Implementing Subprograms

- **Call**
  - → **Save registers**
  - → **provide storage for parameters**
  - → **provide storage for locals**
  - → **save execution status of caller**
  - → **provide access to non-locals**
  - → **transfer control to called subprogram**
- **Return**
  - → **copy back parameter values (if necessary)**
  - → **may deallocate local storage**
  - → **restore access to non-locals**

    (registers)

    variables with same name as locals
  - → **return control to caller**
- **Use a *calling convention* for communicating**

Preliminaries

- **Need memory for code & data**
  - → **code: static (*instruction space*)**
  - → **data: changes with each activation => activation record (*data space*)**
- **Three ways to allocate storage for data:**
  - → **static**
  - → **stack-based (controlled dynamic)**
  - → **dynamic (heap-based)**

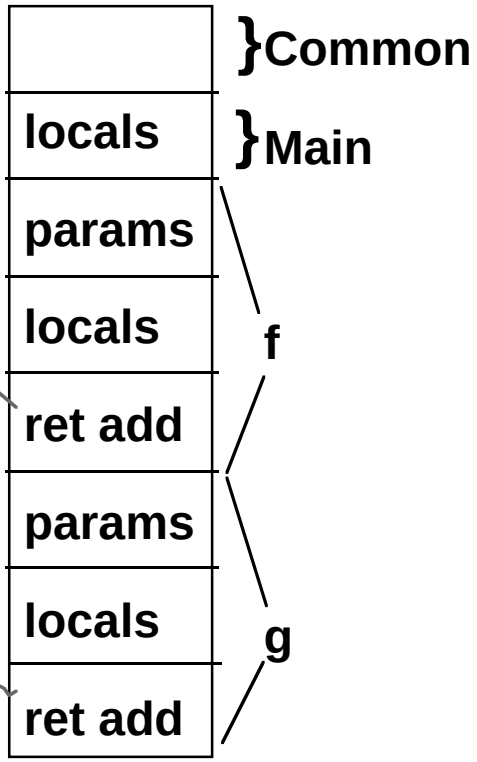
Static Allocation (FORTRAN)

- **Simplifying factors**
  - → **no recursion**
  - → **size of variables known statically**
  - → **access non-local variables with COMMON statement**

- **Result**
  - → **<u>can allocate all memory statically</u>**
  - → **example:**

All variable addresses are determined statically

```
main
  ...
    f (...)
  ...
proc f (...)
  ...
    g (...)
  ...
proc g( )
  ...
    g (...)   -- !!!
```



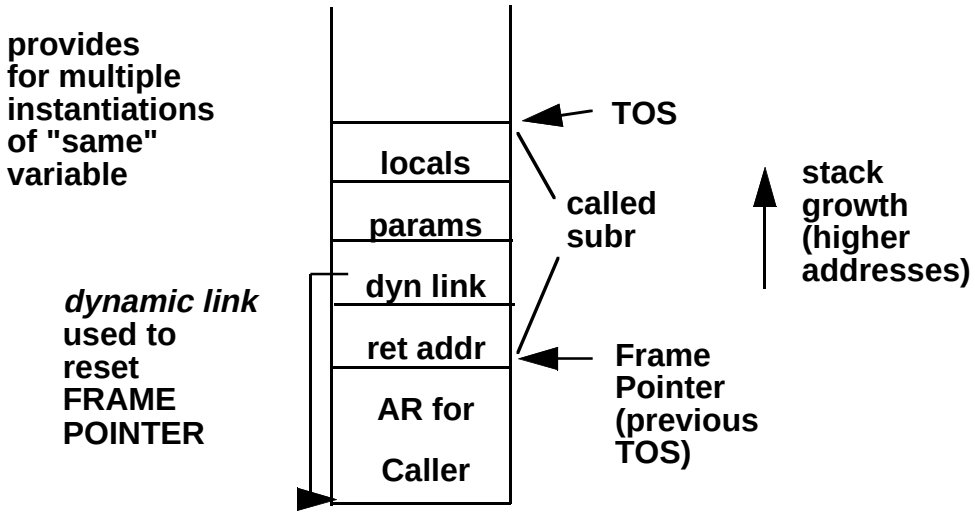
  - → **What about recursion???**

Handling Recursion

- **procedure activations are LIFO => use a stack**
- **for now, two simplifying assumptions:**
  - → **no non-local references**
  - → **size of all variables known statically**

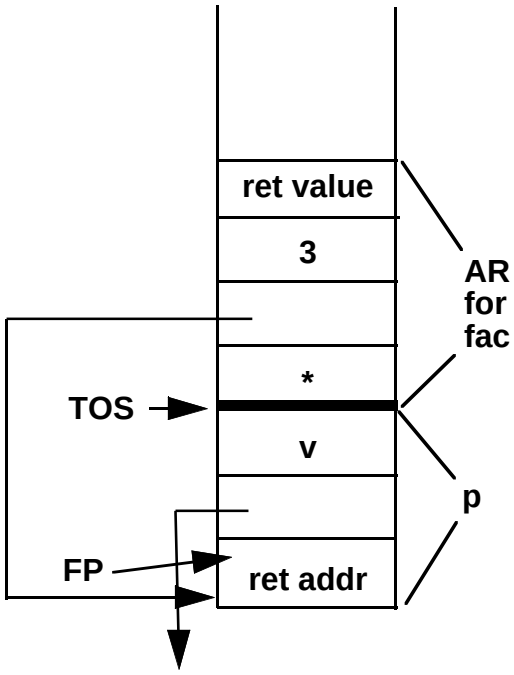
Activation Records on a Stack

- **Call**
  - → **set return addr, dynamic link**
  - → **push actual parameter values**
  - → **allocate space for locals**
  - → **FP := TOS, reset TOS**
- **Return:**
  - → **instruction pointer := mem[FP] (return address)**
  - → **TOS := FP (clear this activation record)**
  - → **FP := mem[FP + 1] (dynamic link)**



Example: factorial

```
program p;
var v : int;
    function fac(n : int) :int;
    begin
        if n ≤ 1 then
            fac := 1
        else
            fac := n * fac(n - 1);
    end;
begin
    v := fac(3);
    print(v)
end.
```



Lifting Restrictions

- **Allow size of variables to be determined dynamically**
  - → **semi-dynamic -- <u>once size is fixed it remains</u>**

    e.g., arrays
  - → **dynamic**

    e.g., varibales
- **Allow non-local references**

Semi-Dynamic Variables

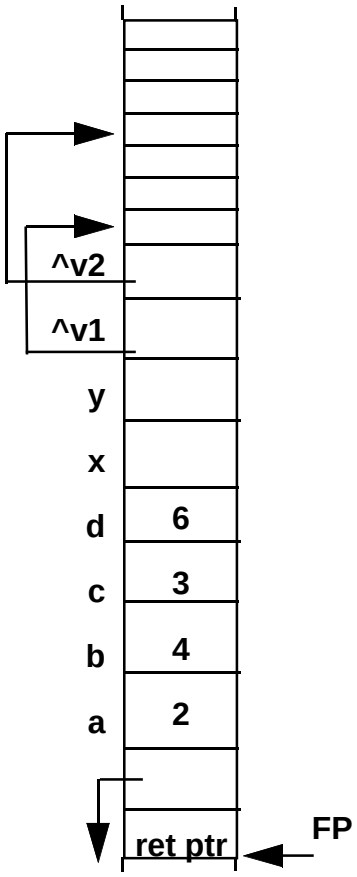
semi-static arrays
semi-dynamic variables
semi-dynamic arrays

- **Size fixed at *unit invocation time***

```
proc p(a, b, c, d: int);
var x,y: int;
    v1[a..b], v2[c..d]: array of int;
...
p(2, 4, 3, 6)
```

- **Solution**

  Allocate space for pointer to each semi-dynamic variable first, then space for actual arrays; offset of pointer known statically.



Dynamic Variables

- **Example: flex array (Algol 68) => size of array may change arbitrarily at runtime**
  - → **cannot be stored on stack**

    proc p;

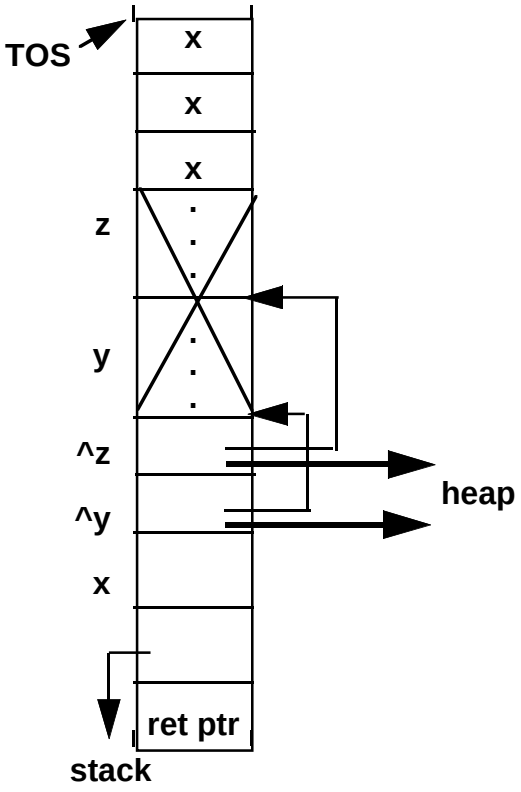
    var x : int;

    y,z : flex array;
  - → **need a heap**

    less effcient

    more flexible
  - → **store pointers to heap in stack**

At any point in time you might need more space but next stack space might be in use.



Non-local References

- **Need**
  - → **which Activation Record (AR)**
  - → **variable's local offset within AR**

    Note: this is *all* we need for a *local* reference; we already have the pointer to the AR

- **Two cases**
  - → **static scoping -- reference is determined by static layout of program**
  - → **dynamic scoping -- reference is determined by call chain**

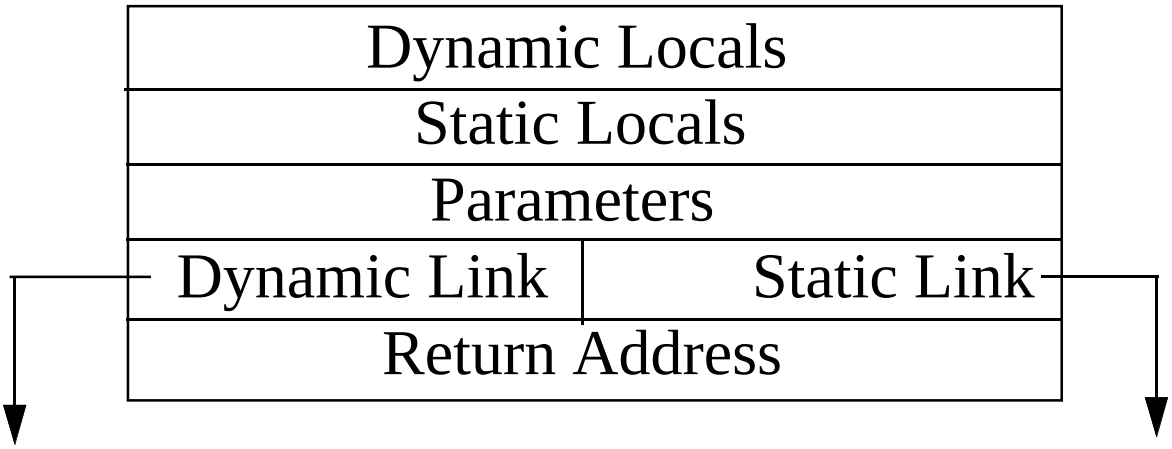
Static Scoping

- **Need access to the static environment => *static link*.**

For a given procedure or function f, f's static link (usually) points to the most recent AR for the procedure or function that statically encloses f.

Exception: where f is passed as a parameter

Let's standardize on the format of an Activation Record:



Static Links

- **Using static links:**
  - → **The AR containing the definition of a variable used in f is always a fixed distance d from f's AR along the static chain. (set of static links)**
  - → **If f uses a non-local x that is defined in g,**

    d = level(f) - level(g) # links that you traverse
  - → **Know levels and that x was defined in g <u>statically</u>!**

- **Setting static links:**
  - → **If a calls b, then b's static link should be set to the AR (level(a) - level(b) + 1) links along the static chain starting at a.**
  - → **cases:**

    level(a) = level(b) - 1 (b in a)

    level(a) = level(b)

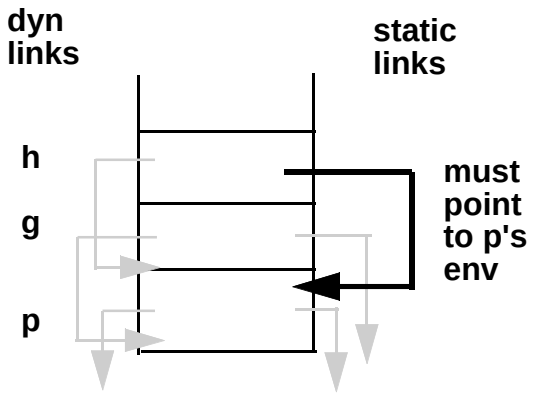
    level(a) > level(b) (b outside a)
  - → **it works!**

```
proc a
    proc b
    proc c
    proc d
    proc e
```

Procedure Parameters

```
proc p;
var x;
    proc h;
    ...x...
    end {h}
...g(h)...
end {p}

proc g(f : procedure);
var x;
...f...
end {g}
```

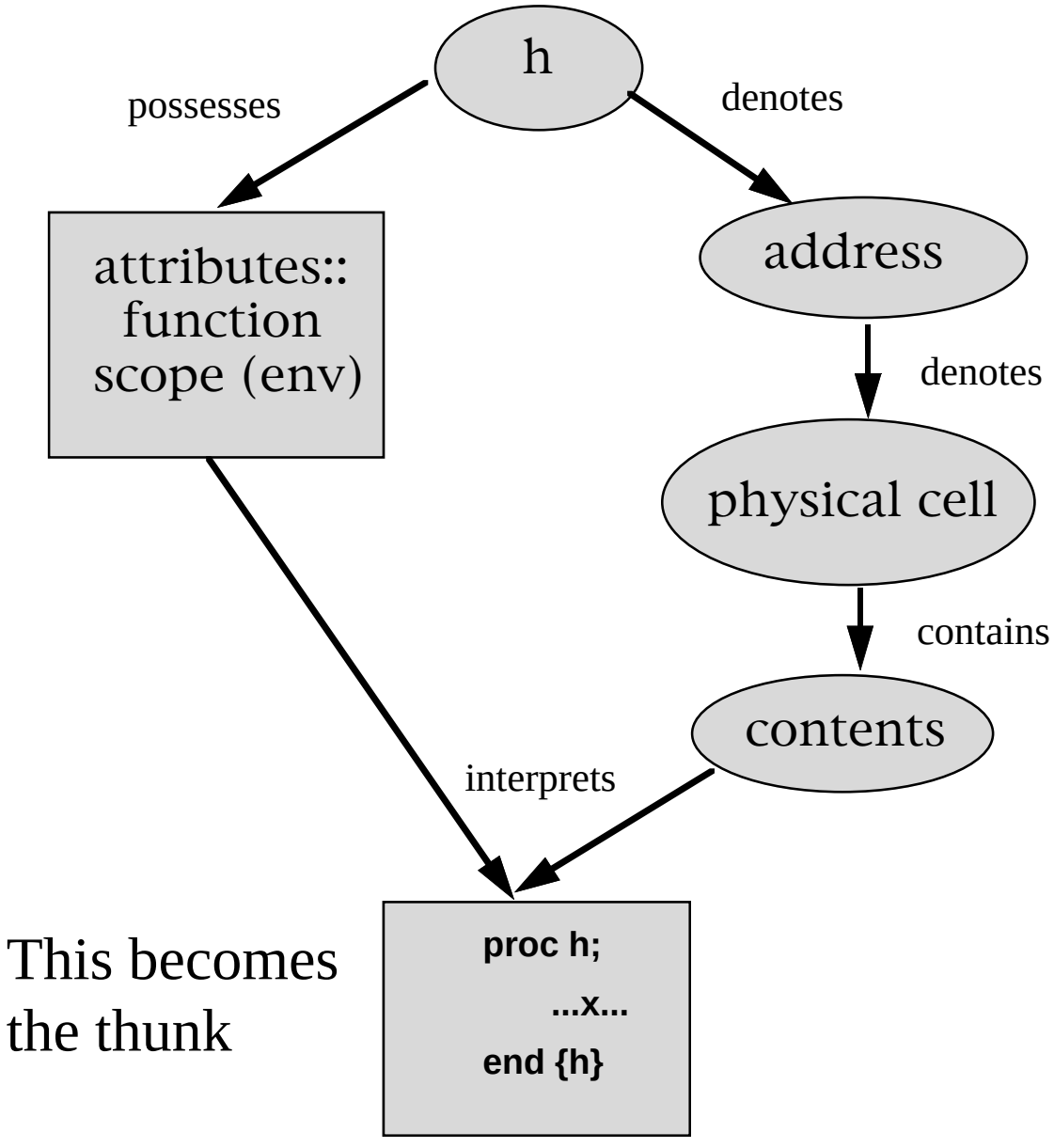
h's (code , env) pair constructed at this point



→ **g can't set up h's static link; it must be passed in from p**

this is the *env* part of a thunk = (code, env)!

Name/Value Graph for a Functor

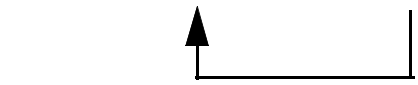


This becomes the thunk

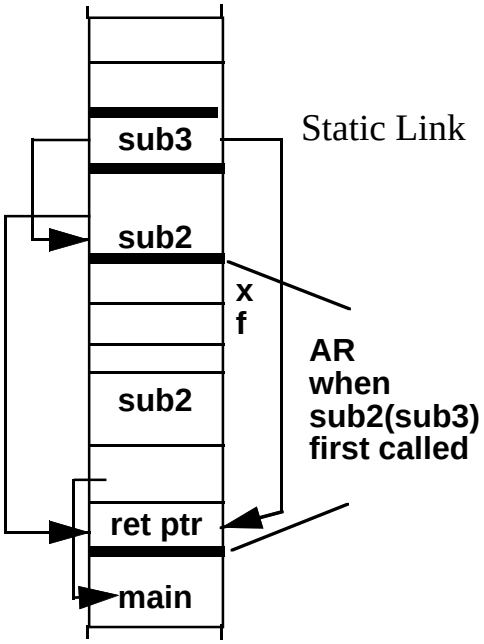
Procedure Parameter Confusion

```
program main;

    procedure sub1;
    ...
    end {sub1}

    procedure sub2 (proc f)
    var x:
        procedure sub3;
            ...
            x := 0;
            ...
        end {sub3}
    ...
    f;
    sub2(sub3);
    end {sub2}
...
sub2(sub1);
end {main}
```

main -> sub2 -> sub2 -> f

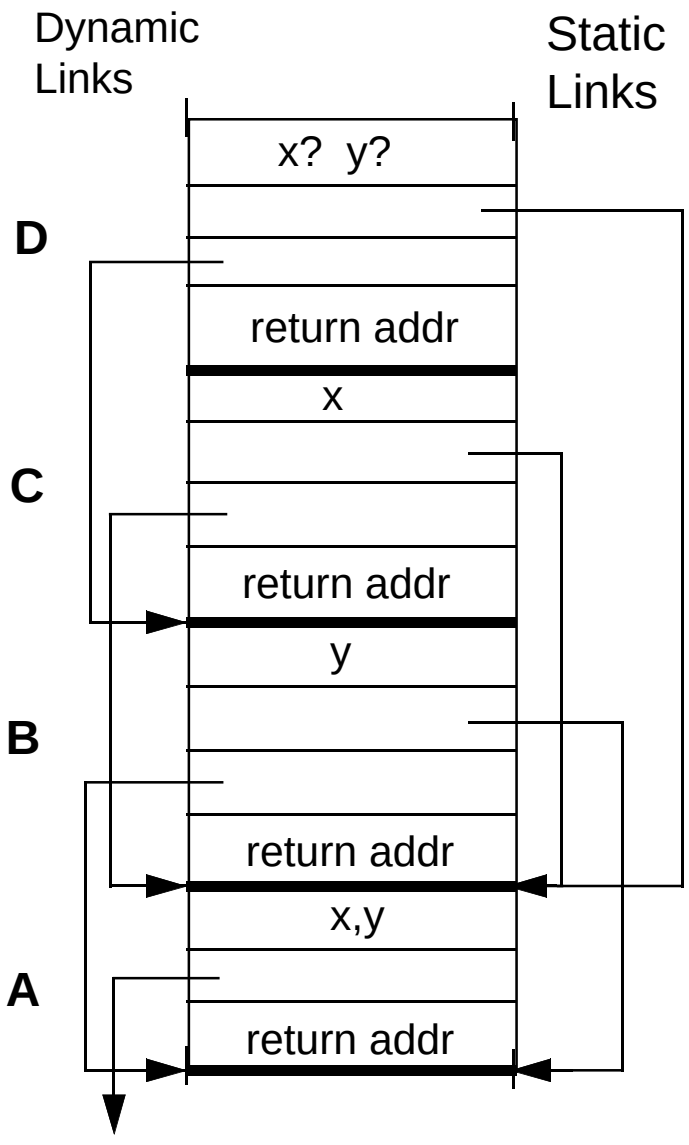


referencing environmnet is not most recent invocation of sub2



Example: A -> B -> C -> D

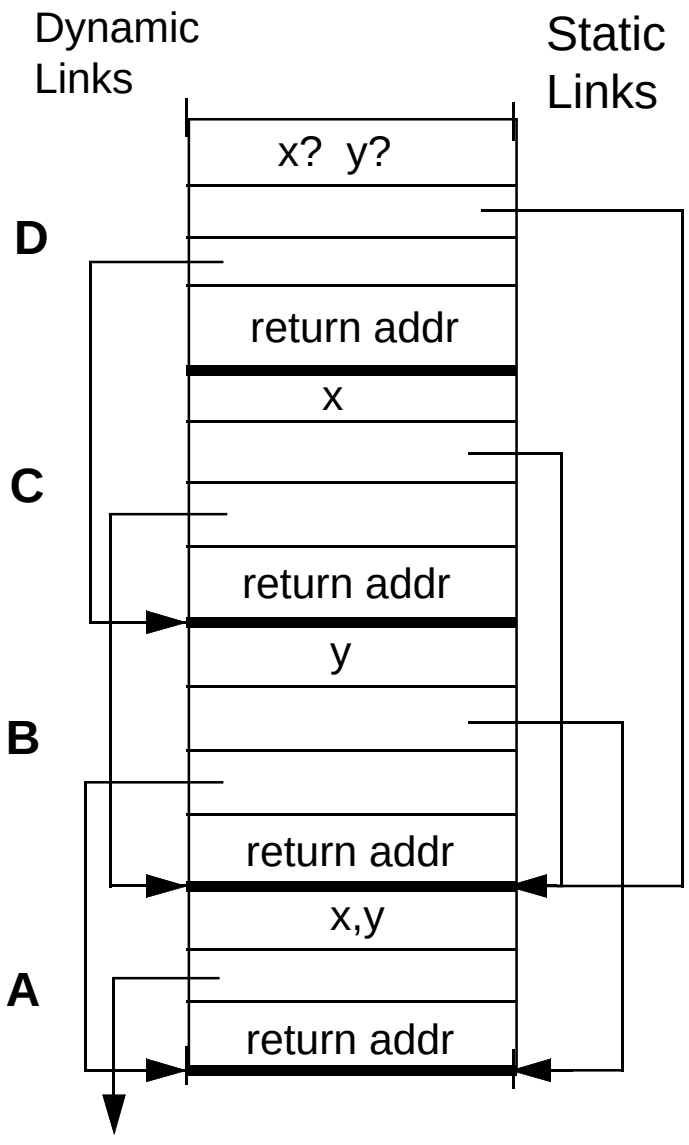
```
proc A;
var x,y;
    proc B;
    var y;
        proc C;
        var x;
        ... x + y..
        D;
        end {C}
        proc D(z);
        ...x + y...
        end {D}
    C;
    ...
    end{B}
B;
...
end{A}
```



→ **When are dynamic & static links the same?**

Example: A -> B -> C -> D Continued

```
proc A;
var x,y;
    proc B;
    var y;
        proc C;
        var x;
        ... x + y..
        D;
        end {C}
        proc D(z);
        ...x + y...
        end {D}
    C;
    ...
    end{B}
B;
...
end{A}
```



Which x and which y depending on whether static or dynamic scoping?

Displays -- an alternative to Static Links

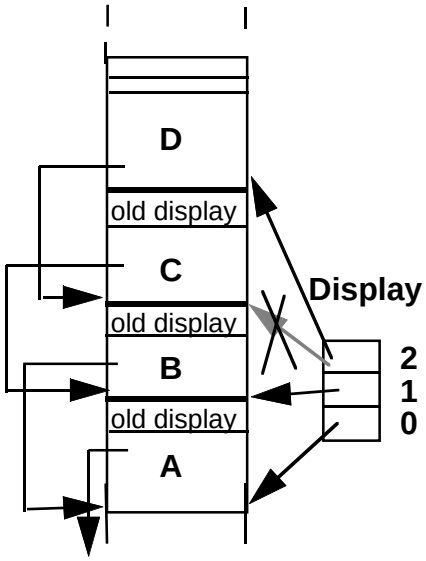
- **A *display* contains pointers to the currently accessible activation records at each static level.**

- **A display is usually implemented as an array, with size equal to the maximum nesting depth of the program.**

A -> B -> C -> D

```
proc A;
var xy;
(1)   proc B;
      var y;
(2)      proc C;
         var x;
         ... x + y..
         D;
         end {C}
(2)      proc D(z);
         ...x + y...
         end {D}
      C;
      ...
      end{B}
B;
...
end{A}
```

D's ref env ≡
D at level 2
B at level 1
A at level 0



when D exits DSP[2] is reset to value stored in D's AR i.e. ^ to C

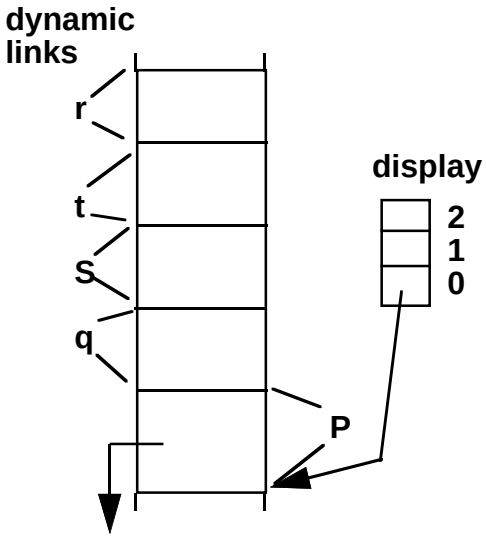
Display Ptr in AR
is placed there when
AR is created

Its value is: Display [Proc Level]

Procedure Parameters with Display

```
Proc P;
var x;
(1) proc q;
    var y;
  (2) proc r;
          ...
          x + y
      end {r}
    ...
    S(r)
    end{q}
...
q;
end {P}

(0) Proc S (proc f);
var x,y;
    proc t(proc g);
        . . .g. . .
    end {t}
. . .t(f). . .
end {S}
```

P->q->S->t->g/r



for uniformity you might want to store *entire* display *all the time*

Displays vs. Static Links

- **References to non-locals:**
  - → **static links: follow ($level_{def}$ - $level_{use}$) static links**
  - → **display: follow one pointer**
- **Procedure call: (f -> g)**
  - → **static links: follow ($level_f$ - $level_g$ + 1) static links**
  - → **display: save all or part of display on stack, update with new values**
- **Procedure return:**
  - → **static links: none**
  - → **display: restore to saved value**

Dynamic Scoping

- **Deep access (reference to x)**
  - → **Follow dynamic links until an AR containing x is found.**
  - → **NOTES:**

    # of dynamic links to be followed cannot be determined statically

    Names of variables must be stored in ARs

- **Shallow Access (reference to x)**
  - → **Maintain central table with entry for each variable in program.**

    Current values of variables live in table, not on stack.
  - → **Procedure call:**

    for each local var x save current value of x (in table) on stack.
  - → **Procedure return:**

    Restore saved values of variables to table.
  - → **All variable access refers to table.**