Programming Language

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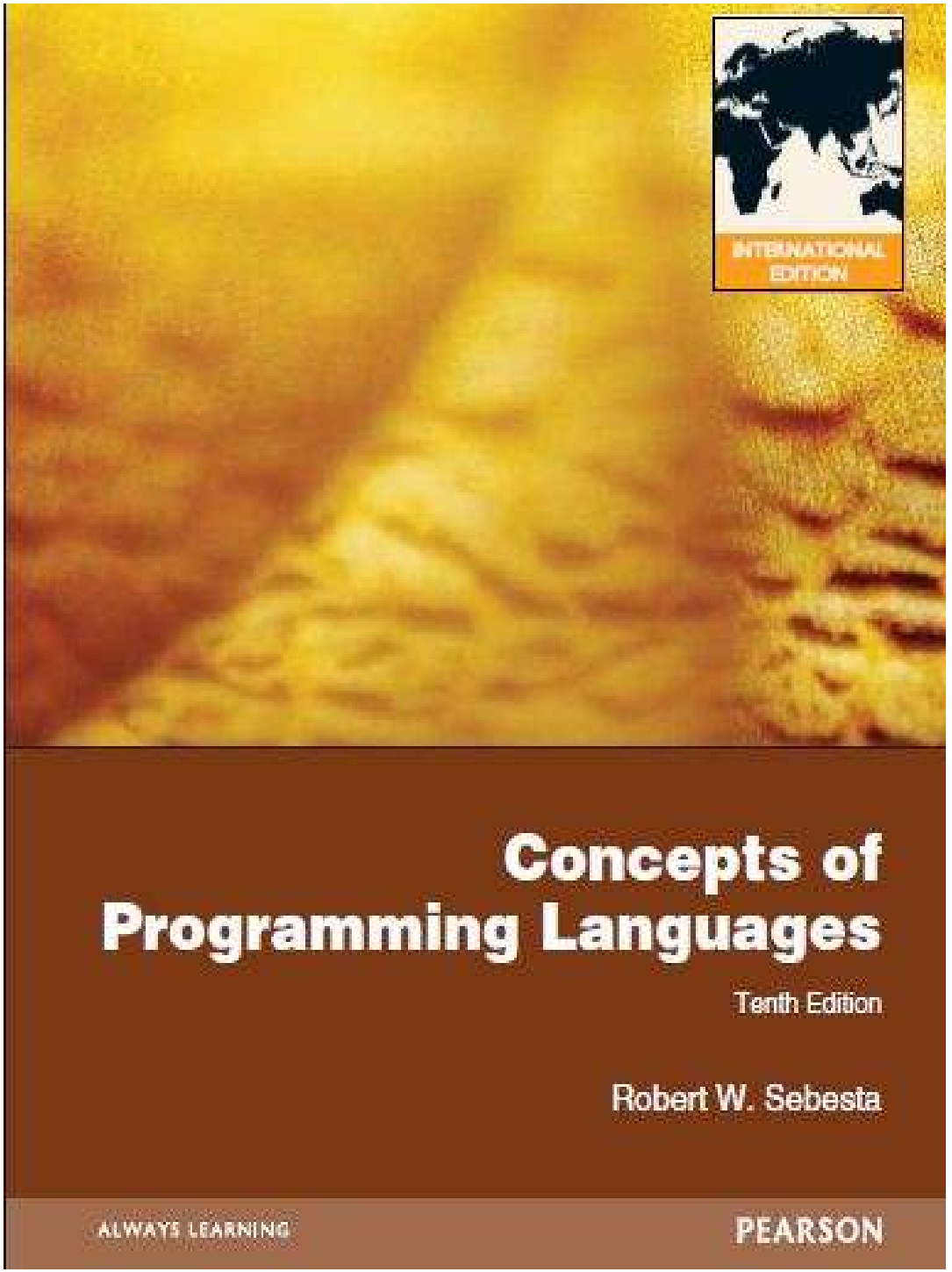


Lecture 8 Concurrency

- 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
- A concurrent algorithm is scalable if the speed of its execution increase when more processers are available.

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

Multiprocessor Architectures (Cont.)

- Single-Instruction Multiple-Data (SIMD) machines
  - Multiple processors that execute the same instruction simultaneously on different data
  - Applications: graphics/video processing
- Multiple-Instruction Multiple-Data (MIMD) machines
  - Multiple processors that operate independently but whose operations can be synchronized.
- 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 (interleaving)
- A *thread of control* in a program is the sequence of program points reached as control flows through the program
- Coroutines (*quasi-concurrency) have a single thread of control*

Concurrency Example

- Sequential programming

```
int summation () {

        int sum = 0;
        int num = 1,000,000;

        for (i=0; i<num; i++)
                sum += i;
        return sum;
}
```

Concurrency Example (Cont.)

- Pthread programming

```
int sum_thread (start, end) {

        int sum = 0;
        for (i=start; i<end; i++)
                sum += i;
        return sum;
}

pthread_create(*sum_thread)
```

Concurrency Example (Cont.)

- OpenMP programming

```
int summation () {

        int sum = 0;
        int num = 1,000,000;

        #omp parallel
        for (i=0; i<num; i++)
                sum += i;
        return sum;
}
```

Coroutine Example

```
function bar(n)
        print("hello")
        print("world")
        coroutine.yield()
        coroutine print("n^2 = "..(n*n))
end
local co = coroutine.create(bar)
coroutine.resume(co, 10)
hello world print("this is the third line.")
coroutine.resume(co)
```

Statement-level Concurrency

- Statement-level concurrency is a relatively simple concept
- Loops including statements that operate on array elements are unwound so that the processing can be distributed over multiple processors
  - a loop that executes 500 repetitions and includes a statement that operates on one of 500 array elements may be unwound so that each of 10 different processors can simultaneously process 50 of the array elements

Motivations for the Use of Concurrency

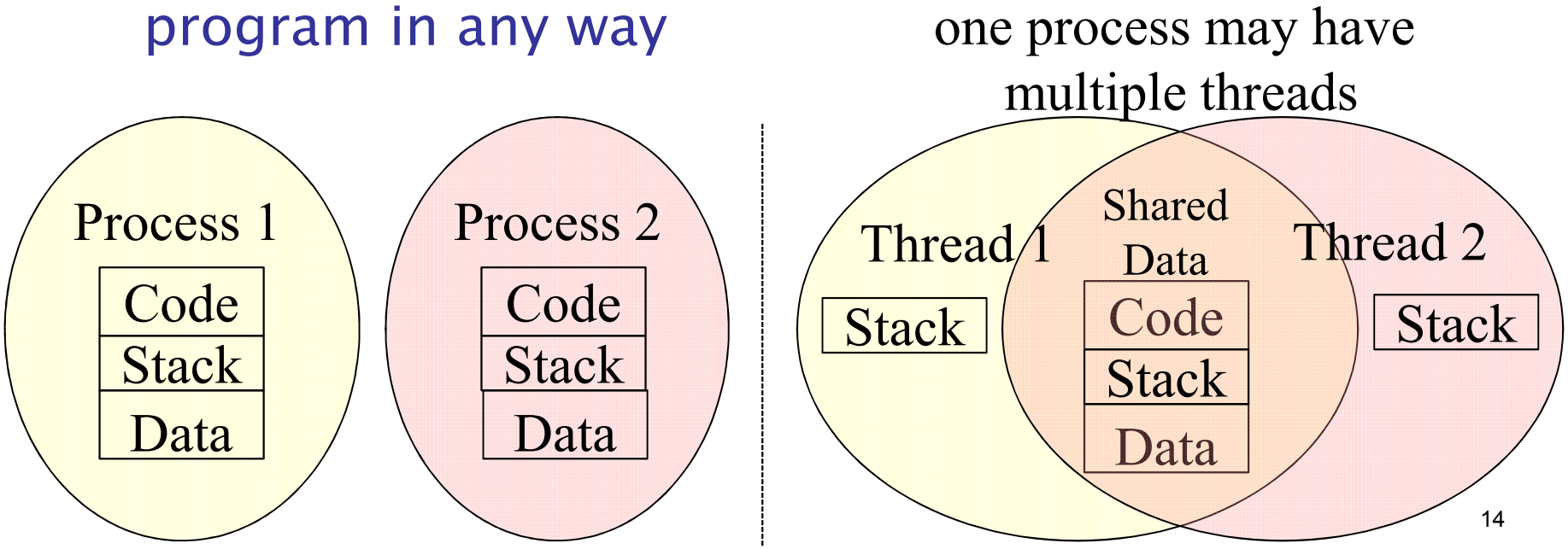
- Multiprocessor computers capable of physical concurrency are now widely used
- Even if a machine has just one processor, a program written to use concurrent execution can be faster than the same program written for nonconcurrent execution
  - the program is not compute bound (the sequential version does not fully utilize the processor)
- Many real-world situations involve concurrency and many program applications are now spread over multiple machines, either locally or over a network

Task

- A *task* (sometimes called *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* (processes) execute in their own address space
- *Lightweight tasks* (threads) 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



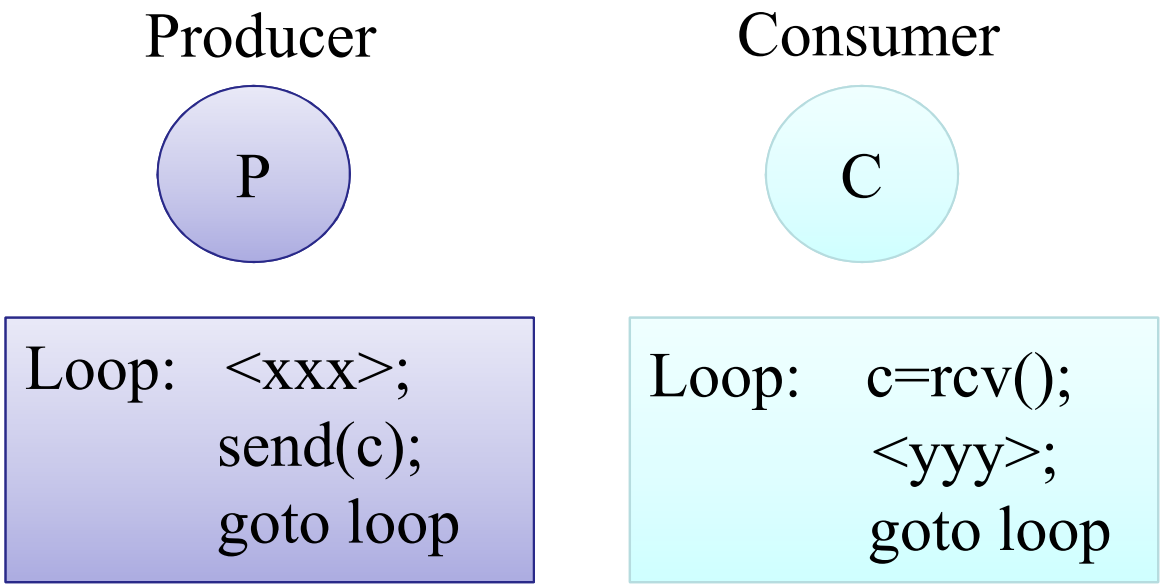
Task Synchronization

- 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)

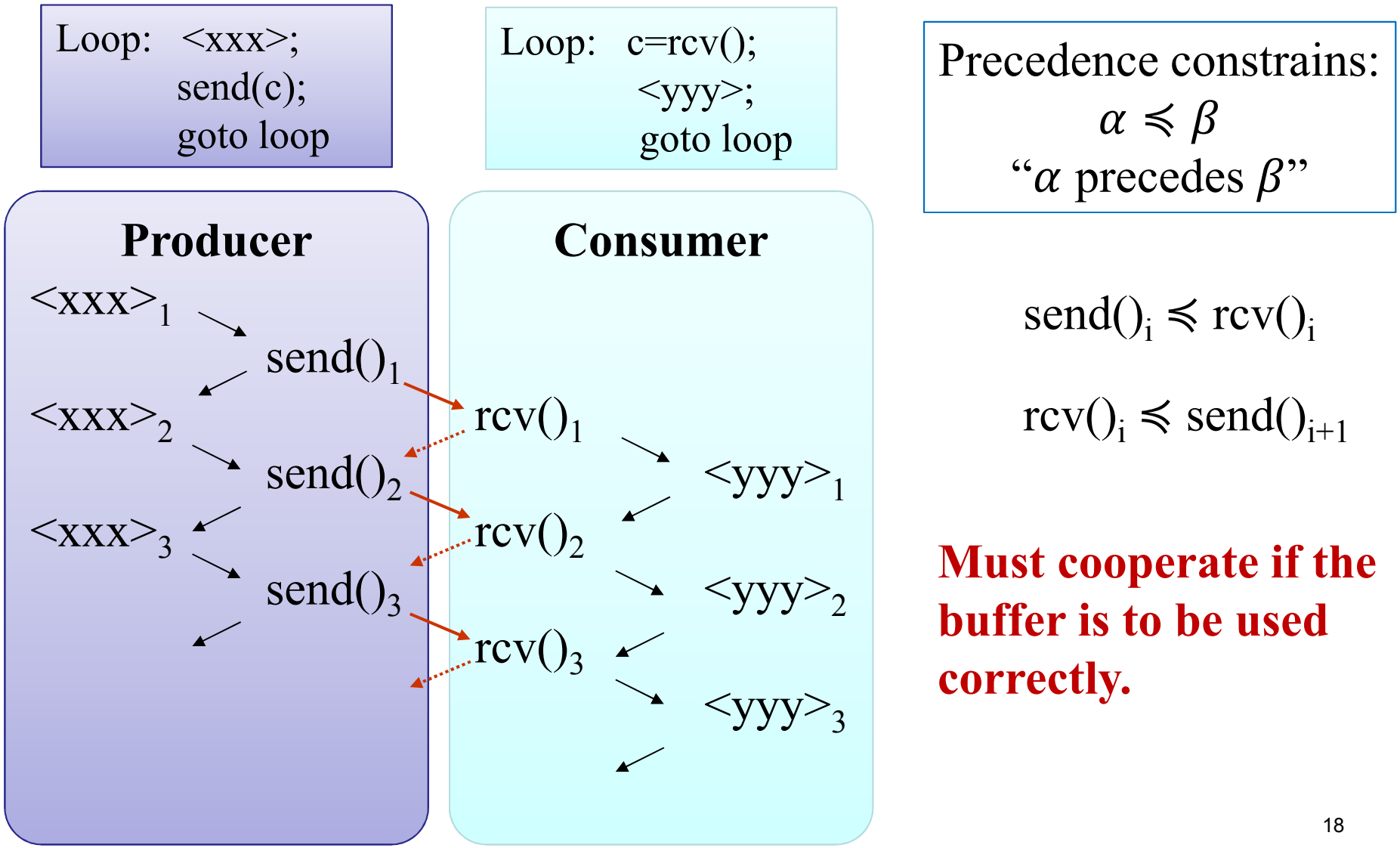
Producer-consumer Problem



Real world examples:

UNIX pipeline,
Word processor / Printer Driver,
Preprocessor / Compiler,
Compiler / Assembler

Cooperation Synchronization



Precedence constrains:

$\alpha \preccurlyeq \beta$

"α precedes β"

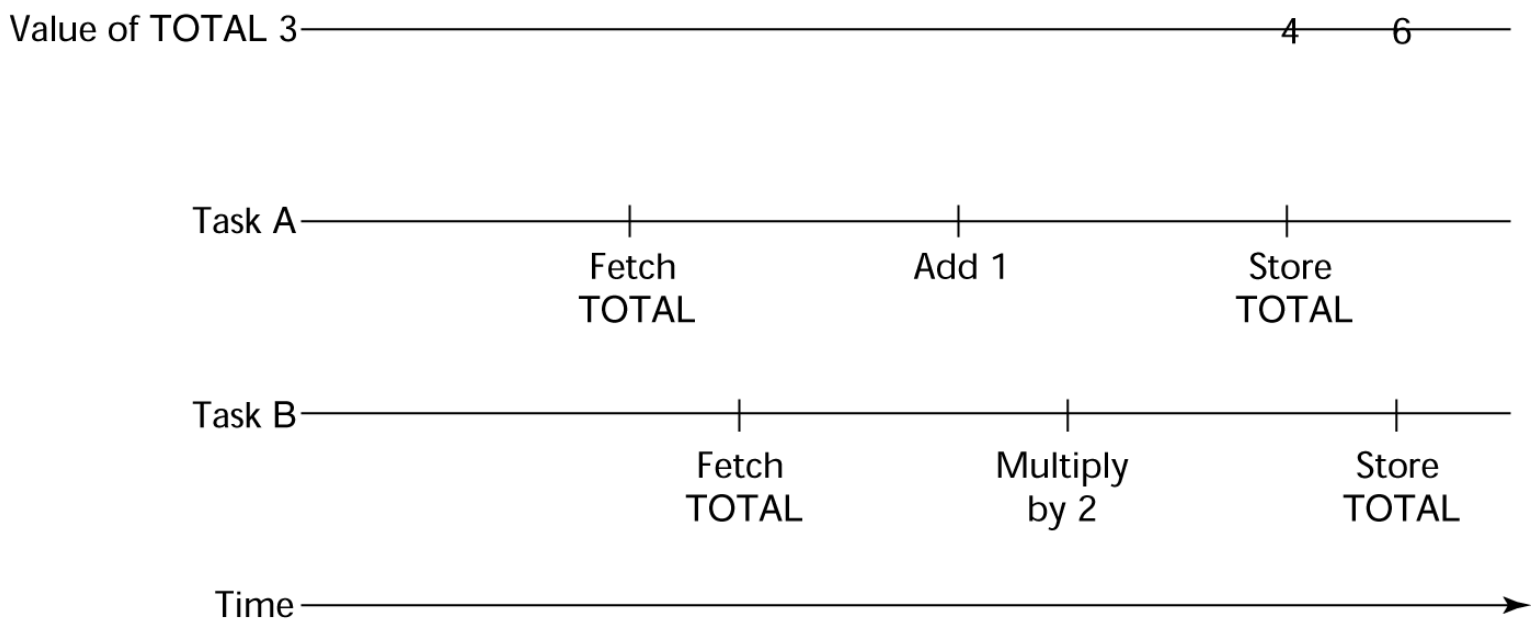
$send()_i \preccurlyeq rcv()_i$

$rcv()_i \preccurlyeq send()_{i+1}$

Must cooperate if the buffer is to be used correctly.

Competition Synchronization

Task A: `TOTAL = TOTAL + 1`
Task B: `TOTAL = 2 * TOTAL`



- Depending on order, there could be four different results

Race condition

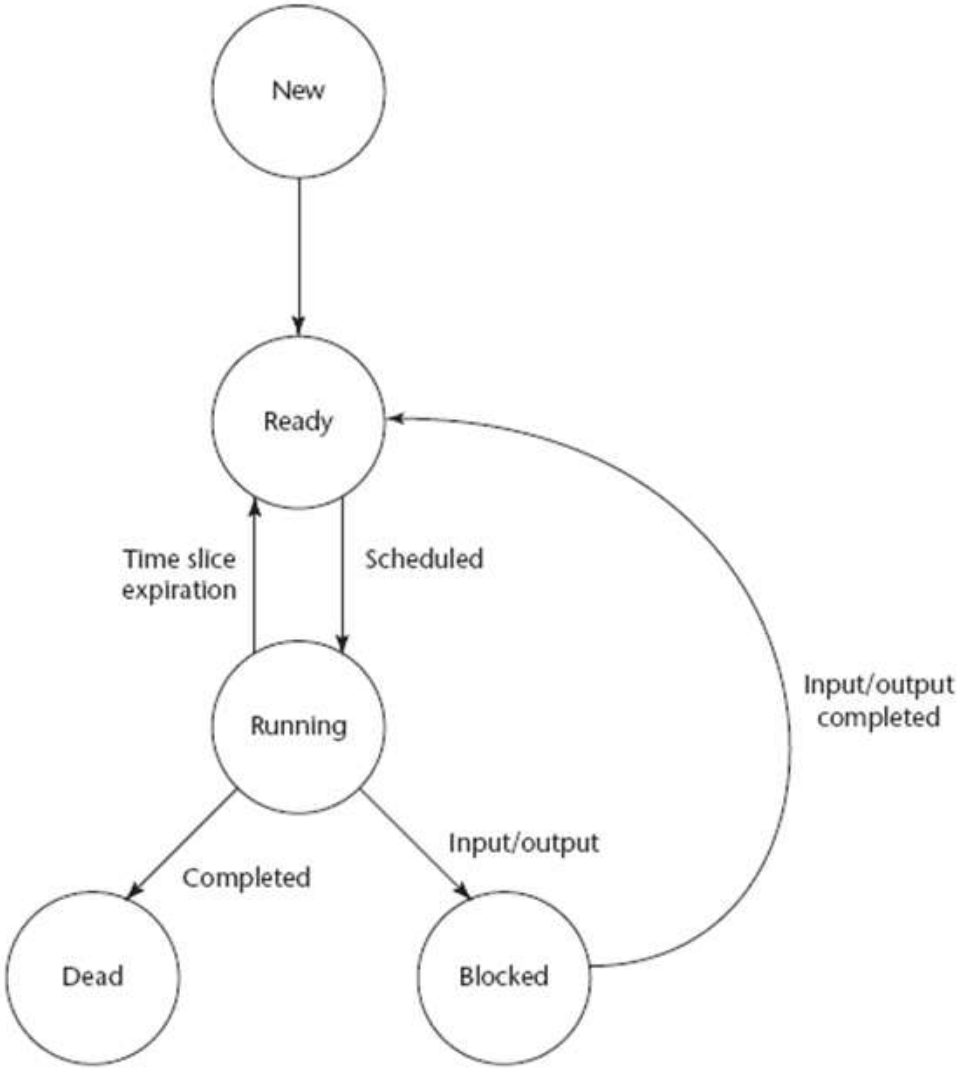
Scheduler

- 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 execution
- *R*eady – ready to run but not currently running (no available processor)
  - Tasks ready to run are stored in the task ready queue
- *Running* – currently executing
- *Blocked* – has been running, but that execution was interrupted by one of several different events (e.g., an input or output operation)
- *Dead* – no longer active in any sense (execution completed or explicitly killed by the program)

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 (meaning that the program cannot continue and thus will never terminate)
  - If all tasks in a concurrent environment lose their liveness, it is called *deadlock*

Design Issues for Concurrency

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

Methods of Providing Synchronization

- Three methods proving mutually exclusive access:
  - Semaphores
  - Monitors
  - Message Passing

Semaphores

- Dijkstra – 1965
- A semaphore is an implementation of a guard on the code that allows only one task to access a shared data structure at a time
- 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 have only two operations, *wait* (pass) 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 (abstract data type) 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 (Cont.)

- `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 increase the counter of `fullspots`

Cooperation Synchronization with Semaphores (Cont.)

- `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 (currently accessed) and 1
  - Such a semaphore is called a *binary semaphore*

Producer Code for Semaphores

```
semaphore access, fullspots, emptyspots;
access.count = 1;
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
  - The buffer will overflow/underflow if the wait of `emptyspots/fullspots` is left out
  - Leaving out the releases of either `emptyspots` or `fullspots` would result in deadlock.
- Misuse of semaphores can cause failures in competition synchronization
  - Leaving out the `wait(access)` statement in either task can cause insecure access to the buffer.
  - Leaving out the `release(access)` statement in either task results in deadlock.

Monitors

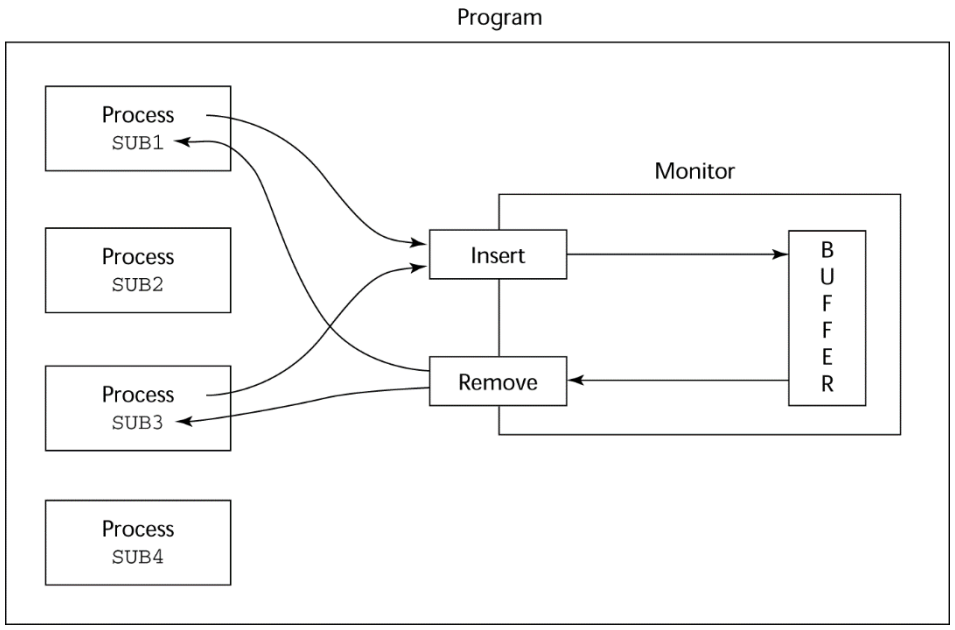
- A monitor is an abstract data type for shared data
- The idea: encapsulate the shared data and its operations into a single program unit to restrict access
- Ada, Java, C#, Pascal-Plus

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



Monitor Example

```
monitor class Account {
  private int balance := 0
  invariant balance >= 0

  public method boolean withdraw(int amount)
     precondition amount >= 0
  {
   if balance < amount then return false
   else { balance := balance - amount ; return true }
  }

  public method deposit(int amount)
     precondition amount >= 0
  {
   balance := balance + amount
  }
}
```

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 for both cooperation and competition synchronization
- 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

Message Passing Rendezvous

- 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*

- 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;
```

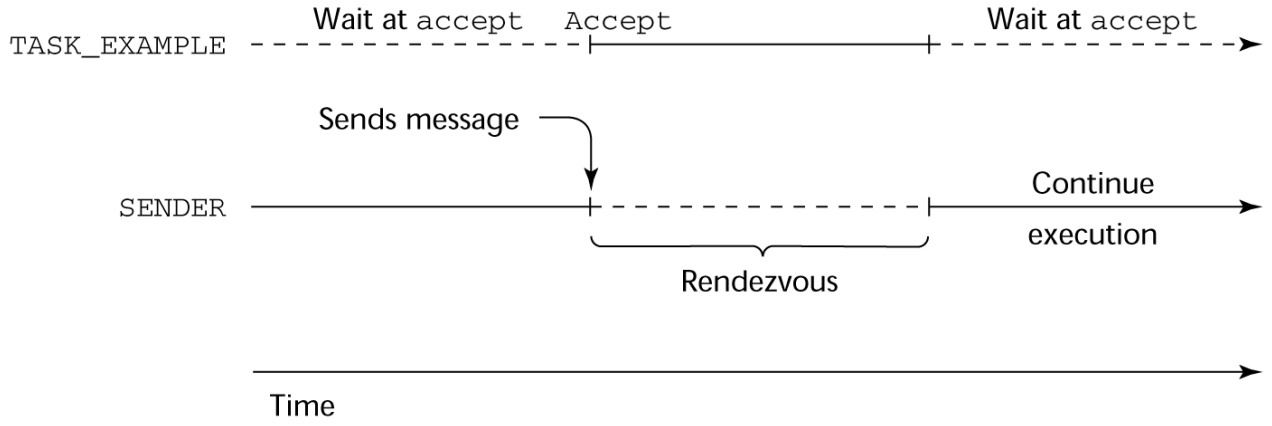
Example of a Task Body

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

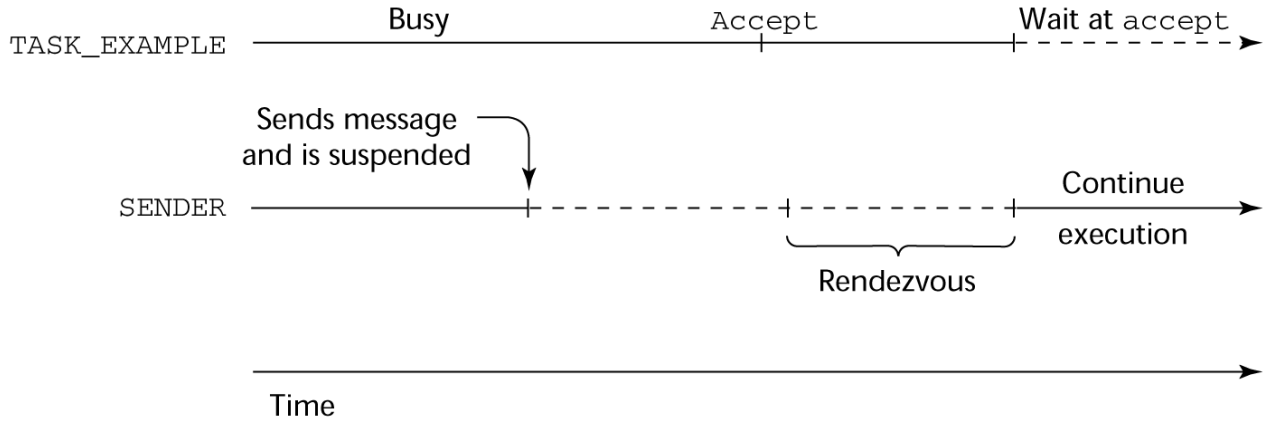
Ada Message Passing Semantics

- 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

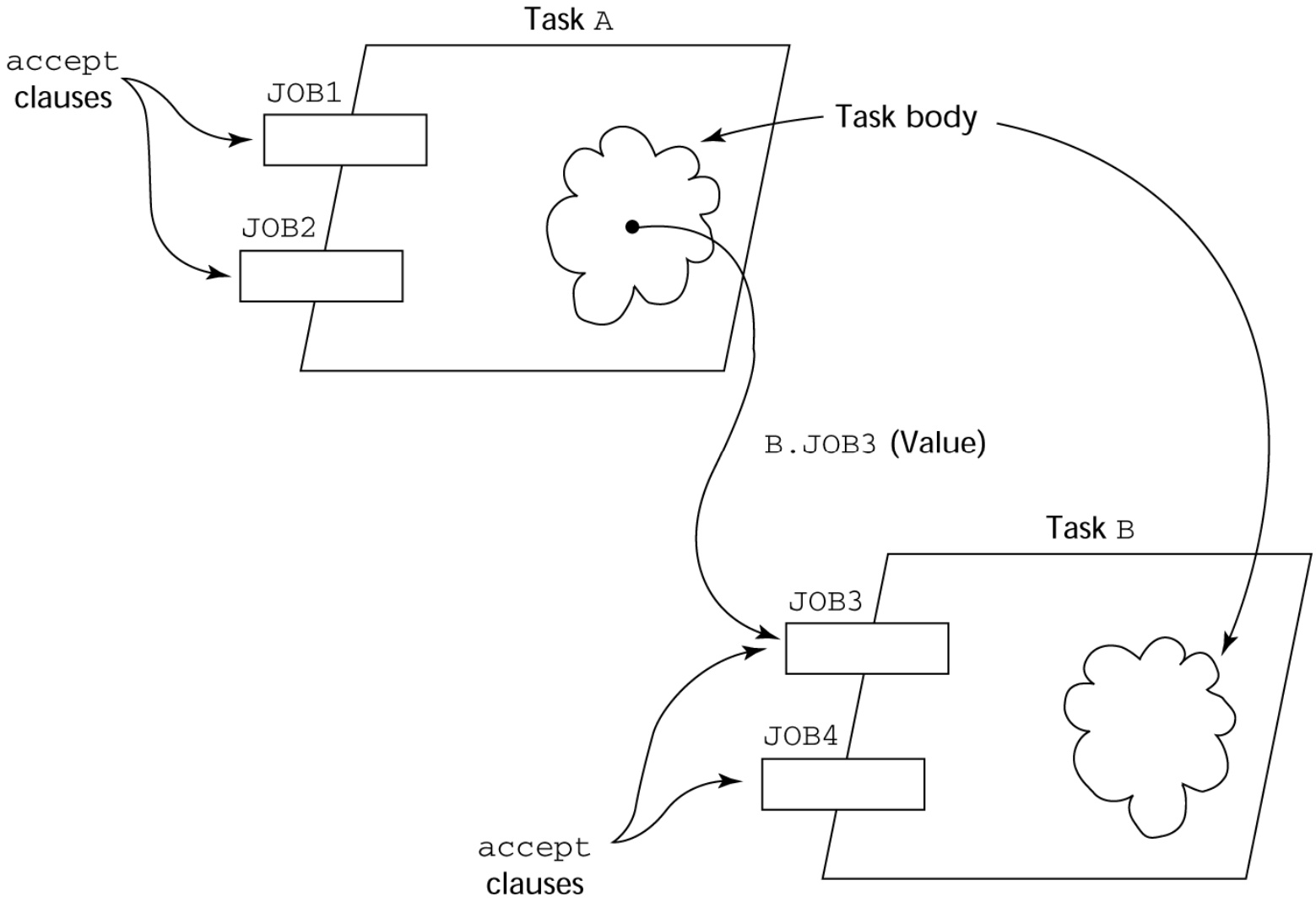


(b) SENDER waits for TASK_EXAMPLE

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 sends messages to other tasks and do not wait for a rendezvous to do their work
  - 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 **`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;
```

Task Termination

- The execution of a task is *completed* if control has reached the end of its code body
- If a task has created no dependent tasks and is completed, it is *terminated*
- If a task has created dependent tasks and is completed, it is not terminated until all its dependent tasks are terminated

The `terminate` Clause

- A `terminate` clause in a `select` is just a `terminate` statement
- A `terminate` clause is selected when no `accept` clause is open
- When a `terminate` is selected in a task, the task is terminated only when its master and all of the dependents of its master are either completed or are waiting at a `terminate`
- A block or subprogram is not left until all of its dependent tasks are terminated

Message Passing Priorities

- The priority of any task can be set with the **`pragma`** `Priority`

  `pragma` `Priority (`static expression`);`
- The priority of a task applies to it only when it is in the task ready queue

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`

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