Compiler Design

Runtime Systems

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Runtime Environment

- Relationship between names and data objects (of target machine)
- Allocation & de-allocation is managed by run time support package
- Each execution of a procedure is an activation of the procedure. If procedure is recursive, several activations may be alive at the same time.
  - If a and b are activations of two procedures then their lifetime is either non overlapping or nested
  - A procedure is recursive if an activation can begin before an earlier activation of the same procedure has ended

Procedure

- A procedure definition is a declaration that associates an identifier with a statement (procedure body)
- When a procedure name appears in an executable statement, it is called at that point
- Formal parameters are the one that appear in declaration. Actual Parameters are the one that appear in when a procedure is called

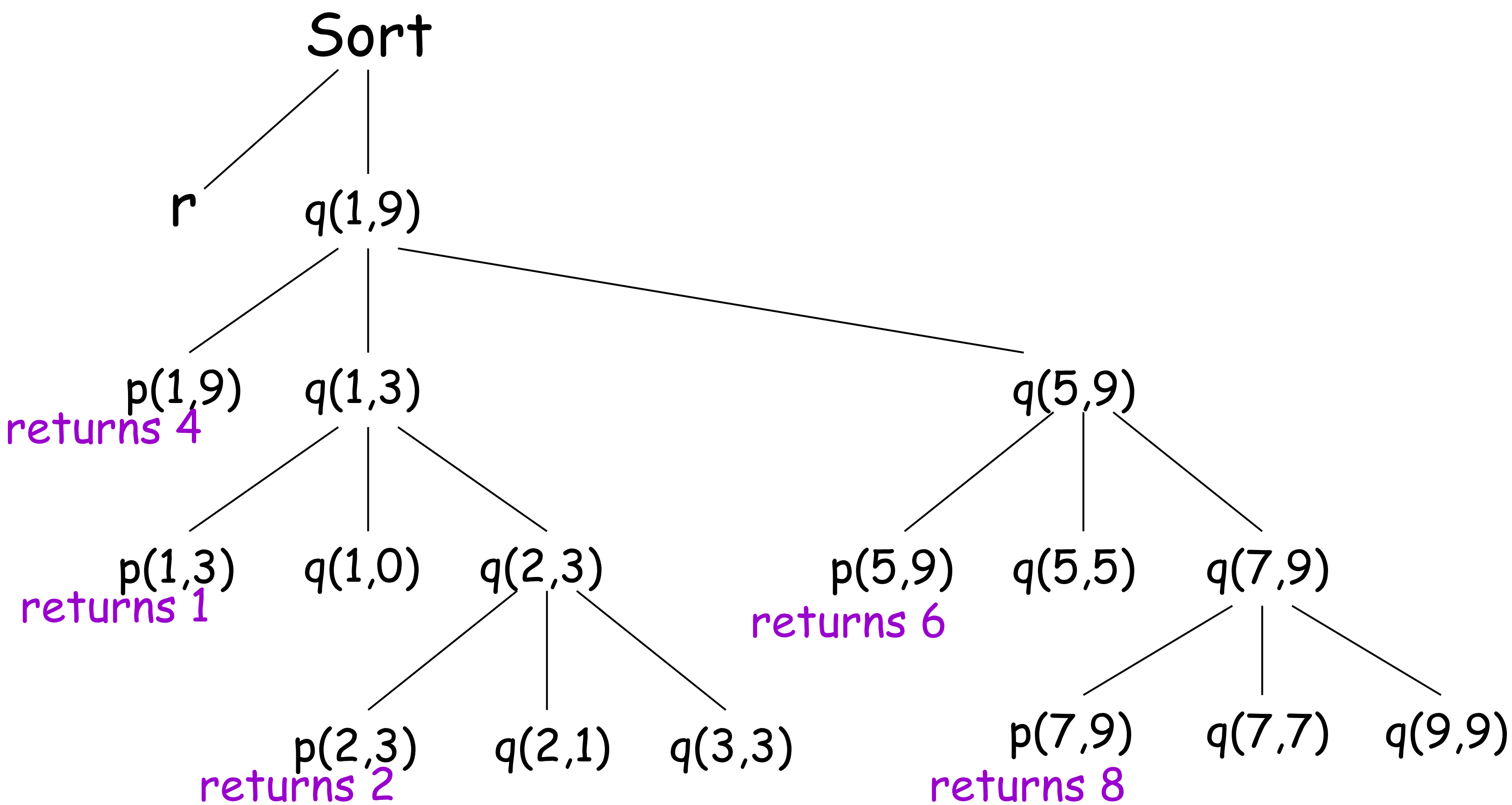
Activation tree

- Control flows sequentially
- Execution of a procedure starts at the beginning of body
- It returns control to place where procedure was called from
- A tree can be used, called an activation tree, to depict the way control enters and leaves activations
  - The root represents the activation of main program
  - Each node represents an activation of procedure
  - The node **a** is parent of **b** if control flows from **a** to **b**
  - The node **a** is to the left of node **b** if lifetime of **a** occurs before **b**

Example

```
program sort;
  var a : array[0..10] of
    integer;

   procedure readarray;
     var i :integer;
           :
   function partition (y, z
              :integer)
  :integer;
     var i, j ,x, v :integer;
        :

   procedure quicksort (m, n
                    :integer);
     var i :integer;
           :
     i:= partition (m,n);
     quicksort (m,i-1);
     quicksort(i+1, n);
        :
begin{main}
    readarray;
    quicksort(1,9)
end.
```

Activation Tree



Control stack

- Flow of control in program corresponds to depth first traversal of activation tree
- Use a stack called control stack to keep track of live procedure activations
- Push the node when activation begins and pop the node when activation ends
- When the node n is at the top of the stack the stack contains the nodes along the path from n to the root

Scope of declaration

- A declaration is a syntactic construct associating information with a name
  - Explicit declaration :Pascal (Algol class of languages)

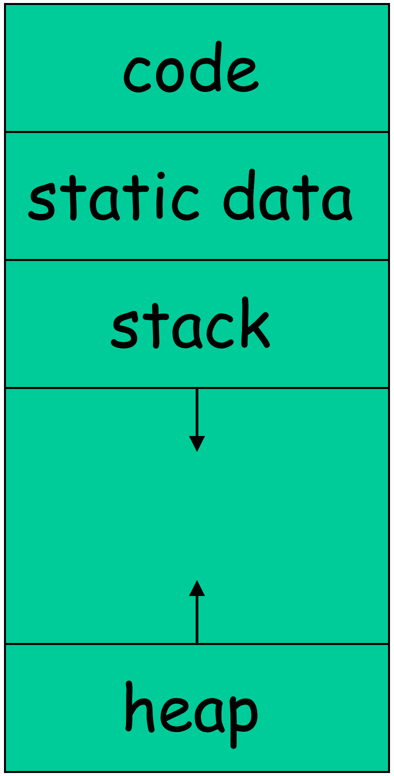
    var i : integer
  - Implicit declaration: Fortran

    i is assumed to be integer
- There may be independent declarations of same name in a program.
- Scope rules determine which declaration applies to a name
- Name binding

$$\text{name} \xrightarrow{\text{environment}} \text{storage} \xrightarrow{\text{state}} \text{value}$$

Storage organization

- The runtime storage might be subdivided into
  - Target code
  - Data objects
  - Stack to keep track of procedure activation
  - Heap to keep all other information



Activation Record

- **temporaries:** used in expression evaluation
- **local data:** field for local data
- **saved machine status:** holds info about machine status before procedure call
- **access link :** to access non local data
- **control link :**points to activation record of caller
- **actual parameters:** field to hold actual parameters
- **returned value**: field for holding value to be returned

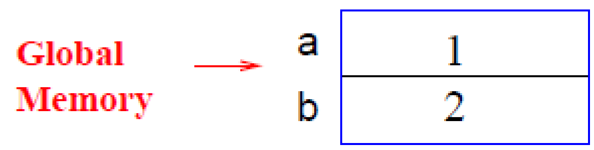
Temporaries
local data
machine status
Access links
Control links
Parameters
Return value

Activation Records: Examples

- Examples on the next few slides by Prof Amitabha Sanyal, IIT Bombay
- C/C++ programs with gcc extensions
- Compiled on x86_64

Example 1 – Vanilla Program in C

```c
int a=1,b=2;
main ()
{
    a = a + b;
}
```



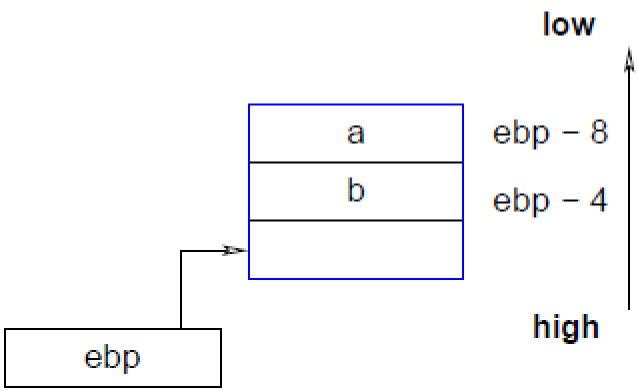
a and b have both been given absolute addresses

compilation of a = a + b

```
...
movl a, %edx
movl b, %eax
addl %edx, %eax
movl %eax, a
...
```

Example 2 – Function with Local Variables

```
void f()
{
    int a, b;
    a = a + b;
}
```



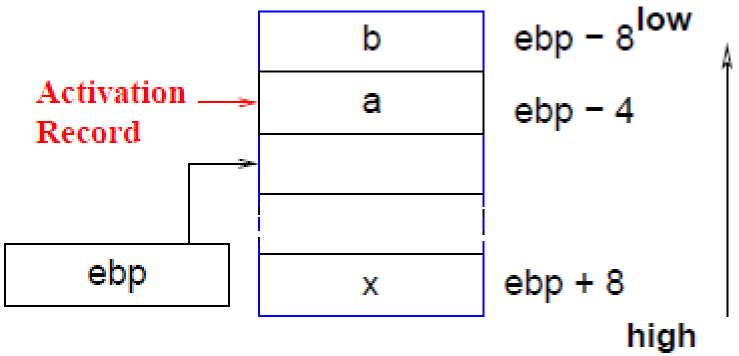
a and b have been given relative address on stack

. . . compilation of a = a + b

```
...
movl -4(%ebp), %eax
addl %eax, -8(%ebp)
...
```

Example 3 – Function with Parameters

```
void f(int x)
{
     int a, b;
     a = x + b;
}
...
```



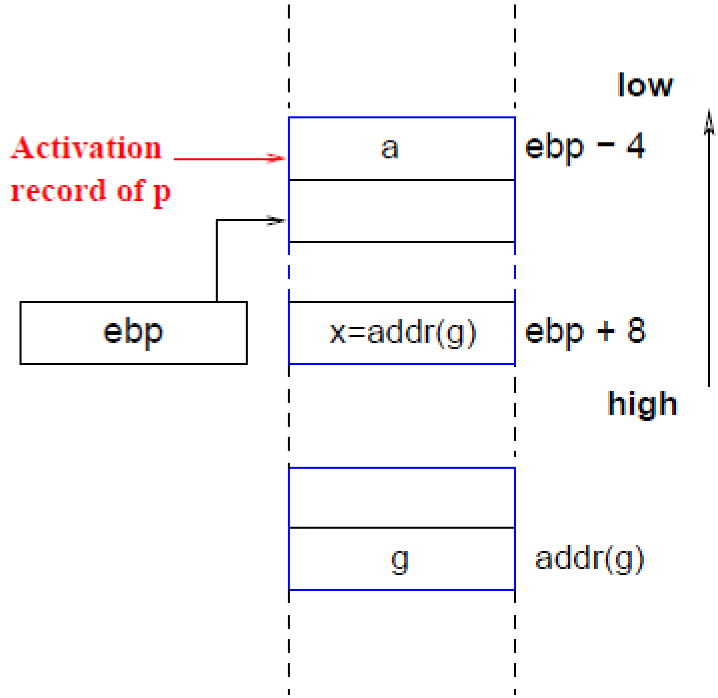
Relative to fp:
a and b − negative address
x − positive address

Compilation of a = x + b

```
...
movl -8(%ebp), %eax
movl 8(%ebp), %edx
addl %edx, %eax
movl %eax, -4(%ebp)
...
```

Example 4 – Reference Parameters

```
int g;
void p(int& x)
{
    int a;
    a = x + 1;
}
main()
{
    p(g);
}
```

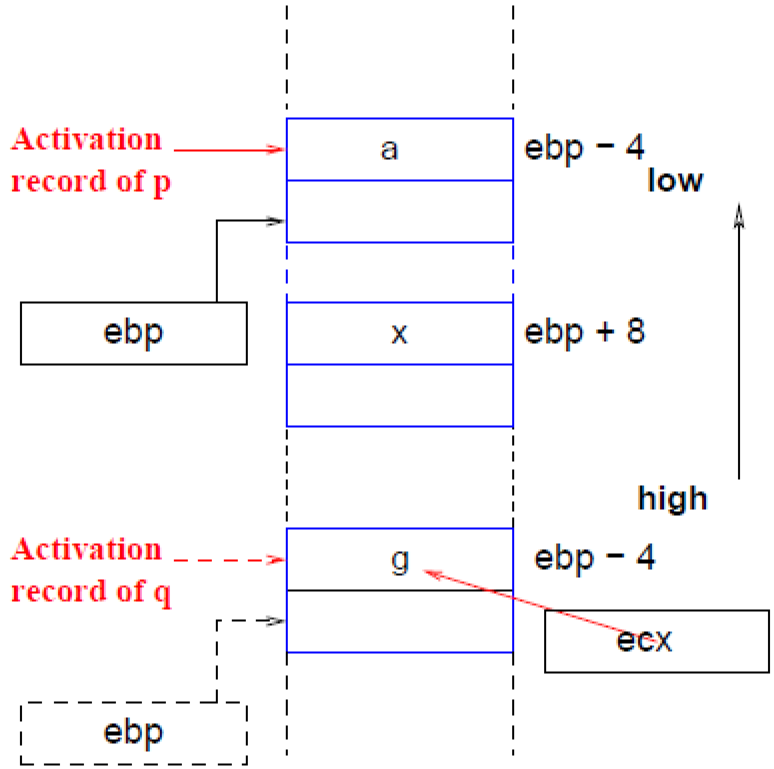


...compilation of a := x + 1

```
movl 8(%ebp), %eax
movl (%eax), %eax
addl $1, %eax
movl %eax, -4(%ebp)
```

Example 5 – Global Variables

```
void q()
{
    int g;
    void p(int x)
    {
        int a;
        a = x + g;
    };
    p(1);
};
```



Compilation of a= x + g

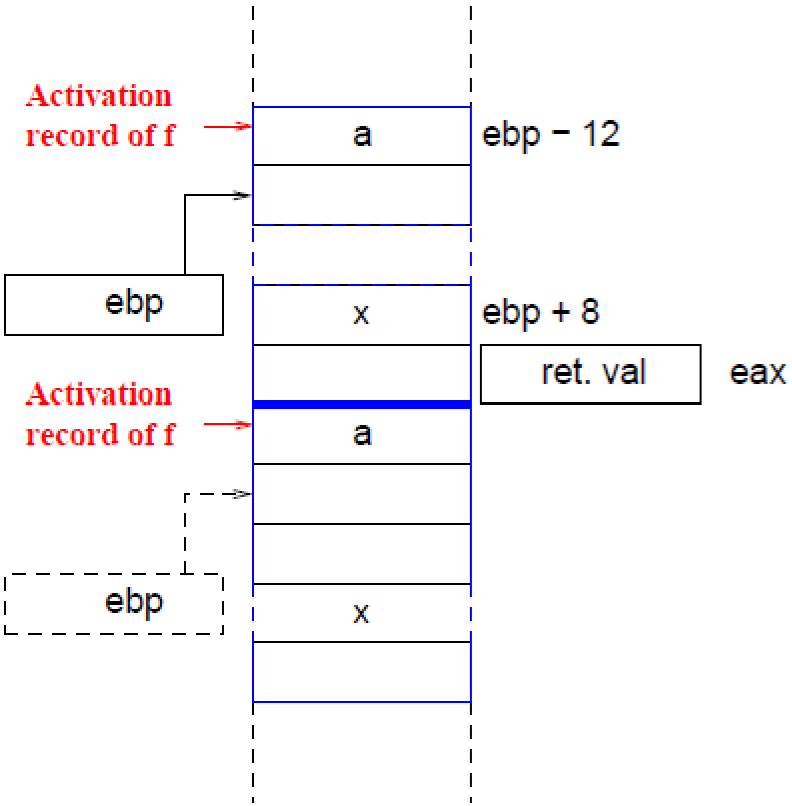
```
...
movl %ecx, %eax ;static link
movl (%eax), %edx
movl 8(%ebp), %eax
addl %edx, %eax
movl %eax, -4(%ebp)
```

Example 6 – Recursive Functions

```
int f(int x)
{
    int a;
    if (x==0) return 1;
    {
        a = f(x-1);
        return(x * a);
    }
}
```

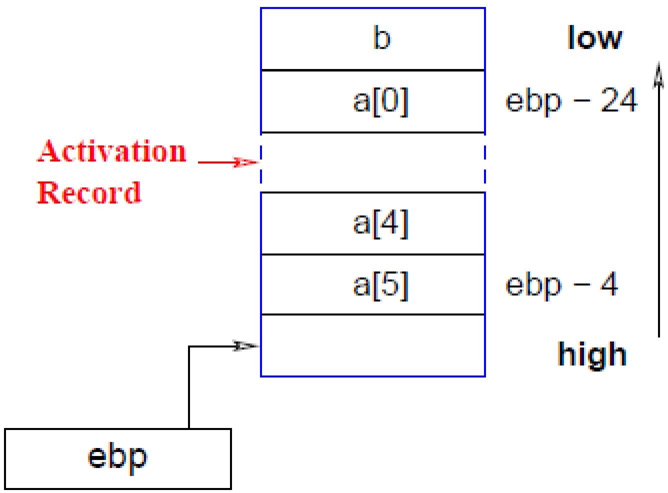
...compilation of a = f(x-1);
return(x * a)

```
...
movl %eax, -12(%ebp)
movl 8(%ebp), %eax
imull -12(%ebp), %eax
```



Example 7 – Array Access

```
void p()
{
    int a[6], b;
    b = a[5];
}
```

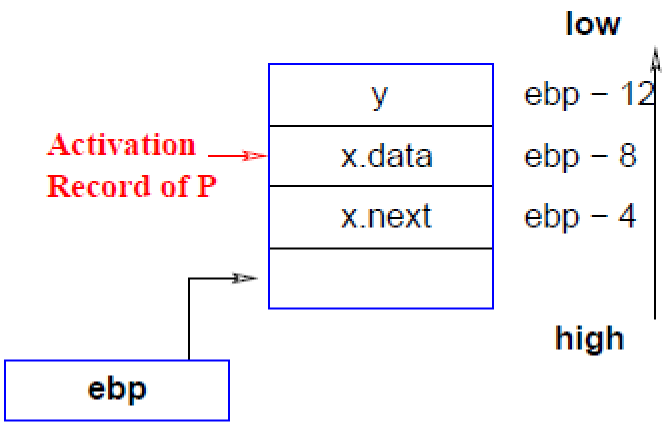


. . . compilation of b = a[5]

```
...
movl -4(%ebp), %eax
movl %eax, -28(%ebp)
...
```

Example 8 – Records and Pointers

```
typedef struct rec
{
    int  data;
    struct rec* next;

} rec;
void p ()
{
    rec x; rec *y;
    x.next = y;
}
```



…compilation of x.data = 5;
x.next = y;

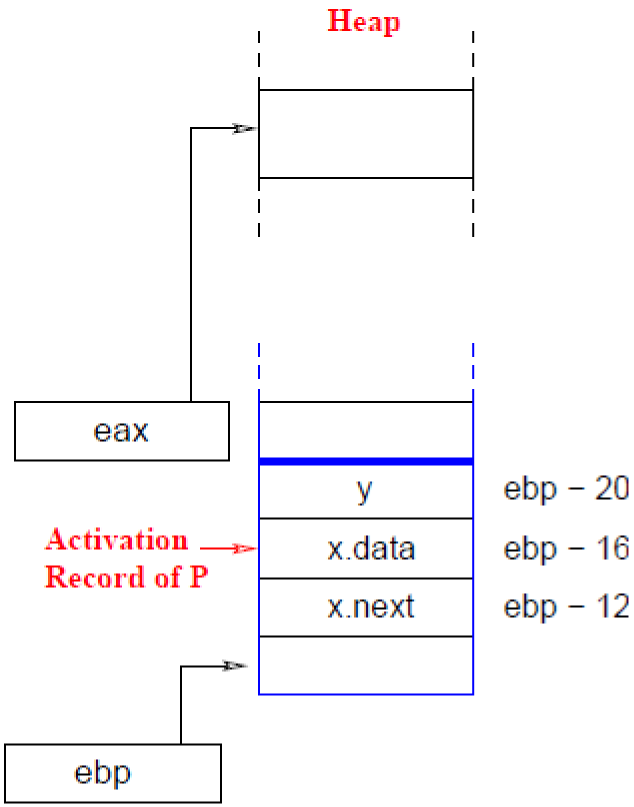
```
...
movl -12(%ebp), %eax
movl %eax, -4(%ebp)
...
```

Example 9 – Dynamically Created Data

```
typedef struct rec
{
    int  data;
    struct rec* next;
} rec;
void p ()
{
    rec x; rec *y;
    y = malloc(4); x.next = y;
}
```

Compilation of y = malloc...; x.next = y;

```
call malloc
movl %eax, -20(%ebp)
movl -20(%ebp), %eax
movl %eax, -12(%ebp)
```



Issues to be addressed

- Can procedures be recursive?
- What happens to locals when procedures return from an activation?
- Can procedure refer to non local names?
- How to pass parameters?
- Can procedure be parameter?
- Can procedure be returned?
- Can storage be dynamically allocated?
- Can storage be de-allocated?

Layout of local data

- Assume byte is the smallest unit
- Multi-byte objects are stored in consecutive bytes and given address of first byte
- The amount of storage needed is determined by its type
- Memory allocation is done as the declarations are processed
  - Keep a count of memory locations allocated for previous declarations
  - From the count *relative* address of the storage for a local can be determined
  - As an *offset* from some fixed position

Layout of local data

- Data may have to be aligned (in a word) padding is done to have alignment.
- When space is important
  - Complier may pack the data so no padding is left
  - Additional instructions may be required to execute packed data
  - Tradeoff between space and execution time

Storage Allocation Strategies

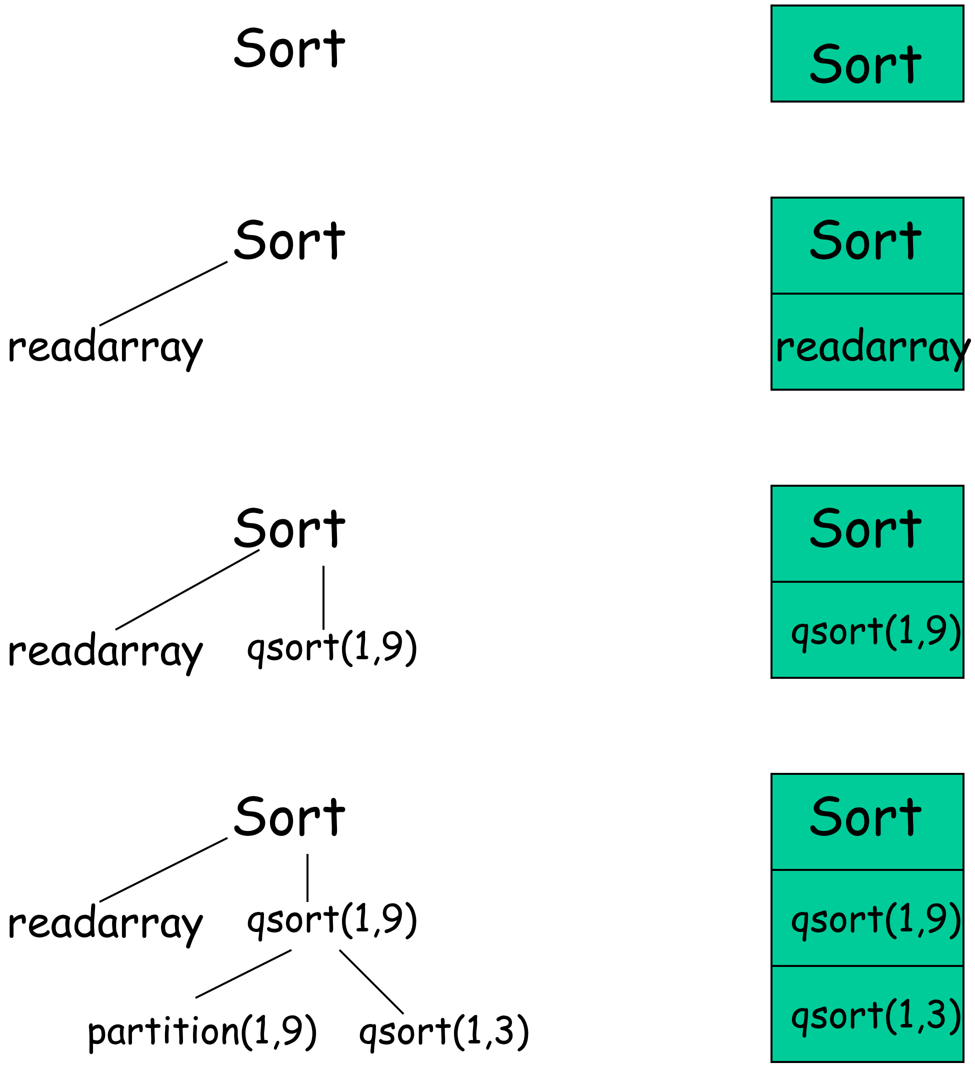
- Static allocation: lays out storage at compile time for all data objects
- Stack allocation: manages the runtime storage as a stack
- Heap allocation :allocates and de-allocates storage as needed at runtime from heap

Static allocation

- Names are bound to storage as the program is compiled
- No runtime support is required
- Bindings do not change at run time
- On every invocation of procedure names are bound to the same storage
- Values of local names are retained across activations of a procedure

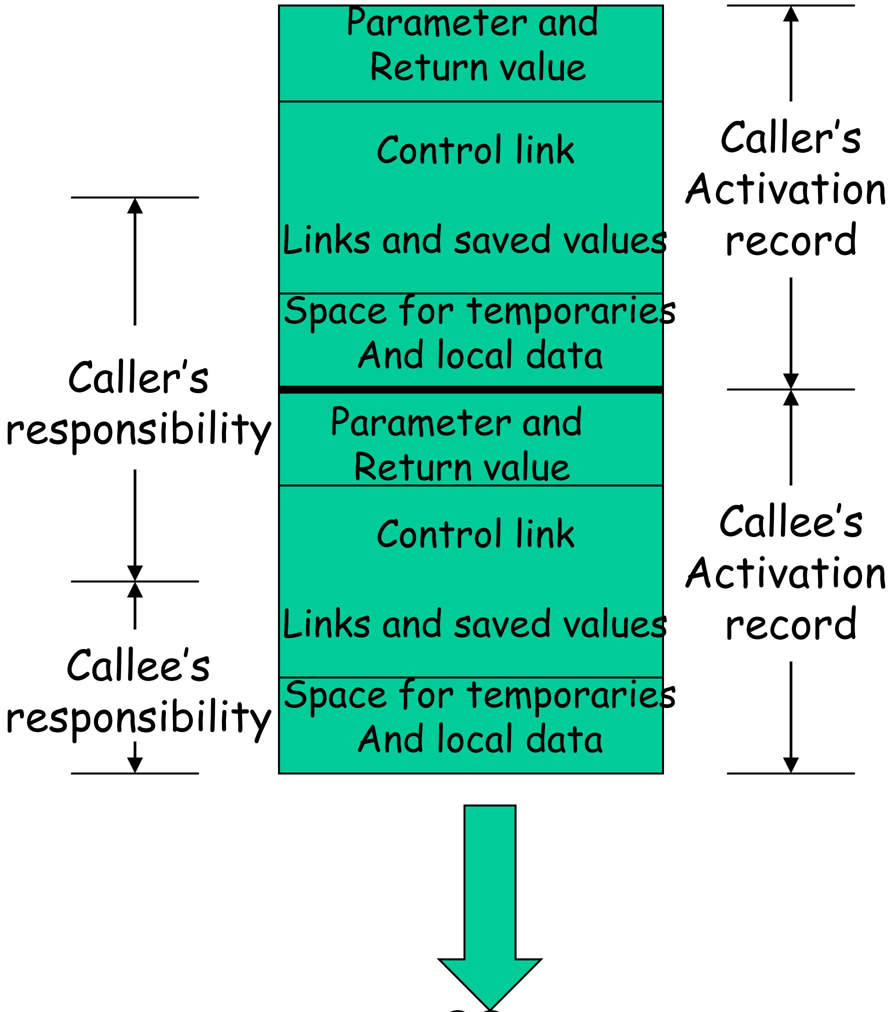
- Type of a name determines the amount of storage to be set aside
- Address of a storage consists of an offset from the end of an activation record
- Compiler decides location of each activation
- All the addresses can be filled at compile time
- Constraints
  - Size of all data objects must be known at compile time
  - Recursive procedures are not allowed
  - Data structures cannot be created dynamically

Stack Allocation



Calling Sequence

- A call sequence allocates an activation record and enters information into its field
- A return sequence restores the state of the machine so that calling procedure can continue execution



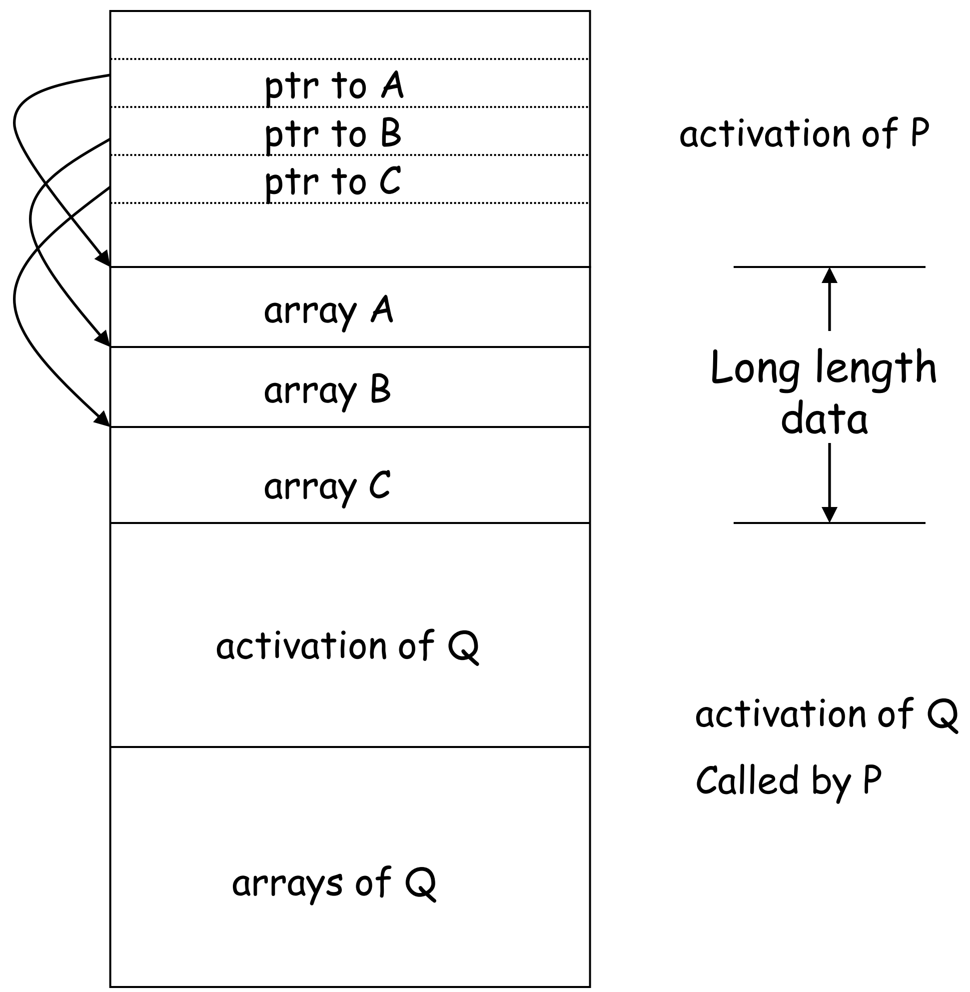
Call Sequence

- Caller evaluates the actual parameters
- Caller stores return address and other values (control link) into callee’s activation record
- Callee saves register values and other status information
- Callee initializes its local data and begins execution

Return Sequence

- Callee places a return value next to activation record of caller
- Restores registers using information in status field
- Branch to return address
- Caller copies return value into its own activation record

Long/Unknown Length Data



Dangling references

Referring to locations which have been deallocated

```
main() {
    int *p;
    p = dangle(); /* dangling reference */
}

int *dangle() {
    int i=23;
    return &i;
}
```

Heap Allocation

- Stack allocation cannot be used if:
  - The values of the local variables must be retained when an activation ends
  - A called activation outlives the caller
- In such a case de-allocation of activation record cannot occur in last-in first-out fashion
- Heap allocation gives out pieces of contiguous storage for activation records

Heap Allocation …

- Pieces may be de-allocated in any order
- Over time the heap will consist of alternate areas that are free and in use
- Heap manager is supposed to make use of the free space
- For efficiency reasons it may be helpful to handle small activations as a special case

Heap Allocation …

- For each size of interest keep a linked list of free blocks of that size
- Fill a request of size s with block of size s' where s' is the smallest size greater than or equal to s.
- When the block is deallocated, return it to the corresponding list

Heap Allocation …

- For large blocks of storage use heap manager
- For large amount of storage computation may take some time to use up memory
  - time taken by the manager may be negligible compared to the computation time

Access to non-local names

- Scope rules determine the treatment of non-local names
- A common rule is *lexical scoping* or *static scoping* (most languages use lexical scoping)
  - Most closely nested declaration
- Alternative is *dynamic scoping*
  - Most closely nested activation

Block

- Statement containing its own data declarations
- Blocks can be nested
  - also referred to as *block structured*
- Scope of the declaration is given by *most closely nested* rule
  - The scope of a declaration in block B includes B
  - If X is not declared in B then an occurrence of X in B is in the scope of declaration of X in B′ such that
    - B′ has a declaration of X
    - B′ is most closely nested around B

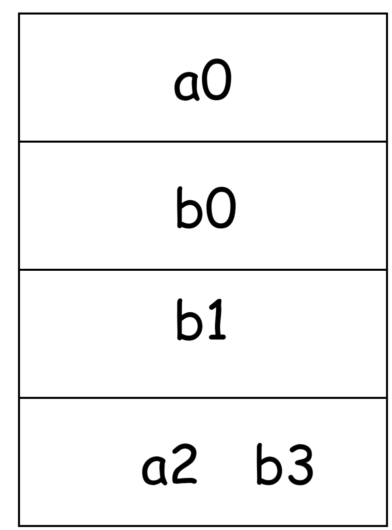
Example

```
main()
{                                   BEGINNING of B0
    int a=0  ---------------------------------------- Scope B0, B1, B3
    int b=0  ---------------------------------------- Scope B0
    {                               BEGINNING of B1
        int b=1  ------------------------------------ Scope B1, B2
        {                           BEGINNING of B2
            int a=2  -------------------------------- Scope B2
            print a, b
        }                           END of B2

        {                           BEGINNING of B3
            int b=3  -------------------------------- Scope B3
            print a, b
        }                           END of B3
        print a, b
    }                               END of B1
    print a, b
}                                   END of B0
```

Blocks …

- Blocks are simpler to handle than procedures
- Blocks can be treated as parameter less procedures
- Either use stack for memory allocation
- OR allocate space for complete procedure body at one time

```
{ // a0
    { // b0
        { // b1
            { // a2
            }
            { //b3
            }
        }
    }
}
```



Lexical scope without nested procedures

- A procedure definition cannot occur within another
- Therefore, all non local references are global and can be allocated at compile time
- Any name non-local to one procedure is non-local to all procedures
- In absence of nested procedures use stack allocation
  - Storage for non locals is allocated statically
  - Any other name must be local to the top of the stack
- Static allocation of non local has advantage:
  - Procedures can be passed/returned as parameters

Scope with nested procedures

```
Program sort;
  var a: array[1..n] of integer;
        x: integer;
  procedure readarray;
    var i: integer;
    begin

    end;
  procedure exchange(i,j:integer)
    begin

    end;
```

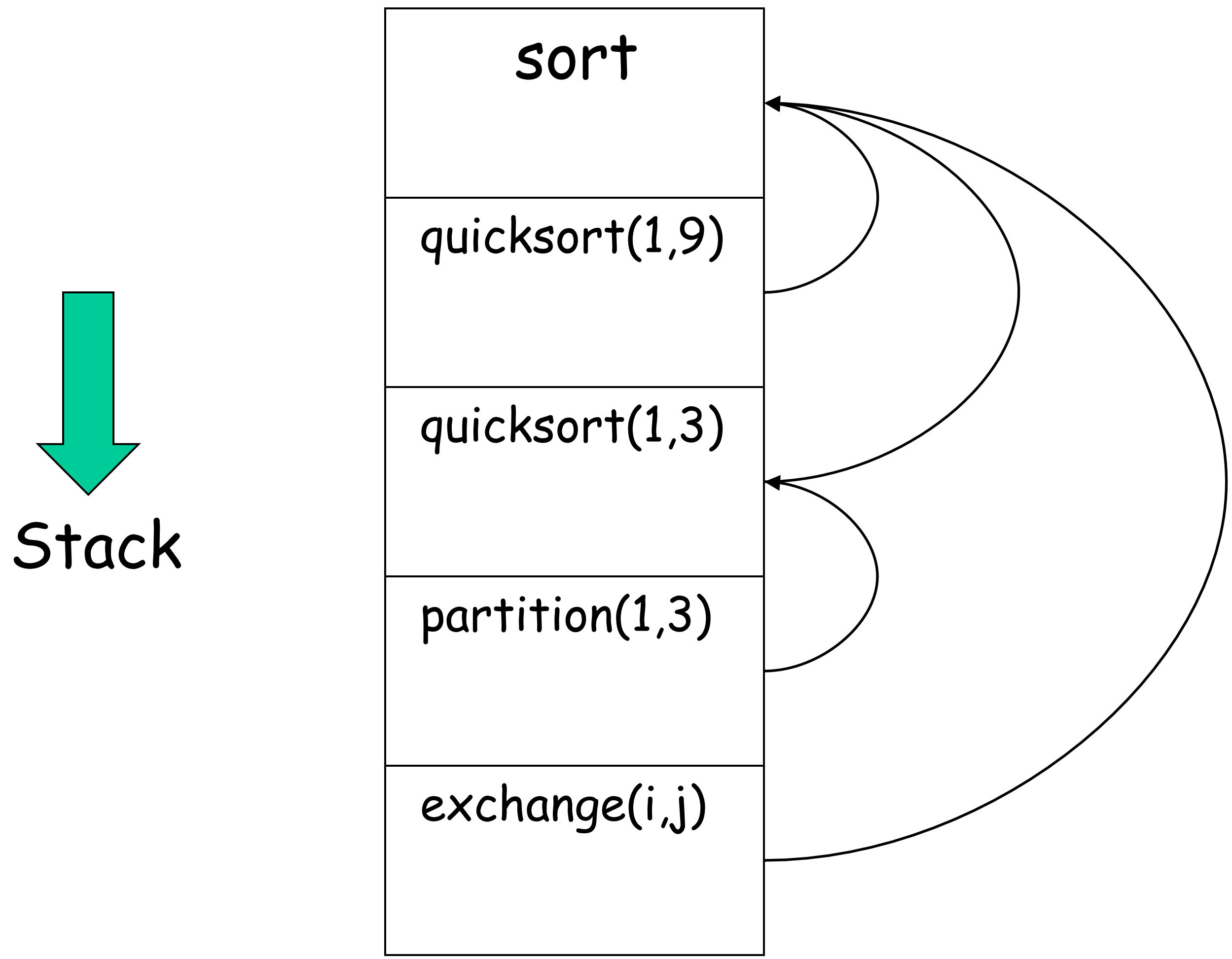
```
procedure quicksort(m,n:integer);
    var k,v : integer;

    function partition(y,z:integer): integer;
        var i,j: integer;
        begin

        end;
    begin
                            .
    end;
begin
            .
end.
```

Nesting Depth

- Main procedure is at depth 1
- Add 1 to depth as we go from enclosing to enclosed procedure

Access to non-local names

- Include a field ‘access link’ in the activation record
- If p is nested in q then access link of p points to the access link in most recent activation of q


Stack
sort
quicksort(1,9)
quicksort(1,3)
partition(1,3)
exchange(i,j)

Access to non local names …

- Suppose procedure p at depth np refers to a non-local *a* at depth na (na ≤ np), then storage for *a* can be found as
  - follow (np-na) access links from the record at the top of the stack
  - after following (np-na) links we reach procedure for which *a* is local
- Therefore, address of a non local *a* in p can be stored in symbol table as
  - (np-na, offset of *a* in record of activation having *a*)

How to setup access links?

- Code to setup access links is part of the calling sequence.
- suppose procedure p at depth np calls procedure x at depth nx.
- The code for setting up access links depends upon *whether or not* the called procedure is nested within the caller.

How to setup access links?

$$np < nx$$

- Called procedure x is nested more deeply than p.
- Therefore, x must be declared in p.
- The access link in x must point to the access link of the activation record of the caller just below it in the stack

How to setup access links?

$$np \geq nx$$

- From scoping rules enclosing procedure at the depth 1,2,… ,nx-1 must be same.
- Follow np-(nx-1) links from the caller.
- We reach the most recent activation of the procedure that statically encloses both p and x most closely.
- The access link reached is the one to which access link in x must point.
- np-(nx-1) can be computed at compile time.

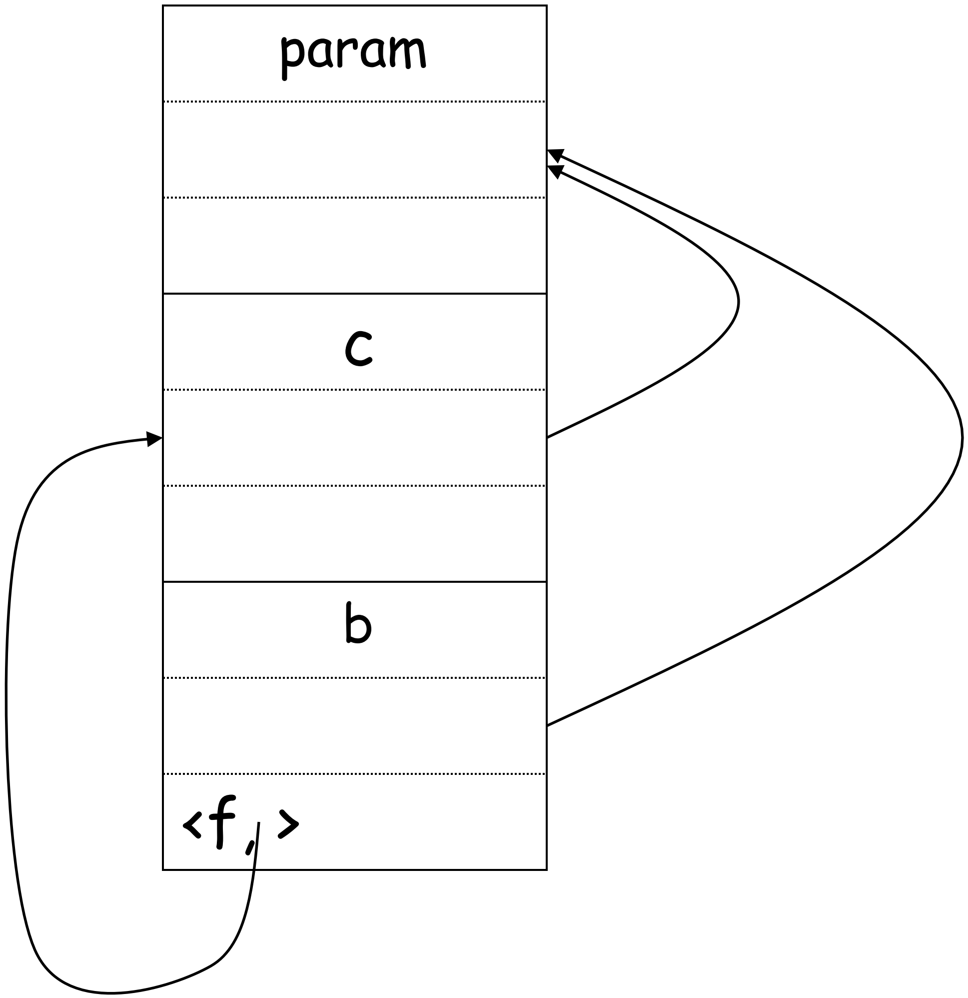
Procedure Parameters

```
program param (input,output);
    procedure b( function h(n:integer): integer);
        begin
          print (h(2))
        end;
    procedure c;
        var m: integer;
        function f(n: integer): integer;
            begin
              return  m + n
            end;
        begin
            m :=0; b(f)
        end;
    begin
        c
    end.
```

Procedure Parameters …

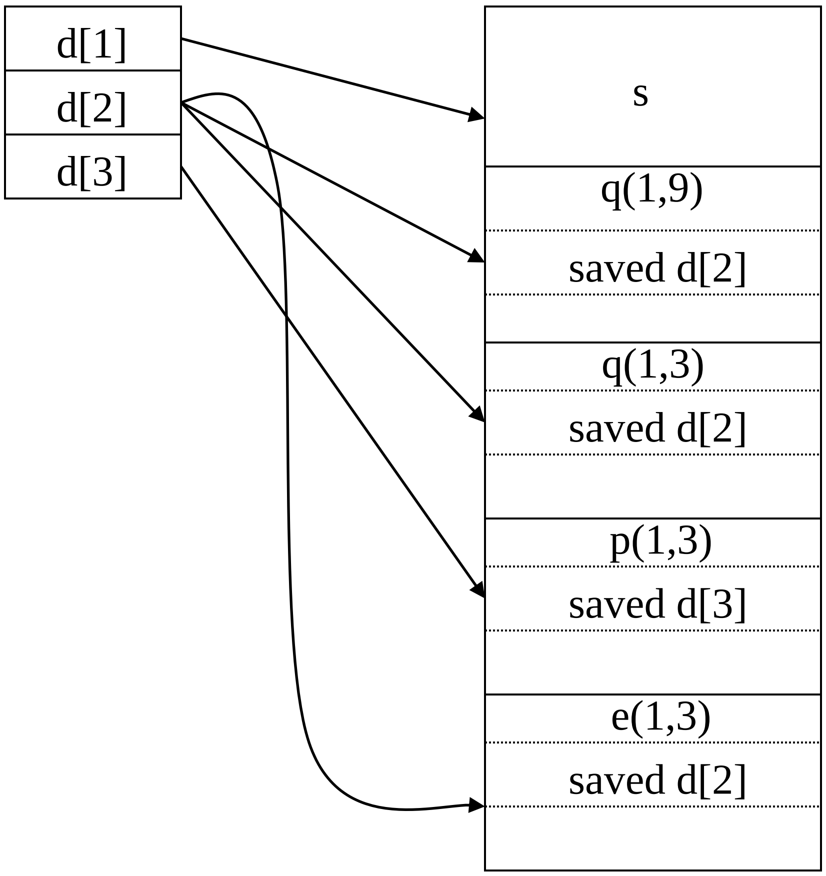
- Scope of m does not include procedure b
- within b, call h(2) activates f
- how is access link for activation of f is set up?
- a nested procedure must take its access link along with it
- when c passes f:
  - it determines access link for f as if it were calling f
  - this link is passed along with f to b
- When f is activated, this passed access link is used to set up the activation record of f

Procedure Parameters ...



Displays

- Faster access to non locals
- Uses an array of pointers to activation records
- Non locals at depth i are in the activation record pointed to by d[i]



Setting up Displays

- When a new activation record for a procedure at nesting depth i is set up:
- Save the value of d[i] in the new activation record
- Set d[i] to point to the new activation record
- Just before an activation ends, d[i] is reset to the saved value

Justification for Displays

- Suppose procedure at depth j calls procedure at depth i
- Case $j < i$ then $i = j + 1$
  - called procedure is nested within the caller
  - first j elements of display need not be changed
  - old value of d[i] is saved and d[i] set to the new activation record
- Case $j \geq i$
  - enclosing procedure at depths 1…i-1 are same and are left un-disturbed
  - old value of d[i] is saved and d[i] points to the new record
  - display is correct as first i-1 records are not disturbed

Dynamic Scoping: Example

- Consider the following program

```
program dynamic (input, output);
 var r: real;

 procedure show;
     begin write(r) end;

 procedure small;
     var r: real;
     begin r := 0.125; show end;

 begin
     r := 0.25;
     show; small; writeln;
     show; small; writeln;
 end.
```

// writeln prints a newline character

Example …

- Output under lexical scoping

  0.250 0.250

  0.250 0.250

- Output under dynamic scoping

  0.250 0.125

  0.250 0.125

Dynamic Scope

- Binding of non local names to storage do not change when new activation is set up

- A non local name x in the called activation refers to same storage that it did in the calling activation

Implementing Dynamic Scope

- Deep Access
  - Dispense with access links
  - use control links to search into the stack
  - term deep access comes from the fact that search may go deep into the stack
- Shallow Access
  - hold current value of each name in static memory
  - when a new activation of p occurs a local name n in p takes over the storage for n
  - previous value of n is saved in the activation record of p

Parameter Passing

- Call by value
  - actual parameters are evaluated and their r-values are passed to the called procedure
  - used in Pascal and C
  - formal is treated just like a local name
  - caller evaluates the actual parameters and places rvalue in the storage for formals
  - call has no effect on the activation record of caller

Parameter Passing …

- Call by reference (call by address)
  - the caller passes a pointer to each location of actual parameters
  - if actual parameter is a name then l-value is passed
  - if actual parameter is an expression then it is evaluated in a new location and the address of that location is passed

Parameter Passing …

- Copy restore (copy-in copy-out, call by value result)
  - actual parameters are evaluated, rvalues are passed by call by value, lvalues are determined before the call
  - when control returns, the current rvalues of the formals are copied into lvalues of the locals

Parameter Passing …

- Call by name (used in Algol)
  - names are copied
  - local names are different from names of calling procedure
  - Issue:

```
swap(x, y) {
    temp = x
    x  = y
    y = temp
}
```

```
swap(i,a[i]):
        temp = i
        i = a[i]
        a[i] = temp
```

3AC for Procedure Calls

S $\rightarrow$ call id (Elist)

Elist $\rightarrow$ Elist , E

Elist $\rightarrow$ E

- Calling sequence
  - allocate space for activation record
  - evaluate arguments
  - establish environment pointers
  - save status and return address
  - jump to the beginning of the procedure

Procedure Calls …

Example

- parameters are passed by reference
- storage is statically allocated
- use param statement as place holder for the arguments
- called procedure is passed a pointer to the first parameter
- pointers to any argument can be obtained by using proper offsets

Procedue Calls

- Generate three address code needed to evaluate arguments which are expressions
- Generate a list of param three address statements
- Store arguments in a list

  $S \rightarrow$ call id (Elist)

  for each item p on queue do emit('param' p)

  emit('call' id.place)

  Elist $\rightarrow$ Elist , E

  append E.place to the end of queue

  Elist $\rightarrow$ E

  initialize queue to contain E.place

Procedure Calls

- Practice Exercise:

How to generate intermediate code for parameters passed by value? Passed by reference?