CS 314 Principles of Programming Languages

Lecture 14: Names, Scopes and Bindings

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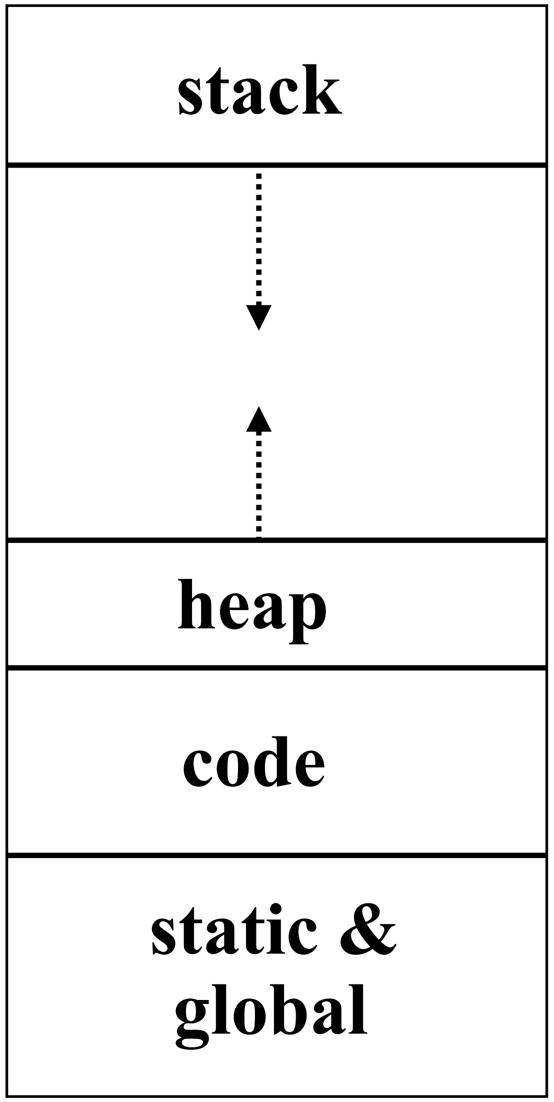
Review: Program Memory Layout

- Static objects are given an absolute address that is retained throughout the execution of the program
- Stack objects are allocated and deallocated in last-in, first-out order, usually in conjunction with subroutine calls and returns
- Heap objects are allocated and deallocated at any arbitrary time



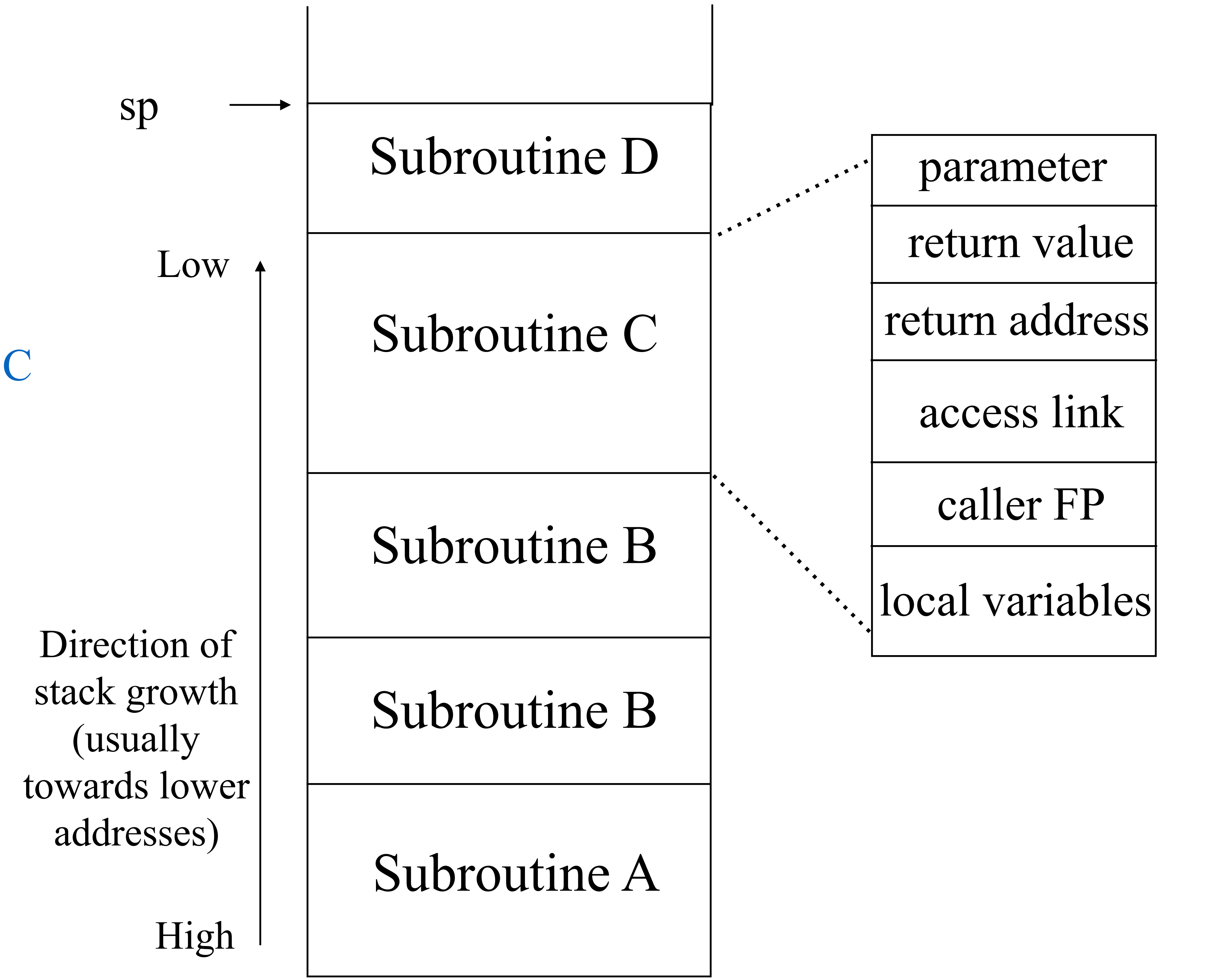
Review: Procedure Activations

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

Calling chain: $A \Rightarrow B \Rightarrow B \Rightarrow C \Rightarrow D$

Example:

procedure C:
  D
procedure B:
  if…then B else C
procedure A:
  B
main program:
  A



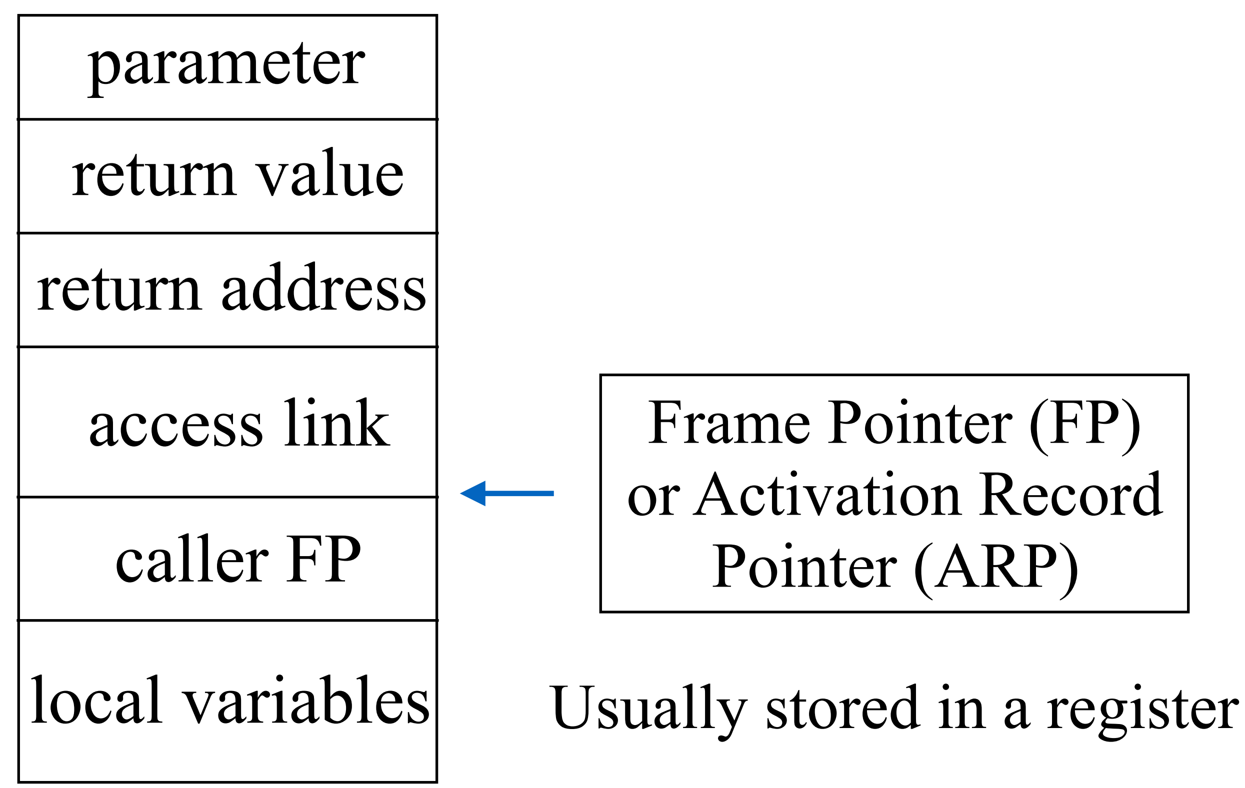
Review: Procedure Activations

- Run-time stack contains frames from main program & active procedure
- Each **stack frame** includes:
  1. Pointer to stack frame of caller
     (**control link** for stack maintenance and dynamic scoping)
  2. Return address (within calling procedure)
  3. Mechanism to find non-local variables (**access link** for lexical scoping)
  4. Storage for parameters, local variables and final values
  5. Other temporaries including intermediate values & saved register

Stack Frame

or

Activation Record



Lexical Scope v.s. Dynamic Scope

Lexical Scope

- Non-local variables are associated with declarations at *compile* time
- Find the smallest block ***syntactically*** enclosing the reference and containing a declaration of the variable

Dynamic Scope

- Non-local variables are associated with declarations at *run* time
- Find the ***most recent, currently*** active run-time stack frame containing a declaration of the variable

Lexical Scope

- Non-local variables are associated with declarations at *compile* time
- Find the smallest block syntactically enclosing the reference and containing a declaration of the variable
- Example:
  - The reference to n in W is associated with two different declarations at two different times
  - The output is?

L

Calling Chain:

$$L \Rightarrow W$$

$$L \Rightarrow D \Rightarrow W$$

```
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
```

Lexical Scope

- Non-local variables are associated with declarations at *compile* time
- Find the smallest block syntactically enclosing the reference and containing a declaration of the variable
- Example:
  - The reference to n in W is associated with two different declarations at two different times
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        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
```

Dynamic Scope

- Non-local variables are associated with declarations at *run* time
- Find the most recent, currently active run-time stack frame containing a declaration of the variable
- Example:
  - The reference to n in W is associated with two different declarations at two different times
  - The output is ?

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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
```

Calling Chain:

$$L \Rightarrow W$$

$$L \Rightarrow D \Rightarrow W$$

Dynamic Scope

- Non-local variables are associated with declarations at *run* time
- Find the most recent, currently active run-time stack frame containing a declaration of the variable
- Example:
  - The reference to n in W is associated with two different declarations at two different times
  - The output is ?

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D

Calling Chain:

$$L \Rightarrow W$$

$$L \Rightarrow D \Rightarrow W$$

```
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
```

Lexical Scope v.s. Dynamic Scope

Lexical Scope

- Non-local variables are associated with declarations at *compile* time
- Find the smallest block ***syntactically*** enclosing the reference and containing a declaration of the variable
- <u>Access link</u> points to the most recently activated immediate lexical ancestor

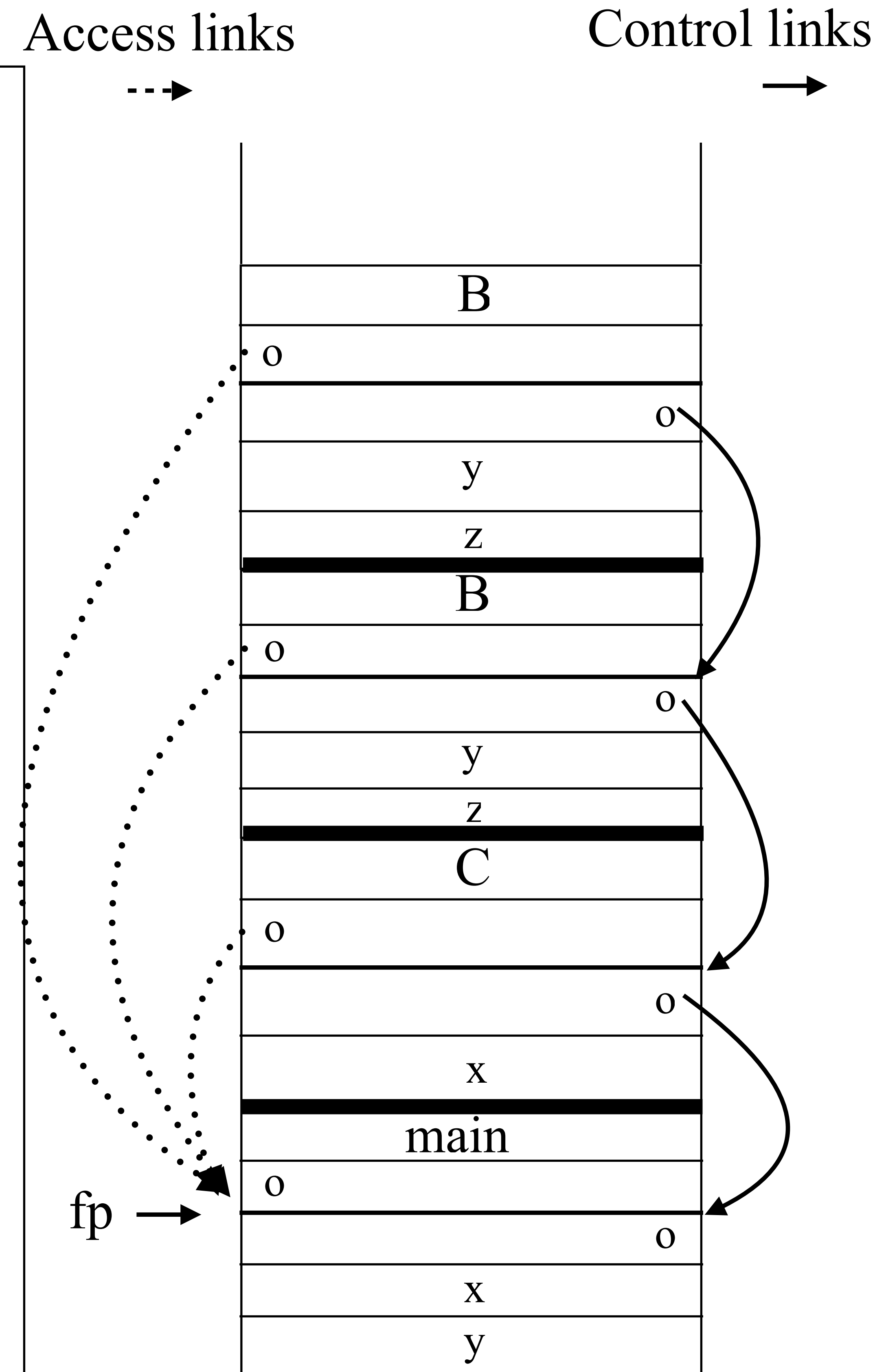
Dynamic Scope

- Non-local variables are associated with declarations at *run* time
- Find the ***most recent, currently*** active run-time stack frame containing a declaration of the variable
- <u>Control link</u> points to the caller

Lexical Scoping and Dynamic Scoping Example

Calling chain: MAIN⇒ C ⇒ B ⇒ B

```
Program
        x, y: integer   // declarations of x and y
        Procedure B     // declaration of B
                y, z: real  // declaration of y and z
                begin
                ...
                y = x + z // occurrences of y, x, and z
                if (...) call B // occurrence of B
                end
         Procedure C    // declaration of C
                x: real
                begin
                ...
                call B // occurrence of B
                end
         begin
           ...
         call C     // occurrence of C
         call B     // occurrence of B
end
```



Context of Procedures

Two contexts

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

Scope Rules:

Each variable reference must be associated with a single declaration.

Two choices:

1. Use static and dynamic context: *lexical scope*
2. Use dynamic context: *dynamic scope*
    - Easy for variables declared locally, and same for *lexical* and *dynamic* scoping
    - Harder for variables not declared locally and not same for *lexical* and *dynamic* scoping

Access to Non-Local Data(Lexical Scoping)

Using access link:

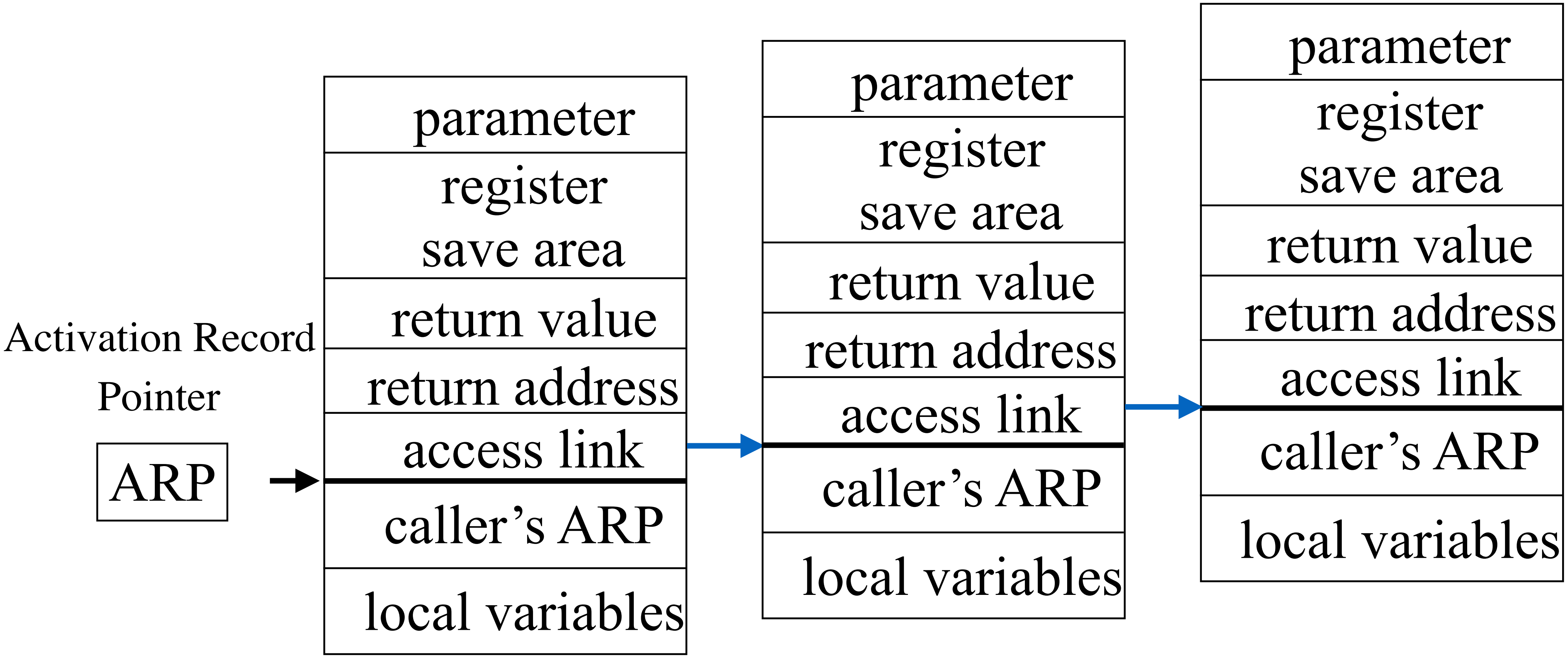
Runtime: To find the value specified by (l,o)
Assume nested procedure has higher index than its parent procedure.

- Need current procedure level k
- If $k = l$, it is a local variable
- If $k > l$, must find l's activation record
  $\Rightarrow$ follow $k - l$ access link
- $k < l$ cannot occur

Access to Non-Local Data(Lexical Scoping): Access Link

Using access links (static links)

- Each AR has a pointer to most recent AR of immediate lexical ancestor
- Lexical ancestor does not need to be the caller



Example: reference to <p, 16> runs up access link to p

Cost of access link is proportional to lexical distance

Access to Non-Local Data(Lexical Scoping)

Using access link:

<u>Runtime</u>: To find the value specified by (l,o)

Assume nested procedure has higher index than its parent procedure.

- Need current procedure level k
- If $k = l$, it is a local variable
- If $k > l$, must find l*'s* activation record
  $\Rightarrow$ follow $k - l$ access link
- $k < l$ cannot occur

Maintaining Access Links

Setting up access link:

If procedure *p* is nested immediately within procedure *q*, the access link for *p* points to the activation record of the *most recent* activation of *q*.

- Calling level k + 1 procedure
  1. Pass my FP as access link
  2. My backward chain will work for lower levels
- Calling procedure at level i ≤ k
  1. Find my link to level i - 1 and pass it to callee
  2. Its access link will work for lower levels

Code Generation: Access to Non-Local Data(Lexical Scoping)

Two important steps

1. *Compile-time*: How do we map a name into a (level, offset) pair?
   We use a block structured symbol table (**compile time**)
   - when we look up a name, we want to get the most recent declaration for the name
   - the declaration may be found in the current procedure or in any ancestor procedure
2. *Run-time*: Given a (level, offset) pair, what's the address?
   - Two classical approaches:
     - ⇒ access link (*static link*)
     - ⇒ display

Lexical Scoping

Symbol table generated at compile time matches declarations and occurrences.
⇒ Each name can be represented as a pair (nesting_level, local_index).

```
Program
  x, y: integer   // declarations of x and y
  Procedure B     // declaration of B
    y, z: real  // declaration of y and z
    begin
      ...
      y = x + z // occurrences of y, x, and z
      if (...) call B // occurrence of B
    end
  Procedure C     // declaration of C
    x: real
    begin
      ...
      call B // occurrence of B
    end
  begin
  ...
  call C     // occurrence of C
  call B     // occurrence of B
end
```

```
Program
  (1,1), (1,2): integer   // declarations of x and y
  Procedure (1,3)     // declaration of B
    (2,1), (2,2): real  // declaration of y and z
    begin
      ...
      (2,1) = (1,1) + (2,2) // occurrences of y, x, and z
      if (...) call (1,3) // occurrence of B
    end
  Procedure (1,4)     // declaration of C
    (2,1): real
    begin
      ...
      call (1,3) // occurrence of B
    end
  begin
  ...
  call (1,4)     // occurrence of C
  call (1,3)     // occurrence of B
end
```

The Display

To improve run-time access costs, use a *display*.

- table of access links for lower levels
- lookup is index from known offset
- takes slight amount of time at call
- a single display or one per frame

Access with the display

assume a value described by (l,o)

- find slot as DP[*l*] in display pointer array
- add offset to pointer from slot

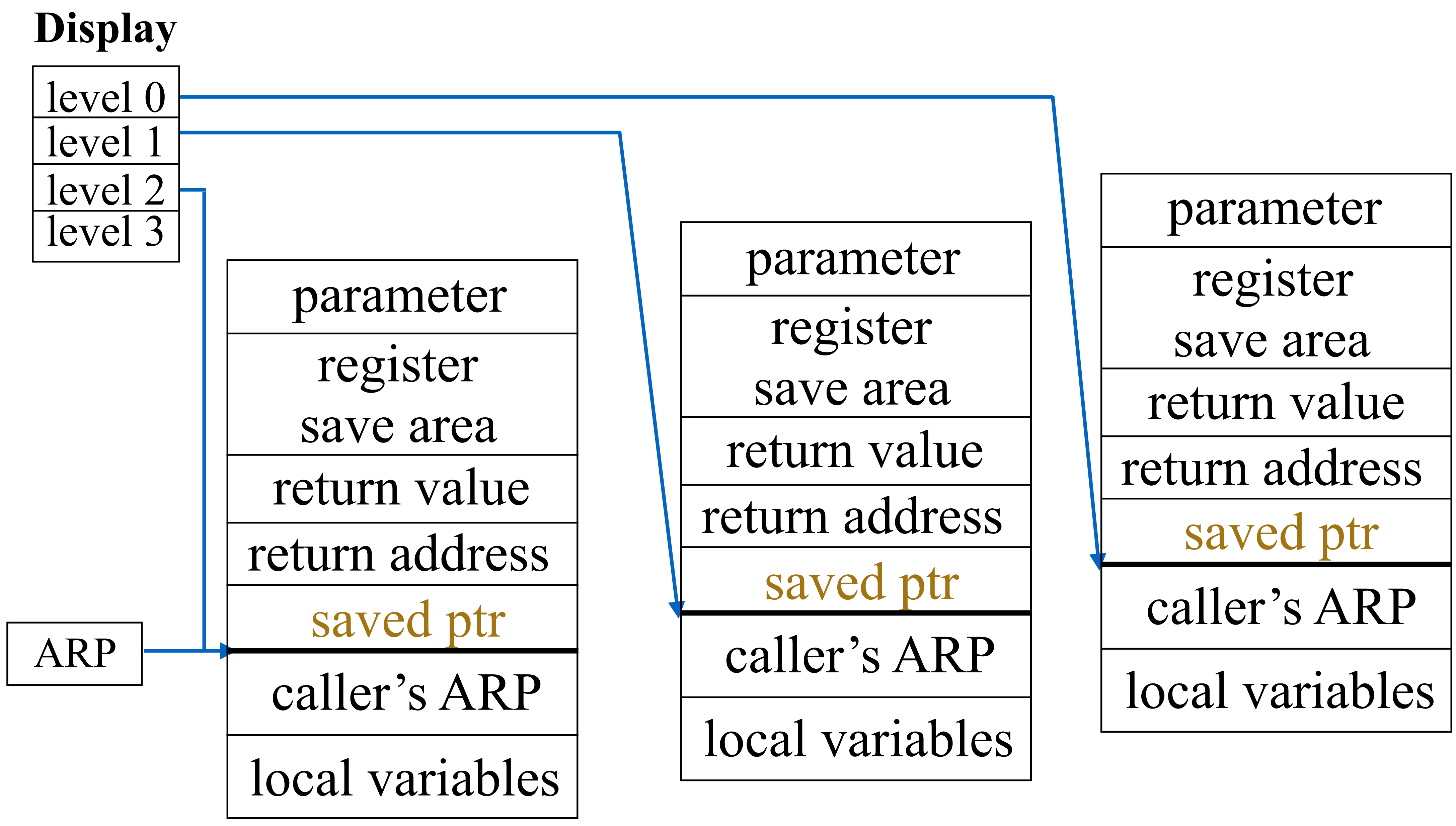
"Setting up the activation frame" now includes display manipulation.

Access to Non - Local Data(Lexical Scoping): Display

Using a display

Cost of access link is constant (APR + offset)

- Global arrays of pointers to nameable array
- Needed ARP is an array access away



Example: reference to <p, 16> looks up p's APR in display and add 16

Display Management

Single global display:

On entry to a procedure at level i:

Save the level i display value
push FP into level i display slot

On return:

Restore the level i display value

parameter
register save area
return value
return address
saved ptr
caller's ARP
local variables

Procedures

- Modularize program structure
  - Actual parameter: information passed from caller to callee (*Argument*)
  - Formal parameter: <u>local</u> variable whose <u>value</u> (usually) is received from caller
- Procedure declaration
  - Procedure names, formal parameters, procedure body with formal local declarations and statement lists, optional result type

    Example: void translate(point *p, int dx)

Parameters

Parameter Association

- Positional association: Arguments associated with formals one-by-one; Example: C, Pascal, Java, Scheme
- Keyword association: formal/actual pairs; mix of positional and keyword possible;
  Example: Ada

  procedure plot(x, y: in real; z: in boolean)

  … plot (0.0, 0.0, z   ⇒ true)

  … plot (z ⇒ true, x ⇒ 0.0, y ⇒ 0.0)

Parameter Passing Modes

- Pass-by-value: C/C++, Pascal, Java/C# (value types), Scheme
- Pass-by-result: Ada, Algol W
- Pass-by-value-result: Ada, Swift
- Pass-by-reference: Fortran, Pascal, C++, Ruby, ML

Pass-by-value

```
begin
    c: array[1...10] of integer;
    m, n: integer;
    procedure r(k, j: integer)
    begin
        k := k + 1;
        j := j + 2;
    end r;
  ...
  m := 5;
  n := 3;
  r(m, n);
  write m,n;
end
```

Output:

5 3

Advantage: Argument protected from changes in callee.
Disadvantage: Copying of values takes execution time and space, especially for aggregate values (e.g.: structs, arrays)

Pass-by-reference

```
begin
       c: array[1...10] of integer;
       m, n: integer;
       procedure r(k,j: integer)
       begin
              k := k + 1;
              j := j + 2;
       end r;
  ...
  m := 5;
  n := 3;
  r(m, n);
  write m, n;
end
```

Output:

6 5

Advantage: more efficient than copying
Disadvantage: leads to aliasing, there are two or more names for the storage location; hard to track side effects

Pass-by-result

```
begin
    c: array[1...10] of integer;
    m, n: integer;
    procedure r(k, j: integer)
    begin
        k := k + 1;   → ERROR:
        j := j + 2;       CANNOT USE PARAMETERS WHICH ARE UNINITIALIZED
    end r;
   ...
   m := 5;
   n := 3;
   r(m, n);
   write m, n;
end
```

Output:

Program doesn’t compile or has runtime error

Pass-by-result

```
begin
      c: array[1...10] of integer;
      m, n: integer;
      procedure r(k, j: integer)
      begin
            k := 1;   → HERE IS A PROGRAM THAT WORKS
            j := 2;
      end r;
    ...
    m := 5;
    n := 3;
    r(m, n);
    write m, n;
end
```

Output: ?

Pass-by-result

```
begin
        c: array[1...10] of integer;
        m, n: integer;
        procedure r(k, j: integer)
        begin
                k := 1;  → HERE IS ANOTHER PROGRAM THAT WORKS
                j := 2;
        end r;
      ...
      m := 5;
      n := 3;
      r(m, m);→ NOTE: CHANGE THE CALL
      write m, n;
end
```

Output: 1 or 2 for m?

Problem: order of copy back makes a difference;
implementation dependent.

Pass-by-value-result

```
begin
    c: array[1...10] of integer;
    m, n: integer;
    procedure r(k, j: integer)
    begin
        k := k + 1;
        j := j + 2;
    end r;
   ...
   m := 5;
   n := 3;
   r(m, n);
   write m, n;
end
```

Output: 6 5

Problem: order of copy back makes a difference;
implementation dependent.

Pass-by-value-result

```
begin
      c: array[1...10] of integer;
      m, n: integer;
      procedure r(k, j: integer)
      begin
            k := k + 1;
            j := j + 2;
      end r;
     ...
     /* set c[m] = m */
     m := 2;
     r(m,c[m]);→  WHAT ELEMENT OF "c" IS ASSIGNED TO?
     write c[1], c[2], c[3], ... c[10];
end
```

Output:

Pass-by-value-result

```
begin
      c: array[1...10] of integer;
      m, n: integer;
      procedure r(k, j: integer)
      begin
            k := k + 1;
            j := j + 2;
      end r;
     ...
     /* set c[m] = m */
     m := 2;
     r(m,c[m]);→  WHAT ELEMENT OF "c" IS ASSIGNED TO?
     write c[1], c[2], c[3], ... c[10];
end
```

Output:

Problem: When is the address computed for the copy-back operation? At procedure call (procedure entry), just before procedure exit, or somewhere in between? (Example: ADA on entry)

Pass-by-value-result

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

WHAT ELEMENT OF "c" IS ASSIGNED TO?

Output:

1 4 3 4 5 … 10 on entry

1 2 4 4 5 … 10 on exit

Problem: When is the address computed for the copy-back operation? At procedure call (procedure entry), just before procedure exit, or somewhere in between? (Example: ADA on entry)

Pass-by-value-result

```
begin
      c: array[1...10] of integer;
      m, n: integer;
      procedure r(k, j: integer)
      begin
            k := k + 1;
            j := j + 2;
      end r;
     ...
     /* set c[m] = m */
     m := 2;
     r(m,c[m]);→  WHAT ELEMENT OF "c" IS ASSIGNED TO?
     write c[1], c[2], c[3], ... c[10];
end
```

Output:

1 4 3 4 5 … 10 on entry

1 2 4 4 5 … 10 on exit

Problem: When is the address computed for the copy-back operation? At procedure call (procedure entry), just before procedure exit, or somewhere in between? (Example: ADA on entry)

Aliasing

Aliasing:

More than two ways to name the same object within a scope

Even without pointers, you can have aliasing through (global⟷formal) and (formal⟷formal) parameter passing.

```
begin
        j, k, m: integer;
        procedure r(a, b: integer)
        begin
                b := 3;
                m := m * a;
        end
        ...
        q(m, k);   → global/formal <m,a> ALIAS PAIR
        q(j, j);   → formal/formal <a,b> ALIAS PAIR
        write y;
end
```

Comparison: by-value-result vs. by-reference

Actual parameters need to evaluate to L-values (addresses).

```
begin
        y: integer;
        procedure p(x: integer)
        begin
                x := x + 1     → ref: x and y are ALIASED
                x := x + y     → val-res: x and y are NOT ALIASED
        end
        ...
        y := 2;
        p(y);
        write y;
end
```

Output:

- pass-by-reference: 6
- pass-by-value-result: 5

Note: *by-value-result*: Requires copying of parameter values (expansive for aggregate values); does not have aliasing, but copy-back order dependence.

Next Lecture

Things to do:

- Read Scott, Chapter 9.1 - 9.3 (4th Edition) or Chapter 8.1 - 8.3 (3rd Edition), Chapter 11.1 - 11.3 (4th Edition)