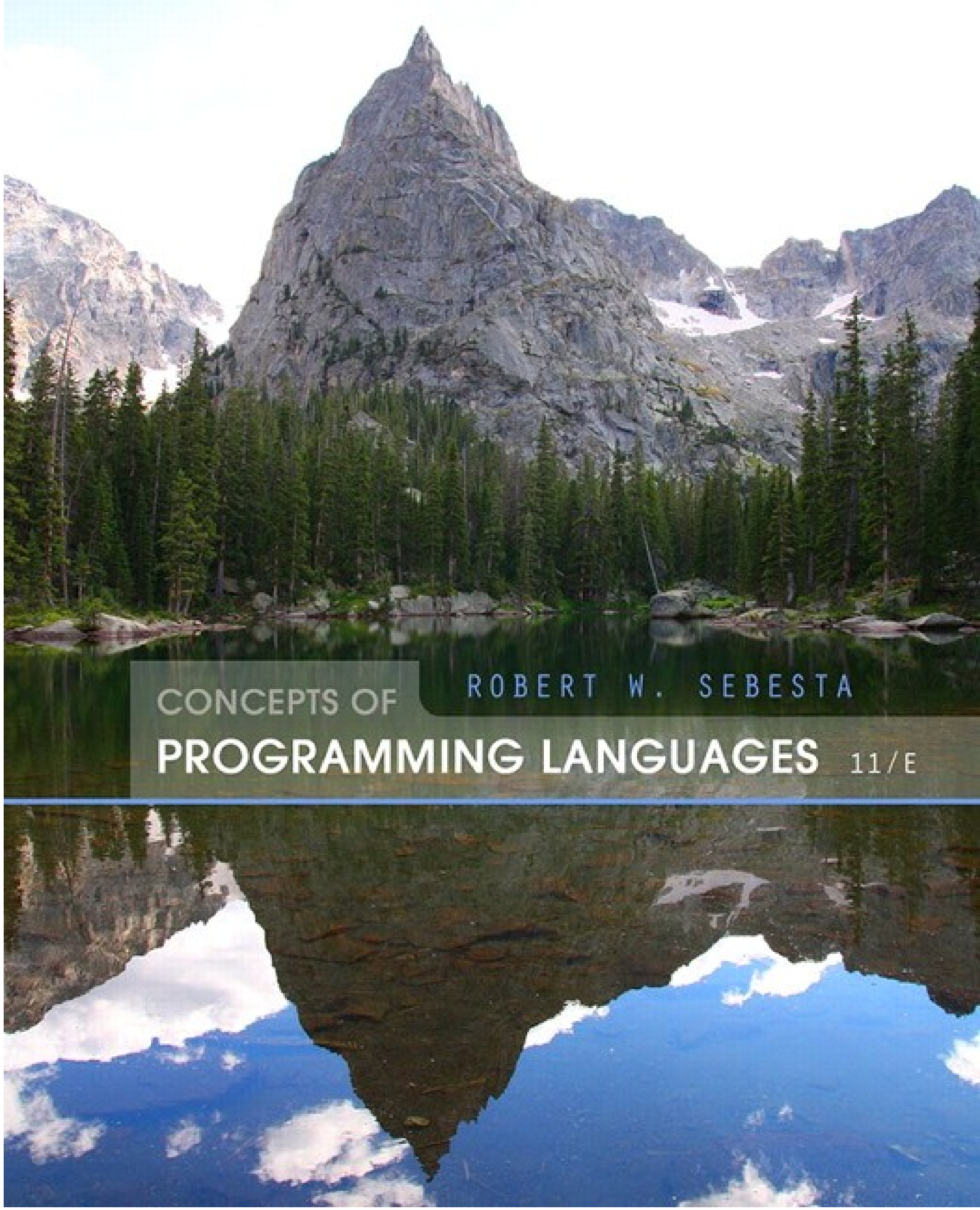
Chapter 13

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

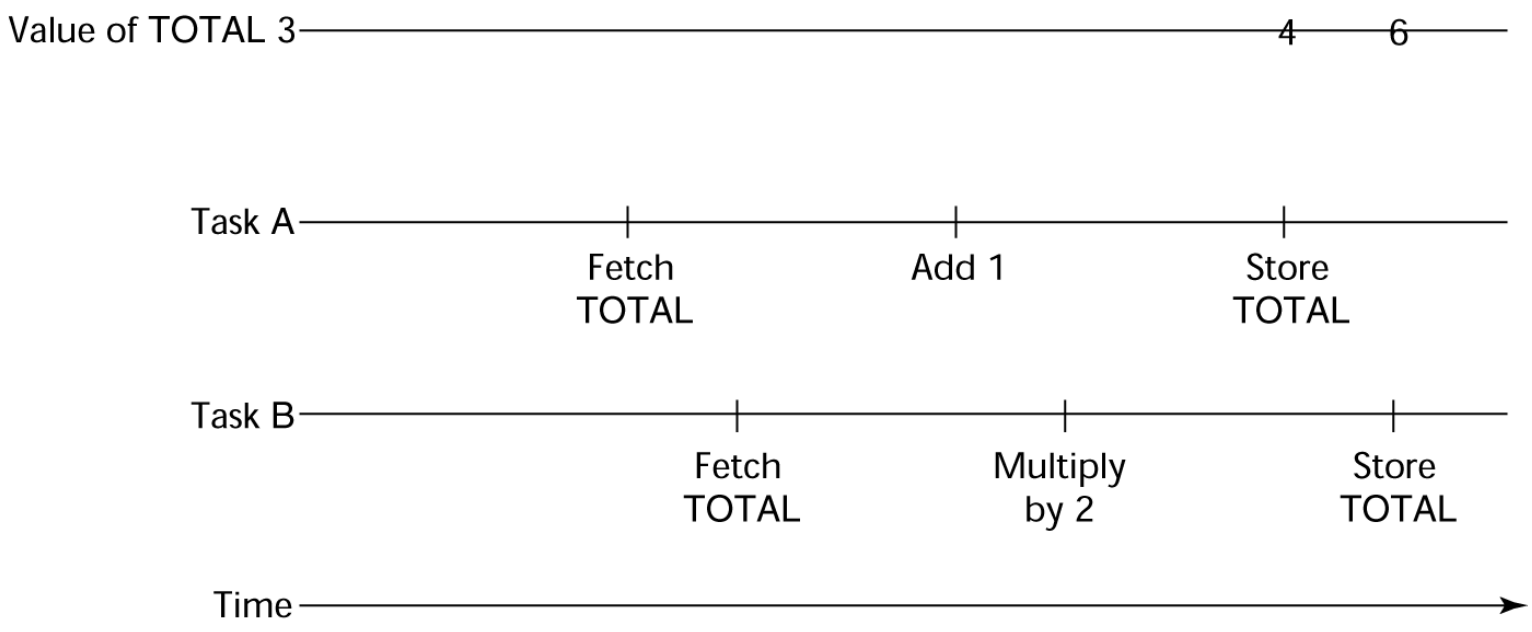
- A mechanism that controls the order in which tasks execute
- Two kinds of synchronization
  - *Cooperation* synchronization
  - *Competition* synchronization
- Task communication is necessary for synchronization, provided by:
  - Shared nonlocal variables
  - Parameters
  - Message passing

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)

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

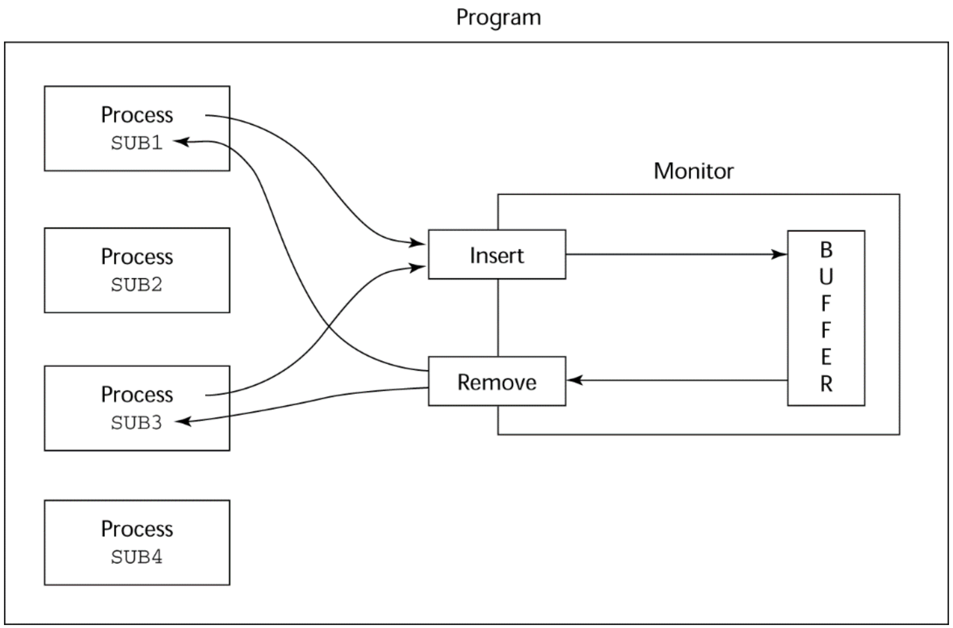
- Ada, Java, C#
- The idea: encapsulate the shared data and its operations to restrict access
- A monitor is an abstract data type for shared data

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 are 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;
```

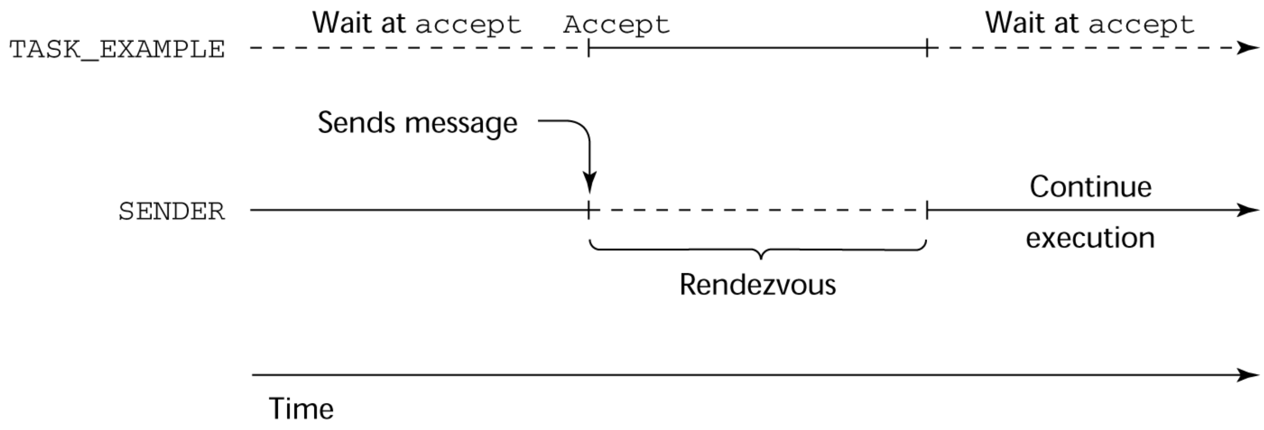
Example of a Task Body

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

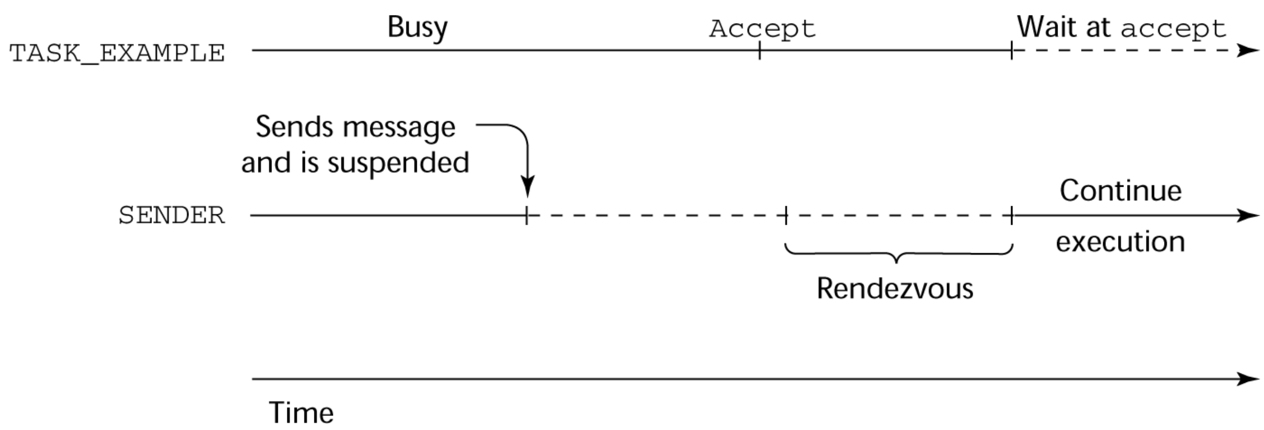
Ada Message Passing Semantics

- 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

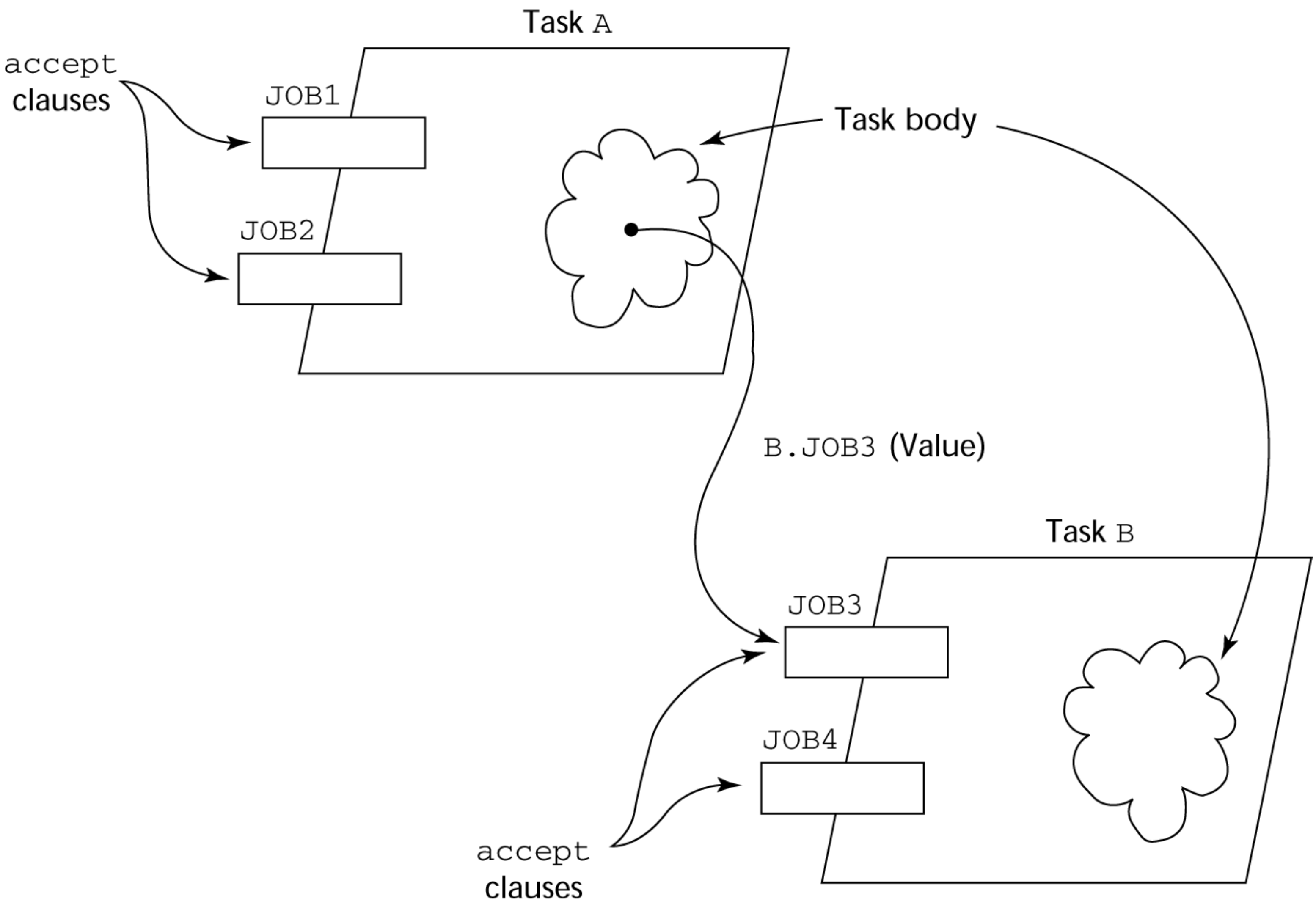


(b) SENDER waits for TASK_EXAMPLE

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



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;
```

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 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
         ...
     end loop;
  end Buf_Task;
```

A Consumer Task

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

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

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

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 `join` method is used to force a method to delay its execution until the run method of another thread has completed its execution

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

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

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