prevent instruction reordering by processor

Prevent instruction reordering by optimizing compiler

Synchronization Hardware

- Many systems provide hardware support for 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

```
void lock()
{
      asm("cli"); // disable interrupt
}
```

```
void unlock()
{
      asm("sti"); // enable interrupt
}
```

- Modern machines provide special atomic hardware instructions
    - Atomic = non-interruptable
  - Either test memory word and set value
  - Or swap contents of two memory words
  - http://en.wikipedia.org/wiki/Read-modify-write

Solution to Critical-section Problem Using Locks

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

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”. That is, the swap takes place only under this condition.

Solution using compare_and_swap

Shared integer "lock" initialized to 0;

Solution:

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

xchg (swap) on x86

*C:\Users\Hank\Downloads\postgresql-9.2.1.tar\postgresql-9.2.1\postgresql-9.2.1\src\include\storage\s_lock.h - Notepad++

File Edit Search View Encoding Language Settings Macro Run Plugins Window ?

s_lock.h

```c

#ifdef __x86_64__        /* AMD Opteron, Intel EM64T */
#define HAS_TEST_AND_SET

typedef unsigned char slock_t;

#define TAS(lock) tas(lock)

static __inline__ int
tas(volatile slock_t *lock)
{
    register slock_t _res = 1;

    /*
     * On Opteron, using a non-locking test before the locking instruction
     * is a huge loss.  On EM64T, it appears to be a wash or small loss,
     * so we needn't bother to try to distinguish the sub-architectures.
     */
    __asm__ __volatile__(
        "   lock            \n"
        "   xchgb   %0,%1   \n"
:       "+q"(_res), "+m"(*lock)
:
:       "memory", "cc");
    return (int) _res;
}

#define SPIN_DELAY() spin_delay()
```

C++ source file | length : 26285 | lines : 1027 | Ln : 214 | Col : 18 | Sel : 0 | UNIX | ANSI | INS

Bounded-waiting Mutual Exclusion with TestandSet()

```
do {
        waiting[i] = TRUE;
        key = TRUE;
        while (waiting[i] && key)
                key = TestAndSet(&lock);
        waiting[i] = FALSE;            Wait until released or no one busy.
        // critical section
        j = (i + 1) % n;
        while ((j != i) && !waiting[j])
                j = (j + 1) % n;       Look for a waiting process.
        if (j == i)
                lock = FALSE;          No process waiting.
        else
                waiting[j] = FALSE;    Process j is waiting. Release it.
        // remainder section
} while (TRUE);
```

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
- 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 provides more sophisticated ways (than Mutex locks) for process to synchronize their activities.
- Semaphore ***S*** – integer variable
- Invented by Edsger Dijkstra in 1965
- 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

Consider P_1 and P_2 that require S_1 to happen before S_2

Create a semaphore "**`synch`**" initialized to 0

`P1:`

    S_1;

    `signal(synch);`

`P2:`

    `wait(synch);`

    S_2;

Can implement a counting semaphore S as a binary semaphore

Semaphore Implementation

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

Semaphore Implementation

Implementation of wait and signal

```
wait (S) {
    while S <= 0
        yield(); // give up CPU time slices
      S--;
 }
signal (S) {
  S++;
}
```

Both methods are atomic

- The execution of wait(S) cannot be interrupted by other executions of wait(S) or executions of signal(S)
- The execution of signal(S) cannot be interrupted by other executions of wait(S) or executions of signal(S)
- Interrupts can occur during executions of wait(S) and signal(S) (preemptive scheduling still works !)

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 scheduler ready queue.

Semaphore Implementation

Implementation of wait:

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

The implementation is correct only if the two methods are atomic !

Implementation of signal:

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

How to ensure atomicity?

```
typedef struct __lock_t {
        int flag;
        int guard;
        queue_t *q;
} lock_t;

void lock_init(lock_t *m) {
        m->flag = 0;
        m->guard = 0;
        queue_init(m->q);
}

void lock(lock_t *m) {
        while (TestAndSet(&m->guard, 1) == 1)      ; //acquire guard lock by spinning
        if (m->flag == 0) {
                m->flag = 1; // lock is acquired
                m->guard = 0;
        } else {
                queue_add(m->q, gettid());
                m->guard = 0;
                block();
        }
}

void unlock(lock_t *m) {
        while (TestAndSet(&m->guard, 1) == 1)      ; //acquire guard lock by spinning
        if (queue_empty(m->q))
                m->flag = 0; // let go of lock; no one wants it
        else
                wakeup(queue_remove(m->q)); // hold lock (for next thread!)
        m->guard = 0;
}
```

wakeup/waiting race

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);`
`...`	`...`
`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**

Classical Problems of Synchronization

Classical problems used to test newly-proposed synchronization schemes

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

Bounded-Buffer Problem

N buffers, each can hold one item

Semaphore full initialized to the value 0

Semaphore empty initialized to the value N.

Bounded Buffer Problem (Cont.)

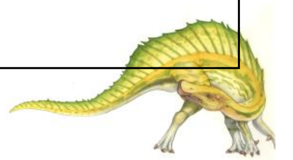
The structure of the producer process

```
do  {

     //   produce an item
     wait (empty);
     //  add the item to the  buffer
      signal (full);
} while (TRUE);
```

The structure of the consumer process

```
do {
        wait (full);
        //  remove an item from  buffer
        signal (empty);
          //  consume the item
  } while (TRUE);
```



Bounded-Buffer Problem

N buffers, each can hold one item

Semaphore mutex initialized to the value 1

Semaphore full initialized to the value 0

Semaphore empty initialized to the value N.

Bounded Buffer Problem (Cont.)

The structure of the producer process

```
do  {

    //   produce an item

    wait (empty);
    wait (mutex);

    //  add the item to the  buffer

     signal (mutex);
     signal (full);
} while (TRUE);
```

The structure of the consumer process

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

          //  remove an item from  buffer

          signal (mutex);
          signal (empty);
          //  consume the item
  } while (TRUE);
```

Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do ***not*** perform any updates
  - Writers – can both read and write
- Problem – allow multiple readers to read at the same time
  - Only one single writer can access the shared data at the same time
- Several variations of how readers and writers are considered – all involve some form of priorities
- Shared Data
  - Data set
  - Semaphore **`rw_mutex`** initialized to 1
  - Semaphore **`mutex`** initialized to 1
  - Integer **`read_count`** initialized to 0

Readers-Writers Problem (Cont.)

The structure of a writer process

```
do {
        wait(rw_mutex);
            ...
        /* writing is performed */
            ...
    signal(rw_mutex);
} while (true);
```

Readers-Writers Problem (Cont.)

The structure of a reader process

```
do {
        wait(mutex);
        read_count++;
        if (read_count == 1)
        wait(rw_mutex);
    signal(mutex);
        ...
        /* reading is performed */
        ...
    wait(mutex);
        read count--;
        if (read_count == 0)
    signal(rw_mutex);
    signal(mutex);
} while (true);
```

Readers-Writers Problem Variations

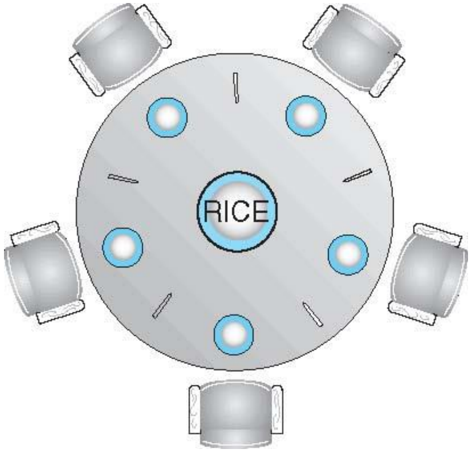
First variation – no reader kept waiting unless writer has permission to use shared object

Second variation – once writer is ready, it performs the write ASAP

Both may have starvation leading to even more variations

Problem is solved on some systems by kernel providing reader-writer locks

Dining-Philosophers Problem



- Philosophers spend their lives alternating 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.

Problems with Semaphores

- Used for 2 independent purposes
  - Mutual exclusion
  - Condition synchronization
- Hard to get right
  - signal (mutex) …. wait (mutex)
  - wait (mutex) … wait (mutex)
  - Omitting of wait (mutex) or signal (mutex) (or both)
  - Small mistake easily leads to deadlock / livelock
- Would it be nice to have?
  - Separation of mutual exclusion and condition synchronization
  - Automatic *wait* and *signal*

Monitors

- Invented by Tony Hoare in 1974
- Like a C++ class
  - Consists of *vars* and *procedures*
  - 3 key differences form a regular class:
    - Only one thread in a monitor at a time (automatic mutual exclusion)
    - Special type of variable, called “condition variable”
      - 3 special ops on a condition variable: *wait*, *signal*, and *broadcast*
    - No public variables allowed (must call procedures to access variables)

Monitors

A high-level abstraction that provides a convenient and effective mechanism for process synchronization

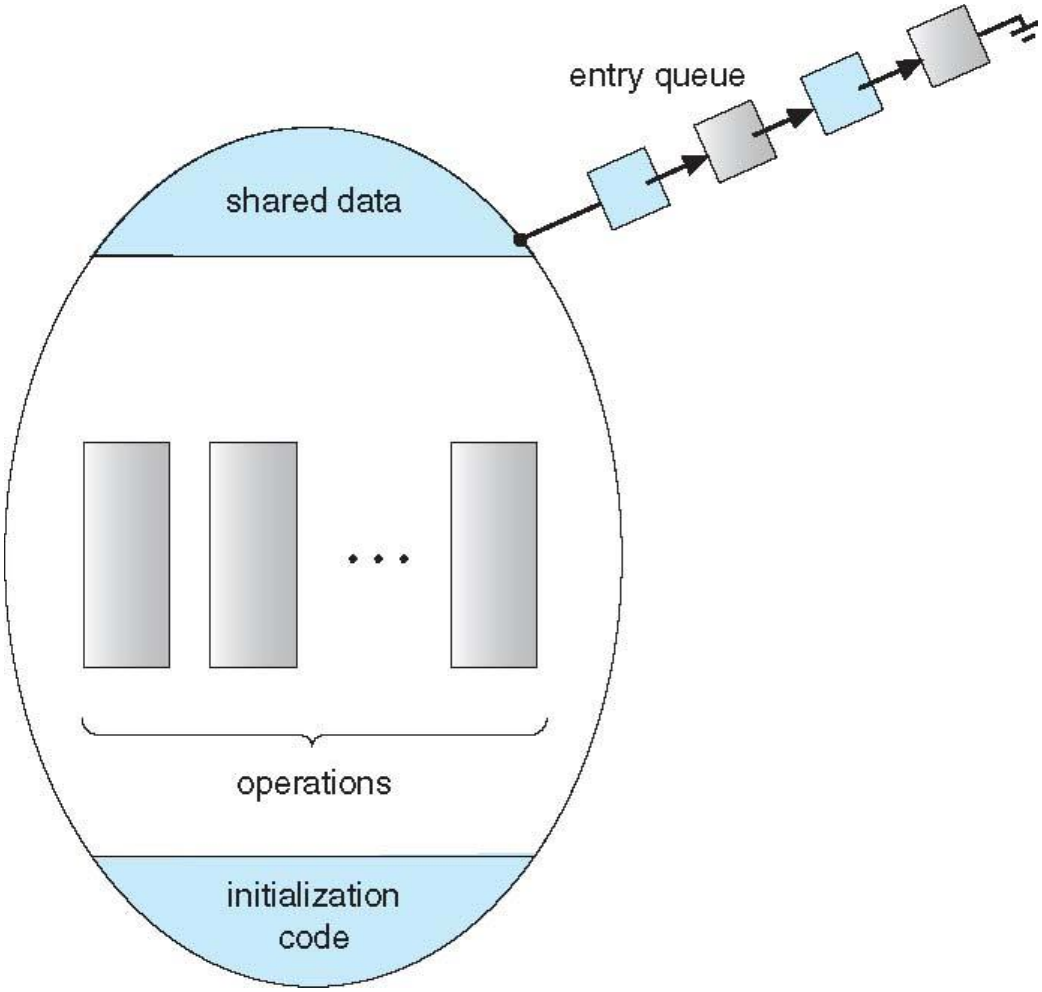
Only one process may be active within the monitor at a time

```
monitor monitor-name
{
    // shared variable declarations
    procedure P1 (…) { …. }
              …

    procedure Pn (…) {……}

    Initialization code ( ….) { … }
              …
}
```

Schematic view of a Monitor



Bounded Buffer by Monitor

```
BoundedBuffer  {

    int BUFFER[MAX_SIZE];
    int head, tail, size;

     Enque (int v)  {
         BUFFER[tail] = v;
         tail = (tail+1) % MAX_SIZE;
          size++;
     }

     Deque (int v)  {
           int i = head;
         head = (head+1) % MAX_SIZE;
         size--;
         return BUFFER[i];
     }

      Init ()   {
         head = tail = size = 0;
      }
 };
```

Any problem?

Bounded Buffer by Monitor

```
BoundedBuffer  {

    int BUFFER[MAX_SIZE];
    int head, tail, size;

     Enque (int v)  {
          while( size == MAX_SIZE);
          BUFFER[tail] = v;
          tail = (tail+1) % MAX_SIZE;
          size++;
     }

     Deque (int v)  {
           while(size==0);
           int i = head;
          head = (head+1) % MAX_SIZE;
          size--;
          return BUFFER[i];
     }

…………
```

Any problem?

Condition Variables

Need a mechanism for condition synchronization

condition x, y;

Automatic *unlock* and *lock* for mutual exclusion

Two operations on a condition variable:

cond.wait ()

- Thread is put on queue for “cond”, goes to sleep.

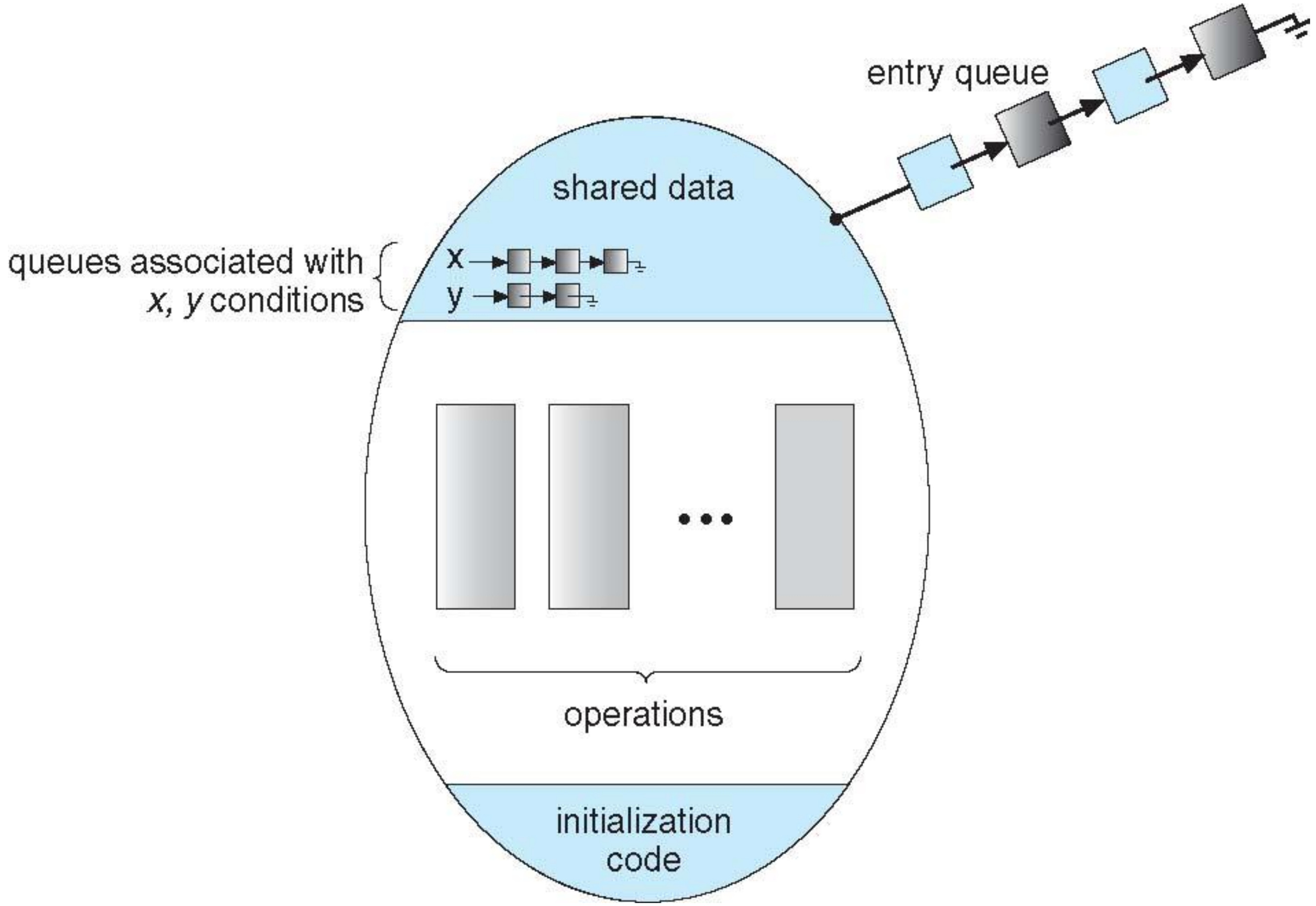
cond.signal ()

- If queue for “cond” not empty, wake up on thread

cond.broadcast()

- Wake up all threads waiting on queue for “cond”

Monitor with Condition Variables

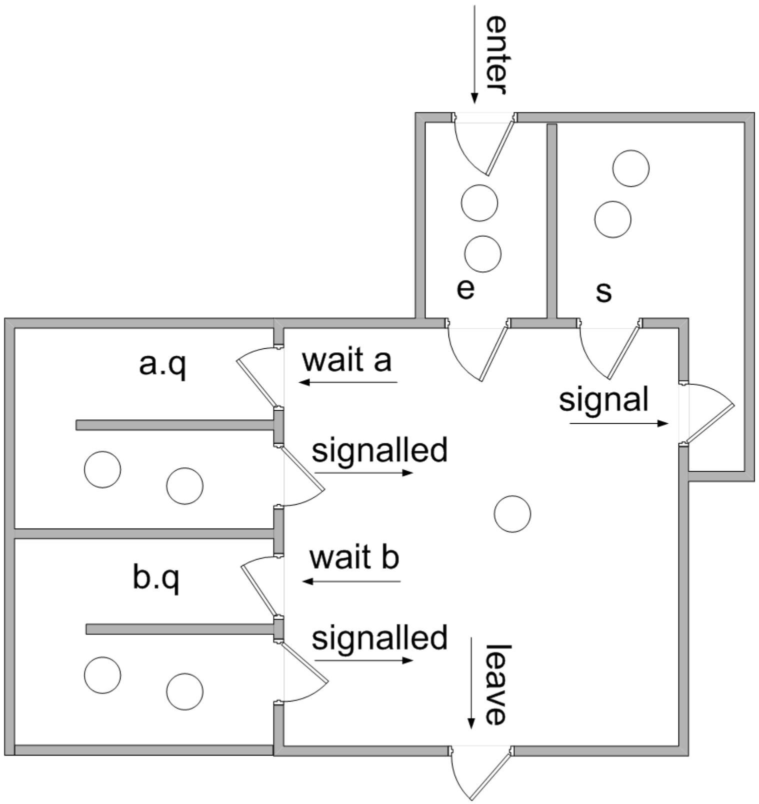


Semantics of Signal

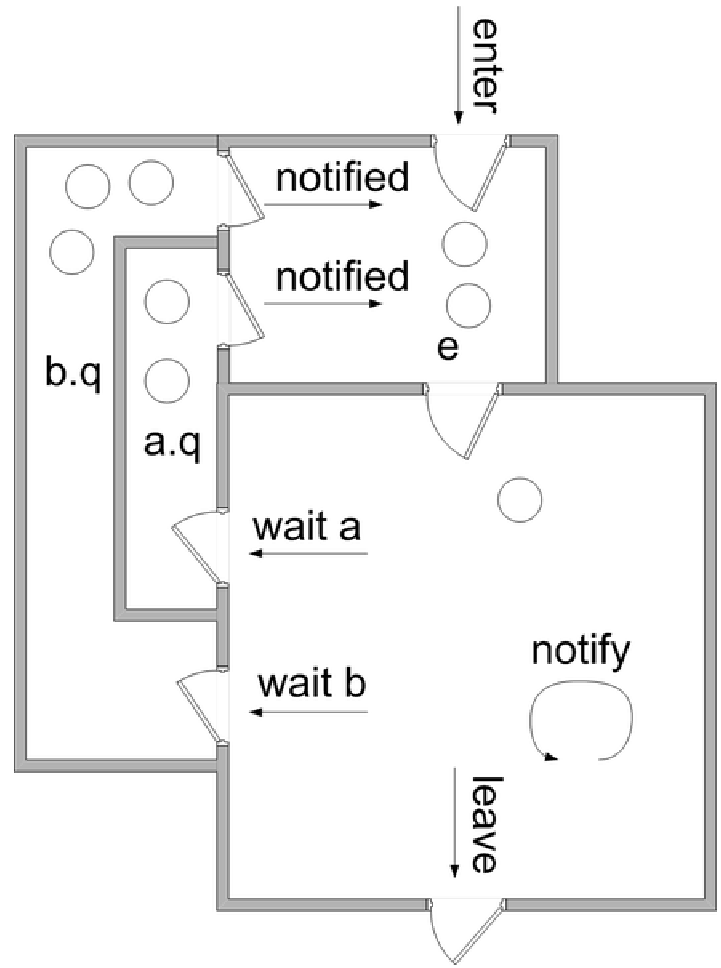
- Signal and Wait (Hoare-style)
  - Signaler passes lock, CPU to waiter; waiter runs immediately
  - Waiter gives lock, CPU back to signaler when
    - It exits critical section
    - Or, it waits again
- Signal and Continue (Mesa-style)
  - signaler continues executing
  - waiter put on ready queue
  - when waiter actually gets to run
    - May have to wait for lock again
    - State may have changed! Use “while”, not “if”
  - Used in Java, Pthread, …)

http://www.cs.mtu.edu/~shene/NSF-3/e-Book/MONITOR/monitor-types.html

Hoare Style vs Mesa Style



Hoare Style



Mesa Style

Bounded Buffer by Monitor

```
BoundedBuffer {

    int BUFFER[MAX_SIZE];
    int head, tail, size;
    cond full, empty;

     Enqueue (int v) {
         while( size == MAX_SIZE)
                  full.wait();
         BUFFER[tail] = v;
         tail = (tail+1) % MAX_SIZE;
         size++;
          if (size ==1)  empty.signal();
     }

       Deque (int v) {
            while(size==0)
                  empty.wait();
            int i = head;
           head = (head+1) % MAX_SIZE;
           size--;
           if ( size == MAX_SIZE-1)
                   full.signal();
           return BUFFER[i];
       }

…………
}
```

Monitor Solution to Dining Philosophers

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

   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);
   }
```

Solution to Dining Philosophers (Cont.)

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

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

Solution to Dining Philosophers (Cont.)

Each philosopher *i* invokes the operations **`pickup()`** and **`putdown()`** in the following sequence:

```
DiningPhilosophers.pickup(i);

    EAT

DiningPhilosophers.putdown(i);
```

No deadlock, but starvation is possible

Hoare Style Monitor Implementation (using semaphores)

- Need mutual exclusion semaphore mutex (init to 1) so that only one process is active within monitor
- Need a semaphore next (next to exit) for the signaling process to suspend itself
  - initialized to zero
- next_count is number of processes blocked on next
- Before exiting a procedure, process must either:
  - Signal other waiting processes in monitor next before exiting, or
  - Signal mutex and exit

Monitor Implementation (Hoare Style)

The monitor "compiler" has to automatically insert this code into compiled procedures:

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

Condition Variable Implementation (Hoare)

Each condition x has a count, and a standard semaphore (with associated queue) initialized to 0

```
x.wait() {
    x.count++;
    if (next_count>0)
        signal(next);
    else
        signal(mutex);
    wait(x.sem);
    x.count--;
}
```

```
x.signal() {
    if (x.count >0){
        next_count++;
        signal(x.sem);
        wait(next);
        next_count--;
    }
}
```

Monitor Implementation (Mesa Style)

Need mutual exclusion semaphore mutex (init to 1) so that only one process is active within monitor

The monitor "compiler" has to automatically insert this code into compiled procedures:

```
Procedure F:
    wait(mutex);
    ...
    body of F
    ...
    signal(mutex);
end;
```

Condition Variable Implementation (Mesa)

Each condition x has a count, and a standard semaphore (with associated queue) initialized to 0

```
x.wait() {
    x.count++;
    signal(mutex);
    wait(x.sem);
    wait(mutex);
}
```

```
x.signal() {
    if (x.count >0){
        x.count--;
        signal(x.sem);
    }
}
```

Difference between Monitors and Semaphores

- Monitors enforce mutual exclusion
- *Semaphore wait* vs. *Monitor wait*
  - Semaphore wait blocks if value is 0
  - Monitor wait always blocks
- *Semaphore signal* vs *Monitor signal*
  - Semaphore signal either wakes up a thread or increments value
  - Monitor signal only has effect if a thread waiting
- Semaphores have “memory”

Resuming Processes within a Monitor

If several processes queued on condition x, and x.signal() executed, which should be resumed?

FCFS frequently not adequate

conditional-wait construct of the form x.wait(c)

- Where c is **priority number**
- Process with lowest number (highest priority) is scheduled next

Single Resource allocation

Allocate a single resource among competing processes using priority numbers that specify the maximum time a process plans to use the resource

```
R.acquire(t);
     ...
  access the resurce;
     ...

 R.release;
```

Where R is an instance of type **`ResourceAllocator`**

A Monitor to Allocate Single Resource

```
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;
      }
}
```

Synchronization Examples

- Solaris
- Windows
- Linux
- Pthreads

Solaris Synchronization

- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing
- Uses **adaptive mutexes** for efficiency when protecting data from short code segments
  - Starts as a standard semaphore spin-lock
  - If lock held, and by a thread running on another CPU, spins
  - If lock held by non-run-state thread, block and sleep waiting for signal of lock being released
- Uses **condition variables**
- Uses **readers-writers** locks when longer sections of code need access to data
- Uses **turnstiles** to order the list of threads waiting to acquire either an adaptive mutex or reader-writer lock
  - Turnstiles are per-lock-holding-thread, not per-object
- Priority-inheritance per-turnstile gives the running thread the highest of the priorities of the threads in its turnstile

Windows Synchronization

- Uses interrupt masks to protect access to global resources on uniprocessor systems
- Uses **spinlocks** on multiprocessor systems
  - Spinlocking-thread will never be preempted
- Also provides **dispatcher objects** user-land which may act mutexes, semaphores, events, and timers
  - **Events**
    - An event acts much like a condition variable
  - Timers notify one or more thread when time expired
  - Dispatcher objects either **signaled-state** (object available) or **non-signaled state** (thread will block)

Linux Synchronization

Linux:

- Prior to kernel Version 2.6, disables interrupts to implement short critical sections
- Version 2.6 and later, fully preemptive

Linux provides:

- Semaphores
- atomic integers
- spinlocks
- reader-writer versions of both

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

Pthreads Synchronization

- Pthreads API is OS-independent
- It provides:
  - mutex locks
  - condition variable
- Non-portable extensions include:
  - read-write locks
  - spinlocks

Java-style monitors

Integrated into the class mechanism

- Annotation “synchronized” can be applied to a member function
  - This function executes with implicit mutual exclusion
- Wait, Signal, and Broadcast are called monitor wait, notify, and notifyAll, respectively

http://docs.oracle.com/javase/tutorial/essential/concurrency/syncmeth.html

```java
public class SynchronizedCounter {
    private int c = 0;

    public synchronized void increment() {
        c++;
    }

    public synchronized void decrement() {
        c--;
    }

    public synchronized int value() {
        return c;
    }
}
```

Alternative Approaches

- Transactional Memory

- OpenMP

- Functional Programming Languages

Transactional Memory

A **memory transaction** is a sequence of read-write operations to memory that are performed atomically.

```
void update()
{
        /* read/write memory */
}
```

OpenMP

OpenMP is a set of compiler directives and API that support parallel progamming.

```
void update(int value)
 {
       #pragma omp critical
       {
             count += value
       }
  }
```

The code contained within the **`#pragma omp critical`** directive is treated as a critical section and performed atomically.

Functional Programming Languages

Functional programming languages offer a different paradigm than procedural languages in that they do not maintain state.

Variables are treated as immutable and cannot change state once they have been assigned a value.

There is increasing interest in functional languages such as Erlang and Scala for their approach in handling data races.

End of Chapter 5