

# Chapter 7: Synchronization Examples



# Chapter 7: Synchronization Examples

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- ❑ Explain the *bounded-buffer*, *readers-writers*, 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

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



# Bounded-Buffer Problem

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- ❑  $n$  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.)

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- The structure of the producer process

```
while (true) {  
    ...  
    /* produce an item in next_produced */  
    ...  
    wait(empty);  
    wait(mutex);  
    ...  
    /* add next produced to the buffer */  
    ...  
    signal(mutex);  
    signal(full);  
}
```



# Bounded Buffer Problem (Cont.)

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- The structure of the consumer process

```
while (true) {  
    wait(full);  
    wait(mutex);  
  
    ...  
    /* remove an item from buffer to next_consumed */  
    ...  
    signal(mutex);  
    signal(empty);  
  
    ...  
    /* consume the item in next consumed */  
    ...  
}
```



# Readers-Writers Problem

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- ❑ 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.)

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- ❑ 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)  
        wait(rw_mutex);  
    signal(mutex);  
    ... /* reading is performed */  
    ...  
    wait(mutex);  
    read_count--;  
    if (read_count == 0)  
        signal(rw_mutex);  
    signal(mutex);  
}
```



# Readers-Writers Problem Variations

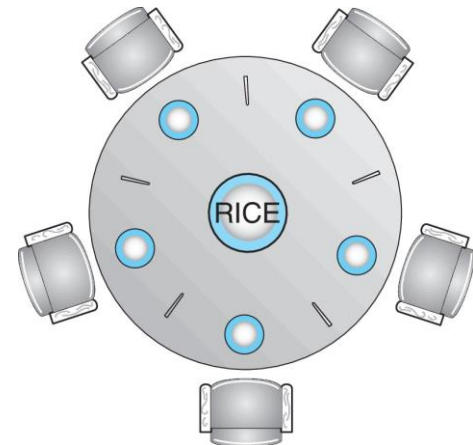
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- ❑ **First** variation – no reader kept waiting unless writer has permission to use shared object
- ❑ **Second** variation – once writer is ready, it performs the write ASAP
- ❑ Both may have starvation leading to even more variations
- ❑ Problem 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

- ❑ Semaphore Solution
- ❑ The structure of Philosopher *i*:

```
while (true){  
    wait (chopstick[i] );  
    wait (chopStick[ (i + 1) % 5] );  
  
    /* eat for awhile */  
  
    signal (chopstick[i] );  
    signal (chopstick[ (i + 1) % 5] );  
  
    /* think for awhile */  
}
```

- ❑ What is the problem with this algorithm?



# Monitor Solution to Dining Philosophers

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```
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.)

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- ❑ 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

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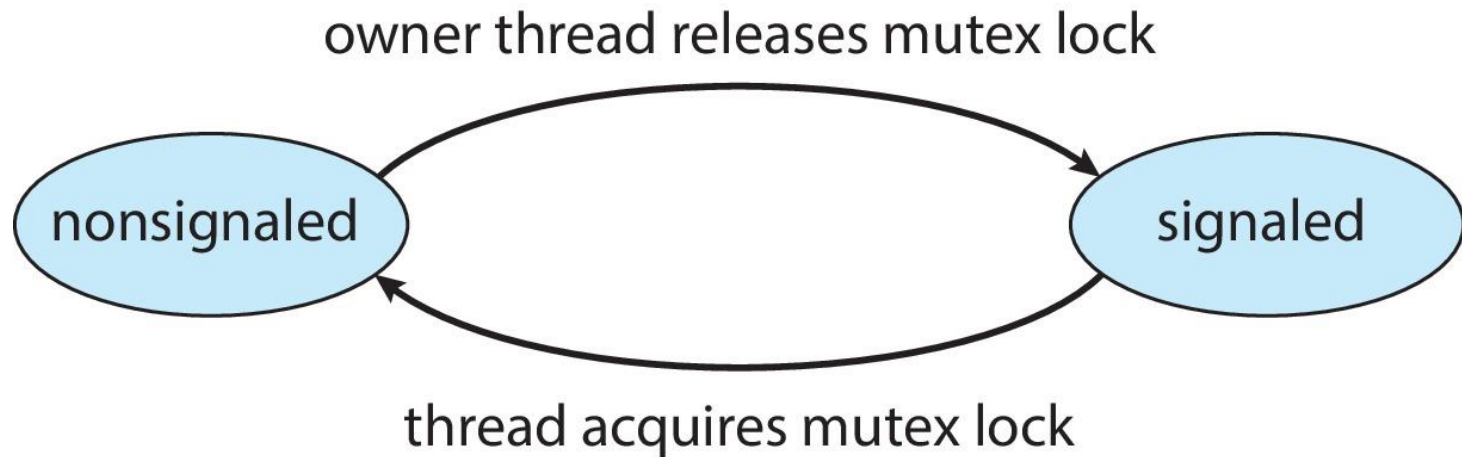
- ❑ Uses interrupt masks to protect access to global resources on uniprocessor systems
- ❑ Uses *spinlocks* on multiprocessor systems
  - Spinlocking-thread will never be preempted
- ❑ Also provides *dispatcher objects* user-land which may act mutexes, semaphores, events, and timers
  - *Events*
    - ▶ 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

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## ❑ 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;
```

<i>Atomic Operation</i>	<i>Effect</i>
<code>atomic_set(&amp;counter,5);</code>	<code>counter = 5</code>
<code>atomic_add(10,&amp;counter);</code>	<code>counter = counter + 10</code>
<code>atomic_sub(4,&amp;counter);</code>	<code>counter = counter - 4</code>
<code>atomic_inc(&amp;counter);</code>	<code>counter = counter + 1</code>
<code>value = atomic_read(&amp;counter);</code>	<code>value = 12</code>



# POSIX Synchronization

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



# POSIX Mutex Locks

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## ❑ 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

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- ❑ 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

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- ❑ 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

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- ❑ 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

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



# Java Monitors

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- ❑ 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];
    }

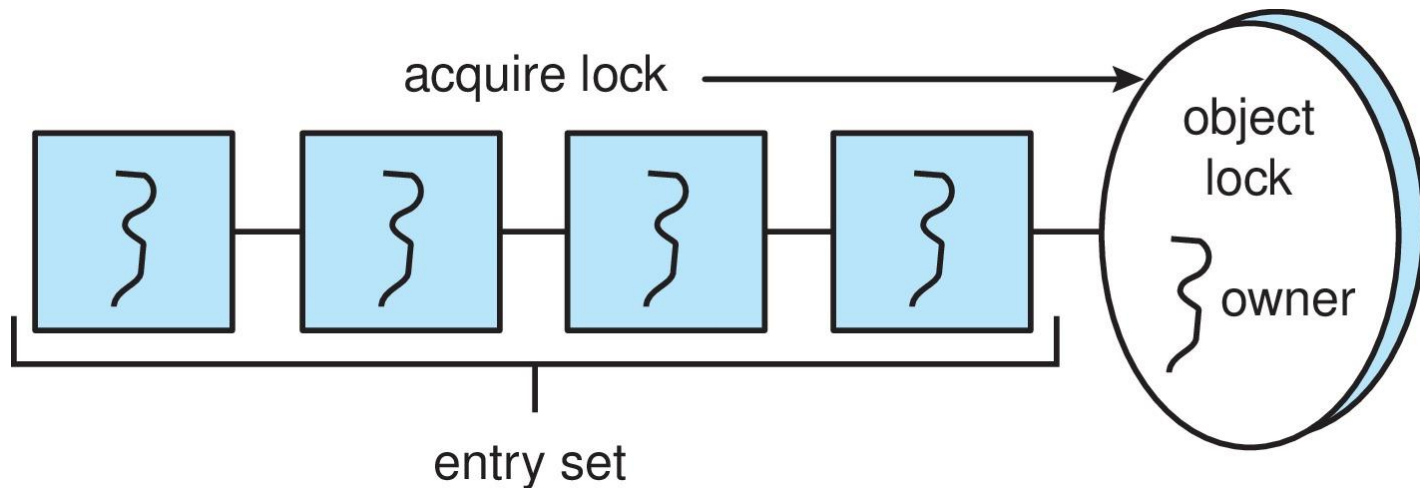
    /* Producers call this method */
    public synchronized void insert(E item) {
        /* See Figure 7.11 */
    }

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



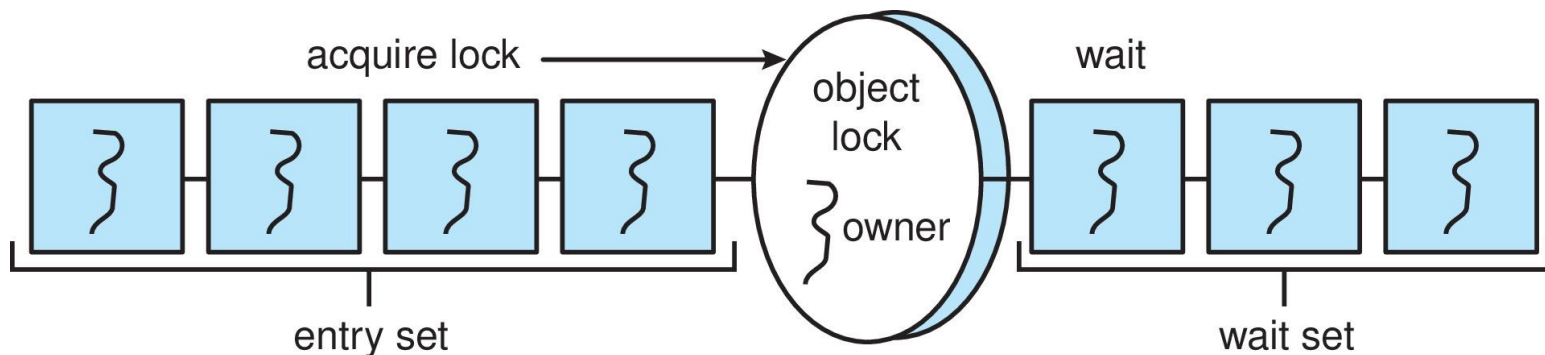
# Java Synchronization

- ❑ 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

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- ❑ 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

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- ❑ 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

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- ❑ 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

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## ❑ 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

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- ❑ Transactional Memory
- ❑ OpenMP
- ❑ Functional Programming Languages





# Transactional Memory

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

    /* modify shared data */

    release();
}
```

```
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

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- ❑ 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.



# Summary

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- ❑ Classic problems of process synchronization include the bounded-buffer, readers–writers, and dining-philosophers problems. Solutions to these problems can be developed using the tools presented in Chapter 6, including mutex locks, semaphores, monitors, and condition variables.
- ❑ Windows uses dispatcher objects as well as events to implement process synchronization tools.
- ❑ Linux uses a variety of approaches to protect against race conditions, including atomic variables, spinlocks, and mutex locks.
- ❑ The POSIX API provides mutex locks, semaphores, and condition variables. POSIX provides two forms of semaphores: named and unnamed. Several unrelated processes can easily access the same named semaphore by simply referring to its name. Unnamed semaphores cannot be shared as easily, and require placing the semaphore in a region of shared memory.



## Summary (Cont.)

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- ❑ Java has a rich library and API for synchronization. Available tools include monitors (which are provided at the language level) as well as reentrant locks, semaphores, and condition variables (which are supported by the API).
- ❑ Alternative approaches to solving the critical-section problem include transactional memory, OpenMP, and functional languages. Functional languages are particularly intriguing, as they offer a different programming paradigm from procedural languages. Unlike procedural languages, functional languages do not maintain state and therefore are generally immune from race conditions and critical sections.



# End of Chapter 7

