Compiler Construction
Lent Term 2015
Lecture 6 (of 16)

- Alternatives for managing access to non-local variables
  - Lambda lifting
  - Static links
  - Heap allocated closures

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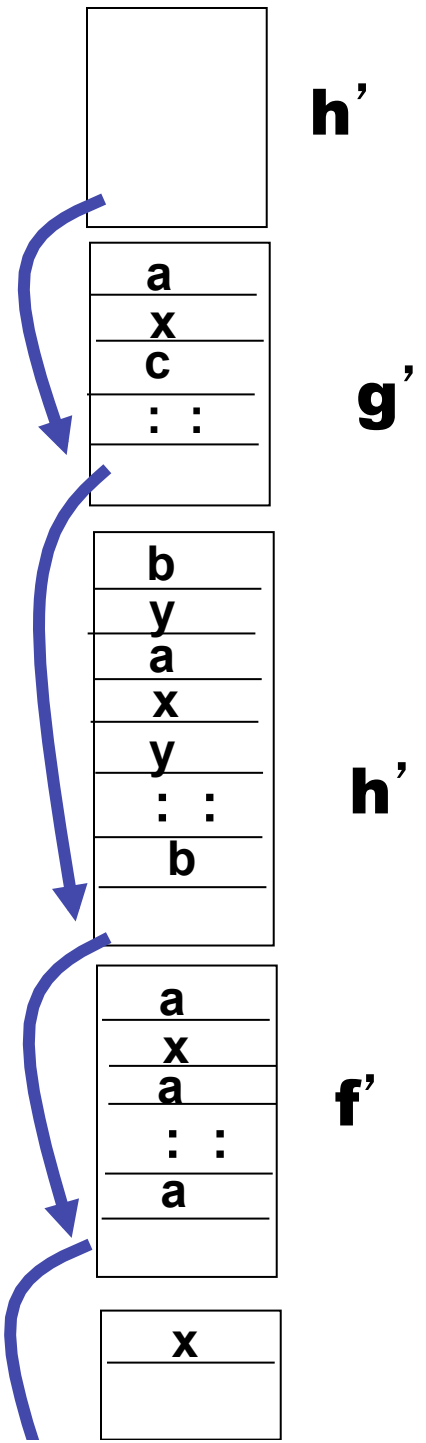
Alternative 1: "Lambda Lifting"

```
fun f(x) {
   let a = …;
   fun h(y) {
     let b = …;
     fun g(w) {
        let c = …;
        if ..
        then return a;
        else return h(c)
     }
     return b + g(y);
   }
   return x + h(a);
}

f(17)
```

```
fun g'(w, x, a, y, b) {
   let c = …;
   if ..
   then return a;
   else return h'(c, x, a )
}
fun h'(y, x, a) {
   let b = …;
   return b + g'(y, x, a, y, b)
}

fun f'(x) {
   let a = …;
   return x + h'(a, x, a);
}

f'(17)
```

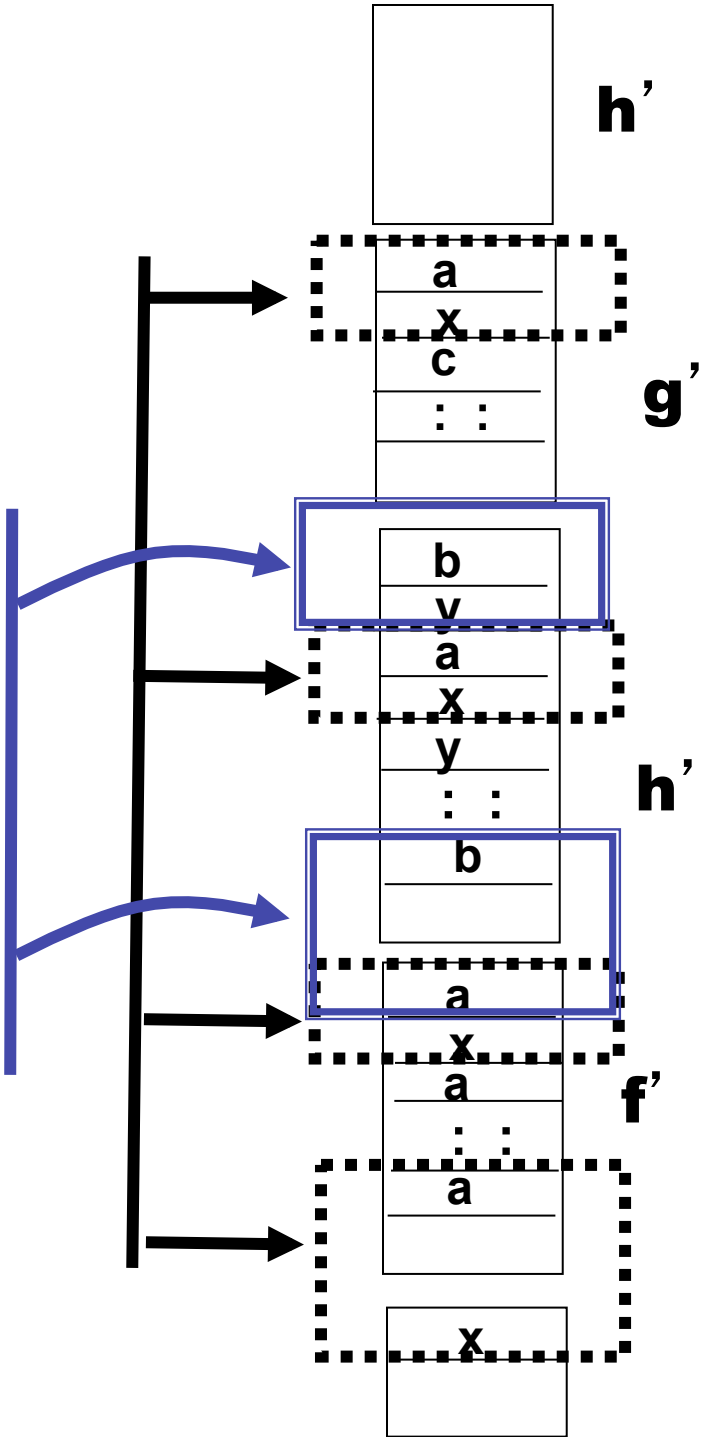
Stack Evaluation

```
fun g'(w, x, a, y, b) {
   let c = …;
   if ..
   then return a;
   else return h'(c, x, a)
}
fun h'(y, x, a) {
   let b = …;
   return b + g'(y, x, a, y, b)
}

fun f'(x) {
   let a = …;
   return x + h'(a, x, a);
}

f'(17)
```



Problem: a lot of Duplication!

```
fun g'(w, x, a, y, b) {
   let c = …;
   if ..
   then return a;
   else return h'(c, x, a)
}
fun h'(y, x, a) {
   let b = …;
   return b + g'(y, x, a, y, b)
}

fun f'(x) {
   let a = …;
   return x + h'(a, x, a);
}

f'(17)
```



Nesting depth

```
fun b(z) = e

 fun g(x1) =
    fun h(x2) =
       fun f(x3) = e3(x1, x2, x3, b, g h, f)
       in
           e2(x1, x2, b, g, h, f)
        end
    in
        e1(x1, b, g, h)
   end
...
b(g(17))
...
```

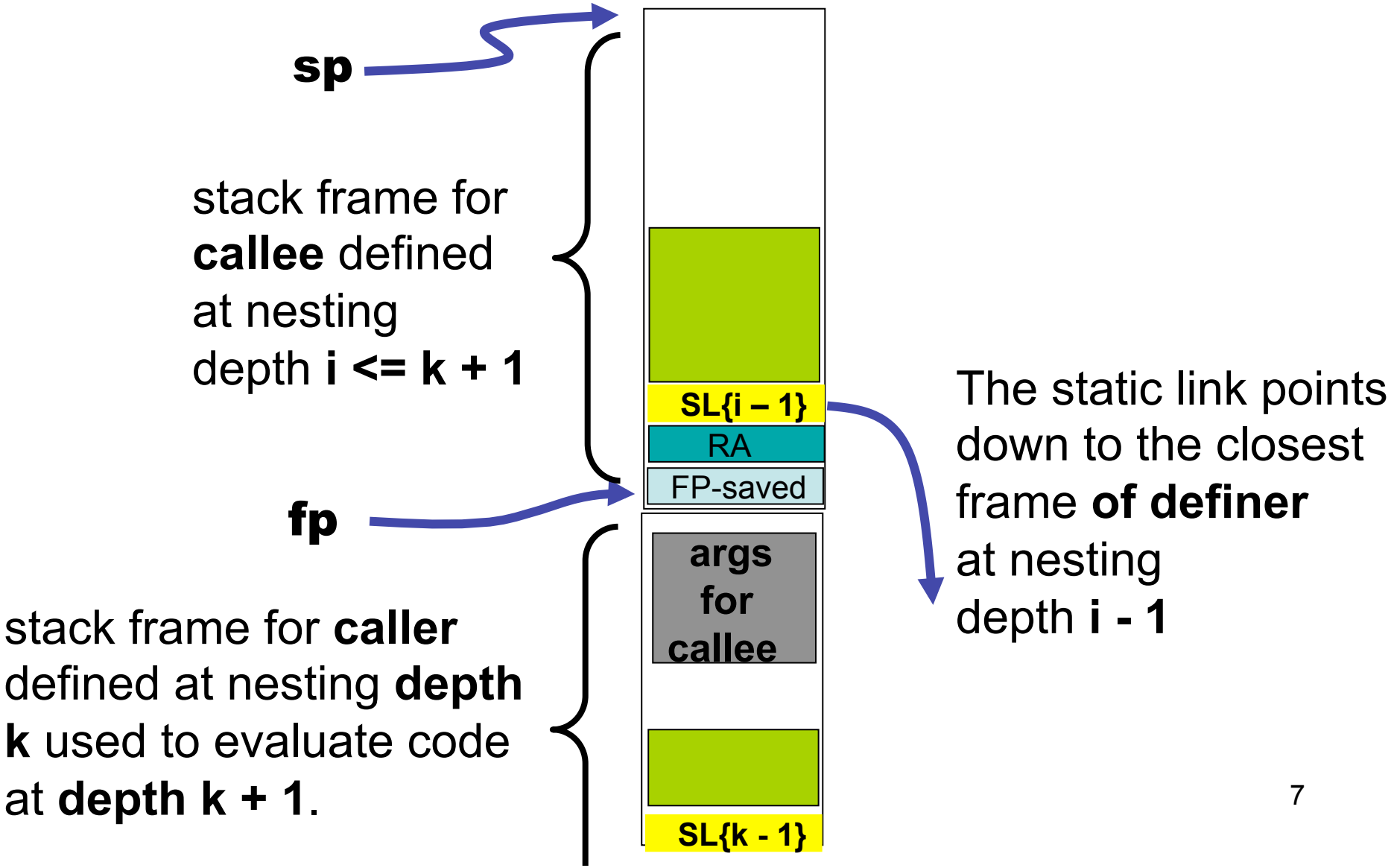
Nesting depth

code in big box is at nesting depth k

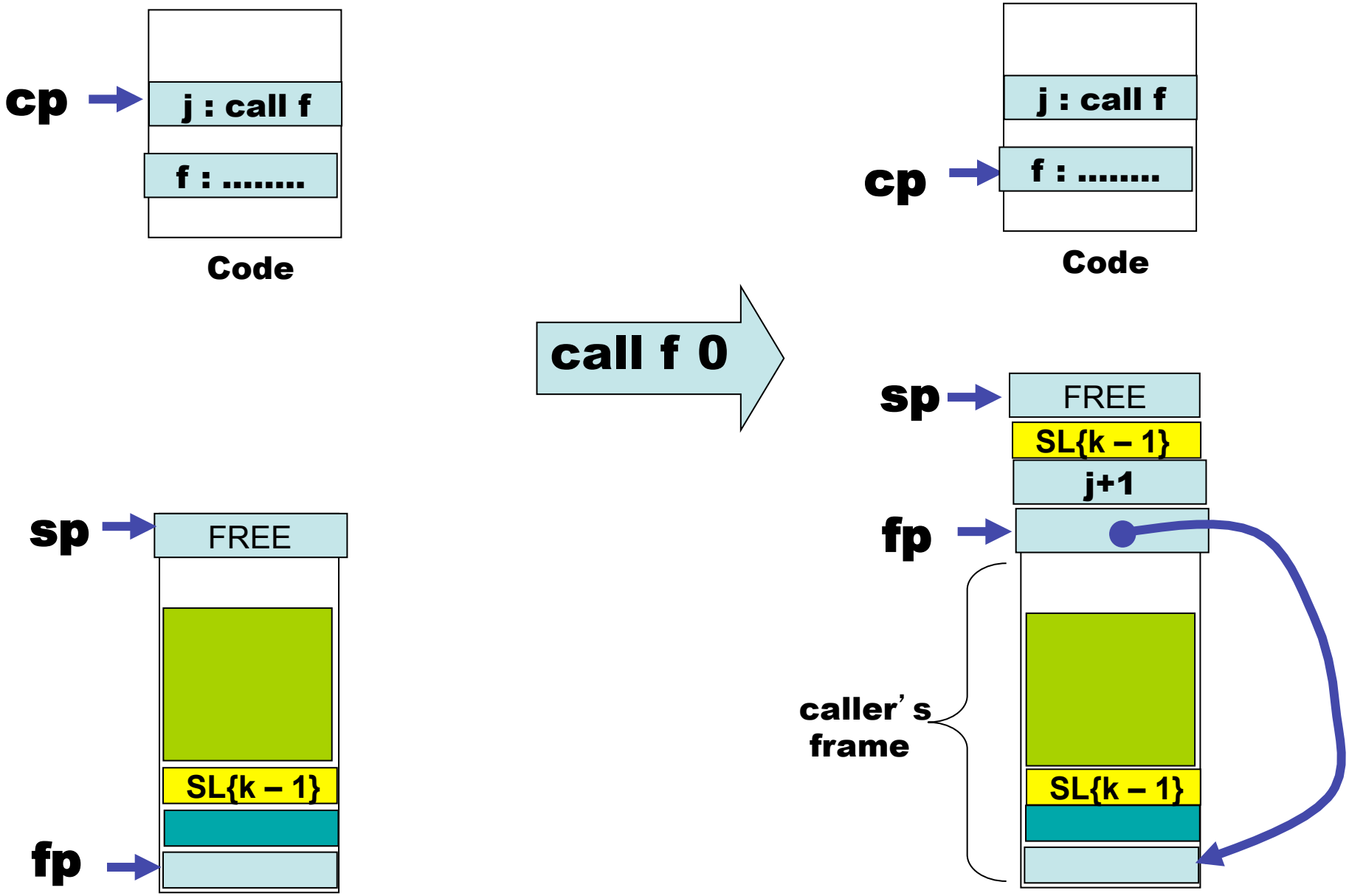
```
fun b(z) = e  nesting depth k + 1

 fun g(x1) =
   fun h(x2) =
     fun f(x3) = e3(x1, x2, x3, b, g h, f)        nesting depth k + 3
     in
        e2(x1, x2, b, g, h, f)
      end                                          nesting depth k + 2
   in
       e1(x1, b, g, h)
  end                                              nesting depth k + 1
...
b(g(17))
...
```


Function g is the **definer** of h. Functions g and b must share a definer defined at depth k-1

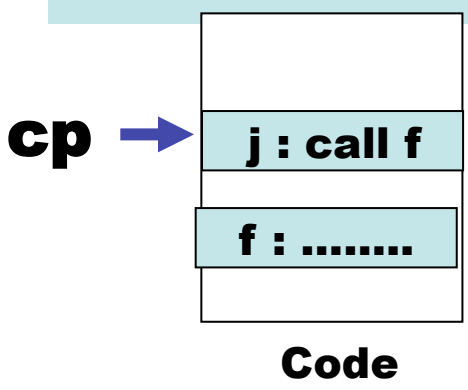
Alternative 2: Augment stack frames with Static Links (here SL{d} means a static link pointing at most recent frame of the definer at depth d)

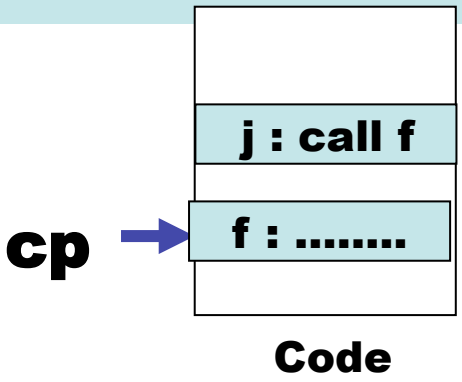


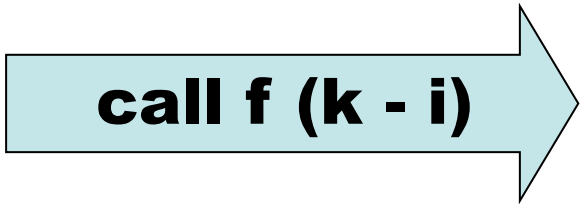
caller and callee at same nesting depth k

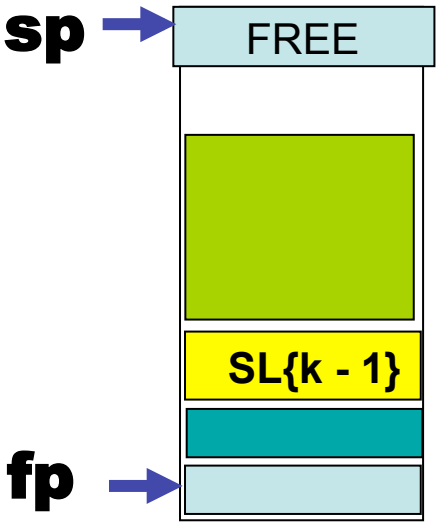


caller at depth k and callee at depth i < k

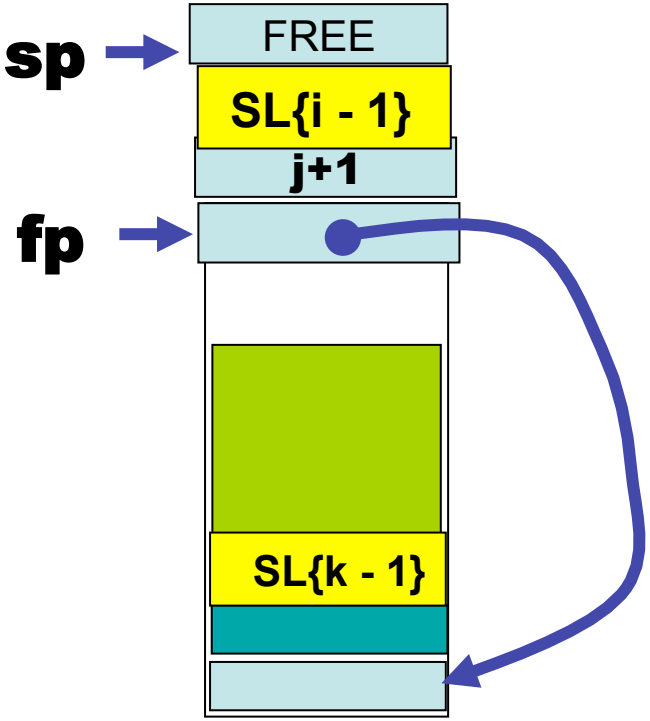




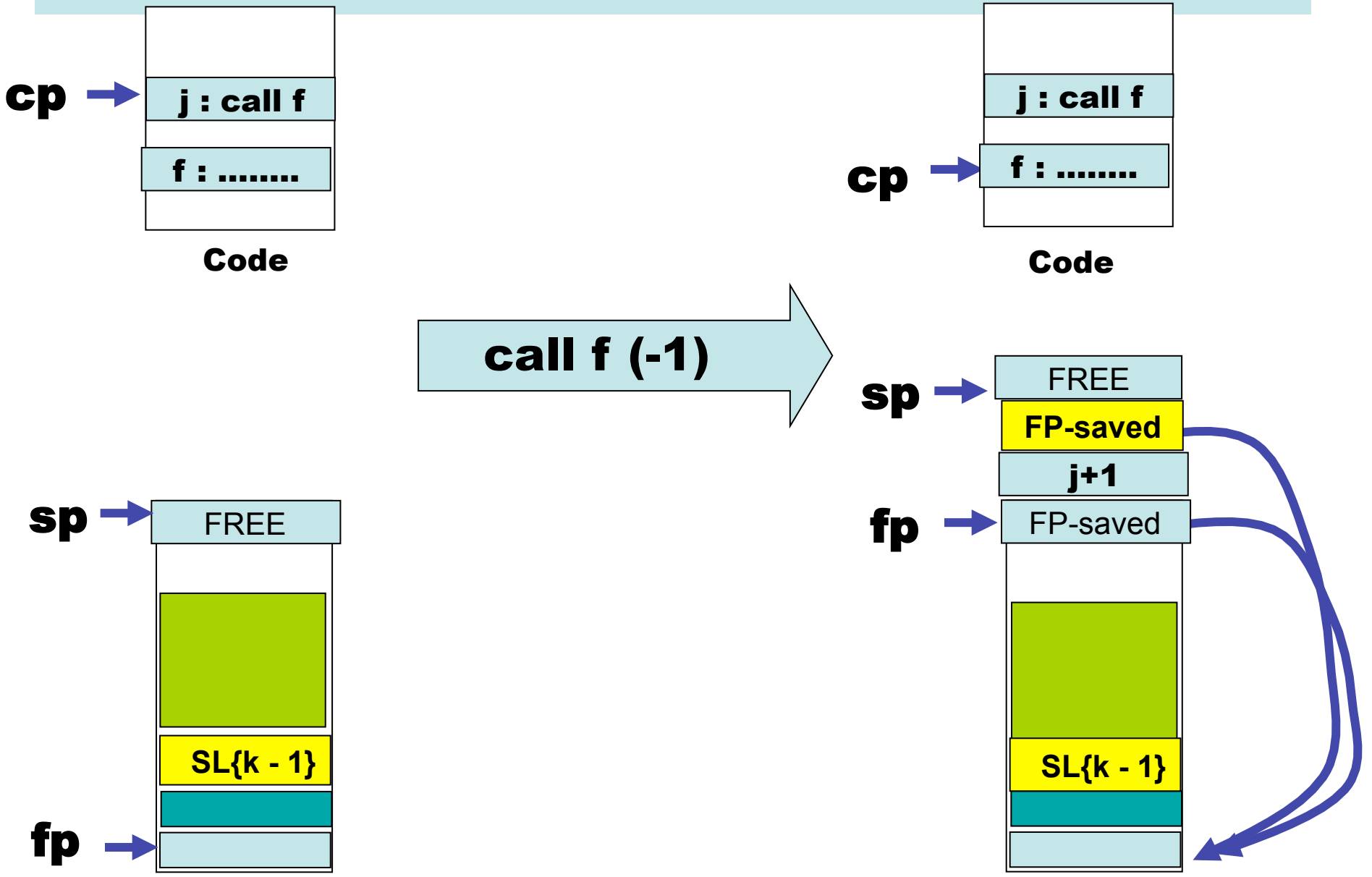




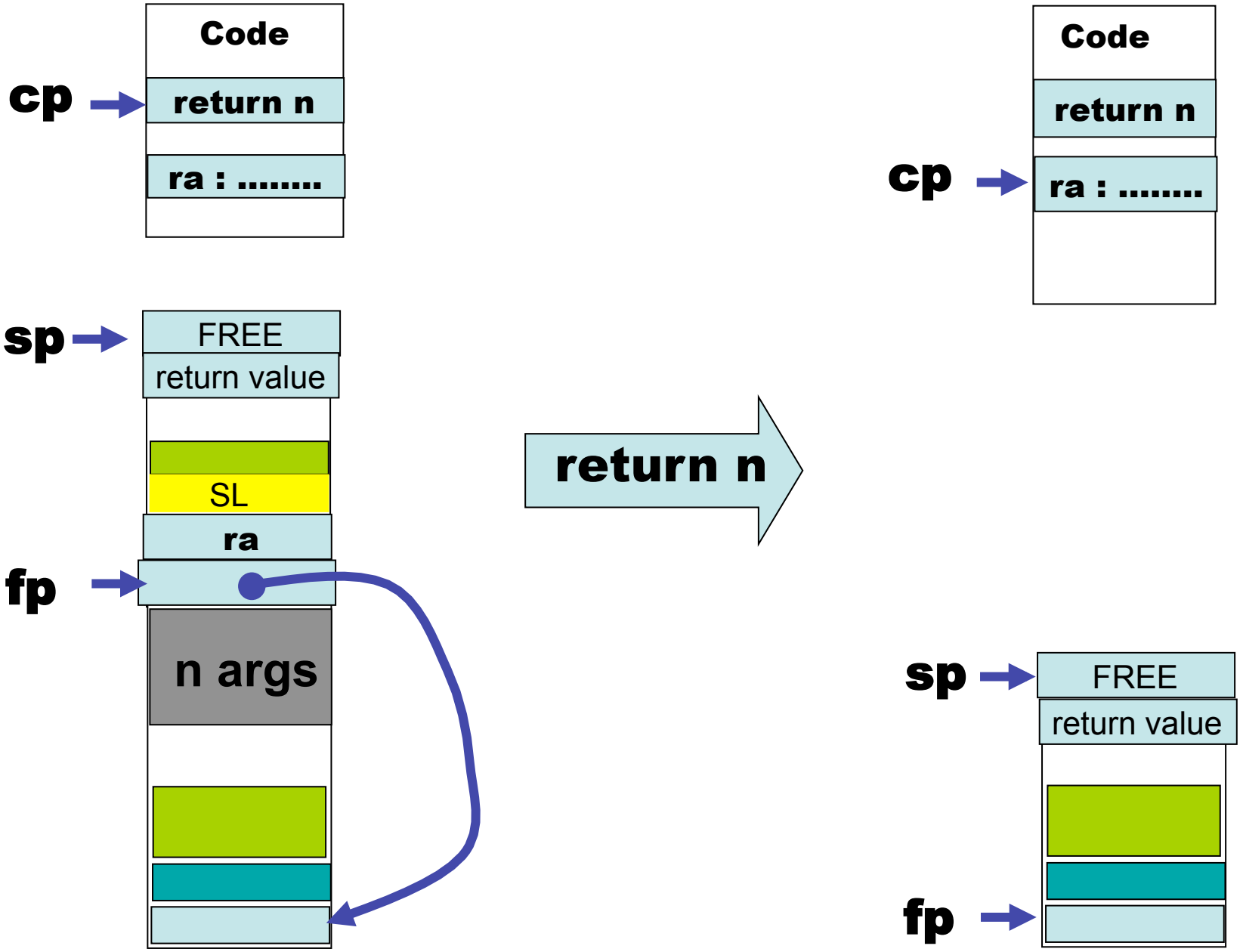

```
p := !(fp + 2);
for c = 1 to k - i
{
   p := !(p + 2);
}
SL{i-1} := p;
```



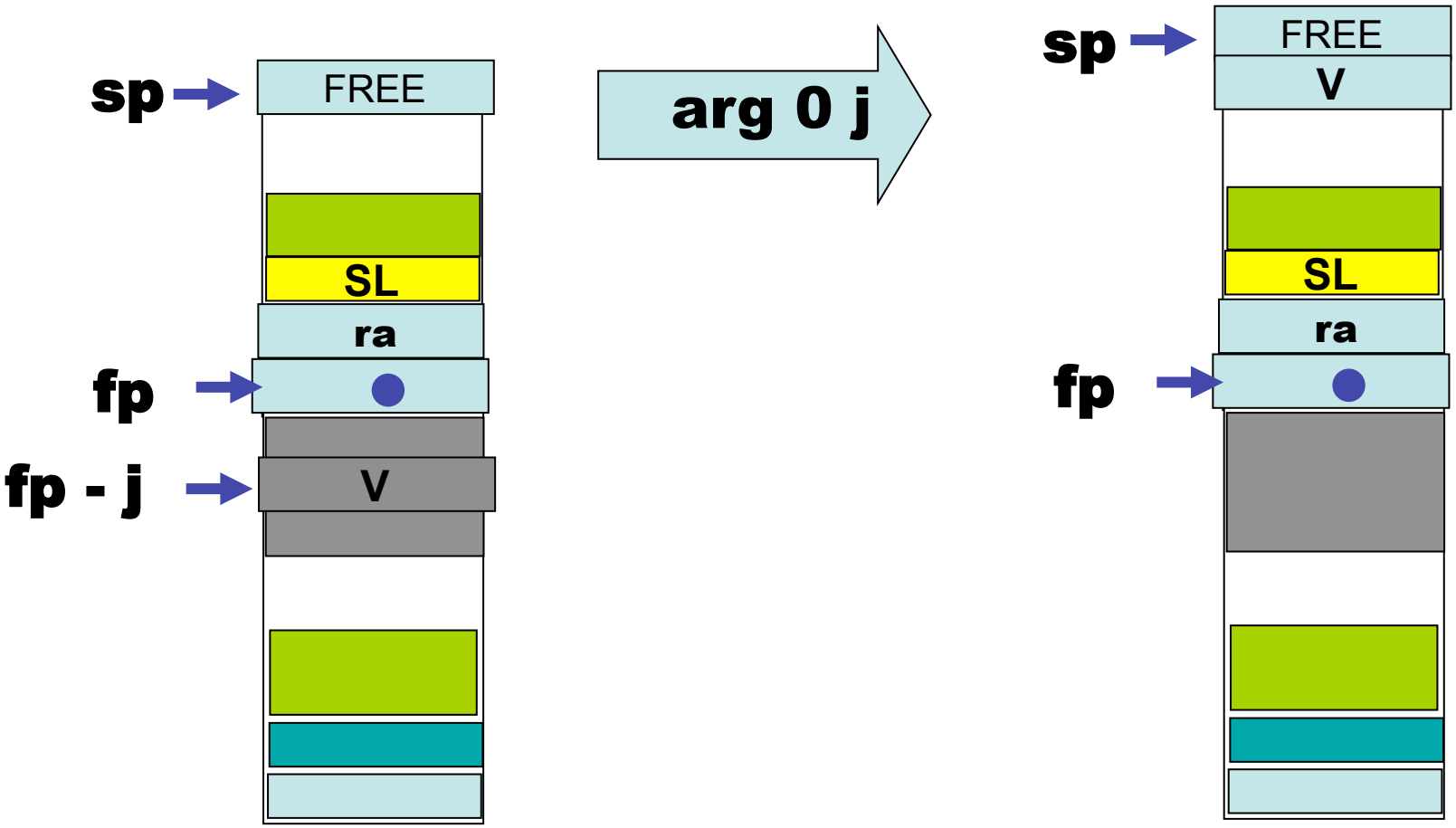
caller at depth k and callee at depth k + 1



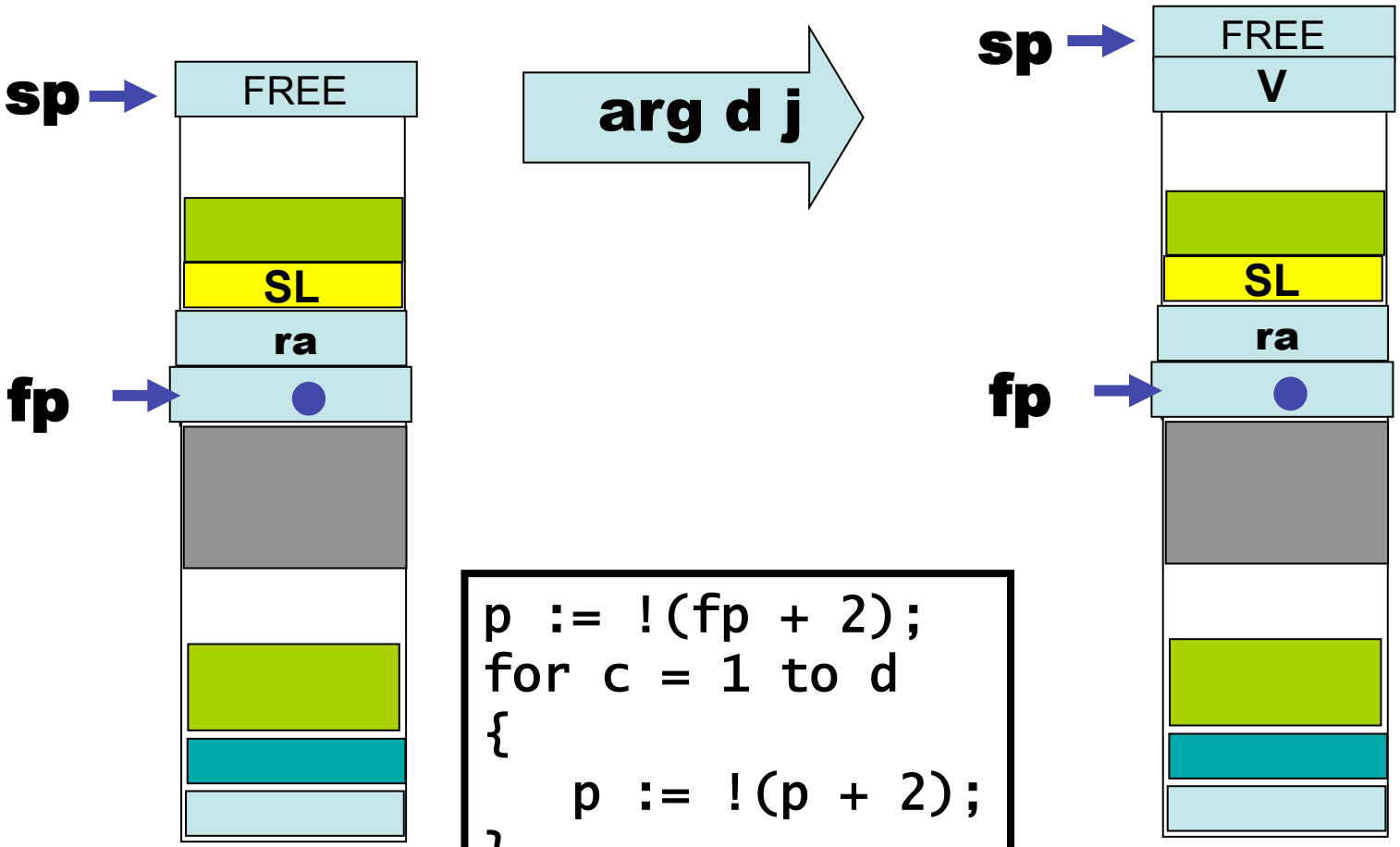
No change to return



Access to argument values at static distance 0



Access to argument values at static distance d, 0 < d




```
p := !(fp + 2);
for c = 1 to d
{
    p := !(p + 2);
}
v := !(p - j);
```

Approach 3 : Closures

Idea : represent the dynamic value of a function/procedure with free variables as a record.

```
let f(y : int) : int =
   let g(x :int) : int = x + y
   in
       g(y * y)
   end
in
    f(17) + f(21)
end
```

Note that the two calls to f are associated with two variants of g --- one with free variable y bound to 17, the other with y bound to 21.

First record : `{ address := g,  y := 17 }`

Second record : `{ address := g,  y := 21 }`

Now pass closure record to the function itself

```
let g(c, x) = x + c.y

let f(y : int) : int =
   let c = { address := g, y := y }
   in
       g(c, y * y)
   end
in
    f(17) + f(21)
end
```

This looks a lot like lambda lifting, but here we package all values for free variables into a single record, together with the function's address.

Why add g's address to the closure record?

This is not really required for this example, but see next slide …

Closures work for functions-as-values!

```
let f(y : int) : int -> int =
  let g(x :int) : int = y + x
  in g end
in
  let add21 : int -> int  = f(21)
  and add17 : int -> int  = f(17)
  in
     add17(3) + add21(-1)
  end
end
```

NOTE: Neither lambda lifting nor static links can implement this example.

WHY?

The values associated with y have to outlive f's activation records!

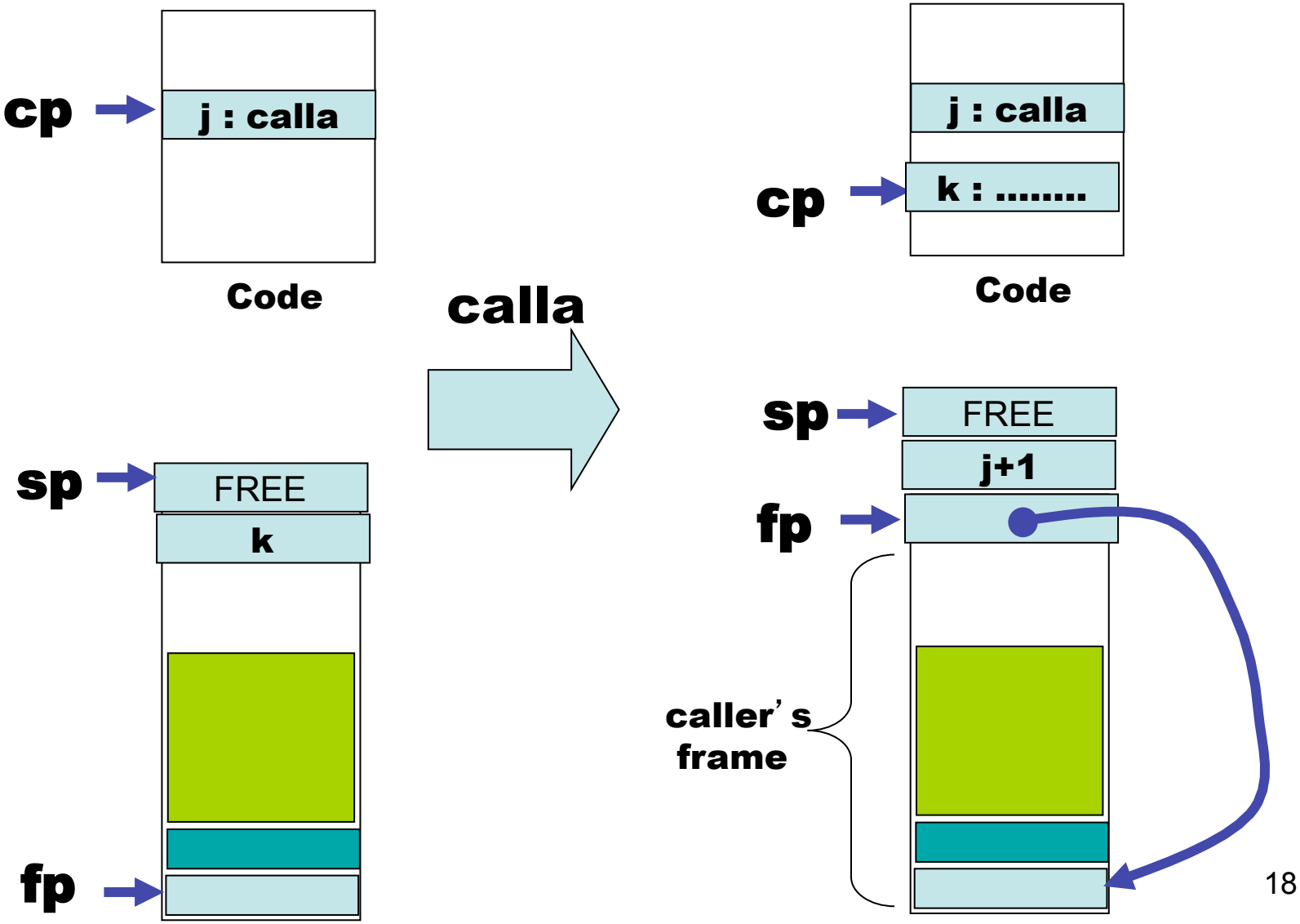
A possible intermediate representation

```
Let g(c, x) = x + c.y

let f(y : int) : int -> int = {address := g, y := y}

let add21 = f(21)

let add17 = f(17)

apply_closure(add17, 3) + apply_closure(add21, -1)
```

Where, in pseudo-code, we have

```
apply_closure(c, v_1, v_2, …, v_k)

        = c.address(c, v_1, v_2, …, v_k)
```

calla : gets address from stack top



Another example

```
let f(y : int) : int -> int =
  let g(x :int) : int = y + x
  and h(x :int) : int = y * x
  in
       if y < 17 then g else h
  end
in
     map f l
end
```

This example may make it clearer why
a closure contains the address of the function.

Here the functions address (either g's or h's) is determined dynamically.

A possible intermediate representation

```
let g(c, x) = c.y + x

let h(c, x) = c.y * x

let f(y : int) : int -> int =
    if y < 17
    then { address := g, y := y }
    else { address := h, y := y }
```

We may want to make a distinction between functions that are called directly

```
f(17)
```

And those called indirectly

```
apply_closure(f(17), 21)
```

Oh, no! What have we done?

We have just implemented a higher level feature (nested functions, first-class functions) using another higher level feature (records).

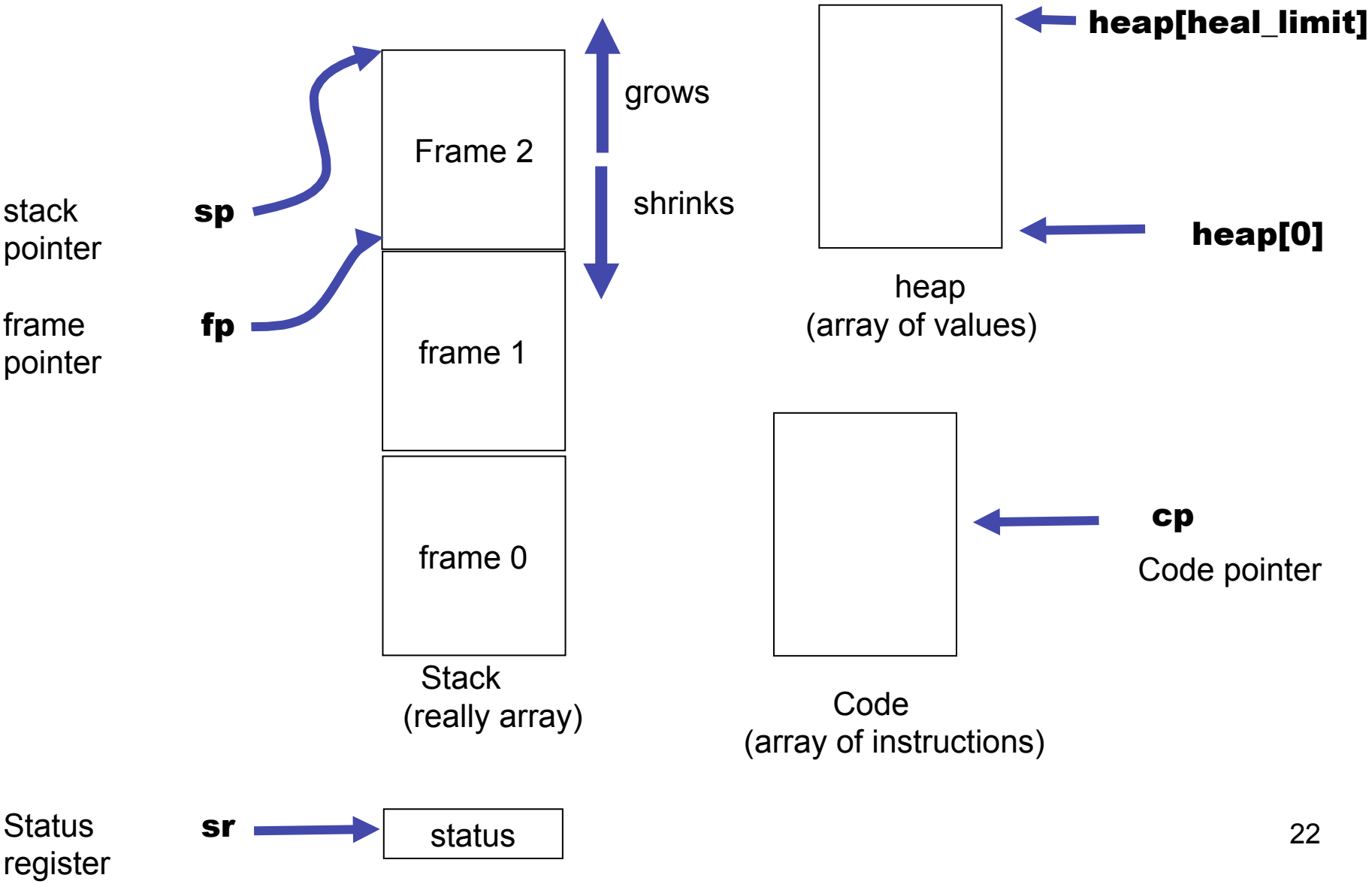
OK, perhaps records are not so high level …

But how do we allocate space for records at run-time?

ANSWER : need a region of storage for “long lived” and “large” data structures (not just closures!)

This is normally called THE HEAP.

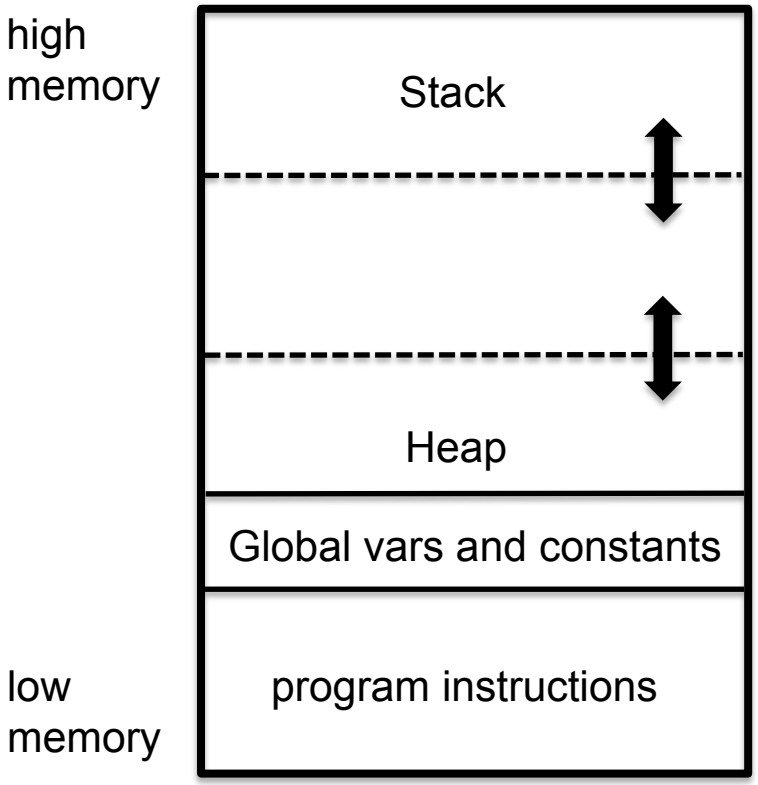
Jargon Virtual Machine (v0.2)



Typical (Low-Level) Memory Layout (UNIX)

Rough schematic of traditional layout in (virtual) memory.

Dealing with Virtual Machines allows us to ignore some of the low-level details….



The heap is used for dynamically allocating memory. Typically either for very large objects or for those objects that are returned by functions/procedures and must outlive the associated activation record.

In languages like Java and ML, the heap must be managed automatically ("garbage collection")

Similar situation with the lifetime of reference cells

```
fun f(a : int) : int ref
{
   let b : int ref := a;
   return b;
}

let z : int ref = f(17);

!z
```

We need some way to store data that outlives the activation record in which it is created.

Solution: The “Heap” ….