PL Summary

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Languages

- Ocaml
- Javascript
- Scala
- GO

Concepts &Techniques

- Syntax
  - Context free grammar
  - Ambiguous grammars
  - Syntax vs. semantics
  - Predictive Parsing
- Static semantics
  - Scope rules
  - Type Rules
- Semantics
  - Small vs. big step
- Runtime management
  - Activation records
  - GC
- Functional programming
  - Lambda calculus
  - Recursion
  - Higher order programming
  - Lazy vs. Eager evaluation
  - Pattern matching
  - Closure
  - Continuation
- Types
  - Type safety
  - Static vs. dynamic
  - Type checking vs. type inference
  - Most general type
  - Polymorphism
  - Type inference algorithm

Type of Context Free Grammars

- Linear Grammars
- *Non-Ambiguous Grammars*
- *LL(1)*
  - *With and without epsilon rules*

Example Languages

- $a^* (a \mid b)^*$
- $a^n b^n$
- $w c w$
- $w c w^r$

Example Grammars

- S → a S b | ε
- S → a S b | ε | ab
- S → a S b | ε | abd

What do I have to know?

- Express a language with a grammar
- Determine if it ambiguous
- Convert into non- ambiguous
- Check if it is LL(1)
- Convert into LL(1)

Static Semantics

Context Analysis

Semantic Analysis

- Properties which are not enforced by the grammar
- Every used identifier is previously defined
- The type of the arguments match the type of the function prototype

Static Scope Rules

- Modern programming languages provide two ways to open new scopes
  - Inline blocks
  - Functions
- C like syntax

  { }
- Ocaml like syntax

  let x = 5 in x + 7

C like

```
void main {
   int x=1;
   int g(z) { return x+z; }
   int f(y) {
      int x = y+1;
      return g(y*x);
  }
  f(3);
  g(4);
```

Javascript

```
var x=1;
function g(z) { return x+z; }
function f(y) {
    var x = y+1;
    return g(y*x);
}
f(3);
g(4);
```

Ocaml

```
let x = 1 in
  let rec g z = x + z
      and
      f y =  let x =  y + 1  in g (y * x)
in
  f 3 , g 4
```

Type Checking and Type Inference

- Statically typed languages permit effective compile time checking of types
  - Proves type-safety
  - Identify subtle interface mismatch
- Type inference
  - Automatically infer the most general type for a given expression

Most General Type Examples

```
fun f x =
   let
     val a = x * 2
     and
     val b = x * 3
 in
[0, x, a, b, x * 4]
```

```
rec fun f x =
   match x with
     [] → 0
     |
     h :: t → 1  + f t
```

```
rec fun f x =
   match x with
     [] → 0
     |
     h :: t → 1
```

```
rec fun f x =
   match x with
     [] → [0]
     |
     h :: t → 1
```

Type Inference Algorithm

- Parse program to build parse tree
- Assign type variables to nodes in tree
- Generate constraints:
  - From environment: literals (2), built-in operators (+), known functions (tail)
  - From form of parse tree: e.g., application and abstraction nodes
- Solve constraints using *unification*
- Determine types of top-level declarations

Example

```
fun f x =
    let
      val a = x
      and
      val b = x
  in
(a, [b])
```

Alternative Formal Semantics

- Operational Semantics
  - The meaning of the program is described "operationally"
  - Natural Operational Semantics
  - Structural Operational Semantics
- Denotational Semantics
  - The meaning of the program is an input/output relation
  - Mathematically challenging but complicated
- Axiomatic Semantics
  - The meaning of the program are observed properties

Natural Semantics for While

axioms

$[ass_{ns}] \langle x := a, s\rangle \rightarrow s[x \mapsto \mathbf{A}[\![a]\!]s]$

$[skip_{ns}] \langle \mathbf{skip}, s\rangle \rightarrow s$

rules

$$[comp_{ns}] \frac{\langle S_1, s\rangle \rightarrow s', \langle S_2, s'\rangle \rightarrow s''}{\langle S_1; S_2, s\rangle \rightarrow s''}$$

$$[if^{tt}_{ns}] \frac{\langle S_1, s\rangle \rightarrow s'}{\langle \text{if } b \text{ then } S_1 \text{ else } S_2, s\rangle \rightarrow s'} \quad \text{if } \mathbf{B}[\![b]\!]s = tt$$

$$[if^{ff}_{ns}] \frac{\langle S_2, s\rangle \rightarrow s'}{\langle \text{if } b \text{ then } S_1 \text{ else } S_2, s\rangle \rightarrow s'} \quad \text{if } \mathbf{B}[\![b]\!]s = ff$$

Natural Semantics for While (More rules)

$[\text{while}^{ff}_{ns}]$

$$\frac{}{\langle \text{while } b \text{ do } S, s\rangle \rightarrow s} \quad \text{if } \mathbf{B}[\![b]\!]s = ff$$

$[\text{while}^{tt}_{ns}]$

$$\frac{\langle S, s\rangle \rightarrow s', \langle \text{while } b \text{ do } S, s'\rangle \rightarrow s''}{\langle \text{while } b \text{ do } S, s\rangle \rightarrow s''} \quad \text{if } \mathbf{B}[\![b]\!]s = tt$$

Structural Semantics for While

axioms

$[ass_{sos}] \langle x := a, s\rangle \Rightarrow s[x \mapsto \mathbf{A}[\![a]\!]s]$

$[skip_{sos}] \langle \mathbf{skip}, s\rangle \Rightarrow s$

rules

$$[comp^1_{sos}] \frac{\langle S_1, s\rangle \Rightarrow \langle S'_1, s'\rangle}{\langle S_1; S_2, s\rangle \Rightarrow \langle S'_1; S_2, s'\rangle}$$

$$[comp^2_{sos}] \frac{\langle S_1, s\rangle \Rightarrow s'}{\langle S_1; S_2, s\rangle \Rightarrow \langle S_2, s'\rangle}$$

Structural Semantics for While if construct

$[if^{tt}_{sos}]$ $\langle$if b then S_1 else S_2, s$\rangle \Rightarrow \langle S_1, s\rangle$ if $\mathbf{B}[\![b]\!]s=tt$

$[if^{ff}_{os}]$ $\langle$if b then S_1 else S_2, s$\rangle \Rightarrow \langle S_2, s\rangle$ if $\mathbf{B}[\![b]\!]s=ff$

Structural Semantics for While while construct

$[\text{while}_{sos}]$ $\langle \text{while b do S}, s \rangle \Rightarrow$
$\langle \text{if b then (S; while b do S) else skip}, s \rangle$

Usages of semantics

- Prove properties of programs
  - Type safety = No undefined behavior
  - Equivalence
  - …
- Define new constructs
- Generic interpreters

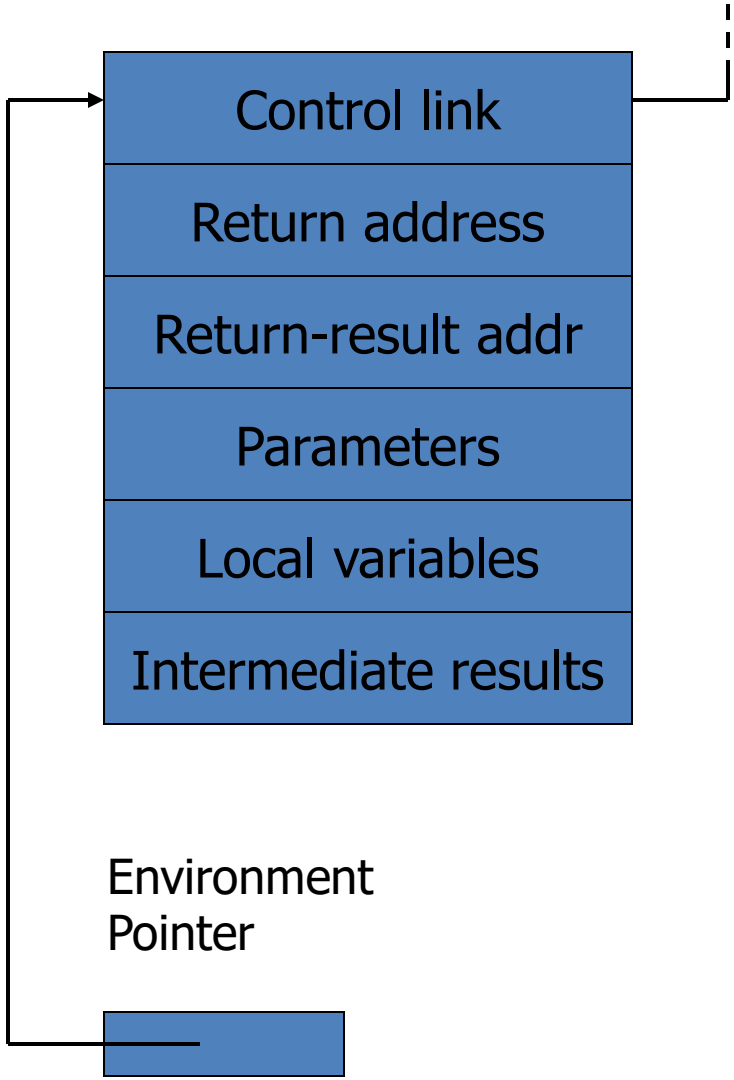
Examples

- If $\langle S_1, s\rangle \Rightarrow^k s'$ then $\langle S_1;S_2, s\rangle \Rightarrow^k \langle S_2, s'\rangle$

Runtime Memory Management

Activation Records and Garbage Collection

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

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

Pass function as argument

OCaml

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

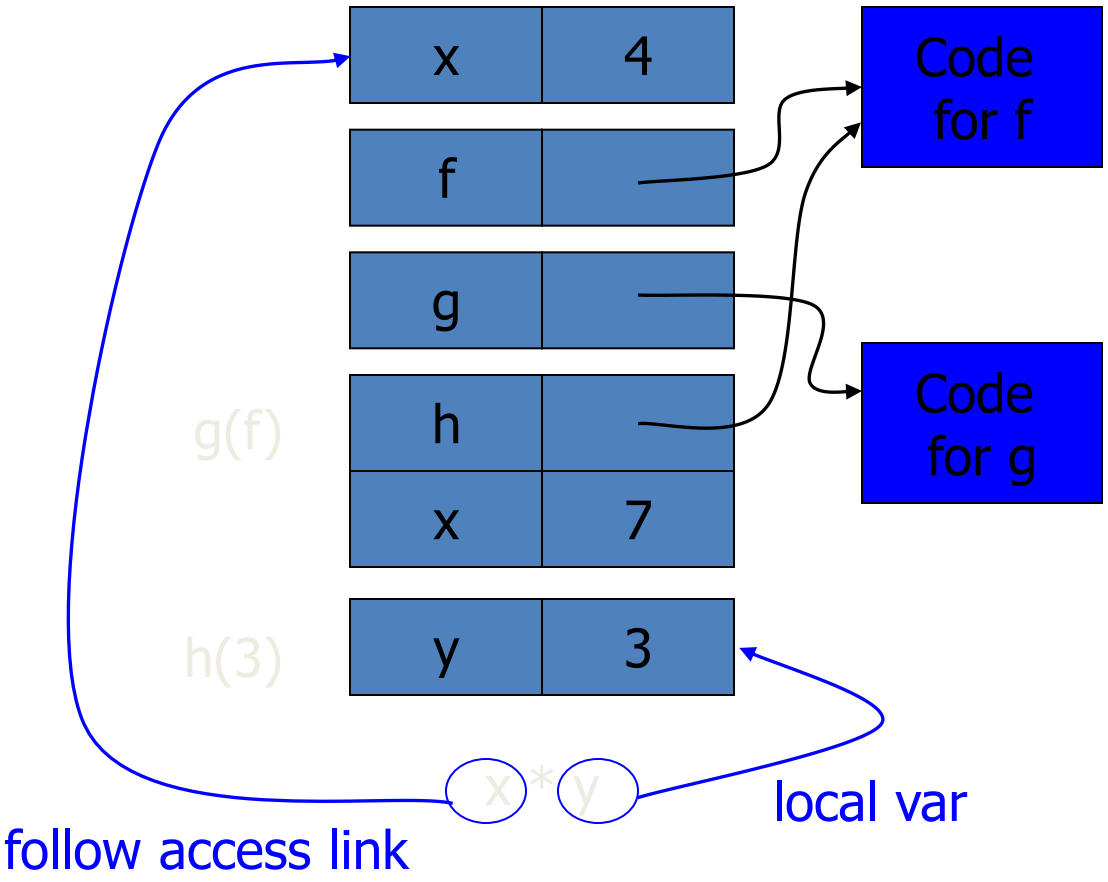
Pseudo-JavaScript

```
{ 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

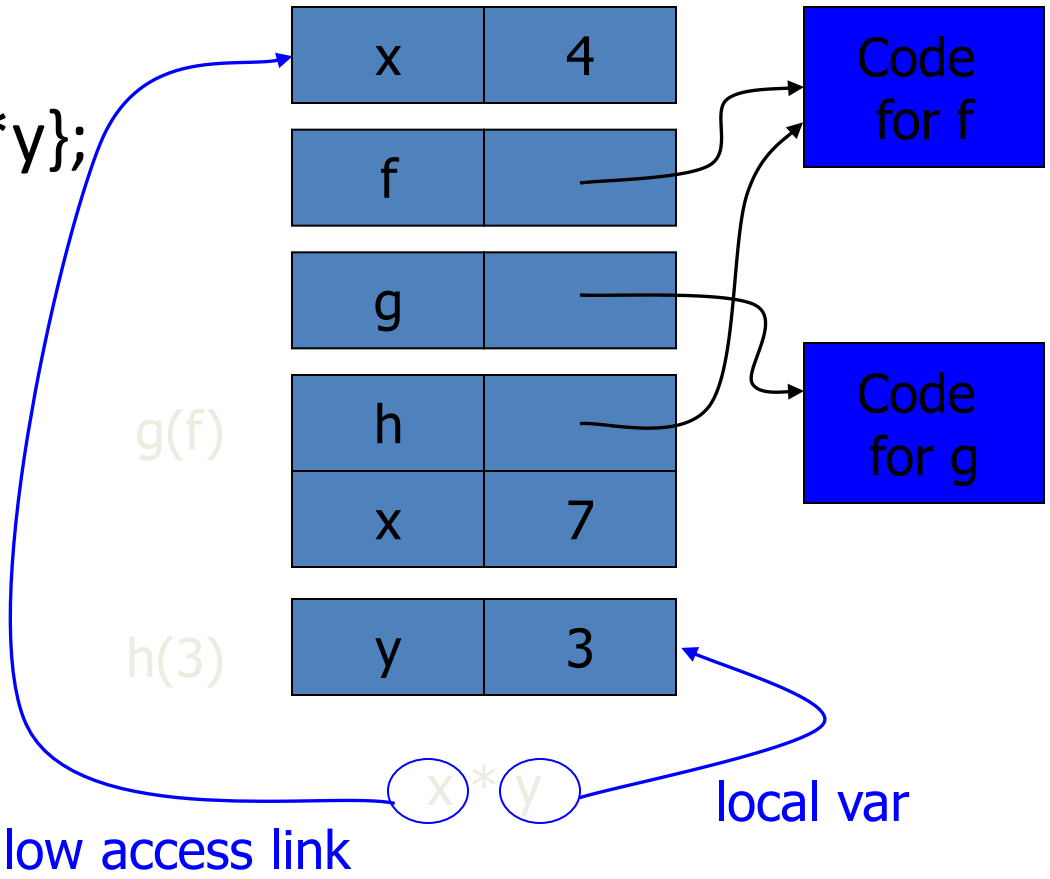
```
let x = 4 in
  let f = fun -> x*y in
    let g = fun h ->
      let
        int x=7
      in
        h(3) + x
     in
    g(f)
```



How is access link for h(3) set?

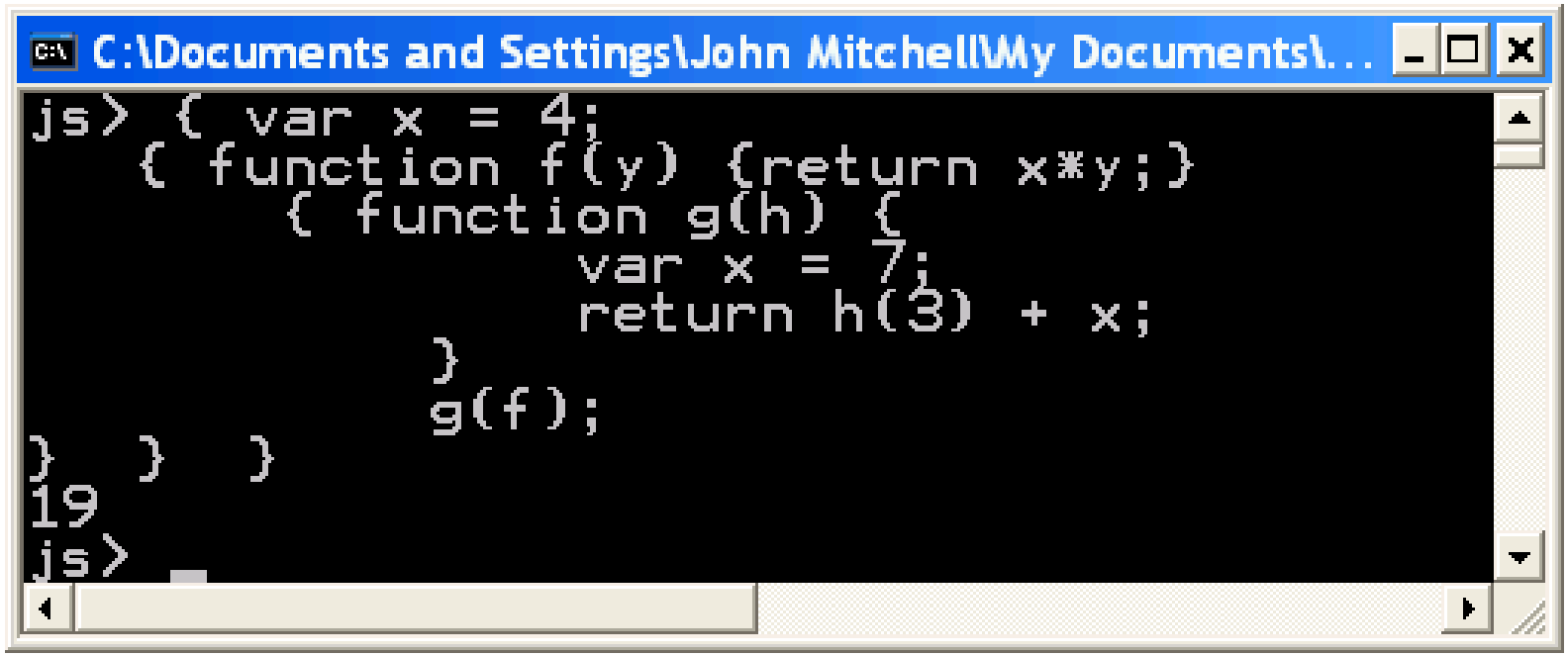
Static Scope for Function Argument

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



How is access link for h(3) set?

Result of function call

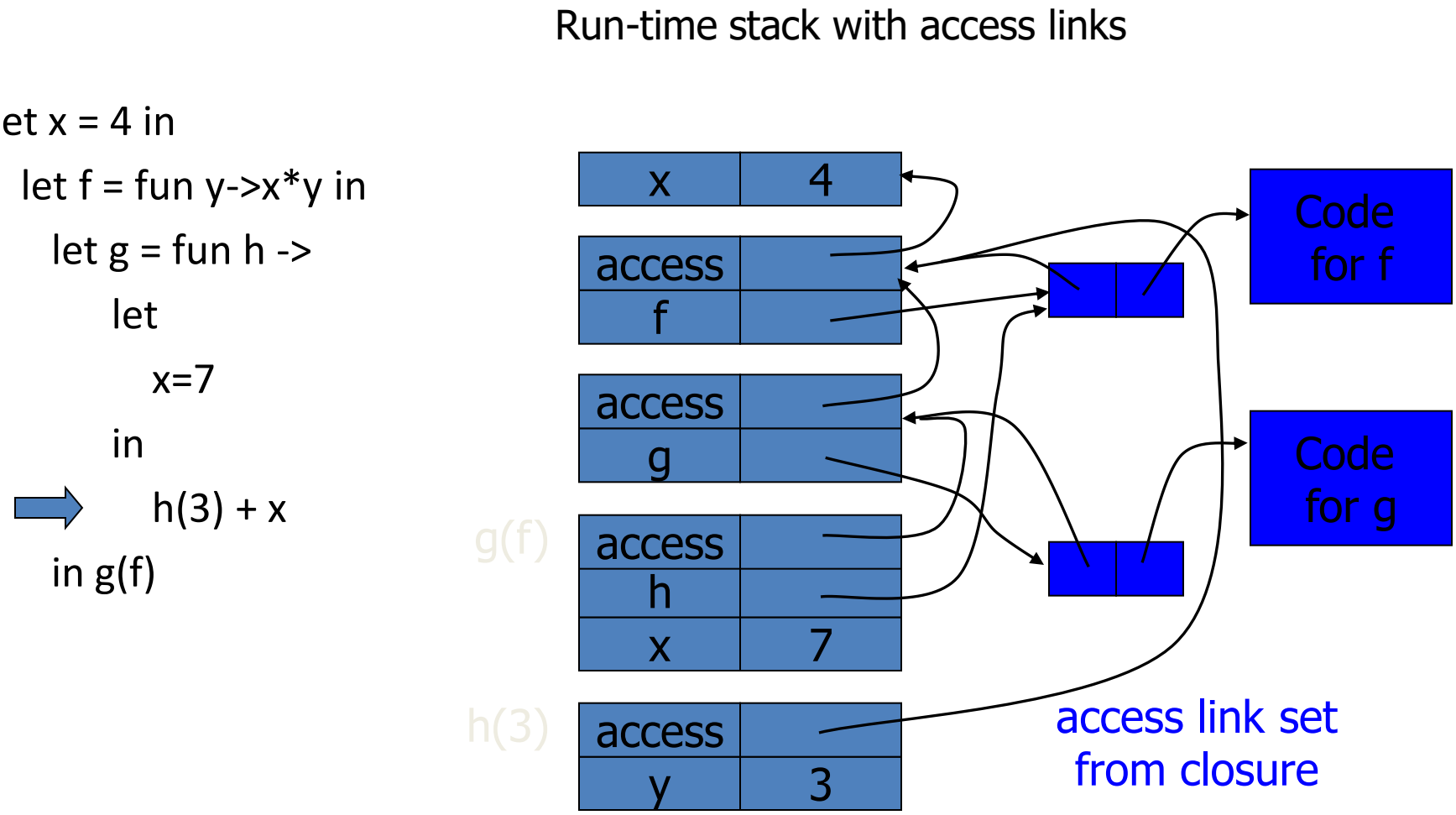


Closures

- 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

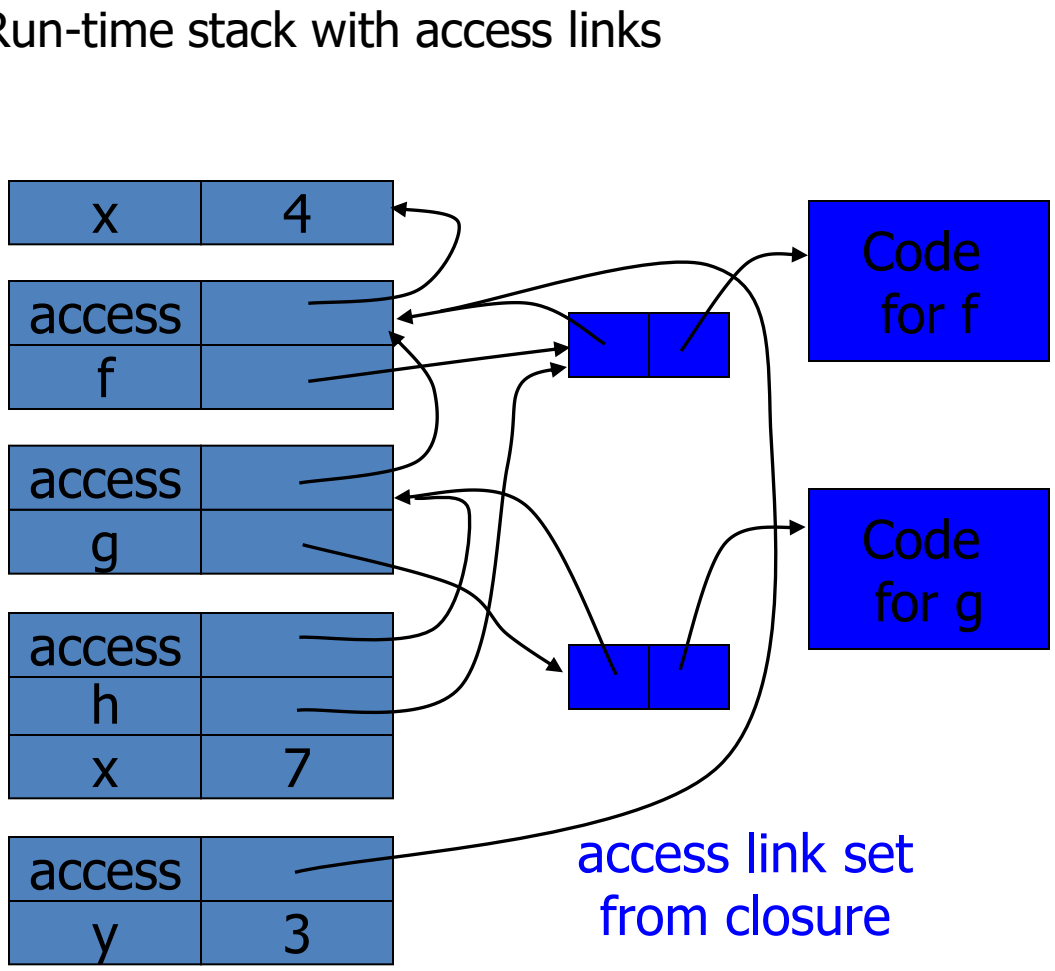
Function Argument and Closures

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



Function Argument and Closures

```
{ var x = 4;
  { function f(y){return x*y};
    { function g(h) {
        int x=7;
        return 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 activ records to find global vars
  - Still deallocate activ records using stack (lifo) order

Return Function as Result

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

```
function compose(f,g)
        {return  function(x) { return g(f (x)) }};
```

- Function “created” dynamically
  - expression with free variables
    values are determined at run time
  - function value is closure = ⟨env, code⟩
  - code *not* compiled dynamically (in most languages)

Example: Return fctn with private state

OCaml

```
let mk_counter = fun init  ->
    let count = ref init in
     let counter = fun inc ->
            (count := !count + inc; !count)
      in
        counter
in
  let c = mk_counter 1
    in
  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

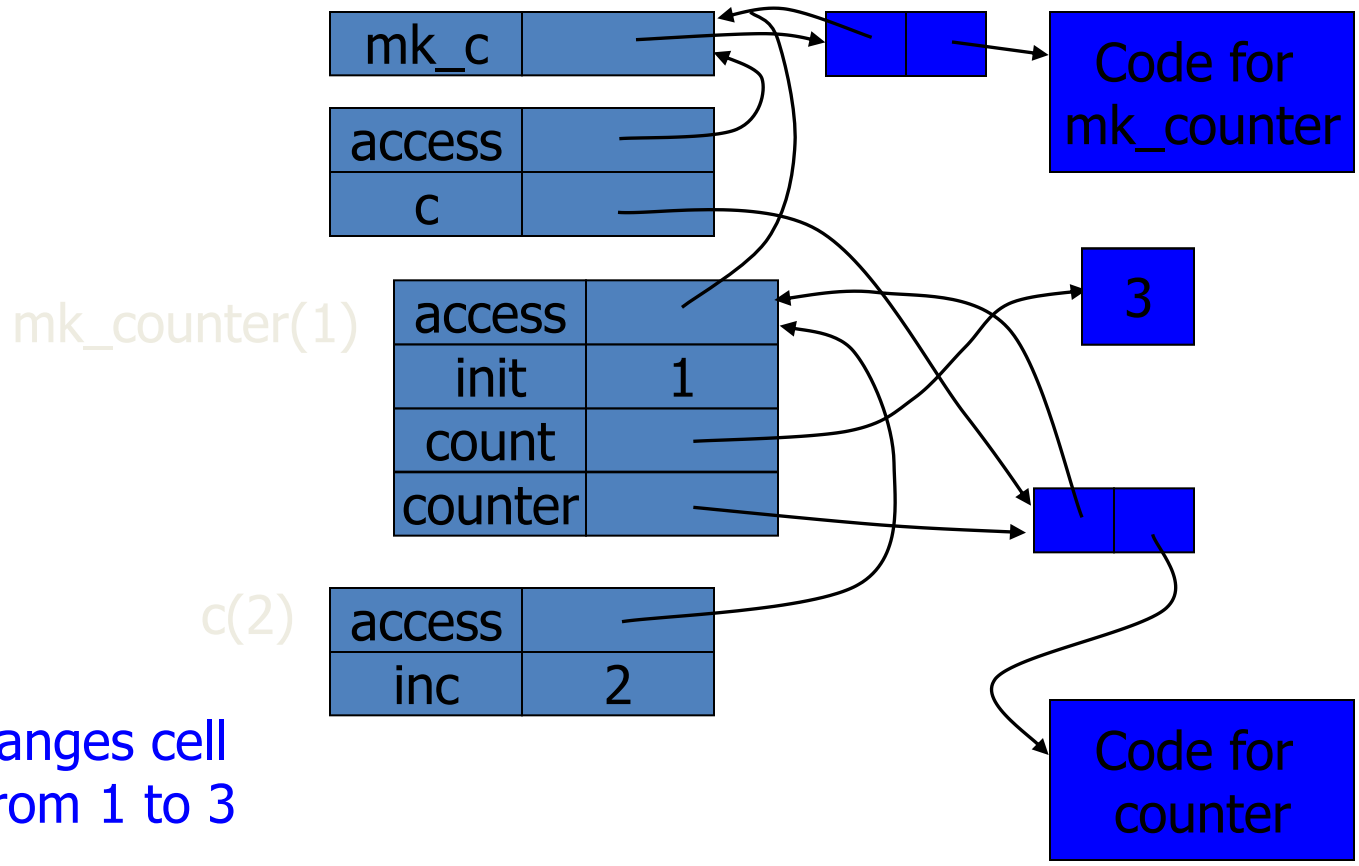
```
function mk_counter (init) {
    var count = init;
    function counter(inc) {count=count+inc; return count};
    return counter};
var c  = mk_counter(1);
c(2) + c(2);
```

Function to “make counter” returns a closure

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

Function Results and Closures

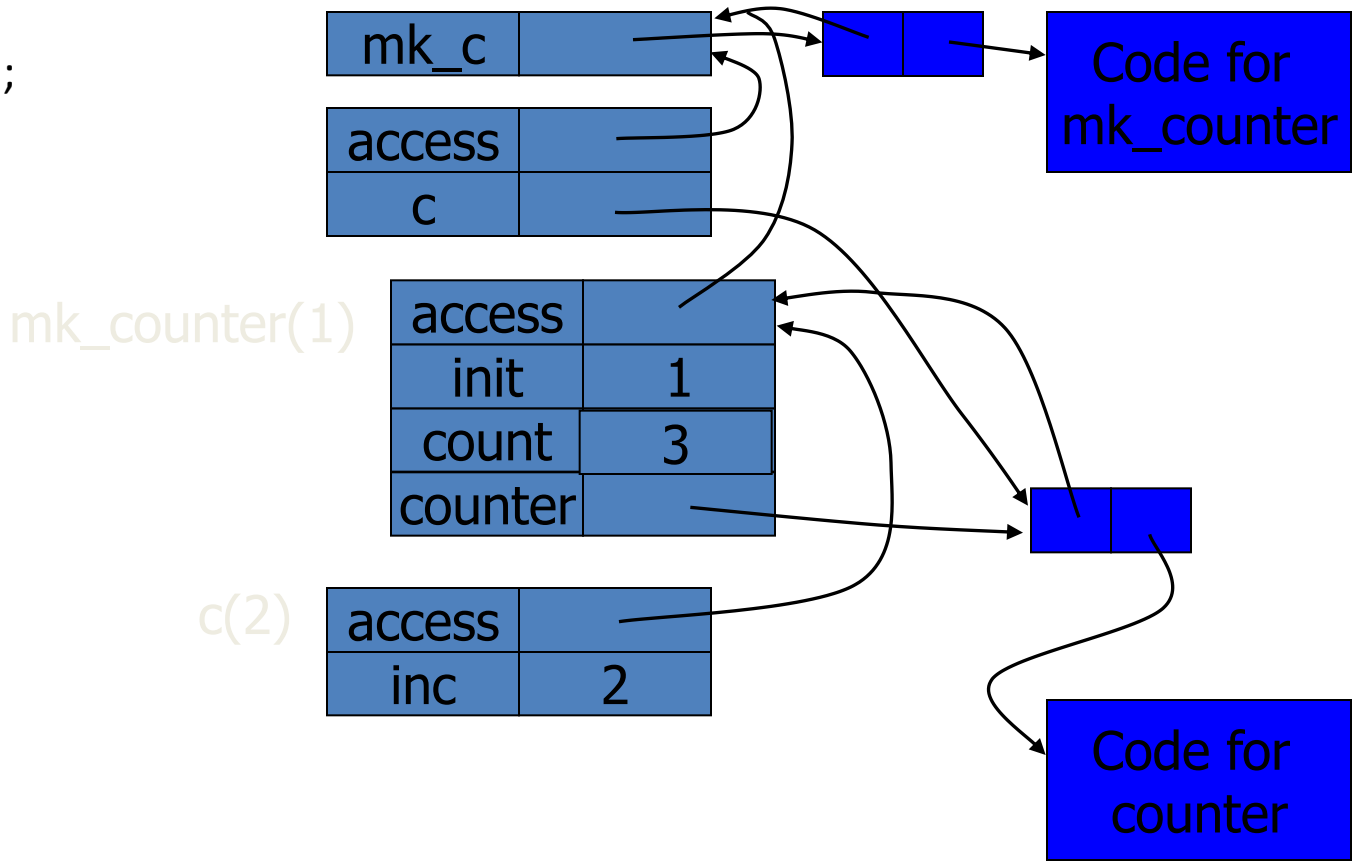
```
let mk_counter =fun init ->
  let count = ref init  in
        let counter = fun inc -> (count := !count + inc; !count)
        in counter
in
let c = mk_counter(1) in
c(2) + c(2)
```



Call changes cell value from 1 to 3

Function Results and Closures

```
function mk_counter (init) {
    var count = init;
    function counter(inc) {count=count+inc; return count};
    return counter};
var c  = mk_counter(1);
c(2) + c(2);
```



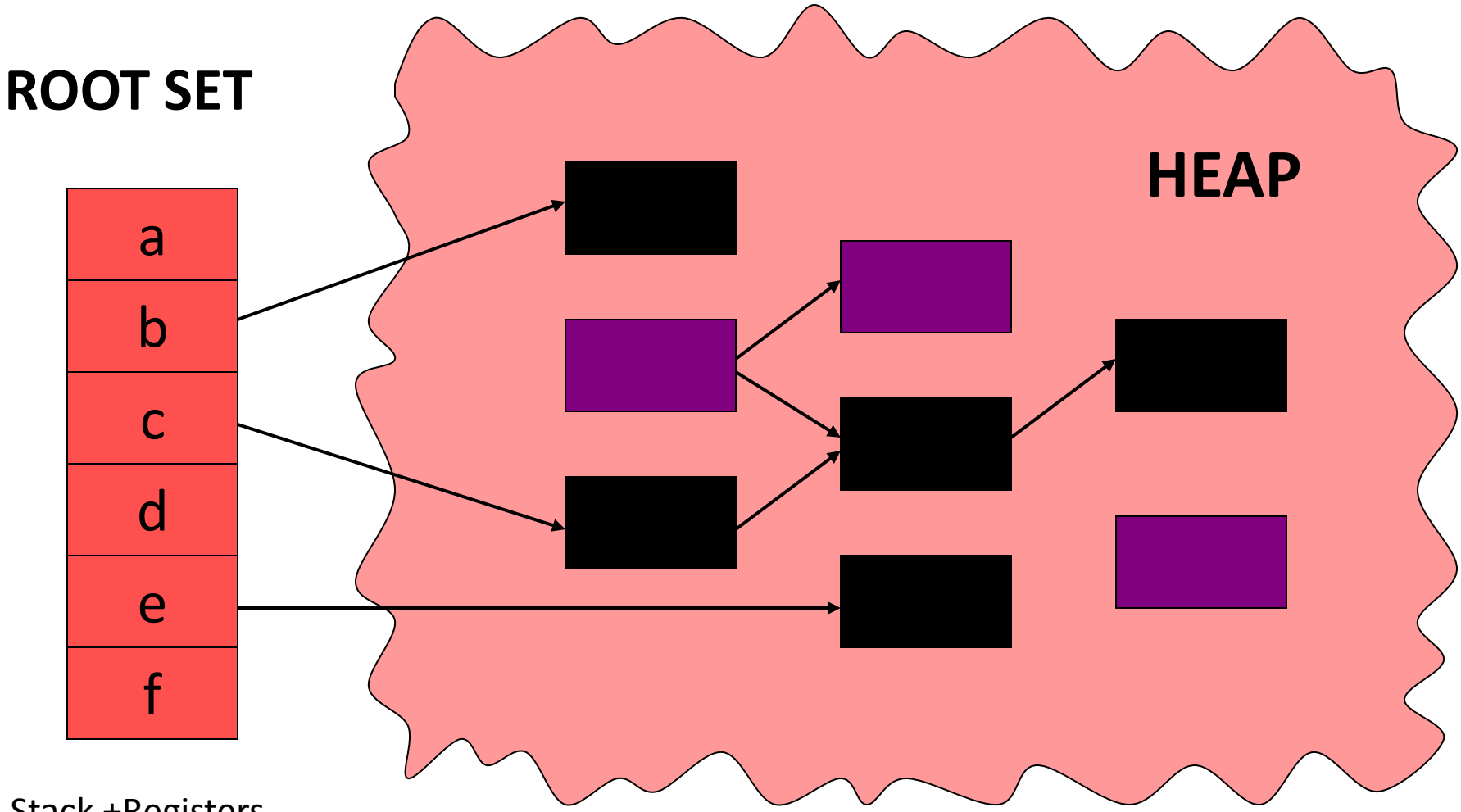
Simple C Program

```
foo (int y) {
  int x = y ;
  if  (x > 8) {
    int x = y + 1 ;
    x = x  + 1 ;
    }
```

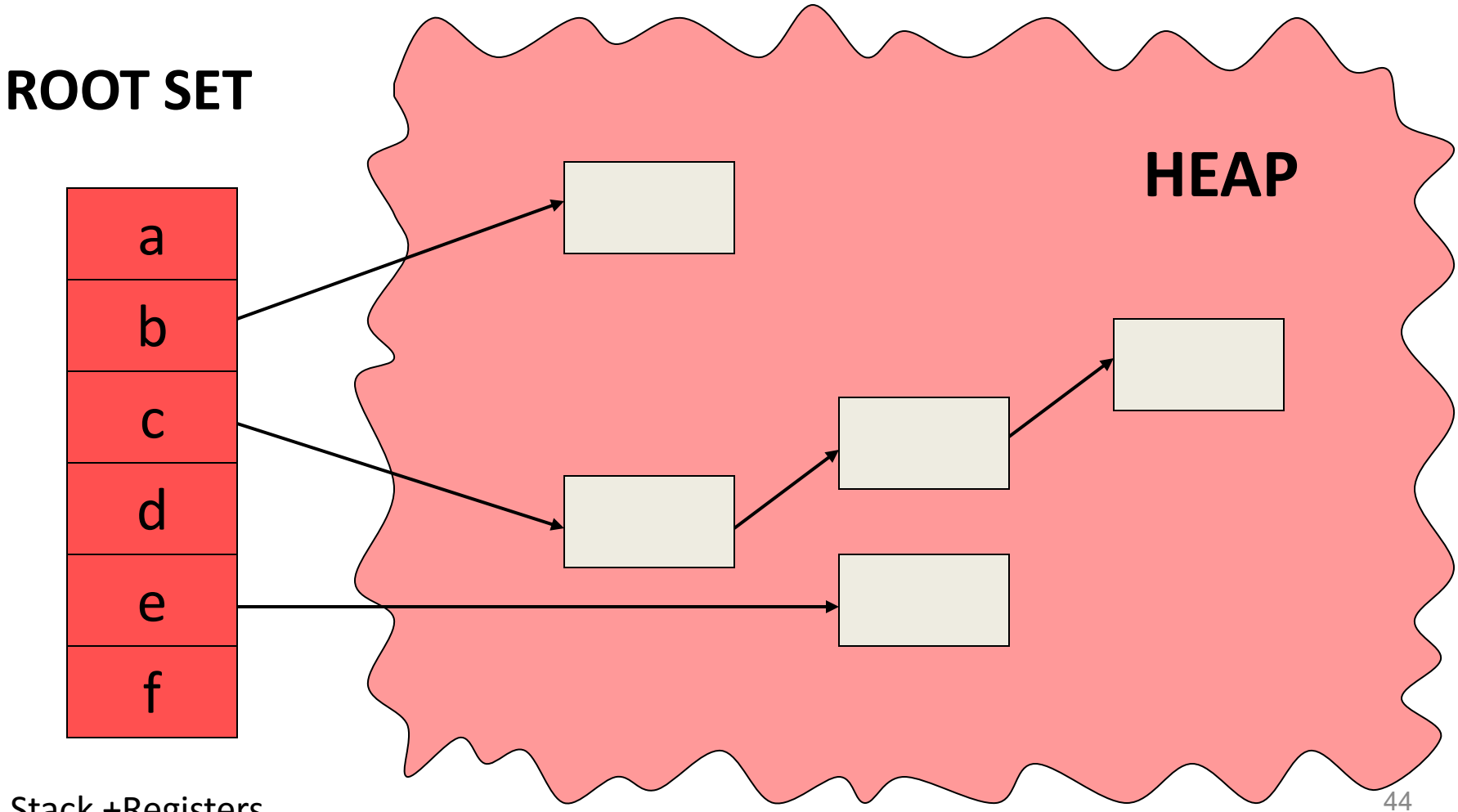
foo(9)

control	
return val	
x	8
y	8
x	9

Garbage Collection



Garbage Collection



Stack +Registers

What is garbage collection

- The runtime environment reuse chunks that were allocated but are not subsequently used garbage chunks
  - not live
- It is undecidable to find the garbage chunks:
  - Decidability of liveness
  - Decidability of type information
- conservative collection
  - every live chunk is identified
  - some garbage runtime chunk are not identified
- Find the reachable chunks via pointer chains
- Often done in the allocation function

Garbage Collection Techniques

- Tracing
  - Scan the reachable heaps from the root
  - Release unreachable elements
  - Cost proportional to reachable heap
- Reference Counting
  - Maintain a counter of references to each chunk of memory
  - The compiler generates the update code for references when pointers are manipulated
  - Release objects with zero reference counter
  - Constant cost

Recommendation

- Read material from recitations and lectures
- Solve last year’s exam both Moed A and B
- Come to reception hours