Shared Memory Model

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Overview

- The Critical-Section Problem
- Software Solutions
- Synchronization Hardware
- Semaphores
- Monitors
- Synchronization Examples

Objectives

- 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

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Producer-Consumer Problem

- The Producer process produces data that must processed by the Consumer Process
- The inter-process communication occurs through a shared buffer (shared memory)
- Bounded Buffer Size
  - The producer process cannot insert a new item if the buffer is full
  - The Consumer process cannot extract an item if the buffer is empty

Producer-Consumer Problem

- Shared data

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

Producer-Consumer Problem

- Producer process

```
item nextProduced;

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


Producer-Consumer Problem

- Consumer process

```
item nextConsumed;

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


Producer-Consumer Problem

- The statements

counter++;
counter--;

must be performed *atomically*.

- Atomic operation means an operation that completes in its entirety without interruption.

Producer-Consumer Problem

- The statement "**count++**" may be implemented in machine language as:

  register1 = counter

  register1 = register1 + 1
  counter = register1

- The statement "**count—**" may be implemented as:

  register2 = counter
  register2 = register2 – 1
  counter = register2

Producer-Consumer Problem

- 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.

Race Condition

- Assume **counter** is initially 5. One interleaving of statements is:

  producer: **register1 = counter** (*register1 = 5*)
  producer: **register1 = register1 + 1** (*register1 = 6*)

  consumer: **register2 = counter** (*register2 = 5*)
  consumer: **register2 = register2 – 1** (*register2 = 4*)

  producer: **counter = register1** (*counter = 6*)
  consumer: **counter = register2** (*counter = 4*)

- The value of **count** may be either 4 or 6, where the correct result should be 5.

Race Condition

- **Race condition**
  - The situation where several processes access and manipulate shared data concurrently.
  - The final value of the shared data depends upon which process finishes last.
- To prevent race conditions, concurrent processes must be **synchronized**.

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 accessed.
- Problem – ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.

Solution to Critical-Section Problem

1. **Mutual Exclusion**
   - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections.
2. **Progress**
   - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely.
3. **Bounded Waiting**.
   - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted.

- Assume that each process executes at a nonzero speed
- No assumption concerning relative speed of the *n* processes.

General Process Structure

- General structure of process P_i

```
do {
    entry section
    critical section
    exit section
    reminder section
} while (TRUE)
```


Possible Solutions

- Software approaches
- Hardware solutions
  - Interrupt disabling
  - Special machine instructions
- Operating System Support
  - Semaphores
- Programming language Support
  - Monitor
  - …

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A Software Solution

```
Boolean lock=FALSE;
Process Pi {
   do {
         while (lock);   // do nothing
         lock=TRUE;
            critical section
         lock=FALSE;
            remainder section
   } while (TRUE);
}
```

Does it work?

Peterson's Solution

- Two process solution
- Assume that the LOAD and STORE instructions are atomic
- The two processes share two variables:
  - int turn;
  - Boolean flag[2]
- The variable turn indicates whose turn it is to enter the critical section.
- 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!

Algorithm for Process P_i

```
do {
        flag[i] = TRUE;
        turn = j;
        while (flag[j] && turn == j);
                critical section
        flag[i] = FALSE;
                remainder section
   } while (TRUE);
}
```

Solution to Critical-section Problem Using Locks

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


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Synchronization Hardware

- Many systems provide hardware support for critical section code
- Uniprocessors – could disable interrupts
  - The running process should be pre-empted during the critical section
- Modern machines provide special atomic hardware instructions

Interrupt Disabling

```
do {
      disable interrupt;
         critical section
      enable interrupt;
         remainder section
} while (1);
```


Previous Solution

```
do {
      while (lock);   // do nothing
      lock=TRUE;
         critical section
      lock=FALSE;
         remainder section
} while (1);
```

The solution does not guaranteed the mutual exclusion because the test and set on lock are not atomic

Test-And-Set Instruction

- Definition:

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

Solution using Test-And-Set

```
Boolean lock=FALSE;

 do {
    while (TestAndSet (&lock ));   // do nothing
        critical section
    lock = FALSE;
        remainder section
 } while (TRUE);
```


Swap Instruction

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


Solution using Swap

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

```
do {
   key = TRUE;
   while ( key == TRUE) Swap (&lock, &key );
       critical section
    lock = FALSE;
       remainder section
 } while (TRUE);
```

This solution guarantees mutual exclusion but not bounded waiting

Bounded-waiting Mutual Exclusion with TestandSet()

```
do {
    waiting[i] = TRUE;
    key = TRUE;
    while (waiting[i] && key) key = TestAndSet(&lock);
    waiting[i] = FALSE;
            // critical section
    j = (i + 1) % n;
    while ((j != i) && !waiting[j]) j = (j + 1) % n;
    if (j == i) lock = FALSE;
    else waiting[j] = FALSE;
            // remainder section
} while (TRUE);
```


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Semaphore

- Synchronization tool that does not require busy waiting
- Semaphore *S* – integer variable
- Can only be accessed via two indivisible (atomic) operations
  - wait() and signal()
  - Originally called P() and V()

Semaphore

```
wait (S) {
        while (S <= 0);     // do nothing
        S--;
}

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

wait() and signal() must be atomic

Semaphore as General Synchronization Tool

- Counting semaphore
  - integer value can range over an unrestricted domain
- Binary semaphore
  - integer value can range only between 0 and 1; can be simpler to implement
  - Also known as mutex locks
- Can implement a counting semaphore S as a binary semaphore

Semaphore as Mutex Tool

- Shared data:
  semaphore mutex=1;
- Process *Pi:*

```
do {
    wait (mutex);
        // Critical Section
    signal (mutex);
        // Remainder section
} while (TRUE);
```

Semaphore Implementation

- Must guarantee that no two processes can execute wait () and signal () on the same semaphore at the same time
- Could have busy waiting (spinlock)
  - Busy waiting wastes CPU cycles
  - But avoids context switches
  - May be useful when the critical section is short and/or rarely occupied
- However applications may spend lots of time in critical sections and therefore, generally, this is not a good solution.

Semaphore Implementation

- Define a semaphore as a record

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

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

Implementation

```
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);
        }
}
```

Semaphore as a 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

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.

Classical Problems of Synchronization

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

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

- Producer Process

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

} while (1);
```

- Consumer Process

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


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

Readers-Writers Problem

- Shared Data
  - Data set
  - Semaphore mutex initialized to 1
  - Semaphore wrt initialized to 1
  - Integer readcount initialized to 0

Readers-Writers Problem

- The structure of a writer process

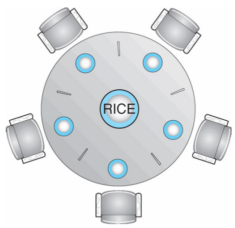
```
do {
    wait (wrt) ;
     // writing is performed
    signal (wrt) ;
} while (TRUE);
```


Readers-Writers Problem

- The structure of a 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) ;
} while (TRUE);
```

Dining-Philosophers Problem



- Shared data
  - Bowl of rice (data set)
  - Semaphore chopstick [5] initialized to 1

Dining-Philosophers Problem

- 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);
```


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)

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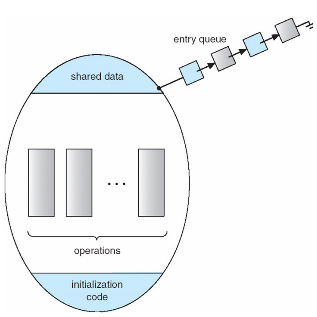
Monitors

- 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 ( ….) {
       …
    }
}
```

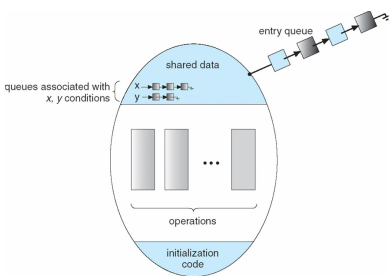

Schematic view of a Monitor



Condition Variables

- condition x, y;
- Two operations on a condition variable:
  - x.wait () – a process that invokes the operation is suspended.
  - x.signal () – resumes one of processes (if any) that invoked x.wait ()

Monitor with Condition Variables



Solution to Dining Philosophers

```
monitor DP {
    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

```
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

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

```
DiningPhilosophters.pickup (i);

EAT

DiningPhilosophers.putdown (i);
```


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;
    }
}
```

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Synchronization Examples

- Solaris
- Windows XP
- Linux
- Pthreads

Solaris Synchronization

- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing
- Adaptive mutexes for efficiency when protecting data from short code segments
- Uses condition variables and readers-writers locks when longer sections of code need access to data

Windows XP Synchronization

- Uses interrupt masks to protect access to global resources from kernel threads on uniprocessor systems
- Uses spinlocks on multiprocessor systems
- For out-of-kernel synch provides dispatcher objects
  - may act as either mutexes and semaphores
- Dispatcher objects may also provide events
  - An event acts much like a condition variable

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
  - spin locks

Pthreads Synchronization

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

Questions?