Run Time Storage Organization

ASU Textbook Chapter 7.1–7.4, and 7.7–7.8

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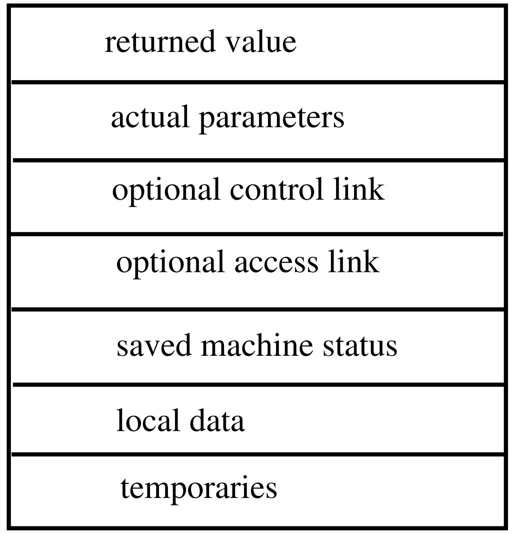
Preliminaries

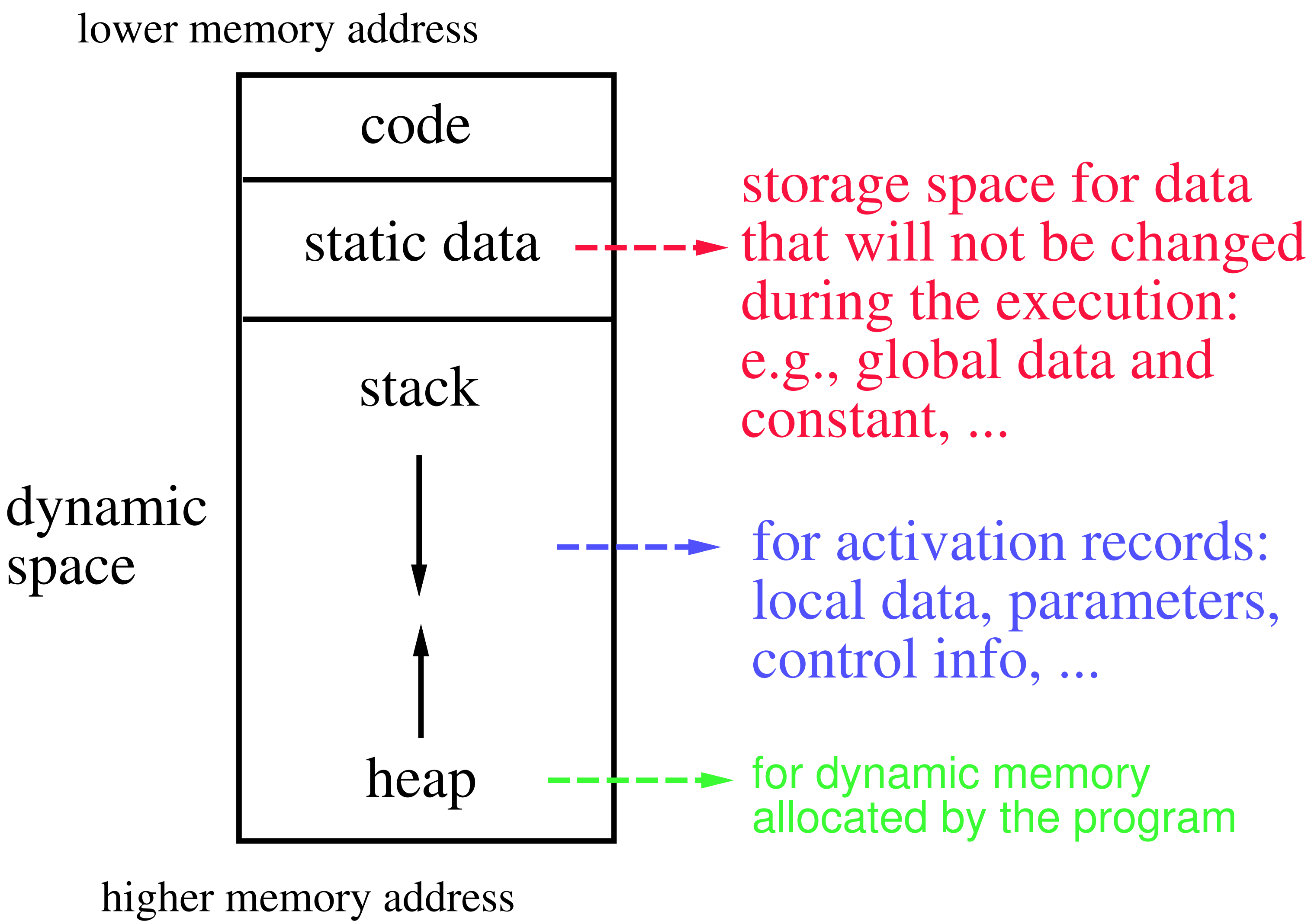
- **During the execution of a program, the same name in the source can denote different data objects in the computer.**
- **The allocation and deallocation of data objects is managed by the run-time support package .**
- **Terminologies:**
  - **name → storage space: the mapping of names to storage spaces is called an environment .**
  - **storage space → value: the current value of a storage space is called its state.**
  - **The association of a name to a storage location is called a binding.**
- **Each execution of a procedure is called an activation .**
  - **If it is a recursive procedure, then several of its activations may exist at the same time.**
  - **Life time: the time between the first and last steps in a procedure.**
  - **A recursive procedure needs not to call itself directly.**

Activation record



- **Activation record: data about an execution of a procedure.**
  - **Parameters:**
    - ▷ ***Formal parameters:*** *the declaration of parameters.*
    - ▷ ***Actual parameters:*** *the values of parameters for this activation.*
  - **Links:**
    - ▷ ***Control (or dynamic) link:*** *a pointer to the activation record of the caller.*
    - ▷ ***Access (or static) link:*** *a pointer to places of non-local data,*

General run time storage layout



Issues in storage allocation

- **There are two different approaches for run time storage allocation.**
  - **Static allocation.**
  - **Dynamic allocation.**
- **Need to worry about how variables are stored.**
  - **That is the management of activation records.**
- **Need to worry about how variables are accessed.**
  - **Global variables.**
  - **Locally declared variables, that is the ones allocated within the current activation record.**
  - **Non-local variables, that is the ones declared and allocated in other activation records and can be accesses here.**
    - ***Non-local variables are different from global variables.***

Static storage allocation (1/3)

- **Static allocation:** uses no stack and heap.
  - Strategies:
    - ▷ *For each procedure in the program, allocate a space for its activation record.*
    - ▷ *A.R.'s can be allocated in the static data area.*
    - ▷ *Names bound to locations at compiler time.*
    - ▷ *Every time a procedure is called, a name always refer to the same pre-assigned location.*
  - Used by simple or early programming languages.
- **Disadvantages:**
  - No recursion.
  - Waste lots of space when inactive.
  - No dynamic allocation.
- **Advantages:**
  - No stack manipulation or indirect access to names, i.e., faster in accessing variables.
  - Values are retained from one procedure call to the next if block structure is not allowed.
    - ▷ *For example: static variables in C.*

Static storage allocation (2/3)

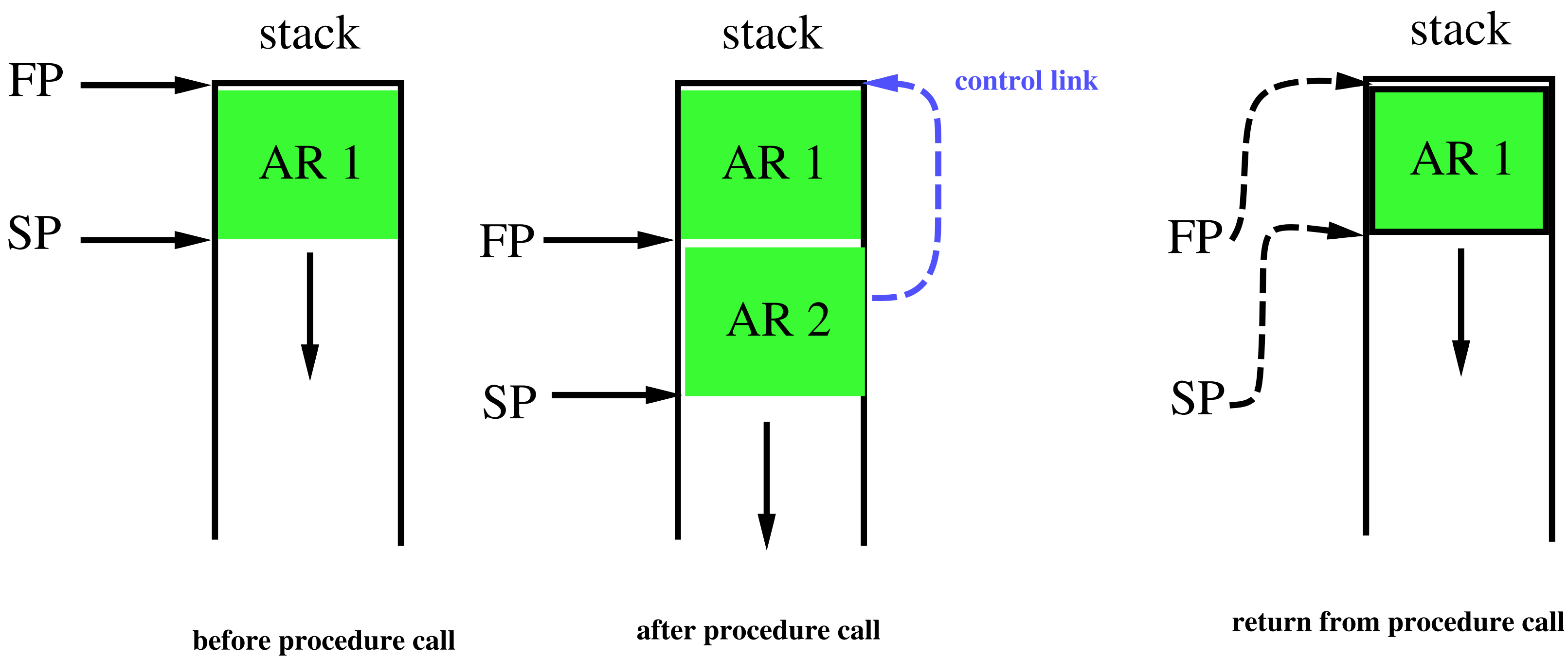
- **On procedure calls,**
  - **the calling procedure:**
    - *First evaluate arguments.*
    - *Copies arguments into parameter space in the A.R. of called procedure.*
      Convention: call that which is passed to a procedure *arguments* *from the calling side, and* *parameters* *from the called side.*
    - *May save some registers in its own A.R.*
    - *Jump and link: jump to the first instruction of called procedure and put address of next instruction (return address) into register RA (the return address register).*
  - **the called procedure:**
    - *Copies return address from RA into its A.R.'s return address field.*
    - *control link := address of the previous A.R.*
    - *May save some registers.*
    - *May initialize local data.*

Static storage allocation (3/3)

- **On procedure returns,**
  - **the called procedure:**
    - *Restores values of saved registers.*
    - *Jump to address in the return address field.*
  - **the calling procedure:**
    - *May restore some registers.*
    - *If the called procedure is actually a function, that is the one that returns values, put the return value in the appropriate place.*

Dynamic storage allocation for STACK (1/3)

- **Stack allocation:**
  - **Each time a procedure is called, a new A.R. is pushed onto the stack.**
  - **A.R. is popped when procedure returns.**
  - **A register (SP for stack pointer) points to top of stack.**
  - **A register (FP for frame pointer) points to start of current A.R.**



Dynamic storage allocation for STACK (2/3)

- **On procedure calls,**
  - **the calling procedure:**
    - ▷ *May save some registers (in its own A.R.).*
    - ▷ *May set optional access link (push it onto stack).*
    - ▷ *Pushes parameters onto stack.*
    - ▷ *Jump and Link: jump to the first instruction of called procedure and put address of next instruction into register RA.*
  - **the called procedure:**
    - ▷ *Pushes return address in RA.*
    - ▷ *Pushes old FP (control link).*
    - ▷ *Sets new FP to old SP.*
    - ▷ *Sets new SP to be old SP + (size of parameters) + (size of RA) + (size of FP). (These sizes are computed at compile time.)*
    - ▷ *May save some registers.*
    - ▷ *Push local data (maybe push actual data if initialized or maybe just their sizes from SP)*

Dynamic storage allocation for STACK (3/3)

- **On procedure returns,**
  - **the called procedure:**
    - ▷ ***Restore values of saved registers if needed.***
    - ▷ ***Loads return address into special register RA.***
    - ▷ ***Restores SP (SP := FP).***
    - ▷ ***restore FP (FP := saved FP).***
    - ▷ ***return.***
  - **the calling procedure:**
    - ▷ ***May restore some registers.***
    - ▷ ***If it is in fact a function that was called, put the return value into the appropriate place.***

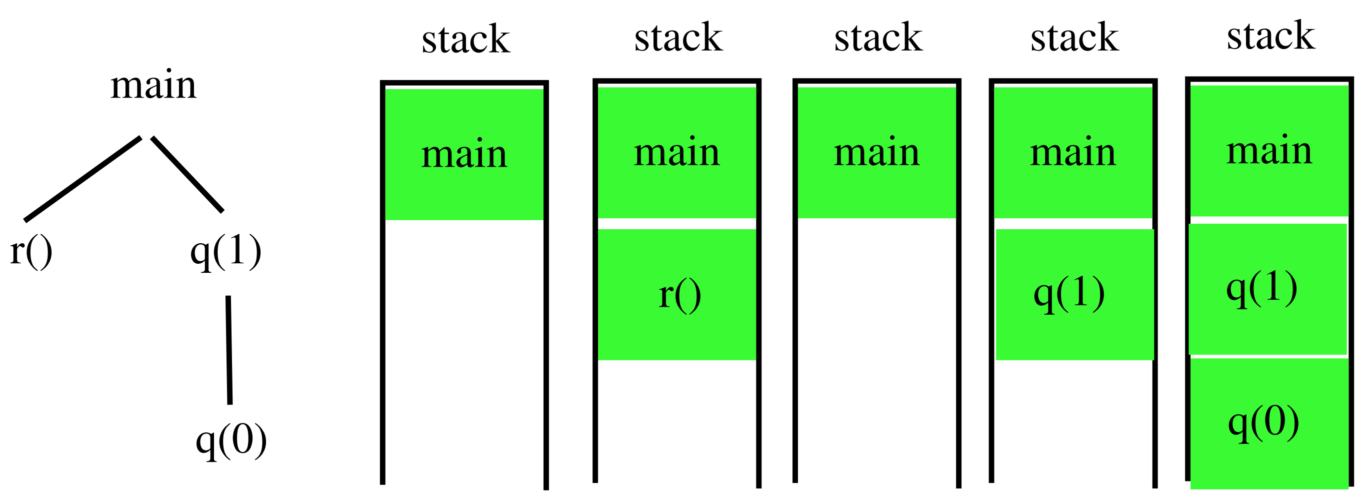
Activation tree

- **Use a tree structure to record the changing of the activation records.**
- **Example:**

```
main{
    r();
    q(1);
}

r{
...
}

q(int i)
{
if(i>0) then q(i-1);
}
```



Dynamic storage allocation for HEAP

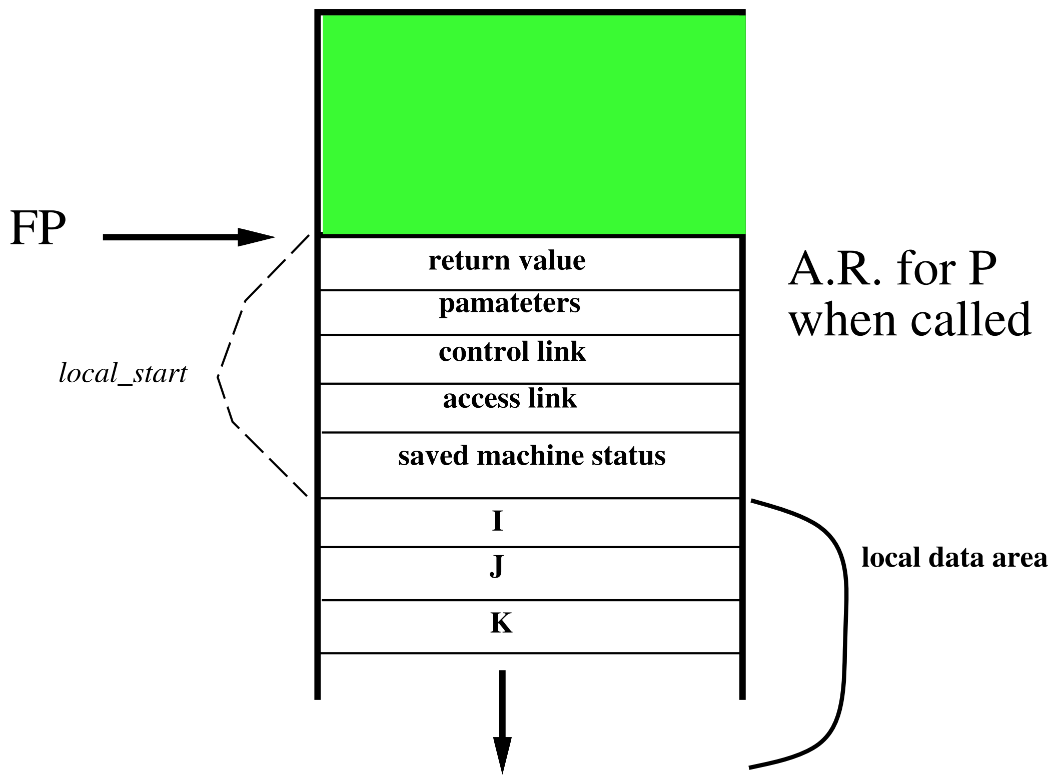
- **Storages requested from programmers during execution:**
  - **Example:**
    - ▷ ***PASCAL:*** new **and** $free$.
    - ▷ ***C:*** $malloc$ **and** $free$.
  - **Issues:**
    - ▷ ***Garbage collection.***
    - ▷ ***Segmentation.***
    - ▷ ***Dangling reference.***
- **More or less O.S. issues.**

Run time variable accesses

- **Global variables:**
  - **Access by using names.**
  - **Addresses known at compile time.**
- **Local variables:**
  - **Stored in the activation record of declaring procedure.**
  - **Access a local variable v in a procedure P by $offset(v)$ from the frame pointer (FP).**
    - ***Let $local\_start(P)$ be the amount of spaces used by data in the activation record of procedure P that are allocated before the local data area.***
    - ***The value $local\_start(P)$ can be computed at compile time.***
    - ***The value $offset(v)$ is the amount of spaces allocated to local variables declared before v.***
    - ***The address of v is FP $+ local\_start(P) + offset(v)$.***
    - ***The actual address is only known at run time, depending on the value of FP.***

Run time variable accesses – example

```
int P()
{
int I,J,K;
...
}
```



- **Address of** J **is FP** $+local\_start(P) + offset(v)$**.**
- $offset(v)$ **is** $1 * sizeof(int)$ **and is known at compile time.**
- $local\_start(P)$ **is known at compile time.**
- **Actual address is only known at run time, i.e., depends on the value of FP.**

Accessing non-local variables

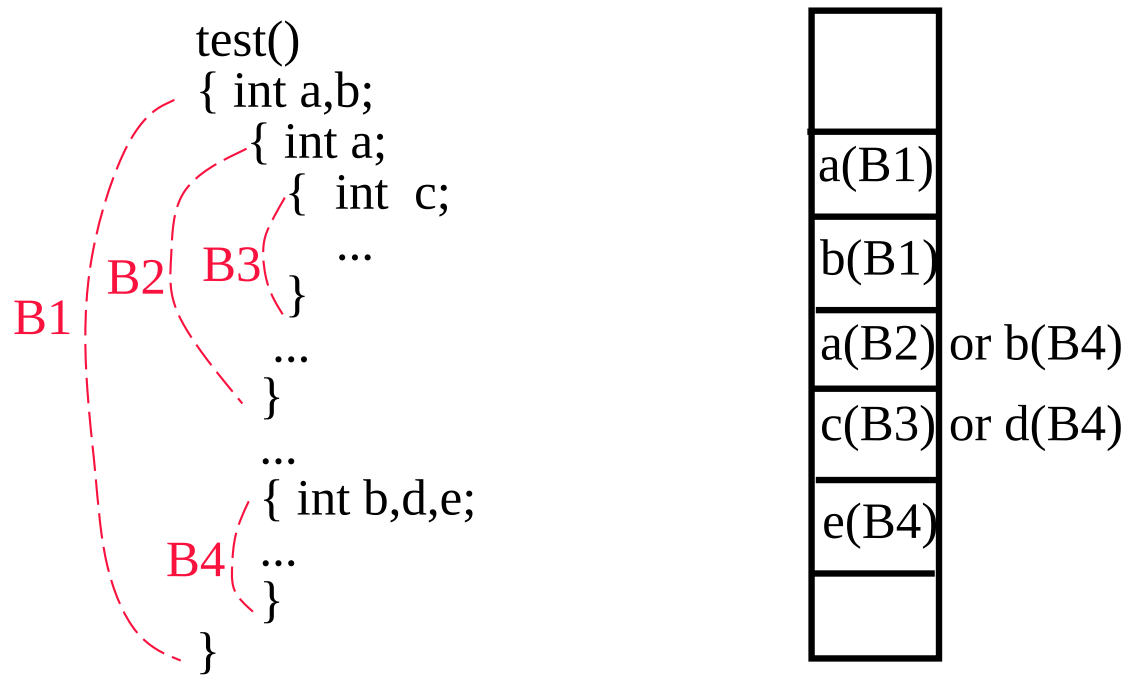
- **Two scoping rules for accessing non-local data.**
  - **Lexical or static scoping.**
    - ▷ *PASCAL, C and FORTRAN.*
    - ▷ *The correct address of a non-local name can be determined at compile time by checking the syntax.*
    - ▷ *Can be with or without block structures.*
    - ▷ *Can be with or without nested procedures.*
  - **Dynamic scoping.**
    - ▷ *LISP.*
    - ▷ *A use of a non-local variable corresponds to the declaration in the "most recently called, still active" procedure.*
    - ▷ *The question of which non-local variable to use cannot be determined at compile time. It can only be determined at run-time.*

Lexical scoping with block structures

- **Block: a statement containing its own local data declaration.**
- **Scoping is given by the following so called most closely nested rule.**
  - **The scope of a declaration in a block B includes B itself.**
  - **If x is used in B, but not declared in B, then we refer to x in a block B', where**
    - ***B' has a declaration x, and***
    - ***B' is more closely nested around B than any other block with a declaration of x.***

Lexical scoping without nested procedures

- **Nested procedure: a procedure that can be declared within another procedure.**
- **If a language does not allow nested procedures, then**
  - **a variable is either global, or is local to the procedure containing it;**
  - **at runtime, all the variables declared (including those in blocks) in a procedure are stored in its A.R., with possible overlapping;**
  - **during compiling, proper offset for each local data is calculated using information known from the block structure.**



Lexical scoping with nested procedures (1/3)

- **In a program with lexical scoping and nested procedures, what are the procedures that can be called in a given procedure Q_0?**
  - **The procedure Q_1 who declares Q_0.**
  - **The procedure Q_i who declares Q_{i-1}, $i > 0$.**
  - **The procedure P_i whom is declared together with, but before, Q_i, $i > 0$**
- **In a procedure declaration tree, Q_0 can call any procedure that is its direct ancestor or the older siblings of its direct ancestor.**
- **A procedure can only access the variables that is global in a procedure that is its direct ancestor.**
  - **When you call a procedure, a variable name follows the lexical scoping rule.**
  - **Use the access link to link to the procedure that is lexically enclosing the called procedure.**
  - **Need to set up the access link properly to access the right storage space.**

Lexical scoping with nested procedures (2/3)

procedure main

procedure a1
procedure s1

procedure a2

procedure b1
procedure q1

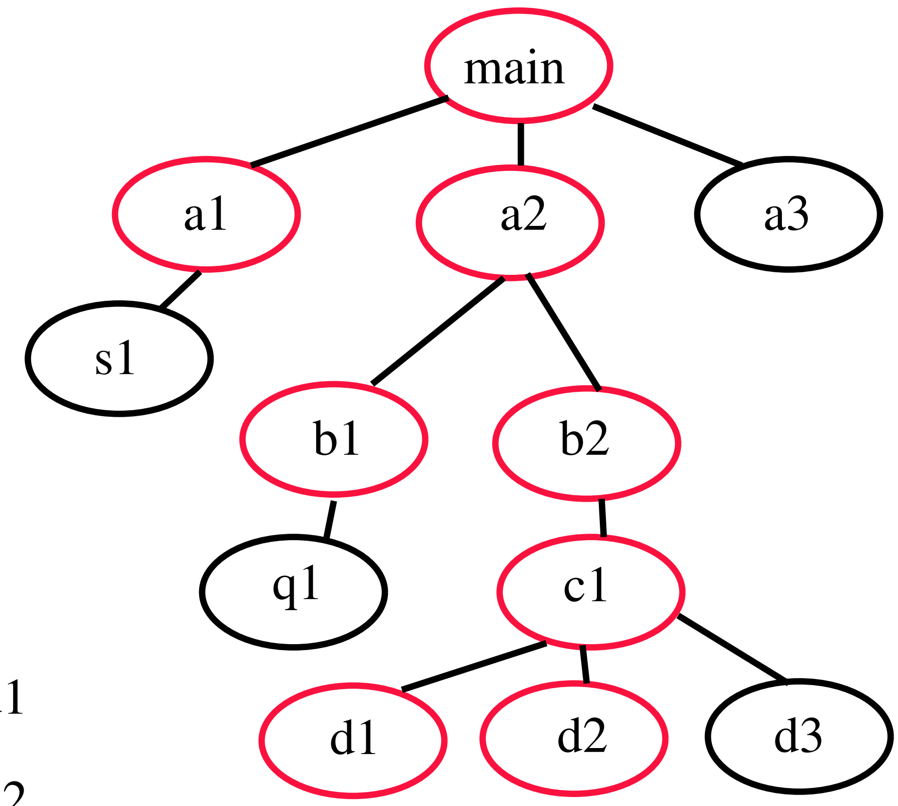
procedure b2

procedure c1

procedure d1

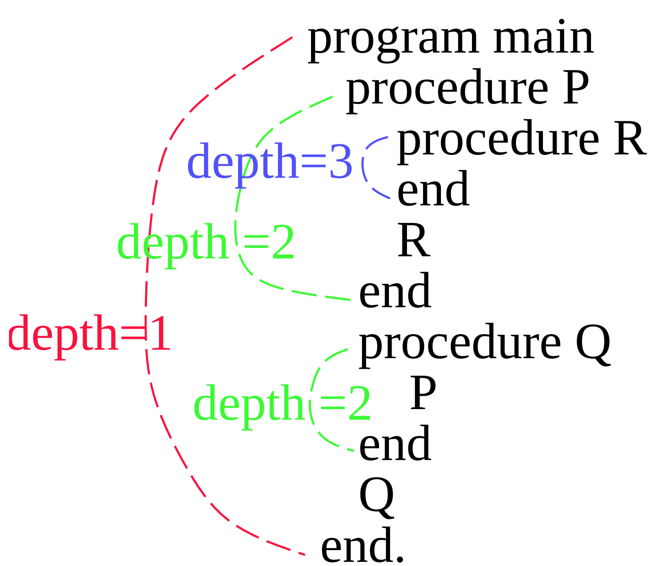
procedure d2
***

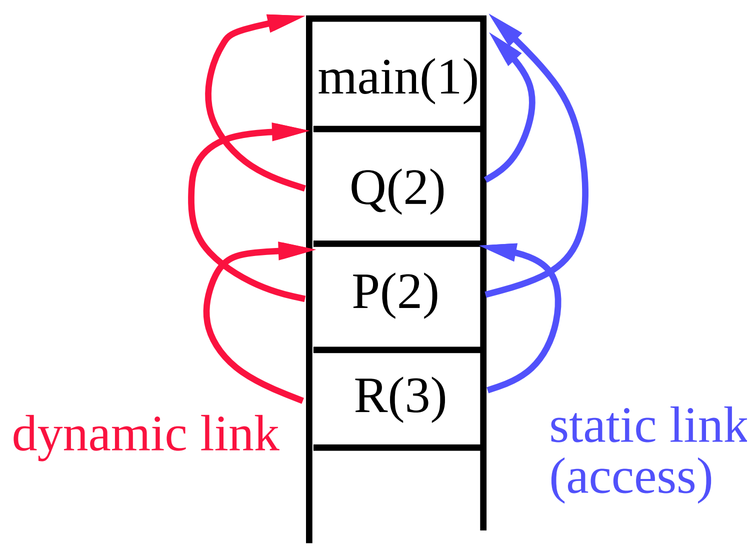
procedure d3



Lexical scoping with nested procedures (3/3)

- **Nesting depth:**
  - **depth of main program = 1.**
  - **add 1 to depth each time entering a nested procedure.**
  - **substrate 1 from depth each time existing from a nested procedure.**
  - **Each variable is associated with a nesting depth.**
  - **Assume in a depth-h procedure, we access a variable at depth k, then**
    - ▷ $h \geq k$.
    - ▷ *follow the access (static) link $h - k$ times, and then use the offset information to find the address.*





Algorithm for setting the links

- **The control link is set to point to the A.R. of the calling procedure.**
- **How to properly set the access link at compile time.**
  - **Procedure p at depth n_p calls procedure x at depth n_x:**
  - **If $n_p < n_x$, then x is enclosed in p and $n_p = n_x - 1$.**
    - ▷ ***Same with setting the control link.***
  - **If $n_p \geq n_x$, then it is either a recursive call or calling a previously declared procedure.**
    - ▷ ***Observation: go up the access link once, then the depth is decreased by 1.***
    - ▷ ***Hence, the access link of x is the access link of p going up $n_p - n_x + 1$ times.***

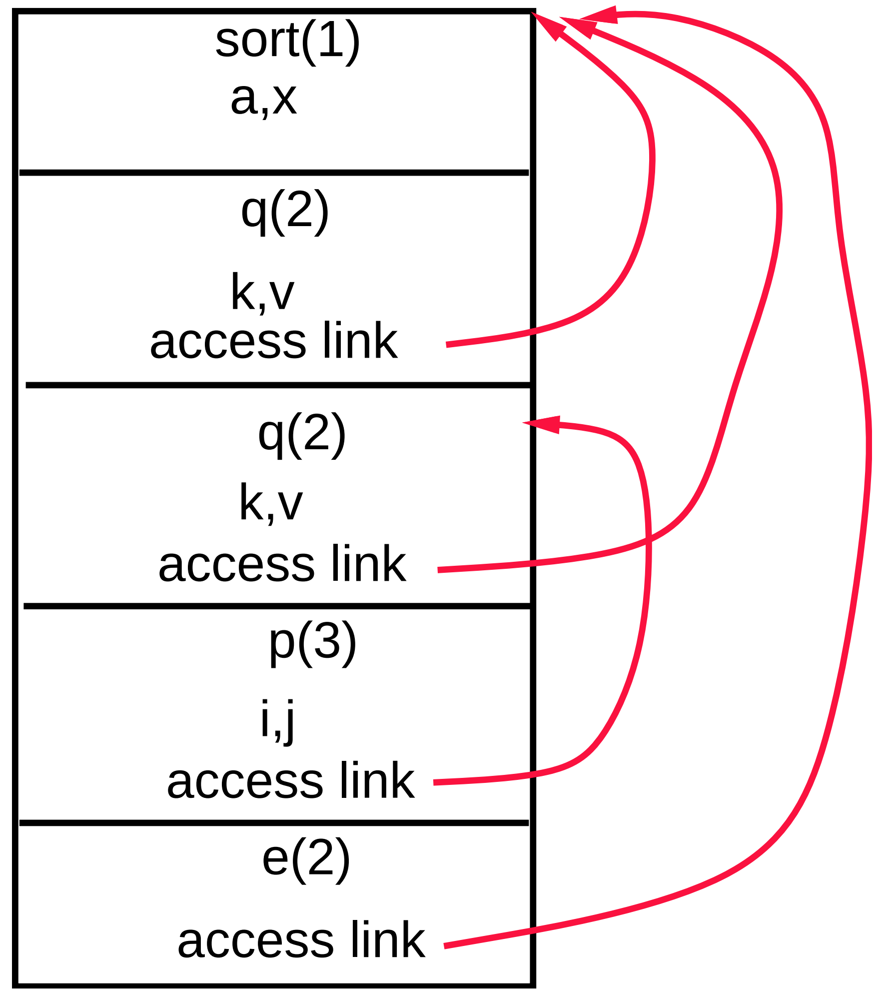
Example

```
Program sort
   var a: array[0..10] of int;
       x: int;
   procedure r
   var i: int;
   begin ...  r
   end

   procedure e(i,j)
   begin ... e
      a[i] <-> a[j]
   end

   procedure q
      var k,v: int;
      procedure p
      var i,j;
      begin ... p
        call e
      end
   begin ... q
        call q or p
   end

begin ... sort
   call q
end
```



Accessing non-local data using DISPLAY

- **Idea:**
  - **Maintain a global array called DISPLAY.**
    - ▷ ***Using registers if available.***
    - ▷ ***Otherwise, stored in the static data area.***
  - **When procedure P at nesting depth k is called,**
    - ▷ ***DISPLAY[1], . . ., DISPLAY[k-1] hold pointers to the A.R.'s of the most recent activation of the $k-1$ procedures that lexically enclose P.***
    - ▷ ***DISPLAY[k] holds pointer to P's A.R.***
    - ▷ ***To access a variable with declaration at depth x, use DISPLAY[x] to get to the A.R. that holds x, then use the usual offset to get x itself.***
    - ▷ ***Size of DISPLAY equals maximum nesting depth of procedures.***
  - **Bad for languages allow recursions.**
- **To maintain the DISPLAY**
  - **When a procedure at nesting depth k is called**
    - ▷ ***Save the current value of DISPLAY[k] in the save-display field of the new A.R.***
    - ▷ ***Set DISPLAY[k] to point to the new A.R., i.e., to its save-display field.***
  - **When the procedure returns, restore DISPLAY[k] using the value saved in the save-display field.**

Access links v.s. DISPLAY

- **Time and space trade-off.**
  - **Access links require more time (at run time) to access non-local data. Especially when non-local data are many nesting levels away.**
  - **DISPLAY probably require more space (at run time).**
  - **Code generated using DISPLAY is simpler.**

Dynamic scoping

- **Dynamic scoping: a use of a non-local variable refers to the one declared in the "most recently called, still active" procedure.**
- **The question of which non-local variable to use cannot be determined at compile time.**
- **It can only be determined at run time.**
- **May need symbol tables at run time.**
- **Two ways to implement non-local accessing under dynamic scoping.**
  - **Deep access.**
  - **Shallow access.**

Dynamic scoping – Example

- **Code:**

```
program main
   procedure test
   var x : int;
   begin
       x := 30;
       call DeclaresX;
       call UsesX;
   end
   procedure DeclaresX
      var x: int;
   begin
      x := 100;
      call UsesX;
   end
   procedure UsesX
   begin
     write(x);
   end
begin
   call test;
end
```

- **Which x is it in the procedure UsesX?**
- **If we were to use static scoping, this is not a legal statement; No enclosing scope declares x.**

Deep access

- **Def: given a use of a non-local variable, use control links to search back in the stack for the most recent A.R. that contains space for that variable.**
  - **Note: this requires that to be possible to tell the set of variables stored in each A.R.**
  - **Need to use the symbol tables at run time.**

Shallow access

- **Idea:**
  - **Maintain a current list of variables.**
  - **Space is allocated (in registers or in the static data area) for every possible variable name that is in the program (i.e., one space for variable x even if there are several declarations of x in different procedures).**
  - **For every reference to x, the generated code refers to the same location.**
- **When a procedure is called,**
  - **it saves, in its own A.R., the current values of all of the variables that it declares itself (i.e., if it declares x and y, then it saves the values of x and y that are currently in the space for x and y).**
  - **It restores those values when it finishes.**
- **Comparisons:**
  - **Shallow access allows fast access to non-locals, but there is overhead on procedure entry and exit proportional to the number of local variables.**
  - **Deep access needs to use a symbol table at run time.**