Chapter 7: Synchronization Examples

Outline

- Explain the bounded-buffer synchronization problem
- Explain the readers-writers synchronization problem
- Explain and dining-philosophers synchronization problems
- Describe the tools used by Linux and Windows to solve synchronization problems.
- Illustrate how POSIX and Java can be used to solve process synchronization problems

二元號誌 (1/2) - binary semaphore

- 二元號誌的值只限定為 0 或 1。
  - 利用硬體對二元數值的運算支援，二元號誌的實作要比計數號誌簡單快速得多。
  - 可以利用二元號誌來實作計數號誌。
- turn, flag, turn+flag
- test&set, compare&swap, swap
- mutex lock, semaphore
- critical region
- monitor

二元號誌 (2/2)

- 計數號誌可以利用兩個二元號誌以及一個整數實作。

void wait(S) {
    wait(S1);
    C--;
    if (C < 0) {
        signal(S1);
        wait(S2);
    }
    signal(S1);
}
	void signal(S) {
	    wait(S1);
	    C++;
	    if (C <= 0)
	        signal(S2);
	    else
	        signal(S1);
	}

臨界區域 (1/4) - critical region

- 臨界區域的使用非常方便。
  - 以下宣告一個具有共享變數 v 的臨界區域，在 B 條件式成立下，如果沒有其他行程在此臨界區域中執行，就會執行 S 敘述：

```
region v when B do S;
```

- 利用臨界區域來實作，程式設計師不用煩惱同步的問題，只要正確地把問題描述在臨界區域內。
- 有限緩衝區問題可以用臨界區域來簡單地解決同步的問題。

臨界區域 (2/4)

- 生產者與消耗者程式可以分別以臨界區域實作如下。

生產者	消耗者

region buffer **when** (count < n) {
    pool[in] = nextp;
    in = (in + 1) % n;
    count++;
}
	region buffer **when** (count > 0) {
	    nextc = pool[out];
	    out = (out + 1) % n;
	    count--;
	}

臨界區域 (3/4)

- 臨界區域 **region** v **when** B **do** S 可利用 mutex、first_delay 及 second_delay 三個號誌實作。
  - mutex 號誌是用來確保臨界區的互斥條件成立。
  - 如果行程因為 B 為 FALSE 而無法進入臨界區，該行程將會在號誌 first_delay 等待。
  - 在號誌 first_delay 等待的行程重新檢查 B 值之前，會離開號誌 first_delay，而在號誌 second_delay 等待。
  - 分成first_delay 與 second_delay兩段式等待的原因，是為了要避免行程持續忙碌地檢查 B 值。
  - 當一個行程離開了臨界區之後，可能因為執行了敘述 S 而改變了 B 的值，所以需要重新檢查。

臨界區域 (4/4)

```
wait(mutex);
while (!B) {
    first_count++;
    if (second_count > 0)
        signal(second_delay);
    else
        signal(mutex);
    wait(first_delay);
    first_count--;
    second_count++;
    if (first_count > 0)
       signal(first_delay);
    else
       signal(second_delay);
    wait(second_delay);
    second_count--;
}
S;
if (first_count > 0)
    signal(first_delay);
else if (second_count > 0)
    signal(second_delay);
else
    signal(mutex);
```

wait(mutex);
while (!B) {
first_count++;
if (first_count > 0)
signal(first_delay);
else
signal(mutex);
~~wait(first_delay);~~
~~first_count--;~~
~~first_count++;~~
~~**if** (first_count > 0)~~
~~**signal**(first_delay);~~
~~**else**~~
~~signal(first_delay);~~
wait(first_delay);
first_count--;
}
S;
if (first_count > 0)
signal(first_delay);
~~**else if** (first_count > 0)~~
~~**signal**(first_delay);~~
else
signal(mutex);

```
wait(mutex);
while (!B) {
    first_count++;
    if (first_count > 0)
        signal(first_delay);
    else
        signal(mutex);
    wait(first_delay);
    first_count--;
}
S;
if (first_count > 0)
    signal(first_delay);
else
    signal(mutex);
```

```
wait(mutex);
while (!B) {
    first_count++;
    signal(mutex);
    wait(first_delay);
    first_count--;
}
S;
if (first_count > 0)
    signal(first_delay);
else
    signal(mutex);
```

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 mutex initialized to the value 1
- Semaphore full initialized to the value 0
- Semaphore empty initialized to the value N.

Bounded Buffer Problem (Cont.)

producer process

```
do {
    //   produce an item
          wait (empty);
          wait (mutex);

    //  add the item to the  buffer

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

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

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

Readers-Writers Problem (Cont.)

- The structure of a reader process

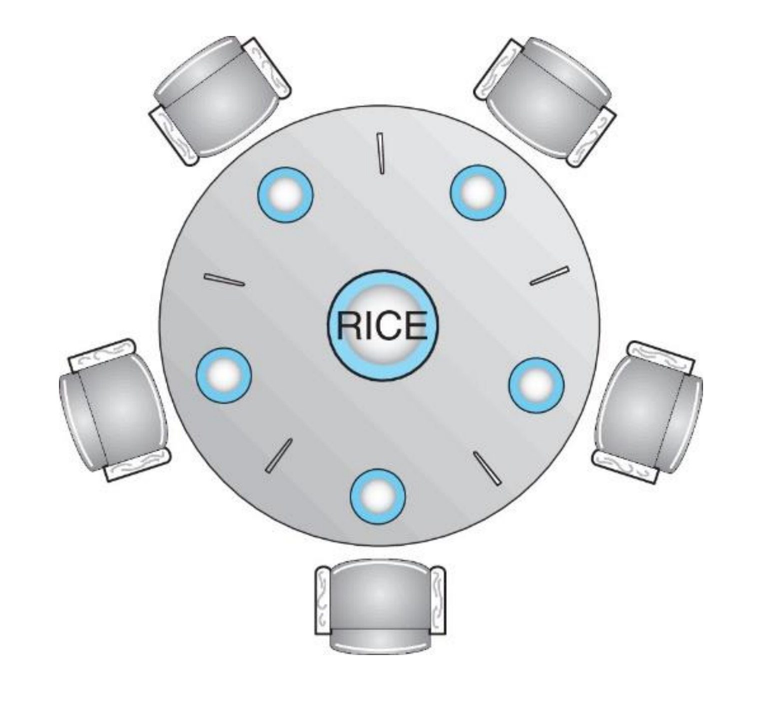
```
while (true){
      wait(mutex);
            read_count++;
            if (read_count == 1) /* first reader */
                  wait(rw_mutex);
      signal(mutex);
         ...
            /* reading is performed */
         ...
      wait(mutex);
            read count--;
            if (read_count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

Readers-Writers Problem Variations

- The solution in previous slide can result in a situation where a writer process never writes. It is referred to as the "First reader-writer" problem.
- The "Second reader-writer" problem is a variation the first reader-writer problem that state:
  - Once a writer is ready to write, no "newly arrived reader" is allowed to read.
- Both the first and second may result in starvation, leading to even more variations
- Problem is solved on some systems by kernel providing reader-writer locks

Dining-Philosophers Problem

- N philosophers’ sit at a round table with a bowel of rice in the middle.
- They spend their lives alternating thinking and eating.
- They do not 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, the shared data
  - Bowl of rice (data set)
  - Semaphore chopstick [5] initialized to 1



Dining-Philosophers Problem Algorithm

- Semaphore Solution
- The structure of Philosopher i :

```
while (true){
    wait (chopstick[i] );
    wait (chopStick[ (i + 1) % 5] );

     /* eat for a while */

    signal (chopstick[i] );
    signal (chopstick[ (i + 1) % 5] );

     /* think for a while */


}
```

- What is the problem with this algorithm?

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);
```

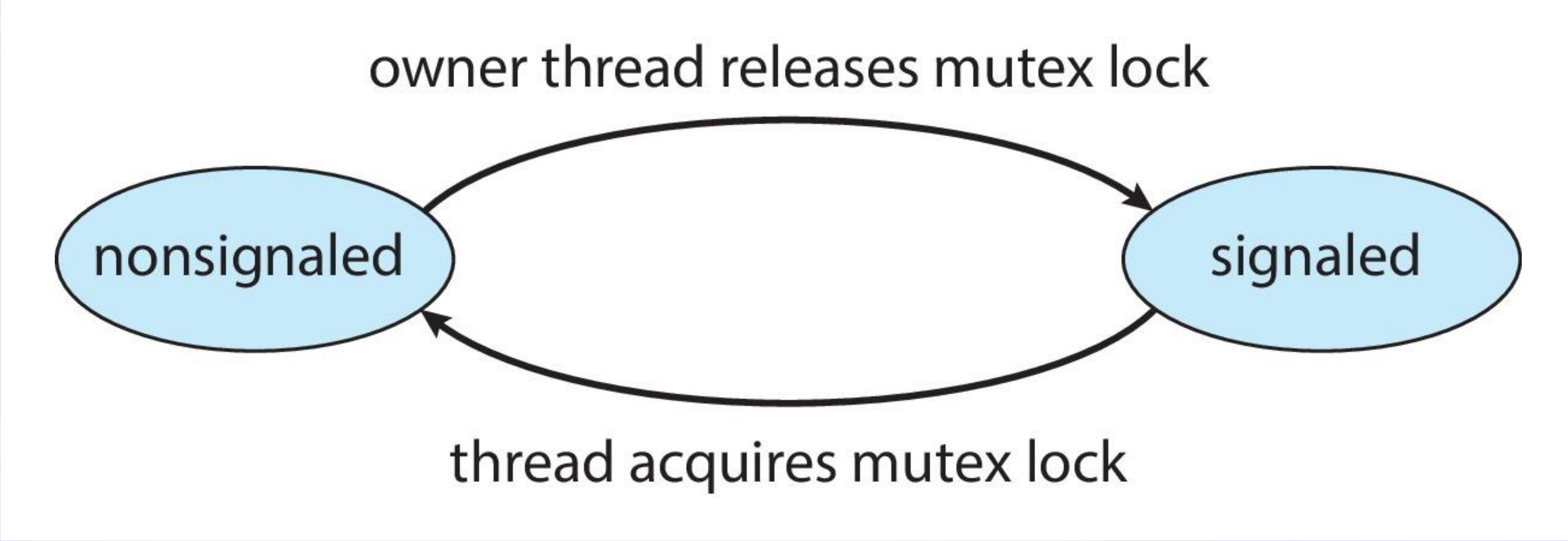
- No deadlock, but starvation is possible

Kernel Synchronization - Windows

- 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)

Kernel Synchronization - Windows

- Mutex dispatcher object



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

Linux Synchronization

- Atomic variables

  `atomic_t` is the type for atomic integer

- Consider the variables

```
atomic_t counter;
int value;
```

Atomic Operation	*Effect*
`atomic_set(&counter,5);`	`counter = 5`
`atomic_add(10,&counter);`	`counter = counter + 10`
`atomic_sub(4,&counter);`	`counter = counter - 4`
`atomic_inc(&counter);`	`counter = counter + 1`
`value = atomic_read(&counter);`	`value = 12`

POSIX Synchronization

- POSIX API provides
  - mutex locks
  - semaphores
  - condition variable
- Widely used on UNIX, Linux, and macOS

POSIX Mutex Locks

- Creating and initializing the lock

```
#include <pthread.h>

pthread_mutex_t mutex;

/* create and initialize the mutex lock */
pthread_mutex_init(&mutex,NULL);
```

- Acquiring and releasing the lock

```
/* acquire the mutex lock */
pthread_mutex_lock(&mutex);

/* critical section */

/* release the mutex lock */
pthread_mutex_unlock(&mutex);
```

POSIX Semaphores

- POSIX provides two versions – **named** and **unnamed**.
- Named semaphores can be used by unrelated processes, unnamed cannot.

POSIX Named Semaphores

- Creating and initializing the semaphore:

```
#include <semaphore.h>
sem_t *sem;

/* Create the semaphore and initialize it to 1 */
sem = sem_open("SEM", O_CREAT, 0666, 1);
```

- Another process can access the semaphore by referring to its name **SEM**.
- Acquiring and releasing the semaphore:

```
/* acquire the semaphore */
sem_wait(sem);

/* critical section */

/* release the semaphore */
sem_post(sem);
```

POSIX Unnamed Semaphores

- Creating and initializing the semaphore:

```
#include <semaphore.h>
sem_t sem;

/* Create the semaphore and initialize it to 1 */
sem_init(&sem, 0, 1);
```

- Acquiring and releasing the semaphore:

```
/* acquire the semaphore */
sem_wait(&sem);

/* critical section */

/* release the semaphore */
sem_post(&sem);
```

POSIX Condition Variables

- Since POSIX is typically used in C/C++ and these languages do not provide a monitor, POSIX condition variables are associated with a POSIX mutex lock to provide mutual exclusion: Creating and initializing the condition variable:

```
pthread_mutex_t mutex;
pthread_cond_t cond_var;

pthread_mutex_init(&mutex,NULL);
pthread_cond_init(&cond_var,NULL);
```

POSIX Condition Variables

- Thread waiting for the condition **`a == b`** to become true:

```
pthread_mutex_lock(&mutex);
while (a != b)
      pthread_cond_wait(&cond_var, &mutex);

pthread_mutex_unlock(&mutex);
```

- Thread signaling another thread waiting on the condition variable:

```
pthread_mutex_lock(&mutex);
a = b;
pthread_cond_signal(&cond_var);
pthread_mutex_unlock(&mutex);
```

Java Synchronization

- Java provides rich set of synchronization features:
  - Java monitors
  - Reentrant locks
  - Semaphores
  - Condition variables

Java Monitors

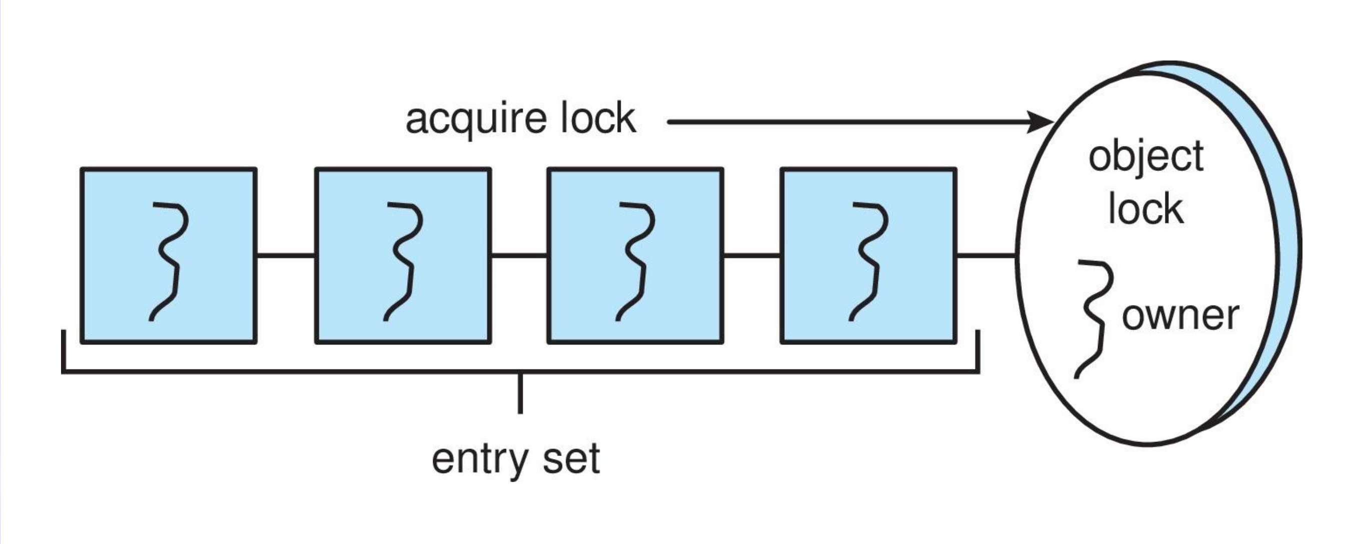
- Every Java object has associated with it a single lock.
- If a method is declared as **`synchronized`**, a calling thread must own the lock for the object.
- If the lock is owned by another thread, the calling thread must wait for the lock until it is released.
- Locks are released when the owning thread exits the **`synchronized`** method.

Bounded Buffer – Java Synchronization

```
public class BoundedBuffer<E>
{
   private static final int BUFFER_SIZE = 5;

   private int count, in, out;
   private E[] buffer;

   public BoundedBuffer() {
      count = 0;
      in = 0;
      out = 0;
      buffer = (E[]) new Object[BUFFER_SIZE];
   }

   /* Producers call this method */
   public synchronized void insert(E item) {
      /* See    Slide 37    */
   }

   /* Consumers call this method */
   public synchronized E remove() {
      /* See    Slide 37    */
   }
}
```

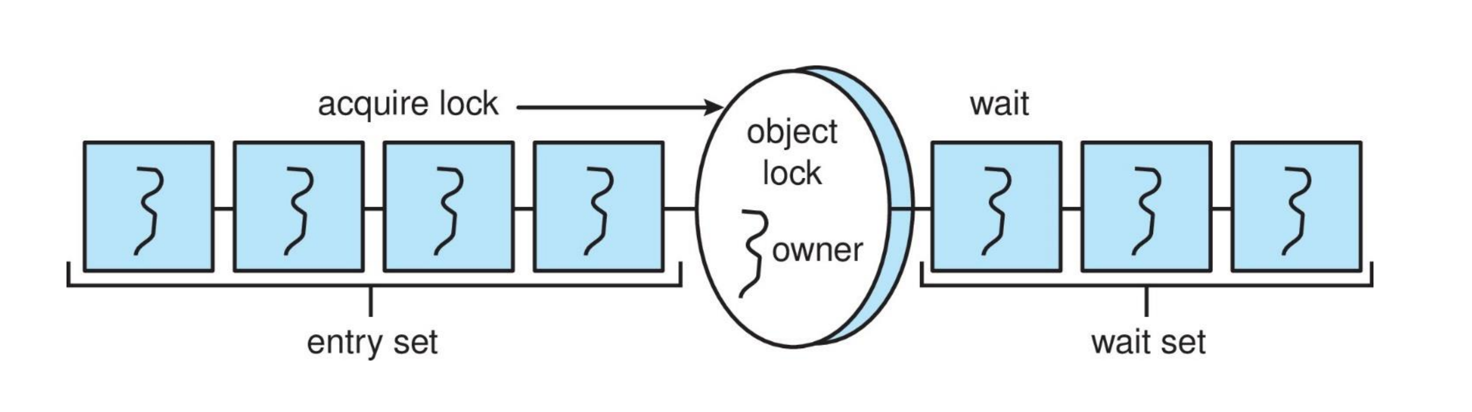
Java Synchronization

- A thread that tries to acquire an unavailable lock is placed in the object's **entry set**:



Java Synchronization

- Similarly, each object also has a **wait set**.
- When a thread calls **`wait()`**:
  1. It releases the lock for the object
  2. The state of the thread is set to blocked
  3. The thread is placed in the wait set for the object



Java Synchronization

- A thread typically calls wait() when it is waiting for a condition to become true.
- How does a thread get notified?
- When a thread calls **`notify()`**:
  1. An arbitrary thread T is selected from the wait set
  2. T is moved from the wait set to the entry set
  3. Set the state of T from blocked to runnable.
- T can now compete for the lock to check if the condition it was waiting for is now true.

Bounded Buffer – Java Synchronization

```
/* Producers call this method */
public synchronized void insert(E item) {
   while (count == BUFFER_SIZE) {
      try {
         wait();
      }
      catch (InterruptedException ie) { }
   }

   buffer[in] = item;
   in = (in + 1) % BUFFER_SIZE;
   count++;

   notify();
}
```

```
/* Consumers call this method */
public synchronized E remove() {
   E item;

   while (count == 0) {
      try {
         wait();
      }
      catch (InterruptedException ie) { }
   }

   item = buffer[out];
   out = (out + 1) % BUFFER_SIZE;
   count--;

   notify();

   return item;
}
```

Java Reentrant Locks

- Similar to mutex locks
- The **`finally`** clause ensures the lock will be released in case an exception occurs in the **`try`** block.

```
Lock key = new ReentrantLock();

key.lock();
try {
   /* critical section */
}
finally {
   key.unlock();
}
```

Java Semaphores

- Constructor:

```
Semaphore(int value);
```

- Usage:

```
Semaphore sem = new Semaphore(1);

try {
   sem.acquire();
   /* critical section */
}
catch (InterruptedException ie) { }
finally {
   sem.release();
}
```

Java Condition Variables

- Condition variables are associated with an **ReentrantLock**.
- Creating a condition variable using **newCondition()** method of **ReentrantLock**:

```
Lock key = new ReentrantLock();
Condition condVar = key.newCondition();
```

- A thread waits by calling the **await()** method, and signals by calling the **signal()** method.

Java Condition Variables

- Example:
- Five threads numbered 0 .. 4
- Shared variable **`turn`** indicating which thread's turn it is.
- Thread calls **`doWork()`** when it wishes to do some work. (But it may only do work if it is their turn.
- If not their turn, wait
- If their turn, do some work for awhile ……
- When completed, notify the thread whose turn is next.
- Necessary data structures:

```
Lock lock = new ReentrantLock();
Condition[] condVars = new Condition[5];

for (int i = 0; i < 5; i++)
   condVars[i] = lock.newCondition();
```

Java Condition Variables

```
/* threadNumber is the thread that wishes to do some work */
public void doWork(int threadNumber)
{
   lock.lock();

   try {
      /**
       * If it's not my turn, then wait
       * until I'm signaled.
       */
      if (threadNumber != turn)
         condVars[threadNumber].await();

      /**
       * Do some work for awhile ...
       */

      /**
       * Now signal to the next thread.
       */
      turn = (turn + 1) % 5;
      condVars[turn].signal();
   }
   catch (InterruptedException ie) { }
   finally {
      lock.unlock();
   }
}
```

Alternative Approaches

- Transactional Memory
- OpenMP
- Functional Programming Languages

Transactional Memory

- Consider a function update() that must be called atomically. One option is to use mutex locks:

```
void update ()
{
   acquire();

   /* modify shared data */

   release();
}
```

- A **memory transaction** is a sequence of read-write operations to memory that are performed atomically. A transaction can be completed by adding **`atomic{S}`** which ensure statements in **`S`** are executed atomically:

```
void update ()
{
   atomic {
      /* modify shared data */
   }
}
```

OpenMP

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

```
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 7