Scope, Function Calls and Storage Management

John Mitchell

Topics

- Block-structured languages and stack storage
- In-line Blocks
  - activation records
  - storage for local, global variables
- First-order functions
  - parameter passing
  - tail recursion and iteration
- Higher-order functions
  - deviations from stack discipline
  - language expressiveness => implementation complexity

Block-Structured Languages

- Nested blocks, local variables
  - Example

new variables declared in nested blocks

outer block

```
{ int x = 2;
    { int y = 3;
        x = y+2;
    }
}
```

inner block

local variable

global variable

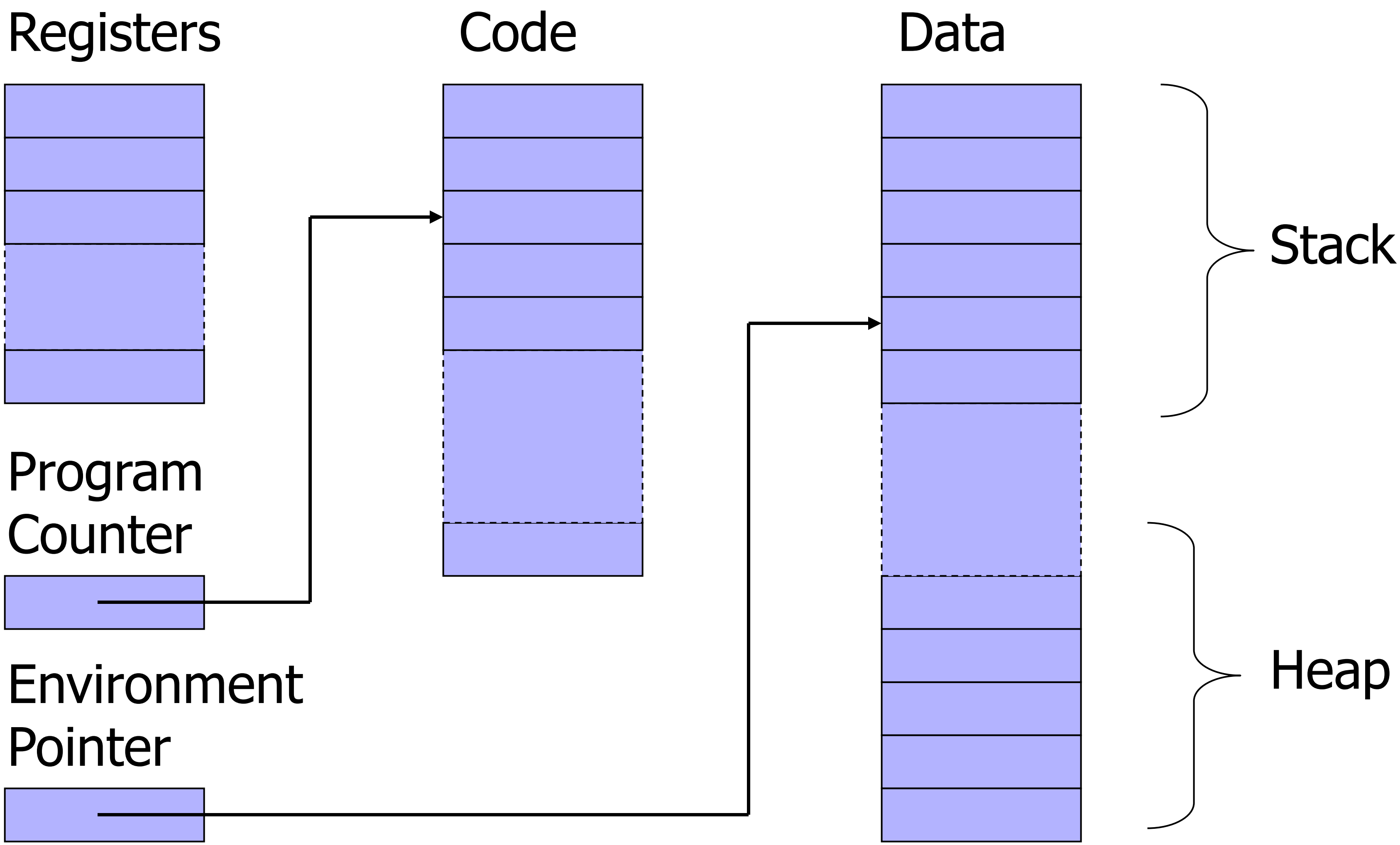
  - Storage management
    - Enter block: allocate space for variables
    - Exits block: some or all space may be deallocated

Examples

- Blocks in common languages
  - C, ~~JavaScript~~ * { … }
  - Algol begin … end
  - ML let … in … end
- Two forms of blocks
  - In-line blocks
  - Blocks associated with functions or procedures
- Topic: block-based memory management, access to local variables, parameters, global variables

* JavaScript functions provide blocks

Simplified Machine Model



Interested in Memory Mgmt Only

- Registers, Code segment, Program counter
  - Ignore registers
  - Details of instruction set will not matter
- Data Segment
  - Stack contains data related to block entry/exit
  - Heap contains data of varying lifetime
  - Environment pointer points to current stack position
    - Block entry: add new activation record to stack
    - Block exit: remove most recent activation record

Some basic concepts

- Scope
  - Region of program text where declaration is visible
- Lifetime
  - Period of time when location is allocated to program

```
{ int x = … ;
    {  int y = … ;
        {  int x = … ;
            ….
        };
    };
};
```

- Inner declaration of x hides outer one.
- Called "hole in scope"
- Lifetime of outer x includes time when inner block is executed
- Lifetime $\neq$ scope
- Lines indicate "contour model" of scope.

In-line Blocks

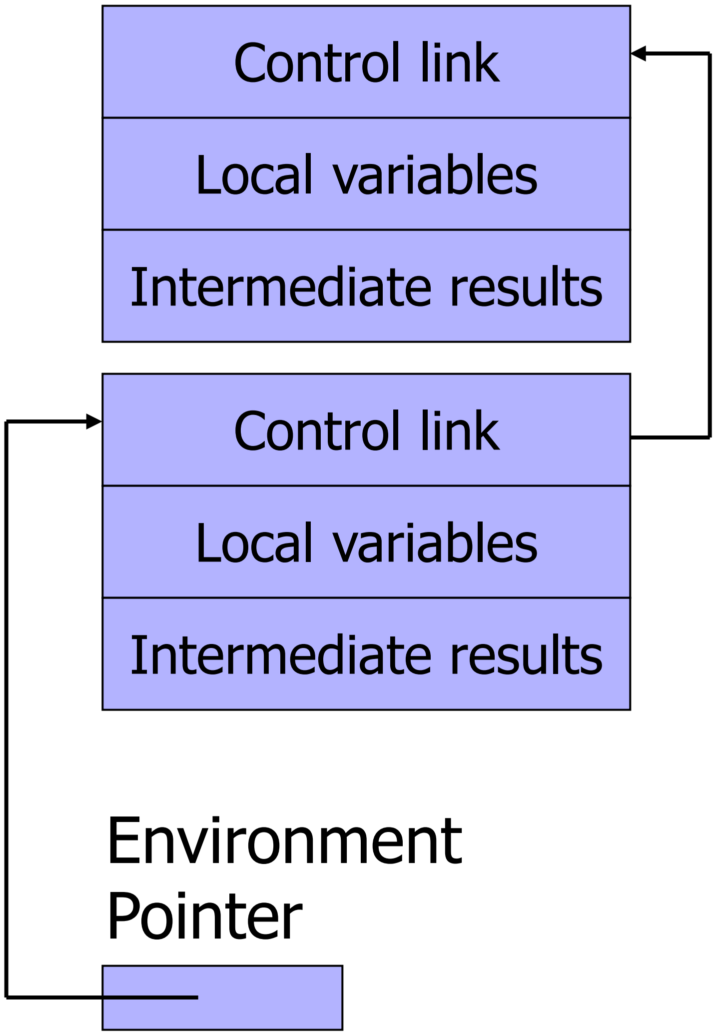
- Activation record
  - Data structure stored on run-time stack
  - Contains space for local variables
- Example

```
{ int x=0;
  int y=x+1;
    {  int z=(x+y)*(x-y);
     };
};
```

Push record with space for x, y
Set values of x, y
    Push record for inner block
    Set value of z
    Pop record for inner block
Pop record for outer block

May need space for variables and intermediate results like (x+y), (x-y)

Activation record for in-line block



- Control link
  - pointer to previous record on stack
- Push record on stack:
  - Set new control link to point to old env ptr
  - Set env ptr to new record
- Pop record off stack
  - Follow control link of current record to reset environment pointer

Can be optimized away, but assume not for purpose of discussion.

Example

```
{ int x=0;
   int y=x+1;
      {  int z=(x+y)*(x-y);
      };
};
```

Push record with space for x, y

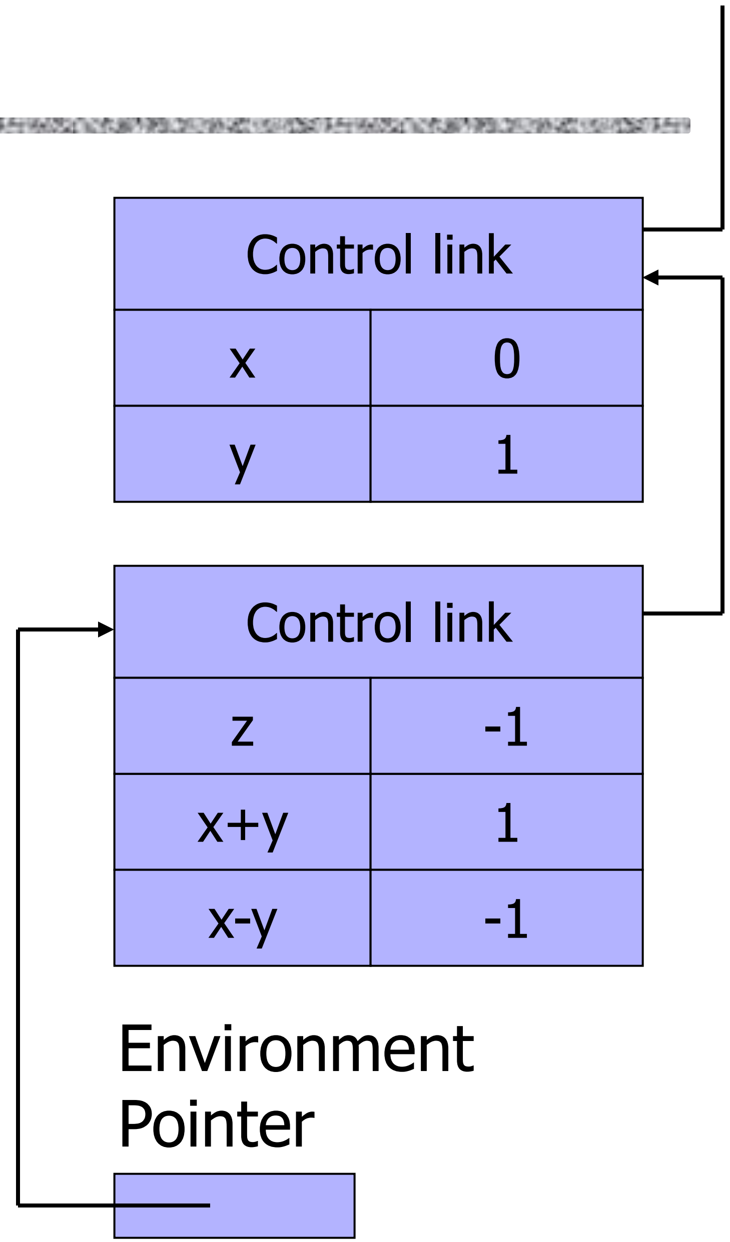
Set values of x, y

  Push record for inner block

  Set value of z

  Pop record for inner block

Pop record for outer block



Scoping rules

- Global and local variables
  - x, y are local to outer block
  - z is local to inner bock
  - x, y are global to inner block

```
{ int x=0;
  int y=x+1;
    {  int z=(x+y)*(x-y);
    };
};
```

- Static scope
  - global refers to declaration in closest enclosing block
- Dynamic scope
  - global refers to most recent activation record

These are same until we consider function calls.

Functions and procedures

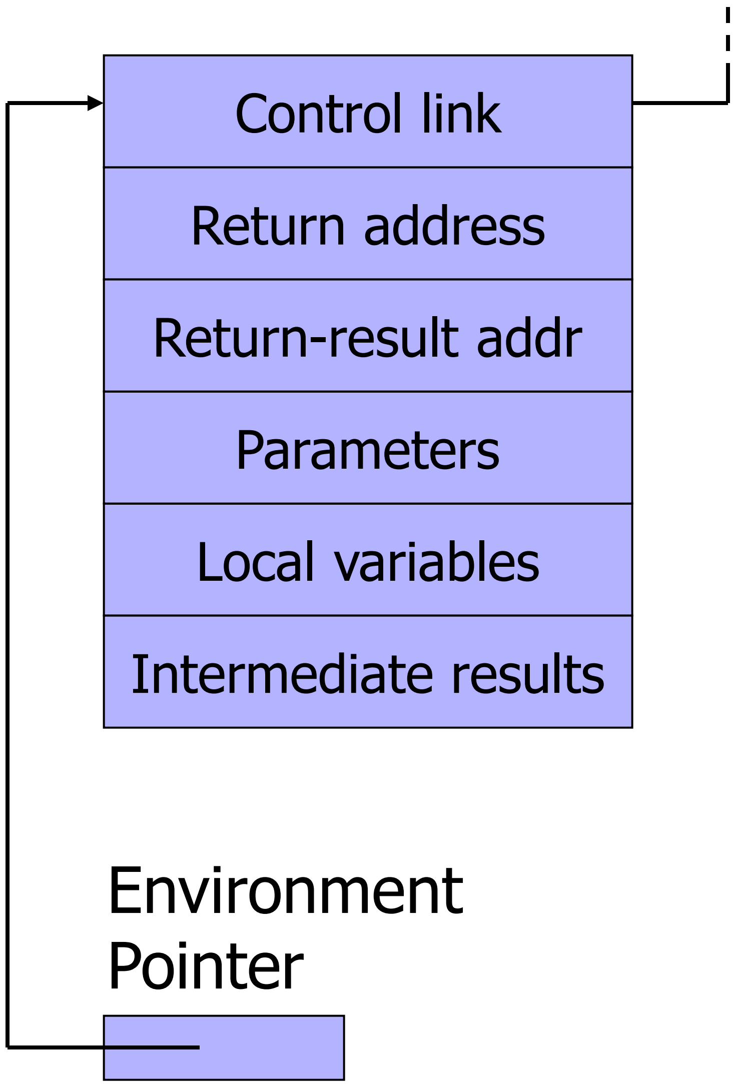
- Syntax of procedures (Algol) and functions (C)

```
procedure P (<pars>)
    begin
        <local vars>
        <proc body>
    end;
```

```
<type> function f(<pars>)
{
    <local vars>
    <function body>
}
```

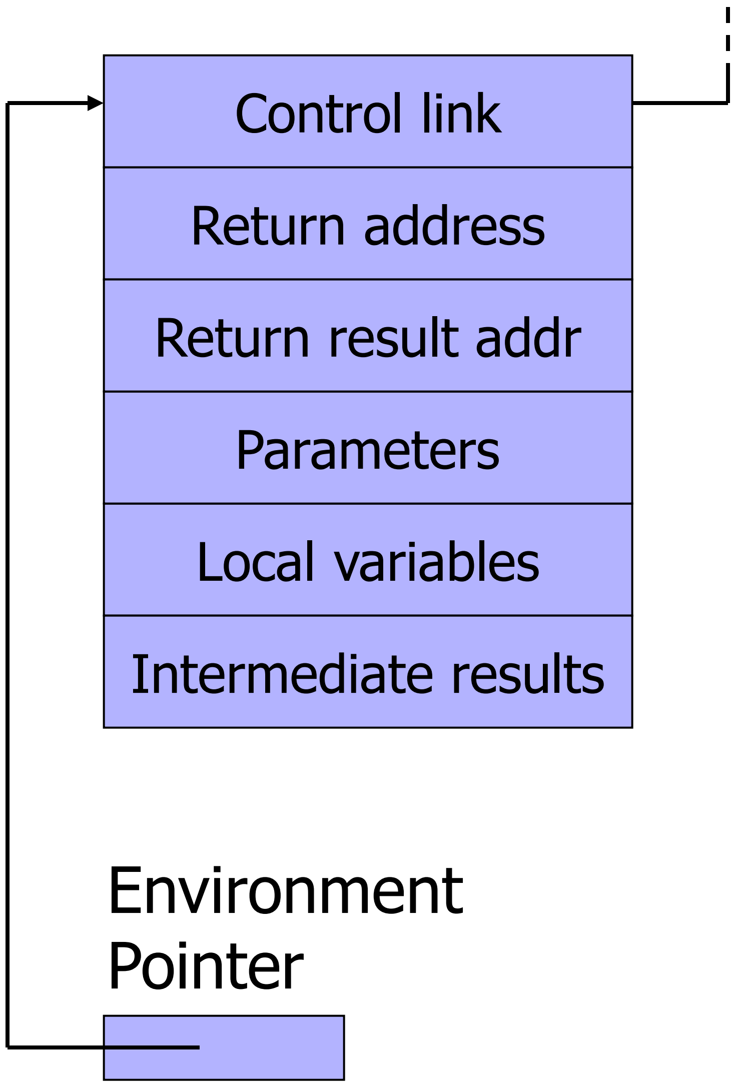
- Activation record must include space for
  - parameters
  - return address
  - return value
    (an intermediate result)
  - location to put return value on function exit

Activation record for function



- Return address
  - Location of code to execute on function return
- Return-result address
  - Address in activation record of calling block to receive return address
- Parameters
  - Locations to contain data from calling block

Example

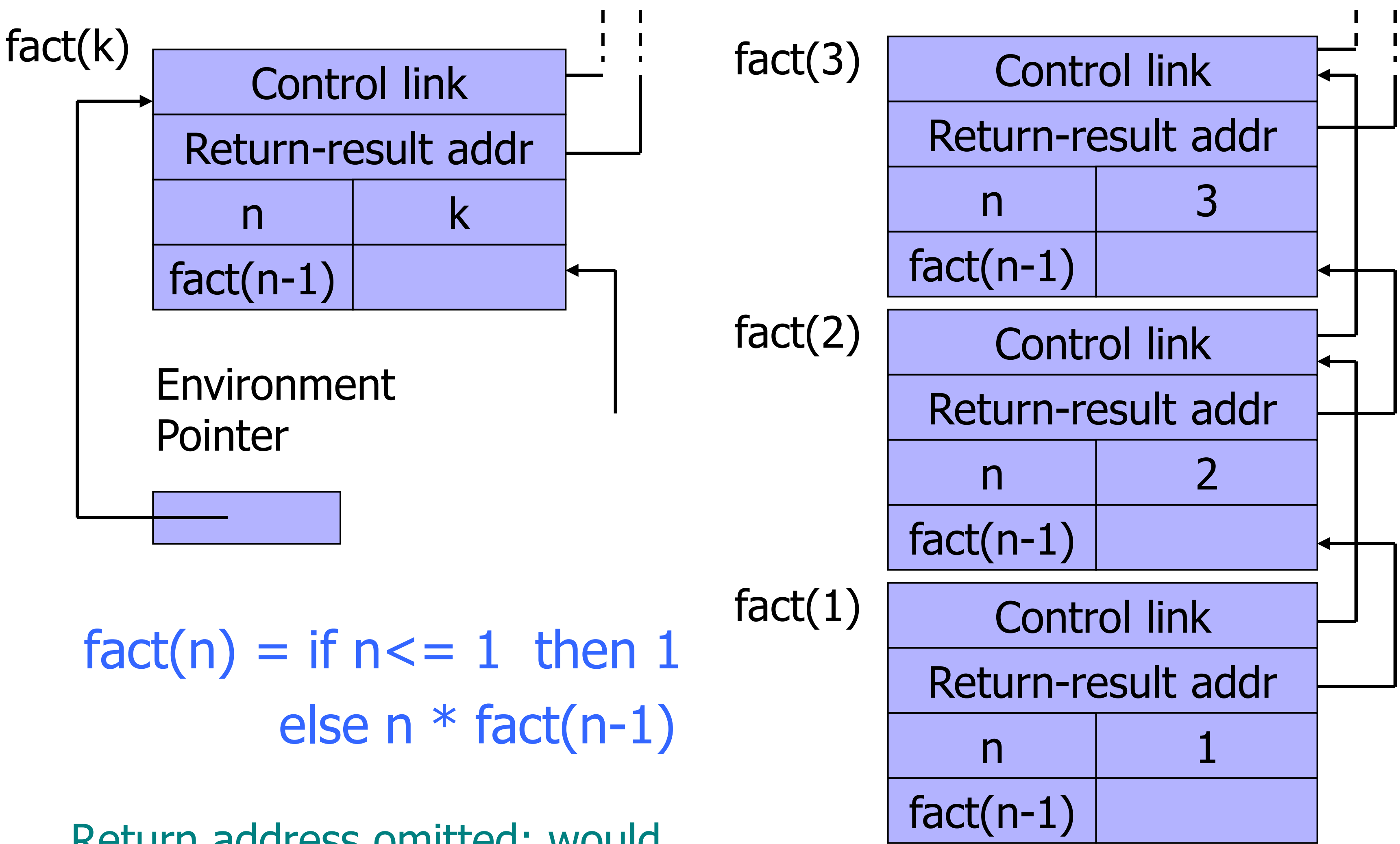


- Function

  fact(n) = if n<= 1 then 1
  else n * fact(n-1)

  - Return result address
  - location to put fact(n)
- Parameter
  - set to value of n by calling sequence
- Intermediate result
  - locations to contain value of fact(n-1)

Function call

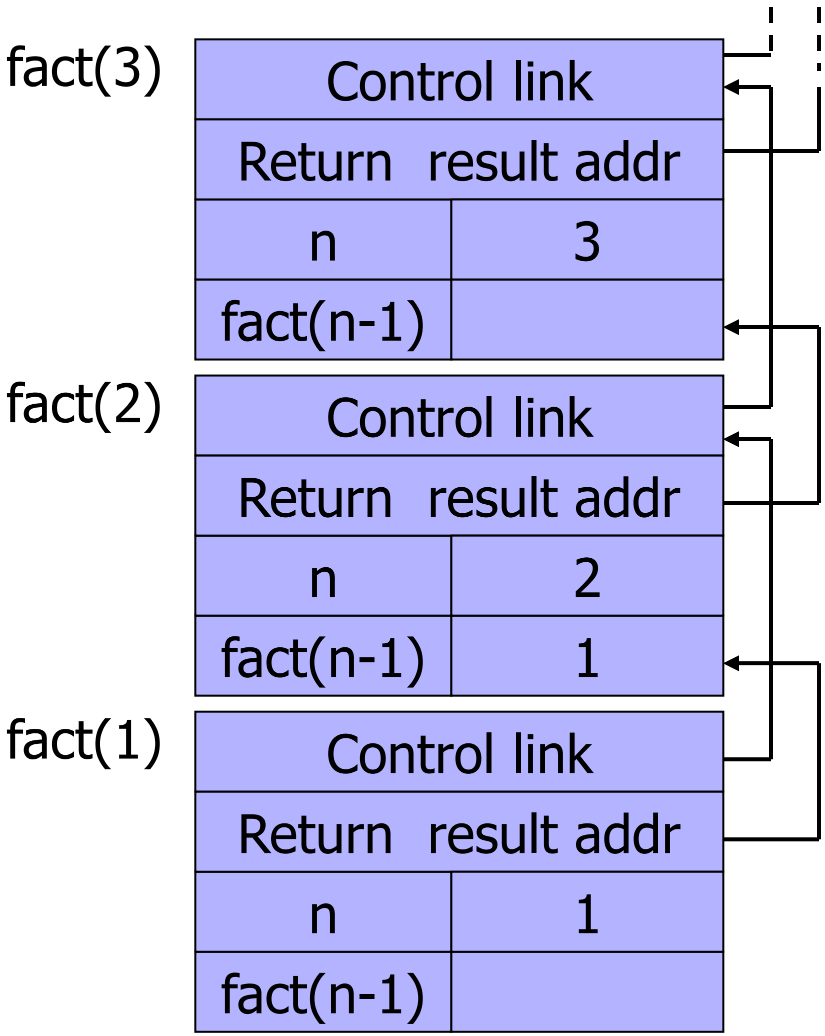


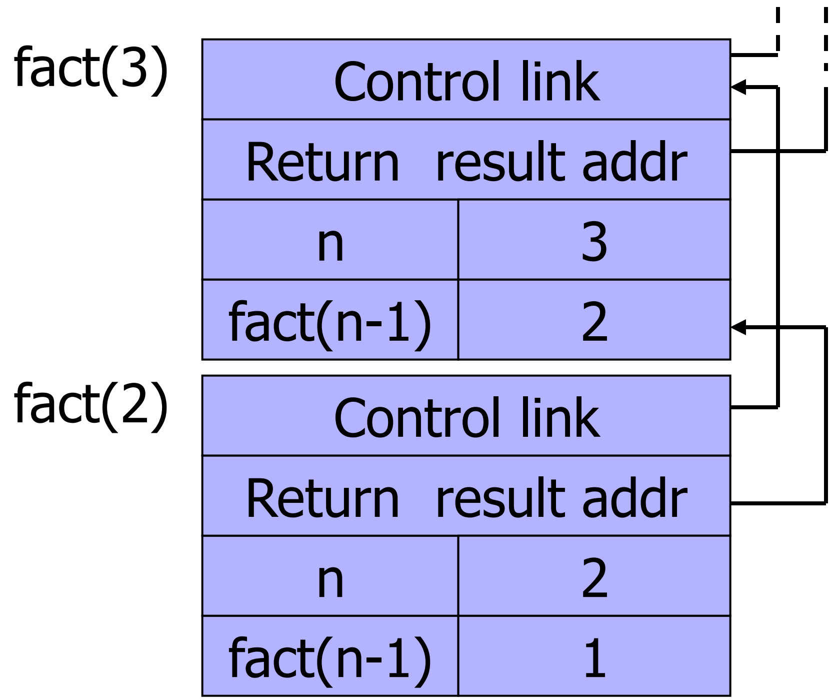
fact(n) = if n<= 1 then 1
else n * fact(n-1)

Return address omitted; would be ptr into code segment

Function return next slide →

Function return





fact(n) = if n<= 1 then 1
else n * fact(n-1)

Topics for first-order functions

- Parameter passing
  - use ML reference cells to describe pass-by-value, pass-by-reference
- Access to global variables
  - global variables are contained in an activation record higher “up” the stack
- Tail recursion
  - an optimization for certain recursive functions

See this yourself: write factorial and run under debugger

ML imperative features

- General terminology: L-values and R-values
  - Assignment   y := x+3
    - Identifier on left refers to location, called its L-value
    - Identifier on right refers to contents, called R-value
- ML reference cells and assignment
  - Different types for location and contents

x : int	non-assignable integer value
y : int ref	location whose contents must be integer
!y	the contents of cell y
ref x	expression creating new cell initialized to x

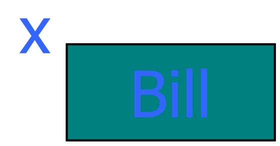
  - ML form of assignment

y := x+3	place value of x+3 in location (cell) y
y := !y + 3	add 3 to contents of y and store in location y

ML examples

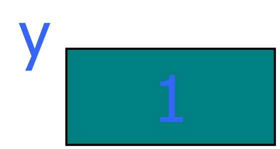
- Create cell and change contents

```
val x = ref “Bob”;
x := “Bill”;
```



- Create cell and increment

```
val y = ref 0;
y := !y + 1;
```



- While loop

```
val i = ref 0;
while !i < 10 do i := !i +1;
!i;
```

Parameter passing

- Pass-by-reference
  - Caller places L-value (address) of actual parameter in activation record
  - Function can assign to variable that is passed
- Pass-by-value
  - Caller places R-value (contents) of actual parameter in activation record
  - Function cannot change value of caller's variable
  - Reduces aliasing (alias: two names refer to same loc)

Example

pseudo-code

```
function f (x) =
    { x = x+1; return x;  }
var y = 0;
print (f(y)+y);
```

pass-by-ref

pass-by-value

Standard ML

```
fun  f (x : int ref) =
    ( x := !x+1;  !x  );
y = ref 0 : int ref;
f(y) + !y;
```

```
fun f (z : int) =
    let val x = ref z in
        x := !x+1; !x
    end;
y = ref 0 : int ref;
f(!y) + !y;
```

Access to global variables

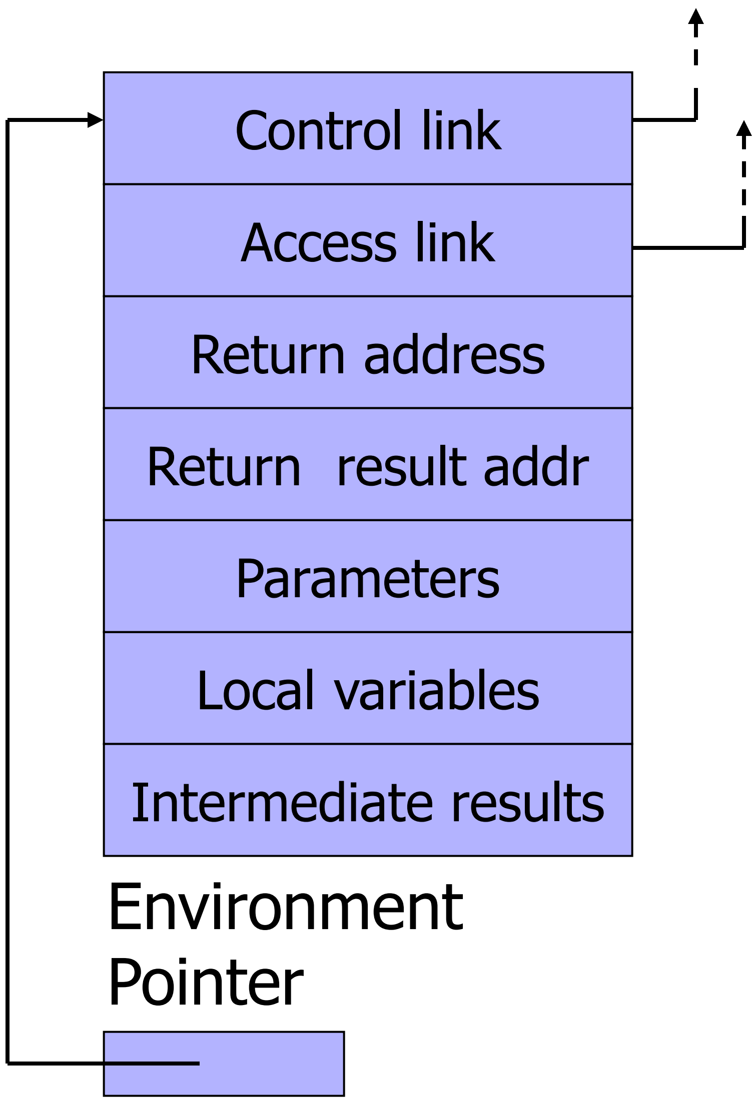
- Two possible scoping conventions
  - Static scope: refer to closest enclosing block
  - Dynamic scope: most recent activation record on stack
- Example

```
var x=1;
function g(z) { return x+z; }
function f(y) {
    var x = y+1;
    return g(y*x);
}
f(3);
```

outer block	x	1
f(3)	y	3
	x	4
g(12)	z	12

Which x is used for expression x+z ?

Activation record for static scope



- Control link
  - Link to activation record of previous (calling) block
- Access link
  - Link to activation record of closest enclosing block in program text
- Difference
  - Control link depends on dynamic behavior of prog
  - Access link depends on static form of program text

Complex nesting structure

```
function m(…) {
   var x=1;
   …
   function n( … ){
     function g(z) { return x+z; }
     …
     { …
          function f(y) {
             var x = y+1;
             return g(y*x); }
        …
       f(3);  … }
   … n( … ) …}
 … m(…)
```

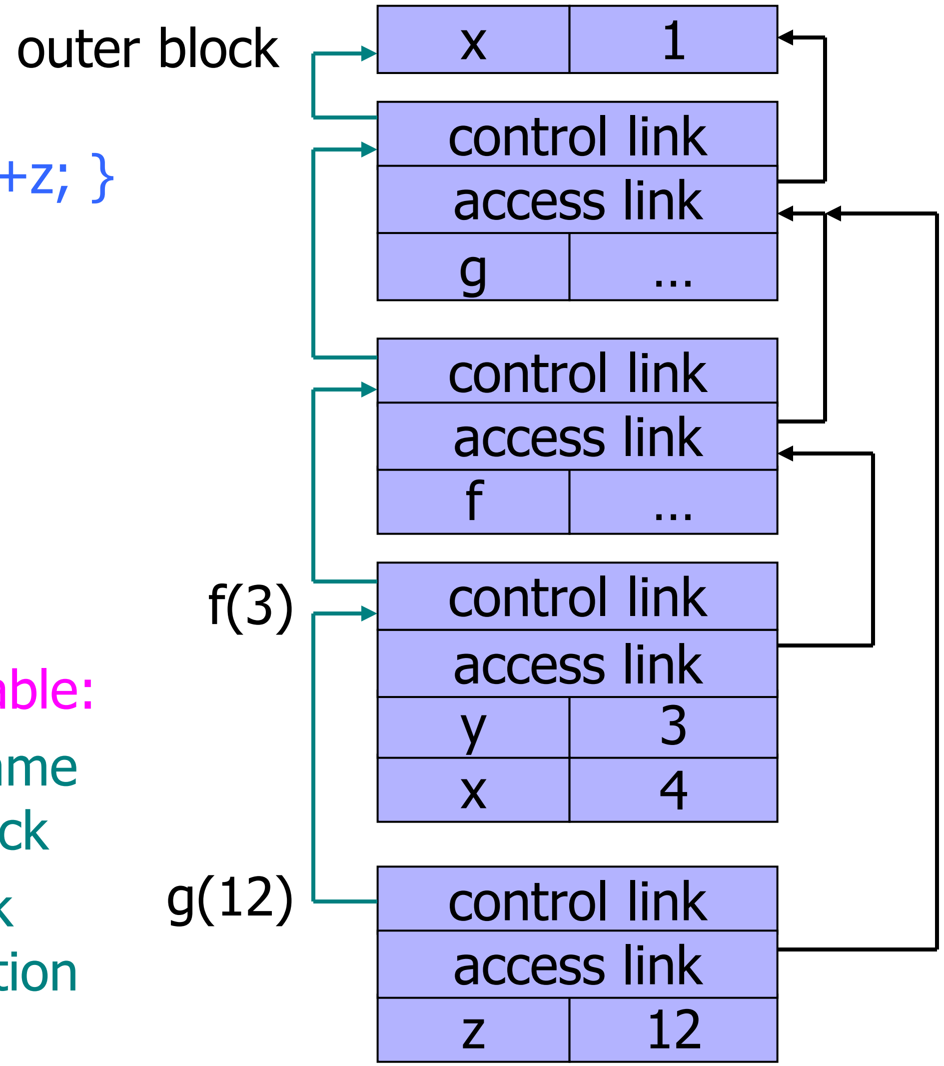
Simplify to

```
var x=1;
   function g(z) { return x+z; }
        function f(y)
          { var x = y+1;
               return g(y*x); }
        f(3);
```

Simplified code has same block nesting, if we follow convention that each declaration begins a new block.

Static scope with access links

```
var x=1;
  function g(z) = { return x+z; }
    function f(y) =
      { var x = y+1;
        return g(y*x); }
    f(3);
```



Use access link to find global variable:

- Access link is always set to frame of closest enclosing lexical block
- For function body, this is block that contains function declaration

Tail recursion (first-order case)

- Function g makes a *tail call* to function f if
  - Return value of function f is return value of g
- Example

tail call   not a tail call

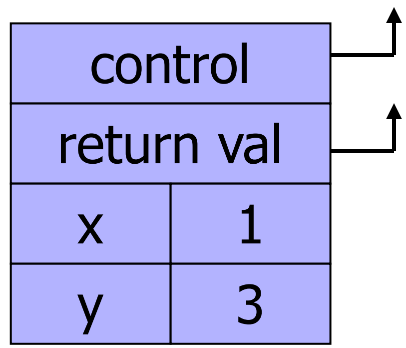
```
fun g(x) = if x>0 then f(x) else f(x)*2
```

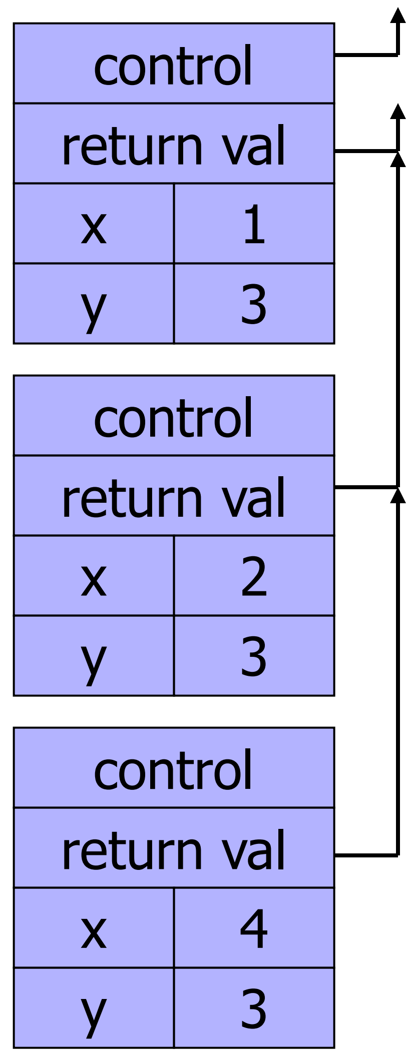
- Optimization
  - Can pop activation record on a tail call
  - Especially useful for recursive tail call
    - next activation record has exactly same form

Example

Calculate least power of 2 greater than y

f(1,3)






```
fun f(x,y) = if x>y
      then x
      else f(2*x, y);
f(1,3) + 7;
```

Optimization

- Set return value address to that of caller

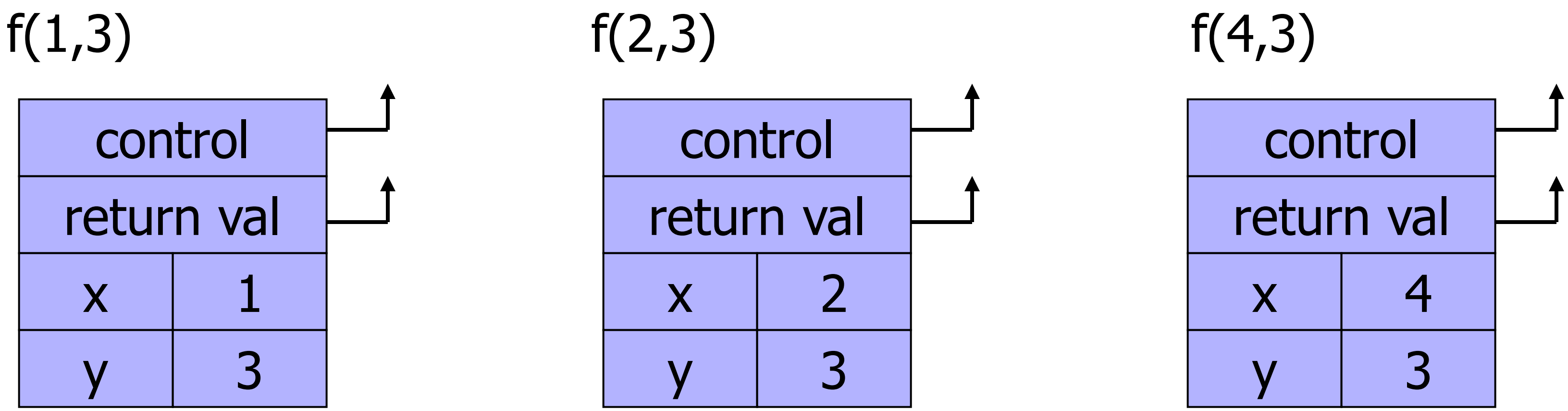
Question

- Can we do the same with control link?

Optimization

- avoid return to caller

Tail recursion elimination




```
fun f(x,y) = if x>y
      then x
      else f(2*x, y);
f(1,3);
```

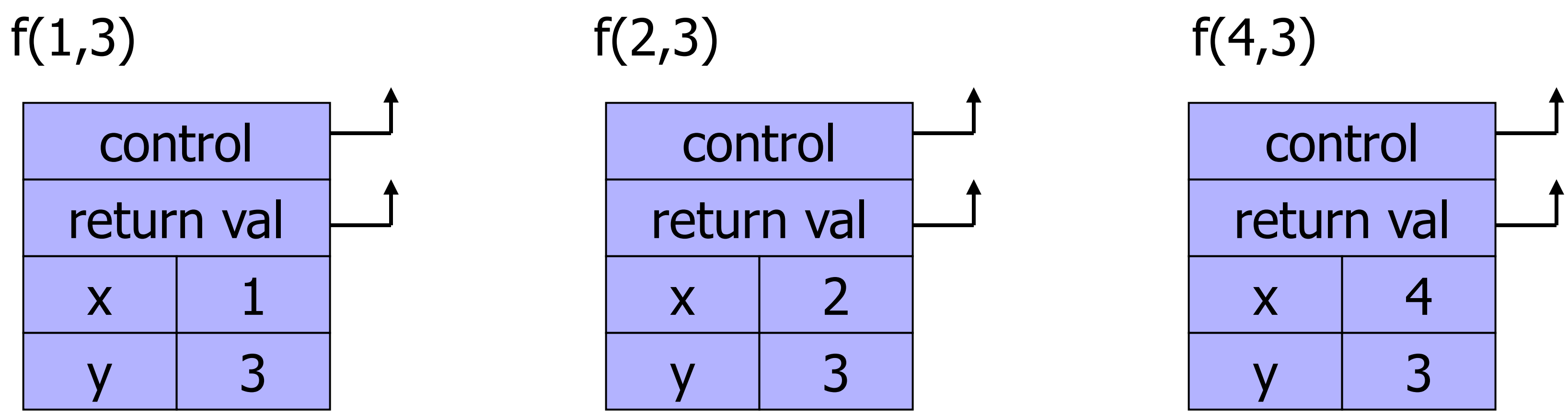
Optimization

- pop followed by push = reuse activation record in place

Conclusion

- Tail recursive function equiv to iterative loop

Tail recursion and iteration




```
fun f(x,y) = if x>y
     then x
     else f(2*x, y);
f(1,y);
```

```
function g(y) {
    var x = 1;
    while (!x>y)
        x = 2*x;
    return x;
}
```

test

loop body

initial value

Higher-Order Functions

- Language features
  - Functions passed as arguments
  - Functions that return functions from nested blocks
  - Need to maintain environment of function
- Simpler case
  - Function passed as argument
  - Need pointer to activation record “higher up” in stack
- More complicated second case
  - Function returned as result of function call
  - Need to keep activation record of returning function

Example

Why this example here at this point in the lecture????

- Map function

```
fun map (f, nil) = nil   |    map(f, x::xs) = f(x) :: map(f,xs)
```

- Modify repeated elements in list

```
fun modify(l) =
    let  val c = ref (hd l)
         fun f(y) = ((if y = !c then c:=y+1 else c:=y);  !c)
    in
         (hd l) :: map(f, tl l)
    end;
```

modify [1,2,2,3,4]   =>   [1,2,3,4,5]

Exercise: pure functional version of modify

Pass function as argument

```
val x = 4;
  fun f(y) = x*y;
    fun g(h) = let
                 val x=7
                  in
                  h(3) + x;
    g(f);
```

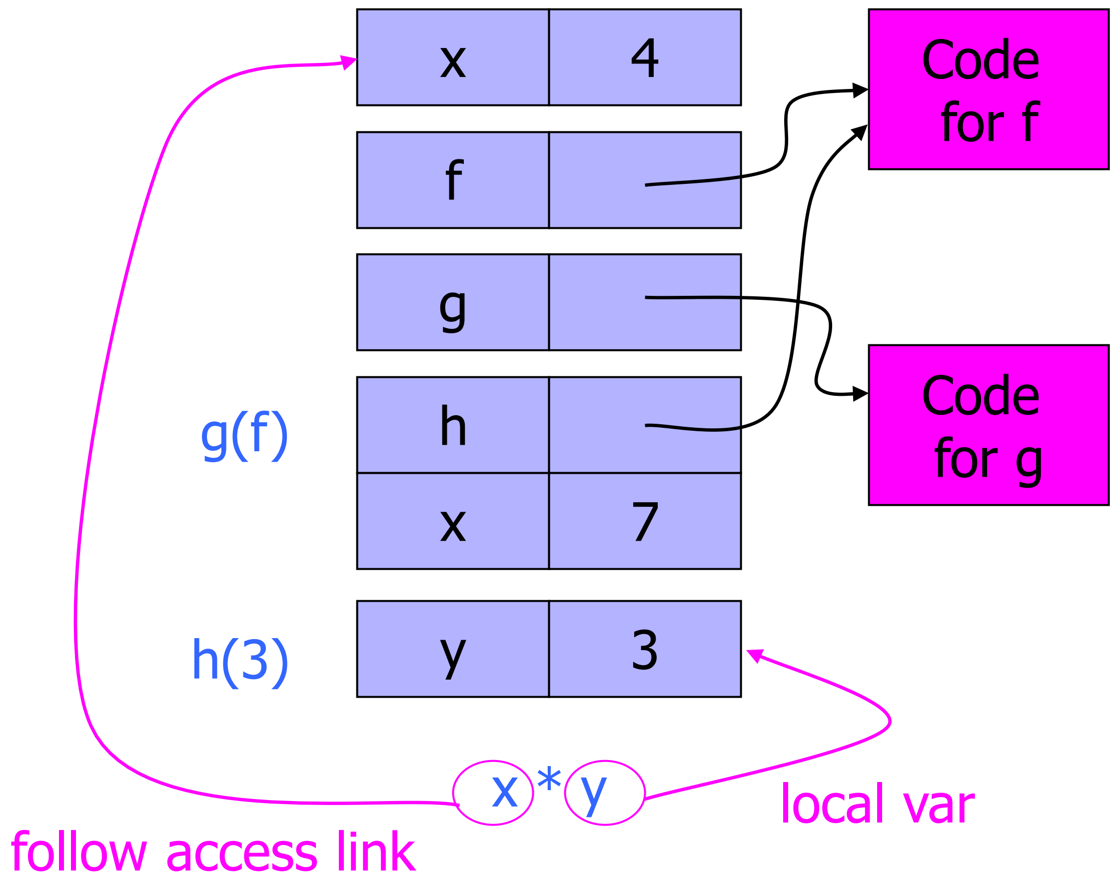
```
{ int x = 4;
  { int f(int y) {return x*y;}
     { int g(int→int h) {
            int x=7;
            return h(3) + x;
        }
        g(f);
} } }
```

There are two declarations of x

Which one is used for each occurrence of x?

Static Scope for Function Argument

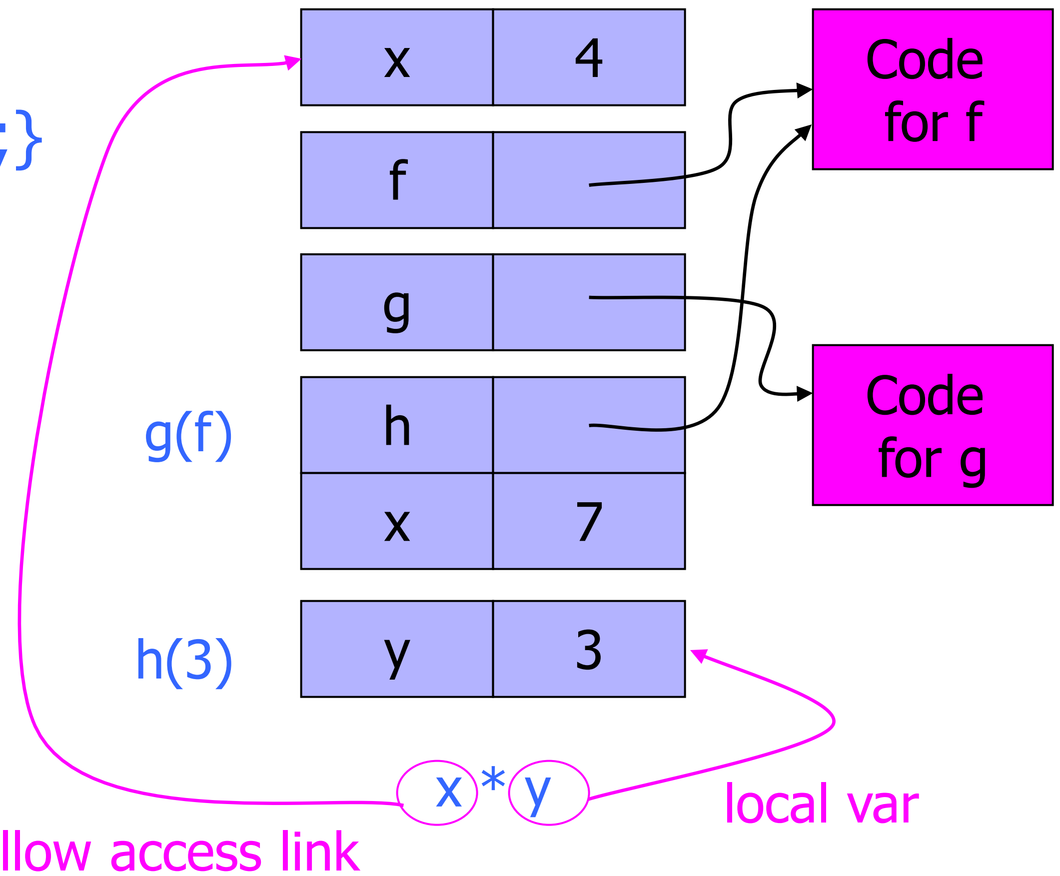
```
val x = 4;
  fun f(y) = x*y;
    fun g(h) =
      let
        val x=7
      in
        h(3) + x;
    g(f);
```



How is access link for h(3) set?

Static Scope for Function Argument

```
{ int x = 4;
  { int f(int y) {return x*y;}
    { int g(int→int h) {
          int x=7;
          return h(3) + x;
          }
      g(f);
} } }
```



How is access link for h(3) set?

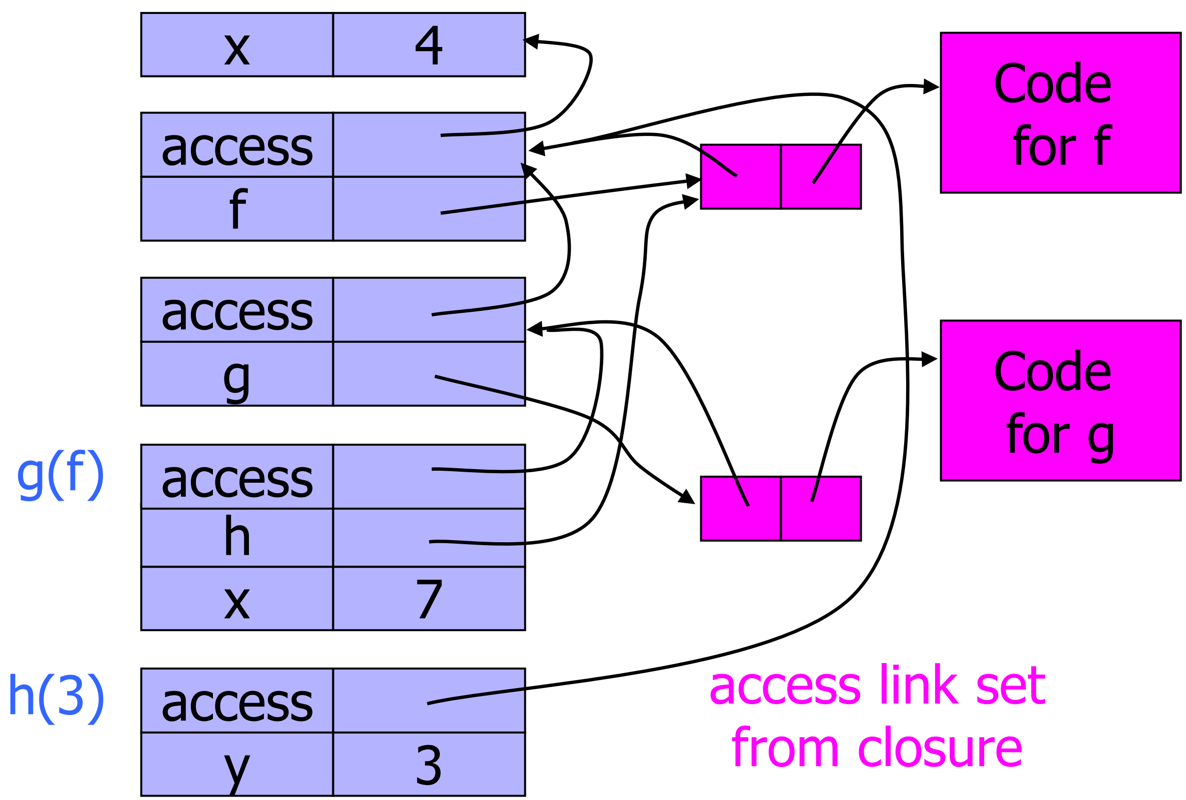
Closures

- Function value is pair *closure* = ⟨*env*, *code* ⟩
- When a function represented by a closure is called,
  - Allocate activation record for call (as always)
  - Set the access link in the activation record using the environment pointer from the closure

Function Argument and Closures

Run-time stack with access links

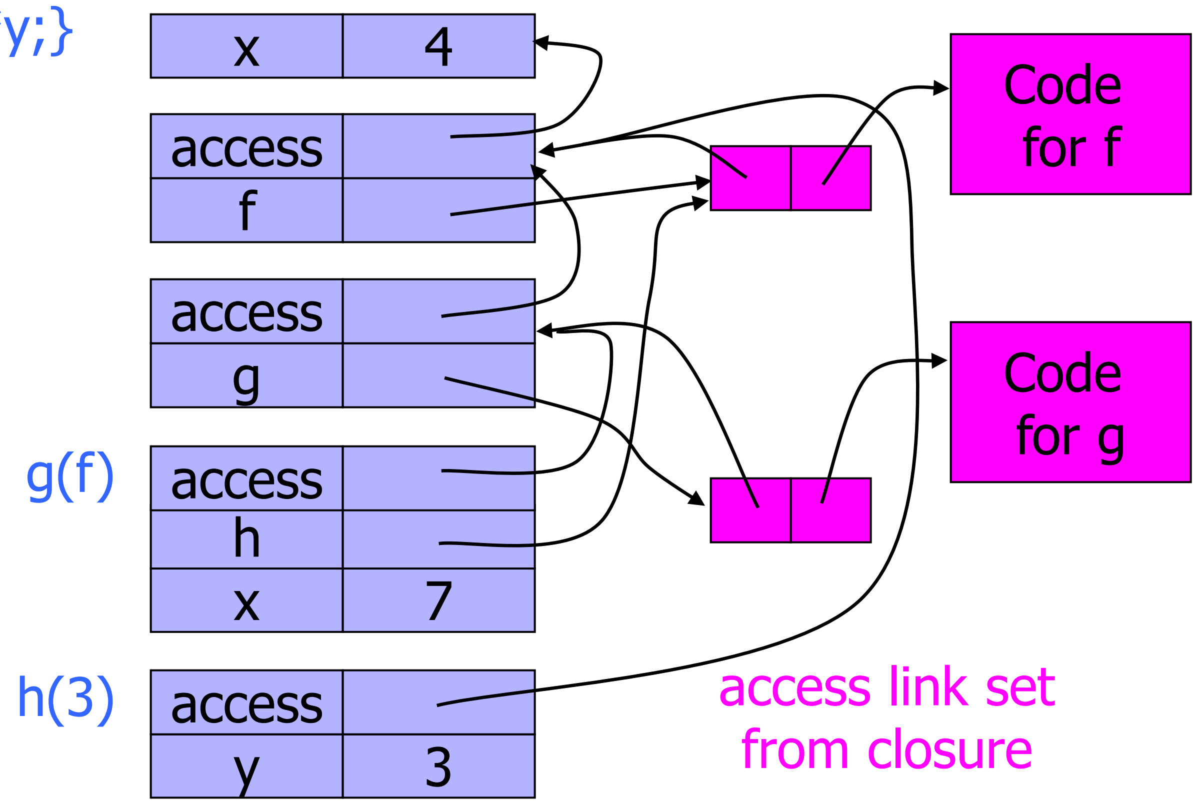
```
val x = 4;
  fun f(y) = x*y;
    fun g(h) =
        let
           val x=7
        in
           h(3) + x;
    g(f);
```



Function Argument and Closures

```
{ int x = 4;
  { int f(int y){return x*y;}
    { int g(int→int h) {
        int x=7;
        return h(3)+x;
      }
      g(f);
}}}
```

Run-time stack with access links



Return Function as Result

- Language feature
  - Functions that return “new” functions
  - Need to maintain environment of function
- Example

  fun compose(f,g) = (fn x => g(f x));
- Function “created” dynamically
  - expression with free variables

    values are determined at run time
  - function value is closure = $\langle$env, code$\rangle$
  - code *not* compiled dynamically (in most languages)

Example: Return fctn with private state

```
fun mk_counter (init : int) =
    let   val count = ref init
          fun counter(inc:int) =
              (count := !count + inc; !count)
    in
          counter
    end;
val c = mk_counter(1);
c(2) + c(2);
```

- Function to "make counter" returns a closure
- How is correct value of count determined in c(2) ?

Example: Return fctn with private state

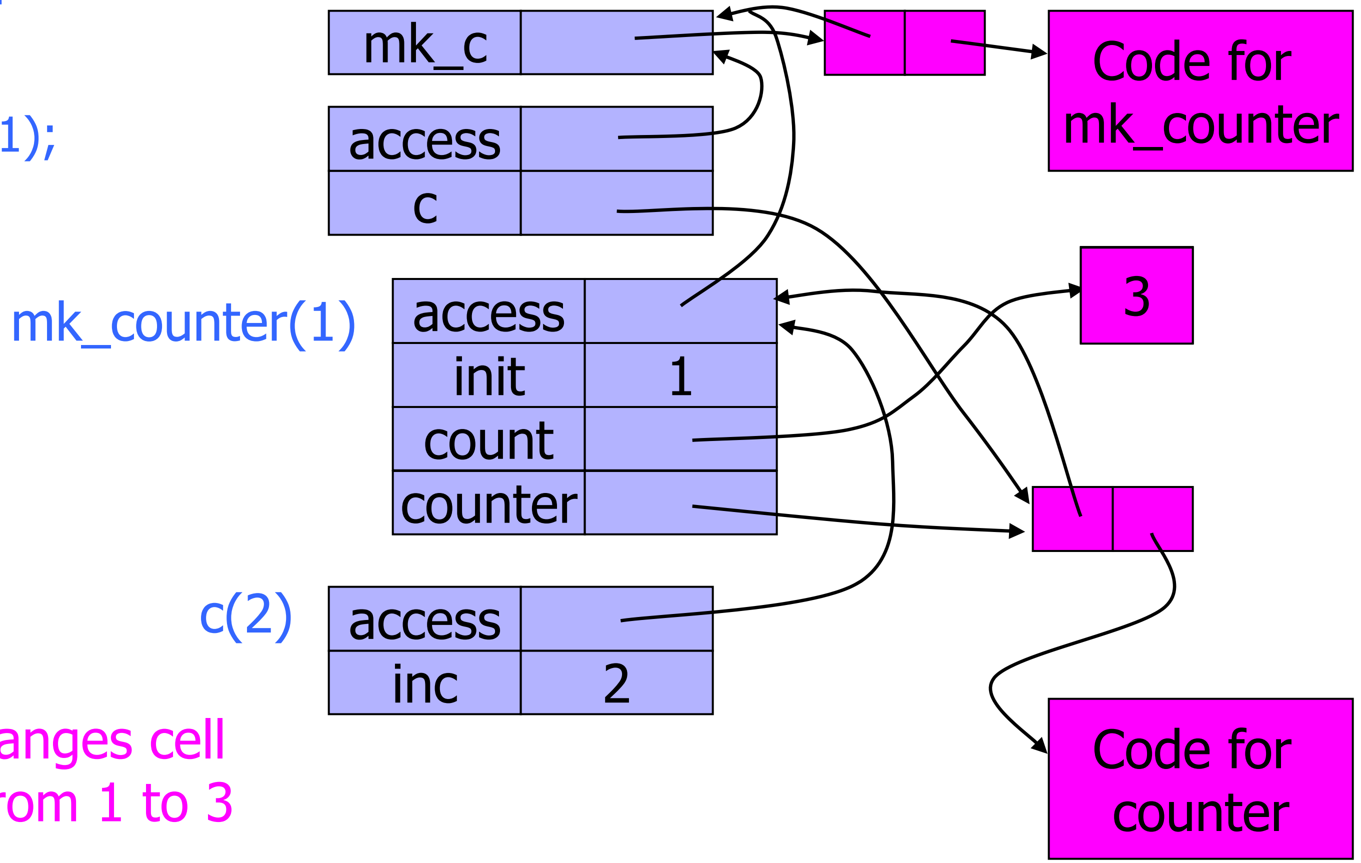
```
{int→int mk_counter (int init) {
        int count = init;
        int counter(int inc) { return count += inc;}
        return counter}
  int→int c  = mk_counter(1);
  print c(2) + c(2);
}
```

Function to “make counter” returns a closure

How is correct value of count determined in call c(2) ?

Function Results and Closures

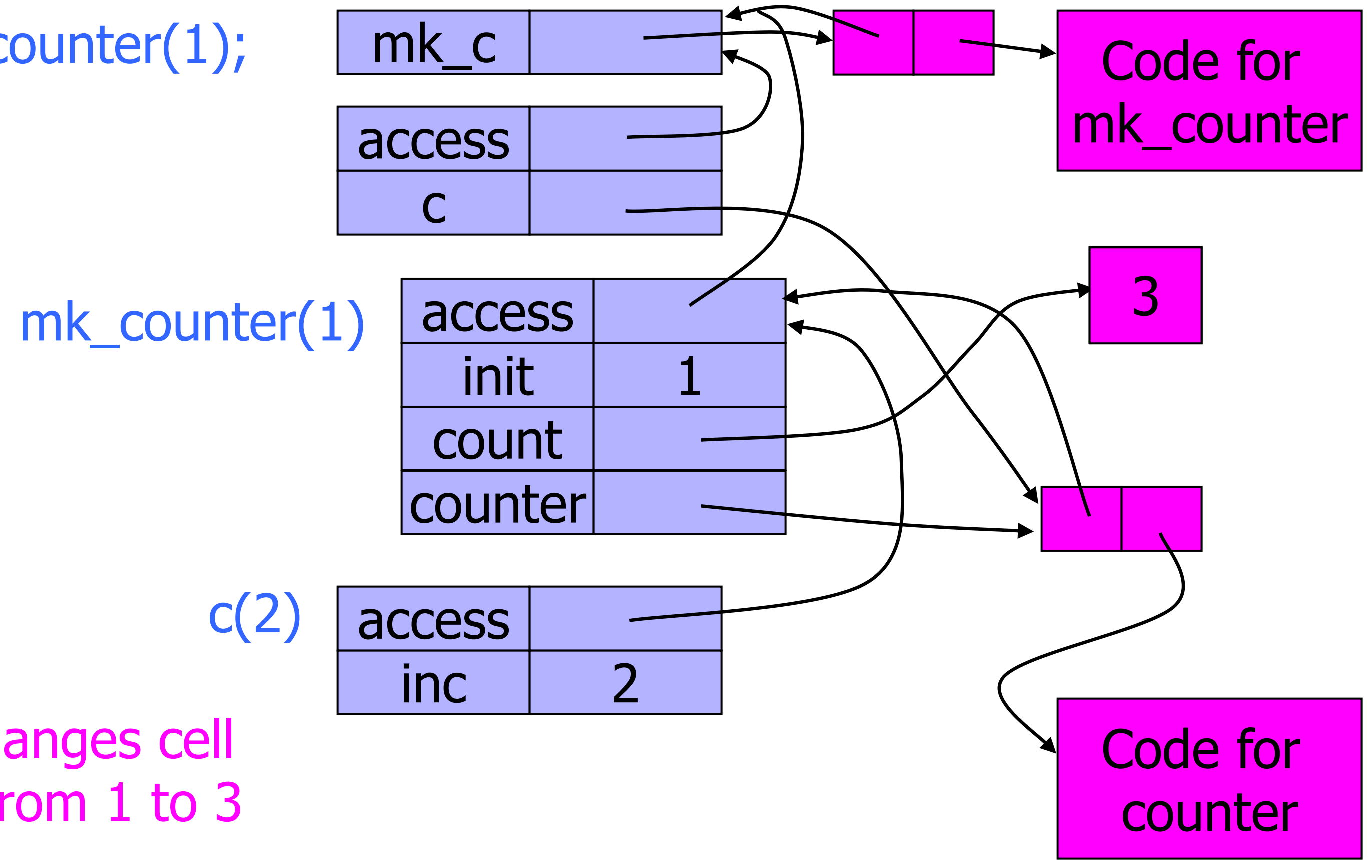
```
fun mk_counter (init : int) =
   let val count = ref init
       fun counter(inc:int) = (count := !count + inc; !count)
       in  counter end
   end;
val c = mk_counter(1);
c(2) + c(2);
```



Call changes cell value from 1 to 3

Function Results and Closures

```
{int→int mk_counter (int init) {
      int count = init;    int counter(int inc) { return count+=inc;}
      }
  int→int c = mk_counter(1);
  print c(2) + c(2);
}
```



Call changes cell value from 1 to 3

Summary: Return Function Results

- Use closure to maintain static environment
- May need to keep activation records after return
  - Stack (lifo) order fails!
- Possible "stack" implementation
  - Forget about explicit deallocation
  - Put activation records on heap
  - Invoke garbage collector as needed
  - Not as totally crazy as is sounds
    - May only need to search reachable data

Summary of scope issues

- Block-structured lang uses stack of activ records
  - Activation records contain parameters, local vars, …
  - Also pointers to enclosing scope
- Several different parameter passing mechanisms
- Tail calls may be optimized
- Function parameters/results require closures
  - Closure environment pointer used on function call
  - Stack deallocation may fail if function returned from call
  - Closures *not* needed if functions not in nested blocks