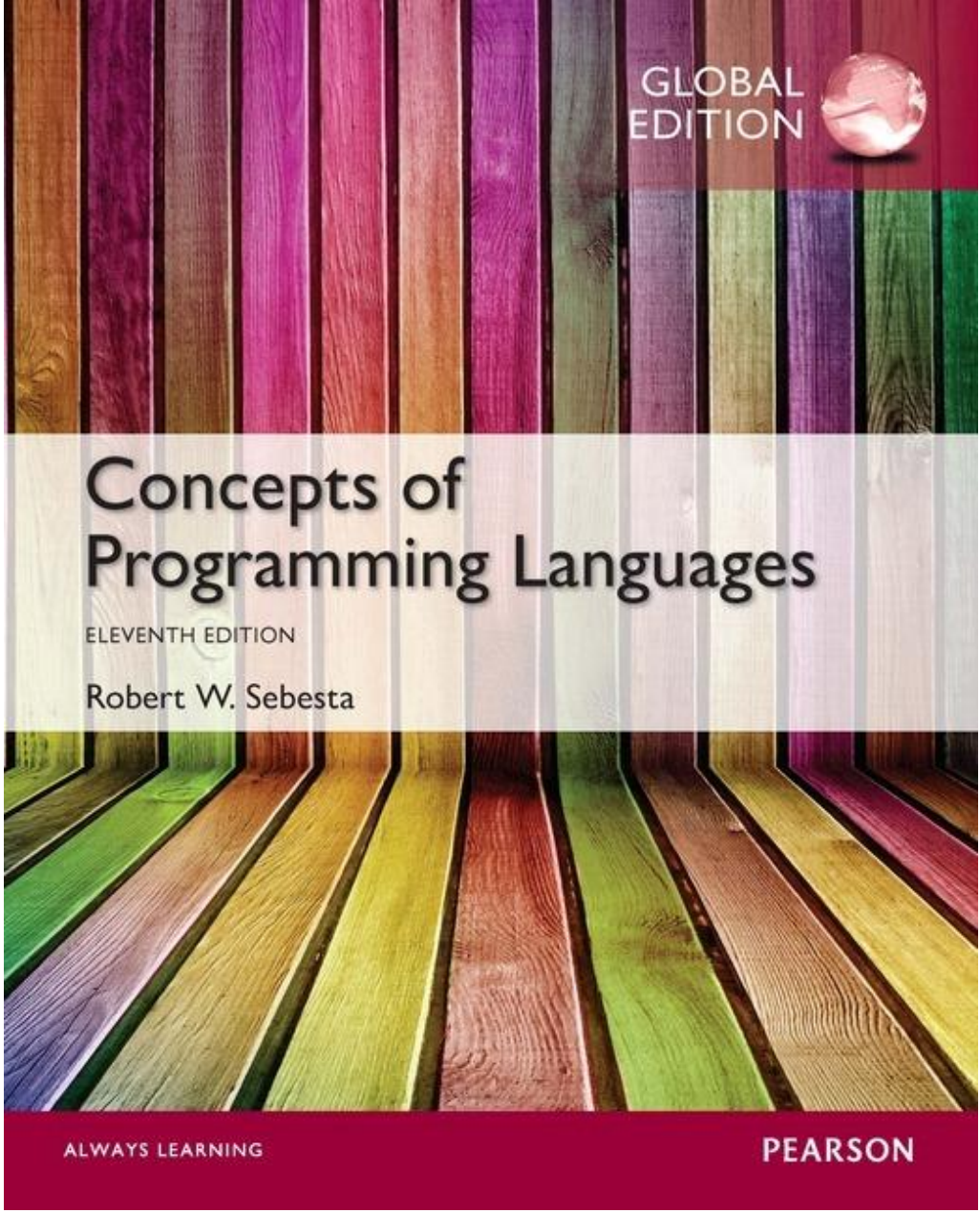
Chapter 9

Subprograms



Chapter 9 Topics

- Introduction
- Fundamentals of Subprograms
- Design Issues for Subprograms
- Local Referencing Environments
- Parameter-Passing Methods
- Parameters That Are Subprograms
- Calling Subprograms Indirectly
- Design Issues for Functions
- Overloaded Subprograms
- Generic Subprograms
- User-Defined Overloaded Operators
- Closures
- Coroutines

Introduction

- Two fundamental abstraction facilities
  - Process abstraction
    - Emphasized from early days
    - Discussed in this chapter
  - Data abstraction
    - Emphasized in the1980s
    - Discussed at length in Chapter 11

Fundamentals of Subprograms

- Each subprogram has a single entry point
- The calling program is suspended during execution of the called subprogram
- Control always returns to the caller when the called subprogram's execution terminates

Basic Definitions

- A *subprogram definition* describes the interface to and the actions of the subprogram abstraction
  - In Python, function definitions are executable; in all other languages, they are non-executable
  - In Ruby, function definitions can appear either in or outside of class definitions. If outside, they are methods of `Object`. They can be called without an object, like a function
  - In Lua, all functions are anonymous
- A *subprogram call* is an explicit request that the subprogram be executed
- A *subprogram header* is the first part of the definition, including the name, the kind of subprogram, and the formal parameters
- The *parameter profile* (aka *signature*) of a subprogram is the number, order, and types of its parameters
- The *protocol* is a subprogram's parameter profile and, if it is a function, its return type

Basic Definitions (continued)

- Function declarations in C and C++ are often called *prototypes*
- A *subprogram declaration* provides the protocol, but not the body, of the subprogram
- A *formal parameter* is a dummy variable listed in the subprogram header and used in the subprogram
- An *actual parameter* represents a value or address used in the subprogram call statement

Actual/Formal Parameter Correspondence

- Positional
  - The binding of actual parameters to formal parameters is by position: the first actual parameter is bound to the first formal parameter and so forth
  - Safe and effective
- Keyword
  - The name of the formal parameter to which an actual parameter is to be bound is specified with the actual parameter
  - *Advantage*: Parameters can appear in any order, thereby avoiding parameter correspondence errors
  - *Disadvantage*: User must know the formal parameter's names

Formal Parameter Default Values

- In certain languages (e.g., C++, Python, Ruby, PHP), formal parameters can have default values (if no actual parameter is passed)
  - In C++, default parameters must appear last because parameters are positionally associated (no keyword parameters)
- Variable numbers of parameters
  - C# methods can accept a variable number of parameters as long as they are of the same type—the corresponding formal parameter is an array preceded by **`params`**
  - In Ruby, the actual parameters are sent as elements of a hash literal and the corresponding formal parameter is preceded by an asterisk.

Variable Numbers of Parameters (continued)

- In Python, the actual is a list of values and the corresponding formal parameter is a name with an asterisk
- In Lua, a variable number of parameters is represented as a formal parameter with three periods; they are accessed with a **`for`** statement or with a multiple assignment from the three periods

Procedures and Functions

- There are two categories of subprograms
  - *Procedures* are collection of statements that define parameterized computations
  - *Functions* structurally resemble procedures but are semantically modeled on mathematical functions
    - They are expected to produce no side effects
      - it modifies neither its parameters nor any variables defined outside the function.
    - In practice, program functions have side effects

Design Issues for Subprograms

- Are local variables static or dynamic?
- Can subprogram definitions appear in other subprogram definitions?
- What parameter passing methods are provided?
- Are parameter types checked?
- If subprograms can be passed as parameters and subprograms can be nested, what is the referencing environment of a passed subprogram?
- Are functional side effects allowed?
- What types of values can be returned from functions?
- How many values can be returned from functions?
- Can subprograms be overloaded?
- Can subprogram be generic?
- If the language allows nested subprograms, are closures supported?

Local Referencing Environments

- Local variables can be stack-dynamic
  - If local variables are stack dynamic, they are bound to storage when the subprogram begins execution and are unbound from storage when that execution terminates.
  - Advantages
    - Support for recursion
    - Storage for locals is shared among some subprograms
  - Disadvantages
    - Allocation/de-allocation, initialization time
    - Indirect addressing
    - Subprograms cannot be history sensitive
- Local variables can be static
    - If local variables are static, they are bound to memory cells before execution begins and remains bound to the same memory cell throughout execution.
  - Advantages and disadvantages are the opposite of those for stack-dynamic local variables

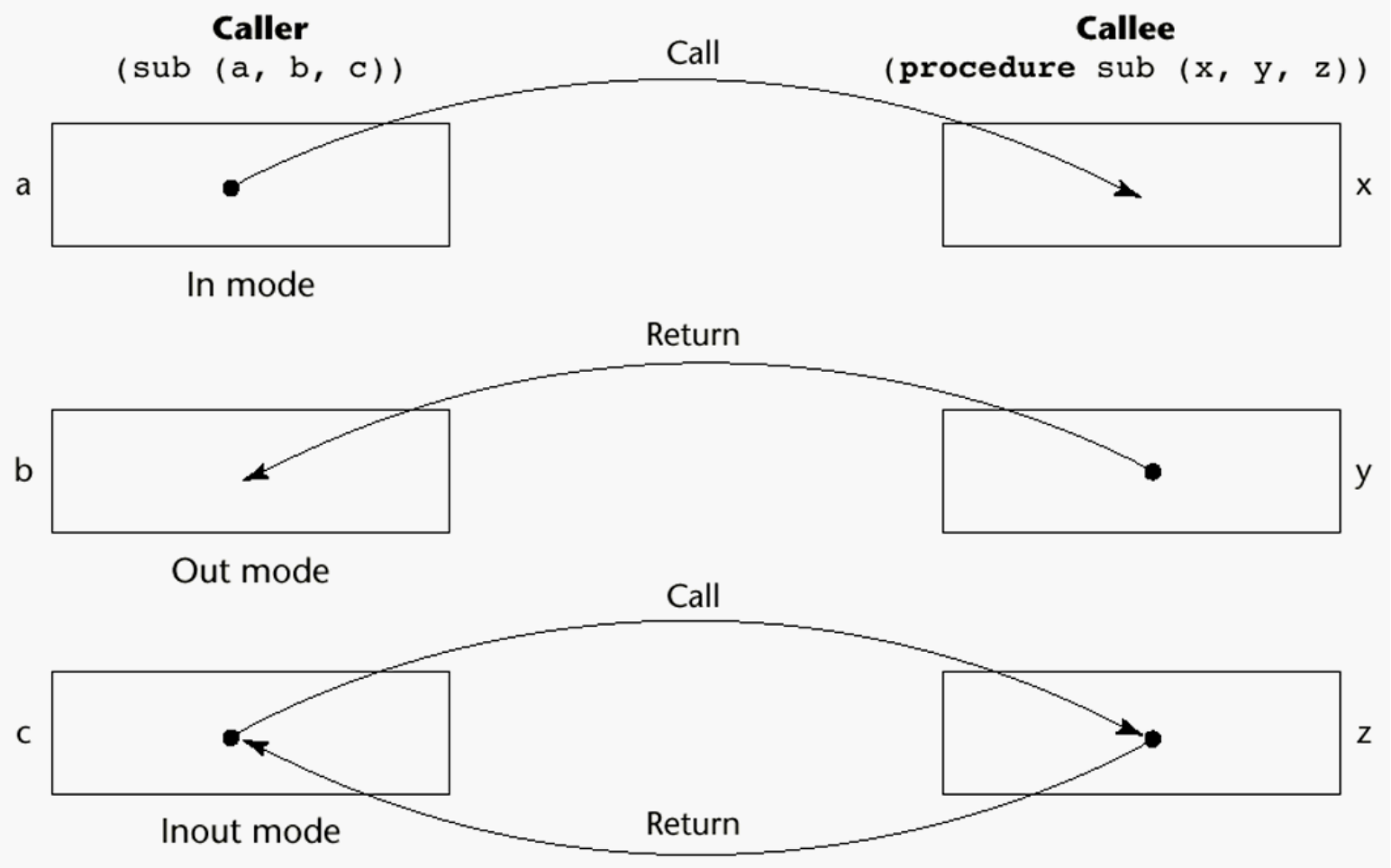
Local Referencing Environments: Examples

- In most contemporary languages, locals are stack dynamic
- In C-based languages, locals are by default stack dynamic, but can be declared `static`
- The methods of C++, Java, Python, and C# only have stack dynamic locals
- In Lua, all implicitly declared variables are global; local variables are declared with `local` and are stack dynamic

Semantic Models of Parameter Passing

- In mode
  - They can receive data from the corresponding actual parameter.
- Out mode
  - They can transmit data to the actual parameter.
- Inout mode
  - They can do both.

Models of Parameter Passing



Conceptual Models of Transfer

- Physically move a value
- Move an access path to a value

Pass-by-Value (In Mode)

- The value of the actual parameter is used to initialize the corresponding formal parameter
  - Normally implemented by copying
  - Can be implemented by transmitting an access path but not recommended (enforcing write protection is not easy)
  - *Disadvantages* (if by physical move): additional storage is required (stored twice) and the actual move can be costly (for large parameters)
  - *Disadvantages* (if by access path method): must write-protect in the called subprogram and accesses cost more (indirect addressing)

Pass-by-Result (Out Mode)

- When a parameter is passed by result, no value is transmitted to the subprogram; the corresponding formal parameter acts as a local variable; its value is transmitted to caller's actual parameter when control is returned to the caller, by physical move
  - Require extra storage location and copy operation
- Potential problems:
  - `sub(p1, p1);` whichever formal parameter is copied back will represent the current value of `p1`
  - `sub(list[sub], sub);` Compute address of list[sub] at the beginning of the subprogram or end?

Pass-by-Value-Result (inout Mode)

- A combination of pass-by-value and pass-by-result
- Sometimes called pass-by-copy
- Formal parameters have local storage
- Disadvantages:
  - Those of pass-by-result
  - Those of pass-by-value

Pass-by-Reference (Inout Mode)

- Pass an access path
- Also called pass-by-sharing
- Advantage: Passing process is efficient (no copying and no duplicated storage)
- Disadvantages
  - Slower accesses (compared to pass-by-value) to formal parameters
  - Potentials for unwanted side effects (collisions)
  - Unwanted aliases (access broadened)

```
fun(total, total);  fun(list[i], list[j];  fun(list[i], i);
```

Pass-by-Name (Inout Mode)

- By textual substitution
- Formals are bound to an access method at the time of the call, but actual binding to a value or address takes place at the time of a reference or assignment
- Allows flexibility in late binding
- Implementation requires that the referencing environment of the caller is passed with the parameter, so the actual parameter address can be calculated

Pass-by-Name (Inout Mode) – Cont.

- Ex:

  In a function:

  ```
  Let add x y = x+y
  add (a*b) (c*d)
  ```

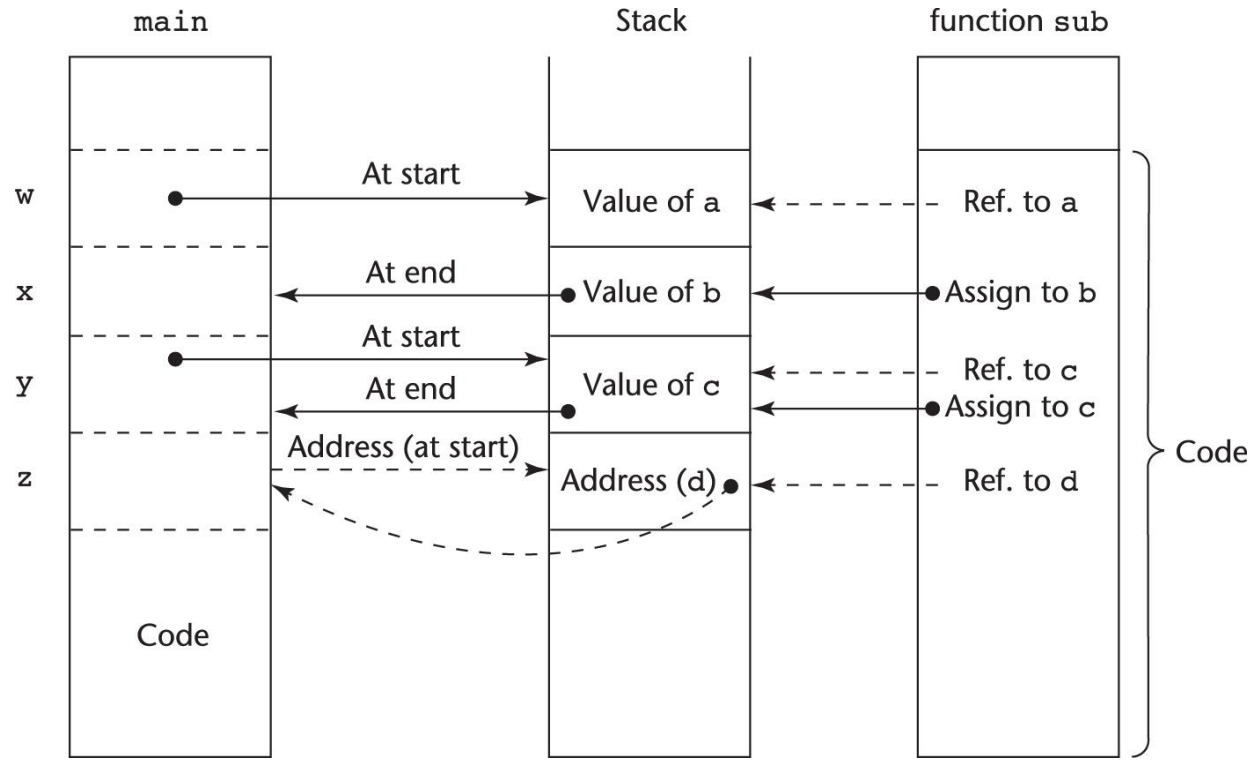
  - Then each use of x and y in the function definition is just a literal substitution of the actual arguments,

    (a*b) and (c*d), respectively

Implementing Parameter-Passing Methods

- In most languages parameter communication takes place thru the run-time stack
- Pass-by-reference are the simplest to implement; only an address is placed in the stack

Implementing Parameter-Passing Methods



Function header: `void sub(int a, int b, int c, int d)`
Function call in main: `sub(w, x, y, z)`
(pass `w` by value, `x` by result, `y` by value-result, `z` by reference)

Parameter Passing Methods of Major Languages

- C
  - Pass-by-value
  - Pass-by-reference is achieved by using pointers as parameters
- C++
  - A special pointer type called reference type for pass-by-reference
- Java
  - All parameters are passed are passed by value
  - Object parameters are passed by reference

Parameter Passing Methods of Major Languages (continued)

- Fortran 95+
  - Parameters can be declared to be in, out, or inout mode
- C#
  - Default method: pass-by-value
    - Pass-by-reference is specified by preceding both a formal parameter and its actual parameter with `ref`
- PHP: very similar to C#, except that either the actual or the formal parameter can specify ref
- Perl: all actual parameters are implicitly placed in a predefined array named `@_`
- Python and Ruby use pass-by-assignment (all data values are objects); the actual is assigned to the formal

Type Checking Parameters

- Considered very important for reliability
- FORTRAN 77 and original C: none
- Pascal and Java: it is always required
- ANSI C and C++: choice is made by the user
  - Prototypes
- Relatively new languages Perl, JavaScript, and PHP do not require type checking
- In Python and Ruby, variables do not have types (objects do), so parameter type checking is not possible

Multidimensional Arrays as Parameters

- If a multidimensional array is passed to a subprogram and the subprogram is separately compiled, the compiler needs to know the declared size of that array to build the storage mapping function

Multidimensional Arrays as Parameters: C and C++

- Programmer is required to include the declared sizes of all but the first subscript in the actual parameter
- Disallows writing flexible subprograms
- Solution: pass a pointer to the array and the sizes of the dimensions as other parameters; the user must include the storage mapping function in terms of the size parameters

Multidimensional Arrays as Parameters: Java and C#

- Similar to Ada
- Arrays are objects; they are all single-dimensioned, but the elements can be arrays
- Each array inherits a named constant (`length` in Java, `Length` in C#) that is set to the length of the array when the array object is created

Design Considerations for Parameter Passing

- Two important considerations
  - Efficiency
  - One-way or two-way data transfer
- But the above considerations are in conflict
  - Good programming suggest limited access to variables, which means one-way whenever possible
  - But pass-by-reference is more efficient to pass structures of significant size

Parameters that are Subprogram Names

- It is sometimes convenient to pass subprogram names as parameters
- Issues:
  1. Are parameter types checked?
  2. What is the correct referencing environment for a subprogram that was sent as a parameter?

Parameters that are Subprogram Names: Referencing Environment

- *Shallow binding*: The environment of the call statement that enacts the passed subprogram
  - Most natural for dynamic-scoped languages
- *Deep binding*: The environment of the definition of the passed subprogram
  - Most natural for static-scoped languages
- *Ad hoc binding*: The environment of the call statement that passed the subprogram

Parameters that are Subprogram Names: Referencing Environment

```
function sub1() {
        var x;
        function sub2() {
                alert(x); // Creates a dialog box
        };
        function sub3() {
                var x;
                x = 3;
                sub4(sub2);
        };
        function sub4(subx) {
                var x;
                x = 4;
                subx();
        };
        x = 1;
        sub3();
};
```

Consider the execution of sub2 when it is called in sub4.

- For **shallow binding**, the referencing environment of that execution is that of sub4, so the reference to x in sub2 is bound to the local x in sub4, and the output of the program is 4.
- For **deep binding**, the referencing environment of sub2's execution is that of sub1, so the reference to x in sub2 is bound to the local x in sub1, and the output is 1.
- For **ad hoc binding**, the binding is to the local x in sub3, and the output is 3.

Calling Subprograms Indirectly

- Usually when there are several possible subprograms to be called and the correct one on a particular run of the program is not know until execution (e.g., event handling and GUIs)
- In C and C++, such calls are made through function pointers

Calling Subprograms Indirectly (continued)

- In C#, method pointers are implemented as objects called *delegates*
  - A delegate declaration:

```
public delegate int Change(int x);
```

    - This delegate type, named `Change`, can be instantiated with any method that takes an **`int`** parameter and returns an **`int`** value

    A method: `static int fun1(int x) { … }`

    Instantiate: `Change chgfun1 = new Change(fun1);`

    Can be called with: `chgfun1(12);`

  - A delegate can store more than one address, which is called a *multicast delegate*

Design Issues for Functions

- Are side effects allowed?
  - Parameters should always be in-mode to reduce side effect (like Ada)
- What types of return values are allowed?
  - Most imperative languages restrict the return types
  - C allows any type except arrays and functions
  - C++ is like C but also allows user-defined types
  - Java and C# methods can return any type (but because methods are not types, they cannot be returned)
  - Python and Ruby treat methods as first-class objects, so they can be returned, as well as any other class
  - Lua allows functions to return multiple values

Overloaded Subprograms

- An *overloaded subprogram* is one that has the same name as another subprogram in the same referencing environment
  - Every version of an overloaded subprogram has a unique protocol
- C++, Java, C#, and Ada include predefined overloaded subprograms
- In Ada, the return type of an overloaded function can be used to disambiguate calls (thus two overloaded functions can have the same parameters)
- Ada, Java, C++, and C# allow users to write multiple versions of subprograms with the same name

Generic Subprograms

- A *generic* or *polymorphic subprogram* takes parameters of different types on different activations
- Overloaded subprograms provide *ad hoc polymorphism*
- *Subtype polymorphism* means that a variable of type T can access any object of type T or any type derived from T (OOP languages)
- A subprogram that takes a generic parameter that is used in a type expression that describes the type of the parameters of the subprogram provides *parametric polymorphism*
  - A cheap compile-time substitute for dynamic binding

Generic Subprograms (continued)

- C++
  - Versions of a generic subprogram are created implicitly when the subprogram is named in a call or when its address is taken with the & operator
  - Generic subprograms are preceded by a **`template`** clause that lists the generic variables, which can be type names or class names

```
template <class Type>
  Type max(Type first, Type second) {
  return first > second ? first : second;
  }
```

Generic Subprograms (continued)

- Java 5.0
  - Differences between generics in Java 5.0 and those of C++:
  1. Generic parameters in Java 5.0 must be classes
  2. Java 5.0 generic methods are instantiated just once as truly generic methods
  3. Restrictions can be specified on the range of classes that can be passed to the generic method as generic parameters
  4. Wildcard types of generic parameters

Generic Subprograms (continued)

- Java 5.0 (continued)

```
public static <T> T doIt(T[] list) { … }
```

  - The parameter is an array of generic elements (`T` is the name of the type)
  - A call:

```
doIt<String>(myList);
```

Generic parameters can have bounds:

```
public static <T extends Comparable> T
  doIt(T[] list) { … }
```

The generic type must be of a class that implements the `Comparable` interface

Generic Subprograms (continued)

- Java 5.0 (continued)
  - Wildcard types

    `Collection<?>` is a wildcard type for collection classes

```
void printCollection(Collection<?> c) {
   for (Object e: c) {
     System.out.println(e);
   }
 }
```

  - Works for any collection class

Generic Subprograms (continued)

- C# 2005
  - Supports generic methods that are similar to those of Java 5.0
  - One difference: actual type parameters in a call can be omitted if the compiler can infer the unspecified type
    - Another – C# 2005 does not support wildcards

Generic Subprograms (continued)

- F#
  - Infers a generic type if it cannot determine the type of a parameter or the return type of a function – *automatic generalization*
  - Such types are denoted with an apostrophe and a single letter, e.g., `'a`
  - Functions can be defined to have generic parameters

```
let printPair (x: 'a) (y: 'a) =
    printfn "%A %A" x y
```

    - `%A` is a format code for any type
    - These parameters are not type constrained

Generic Subprograms (continued)

- F# (continued)
  - If the parameters of a function are used with arithmetic operators, they are type constrained, even if the parameters are specified to be generic
  - Because of type inferencing and the lack of type coercions, F# generic functions are far less useful than those of C++, Java 5.0+, and C# 2005+

User-Defined Overloaded Operators

- Operators can be overloaded in Ada, C++, Python, and Ruby
- A Python example

```
def __add__ (self, second) :
  return Complex(self.real + second.real,
                 self.imag + second.imag)
```

Use: To compute `x + y`, `x.__add__(y)`

Closures

- A *closure* is a subprogram and the referencing environment where it was defined
  - The referencing environment is needed if the subprogram can be called from any arbitrary place in the program
  - A static-scoped language that does not permit nested subprograms doesn't need closures
  - Closures are only needed if a subprogram can access variables in nesting scopes and it can be called from anywhere
  - To support closures, an implementation may need to provide unlimited extent to some variables (because a subprogram may access a nonlocal variable that is normally no longer alive)

Closures (continued)

- A JavaScript closure:

```
function makeAdder(x) {
  return function(y) {return x + y;}
}
...
var add10 = makeAdder(10);
var add5 = makeAdder(5);
document.write("add 10 to 20: " + add10(20) +
               "<br />");
document.write("add 5 to 20: " + add5(20) +
               "<br />");
```

  - The closure is the anonymous function returned by `makeAdder`

Closures (continued)

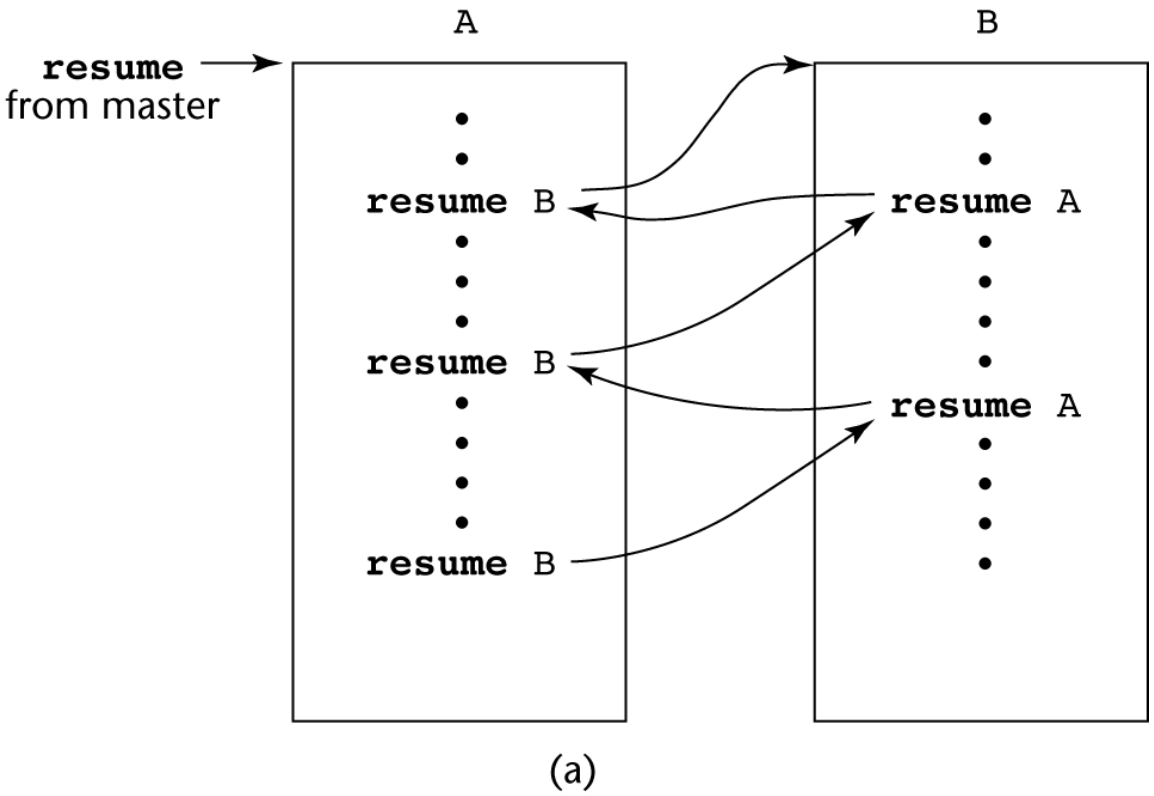
- C#
  - We can write the same closure in C# using a nested anonymous delegate
  - `Func<int, int>` (the return type) specifies a delegate that takes an `int` as a parameter and returns and `int`

```
static Func<int, int> makeAdder(int x) {
   return delegate(int y) {return x + y;};
}
...
Func<int, int> Add10 = makeAdder(10);
Func<int, int> Add5 = makeAdder(5);
Console.WriteLine("Add 10 to 20: {0}", Add10(20));
Console.WriteLine("Add 5 to 20: {0}", Add5(20));
```

Coroutines

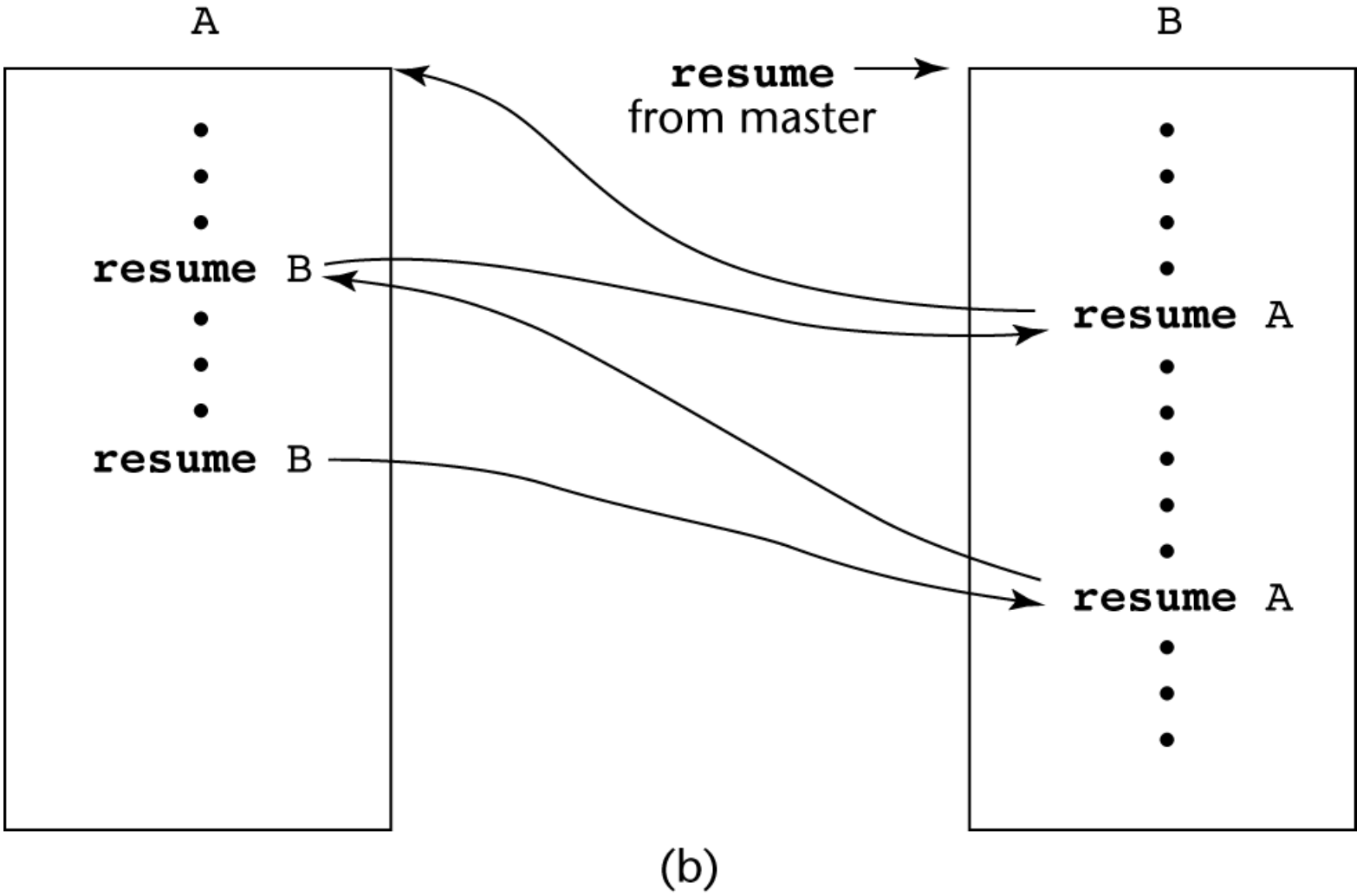
- A *coroutine* is a subprogram that has multiple entries and controls them itself – supported directly in Lua
- Also called *symmetric control:* caller and called coroutines are on a more equal basis
- A coroutine call is named a *resume*
- The first resume of a coroutine is to its beginning, but subsequent calls enter at the point just after the last executed statement in the coroutine
- Coroutines repeatedly resume each other, possibly forever
- Coroutines provide *quasi-concurrent execution* of program units (the coroutines); their execution is interleaved, but not overlapped

Coroutines Illustrated: Possible Execution Controls



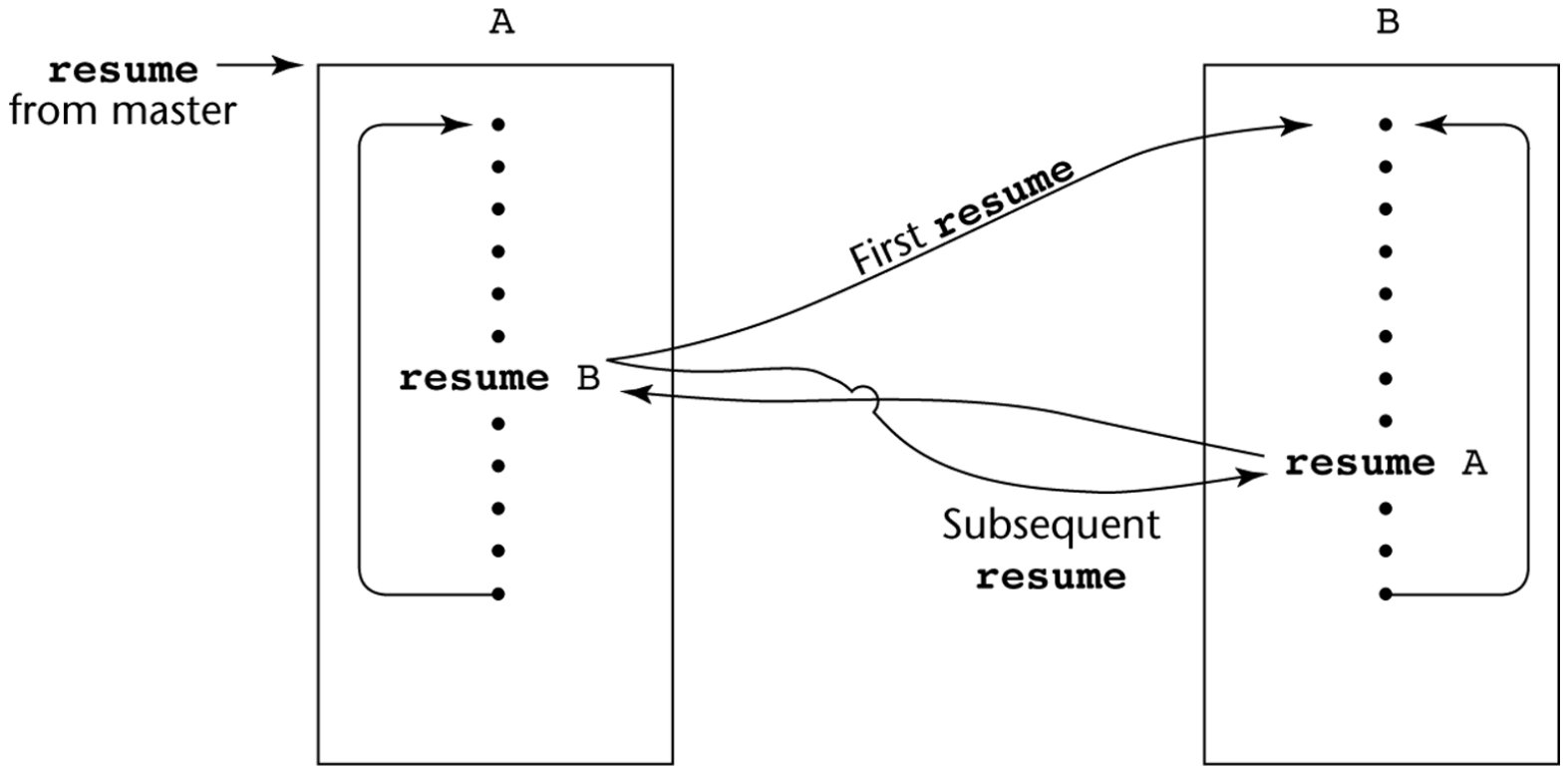
- The execution of **coroutine A** is started by the master unit. After some execution, A starts B. When **coroutine B** in Figure first causes control to return to **coroutine A**, the semantics is that A continues from where it ended its last execution.

Coroutines Illustrated: Possible Execution Controls



(b)

Coroutines Illustrated: Possible Execution Controls with Loops



- In this case, A is started by the master unit. Inside its main loop, A resumes B, which in turn resumes A in its main loop.

Summary

- A subprogram definition describes the actions represented by the subprogram
- Subprograms can be either functions or procedures
- Local variables in subprograms can be stack-dynamic or static
- Three models of parameter passing: in mode, out mode, and inout mode
- Some languages allow operator overloading
- Subprograms can be generic
- A closure is a subprogram and its ref. environment
- A coroutine is a special subprogram with multiple entries