操作系统原理及应用

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Chapter 6 Process Synchronization

Outline

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Monitors
- Synchronization Examples

Background

- Concurrent access to shared data may result in data inconsistency.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.

Background

- **Shared-memory solution to bounded-buffer problem (Chapter 3) allows at most *n* – 1 items in buffer at the same time.**
- **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 count that keeps track of the number of full buffers**

Bounded-Buffer

- **Shared data**

```
#define BUFFER_SIZE 10
typedef struct {
  . . .
} item;
item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
int counter = 0;
```

Bounded-Buffer

- Producer process

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

Bounded-Buffer

- **Consumer process**

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

Bounded-Buffer

- **The statements**

  counter++;

  counter--;

  must be performed ***atomically*****.**
- **Atomic operation means an operation that completes in its entirety without interruption.**

Bounded-Buffer

- The statement "**count++**" may be implemented in machine language as:
  - **$register_1$ = counter**
  - **$register_1$ = $register_1$ + 1**
  - **counter = $register_1$**
- The statement "**count--**" may be implemented as:
  - **$register_2$ = counter**
  - **$register_2$ = $register_2$ – 1**
  - **counter = $register_2$**

Bounded-Buffer

- **If both the producer and consumer attempt to update the buffer concurrently, the assembly language statements may get interleaved.**
- **Interleaving depends upon how the producer and consumer processes are scheduled.**

Bounded-Buffer

- Assume counter is initially 5, what is it finally?

Producer	Consumer
register1 = counter	register2 = counter
register1 = register1 + 1	register2 = register2 – 1
counter = register1	counter = register2

Race Condition

- **Race condition occurs, if:**
  - **two or more processes/threads access and manipulate the same data concurrently**
  - **the outcome of the execution depends on the particular order in which the access takes place.**
- **To prevent race conditions, concurrent processes must be synchronized.**

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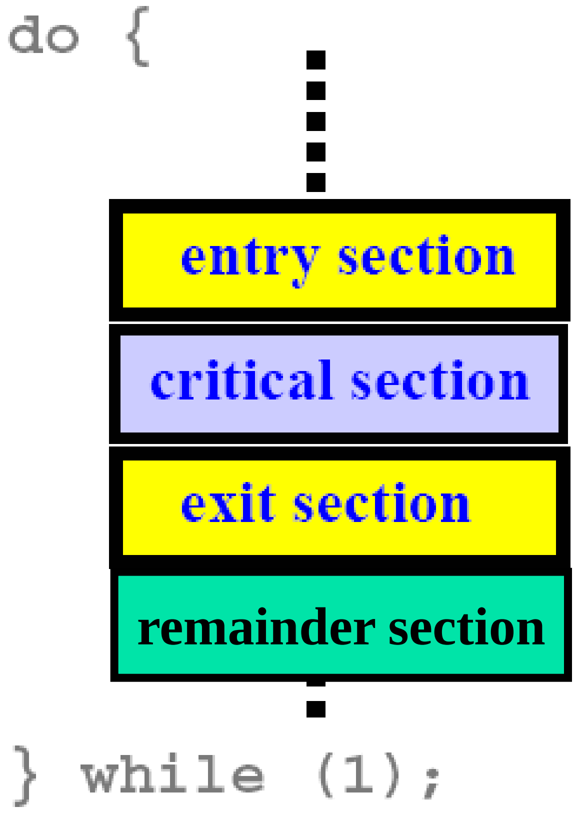
The Critical-Section Problem

- ***n*** **processes all competing to use some shared data**
- **Each process has a code segment, called *critical section*, in which the shared data is changed.**
- **Problem – ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.**

The Critical-Section Problem

- **Thus, the execution of critical sections must be *mutually exclusive* (e.g., at most one process can be in its critical section at any time).**
- **The *critical-section problem* is to design a protocol that processes can use to cooperate.**

The Critical Section Protocol



- A critical section protocol consists of **two** parts: an ***entry section*** and an ***exit section***.
- Between them is the critical section that must run in a **mutually exclusive** way.

Solution to Critical-Section Problem

- Any solution to the critical section problem must satisfy the following three conditions:
  - Mutual Exclusion（互斥、忙则等待）
  - Progress（空闲让进）
  - Bounded Waiting（有限等待）
- Moreover, the solution cannot depend on relative speed of processes and scheduling policy.

Mutual Exclusion

- If a process P is executing in its critical section, then *no* other processes can be executing in their critical sections.
- The critical section protocol should be capable of blocking processes that wish to enter but cannot.
- Moreover, when the process that is executing in its critical section exits, the critical section protocol must be able to know this fact and allows a waiting process to enter.

Progress

- If no process is executing in its critical section and some processes wish to enter their critical sections, then
  - Only those processes that are waiting to enter can participate in the competition (to enter their critical sections).
  - No other process can influence this decision.
  - This decision cannot be postponed indefinitely.

Bounded Waiting

- After a process made a request to enter its critical section and before it is granted the permission to enter, there exists a *bound* on the number of times that other processes are allowed to enter.
- Hence, even though a process may be blocked by other waiting processes, it will not be waiting forever.
- Assume that each process executes at a nonzero speed
- No assumption concerning relative speed of the *n* processes

Initial Attempts to Solve Problem

- Only 2 processes, P_0 and P_1
- General structure of process P_i (other process P_j)

```
do {
        entry section
        critical section
        exit section
        remainder section
} while (1);
```

- Processes may share some common variables to synchronize their actions.

Algorithm 1

- Shared variables:
  - int turn;
    initially turn = i (or turn=j)
- Process P_i :

```
do {    while (turn != i) ;
             critical section
             turn = j;
             remainder section
      } while (1);
```

- are forced to run in an alternating way.
- Satisfies mutual exclusion, but not progress

Algorithm 2

- Shared variables
  - boolean flag[2];
    initially flag[0] = flag[1] = false.
  - flag [i] = true $\Rightarrow$ P_i ready to enter its critical section
- Process P_i

```
do {        flag[i] = true;
            while (flag[j]) ;
              critical section
            flag [i] = false;
              remainder section
        } while (1);
```

- Satisfies mutual exclusion, but not progress.

Is the following algorithm correct?

- **Shared variables**
  - **boolean flag[2];**

    initially flag[0] = flag[1] = false.
- **Process P_i :**

```
do {        while (flag[j]) ;
               flag[i] = true;
               critical section
               flag [i] = false;
               remainder section
            } while (1);
```

Algorithm 3——Peterson's Solution

- Combined shared variables of algorithms 1, 2.
- Process P_i

```
do {    flag [i] = true;
        turn = j;
        while (flag [j] and turn == j) ;
            critical section
        flag [i] = false;
            remainder section
    } while (1);
```

- Meets all three requirements; solves the critical-section problem **for two processes**.

Bakery Algorithm

Critical section for n processes

- Before entering its critical section, process receives a number. Holder of the smallest number enters the critical section.
- If processes P_i and P_j receive the same number, if $i < j$, then P_i is served first; else P_j is served first.
- The numbering scheme always generates numbers in non-decreasing order of enumeration; i.e., 1,2,3,3,3,3,4,5...

Bakery Algorithm

- **Notation**
  - **(a,b) < (c,d) if $a < c$ or if $a = c$ and $b < d$**
  - **max ($a_0,\dots, a_{n-1}$) is a number k, such that $k \geq a_i$ for i from 0 to $n - 1$**
- **Shared data**

```
boolean choosing[n];
int number[n];
```

Data structures are initialized to false and 0 respectively

Bakery Algorithm

```
do {
        choosing[ i ] = true;
        number[ i ] = max(number[0], number[1], …, number [n – 1])+1;
        choosing[ i ] = false;
        for (j = 0; j < n; j++) {
           while (choosing[ j ]) ;
           while ((number[ j ] != 0) && ((number[ j ],j) < (number[ i ],i))) ;
           }
        critical section
        number[ i ] = 0;
        remainder section
} while (1);
```

Discussion

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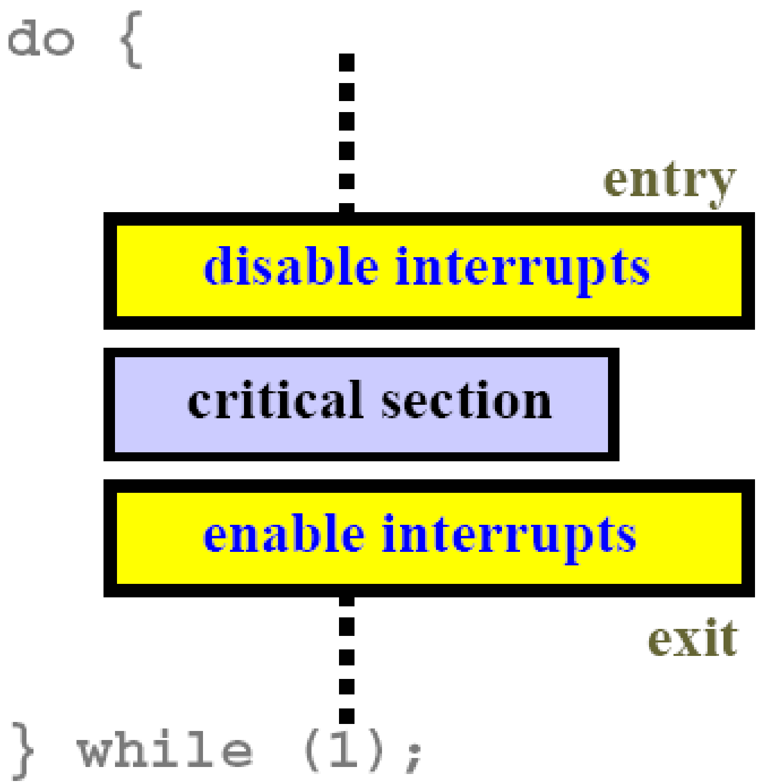
Hardware Support

- There are two types of hardware synchronization supports
  - Disabling/Enabling interrupts
    - This is slow and difficult to implement on multiprocessor systems.
  - Special machine instructions
    - TestAndSet (TS)
    - Swap

Interrupt Disabling



- Because interrupts are disabled, no context switch will occur in a critical section.
- Infeasible in a multiprocessor system because all CPUs must be informed.
- Some features that depend on interrupts (*e.g.*, clock) may not work properly.

TestAndSet

- **Test and modify the content of a word atomically**

```
boolean TestAndSet(boolean &target)
{
    boolean rv = &target;
    &target = true;
    return rv;
}
```

Mutual Exclusion with TestAndSet

- Shared data:

```
boolean lock = false;
```

- Process P_i

```
do {
    while (TestAndSet(lock)) ;
        critical section
    lock = false;
        remainder section
}
```

Swap

- **Atomically swap two variables.**

```
void Swap(boolean &a, boolean &b)
{
    boolean temp = &a;
    &a = &b;
    &b = temp;
}
```

Mutual Exclusion with Swap

- Global Shared data

  boolean lock; (initialized to false):
- Local variable for each process

  boolean key;
- Process P_i

```
do {   key = true;
       while (key == true)
              Swap(lock,key);
       critical section
       lock = false;
       remainder section
   }
```

Satisfying Three Conditions with TestAndSet

Initially Boolean waiting[i] = false; lock=false

Entry Section

```
waiting[ i ] = true;
key = true;
while (waiting[ i ] && key)
    key = TestAndSet(lock);
waiting[i] = false;
```

如果删除该语句，
会产生什么后果？

Exit Section

```
j = (i+1)%n
while ((j!=i) && !waiting[ j ])
    j = (j+1)%n;
if (j == i)
    lock = false;
else
    waiting[ j ] = false;
```

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Semaphores

- Synchronization tool
- Semaphore *S* – integer variable
- can only be accessed via two standard atomic operations

wait (*S*): P()

while *S* $\leq$ 0;

S--;

signal (*S*): V()

S++;

Two Types of Semaphores

- ***Counting* semaphore** – integer value can range over an unrestricted domain.
- ***Binary* semaphore** – integer value can range only between 0 and 1; also called **mutex locks**.
- **Can implement a counting semaphore *S* as a binary semaphore.**

Critical Section of n Processes

- **Shared data:**

  semaphore mutex; //initially *mutex* = 1

- **Process P_i:**

```
do {
    wait(mutex);
        critical section
    signal(mutex);
        remainder section
} while (1);
```

Wrong or Right?

Semaphore as a General Synchronization Tool

- **Execute *B* in P_j only after *A* executed in P_i**
- **Use semaphore *flag* initialized to 0**
- **Code:**

P_i	P_j
⋮	⋮
A	***wait (flag)***
signal (flag)	***B***

Semaphore Implementation

- The main disadvantage of the above classical semaphore definition is that it requires busy waiting.（while a process is in its critical section, any other process that tries to enter its critical section must loop continuously in the entry section）
- This type of semaphore is also called a spinlock (自旋锁) because the process spins while waiting for the lock.
- To overcome the need for busy waiting, the process can block itself rather than engaging in busy waiting.

Semaphore Implementation

- Define a semaphore as a record

```
typedef struct {
    int value;
    struct process *L; // waiting queue
} semaphore;
```

- Assume two simple operations:
  - block() suspends the process that invokes it.
  - wakeup(*P*) resumes the execution of a blocked process P.

Implementation

- Semaphore operations now defined as

wait(*S*):

```
S.value--;
if (S.value < 0) {
        add this process to S.L;
        block();
}
```

signal(*S*):

```
S.value++;
if (S.value <= 0) {
        remove a process P from S.L;
        wakeup(P);
}
```

Implementation

- **If the semaphore value is negative, its magnitude is the number of processes waiting on that semaphore.**
- **The critical aspect of semaphores is that they be executed atomically. (Critical-section Problem)**
- **Busy waiting has not been completely eliminated.**
  - **Busy waiting has been removed from the critical sections of application programs.**
  - **Furthermore, we have limited busy waiting to the critical sections of the wait() and signal() operations.**

Exercises

- 5个进程共享某一临界资源，则互斥信号量的取值范围是多少？
- 有4个进程共享一程序段，而每次最多允许2个进程进入该程序段，则信号量的初值是多少？

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 all 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.**

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Classical Problems of Synchronization

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

Bounded-Buffer Problem

- **Shared data**
  - **Semaphore: full, empty, mutex;**
  - **Initially: full = 0, empty = n, mutex = 1**

Bounded-Buffer Problem Producer Process

```
do {    …
        produce an item in nextp
            …
        wait(empty);
        wait(mutex);
            …
        add nextp to buffer
            …
        signal(mutex);
        signal(full);
    } while (1);
```

Bounded-Buffer Problem Consumer Process

```
do {
    wait(full)
    wait(mutex);
    …
    remove an item from buffer to nextc
    …
    signal(mutex);
    signal(empty);
    …
    consume the item in nextc
    …
} while (1);
```

作业1

- 在生产者——消费者问题中，信号量mutex，empty，full的作用是什么？如果分别对调生产者进程中的两个wait操作和两个signal操作，则可能发生什么情况？

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.
  - First readers-writers problem——Reader first
  - Second readers-writers problem——Writer first

First Readers-Writers Problem

- **Shared data**

  int readcount;

  semaphore wrt, mutex;

- **Initially**

  mutex = 1, wrt = 1, readcount = 0

First Readers-Writers Problem
Writer Process

```
do {
    wait(wrt);
            ...
        writing is performed
            ...
    signal(wrt);
} while (1)
```

First Readers-Writers Problem Reader Process

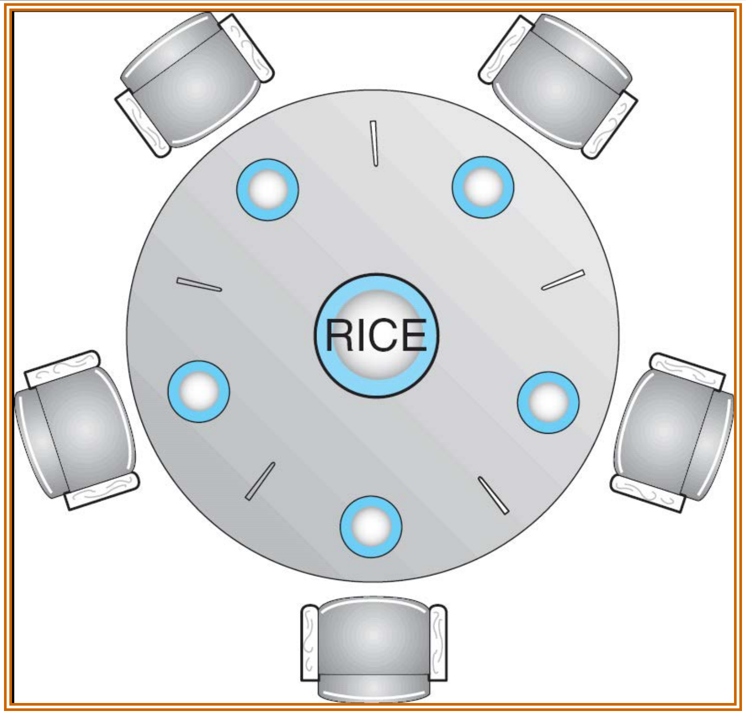
```
do {
    wait(mutex);
    readcount++;
    if (readcount == 1)
        wait(wrt);
    signal(mutex);
        ...
     reading is performed
       ...
    wait(mutex);
    readcount--;
    if (readcount == 0)
        signal(wrt);
    signal(mutex):
}
```

Wrong or Right?

作业2

- 用信号量解决无饥饿的读者——写者问题。

Dining-Philosophers Problem



- **Shared data**

  semaphore chopstick[5];

  Initially all values are 1

Dining-Philosophers Problem

- **Philosopher *i*:**

```
do {
  wait(chopstick[i])
  wait(chopstick[(i+1) % 5])
    …
   eat
    …
  signal(chopstick[i]);
  signal(chopstick[(i+1) % 5]);
    …
   think
    …
} while (1);
```

Wrong or Right?

Exercise

- 用信号量解决“独木桥”问题：同一方向的行人可连续过桥，当某一方向有人过桥时，另一方向的人必须等待；当某一方向无人过桥时，另一方向的行人可以过桥。

Exercise

- **Shared data**

  int countA = 0 //表示A方向上已在独木桥上的行人数目

  int countB = 0 //表示B方向上已在独木桥上的行人数目

  semaphore MA =1 //实现对countA的互斥修改

  MB =1 //实现对countB的互斥修改

  mutex =1 //实现两个方向的行人对独木桥的互斥使用

Exercise

A方向过桥进程：

B方向过桥进程?

```
do{
    wait(MA);
    countA ++;
    if (countA == 1) then wait(mutex);
    signal(MA);
    过桥;
    wait(MA);
    countA --;
    if (countA == 0) then signal(mutex);
    signal(MA)
  } while (1);
```

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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)

把分散在各进程中的临界区集中起来管理

Monitors

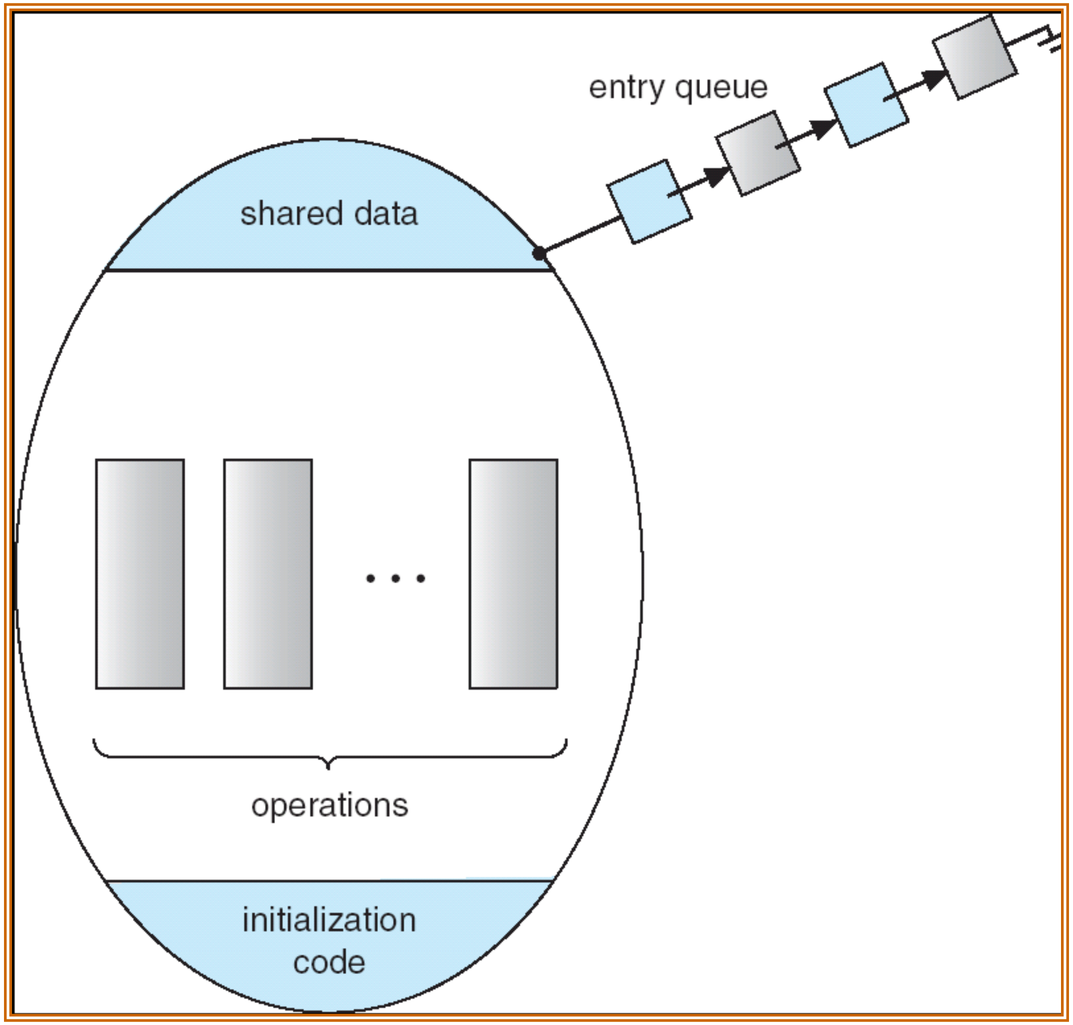
- High-level synchronization construct that allows the safe sharing of an abstract data type among concurrent processes.

```
monitor monitor-name
{    shared variable declarations
     procedure body P1 (…) {
        . . .}
     procedure body P2 (…) {
        . . .}
     procedure body Pn (…) {
         . . .}
     {  initialization code}
}
```

Monitors: Mutual Exclusion

- ***No more than one process*** **can be executing** ***within*** **a monitor.**
- **When a process calls a monitor procedure and the monitor has a process running, the caller will be blocked outside of the monitor.**
- **Thus,** ***mutual exclusion*** **is guaranteed within a monitor.**

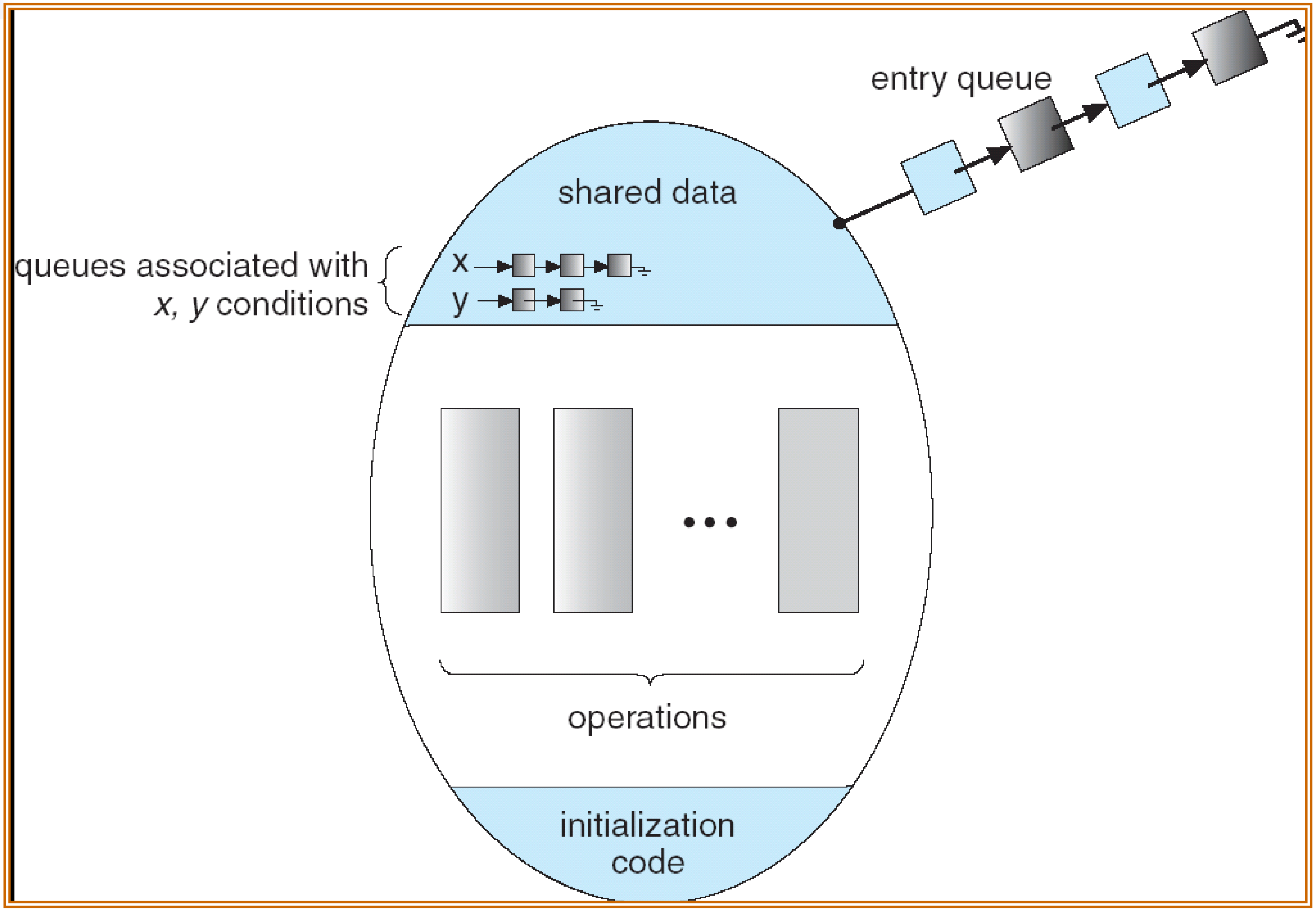
Schematic View of a Monitor



Condition Variables

- To allow a process to wait within the monitor, a condition variable must be declared, as condition x, y;
- Condition variable can only be used with the operations wait and signal.
  - x.wait() means that the process invoking this operation is suspended until another process invokes x.signal();
  - The x.signal() operation resumes exactly one suspended process. If no process is suspended, then the signal() operation has no effect.

Monitor With Condition Variables



Condition Variables

- Consider the released process and the signaling process
  - There are two processes executing in the monitor, and mutual exclusion is violated!
- Approaches to address this problem
  - The released process takes the monitor and the signaling process waits somewhere.（唤醒并等待）
  - The released process waits somewhere and the signaling process continues to use the monitor.（唤醒并继续）

Semaphore vs. Condition

Semaphores	Condition Variables
Can be used anywhere, but not in a monitor	Can only be used in monitors
`wait()` does not always block its caller	`wait()` always blocks its caller
`signal()` either releases a process, or increases the semaphore counter	`signal()` either releases a process, or the signal is lost as if it never occurs
If `signal()` releases a process, the caller and the released *both continue*	If `signal()` releases a process, either the caller or the released continues, but *not both*

Monitor vs. Process

- 管程定义的是公用数据结构，而进程定义的是私有数据结构
- 管程把共享变量上的同步操作集中起来，而临界区却分散在每个进程中
- 管程是为管理共享资源而建立的，进程主要是为占有系统资源和实现系统并发性而引入的
- 管程是被欲使用共享资源的进程所调用，管程和调用它的进程不能并发工作，而进程之间能并发工作
- 管程是语言或操作系统的成分，不必创建或撤销，而进程有生命周期，由创建而产生至撤销便消亡

Dining Philosophers

```
monitor dp
{
    enum {thinking, hungry, eating} state[5];
    condition self[5];
    void pickup(int i)              // following slides
    void putdown(int i)             // following slides
    void test(int i)                // following slides
    void init()
    {  for (int i = 0; i < 5; i++)
           state[i] = thinking;  }
}
```

Dining Philosophers

```
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);
}
```

Dining Philosophers

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

Dining Philosophers

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

  dp.pickup (i)

  EAT

  dp.putdown (i)

Monitor Implementation Using Semaphores

- Variables

确保管程的互斥调用

semaphore mutex; // (initially = 1)

semaphore next; // (initially = 0)

int next-count = 0;

管程内挂起进程的总数

防止执行Signal操作后两个进程同时在管程中

- Each external procedure *F* will be replaced by

```
wait (mutex);
    …
  body of F;
    …
if (next-count > 0)
  signal (next)
else signal (mutex);
```

- Mutual exclusion within a monitor is ensured.

Monitor Implementation

- For each condition variable *x*, we have

```
semaphore x-sem; // (initially  = 0)
int x-count = 0;
```

挂起等待资源的进程

- The operation x.wait can be implemented as

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

Monitor Implementation

- The operation x.signal can be implemented as

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

Monitor Implementation

- ***Conditional-wait*** **construct: x.wait(c)**
  - **c – integer expression evaluated when the wait operation is executed.**
  - **value of c (a *priority number*) stored with the name of the process that is suspended.**
  - **when x.signal() is executed, process with smallest associated priority number is resumed next.**

Monitor Implementation

- Check two conditions to establish correctness of system
  - User processes must always make their calls on the monitor in a correct sequence.
  - Must ensure that an uncooperative process does not ignore the mutual-exclusion gateway provided by the monitor, and try to access the shared resource directly, without using the access protocols.

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- **Monitors**
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Solaris Synchronization

- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing.
- Uses *adaptive mutex* for efficiency when protecting data from short code segments.
- Uses *condition variables* , *semaphore*, and *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.

Windows XP Synchronization

- Uses interrupt masks (中断屏蔽) to protect access to global resources on uniprocessor systems.
- Uses *spinlocks* on multiprocessor systems.
- Also provides *dispatcher objects* which may act as mutex and semaphores.
- Dispatcher objects may also provide *events*. An event acts much like a condition variable.

Linux Synchronization

- Linux
  - disables interrupts to implement short critical sections
- Linux provides
  - semaphores
  - spinlocks

Pthreads Synchronization

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