Chapter 10

Implementing Subprograms

“The purpose of this chapter is to explore methods for implementing subprograms in the major imperative languages. The discussion will provide the reader with some insight into how such language “works”? The increased difficulty of implementing subprograms is caused by the need to include support for recursion and for mechanisms to access nonlocal variables.

10.1 The General Semantics of Calls and Returns

- *Subprogram linkage*
  - the subprogram call and return operations of a language are together called its subprogram linkage
  - Any implementation method for subprograms must be based on the semantics of subprogram linkage
- *The actions associated with <u>subprogram</u> <u>call</u>*
  - includes parameter passing mechanism
  - causes storage to be allocated for local variables and bind those variables to that storage
  - save the execution status of calling program unit
  - arranges to transfer control to the code of subprogram and ensure that control can return to the proper place when the subprogram execution is completed
  - cause some mechanism to be created to provide access to nonlocal variables
- *The actions associated with <u>subprogram</u> <u>return</u>*
  - if the subprogram has parameters that are out mode and are implemented by copy, the first action of the return process is to move local values of the associated formal parameters to the actual parameters

    ⇔ how about by-reference or by-copy ?
  - deallocate the storage used for local variables
  - return the mechanism used for nonlocal references
  - control must be returned to the calling program unit

10.2 Implementing "Simple" Subprograms

- Subprograms in early version of FORTRAN
  - subprograms can not be recursive
  - All referencing of nonlocal variables in FORTRAN 77 is through `COMMON`
  - variables declared in subprograms are statically allocated
- The semantics of a FORTRAN 77 ***subprogram call***
  1) Save the execution status of the current program unit
  2) Carry out the parameter-passing process
  3) Pass the return address to the callee
  4) Transfer control to the callee
- The semantics of a FORTRAN 77 ***subprogram return***
  - If pass-by-value-result parameters are used, the current values of those parameters are moved to the corresponding actual parameters
  - If the subprogram is a function, the function value is moved to a place accessible to the caller
  - The execution status of caller is restored
  - Control is transferred back to the caller
- The call and return actions requires ***storage*** for the following:
  - Status information about the caller
  - Parameters
  - Return address
  - Function value for function subprograms

- A FORTRAN 77 subprogram consists of two parts each of which is fixed size:
  - the actual code of subprogram, which is static
  - the local variables and data areas for call/return actions

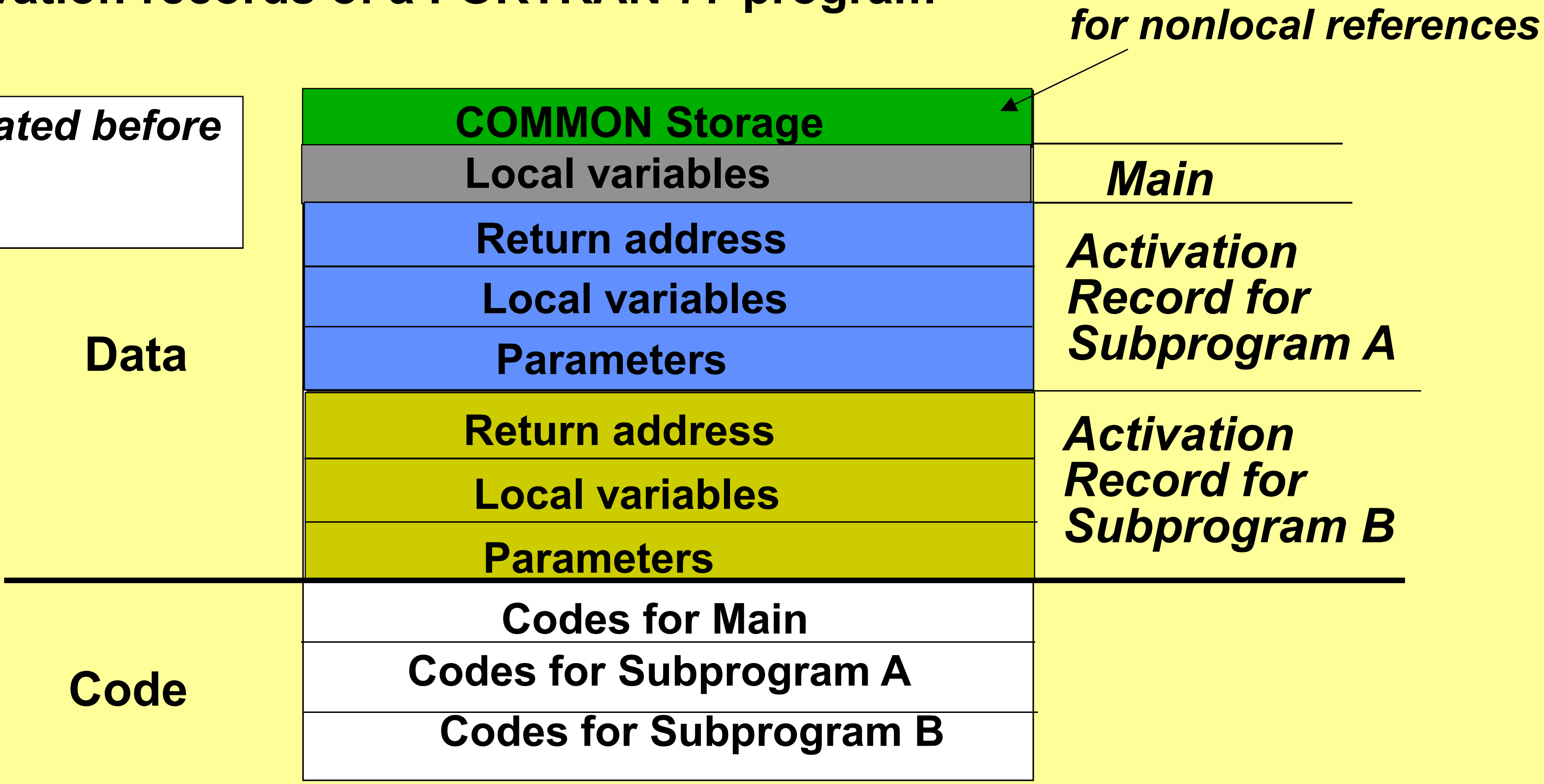
    ⇔ the noncode part of a subprogram is associated with a particular execution, or activation, of subprogram, and is therefore called an *activation record*

    ⇔ because FORTRAN 77 does not support recursion, there can be *only one active version of subprogram a given subprogram at a time*

      ⇒ there can only *a single instance of the activation record* for a subprogram, and *can be statically allocated*

- Code and activation records of a FORTRAN 77 program

** They are allocated before execution*
** Linking*



9.3 Implementing Subprograms with Stack-Dynamic Local Variables (with recursion)

(1) More Complex Activation Records

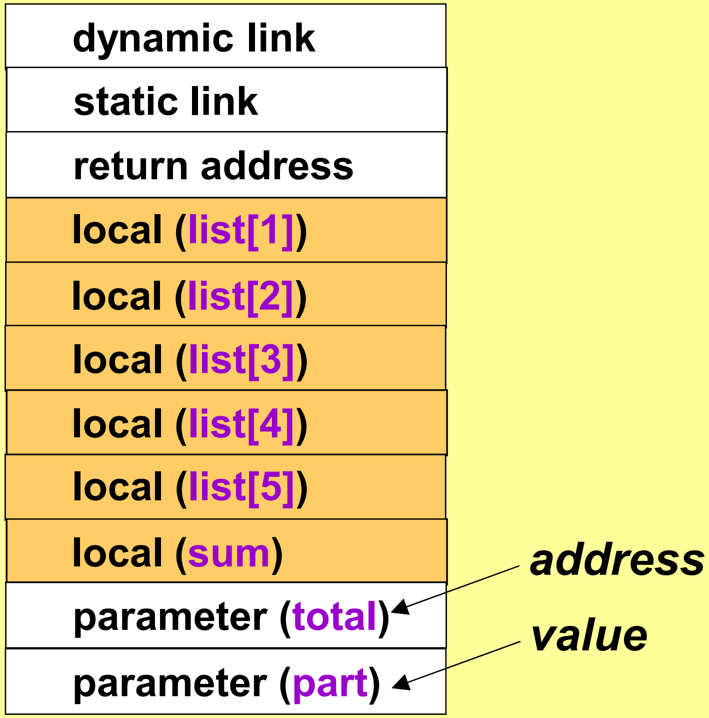
- Subprogram linkage in ALGOL-like languages is more complex than the linkage of FORTRAN 77 subprograms for the following reasons :
  - Parameters are usually passed by two different methods
    - ⇔ For example, in Modular-2, they are passed by value or reference
  - Variables declared in subprograms are often dynamically allocated
  - *Recursion* adds the possibility of *multiple simultaneous activations of a subprogram*
    - ⇔ requires *multiple instances of activation records*
    - ⇔ each activation requires its own copy of the formal parameters and the dynamically allocated local variables, along with the return address
  - ALGOL-like languages use *static scoping* to provide access to nonlocal variables. Support for these nonlocal accesses must be part of the linkage mechanism

- Creation of activation record
  - Activating a procedure requires the dynamic creation of an instance of the activation record for the procedure
  - Because the call and return semantics specify that the subprogram last called is the first completed, it is reasonable to create instance of these activation records on *stack*
    - ⇔ Every procedure activation, whether recursive or nonrecursive, creates a new instance of an activation record on stack

- Activation record
    - ⇔ the format (and size) of an activation record for a given subprogram is known at compile time
    - ⇔ an activation record format is a template for instance of the activation record
  - *Local variables* are bound to storage within an activation record
  - *Static link* (also called *static scope pointer*)
    - ⇔ points to the activation record instance of an activation of the static parent
    - ⇔ used for accesses to nonlocal variables
  - *Dynamic link*
    - ⇔ a pointer to an instance of the activation record of caller (dynamic parent)
    - ⇔ in static-scoped languages, this link is used to in the destruction of current activation record instance when the procedure completes its execution
  - *Return address* : (code_segment, offset)
  - (Actual) Parameters
    - ⇔ the values or addresses provided by the caller

– Example

```
procedure sub (var total : real ;
                   part : integer) ;
   var list : array [1..5] of integer ;
   sum : real ;
   begin
      sum = total + sum ;
   end ;
```



dynamic link

static link

return address

local (list[1])

local (list[2])

local (list[3])

local (list[4])

local (list[5])

local (sum)

parameter (total)

parameter (part)

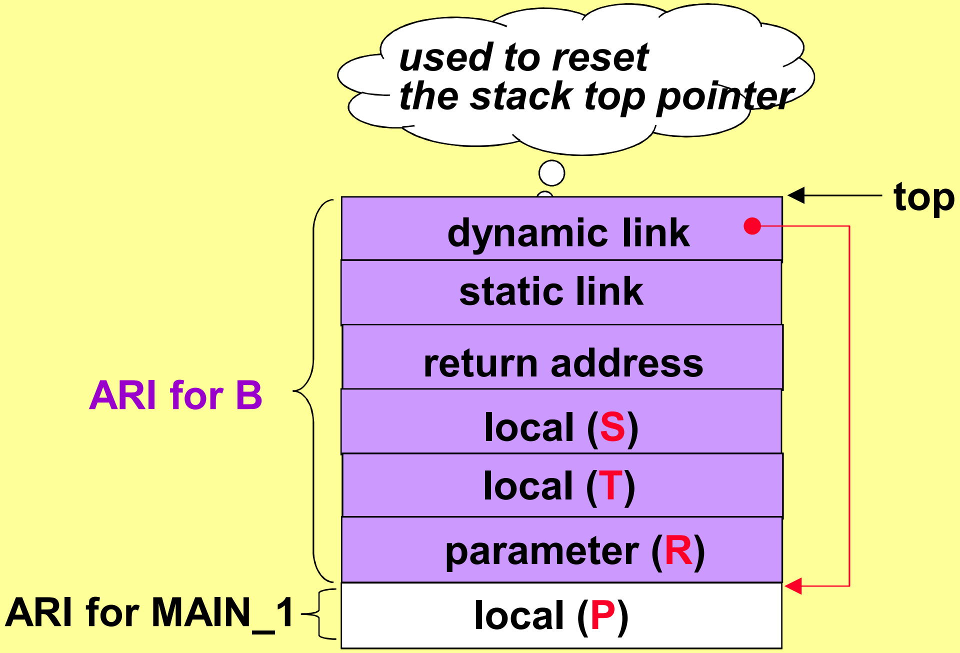
address

value

activation recode for sub

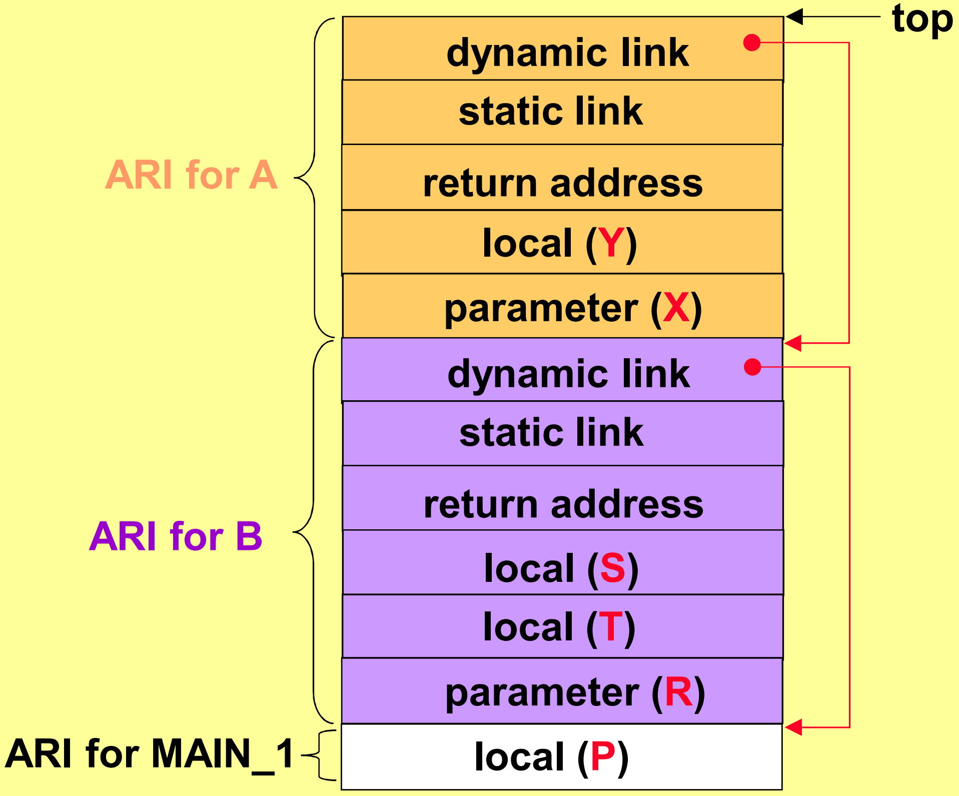
(2) Example Without Recursion and Nonlocal References

```
program MAIN_1
 var P : real;
 procedure A(X:integer);
  var Y:boolean;
  procedure C(Q:boolean);
   begin
    P=P+1;                3
   end
  begin
   …                      2
   C(Y);
   …
  end {end of procedure A}
 procedure B(R:real);
  var S,T;
  begin
   …                      1
   A(S);
   …
  end ({end of procedure B}
 begin {Main_1}
  …
  B(P);
  …
 end
```



At 1

MAIN_1 -> B(P) -> A(S) -> C(Y)



top

ARI for A

dynamic link

static link

return address

local (Y)

parameter (X)

ARI for B

dynamic link

static link

return address

local (S)

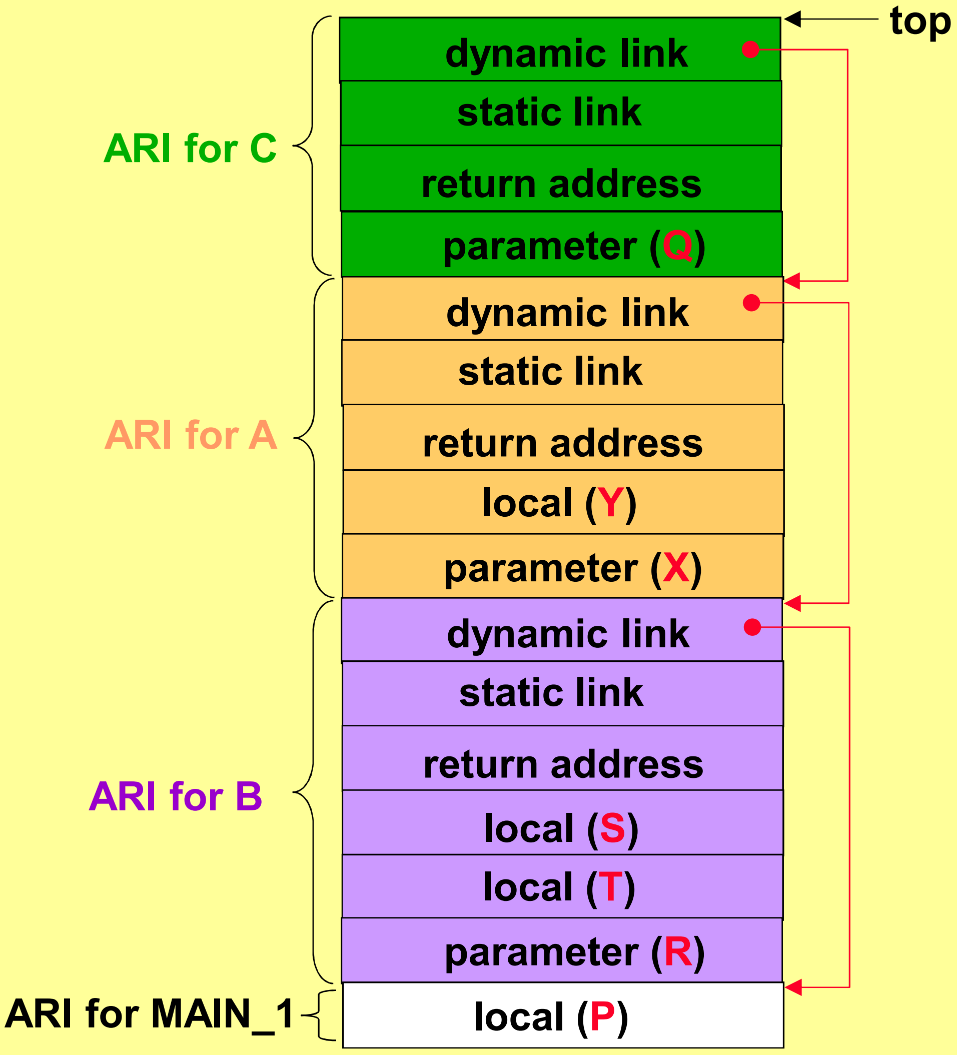
local (T)

parameter (R)

ARI for MAIN_1

local (P)

At 2



top

ARI for C

dynamic link

static link

return address

parameter (Q)

ARI for A

dynamic link

static link

return address

local (Y)

parameter (X)

ARI for B

dynamic link

static link

return address

local (S)

local (T)

parameter (R)

ARI for MAIN_1

local (P)

At 3

- **Dynamic Chain** (or *call chain*)
  - the collection of dynamic links present in the stack at a given time
  - represents the dynamic history of how execution got to its current position
- **Local_Offset**
  - references to local variables can be represented in the code as *offsets from the beginning of the activation record* of the local scope -> local_offset
  - the local_offset of a variable in an activation record can be *determined at compile time*, using the order, types, and sizes of variables declared in the procedure associated with the activation record

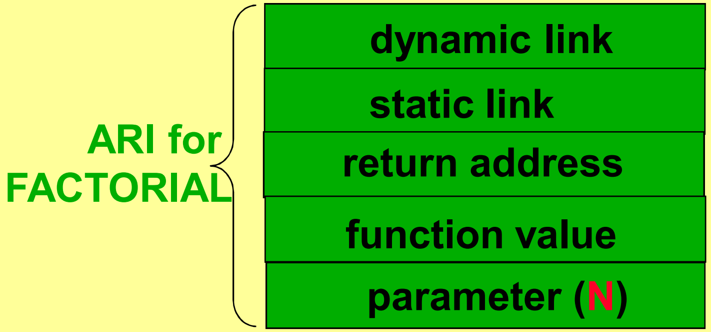
(3) Recursion

- Example : Using recursion to Compute the factorial

```
Program TEST
  var VALUE:integer;

  function FACTORIAL(N:integer);
    begin                                          1
      if N<=1
         then FACTORIAL:=1
         else FACTORIAL:= N*FACTORIAL(N-1);
    end                                            2

  begin
    VALUE:=FACTORIAL(3);
    writeln("factorial 3 is:", VALUE)              3
  end.
```



ARI for FACTORIAL

dynamic link

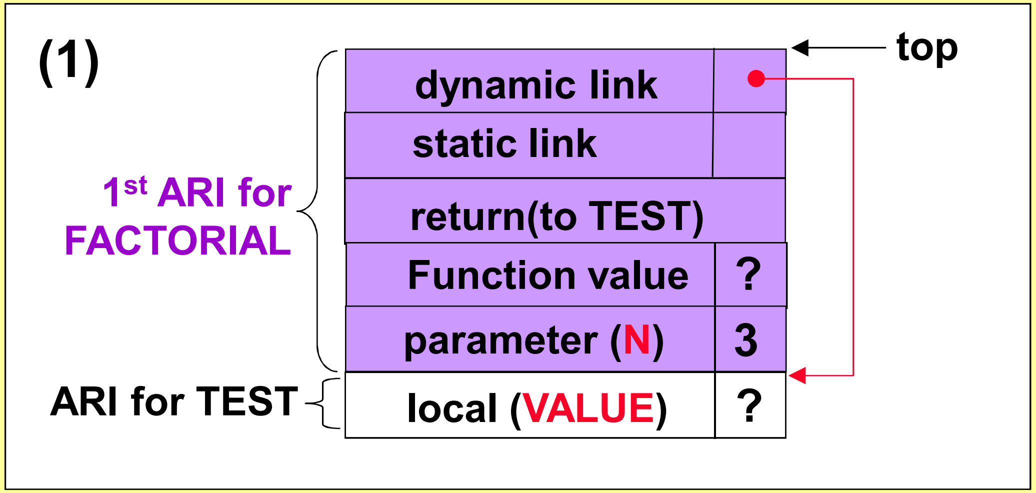
static link

return address

function value

parameter (N)

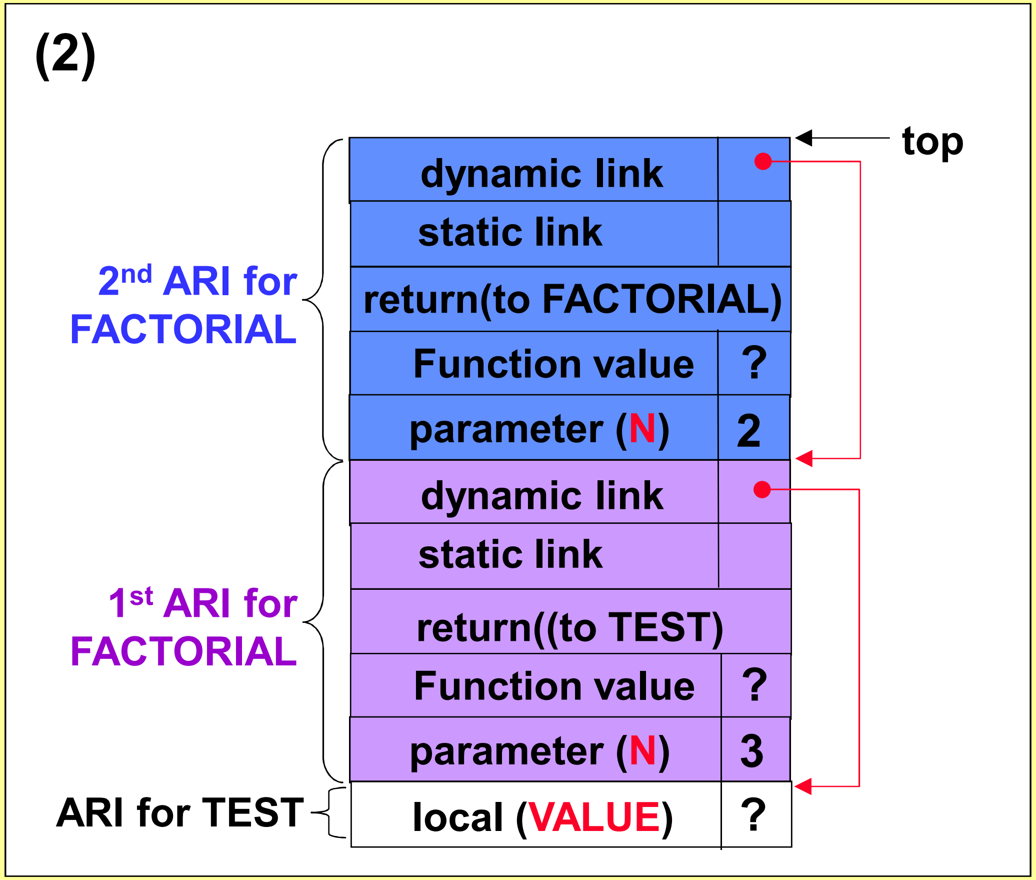
(1)



top

1st ARI for FACTORIAL	dynamic link	●
	static link	
	return(to TEST)	
	Function value	?
	parameter (N)	3
ARI for TEST	local (VALUE)	?

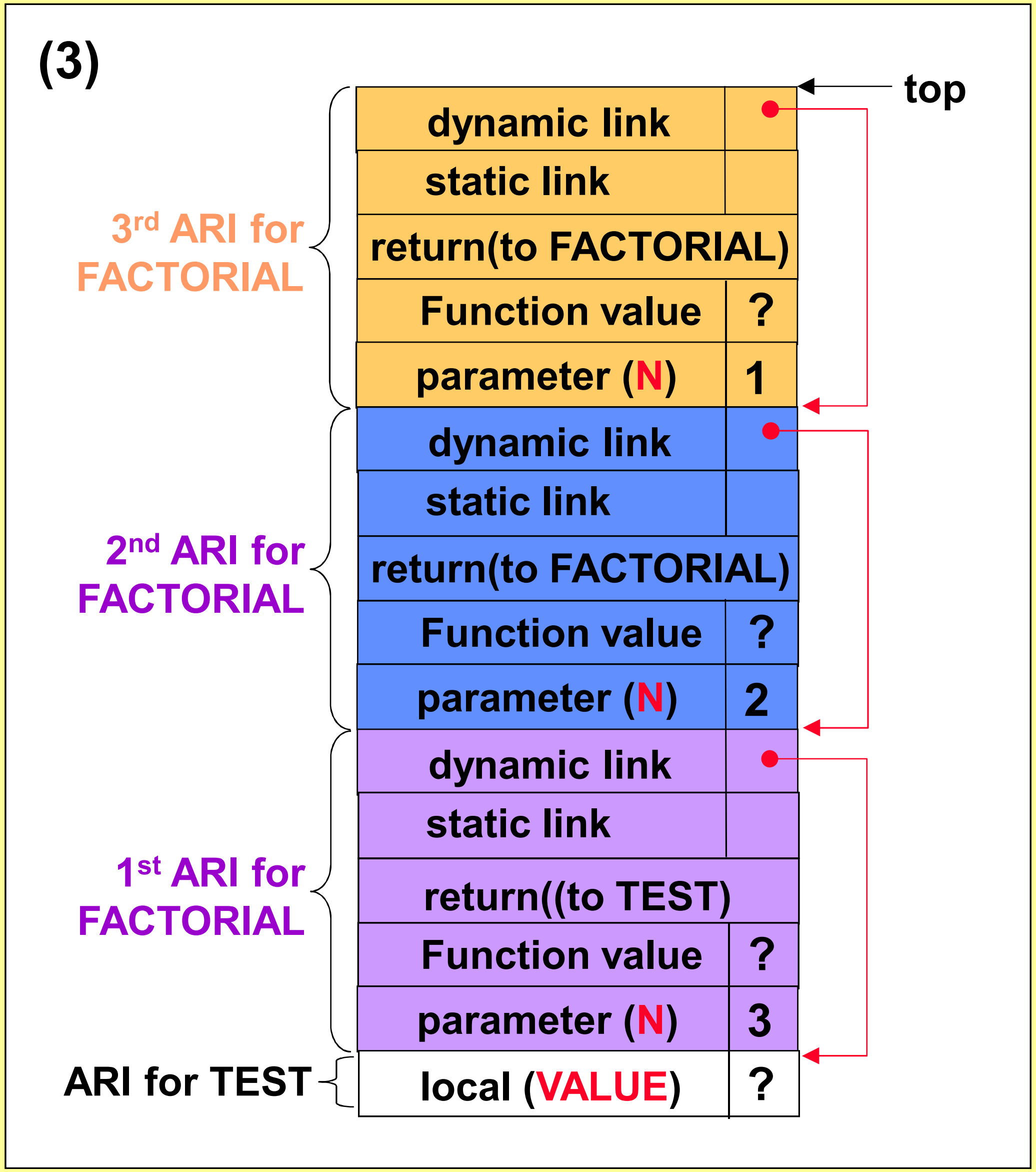
(2)



top

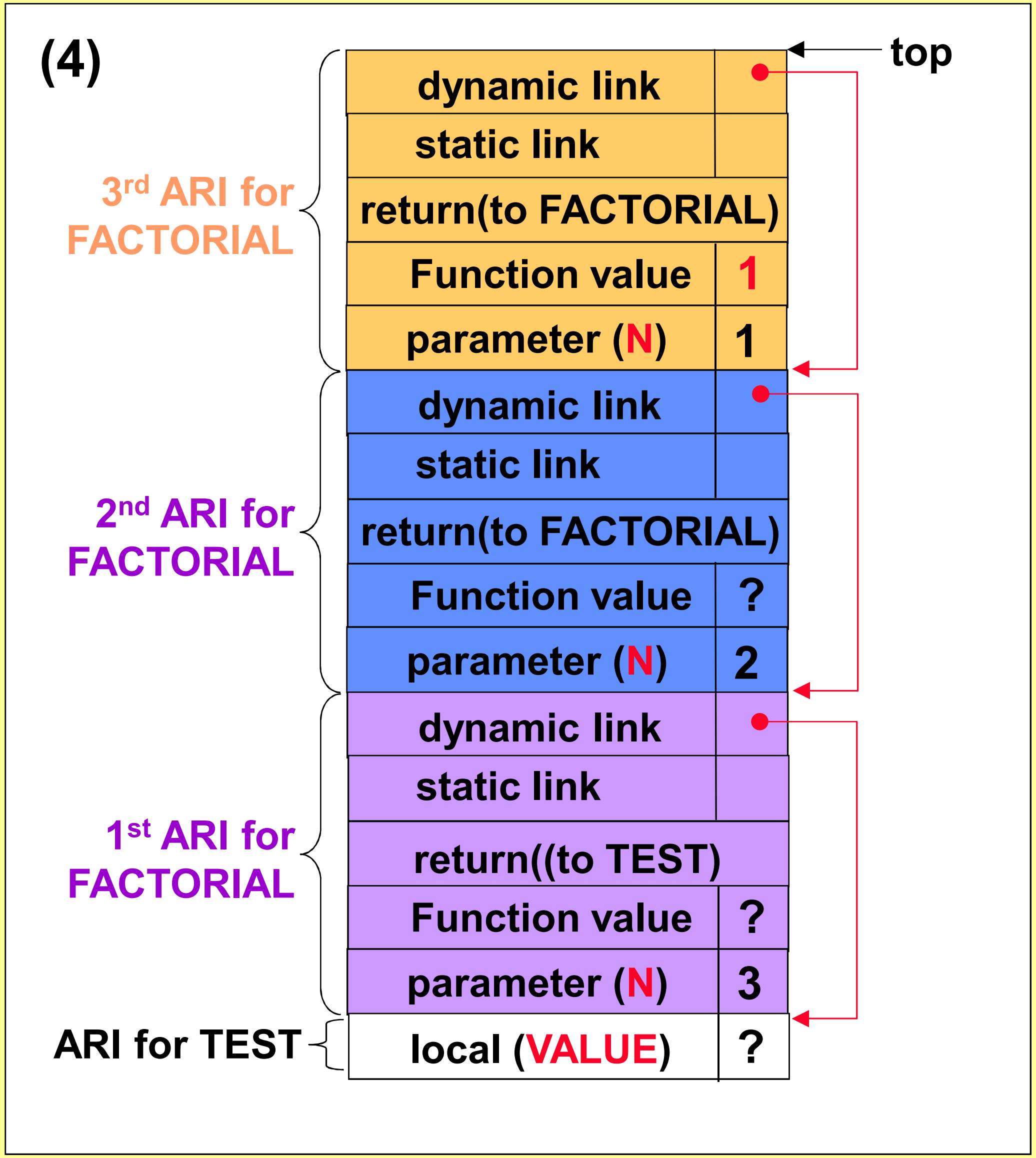
2nd ARI for FACTORIAL	dynamic link	●
	static link	
	return(to FACTORIAL)	
	Function value	?
	parameter (N)	2
1st ARI for FACTORIAL	dynamic link	●
	static link	
	return((to TEST)	
	Function value	?
	parameter (N)	3
ARI for TEST	local (VALUE)	?

(3)



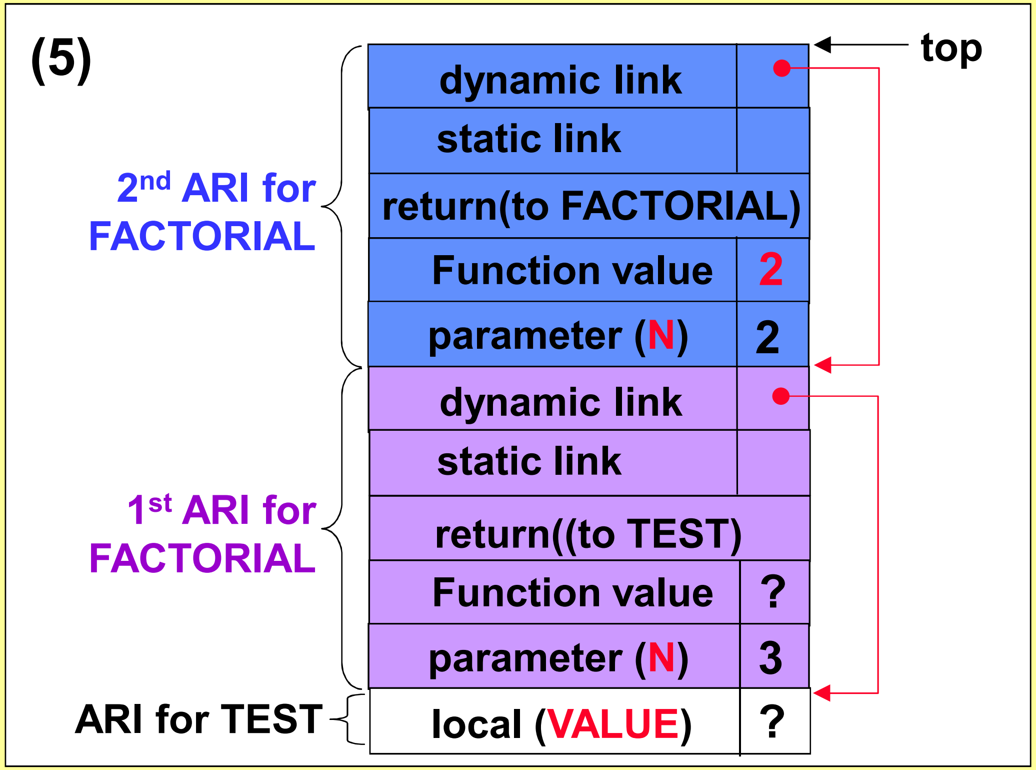
top

3rd ARI for FACTORIAL	dynamic link	●
	static link	
	return(to FACTORIAL)	
	Function value	?
	parameter (N)	1
2nd ARI for FACTORIAL	dynamic link	●
	static link	
	return(to FACTORIAL)	
	Function value	?
	parameter (N)	2
1st ARI for FACTORIAL	dynamic link	●
	static link	
	return((to TEST)	
	Function value	?
	parameter (N)	3
ARI for TEST	local (VALUE)	?



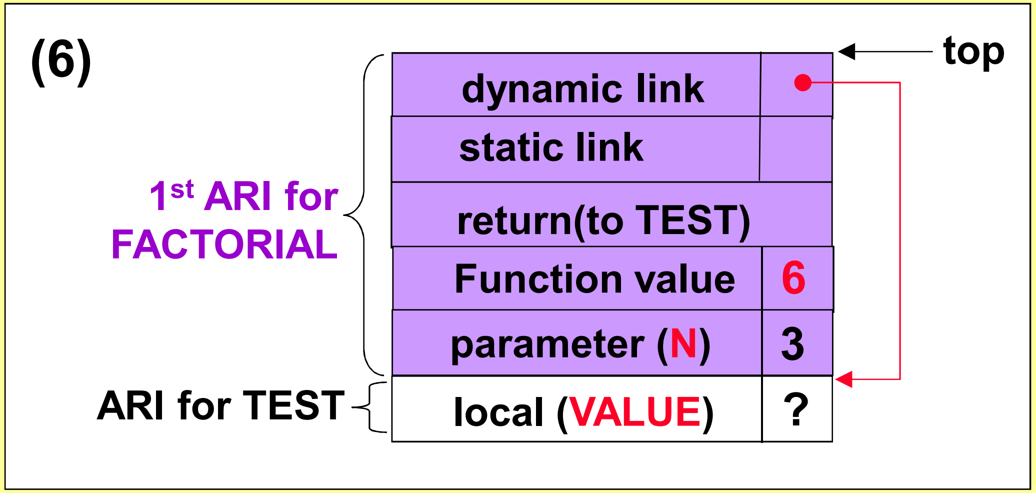
(4)

3rd ARI for FACTORIAL	dynamic link	●	← top
	static link		
	return(to FACTORIAL)		
	Function value	1	
	parameter (N)	1	
2nd ARI for FACTORIAL	dynamic link	●	
	static link		
	return(to FACTORIAL)		
	Function value	?	
	parameter (N)	2	
1st ARI for FACTORIAL	dynamic link	●	
	static link		
	return((to TEST)		
	Function value	?	
	parameter (N)	3	
ARI for TEST	local (VALUE)	?	



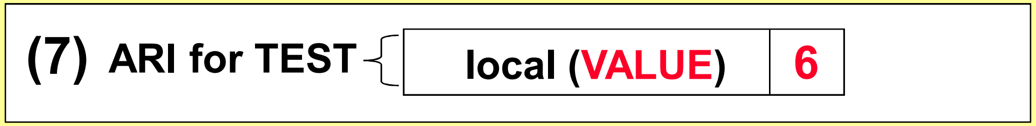
(5)

2nd ARI for FACTORIAL	dynamic link	●	← top
	static link		
	return(to FACTORIAL)		
	Function value	2	
	parameter (N)	2	
1st ARI for FACTORIAL	dynamic link	●	
	static link		
	return((to TEST)		
	Function value	?	
	parameter (N)	3	
ARI for TEST	local (VALUE)	?	



(6)

1st ARI for FACTORIAL	dynamic link	●	← top
	static link		
	return(to TEST)		
	Function value	6	
	parameter (N)	3	
ARI for TEST	local (VALUE)	?	



(7)

ARI for TEST	local (VALUE)	6

10.4 Nested Subprogram

- all variables that can be nonlocally accessed are in activation record instances, and therefore are somewhere in the stack

- A reference to a nonlocal variables : two-step
  1) to find the instance of the activation record in the stack where the variable was allocated
  2) to use the local_offset of the variable (within the activation record instance) to actually access it

- Semantic rules of static-scoped language
  - in a given subprogram, only variables that are declared in static ancestor scopes cab be nonlocally accessed
  - activation record instances of all the static ancestors are guaranteed to exist on the stack when variables in them are referenced by a nested procedure
    - ⇔ A procedure is callable only when all of its static ancestor program units are active
  - the correct declaration is the first one found when looking through the enclosing scopes, most closely nested first
    - ⇔ So to support nonlocal references, it must be possible *to find all of the instances of activation records in the stack that correspond to those static ancestors*
      - ⇒ Using *Static chain*
      - ⇒ Using *Display*

- **Static Chains**
  - a chain of static links that connect certain activation record instances in the stack
    - ⇔ It links all the static ancestors of an existing subprogram, in order of static parent first
  - when a reference is made to a nonlocal variable, the activation record instance containing the variable can be found *by searching the static chain until a static ancestor activation instance is found that contains the variable*
  - because the nesting of scope is *known at compile time*, the compiler can determine not only that a reference is nonlocal, but also the length of the static chain needed to reach the activation record instance that actually contains the nonlocal object
  - Static_depth
    - ⇔ an integer associated with a static scope that indicates how deeply it is nested in the outermost scope
  - Nesting_depth (or chain_offset) of reference
    - ⇔ the length of the static chain needed to reach the correct activation record instance for a nonlocal reference
    - ⇔ the difference between the static_depth of the procedure containing the reference to X and the static_depth of the procedure containing the declaration for X
  - Actual reference : (*chain_offset, local_offset*)

```
program A ;
    procedure B ;
        procedure C ;
        end; { of procedure C }
    end; { of procedure B)
end ;
```

- static_depth
  A : 0, B : 1, C : 2

-chain_offset when C refers
  the variable in A : 2

```
MAIN_2
var X : integer
  BIGSUB
  var A, B, C : integer ;
    SUB1
     var A, D : integer ;
      A : = B + C ;
    SUB2
     var B, E : integer ;

      SUB3
       var C, E : integer ;
       SUB1 ;
       E := B + A ;

     ....
     SUB3 ;
     ....
     A := D + E ;

   SUB2 ;

 BIGSUB ;
```

- Calling Sequence
  MAIN_2 calls BIGSUB
  BIGSUB calls SUB2
  SUB2 calls SUB3
  SUB3 calls SUB1

A : (0, 3)
B : (1, 4)
C : (1, 5)

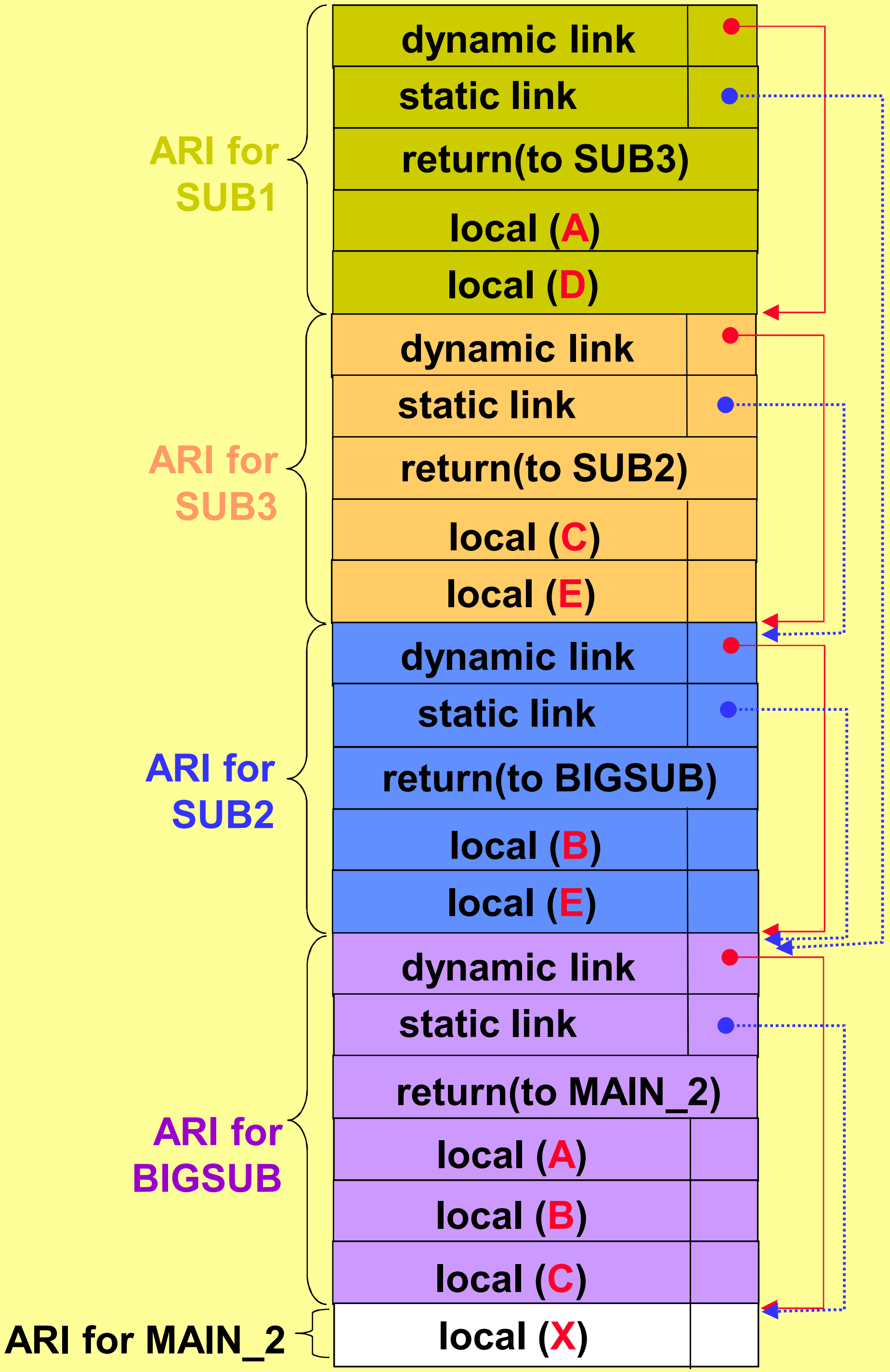
0	dynamic link
1	static link
2	return address
3	local 1
4	local 2

activation record format

E : (0, 4)
B : (1, 3)
A : (2, 3)

A : (1, 3)
D : ? (Error)
E : (0, 4)

(chain offset, local-offset)



ARI for SUB1

dynamic link

static link

return(to SUB3)

local (A)

local (D)

ARI for SUB3

dynamic link

static link

return(to SUB2)

local (C)

local (E)

ARI for SUB2

dynamic link

static link

return(to BIGSUB)

local (B)

local (E)

ARI for BIGSUB

dynamic link

static link

return(to MAIN_2)

local (A)

local (B)

local (C)

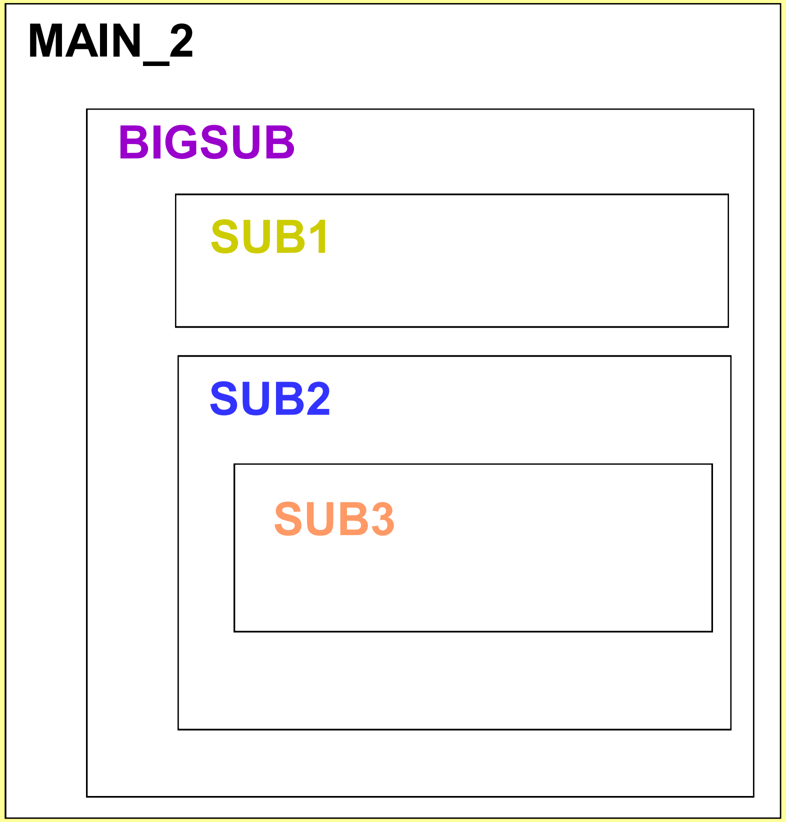
ARI for MAIN_2

local (X)

Calling Sequence

MAIN_2 **->** *BIGSUB* **->** *SUB2* **->**
SUB3 **->** *SUB1*

Program Structure



MAIN_2

BIGSUB

SUB1

SUB2

SUB3

– How the static chain is maintained during program execution ?

⇔ actions required at subprogram return

⇒ trivially, nothing to do because its activation record is removed from the stack

⇔ actions required at subroutine call : the most recent activation record instance of the parent scope must be found at the time of the call,

방법 1)

→ looking at activation record instance on the dynamic chain until the first one of parent scope is found, at run-time

방법 2)

→ at compiler time : *compiler compute the nesting_depth between caller and the procedure that declared the called program*.

→ at the time of the call : the static link of the called procedure's activation record instance is determined by *moving down the static chain of the caller the number of links equal to the nesting depth computed at compiler time*

– Problems of static chain method

⇔ references to variables in scope beyond the static parent are costly

⇒ the static chain must be followed, one link per enclosing scope from the reference to the declaration, to accomplish the access

⇔ it is difficult for a programmer working on time-critical program to estimate the costs of nonlocal references, since the cost of each reference depends on the depth of nesting

- **Display**
  - the static links are collected in a single array called a display, rather than being stored in the activation records
  - the contents of the display at any specific time are *a list of addresses of the accessible activation record instances* - one for each active scope - in the order in which they are nested
  - nonlocal reference : (display_offset, local_offset)
  - access to nonlocals using a display
    - ⇔ the link to correct activation record, which resides in the display, is found using a statically computed value called the *display_offset*
    - ⇔ the local offset within the activation record instance is computed and used exactly as with static chain implementations
  - In general, the pointer at position k of the display points to an activation record instance for a procedure with a static depth of k
  - How to modify the display to reflect the new scope situation ?
    - ⇔ the display modification required for a call to procedure P, which has a static_depth of k, is
      - ⇒ Save, in the new activation record instance, a copy of the pointer at position k in the display
      - ⇒ Place the link to the activation record instance for P at position k in the display
    - ⇔ at termination, the saved pointer in the activation record instance of the terminating subprogram to be placed back in the display

– Example : a call to procedure P by procedure Q (Q -> P)

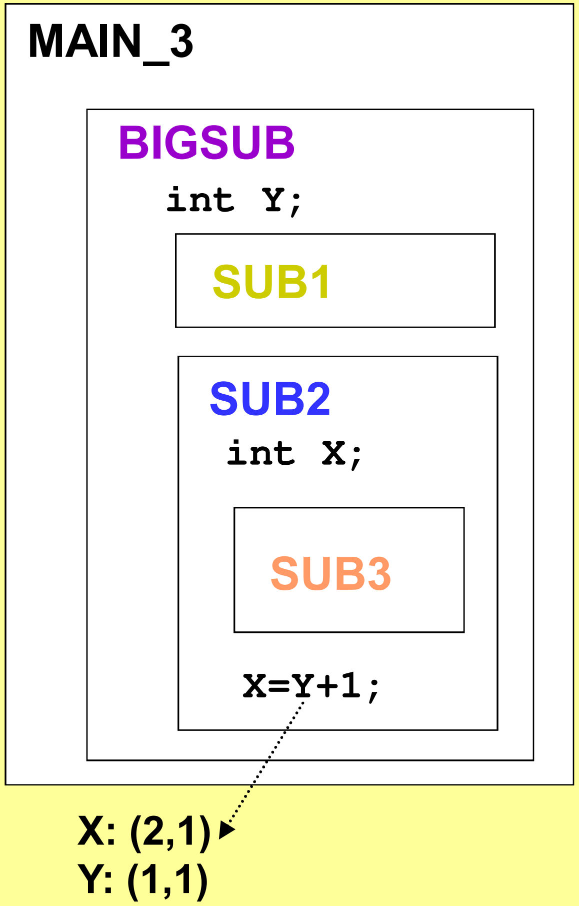
⇔ Qsd = Psd

⇔ Qsd < Psd

⇔ Qsd > Psd

Psd : static_depth of P
Qsd : static_depth of Q

Program Structure



MAIN_3

BIGSUB

```
int Y;
```

SUB1

SUB2

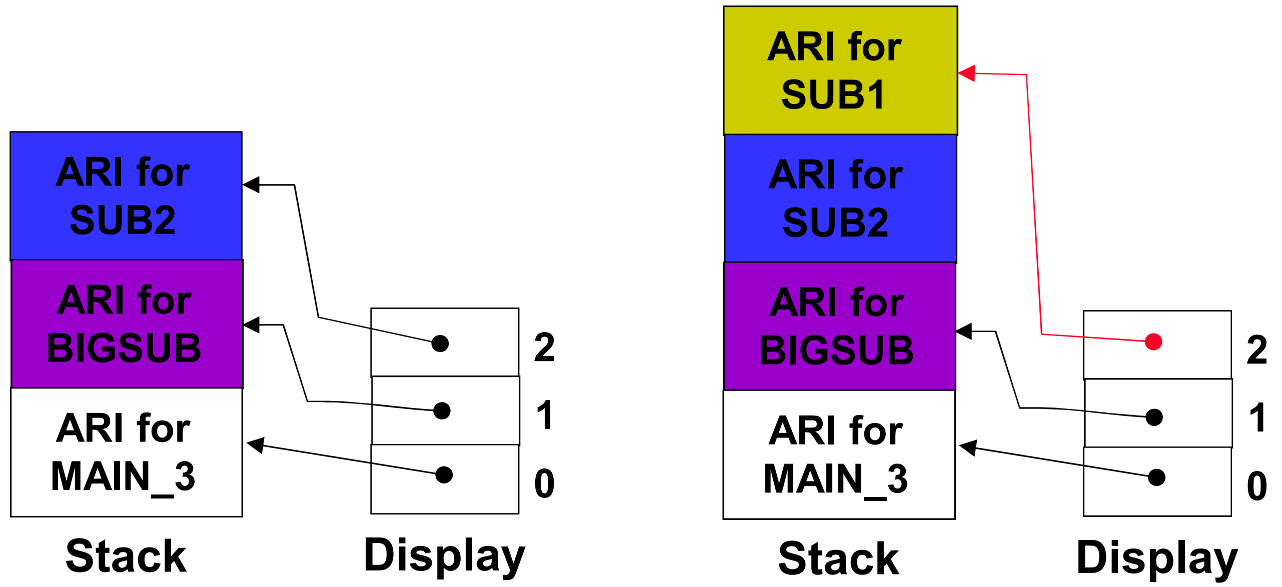
```
int X;
```

SUB3

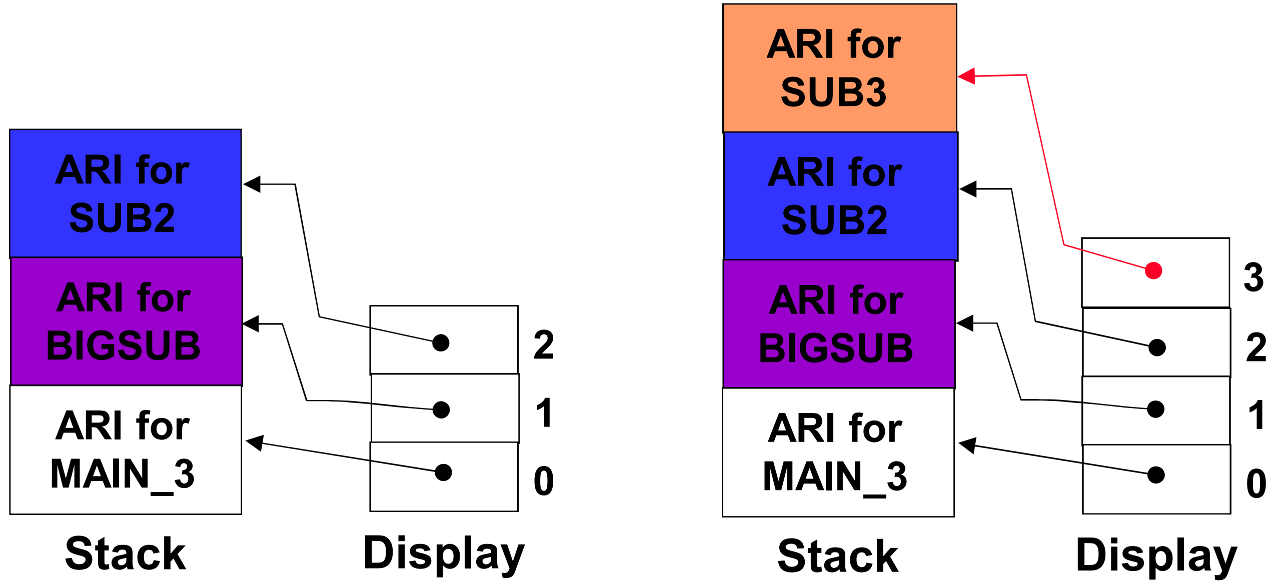
```
X=Y+1;
```

X: (2,1)
Y: (1,1)

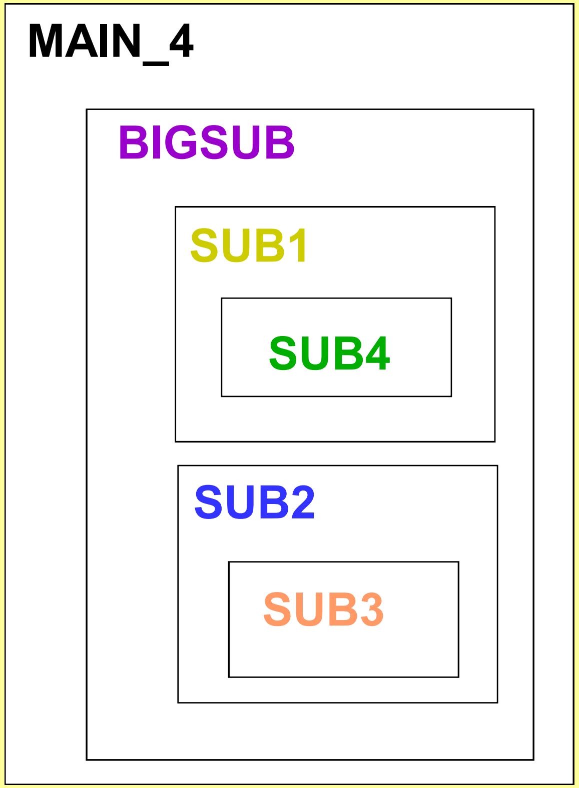
1) Qsd = Psd (MAIN_3 -> BIGSUB -> *SUB2 -> SUB1*)



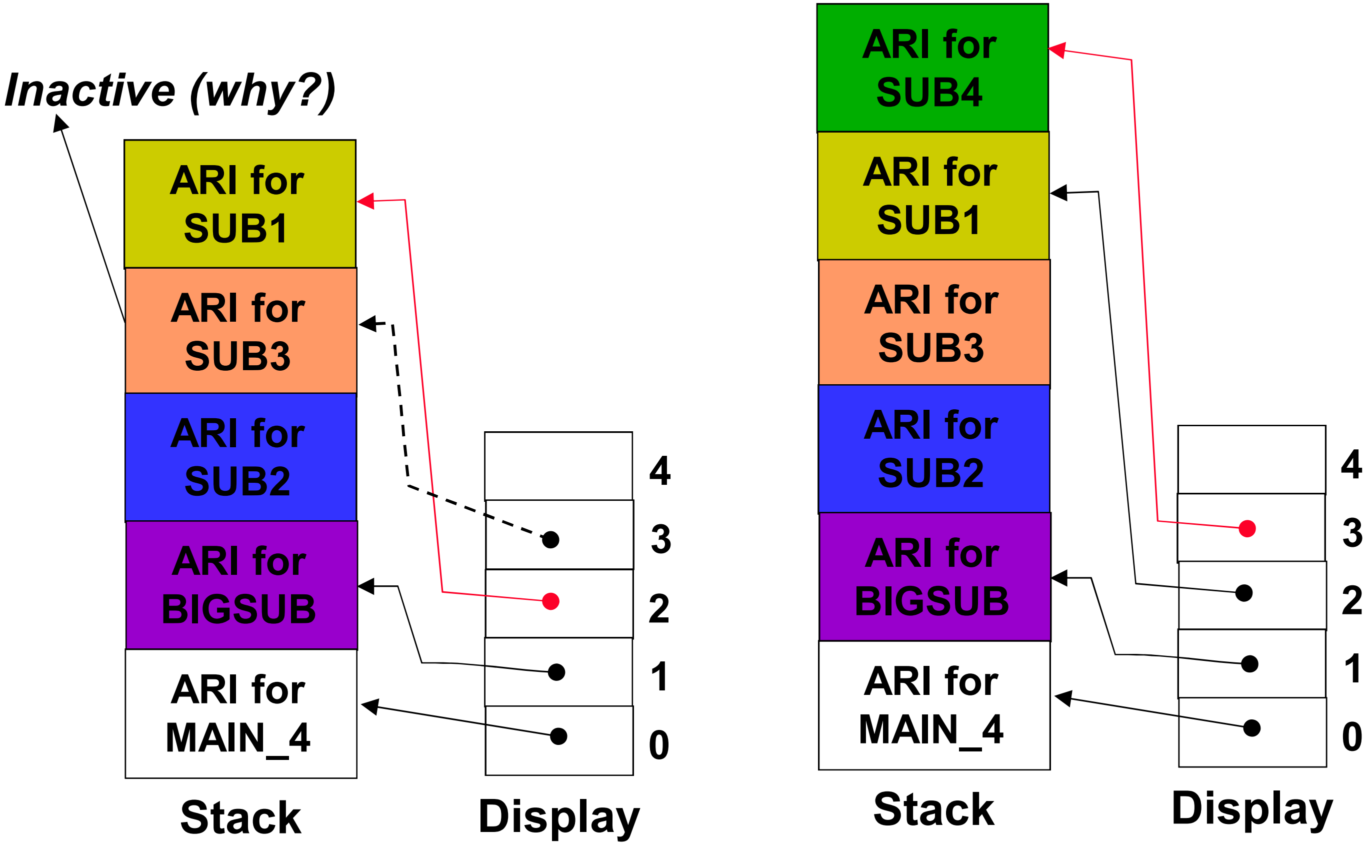
2) Qsd < Psd (MAIN_3 -> BIGSUB -> *SUB2 -> SUB3*)



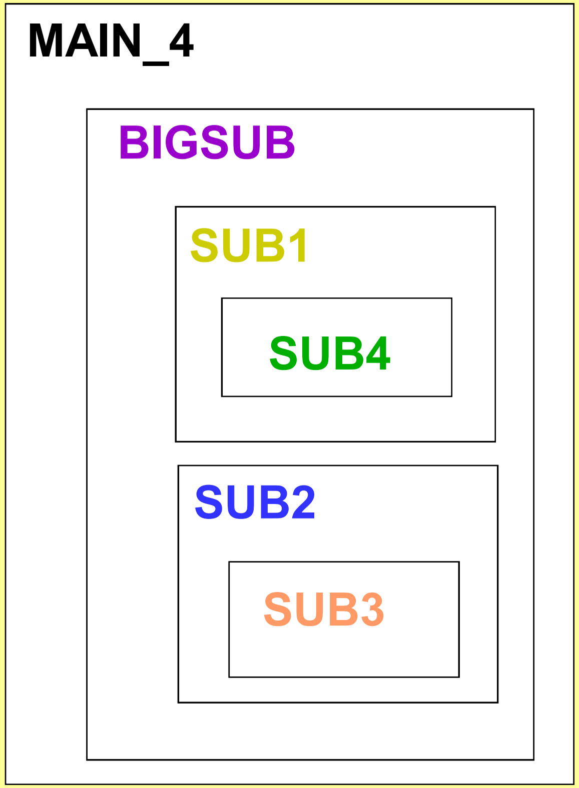
Program Structure



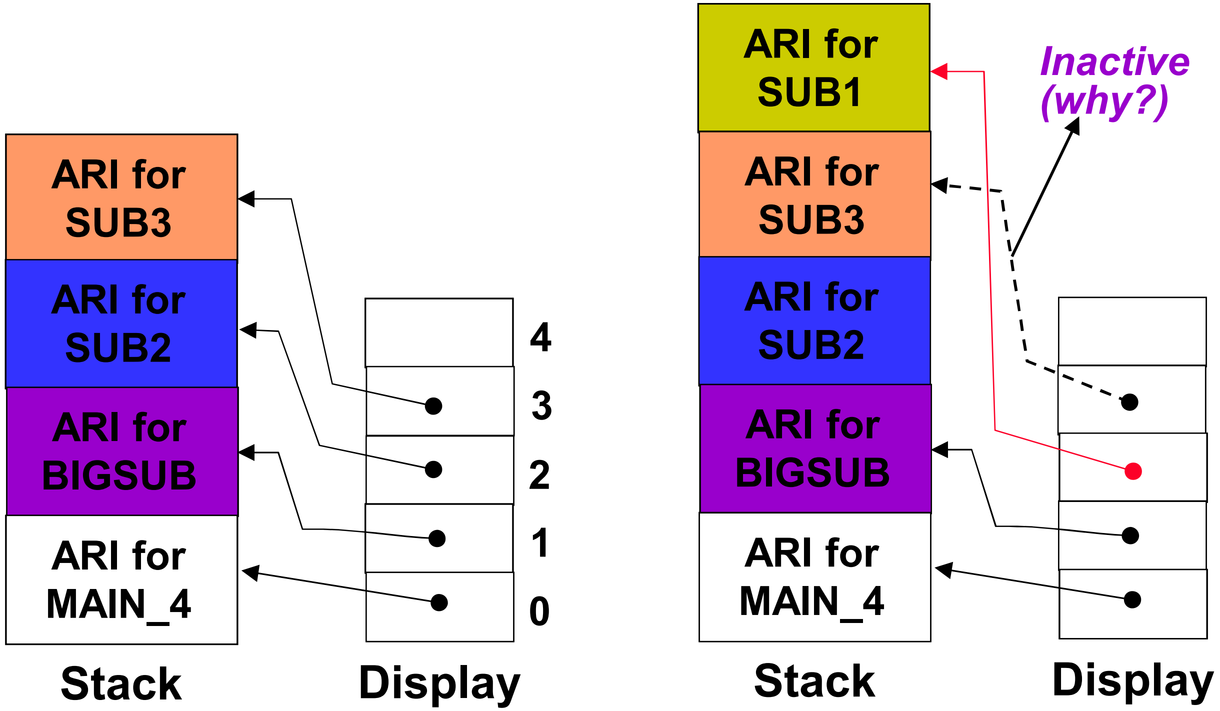
2') Qsd < Psd (MAIN_4 -> BIGSUB -> *SUB2 -> SUB3* *-> SUB1 -> SUB4*)



Program Structure



3) Qsd < Psd (MAIN_4 -> BIGSUB -> *SUB2* -> *SUB3* *-> SUB1*)



- Implementation of display
  - ⇔ the maximum size of display, which is the maximum static_depth of any subprogram in the program, can be determined by the compiler
  - ⇔ can be stored as a run-time static array in memory
    - ⇒ nonlocal accesses cost one more memory cycle than local accesses, if the machine has indirect addressing through memory location
  - ⇔ to place the display in registers
    - ⇒ do not require the extra memory cycle

- Static chaining *vs*. display method
  - references to local variables would be slower with a display than with static chains if the display is not stored in registers (adds a level of indirection)
  - references to nonlocal variables that are more than one static level away will be faster with display than static chain
  - the time is equal for all nonlocal references when a display is used
  - the maintenance at a procedure call is faster with static chains, unless the called program is more a few static levels away
  - Overall comparison
    - ⇔ *displays* are better if there is deep static nesting and many references to distant nonlocal variables
    - ⇔ *static chaining* is better if there are few nesting levels and few references to distant nonlocal variables, which is the more common situation
      - ⇒ usual nesting level is less than three

10.5 Blocks

- Block = compound statement + data declaration

- Implementation of Block

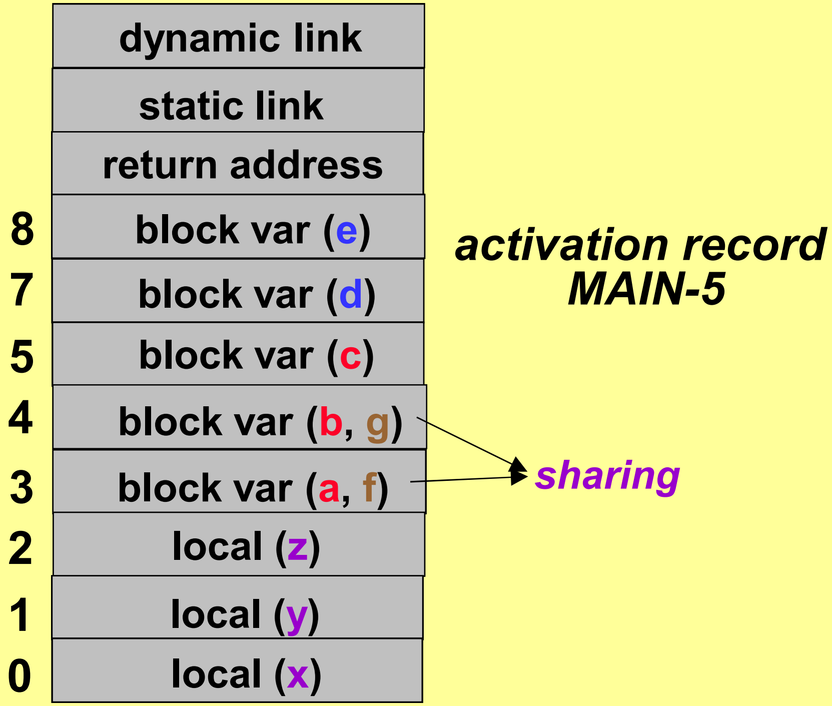
  방법 1) treated as parameterless procedures that are always called from the same place in the program

  ⇔ maximum nesting grows -> display size grows

  방법 2) the amount of space required for block variables can be allocated next to local variables in the activation record

  ⇒ Offsets for all block variables can be statically computed, so block variables can be addressed exactly as if they were local variables

```
MAIN-5() {
  int x, y, z ;
  while (… …) {
    int a, b, c ;
    …
    while (… …) {
      int d, e ;
      …
    }
  }
  while (… …) {
    int f, g ;
    …
  }
}
```



	dynamic link
	static link
	return address
8	block var (e)
7	block var (d)
5	block var (c)
4	block var (b, g)
3	block var (a, f)
2	local (z)
1	local (y)
0	local (x)

activation record MAIN-5

sharing

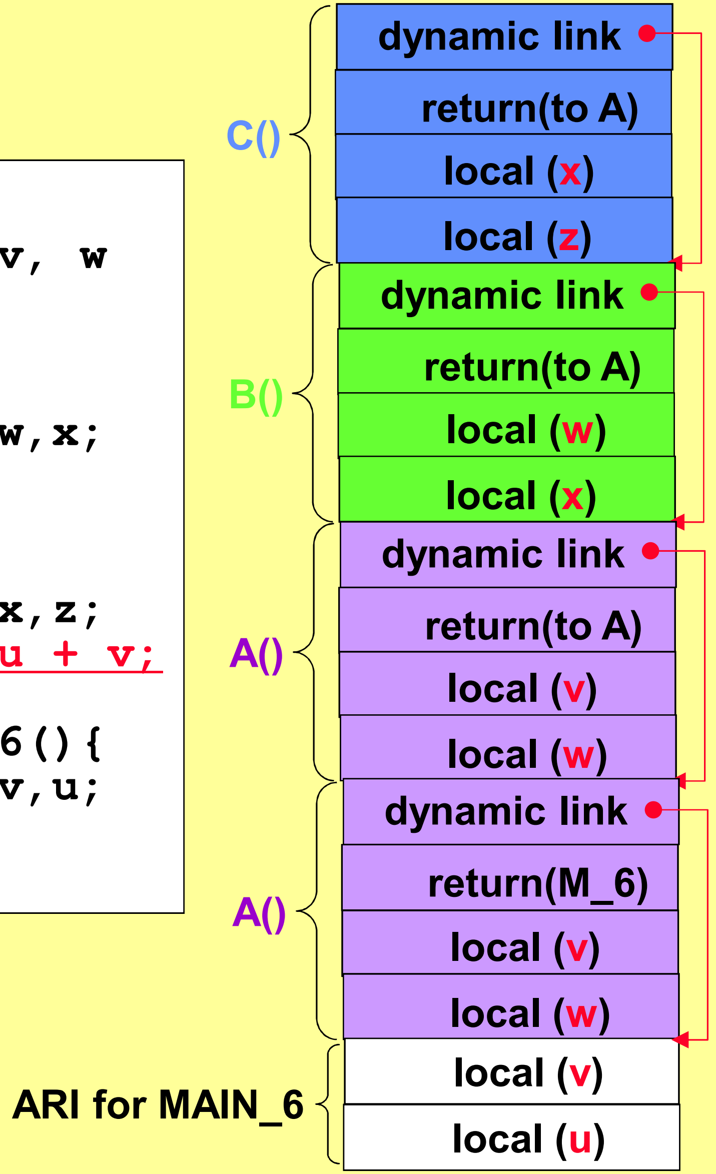
10.6 Implementing Dynamic Scoping

– there are at least two distinct ways in which nonlocal references in a dynamic-scoped language can be implemented : *deep access* and *shallow access*

(1) Deep Access

- the nonlocal reference can be resolved by searching through the declaration in the other subprograms that are currently active, beginning with the one most recently activated
  - dynamic-chain is followed
  - this method is called deep access because access may require searching deep in the stack
- In a dynamic-scoped language, there is no way to determine at compile time the length of the chain that must be searched
  - typically slow than static scoped language
- Activation record must store the names of variables for the search process
- Example : Calling sequence : MAIN_6 -> A -> A -> B -> C

```
A(){
 int v, w
 …
}
B(){
 int w,x;
 …
}
C(){
 int x,z;
 x:= u + v;
}
Main_6(){
 int v,u;
 …
}
```



(2) Shallow Access

– Variables declared in subprograms are not stored in the activation records of those subprograms

- Implementations

방법1) to have a separate stack for each variable name in a complete program

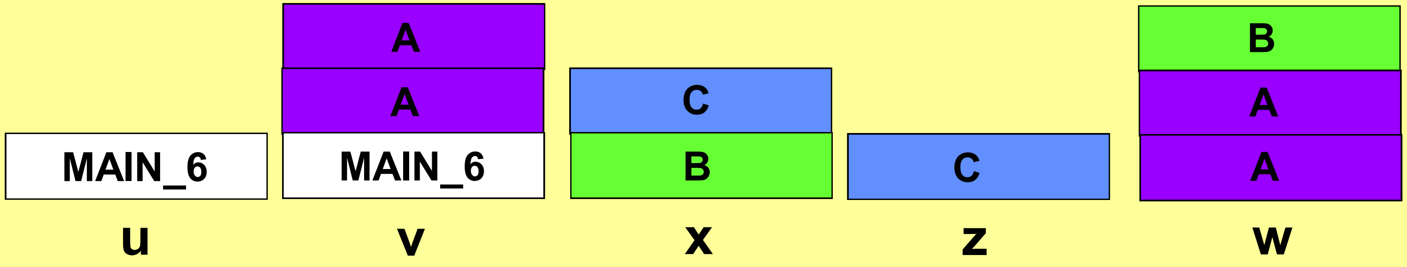
⇔ every time a new variable with a particular name is created by a declaration at the beginning of a subprogram activation, it is given a cell on the stack for its name

⇔ every reference to the name is to the variable on top of the stack

⇔ fast references to variables, but maintaining the stacks at the entrances and exits of subprogram is expensive

```
A(){
 int v, w
 …
}
B(){
 int w,x;
 …
}
C(){
 int x,z;
 x:= u + v;
}
Main_6(){
 int v,u;
 …
}
```

MAIN_6 -> A -> A -> B -> C



<Homework> #1 ~ #6

<Homework>

1. Show the stack with all activation record instances, including static and dynamic chains, when execution reaches position ① in the following skeletal program. Assume **Bigsub** is at level 1.

```
procedure Bigsub is
  procedure A is
    procedure B is
      begin -- of B
        . . . ①
      end; -- of B
    procedure C is
      begin -- of C
        . . .
        B;
        . . .
      end; -- of C
    begin -- of A
      . . .
      C;
      . . .
    end; -- of A
  begin -- of Bigsub
    . . .
    A;
    . . .
end; -- of Bigsub
```

2. Show the stack with all activation record instances, including static and dynamic chains, when execution reaches position ① in the following skeletal program. Assume **Bigsub** is at level 1.

```
procedure Bigsub is
  MySum : Float;
  procedure A is
    X : Integer;
    procedure B(Sum : Float) is
      Y, Z : Float;
      begin -- of B
        . . .
        C(Z)
        . . .
      end; -- of B
    begin -- of A
      . . .
      B(X);
      . . .
    end; -- of A
  procedure C(Plums : Float) is
    begin -- of C
      . . . ①
  end; -- of C
  L : Float;
  begin -- of Bigsub
    . . .
    A;
    . . .
  end; -- of Bigsub
```

```
procedure Bigsub is
  procedure A(Flag:Boolean) is
    procedure B is
       . . .
       A(false);
    end; -- of B
  begin -- of A
     if flag
        then B;
        else C;
     . . .
  end; -- of A
  procedure C is
    procedure D is
       . . . ①
    end; -- of D
    . . .
    D;
  end; -- of C
  begin -- of Bigsub
    . . .
    A(true);
    . . .
  end; -- of Bigsub
```

Bigsub calls A
A calls B
B calls A
A calls C
C calls D

3. Show the stack with all activation record instances, including static and dynamic chains, when execution reaches position ① in the following skeletal program. Assume Bigsub is at level 1.

4. Show the stack with all activation record instances, including dynamic chain, when execution reaches position ① in the following skeletal program. This program uses the deep-access method to implement dynamic scoping.

```
void fun1() {
  float a;
  . . .
}
void fun2() {
  int b, c;
  . . .
}
void fun3() {
  float d;
  . . . ①
}
void main() {
  char e, f, g;
  . . .
}

main calls fun2
fun2 calls fun1
fun1 calls fun1
fun1 calls fun3
```

5. Assume that the program of Problem 4 is implemented using the shallow-access method using a stack for each variable name. Show the stacks for the time of the execution of fun3, assuming execution found its way to that point through the sequence of calls shown in Problem 4.
6. Although local variables in Java methods are dynamically allocated at the beginning of each activation, under what circumstances could the value of a local variable in a particular activation retain the value of the previous activation?