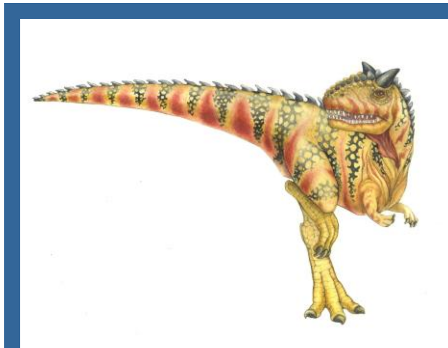
Chapter 7: Synchronization Examples



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

Classical Problems of Synchronization

- Classical problems used to test newly-proposed synchronization schemes
  - Bounded-Buffer Problem
  - Readers and Writers Problem
  - Dining-Philosophers Problem

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

Readers-Writers Problem (Cont.)

- 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) {
   down(rw_mutex);
          ...
       /* writing is performed */
          ...
    up(rw_mutex);
}
```

Readers-Writers Problem (Cont.)

- The structure of a reader process

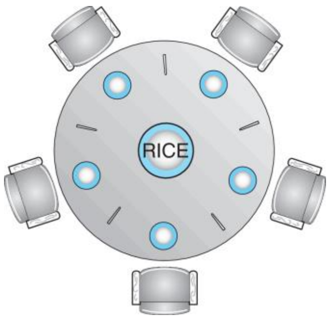
```
while (true){
        down(mutex);
        read_count++;
        if (read_count == 1) /* first reader */
              down(rw_mutex);
        up(mutex);
        ...
        /* reading is performed */
        ...
        down(mutex);
        read_count--;
        if (read_count == 0) /* last reader */
                 up(rw_mutex);
        up(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){
    down (chopstick[i] );
    down (chopStick[ (i + 1) % 5] );

     /* eat for awhile */

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

     /* think for awhile */

}
```

- What is the problem with this algorithm?

Solutie corecta cu semafoare

```
#define THINKING        0
#define HUNGRY          1
#define EATING          2
int state[N];
semaphore_t   mutex = {1};
semaphore_t   ph[N];   // toate initializate cu 0
void philosopher(int i) {
        while(true) {
                think();
                take_forks(i);
                eat();
                put_forks(i);
        }
}
```

Solutie corecta cu semafoare

```
void take_forks(int i) {
        down(mutex);
        state[i] = HUNGRY;
        test(i);
        up(mutex);
        down(ph[i]);
}
void put_forks(int i) {
        down(mutex);
        state[i] = THINKING;
        test((i – 1) % N));
        test((i + 1) % N));
        up(mutex);
}
```

```
void test(int i) {
        if(state[i] == HUNGRY &&
          state[(i-1)%N] != EATING) &&
          state[(i+1)%N] != EATING)
        {
                state[i] = EATING;
                up(ph[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);
```

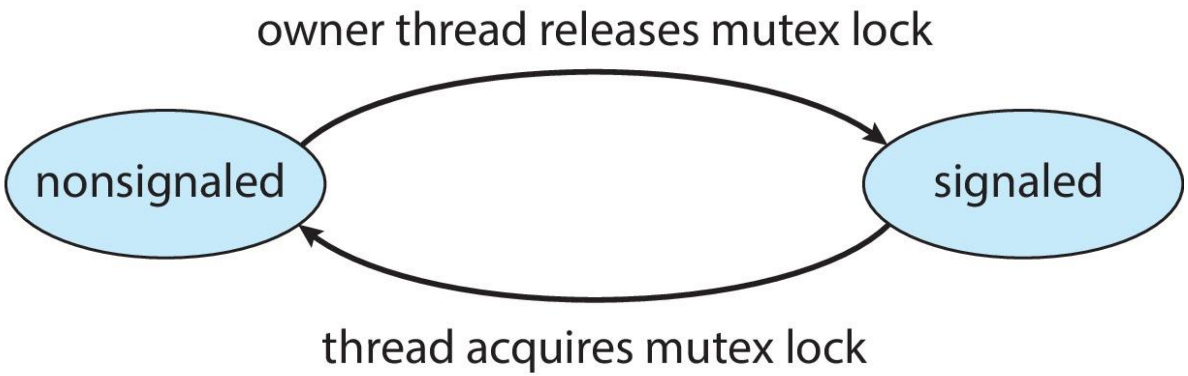
- No deadlock, but starvation is possible

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`

Sincronizare in Solaris

- lock-uri adaptive (adaptive locks), variabile de conditie, semafoare, reader-writer locks, turnstiles
- lock-uri adaptive
  - folosite pt sectiuni critice scurte (cateva sute de instructiuni)
  - comportament polimorf spinlock-semafor
  - daca un thread vrea acces la date protejate de un lock detinut de un alt thread care ruleaza pe alt CPU, lock-ul se comporta ca un spinlock
  - daca lock-ul e detinut de un thread care nu ruleaza momentan pe nici un procesor, threadul care incearca sa obtina lock-ul va fi pus in stare dormanta (sleep), i.e., lock-ul se comporta ca un semafor
  - pe un sistem uniprocesor, cand un thread incearca sa obtina un lock detinut de alt thread, comportamentul lock-ului e intotdeauna de tip semafor

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 an 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 an 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);
```

Producator-consumator POSIX

```c
#include <stdio.h>
#include <pthread.h>

#define ITEMS           8
#define BUFFER_SIZE     4
int buffer[BUFFER_SIZE];

void *producer(void*);
void *consumer(void*);

int spaces, items, tail;
pthread_cond_t space, item;
pthread_mutex_t buffer_mutex;

int main()
{
        pthread_t producer_thread, consumer_thread;
        void *thread_return;
        int result;

        spaces = BUFFER_SIZE;
        items = 0;
        tail = 0;

        pthread_mutex_init(&buffer_mutex, NULL);
        pthread_cond_init(&space, NULL);
        pthread_cond_init(&item, NULL);

        if(pthread_create(&producer_thread, NULL, producer, NULL) ||
           pthread_create(&consumer_thread, NULL, consumer, NULL))
                exit(1);

        if(pthread_join(producer_thread, &thread_return))
                exit(1);
        else
                printf("producer returns with %d\n", (int)thread_return);

        if(pthread_join(consumer_thread, &thread_return))
                exit(1);
        else
                printf("consumer returns with %d\n", (int)thread_return);
        exit(0);
}
```

Producator-consumator POSIX

```
void *producer(void *arg)
{
        int i;

        for(i = 0; i < ITEMS; i++)
        {
                pthread_mutex_lock(&buffer_mutex);
                while(spaces == 0)
                        pthread_cond_wait(&space, &buffer_mutex);
                buffer[(tail + items) % BUFFER_SIZE] = i;
                items += 1;
                spaces -= 1;
                printf("producer puts %d\n", i);
                pthread_mutex_unlock(&buffer_mutex);
                pthread_cond_signal(&item);
        }
        pthread_exit(0);
        return (void*)0;
}

void *consumer(void *arg)
{
        int i, b;

        for(i = 0; i < ITEMS; i++)
        {
                pthread_mutex_lock(&buffer_mutex);
                while(items == 0)
                        pthread_cond_wait(&item, &buffer_mutex);
                b = buffer[tail % BUFFER_SIZE];
                tail += 1;
                items -= 1;
                spaces += 1;
                printf("consumer gets %d\n", b);
                pthread_mutex_unlock(&buffer_mutex);
                pthread_cond_signal(&space);
        }
        pthread_exit(0);
        return (void*)0;
}
```

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 */
   }
}
```

Memorie tranzactionala

- software transactional memory, Herlihy & Moss 1993
- am vazut deja ex. LL/SC
- exploateaza ideea de tranzactii din baze de date (v. proprietati ACID) si controlul optimist al concurentei
- un thread termina modificarile operate pe o zona de memorie partajata fara a se coordona cu alte threaduri
- se inregistreaza fiecare operatie de citire/scriere intr-un log
- la finalul tranzactiei se incearca operatia de *commit*
  - daca reuseste (i.e., nici o alta tranzactie nu a apucat sa faca un commit reusit intre timp), tranzactia e validata si modificarile devin permanente
  - daca esueaza, tranzactia e abandonata (aborted) si se re-executa de la inceput pana reuseste (*transaction roll-back*)
- beneficiu major: grad crescut de concurenta, thread-urile nu au nevoie sa se sincronizeze prin lock-uri la accesul memoriei partajate

Suport HW pt. memorie tranzactionala

- ex. Intel TSX (Transactional Synchronization Extension), extensie ISA x86, microarhitectura Haswell (2013)
- accesibila prin intermediul a doua interfete
  - HLE (Hardware Lock Elision) – backward compatibility
  - RTM (Restricted Transactional Memory)
- HLE adauga doua prefixuri de instr. XACQUIRE & XRELEASE
  - se pot folosi doar pt anumite instructiuni care trebuie prefixate explicit cu LOCK
  - permite executia optimista a sectiunii critice sarind scrierea lock-ului, a.i. acesta apare liber pt alte threaduri
  - o tranzactie esuata determina reluarea operatiei de la instructiunea prefixata cu XACQUIRE

Suport HW pt. memorie tranzactionala

- RTM adauga la ISA trei noi instructiuni
  - XBEGIN – marcheaza inceputul zonei de memorie tranzactionala
  - XEND - marcheaza sfarsitul zonei de memorie tranzactionala
  - XABORT – abandoneaza explicit o tranzactie
  - esecul tranzactiei redirecteaza executia catre codul specificat de instr. XBEGIN, iar codul de eroare e stocat in registrul EAX
- instructiunea XTEST permite testarea starii procesorului (este sau nu in mijlocul executiei unei regiuni de memorie tranzactionala)

RTM elision pt. pthread_mutex_lock

```
void elided_lock_wrapper(lock) {
        if(_xbegin() == _XBEGIN_STARTED) { // start tranzactie
                if(lock  e liber)
                        return;    // executa SC in tranzactie
                _xabort(0xff);     // abandoneaza tranzactia
        }
        obtine lock
}
void elided_unlock_wrapper(lock) {
        if (lock e liber)
                _xend();           // comite tranzactia
        else
                elibereaza lock;
}
```

Java Synchronization

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

Java Monitors

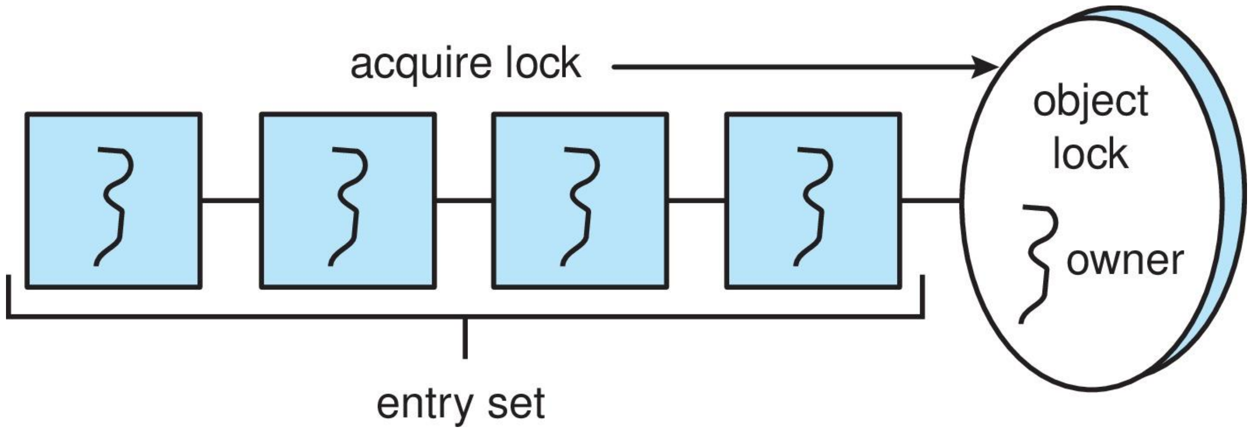
- Every Java object has associated with it a single lock.
- If a method is declared as **`synchronized`**, a calling thread must own the lock for the object.
- If the lock is owned by another thread, the calling thread must wait for the lock until it is released.
- Locks are released when the owning 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 Figure 7.11 */
   }

   /* Consumers call this method */
   public synchronized E remove() {
      /* See Figure 7.11 */
   }
}
```

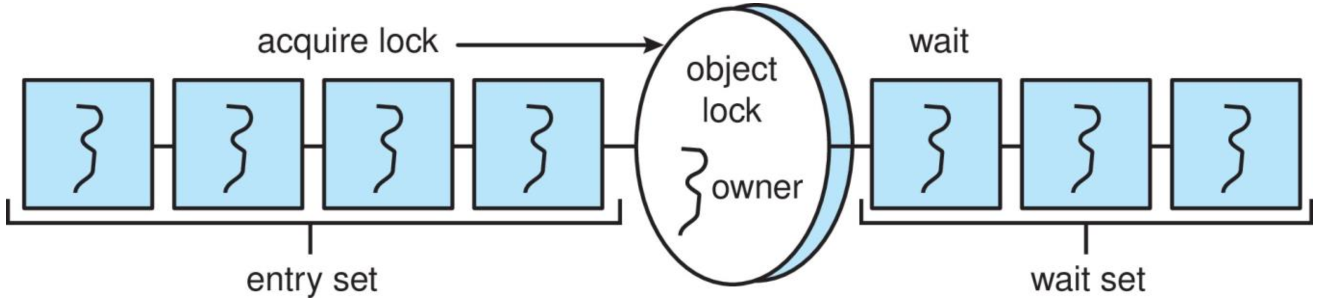
Java Synchronization

- 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();
}
```

Bounded Buffer – Java Synchronization

```
/* 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

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 7