# Statement Basics

- The meaning of a single statement executed in a state s is a new state s', which reflects the effects of the statement

  $M_{stmt}$( stmt , s) = s'



# Assignment Statements

$M_a(x := E, s) \Delta=$

$s' = \{<i_1', v_1'>, <i_2', v_2'>, ..., <i_n', v_n'>\}$,

where for j = 1, 2, ..., n,

$v_j' = VARMAP(i_j, s)$ if $i_j \neq x$

$v_j' = M_e(E, s)$ if $i_j = x$

## Sequence of Statements

$M_{stmt}$( stmt1; stmt2 , s) $\Delta$=
$M_{stmt}$( stmt2 , $M_{stmt}$( stmt1 , s))

or

$M_{stmt}$( stmt1; stmt2 , s) = s'' where
s' = $M_{stmt}$( stmt1 , s)
s'' = $M_{stmt}$( stmt2 , s')



## Sequence of Statements

```
x := 5;                          } P0
y := x + 1;              } P1
write(x * y);   } P2
```

Initial state $s_0$ = <$mem_0$, $i_0$, $o_0$>

$M_{stmt}( P_0, s_0) = M_{stmt}( P_1, \underbrace{M_a( x := 5 \;, s_0)}_{s_1})$

$s_1$ = <$mem_1$, $i_1$, $o_1$> where
VARMAP(x, $s_1$) = 5
VARMAP(z, $s_1$) = VARMAP(z, $s_0$) for all $z \neq x$
$i_1 = i_0$, $o_1 = o_0$

## Sequence of Statements

```
x := 5;
y := x + 1;
write(x * y);
```

$\left.\begin{array}{l}\text{x := 5;}\\ \left.\begin{array}{l}\text{y := x + 1;}\\ \left.\text{write(x * y);}\right\}\textbf{P2}\end{array}\right\}\textbf{P1}\end{array}\right\}\textbf{P0}$

$M_{stmt}( P_1, s_1) = M_{stmt}( P_2, \underbrace{M_a( y := x + 1, s_1)}_{s_2})$

$s_2 = \langle mem_2, i_2, o_2 \rangle$ where

$VARMAP(y, s_2) = M_e( x + 1, s_1) = 6$

$VARMAP(z, s_2) = VARMAP(z, s_1)$ for all $z \neq y$

$i_2 = i_1, o_2 = o_1$



## Sequence of Statements

$\left.\begin{array}{l}\text{x := 5;}\\ \left.\begin{array}{l}\text{y := x + 1;}\\ \left.\text{write(x * y);}\right\}\textbf{P2}\end{array}\right\}\textbf{P1}\end{array}\right\}\textbf{P0}$

$M_{stmt}( P_2, s_2) = M_{stmt}( write(x * y), s_2) = s_3$

$s_3 = \langle mem_3, i_3, o_3 \rangle$ where

$VARMAP(z, s_3) = VARMAP(z, s_2)$ for all z

$i_3 = i_2, o_3 = o_2 \cdot M_e( x * y , s_2) = o_2 \cdot 30$

## Sequence of Statements

Therefore,

$M_{stmt}(P, s_0) = s_3 = \langle mem_3, i_3, o_3 \rangle$ where

$VARMAP(y, s_3) = 6$

$VARMAP(x, s_3) = 5$

$VARMAP(z, s_3) = VARMAP(z, s_0)$ for all $z \neq x, y$

$i_3 = i_0$

$o_3 = o_0 \cdot 30$



## Logical Pretest Loops

- The meaning of the loop is the value of program variables after the loop body has been executed the prescribed number of times, assuming there have been no errors
- The loop is converted from iteration to recursion, where the recursion control is mathematically defined by other recursive state mapping functions
- Recursion is easier to describe with mathematical rigor than iteration

# Logical Pretest Loop

- $M_l$(while B do L, s) $\Delta$=
  if $M_b$(B, s) = false then
  s
  else
  $M_l$(while B do L, $\mathbf{M_{stmt}(L,\ s)}$)



# Postest Loop ?

- $M_{ptl}$(do L until not B, s) $\Delta$ = ?

## Key Points of Denotational Semantics

- Advantages
  - **Compact & precise**, with solid mathematical foundation
  - Provide a **rigorous** way to think about programs
  - Can be used to prove the correctness of programs
  - Can be an aid to language design



## Key Points of Denotational Semantics

- Disadvantages
  - **Require mathematical sophistication**
  - Hard for programmer to use
- Uses
  - Semantics for Algol-60, Pascal, etc.
  - Compiler generation and optimization

# Summary

- Each form of semantic description has its place
- Operational semantics
  - Informally describe the meaning of language constructs in terms of their effects on an ideal machine
- Denotational semantics
  - Formally define mathematical objects and functions to represent the meanings



# Subroutine

In Text: Chapter 9

# Outline [1]

- Definitions
- Design issues for subroutines
- Parameter passing modes and mechanisms
- Advanced subroutine issues



# Subroutine

- A sequence of program instructions that perform a specific task, packaged as a unit
- The unit can be used in programs whenever the particular task should be performed

## Subroutine

- Subroutines are the fundamental building blocks of programs
- They may be defined within programs, or separately in libraries that can be used by multiple programs
- In different programming languages, a subroutine may be called a **procedure**, a **routine**, a **method**, or a **subprogram**



## Characteristics of Subroutines/ Subprograms

- Each subroutine has **a single entry point**
- **The caller is suspended** during the execution of the callee subroutine
- **Control always returns to the caller** when callee subroutine's execution terminates

## Parameters

- A subroutine may be written to expect one or more data values from the calling program
- The expected values are called **parameters** or **formal parameters**
- The actual values provided by the calling program are called **arguments** or **actual parameters**



## Actual/Formal Parameter Correspondence

- Two options
  - Positional parameters
    - In nearly all programming languages, the binding is done by position
    - E.g., the first actual parameter is bound to the first formal parameter
  - Keyword parameters
    - Each formal parameter and the corresponding actual parameter are specified together
    - E.g., Sort (List => A, Length => N)

# Keyword Parameters

- Advantages
  - Order is irrelevant
  - When a parameter list is long, developers won't make the mistake of wrongly ordered parameters
- Disadvantages
  - Users must know and specify the names of formal parameters



# Default Parameter

- A parameter that has a default value provided to it
- If the user does not supply a value for this parameter, the default value will be used
- If the user does supply a value for the default parameter, the user-specified value is used

# An Example in Ada

```
procedure sort (list   : List_Type;
                length : Integer := 100);
...
sort (list => A);
```



# Design issues for subroutines

- What parameter passing methods are provided?
- Are parameter types checked?
- What is the **referencing environment** of a passed subroutine?
- Can subroutine definitions be nested?
- Can subroutines be overloaded?
- Are subroutines allowed to be generic?
- Is separate/independent compilation supported?

## Parameter-Passing Methods

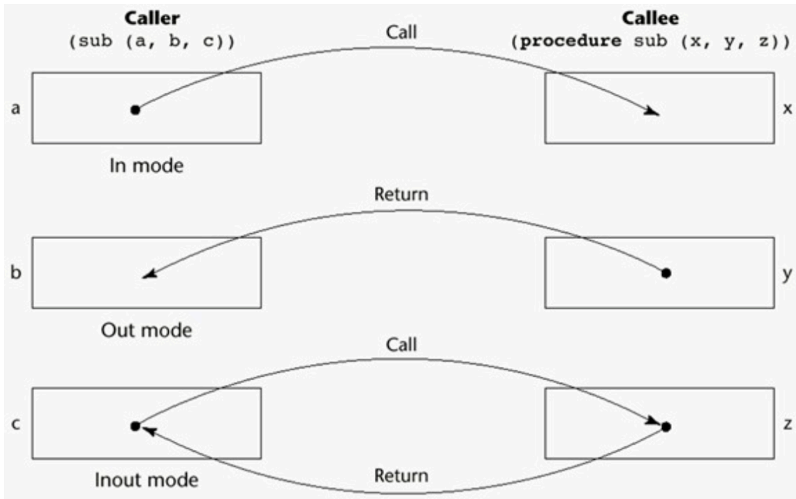
- Ways in which parameters are transmitted to and/or from callee subroutines
  - Semantic models
  - Implementation models



## Semantic Models

- Formal parameters are characterized by one of three distinct semantic models
  - **In mode**: They can receive data from the corresponding actual parameters
  - **Out mode**: they can transmit data to the actual parameters
  - **Inout mode**: they can do both

# Models of Parameter Passing






# An Example

```
public int[] merge(int[] arr1, int[] arr2) {
    int[] arr = new int[arr1.length + arr2.length];
    for (int i = 0; i < arr2.length; i++) {
        arr[i] = arr1[i];
        arr2[i] = arr1[i] + arr2[i];
        arr[i + arr1.length] = arr2[i];
    }
    return arr;
}
```

Which parameter is in mode, out mode, or inout mode?

## Implementation Models

- A variety of models have been developed by language designers to guide the implementation of the three basic parameter transmission modes
  - Pass-by-value
  - Pass-by-result
  - Pass-by-value-result
  - Pass-by-reference
  - Pass-by-name



## Pass-by-Value

- The value of the actual parameter is used to initialize the corresponding formal parameter, which then acts as a local variable in the subprogram
- Implement in-mode semantics
- Implemented by copy

# Pros and Cons

- Pros
  - Fast for scalars, in both linkage cost and access time
  - No side effects to the parameters
- Cons
  - Require extra storage for copying data
  - The storage and copy operations can be costly if the parameter is large, such as an array with many elements



# Pass-by-Result

- No value is transmitted to a subroutine
- The corresponding formal parameter acts as a local variable, whose value is transmitted back to the caller's actual parameter
  - E.g.,
```
void Fixer(out int x, out int y) {
    x = 17;
    y = 35;
}
```
- Implement out-mode parameters

## Pros and Cons

- Pros
  - Same as pass-by-value
- Cons
  - The same cons of pass-by-value
  - Parameter collision
    - E.g., Fixer(x, x), what will happen?
    - If the assignment statements inside Fixer() can be reordered, what will happen?



## Pass-by-Value-Result

- A combination of pass-by-value and pass-by-result, also called **pass-by-copy**
- Implement inout-mode parameters
- Two steps
  - The value of the actual parameter is used to initialize the corresponding formal parameter
  - The formal parameter acts as a local variable, and at subroutine termination, its value is transmitted back to the actual parameter

# Pros and Cons

- Pros
  - Same as pass-by-reference, which is to be discussed next
- Cons
  - Same as pass-by-result



# Pass-by-Reference

- A second implementation model for inout-mode parameters
- Rather than copying data values back and forth, it shares an access path, usually an address, with the caller
  - E.g., void fun(int &first, int &second)

# Pros and Cons

- Pros
  - Passing process is efficient in terms of time and space
- Cons
  - Access to the formal parameters is slower than pass-by-value parameters due to indirect access via reference
  - Side effects to parameters
  - Aliases can be created