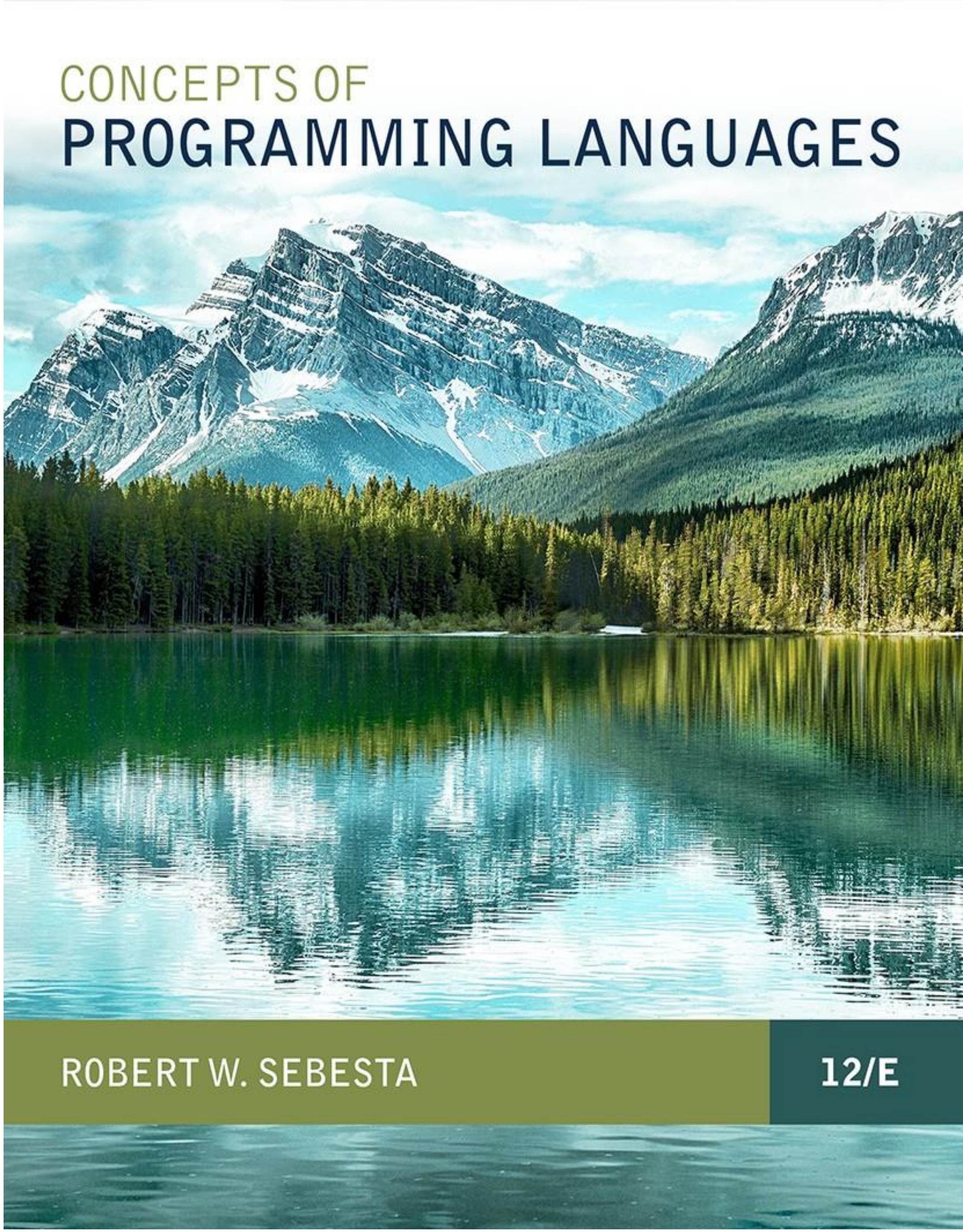
# Chapter 13

## Concurrency

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# Chapter 13 Topics

- Introduction
- Introduction to Subprogram-Level Concurrency
- Semaphores
- Monitors
- Message Passing
- Ada support for Concurrency
- Java Threads
- C# Threads
- Concurrency in Functional Languages
- Statement-Level Concurrency

# Introduction

- Concurrency can occur at four levels:
  - Machine instruction level
  - High-level language statement level
  - Unit level
  - Program level
- Because there are no language issues in instruction- and program-level concurrency, they are not addressed here

# Multiprocessor Architectures

- Late 1950s - one general-purpose processor and one or more special-purpose processors for input and output operations
- Early 1960s - multiple complete processors, used for program-level concurrency
- Mid-1960s - multiple partial processors, used for instruction-level concurrency
- Single-Instruction Multiple-Data (SIMD) machines
- Multiple-Instruction Multiple-Data (MIMD) machines
- A primary focus of this chapter is shared memory MIMD machines (multiprocessors)

# Categories of Concurrency

- Categories of Concurrency:
  - *Physical concurrency* – Multiple independent processors ( multiple threads of control)
  - *Logical concurrency* – The appearance of physical concurrency is presented by time-sharing one processor (software can be designed as if there were multiple threads of control)
- Coroutines (*quasi-concurrency) have a single thread of control*
- A *thread of control* in a program is the sequence of program points reached as control flows through the program

# Motivations for the Use of Concurrency

- Multiprocessor computers capable of physical concurrency are now widely used
- Even if a machine has just one processor, a program written to use concurrent execution can be faster than the same program written for nonconcurrent execution
- Involves a different way of designing software that can be very useful—many real-world situations involve concurrency
- Many program applications are now spread over multiple machines, either locally or over a network

# Introduction to Subprogram-Level Concurrency

- A *task* or *process* or *thread* is a program unit that can be in concurrent execution with other program units
- Tasks differ from ordinary subprograms in that:
  - A task may be implicitly started
  - When a program unit starts the execution of a task, it is not necessarily suspended
  - When a task's execution is completed, control may not return to the caller
- Tasks usually work together

# Two General Categories of Tasks

- *Heavyweight tasks* execute in their own address space
- *Lightweight tasks* all run in the same address space – more efficient
- A task is *disjoint* if it does not communicate with or affect the execution of any other task in the program in any way

# Task Synchronization

- A mechanism that controls the order in which tasks execute
- Two kinds of synchronization
  - *Cooperation* synchronization
  - *Competition* synchronization
- Task communication is necessary for synchronization, provided by:
  - Shared nonlocal variables
  - Parameters
  - Message passing

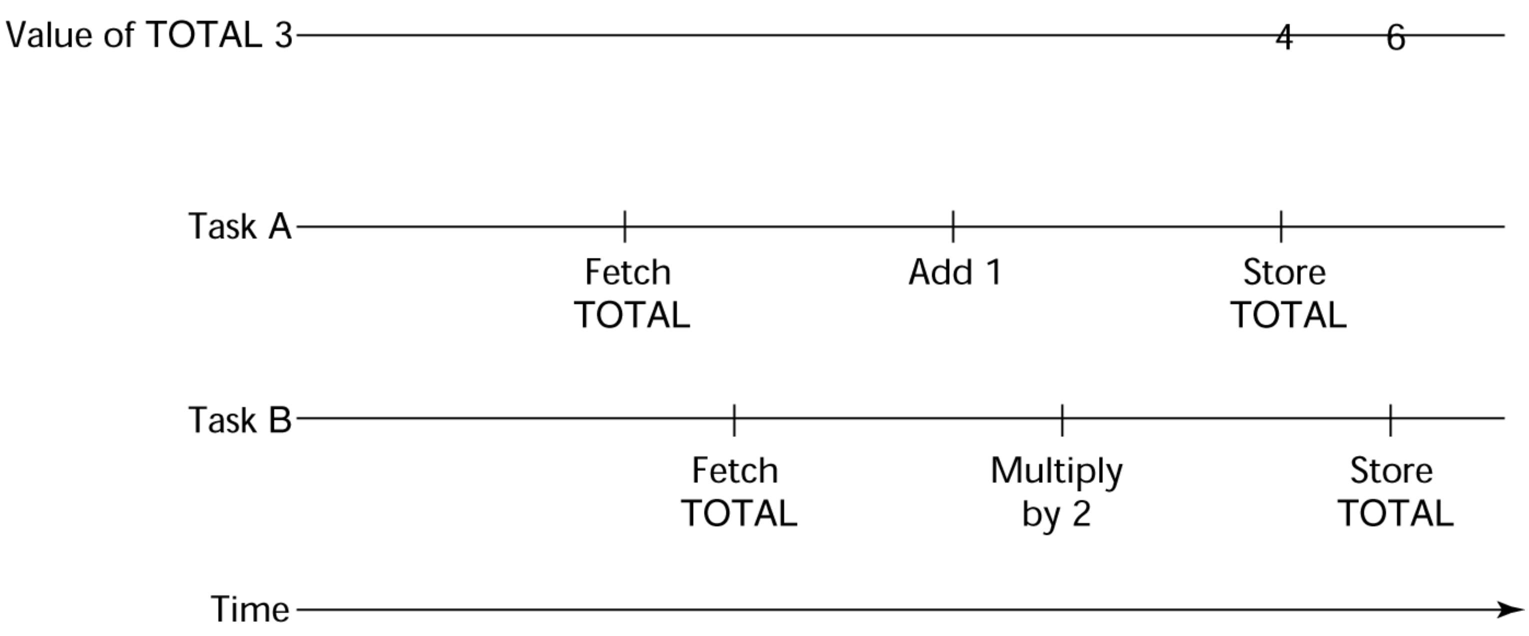
# Kinds of synchronization

- *Cooperation*: Task A must wait for task B to complete some specific activity before task A can continue its execution, e.g., the producer-consumer problem
- *Competition*: Two or more tasks must use some resource that cannot be simultaneously used, e.g., a shared counter
  - Competition is usually provided by mutually exclusive access (approaches are discussed later)

# Need for Competition Synchronization

Task A: `TOTAL = TOTAL + 1`

Task B: `TOTAL = 2 * TOTAL`




- Depending on order, there could be four different results

# Scheduler

- Providing synchronization requires a mechanism for delaying task execution
- Task execution control is maintained by a program called the *scheduler*, which maps task execution onto available processors

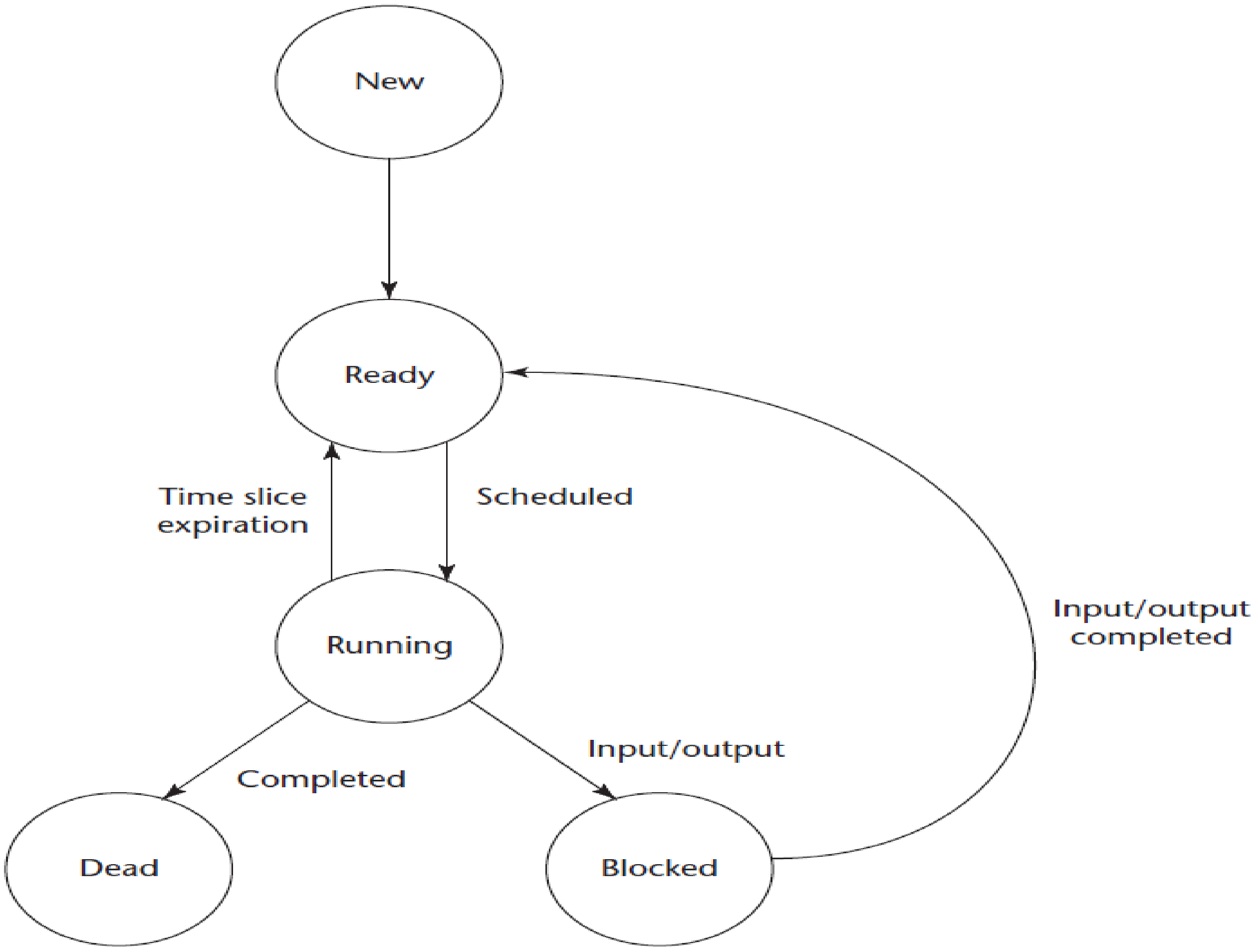
# Task Execution States

- *New* – created but not yet started
- *Ready* – ready to run but not currently running (no available processor)
- *Running*
- *Blocked* – has been running, but cannot now continue (usually waiting for some event to occur)
- *Dead* – no longer active in any sense

# Task Execution States (continued)

**Figure 13.2**

Flow diagram of task states



# Liveness and Deadlock

- *Liveness* is a characteristic that a program unit may or may not have
  - In sequential code, it means the unit will eventually complete its execution
- In a concurrent environment, a task can easily lose its liveness
- If all tasks in a concurrent environment lose their liveness, it is called *deadlock*

# Design Issues for Concurrency

- Competition and cooperation synchronization*
- Controlling task scheduling
- How can an application influence task scheduling
- How and when tasks start and end execution
- How and when are tasks created

  * The most important issue

# Methods of Providing Synchronization

- Semaphores
- Monitors
- Message Passing

# Semaphores

- Dijkstra - 1965
- A *semaphore* is a data structure consisting of a counter and a queue for storing task descriptors
  - A task descriptor is a data structure that stores all of the relevant information about the execution state of the task
- Semaphores can be used to implement guards on the code that accesses shared data structures
- Semaphores have only two operations, *wait* and *release* (originally called *P* and *V* by Dijkstra)
- Semaphores can be used to provide both competition and cooperation synchronization

# Cooperation Synchronization with Semaphores

- Example: A shared buffer
- The buffer is implemented as an ADT with the operations `DEPOSIT` and `FETCH` as the only ways to access the buffer
- Use two semaphores for cooperation: `emptyspots` and `fullspots`
- The semaphore counters are used to store the numbers of empty spots and full spots in the buffer

# Cooperation Synchronization with Semaphores (continued)

- `DEPOSIT` must first check `emptyspots` to see if there is room in the buffer
- If there is room, the counter of `emptyspots` is decremented and the value is inserted
- If there is no room, the caller is stored in the queue of `emptyspots`
- When `DEPOSIT` is finished, it must increment the counter of `fullspots`

# Cooperation Synchronization with Semaphores (continued)

- `FETCH` must first check `fullspots` to see if there is a value
  - If there is a full spot, the counter of `fullspots` is decremented and the value is removed
  - If there are no values in the buffer, the caller must be placed in the queue of `fullspots`
  - When `FETCH` is finished, it increments the counter of `emptyspots`
- The operations of `FETCH` and `DEPOSIT` on the semaphores are accomplished through two semaphore operations named *wait* and *release*

# Semaphores: Wait and Release Operations

```
wait(aSemaphore)
if aSemaphore’s counter > 0 then
   decrement aSemaphore’s counter
else
   put the caller in aSemaphore’s queue
   attempt to transfer control to a ready task
     -- if the task ready queue is empty,
     -- deadlock occurs
end

release(aSemaphore)
if aSemaphore’s queue is empty then
   increment aSemaphore’s counter
else
   put the calling task in the task ready queue
   transfer control to a task from aSemaphore’s queue
end
```

# Producer and Consumer Tasks

```
semaphore fullspots, emptyspots;
fullstops.count = 0;
emptyspots.count = BUFLEN;
task producer;
     loop
     -- produce VALUE --
     wait (emptyspots); {wait for space}
     DEPOSIT(VALUE);
     release(fullspots); {increase filled}
     end loop;
end producer;
task consumer;
     loop
     wait (fullspots);{wait till not empty}}
     FETCH(VALUE);
     release(emptyspots); {increase empty}
     -- consume VALUE --
     end loop;
end consumer;
```

# Competition Synchronization with Semaphores

- A third semaphore, named `access`, is used to control access (competition synchronization)
  - The counter of **`access`** will only have the values 0 and 1
  - Such a semaphore is called a *binary semaphore*
- Note that wait and release must be atomic!

# Producer Code for Semaphores

```
semaphore access, fullspots, emptyspots;
access.count = 0;
fullstops.count = 0;
emptyspots.count = BUFLEN;
task producer;
   loop
   -- produce VALUE --
   wait(emptyspots); {wait for space}
   wait(access);     {wait for access)
   DEPOSIT(VALUE);
   release(access); {relinquish access}
   release(fullspots); {increase filled}
   end loop;
end producer;
```

# Consumer Code for Semaphores

```
task consumer;
   loop
   wait(fullspots);{wait till not empty}
   wait(access);    {wait for access}
   FETCH(VALUE);
   release(access); {relinquish access}
   release(emptyspots); {increase empty}
   -- consume VALUE --
   end loop;
end consumer;
```

# Evaluation of Semaphores

- Misuse of semaphores can cause failures in cooperation synchronization, e.g., the buffer will overflow if the wait of `fullspots` is left out
- Misuse of semaphores can cause failures in competition synchronization, e.g., the program will deadlock if the release of `access` is left out

# Monitors

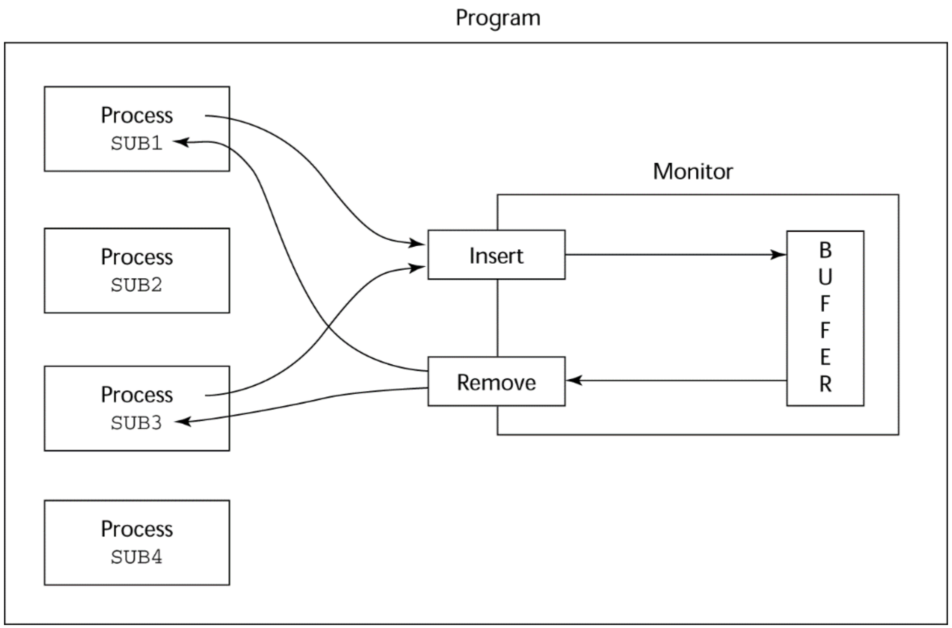
- Ada, Java, C#
- The idea: encapsulate the shared data and its operations to restrict access
- A monitor is an abstract data type for shared data

# Competition Synchronization

- Shared data is resident in the monitor (rather than in the client units)
- All access resident in the monitor
  - Monitor implementation guarantee synchronized access by allowing only one access at a time
  - Calls to monitor procedures are implicitly queued if the monitor is busy at the time of the call

# Cooperation Synchronization

- Cooperation between processes is still a programming task
  - Programmer must guarantee that a shared buffer does not experience underflow or overflow



# Evaluation of Monitors

- A better way to provide competition synchronization than semaphores
- Semaphores can be used to implement monitors
- Monitors can be used to implement semaphores
- Support for cooperation synchronization is very similar as with semaphores, so it has the same problems

# Message Passing

- Message passing is a general model for concurrency
  - It can model both semaphores and monitors
  - It is not just for competition synchronization
- Central idea: task communication is like seeing a doctor--most of the time she waits for you or you wait for her, but when you are both ready, you get together, or *rendezvous*

# Message Passing Rendezvous

- To support concurrent tasks with message passing, a language needs:

  – A mechanism to allow a task to indicate when it is willing to accept messages

  – A way to remember who is waiting to have its message accepted and some “fair” way of choosing the next message

- When a sender task’s message is accepted by a receiver task, the actual message transmission is called a *rendezvous*

# Ada Support for Concurrency

- The Ada 83 Message-Passing Model
  - Ada tasks have specification and body parts, like packages; the spec has the interface, which is the collection of entry points:

```
task Task_Example is
  entry ENTRY_1 (Item : in Integer);
end Task_Example;
```

# Task Body

- The `body` task describes the action that takes place when a rendezvous occurs
- A task that sends a message is suspended while waiting for the message to be accepted and during the rendezvous
- Entry points in the spec are described with **`accept`** clauses in the body

```
accept entry_name (formal parameters) do
   ...
end entry_name;
```

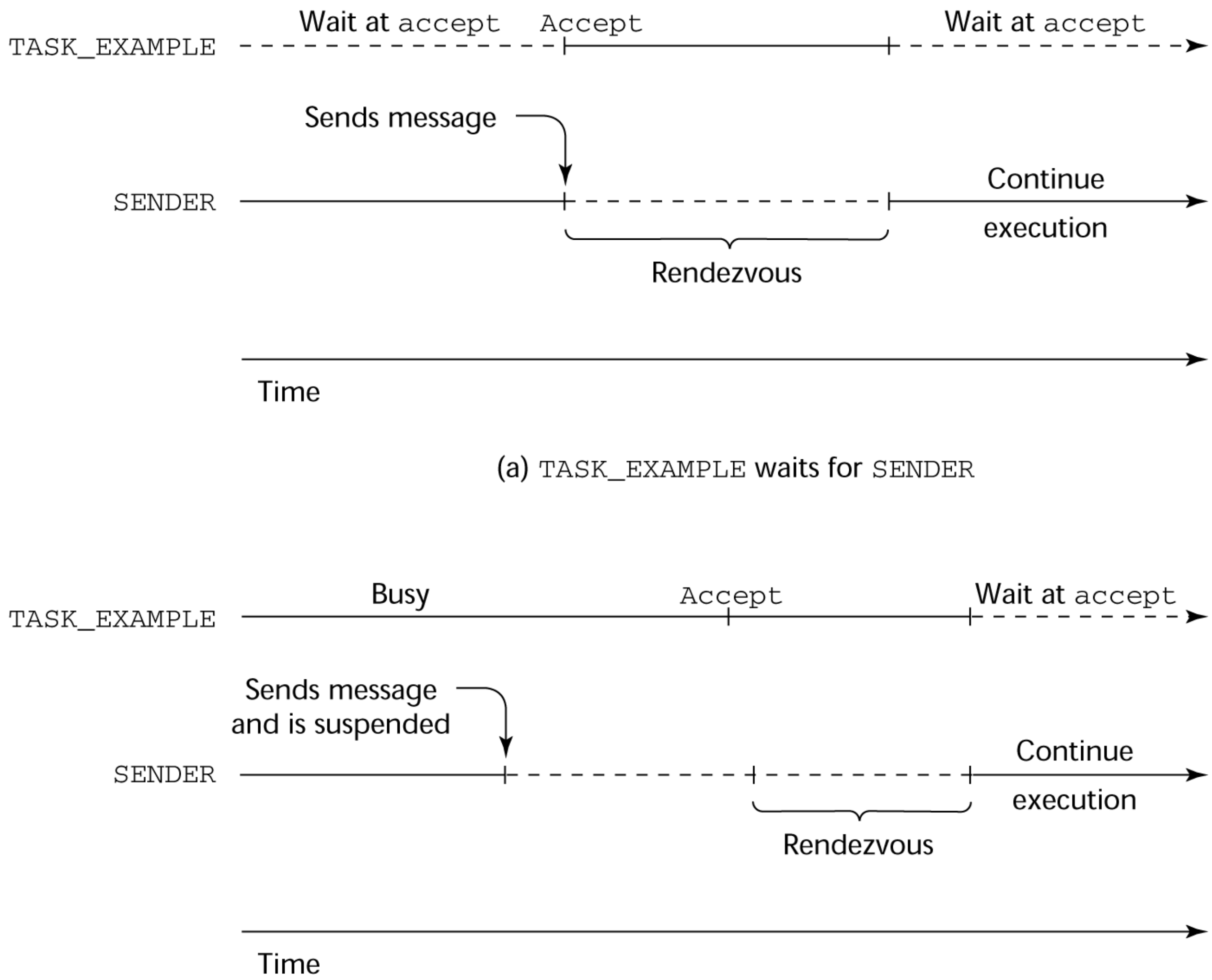
# Example of a Task Body

```
task body Task_Example is
   begin
   loop
     accept Entry_1 (Item: in Float) do
     ...
     end Entry_1;
   end loop;
 end Task_Example;
```

# Ada Message Passing Semantics

- The task executes to the top of the `accept` clause and waits for a message
- During execution of the `accept` clause, the sender is suspended
- `accept` parameters can transmit information in either or both directions
- Every `accept` clause has an associated queue to store waiting messages

# Rendezvous Time Lines



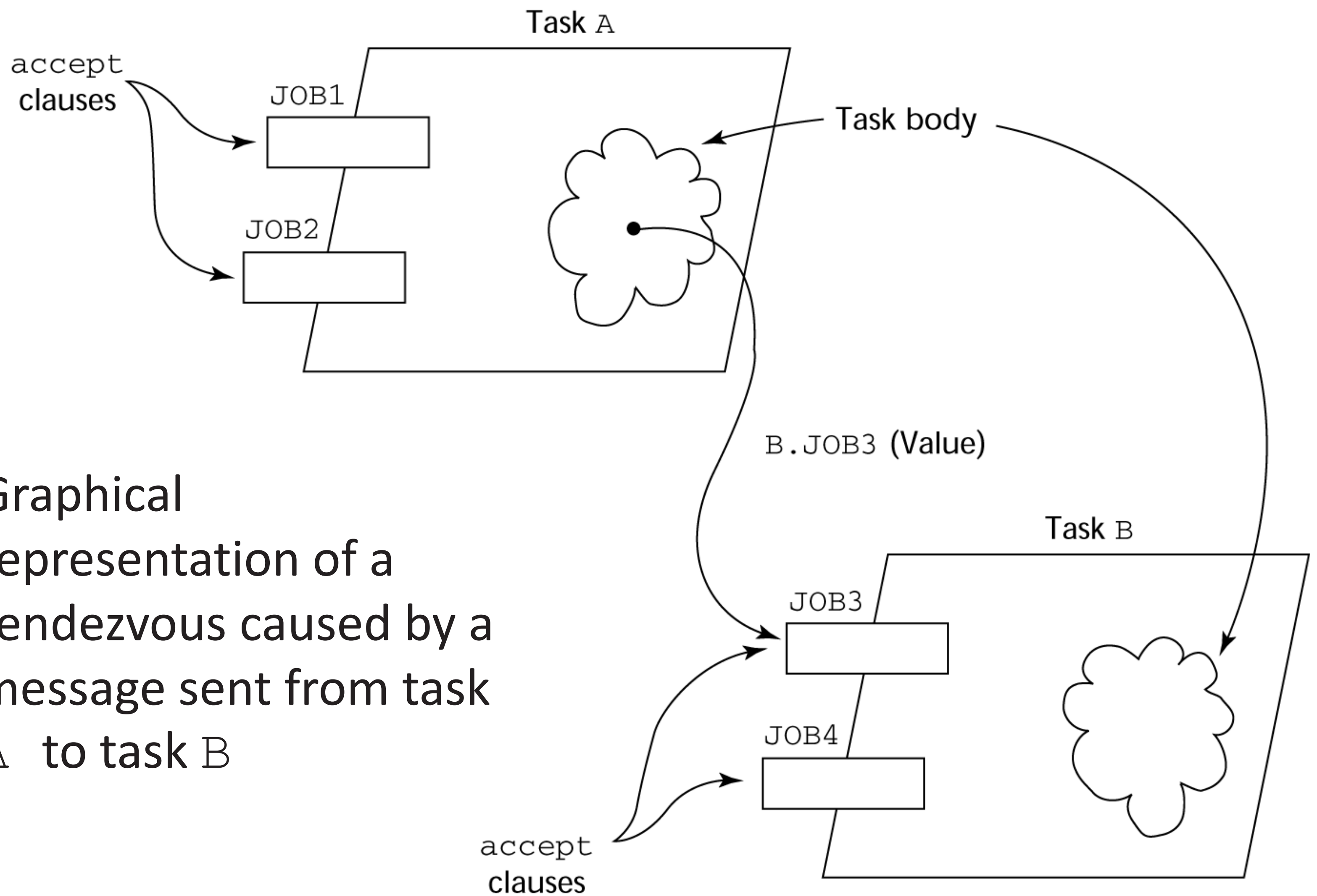

(a) TASK_EXAMPLE waits for SENDER

(b) SENDER waits for TASK_EXAMPLE

# Message Passing: Server/Actor Tasks

- A task that has `accept` clauses, but no other code is called a *server task* (the example above is a server task)
- A task without `accept` clauses is called an *actor task*
  - An actor task can send messages to other tasks
  - Note: A sender must know the `entry` name of the receiver, but not vice versa (asymmetric)

# Graphical Representation of a Rendezvous




Graphical representation of a rendezvous caused by a message sent from task A to task B

# Multiple Entry Points

- Tasks can have more than one **`entry`** point
  - The specification task has an **`entry`** clause for each
  - The task body has an **`accept`** clause for each **`entry`** clause, placed in a **`select`** clause, which is in a loop

# A Task with Multiple Entries

```
task body Teller is
  loop
    select
      accept Drive_Up(formal params) do
      ...
      end Drive_Up;
      ...
    or
      accept Walk_Up(formal params) do
      ...
      end Walk_Up;
      ...
    end select;
  end loop;
end Teller;
```

In this task, there are two **accept** clauses, `Walk_Up` and `Drive_Up`, each of which has an associated queue. The action of the **select**, when it is executed, is to examine the queues associated with the two **accept** clauses.

# Semantics of Tasks with Multiple `accept` Clauses

- If exactly one `entry` queue is nonempty, choose a message from it
- If more than one `entry` queue is nonempty, choose one, nondeterministically, from which to accept a message
- If all are empty, wait
- The construct is often called a selective wait
- Extended `accept` clause – code following the clause, but before the next clause
  - Executed concurrently with the caller

# Cooperation Synchronization with Message Passing

- Provided by Guarded `accept` clauses

```
when not Full(Buffer) =>
  accept Deposit (New_Value) do
    ...
  end
```

- An `accept` clause with a with a `when` clause is either *open* or *closed*
  - A clause whose guard is true is called *open*
  - A clause whose guard is false is called *closed*
  - A clause without a guard is always open

# Semantics of `select` with Guarded `accept` Clauses:

- `select` first checks the guards on all clauses
- If exactly one is open, its queue is checked for messages
- If more than one are open, non-deterministically choose a queue among them to check for messages
- If all are closed, it is a runtime error
- A `select` clause can include an `else` clause to avoid the error
  - When the `else` clause completes, the loop repeats

# Competition Synchronization with Message Passing

- Modeling mutually exclusive access to shared data
- Example--a shared buffer
- Encapsulate the buffer and its operations in a task
- Competition synchronization is implicit in the semantics of `accept` clauses
  - Only one `accept` clause in a task can be active at any given time

# Partial Shared Buffer Code

```
task Buf_Task is
   entry Deposit(Item : in Integer);
   entry Fetch(Item : out Integer);
end Buf_Task;

task body Buf_Task is
  Bufsize : constant Integer := 100;
  Buf    :  array (1..Bufsize) of Integer;
  Filled : Integer range 0..Bufsize := 0;
  Next_In,
  Next_Out : Integer range 1..Bufsize := 1;
begin
  loop
    select
      when Filled < Bufsize =>
         accept Deposit(Item : in Integer) do
           Buf(Next_In) := Item;
         end Deposit;
        Next_In := (Next_In mod Bufsize) + 1;
        Filled := Filled + 1;
    or
      when Filled > 0 =>
        accept Fetch(Item : out Integer) do
          Item := Buf(Next_Out);
        end Fetch;
        Next_Out := (Next_Out mod Bufsize) + 1;
        Filled := Filled - 1;
    end select;
   end loop;
end Buf_Task;
```

An example of an Ada task that implements a monitor for a buffer. The buffer behaves very much like the buffer in Section 13.3, in which synchronization is controlled with semaphores.

# A Producer and Consumer Task

```
task Producer;
task Consumer;
task body Producer is
  New_Value : Integer;
begin
  loop
    -- produce New_Value --
    Buf_Task.Deposit(New_Value);
  end loop;
end Producer;

task body Consumer is
  Stored_Value : Integer;
begin
  loop
    Buf_Task.Fetch(Stored_Value);
    -- consume Stored_Value --
  end loop;
end Consumer;
```

The tasks for a producer and a consumer that could use Buf_Task

# Concurrency in Ada 95

- Ada 95 includes Ada 83 features for concurrency, plus two new features
  - Protected objects: A more efficient way of implementing shared data to allow access to a shared data structure to be done without rendezvous
  - Asynchronous communication
  - A protected object is not a task; it is more like a monitor.

# Ada 95: Protected Objects

- A *protected object* is similar to an abstract data type
- Access to a protected object is either through messages passed to entries, as with a task, or through protected subprograms
- A *protected procedure* provides mutually exclusive read-write access to protected objects
- A *protected function* provides concurrent read-only access to protected objects

# A protected object example

```
protected Buffer is
  entry Deposit(Item : in Integer);
  entry Fetch(Item : out Integer);
  private
    Bufsize : constant Integer := 100;
    Buf    : array  (1..Bufsize) of Integer;
    Filled : Integer range 0..Bufsize := 0;
    Next_In,
    Next_Out : Integer range 1..Bufsize := 1;
    end Buffer;

  protected body Buffer is
    entry Deposit(Item : in Integer)
       when Filled < Bufsize is
      begin
      Buf(Next_In) := Item;
      Next_In := (Next_In mod Bufsize) + 1;
      Filled := Filled + 1;
      end Deposit;
    entry Fetch(Item : out Integer) when Filled > 0 is
      begin Item := Buf(Next_Out);
      Next_Out := (Next_Out mod Bufsize) + 1;
      Filled := Filled - 1;
      end Fetch;
  end Buffer;
```

The buffer problem that is solved with a task in the previous subsection can be more simply solved with a protected object. Note that this example does
not include protected subprograms.

# Evaluation of the Ada

- Message passing model of concurrency is powerful and general
- Protected objects are a better way to provide synchronized shared data
- In the absence of distributed processors, the choice between monitors and tasks with message passing is somewhat a matter of taste
- For distributed systems, message passing is a better model for concurrency

# Java Threads

- The concurrent units in Java are methods named `run`
  - A `run` method code can be in concurrent execution with other such methods
  - The process in which the `run` methods execute is called a *thread*

```
class myThread extends Thread
  public void run () {…}
}
…
Thread myTh = new MyThread ();
myTh.start();
```

# Controlling Thread Execution

- The `Thread` class has several methods to control the execution of threads
  - The `yield` is a request from the running thread to voluntarily surrender the processor
  - The `sleep` method can be used by the caller of the method to block the thread (The sleep method has a single parameter, which is the integer number of milliseconds that the caller of sleep wants the thread to be blocked. After the specified number of milliseconds has passed, the thread will be put in the task-ready queue.)
  - The `join` method is used to force a method to delay its execution until the run method of another thread has completed its execution

```
public void run() {
  . . .
  Thread myTh = new Thread();
  myTh.start();
  // do part of the computation of this thread
  myTh.join();  // Wait for myTh to complete
  // do the rest of the computation of this thread
}
```

# Thread Priorities

- A thread's default priority is the same as the thread that create it
  - If `main` creates a thread, its default priority is `NORM_PRIORITY`
- Threads defined two other priority constants, `MAX_PRIORITY` and `MIN_PRIORITY`
- The priority of a thread can be changed with the methods `setPriority`

# Semaphores in Java

- The java.util.concurrent.Semaphore package defines the Semaphore class. Objects of this class implement counting semaphores.
- The Semaphore class defines two methods, acquire and release, which correspond to the wait and release operations described in Section 13.3.

The basic constructor for `Semaphore` takes one integer parameter, which initializes the semaphore's counter. For example, the following could be used to initialize the `fullspots` and `emptyspots` semaphores for the buffer example of Section 13.3.2:

```
fullspots = new Semaphore(0);
emptyspots = new Semaphore(BUFLEN);
```

The deposit operation of the producer method would appear as follows:

```
emptyspots.acquire();
deposit(value);
fullspots.release();
```

Likewise, the fetch operation of the consumer method would appear as follows:

```
fullspots.acquire();
fetch(value);
emptyspots.release();
```

# Competition Synchronization with Java Threads

- A method that includes the `synchronized` modifier disallows any other method from running on the object while it is in execution

```
…
public synchronized void deposit( int i) {…}
public synchronized int fetch() {…}
…
```

- The above two methods are synchronized which prevents them from interfering with each other
- If only a part of a method must be run without interference, it can be synchronized thru `synchronized` statement

```
synchronized (expression)
    statement
```

# Cooperation Synchronization with Java Threads

- Cooperation synchronization in Java is achieved via `wait`, `notify`, and `notifyAll` methods
  - All methods are defined in `Object`, which is the root class in Java, so all objects inherit them
- The `wait` method must be called in a loop
- The `notify` method is called to tell one waiting thread that the event it was waiting has happened
- The `notifyAll` method awakens all of the threads on the object's wait list

```
// Queue
// This class implements a circular queue for storing int
// values. It includes a constructor for allocating and
// initializing the queue to a specified size. It has
// synchronized methods for inserting values into and
// removing values from the queue.

class Queue {
  private int [] que;
  private int nextIn,
              nextOut,
              filled,
              queSize;
```

```
  public synchronized void deposit (int item)
         throws InterruptedException {
    try {
      while (filled == queSize)
        wait();
      que [nextIn] = item;
      nextIn = (nextIn % queSize) + 1;
      filled++;
      notifyAll();
    }  //** end of try clause
    catch(InterruptedException e) {}
  }  //** end of deposit method

  public synchronized int fetch()
      throws InterruptedException {
    int item = 0;
    try {
      while (filled == 0)
        wait();
      item = que [nextOut];
      nextOut = (nextOut % queSize) + 1;
      filled--;
      notifyAll();
    }  //** end of try clause
    catch(InterruptedException e) {}
    return item;
  }  //** end of fetch method
}  //** end of Queue class
```

```
class Producer extends Thread {
  private Queue buffer;
  public Producer(Queue que) {
    buffer = que;
  }
  public void run() {
     int new_item;
     while (true) {
      //-- Create a new item
      buffer.deposit(new_item);
     }
   }
}
```

```
class Consumer extends Thread {
  private Queue buffer;
  public Consumer(Queue que) {
    buffer = que;
  }
  public void run() {
    int stored_item;
    while (true) {
      stored_item = buffer.fetch();
      //-- Consume the stored_item
    }
  }
}
```

The following code creates a Queue object, and a Producer and a Consumer object, both attached to the Queue object, and starts their execution:

```
Queue buff1 = new Queue(100);
Producer producer1 = new Producer(buff1);
Consumer consumer1 = new Consumer(buff1);
producer1.start();
consumer1.start();
```

# Java's Thread Evaluation

- Java's support for concurrency is relatively simple but effective
- Not as powerful as Ada's tasks

# C# Threads

- Loosely based on Java but there are significant differences
- Basic thread operations
  - Any method can run in its own thread
  - A thread is created by creating a `Thread` object
  - Creating a thread does not start its concurrent execution; it must be requested through the `Start` method
  - A thread can be made to wait for another thread to finish with `Join`
  - A thread can be suspended with `Sleep`
  - A thread can be terminated with `Abort`

# Synchronizing Threads

- Three ways to synchronize C# threads
  - The `Interlocked` class
    - Used when the only operations that need to be synchronized are incrementing or decrementing of an integer
  - The `lock` statement
    - Used to mark a critical section of code in a thread

      lock (expression) {… }
  - The `Monitor` class
    - Provides four methods that can be used to provide more sophisticated synchronization

# C#'s Concurrency Evaluation

- An advance over Java threads, e.g., any method can run its own thread
- Thread termination is cleaner than in Java
- Synchronization is more sophisticated

# Statement-Level Concurrency

- Objective: Provide a mechanism that the programmer can use to inform compiler of ways it can map the program onto multiprocessor architecture
- Minimize communication among processors and the memories of the other processors

# High-Performance Fortran

- A collection of extensions that allow the programmer to provide information to the compiler to help it optimize code for multiprocessor computers
- Specify the number of processors, the distribution of data over the memories of those processors, and the alignment of data

# Primary HPF Specifications

- Number of processors

```
!HPF$ PROCESSORS procs (n)
```

- Distribution of data

!HPF$ DISTRIBUTE (*kind*) ONTO procs ::
    *identifier_list*

  - *kind* can be BLOCK (distribute data to processors in blocks) or CYCLIC (distribute data to processors one element at a time)

- Relate the distribution of one array with that of another

ALIGN *array1_element* WITH *array2_element*

# Statement-Level Concurrency Example

```
      REAL list_1(1000), list_2(1000)
      INTEGER list_3(500), list_4(501)
!HPF$ PROCESSORS proc (10)
!HPF$ DISTRIBUTE (BLOCK) ONTO procs ::
                          list_1, list_2
!HPF$ ALIGN list_1(index) WITH
             list_4 (index+1)
      …
      list_1 (index) = list_2(index)
      list_3(index) = list_4(index+1)
```

# Statement-Level Concurrency (continued)

- `FORALL` statement is used to specify a list of statements that may be executed concurrently

```
FORALL (index = 1:1000)
     list_1(index) = list_2(index)
```

- Specifies that all 1,000 RHSs of the assignments can be evaluated before any assignment takes place

# Summary

- Concurrent execution can be at the instruction, statement, or subprogram level
- Physical concurrency: when multiple processors are used to execute concurrent units
- Logical concurrency: concurrent united are executed on a single processor
- Two primary facilities to support subprogram concurrency: competition synchronization and cooperation synchronization
- Mechanisms: semaphores, monitors, rendezvous, threads
- High-Performance Fortran provides statements for specifying how data is to be distributed over the memory units connected to multiple processors