Scope and Activation Records

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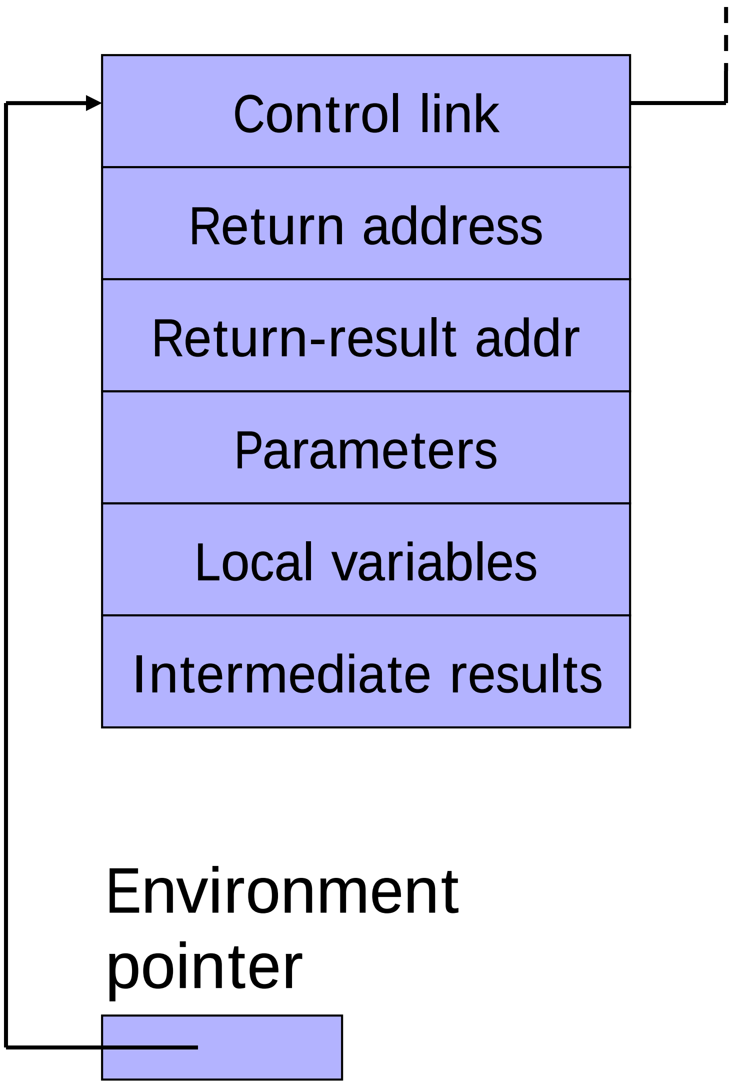
Activation Records for Functions

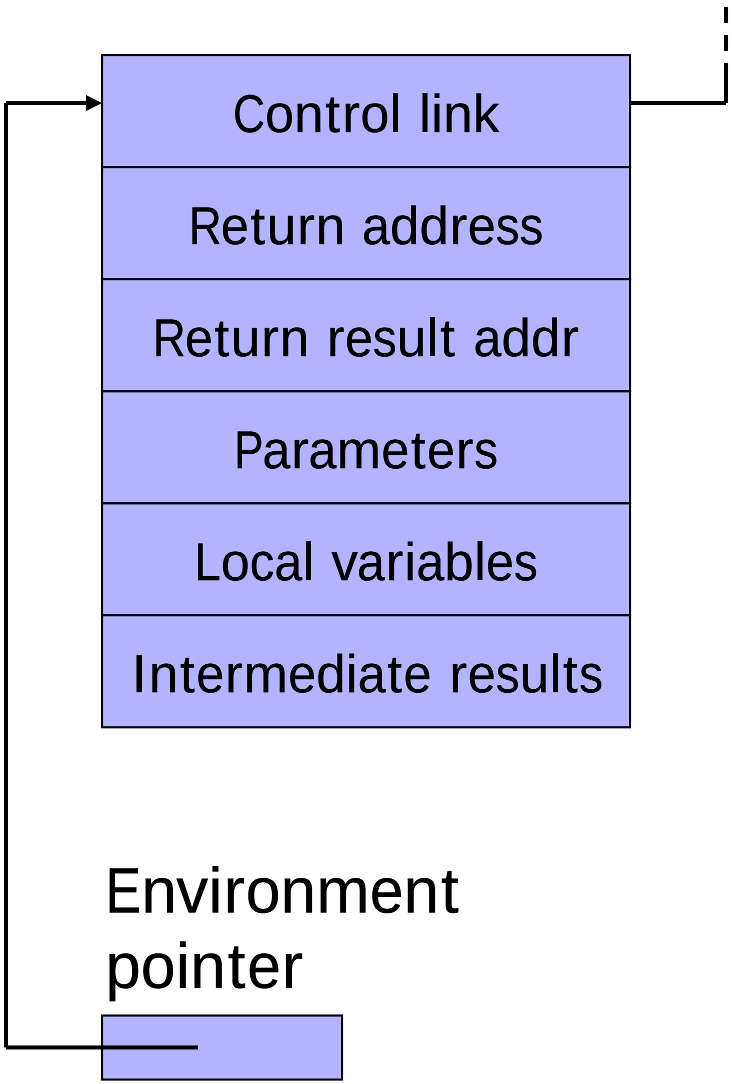
- Block of information (“frame”) associated with each function call, including:
  - Parameters
  - Local variables
  - Return address
  - Location to put return value when function exits
  - Control link to the caller’s activation record
  - Saved registers
  - Temporary variables and intermediate results
  - (not always) Access link to the function’s static parent

Activation Record Layout



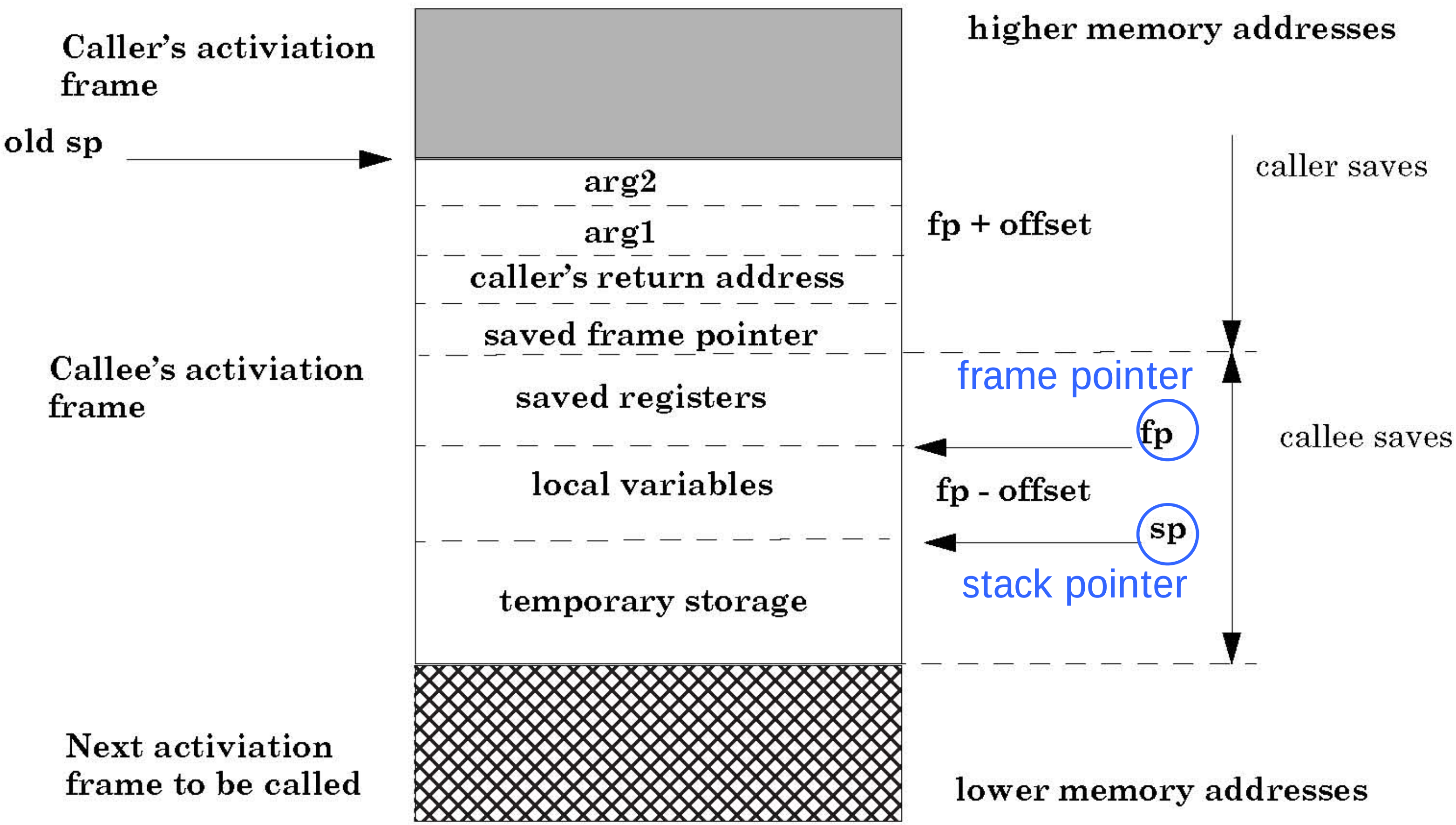
- Return address
  - Location of code to execute on function return
- Return-result address
  - Address in activation record of calling block to receive returned value
- Parameters
  - Locations to contain data from calling block

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)

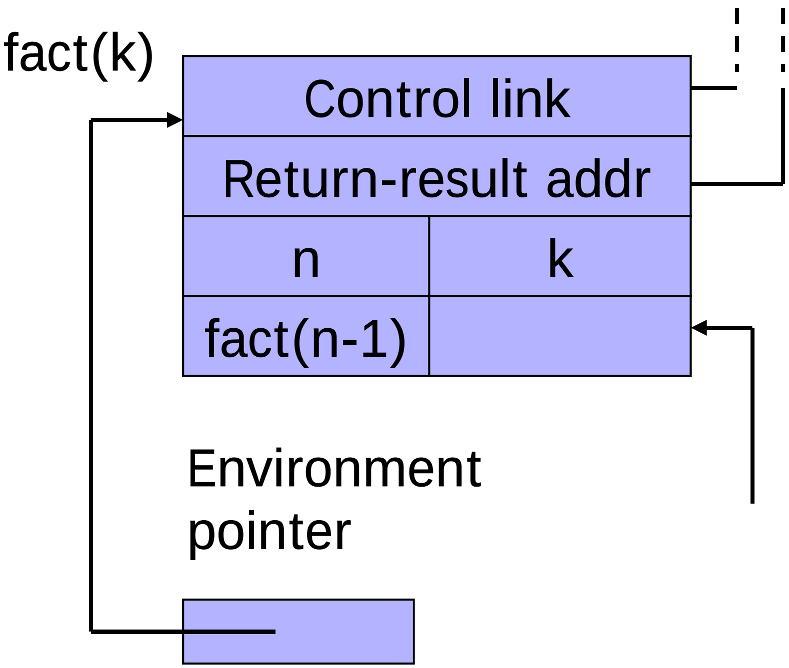
Typical x86 Activation Record

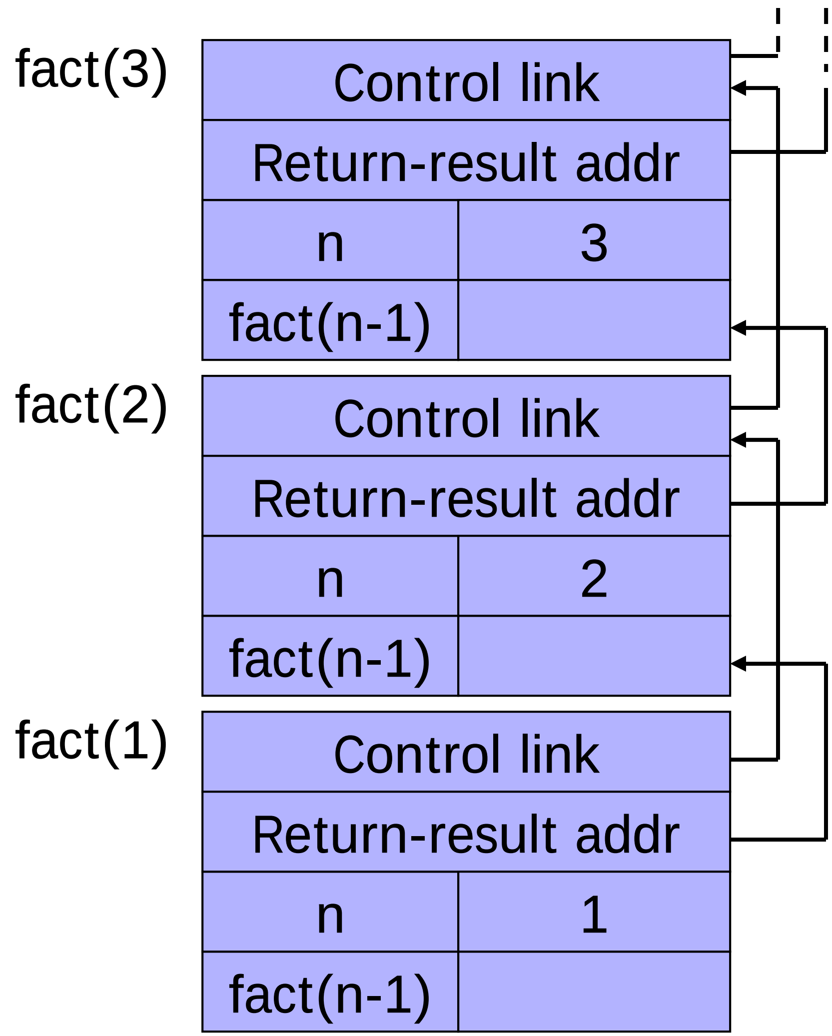


Run-Time Stack

- Activation records are kept on the stack
  - Each new call pushes an activation record
  - Each completing call pops the topmost one
  - Stack has all records of all active calls at any moment during execution (topmost record = most recent call)
- Example: fact(3)
  - Pushes one activation record on the stack, calls fact(2)
  - This call pushes another record, calls fact(1)
  - This call pushes another record, resulting in three activation records on the stack

Function Call

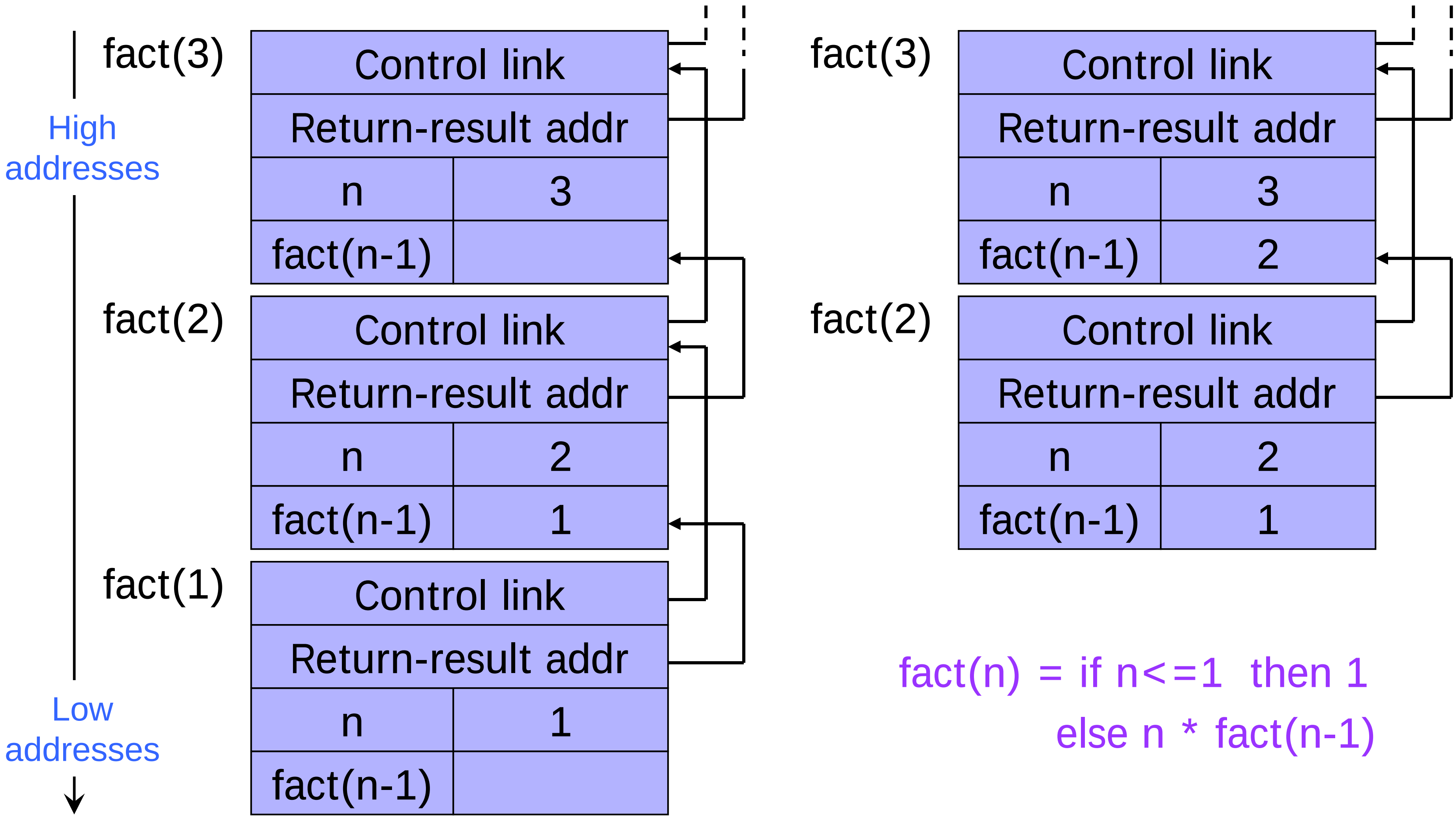




fact(n) = if n<= 1 then 1
else n * fact(n-1)

Return address omitted; would be a pointer into code segment

Function Return



fact(n) = if n<=1 then 1

else n * fact(n-1)

Scoping Rules

- Global and local variables

  x, y are local to outer block

  z is local to inner bock

  x, y are <u>global</u> 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
- Do you see the difference? (think function calls)

Static vs. Dynamic Scope

- 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)

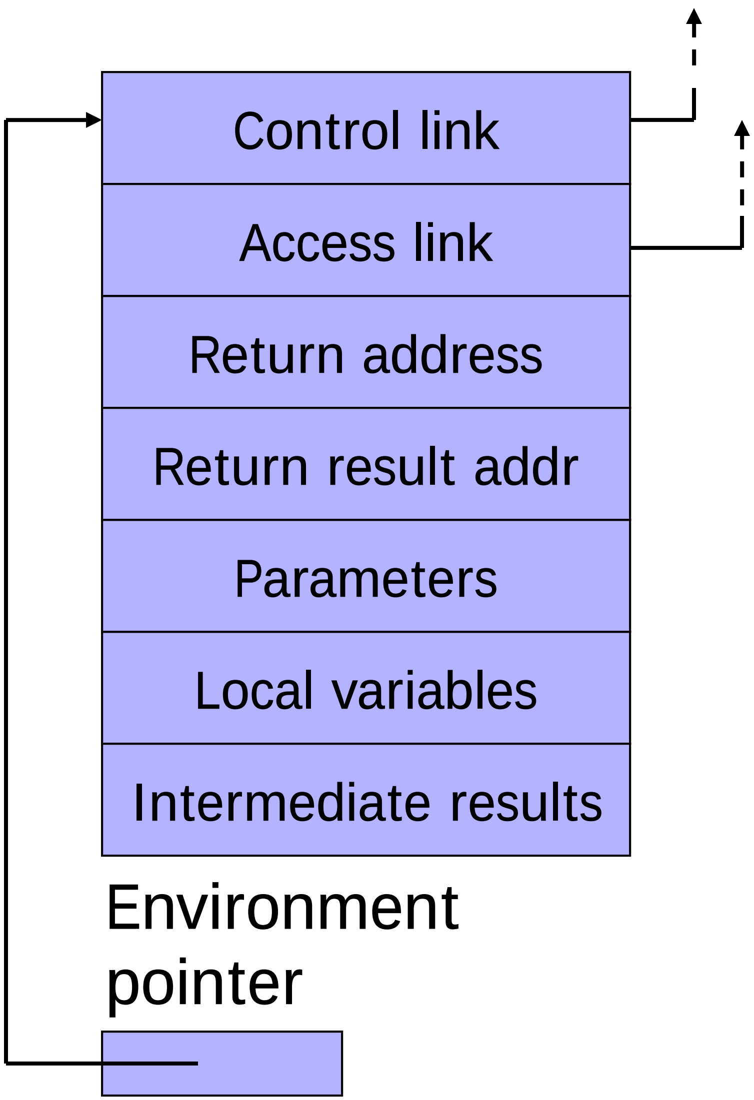
z	12

Which x is used for expression x+z ?

static scope

dynamic scope

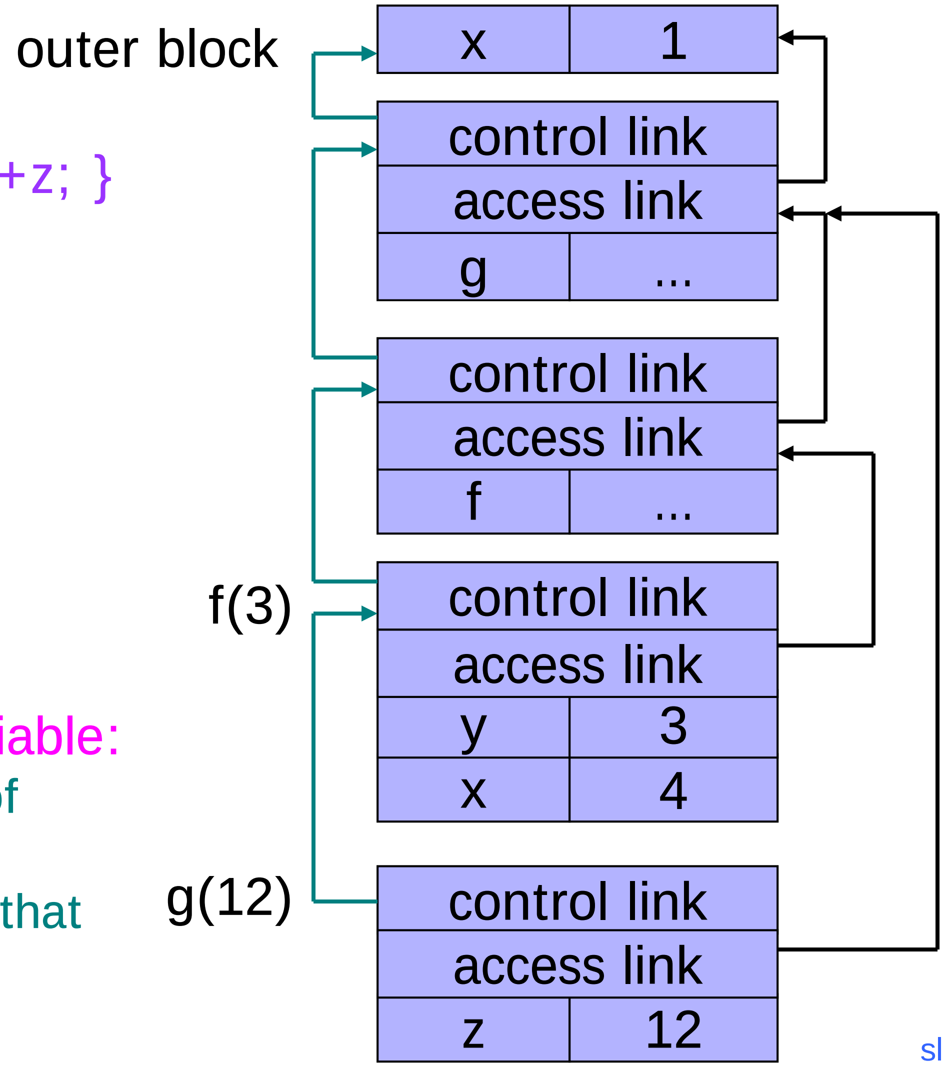
Activation Record For Static Scope



- **Control link**
  - Link to activation record of previous (calling) block
  - Depends on dynamic behavior of the program
- **Access link**
  - Link to activation record of closest lexically enclosing block in program text
    - Is this needed in C? (why?)
  - Depends on the static program text

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 the block that contains function definition

Variable Arguments (Redux)

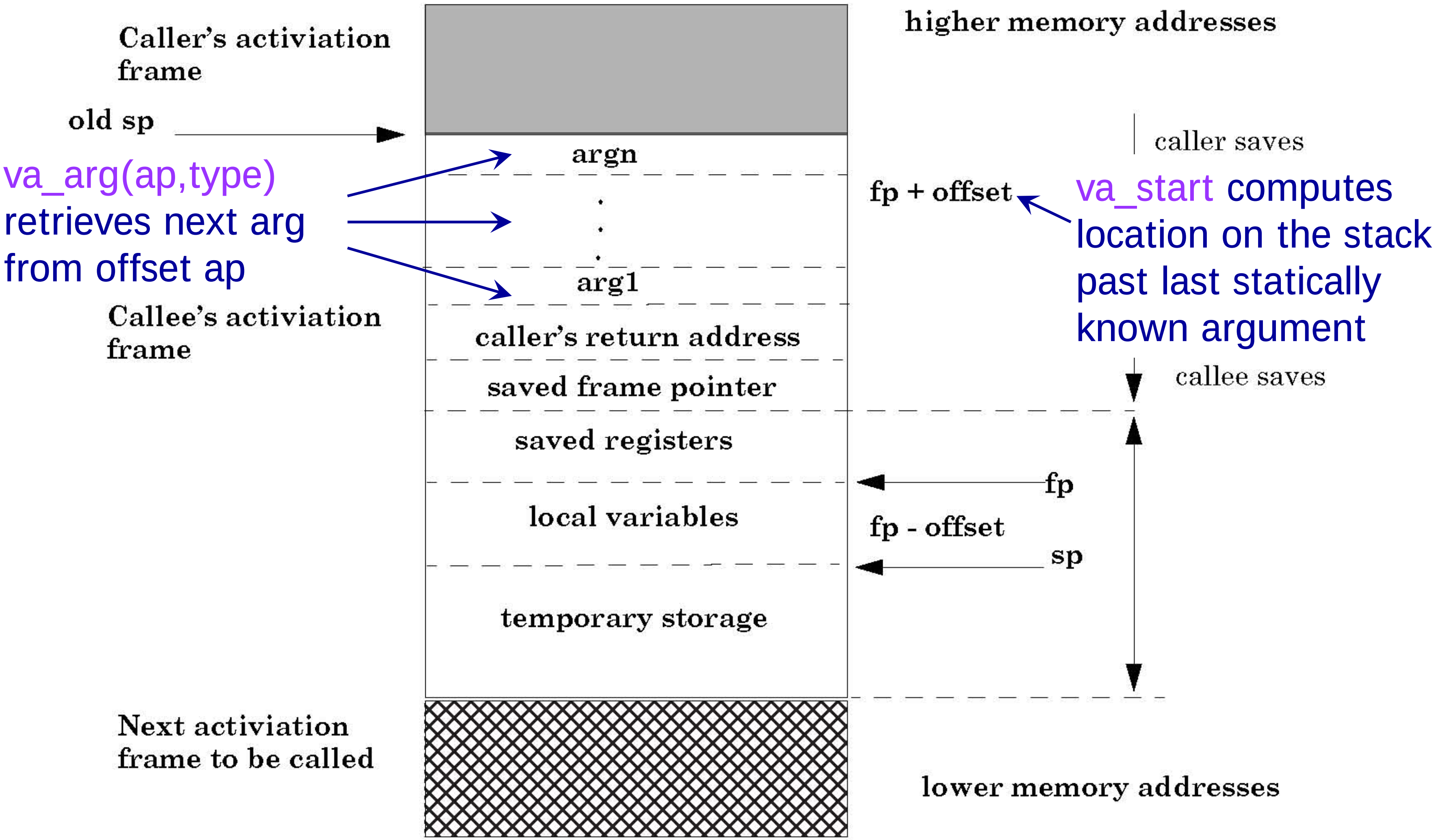
- Special functions va_start, va_arg, va_end compute arguments at run-time (how?)

```
void printf(const char* format, ...)
{
      int i; char c; char* s; double d;
      va_list ap;  /* declare an "argument pointer" to a variable arg list */
      va_start(ap, format);  /* initialize arg pointer using last known arg */

      for (char* p = format; *p != '\0'; p++) {
         if (*p == '%') {
            switch (*++p) {
               case 'd':
                  i = va_arg(ap, int); break;
               case 's':
                  s = va_arg(ap, char*); break;
               case 'c':
                  c = va_arg(ap, char); break;
               }
               ... /* etc. for each % specification */
            }
      }
      ...

      va_end(ap);  /* restore any special stack manipulations */
}
```

Activation Record for Variable Args



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

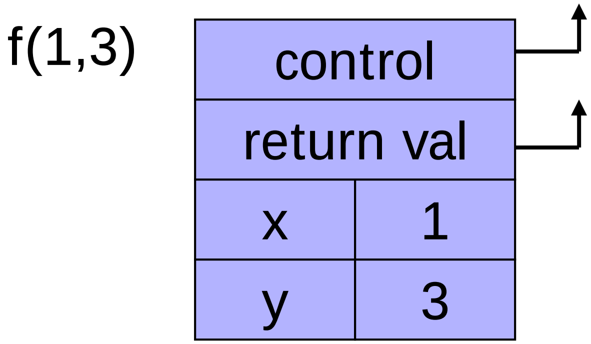
tail call　　　　　　　　　　　not a tail call

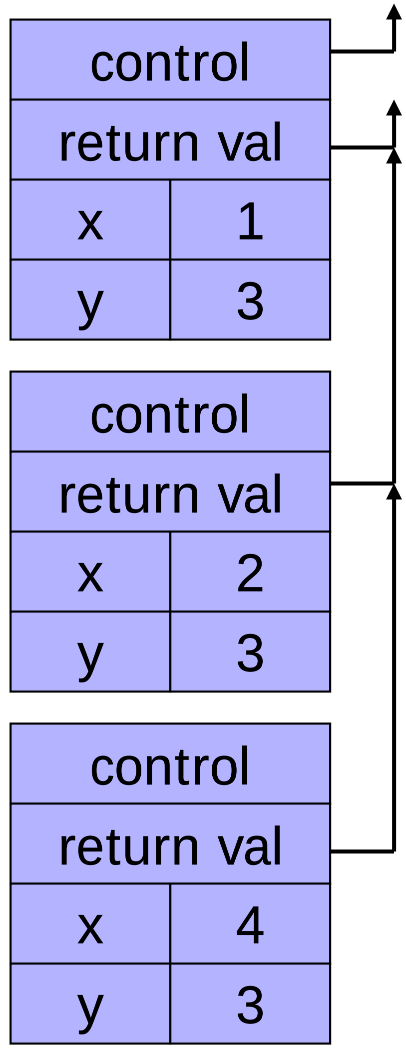
fun g(x) = if x>0 then f(x) else f(x)*2

- Optimization: can pop current activation record on a tail call
  - Especially useful for recursive tail call because next activation record has exactly same form

Example of Tail Recursion

Calculate least power of 2 greater than y






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

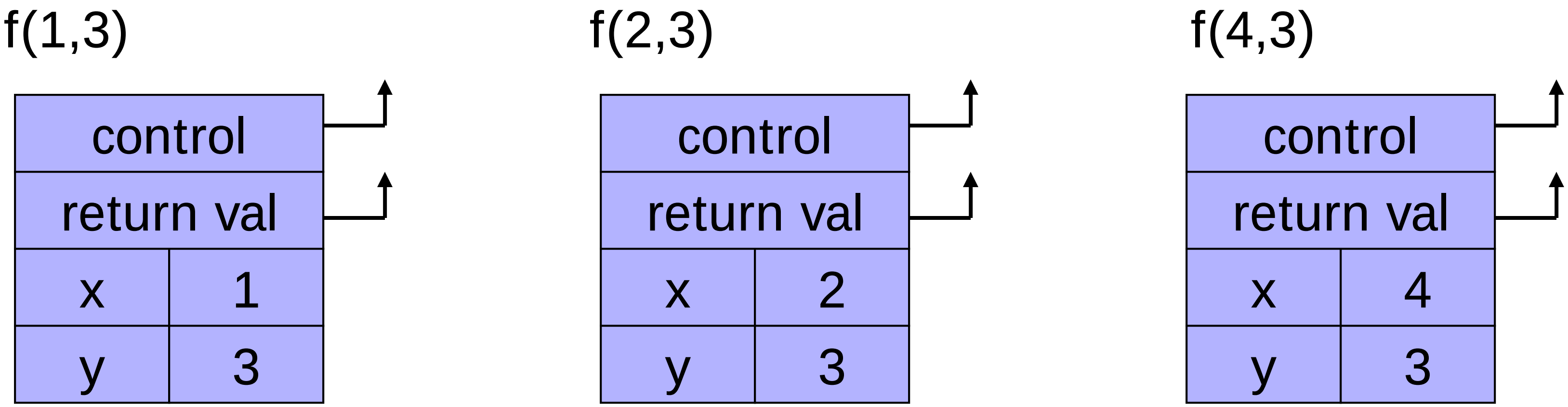
Optimization

- Set return value address to that of caller
- Can we do same with control link?

Optimization

- Avoid return to caller
- Does this work with dynamic scope?

Tail Recursion Elimination

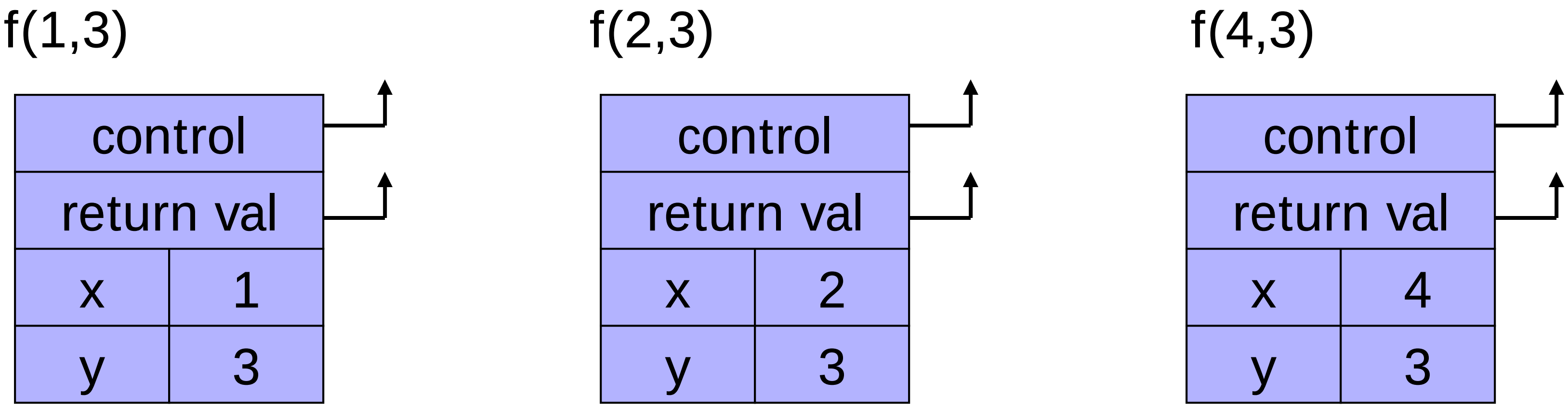



```
fun f(x,y) = if x>y
      then x
      else f(2*x, y);
f(1,3) + 7;
```

Optimization

- pop followed by push - reuse activation record in place
- Tail recursive function is equivalent to iterative loop

Tail Recursion and Iteration




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

test

loop body

initial value

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

Higher-Order Functions

- Function passed as argument
  - Need pointer to activation record “higher up” in stack
- Function returned as the result of function call
  - Need to keep activation record of the returning function (why?)
- Functions that take function(s) as input and return functions as output are known as <u>functionals</u>

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);
```

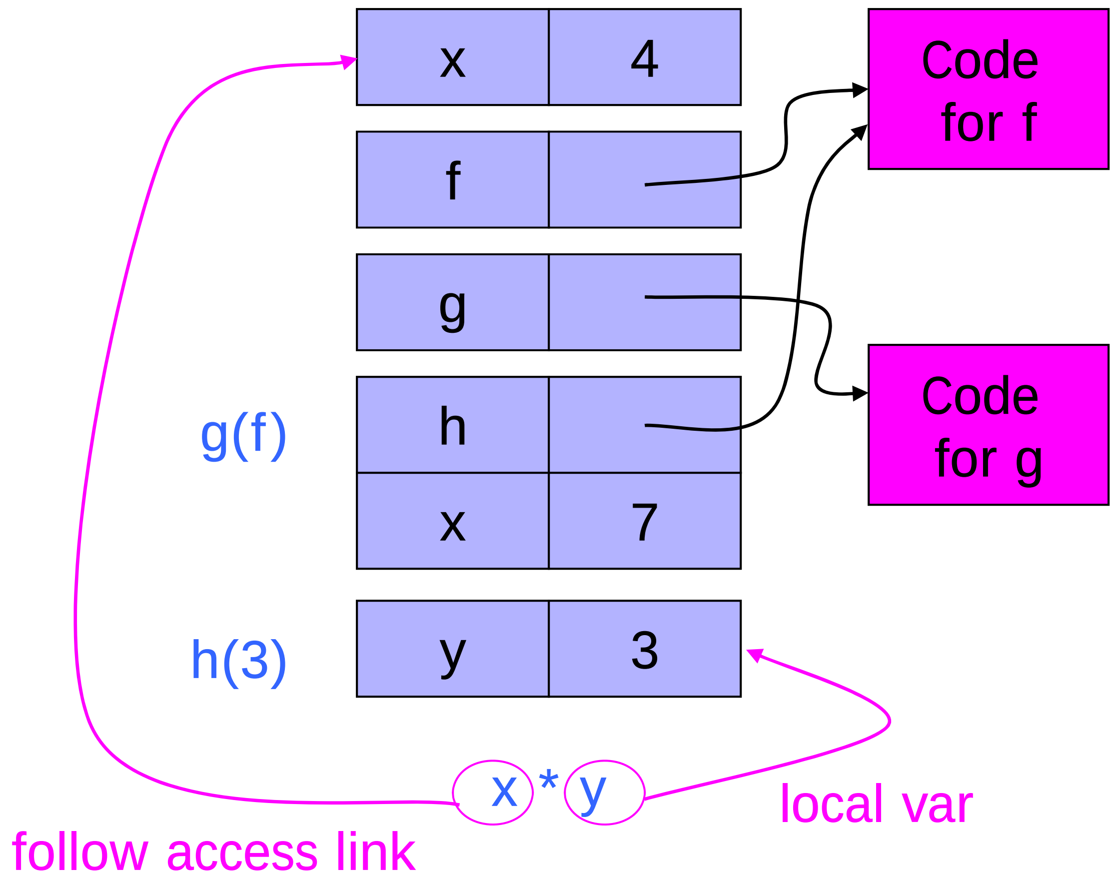
```
{ var x = 4;
   { function f(y) {return x*y;}
      { function g(h) {
              var x = 7;
              return h(3) + x;
        }
        g(f);
} } }
```

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);
```



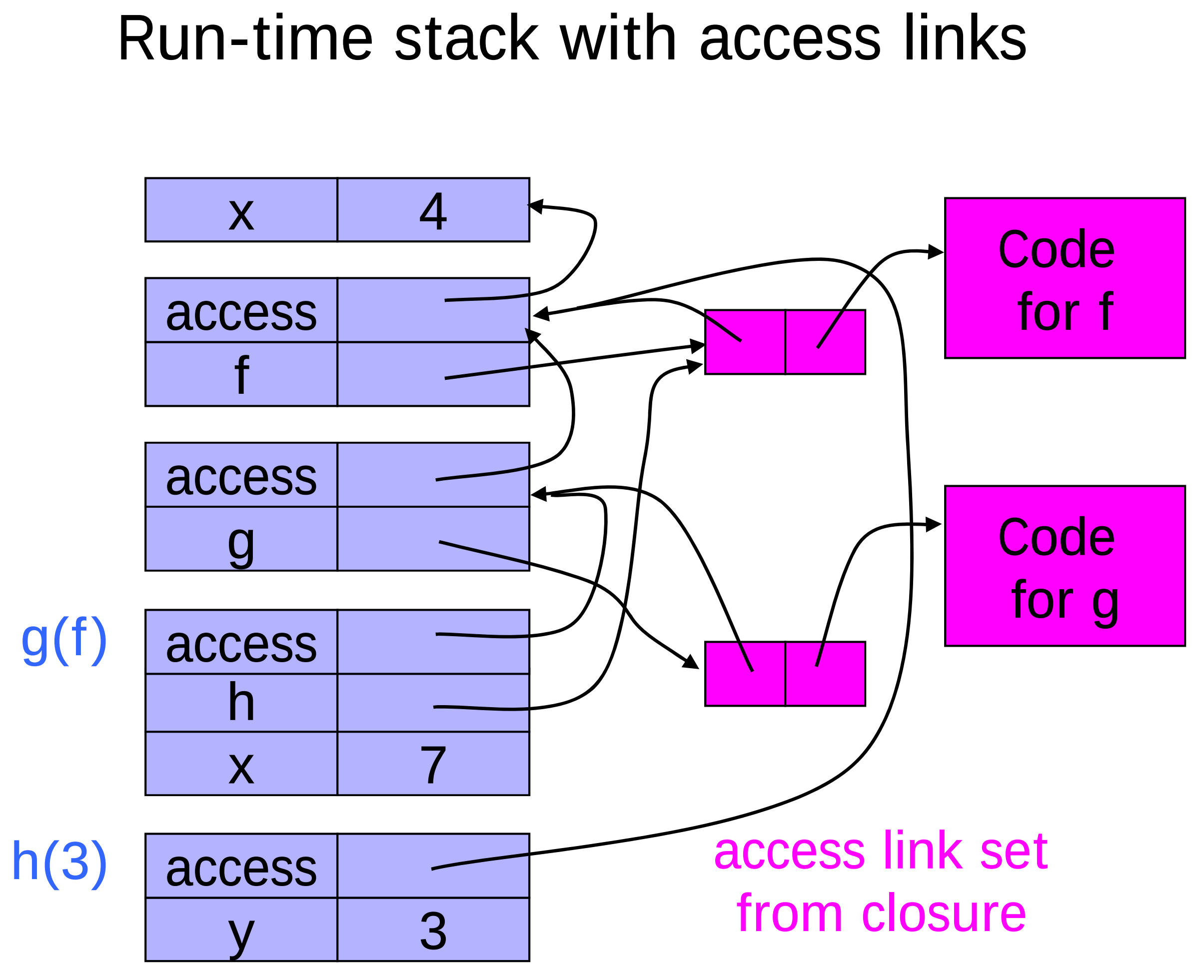
How is access link for h(3) set?

Closures

- Function value is pair closure = $\langle$env, code $\rangle$
  - Idea: statically scoped function must carry a link to its static environment with it
  - Only needed if function is defined in a nested block (why?)
- 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

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



Summary: Function Arguments

- Use closure to maintain a pointer to the static environment of a function body
- When called, set access link from closure
- All access links point “up” in stack
  - May jump past activation records to find global vars
  - Still deallocate activation records using stack (last-in-first-out) order

Return Function as Result

- Language feature (e.g., ML)
- Functions that return “new” functions
  - Example: fun compose(f,g) = (fn x => g(f x));
  - Function is “created” dynamically
    - Expression with free variables; values determined at run-time
  - Function value is closure = ⟨env, code⟩
  - Code <u>not</u> compiled dynamically (in most languages)
  - Need to maintain environment of the creating function (why?)

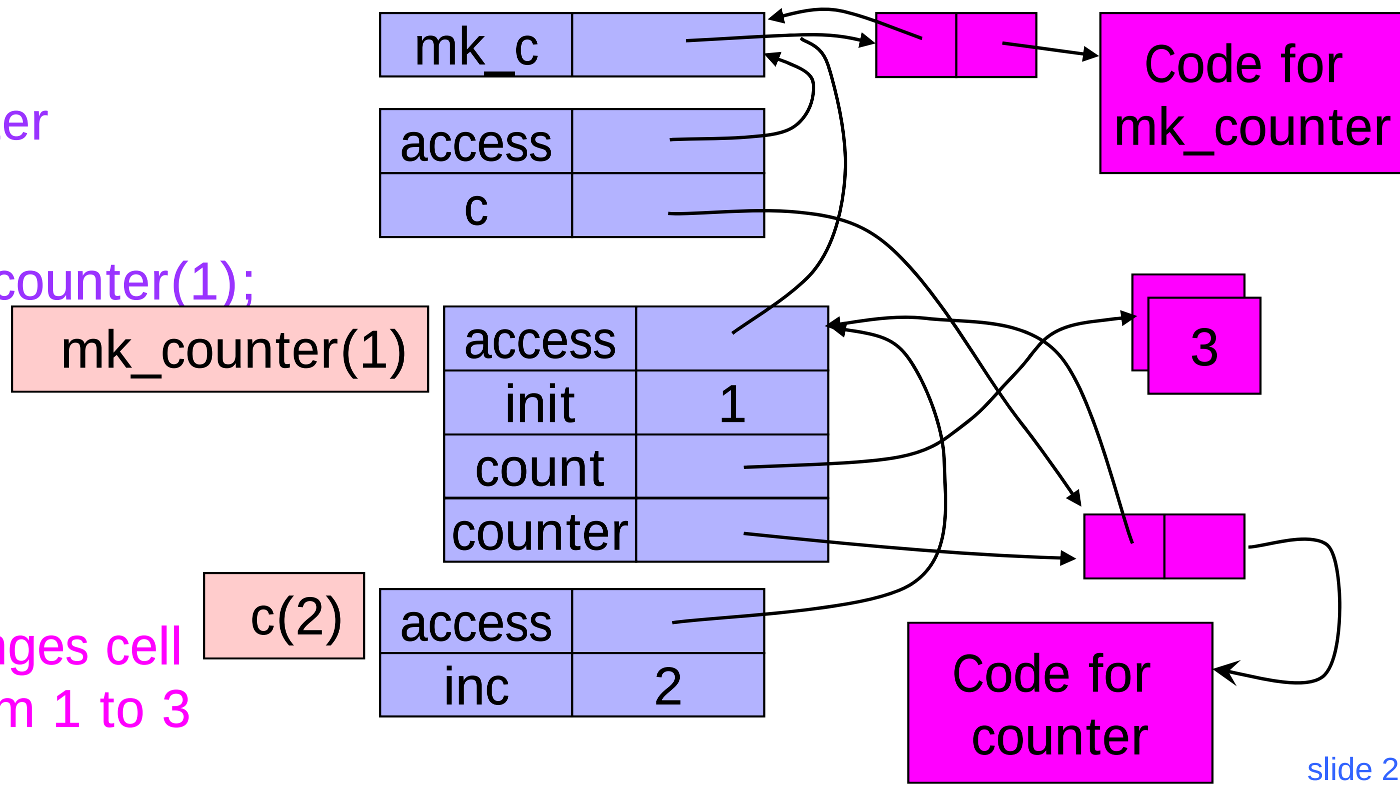
Return Function with Private State

```
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) ?

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;
val c = mk_counter(1);
c(2) + c(2);
```



Call changes cell value from 1 to 3

Closures in Web Programming

- Useful for event handlers

```
function AppendButton(container, name, message) {
    var btn = document.createElement('button');
    btn.innerHTML = name;
    btn.onclick = function(evt) { alert(message); }
    container.appendChild(btn);
}
```

- Environment pointer lets the button's click handler find the message to display

Managing Closures

- Closures as used to maintain static environment of functions as they are passed around
- May need to keep activation records after function returns (why?)
  - Stack (last-in-first-out) order fails! (why?)
- Possible “stack” implementation:
  - Put activation records on heap
  - Instead of explicit deallocation, invoke garbage collector as needed
    - Not as totally crazy as is sounds (may only need to search reachable data)