

## Part VI: Procedural Language Design Issues

### CSC 324: Principles of Programming Languages

#### Procedural Language Design Issues

##### READING:

Sebesta 4.3,4.4,4.8–4.10;  
8.1–8.5,8.11; 9.1–9.5

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#### Components of a Procedure

1. Name
2. Formal parameters, optionally with types
  - **parameter** (formal parameter)  
Local variable whose value is received from caller
  - **argument** (actual parameter)  
The info passed from caller to callee
3. Body, which is a syntactic construct in the language:
  - Block, i.e., declarations and statements
  - Expression
  - Conjunction of terms
4. Optional result, optionally with a type

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#### Procedures: A Control Abstraction

- A block of code that can be called (imperative)
- A lambda expression (functional)
- A horn clause (logic programming)

#### Procedures modularize program structure

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#### Procedure Implementation Issues

The general notion of a procedure leaves a number of points unspecified:

- How to pass parameters when the procedure is called
- How to maintain local state and control information
- How to access non-local names within a procedure body

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## Parameter Passing

Matching arguments with parameters:

### 1. Positional association:

- Arguments are associated with parameters left to right

### 2. Keyword association:

- Arguments are given tags, eg:  
procedure plot (x,y: real; penup:  
boolean)  
...  
plot(0.0, 0.0, penup=>true)  
plot(penup=>true, x=>0.0, y=>0.0)

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## Parameter Passing

### 3. Optional arguments:

- E.g., C printf(...)
- Extra arguments are packaged into some structure
- Passed to special parameter

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## Passing Modes

How to treat arguments

(pass-by-x/call-by-x):

### 1. Pass by value

(Java, C, C++, Pascal, Ada, Scheme, Algol68)

### 2. Pass by result

(Ada)

### 3. Pass by value-result

(some Fortrans, Ada)

### 4. Pass by reference

(Java objects, C++ with &, some Fortrans, Pascal with var, COBOL)

### 5. Pass by name

(Algol 60)

## Example for Passing Modes

```
{ c : array[1..10] of integer;
  m,n integer;
  procedure r (i , j : integer ) begin
    i := i + 1;
    j := j + 2
  end r;
  ...
  m := 2;
  n := 3;
  r(m,n);           // call 1
  write m, n ;     // print 1

  m := 2;
  c[1] := 1;
  c[2] := 4;
  c[3] := 8;
  r(m,c[m]);           // call 2
  write m,c[1],c[2],c[3]; // print 2
}
```

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## Pass by Value

- Initial values of parameters copied from current values of arguments
- Final values of parameters are “lost” at return time (like local variables).
- Example:

```
at call 1: i = 2 j = 3
print 1:
at call 2: i = 2 j = 4
print 2:
```
- Benefit: Arguments protected from changes in procedure.
- Problem: Requires copying of values: costs time and space, especially for large aggregates.

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## Pass by Result (Example)

Suppose proc `r` initializes `i` and `j` to 0:

- `call 1`:
  - final values of `i` and `j`:
  - `m` and `n` are set to:
- `print 1`:
- `call 2`: more problematic
  - final values of `i` and `j`:
  - which element of `c` is modified, `c[1]` or `c[2]`?
- `print 2`:
  - If `c[1]` is modified:
  - If `c[2]` is modified:

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## Pass by Result

- No initial values of parameters
  - Final values of parameters are copied back to arguments
  - Example: does not work, as written
- ⇒ For **output** values only. Used to indicate that a parameter is intended solely for returning a result.

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## Problems with Pass by Result

- Requires copying of values: costs time and space, especially for large aggregates. (Cf. Call by value.)
- What if the argument is not a variable?  
E.g., `r(1, 2)`;
- What if a variable is used twice in the argument list?  
E.g., `r(m, m)`;
- What about calculations to determine locations of arguments?  
E.g., which `c[m]`?

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## Pass by Value-Result

- Initial values of parameters copied from current values of arguments
- Final values of parameters copied back to arguments

⇒ Combines functionality of pass by value and pass by result for **same** parameter.

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## Further Specifying Pass by Result

With pass by result or pass by value-result, order of assignments and address computations is important.

Options:

1. Perform return address computations at call time:  
On second return:  
m set to 3; c[2] set to 6  
print 2:

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## Pass by Value-Result (Example)

- call 1:
  - initial: i = j =
  - final: i = j =
  - return: m and n set to:
- print 1:
- call 2:
  - initial: i = j =
  - final: i = j =
  - return: which element of c is modified, c[2] or c[3]?
- print 2:
  - if c[2] is modified:
  - if c[3] is modified:

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## Further Specifying Pass by Result (cont'd)

2. Perform return address computations at return time:
  - (a) Before any assignments:
    - On second return: same as above, but might not be if procedure has side-effects
  - (b) Just before that assignment, in order:
    - On second return:  
m set to 3; c[3] set to 6  
print 2:

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## Pass by Reference (Example)

### Pass by Reference

- Formal parameters are pointers to the actual parameters (arguments).
- Address computations are performed at procedure call.
- Changes to the formal parameters are thus changes to the actual parameters.

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- call 1:
  - initial:     i =     j =
  - final:     i =     j =
  - return: m, n are:
- print 1:
- call 2:
  - initial:     i =     j =
  - final:     i =     j =
  - return: m, c[2] are:
- print 2:

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### Pass by Reference

- Benefit: No copying for variables
- Problem: allow redefinition of expressions and constants?
- Problem: Leads to **aliasing**
  - two or more visible names for same location
  - can cause side effects not visible from code itself

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### Aliasing

```
{ y : integer ;  
  procedure p ( x : integer ) begin  
    x := x + 1;  
    x := x + y  
  end p;  
  ...  
  y := 2;  
  p(y);  
  write y  
}
```

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### Aliasing

Pass by Reference:

- The identifiers `x` and `y` refer to the same location in call of `p`.
- Result of “`write y`”?

Pass by Value-Result:

- The identifiers `x` and `y` refer to different locations in call of `p`.
- Result of “`write y`”?

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```
{ i, j, k : integer ;  
  procedure q ( a, b : integer ) begin  
    a := i * b;  
    b := i * b;  
  end q;  
  ...  
  i := 2; j := 3; k := 4;  
  q(i,j);  
  q(k,k);  
}
```

- First call has global-formal aliases:
  - `a` and `i`
  - `b` and `j`
- Second call has formal-formal alias:
  - `a` and `b`

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### Pass by Name (Example)

#### Pass by Name

- A “name” for the argument is passed in to procedure
- Like textual substitution of argument in procedure
- Thus address computations are done whenever parameter is used
- Like pass-by-reference for scalar parameters

- Example:
  - call 1: `m, n` set to:
  - print 1:
  - call 2: `m, c[m]` set to:
  - print 2:
- Benefit: same as pass by reference
- Problems: Inefficient, requires a *thunk*:
  - essentially a little program is passed that represents the argument
  - evaluates argument in caller’s environment

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## Procedure Activations

### Summary of Parameter Passing Modes

- Pass by value
- Pass by result
- Pass by value-result
- Pass by reference
- Pass by name

Lifetime of procedure:

- Begins when control enters activation (call)
- Ends when control returns from activation

Activation Tree:

- Shows flow of control from one activation to another
- Root: Main program
- Edges: Call from one procedure to another (read left to right)
- Leaves: Procedures that call no other procedures

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## Sample Activation Trees

### Example

```
main
  procedure P
  begin
    procedure S begin ... end S;
    if random(1) < 1 then P()
    else { S(); Q() }
  end P;
  procedure Q begin ... end Q;
  P;
  Q;
  P;
end
```

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## Activation Trees and Stack Frames

Running a program corresponds to a **traversal** of (one of) its activation tree(s).

We can represent the traversal of the tree using a **stack**.

Each item on the stack is called a **frame**.

⇒ The stack of frames not only maintains the call sequence info, but also keeps track of the local and non-local environment for each procedure.

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## Procedure Activation and Run-time Stack

On a call:

1. Set up stack frame on top of run-time stack (current context)
2. Do the real work of the procedure body
3. Release stack frame and restore caller's context (as new top of stack)

Run-time stack establishes a **context** for a procedure invocation

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## Content of Stack Frames

- Run-time stack contains frames for main program and each active procedure.
- Each stack frame includes:
  1. Pointer to stack frame of caller (Control Link)
  2. Return address (within caller)
  3. Mechanism to find non-local variables (Access Link)
  4. Storage for parameters
  5. Storage for local variables
  6. Storage for temporary and final values
- In a language with first-class functions, this is more complex.

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## Context of Procedures

**Two** contexts:

- **static** placement in source code (same for each invocation)
- **dynamic** run-time stack context (different for each invocation)

**Name Resolution:** Given the **use** of a name (variable or procedure name), which **instance** of the entity with that name is referred to?

⇒ Both static and dynamic contexts play a role in this determination.

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## Some Terminology

### Scope

Each use of a name must be associated with a single entity at run-time (ie, an offset within a stack frame).

The **scope** of a declaration of a name is the part of the program in which a use of that name refers to that declaration.

The design of a language includes **scope rules** for resolving the mapping from the use of each name to its appropriate declaration.

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A name is:

- **visible** to a piece of code if its scope includes that piece of code.
- **local** to a piece of code (block/procedure/main program) if its declaration is within that piece of code.
- **non-local** to a piece of code if it is visible, but its declaration is not within that piece of code.

A declaration of a name is **hidden** if another declaration supersedes it in scope.

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### Scope Rules

Two choices:

1. Use static context: **lexical scope**
2. Use dynamic context: **dynamic scope**

For local names, these are the same.

⇒ Harder for non-local names, and not necessarily the same for both types of scope.

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### Scope Example

```
program L;
  var n: char;    {n declared in L}

  procedure W;
  begin
    write(n);    {n referenced in W}
  end;

  procedure D;
  var n: char; {n declared in D}
  begin
    n:= 'D';    {n referenced in D}
    W
  end;

begin
  n:= 'L';      {n referenced in L}
  W;
  D
end.
```

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## Lexical Scope

- Names are associated with declarations at *compile* time
- Find the smallest block syntactically enclosing the reference and containing a declaration of the name
- Example:
  - The reference to  $x$  in  $W$  is associated with the declaration of  $x$  in  $L$
  - The output is?

**Benefit:** Easy to determine the right declaration for a name from the text of the program.

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## Dynamic Scope

- Names are associated with declarations at *run* time
- Find the most recent, currently active run-time stack frame containing a declaration of the name
- Example:
  - The reference to  $x$  in  $W$  is associated with two different declarations at two different times
  - The output is?

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## Dynamic Scope: Pros and Cons

**Benefit:** reduces need for parameters.

**Problems:**

- hard to understand behavior from the text alone.
- renaming variables can have unexpected results.
- no protection of one's local variables from a called procedure.  
(I.e, if  $A$  calls  $B$ ,  $B$  can modify  $A$ 's local variables.)
- can be slower to execute.

**NOTE:** Most languages use lexical scope, although early interpreted languages used dynamic scope because of the flexibility and ease of implementation.

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## Scoping and the Run-time Stack

**Access link** shows where to look for non-local names.

**Static Scope:**

Access link points to stack frame of the lexically enclosing procedure  
(total no. links to follow determined at **compile time**)

**Dynamic Scope:**

Access link points to stack frame of caller

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## Nested Procedures and Static Scope

```
program
  a,b,c : integer;           // 1
  procedure r
    a : integer;             // 5
    ... a ... b ... c
  end r;                       // 6
  procedure p
    c : integer;             // 3
    procedure s
      d,e : integer          // 8
      ... a ... b ... c ...
      r;                       // 9
    end s;
    r;                         // 4
    s;                          // 7
  end p;

  p;                           // 2
end
```

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## Nesting Depth

**Nesting depth** of a procedure is how many lexical levels deep it is.

- Main program has nesting depth 1.
- Body of `p` has nesting depth 2.
- Body of `s` has nesting depth 3.

**Note: Declarations** of `p` and `r` have nesting depth 1, but declarations and statements **within** `p` and `r` have nesting depth 2.

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## Nesting Depth and Access Links

```
.
.
.
procedure v
.
.
begin /* v */
.
.
...u...; /* use of u */
.
.
end; /* v */
.
.
```

To determine the access link for name `u`, follow  $n - m$  access links from `proc v` in which `u` is used, where  $n$  is the nesting depth of the body of `v` and  $m$  is the nesting depth of the declaration of `u`.

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## Run-Time Stack Trace

Trace through above program, showing snapshot of run-time stack at points 1, 3, 5, 8, 5 (again).

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## Dynamic Scope Example

```
program
  a : integer;
  procedure z
    a : integer; ...
    a := 1;
    y;
    output a;
  end z;
  procedure w
    a : integer; ...
    a := 2;
    y;
    output a;
  end w;
  procedure y ...
    a := 0;
  end y;
  a := 5;
  z;
  w;
  output a;
end
```

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### Using a Display

- If a procedure is at nesting depth  $n$ , it may have to follow  $n - 1$  static links to find variable addresses
- Display is an array of pointers to stack frames
- A variable is stored at an offset in the frame pointed to by the  $i$ 'th display element, where  $i$  is the nesting level of procedure where variable was declared
- Display must be maintained along with run-time stack

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## Optimizing Variable Access

**Problem:** Accessing non-local names requires following links up the access link chain.

### Solution for lexical scoping only:

Maintain a vector of currently-active static-chain frames.

- Called the **display**
- Pioneered in Algol60
- Makes addresses directly accessible

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## Display in Static Example

For example, during execution of proc  $s$ :

D[1]: Pointer to stack frame for main pgm

D[2]: Pointer to stack frame for procedure  $p$

D[3]: Pointer to stack frame for procedure  $s$

- Address of  $d$  is  $D[3] + \text{Offset} + 0$
- Address of  $e$  is  $D[3] + \text{Offset} + 1$
- Address of  $c$  is  $D[2] + \text{Offset} + 0$
- Address of  $a$  is  $D[1] + \text{Offset} + 0$
- Address of  $b$  is  $D[1] + \text{Offset} + 1$

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## Summary of Part VI: Procedural Language Design Issues

- Components of a procedure
  - name
  - parameters
  - body
  - optional result
- Parameter passing
  - pass by value
  - pass by result
  - pass by value-result
  - pass by reference
  - pass by name
- Aliasing through parameter passing
- Procedure Activations
- Stack frames
- Lexical scope
- Dynamic scope
- Implementing scope with stack frames
- Displays