Administrivia

Project 1 is due **tonight** by 11:59PM.

Project 2 is out and is due Monday 4/22 by 11:59PM.

Discussion sections are office hours (except A6, A4 is in CDS 907)

The final exam for this course is Wednesday 5/08 3–5PM in STO B50 (this room).

If you need accommodations for the exam, please send me an email ASAP.

Subroutines III: Activation Records and Closures

Principles of Programming Languages
Lecture 22

CAS CS 320

Objectives

Understand the relationship between **subroutines** and **lexically scoped** variable bindings.

Discuss the **call stack** as a construct for managing the execution of subroutines.

Look at how subroutines can **capture variables** in a language with higher-order functions and nested definitions.

Discuss **closures** as a construct for managing captured variables.

Keywords

formal parameters vs. actual parameters

local vs. global variables

nested vs. enclosing subroutines

scope

environment

activation records

call stack

Practice Problem

```
let f x y =
  let y = x + x in
  let x = x + y in
  x

let g () =
  let _ = print_endline "calling g..." in
  0

let _ = f (g ()) (g ())
```

What does this program print under call-by-value evaluation?
What does it print under call-by-name evaluation?

Answer

Call-by-value:

```
calling g...
calling g...
```

Call-by-name:

```
calling g...
calling g...
calling g...
```

```
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Recap/Review

Recall: Dynamic Scoping

```
f() { x=0; g; }
g() { y=$x; }
x=1; f; echo $y;
```

(Bash)

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This is a temporal view, i.e., was there a computation done beforehand which affected the value of a variable?

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This is a temporal view, i.e., was there a computation done beforehand which affected the value of a variable?

(It is uncommon in modern programming languages, but easier to implement)

Recall: Lexical Scoping

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x = 0
def f():
    x = 1
    return(x)
assert(f() == 1)
assert(x == 0)
```

(Python)

```ocaml
let x = 0
let y = let x = 1 in x

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(This is far more common in modern programming languages)

Recall: Restricting Scope

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  (e.g. let-bindings, Project 3)

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» The binding defines its own scope
  (e.g. let-bindings, Project 3)

» A subroutine or code block defines the scope of the bindings appearing in it
  (e.g. python function, Project 2)

Anatomy of a Function

```
...

func f(x) {
    print(x + 5)
}

func subroutine(x, y) {
    print(n)
    m = x + y
    f(m)
    ...
}
...

n = 0
subroutine(n, n + 1)

...
```

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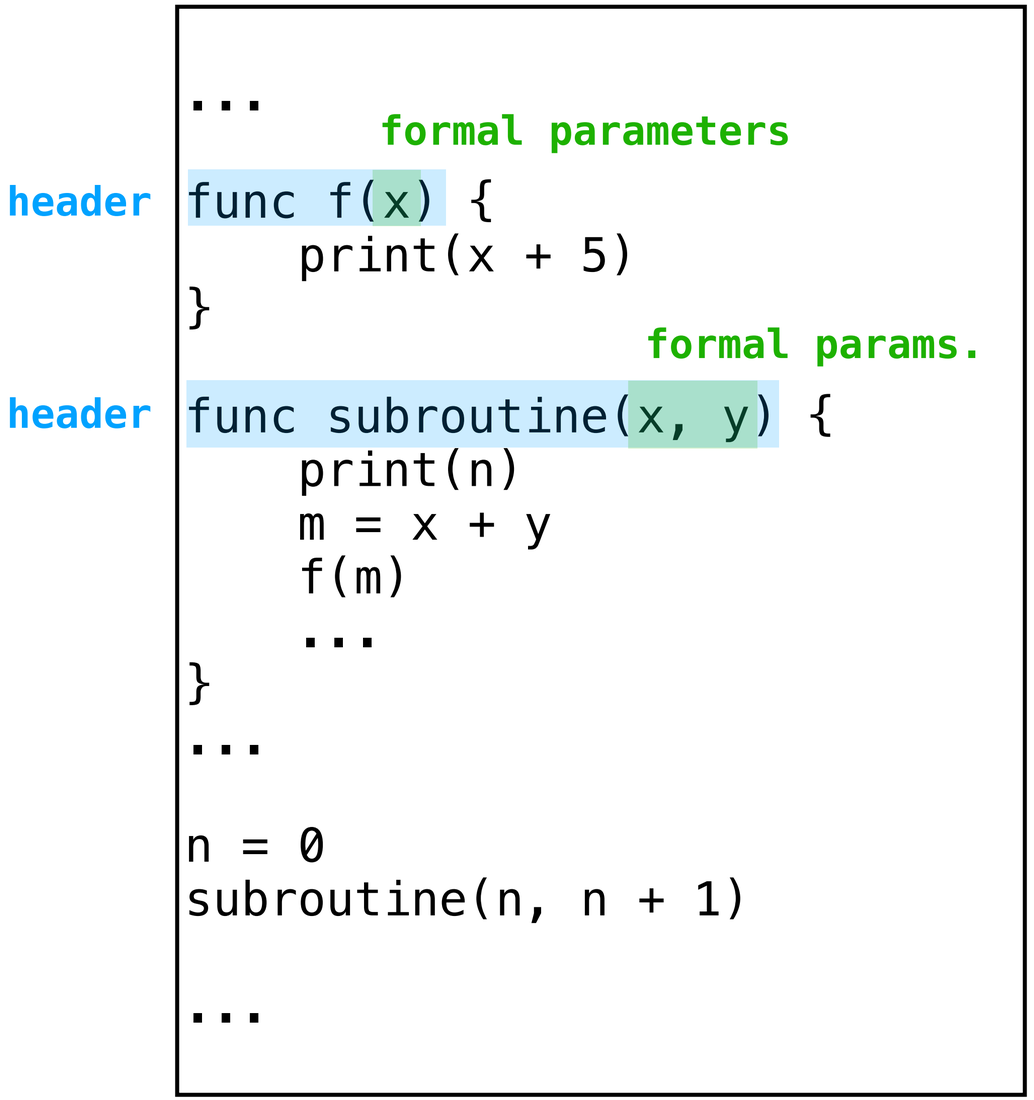

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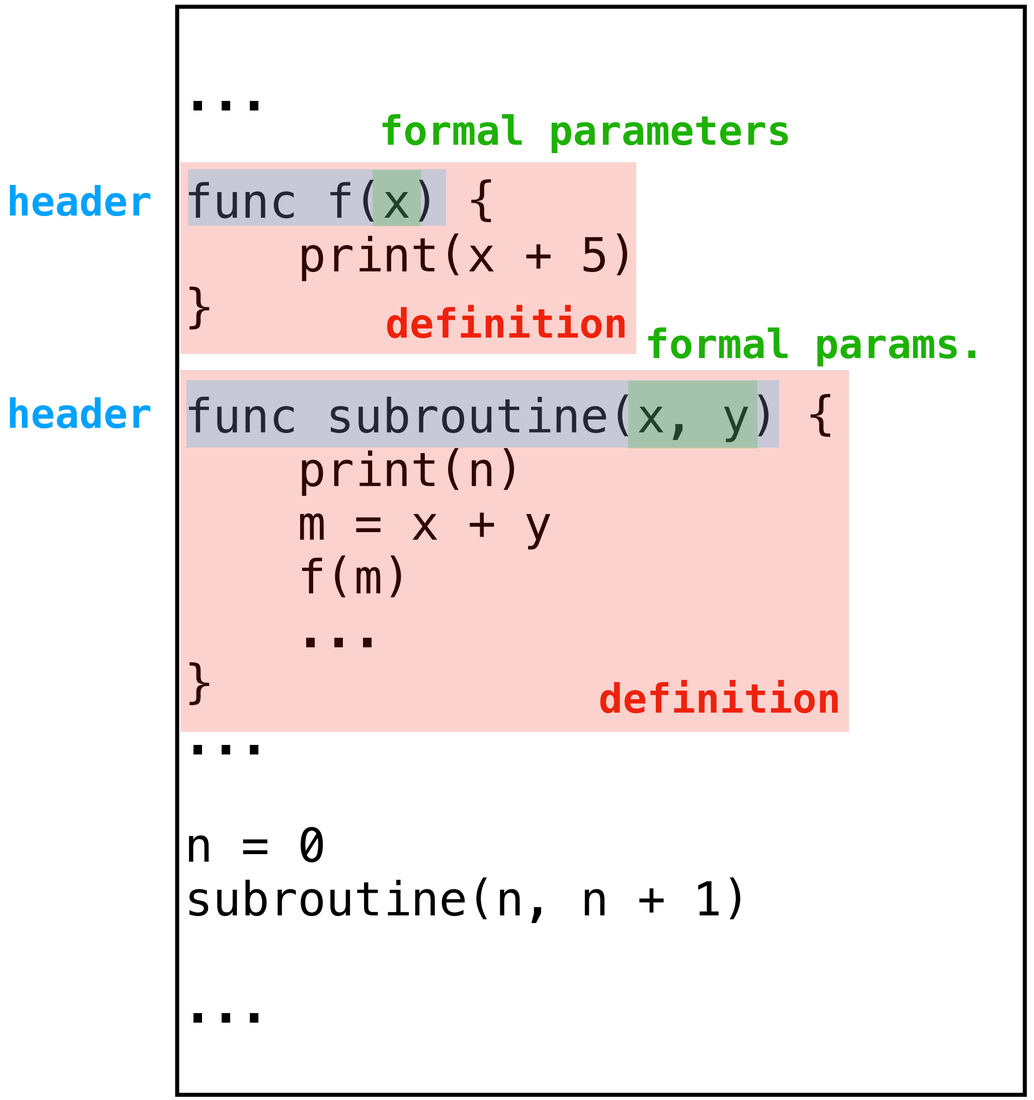

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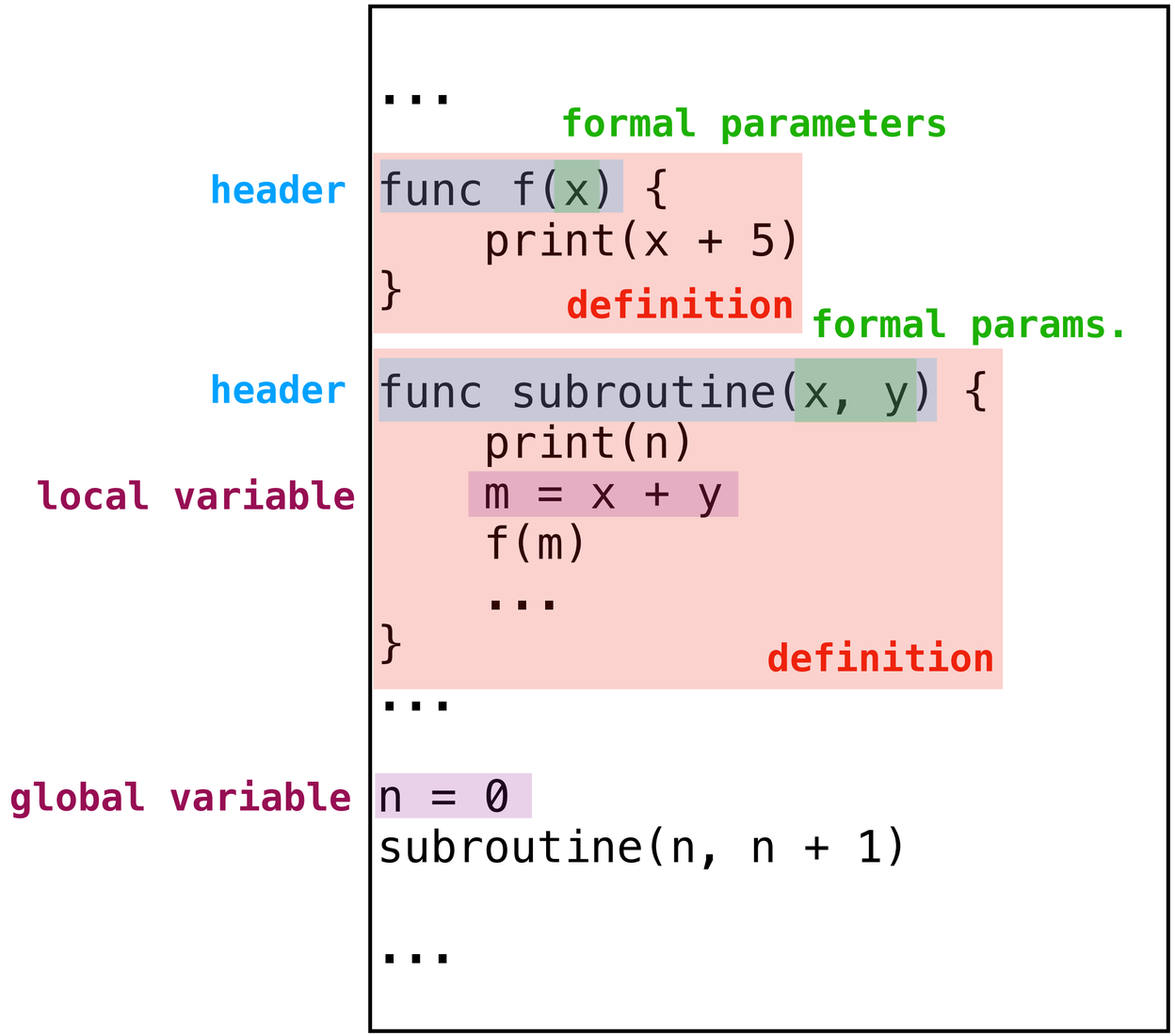

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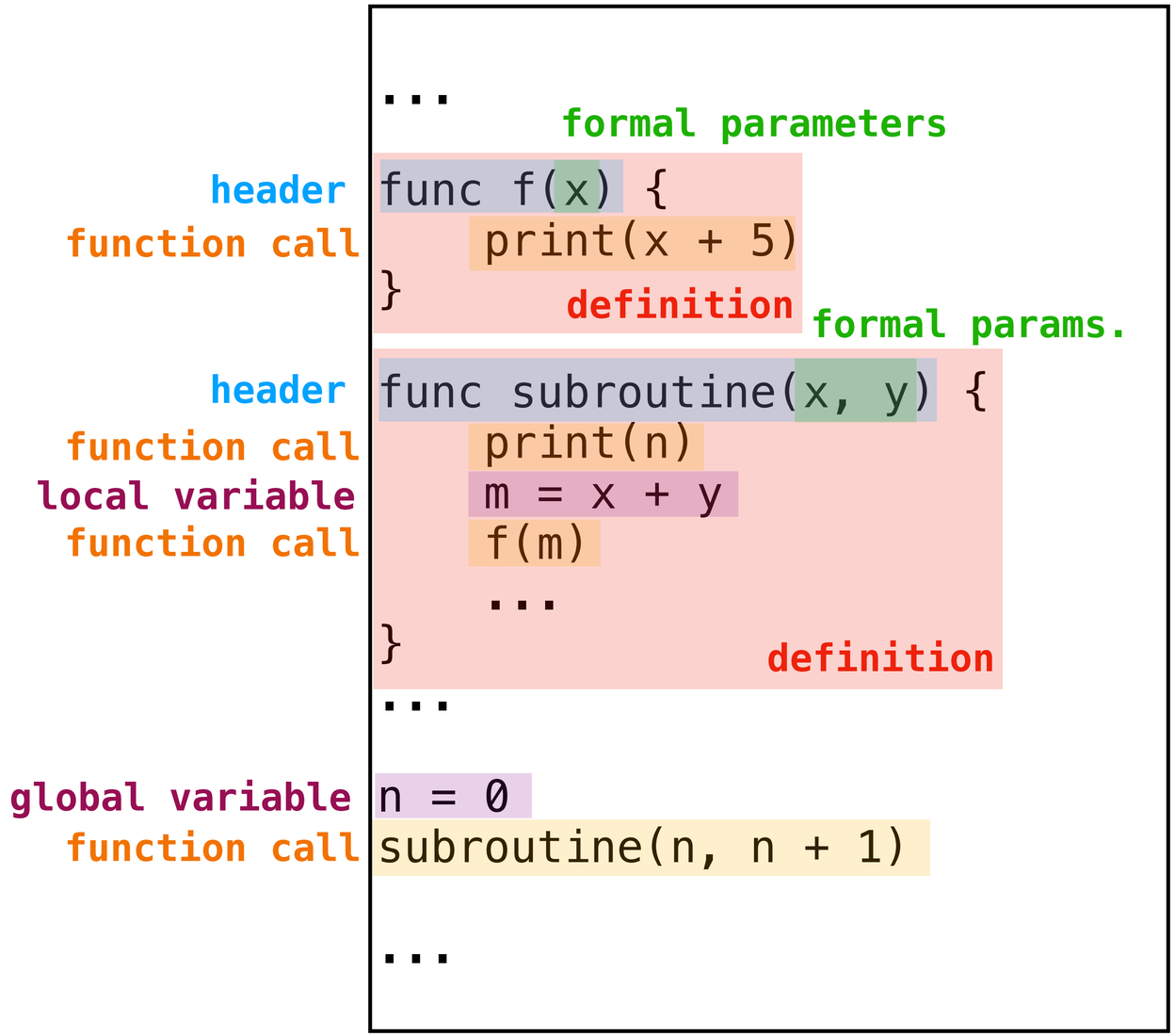

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func subroutine(x, y) {
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    m = x + y
    f(m) actual parameter
    ...
}
...

n = 0
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```

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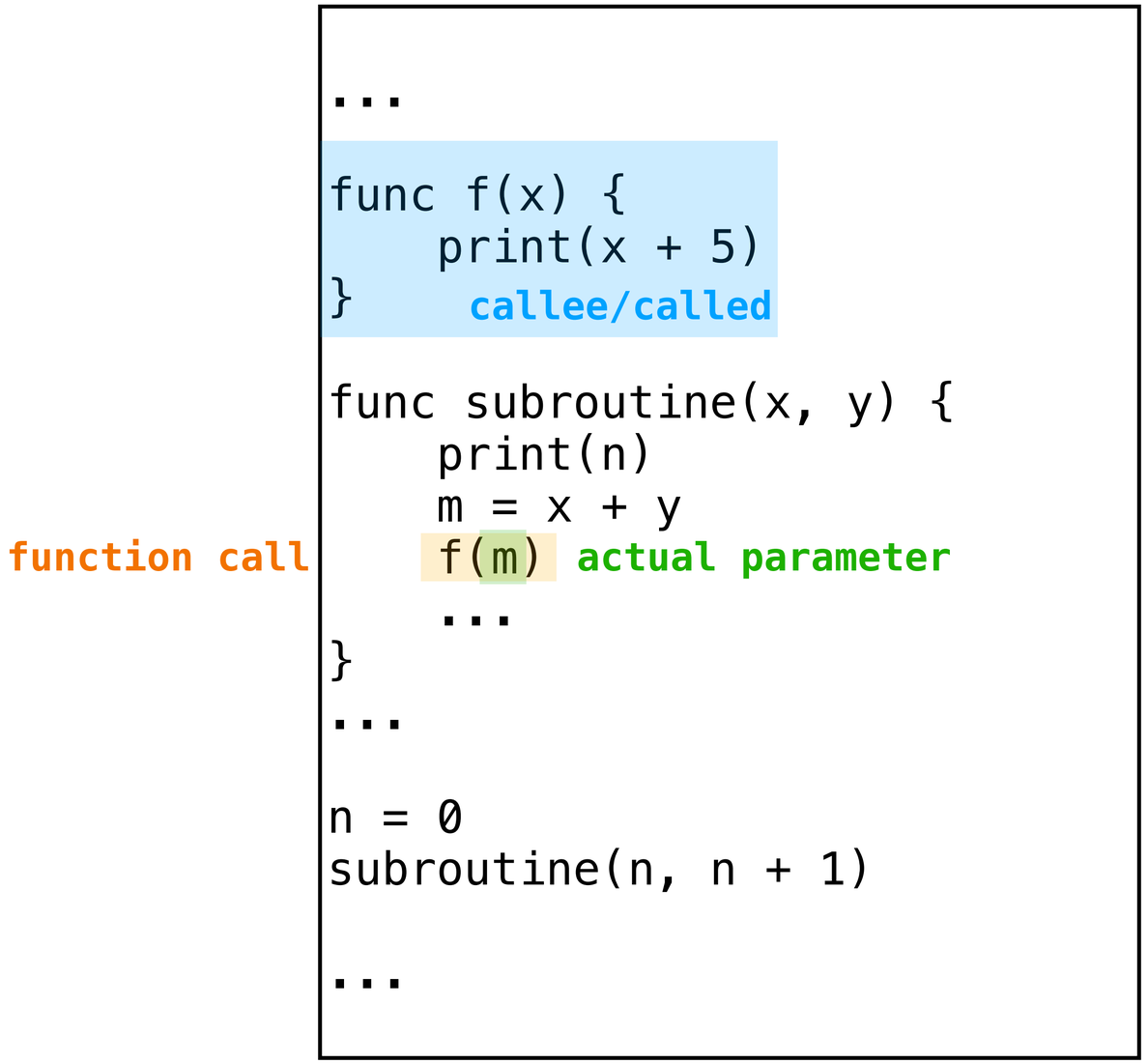

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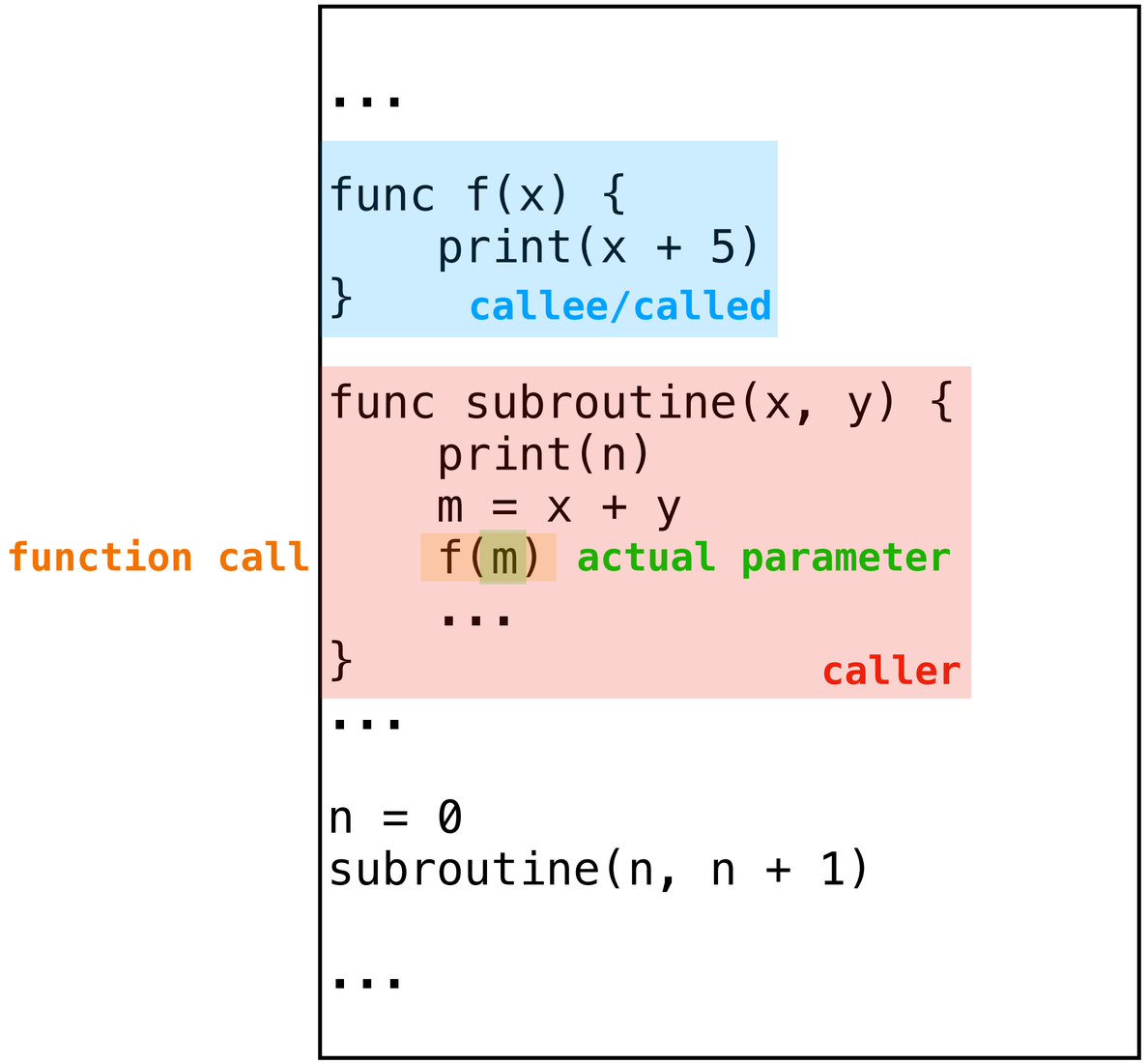

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function call

actual parameters

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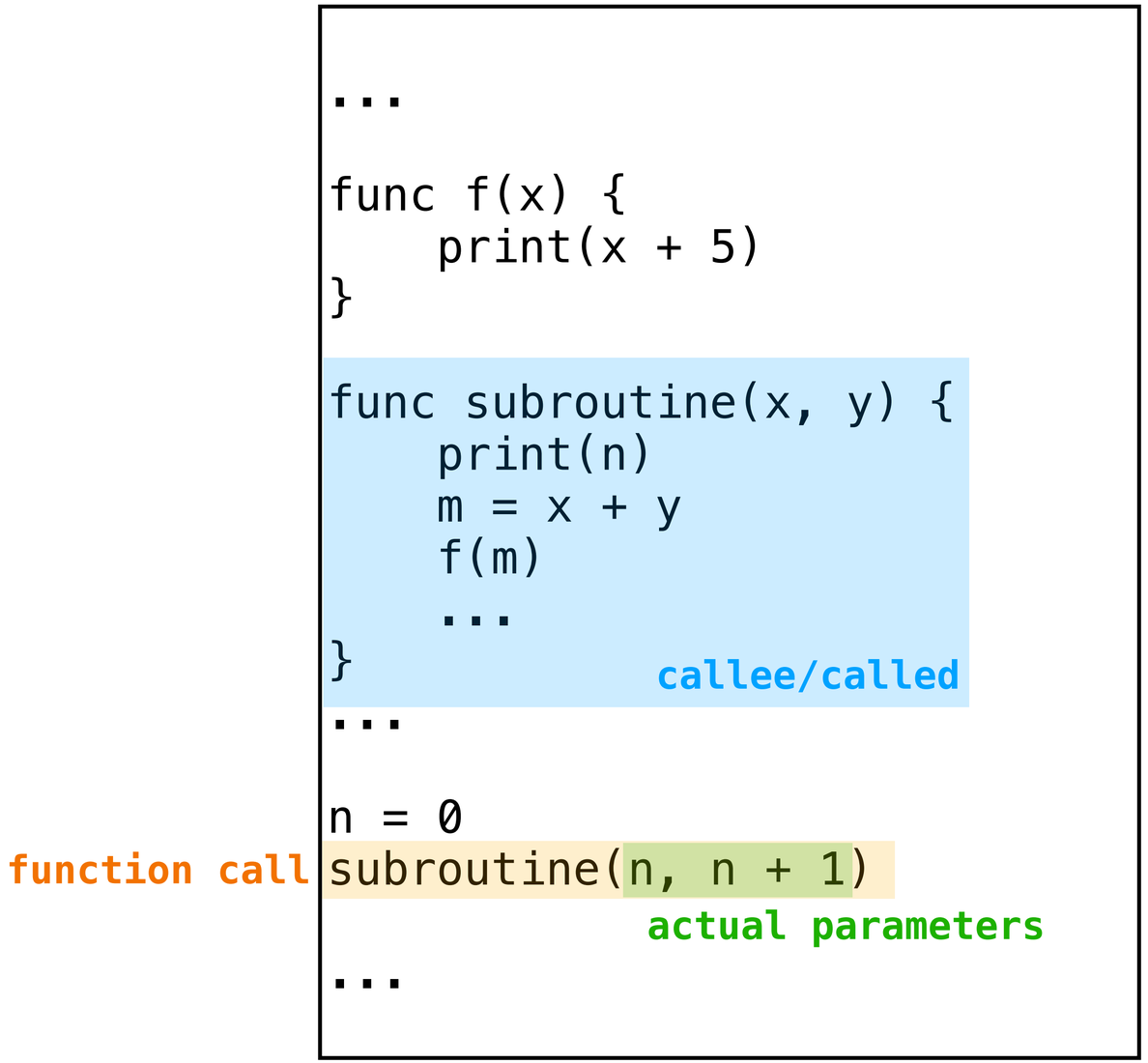

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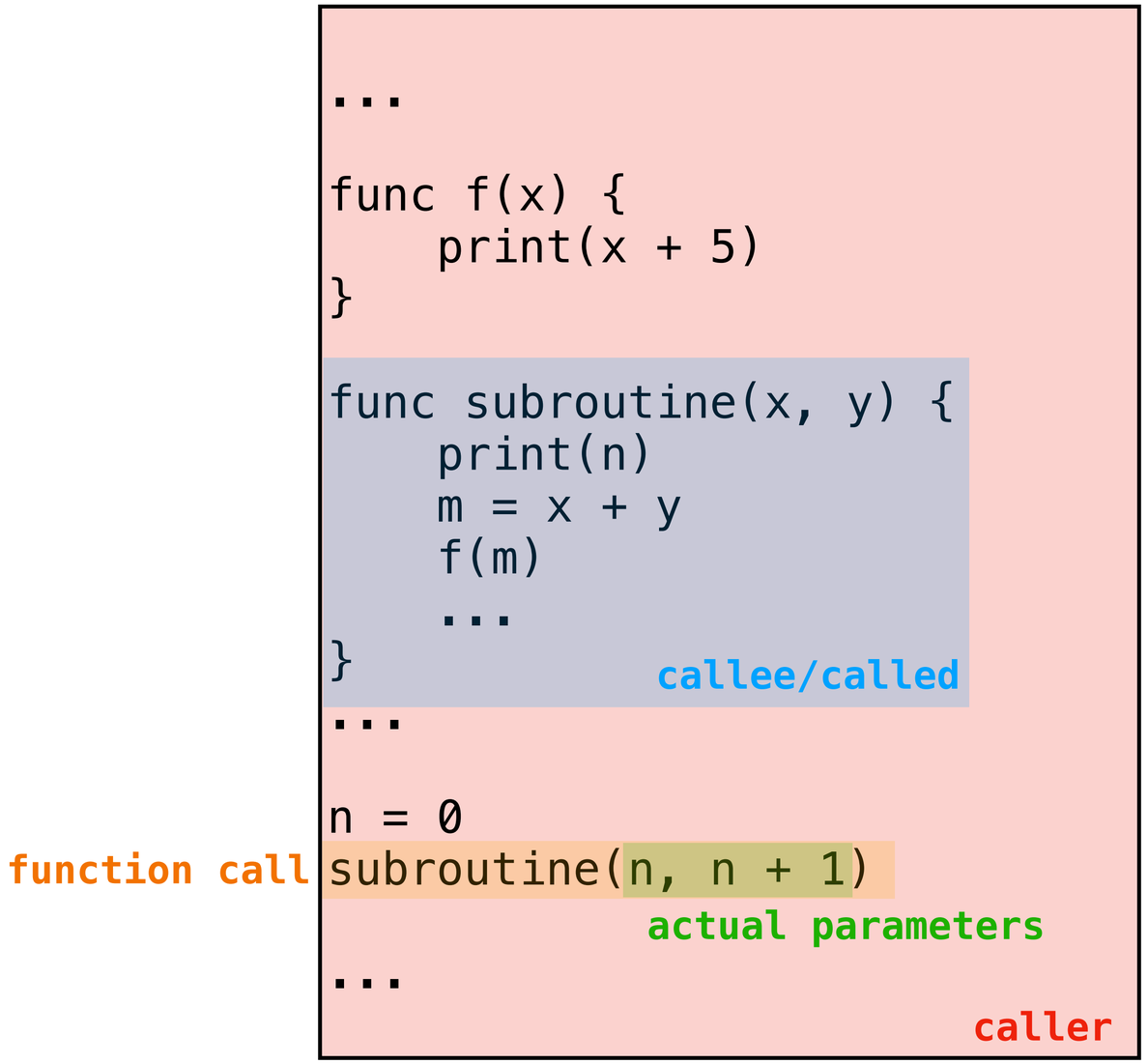

Anatomy of a Function

```
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func f(x) {
    n = 3
    func subroutine(x, y) {
        print(n)
        m = x + y
        f(m)
    }
    print(x + 5)
}
...
```

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nested subroutine

Anatomy of a Function

enclosing subroutine

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This is similar to Python

A Toy Language

```
<prog>  ::= { <com> }
<com>   ::= . | ▷ <ident> | <ident>
          | : <prog> ; | # | Return
          | <val>
<val>   ::= ...
<ident> ::= ...
```

Our Language

```
2 ▷ x
(def test): ▷ n
  x ▷ y
  n .
; ▷ test

3 test #
```

Python

```
x = 2
def test(n):
  y = x
  print(n)


test(3)
```

The following toy language is a fragment of the language from Project 2, dealing only with subroutines and variables.

(we will use this in several examples)

The Call Stack

Motivation

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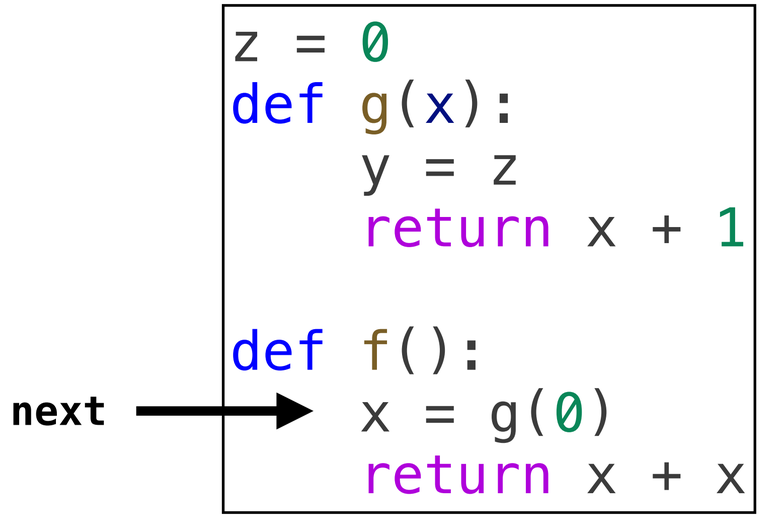
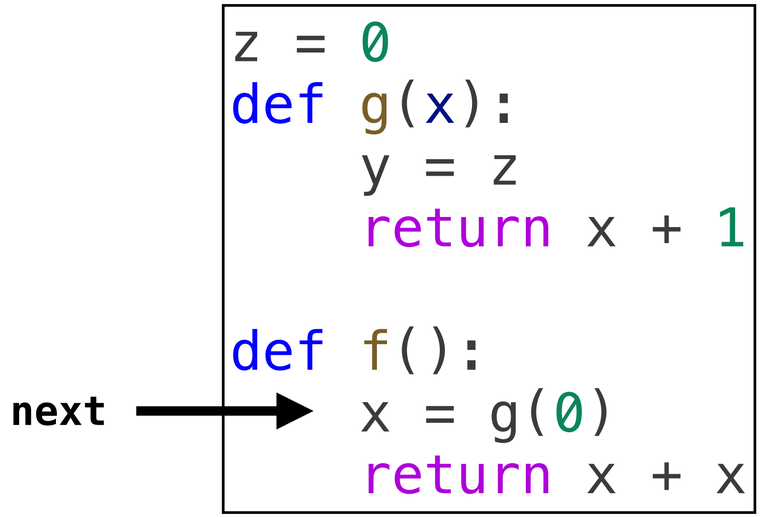
The call stack organizes the back-and-forth of jumping into and out of functions.

Before Transferring Control to the Callee



Before Transferring Control to the Callee

» create an **activation record** for the callee



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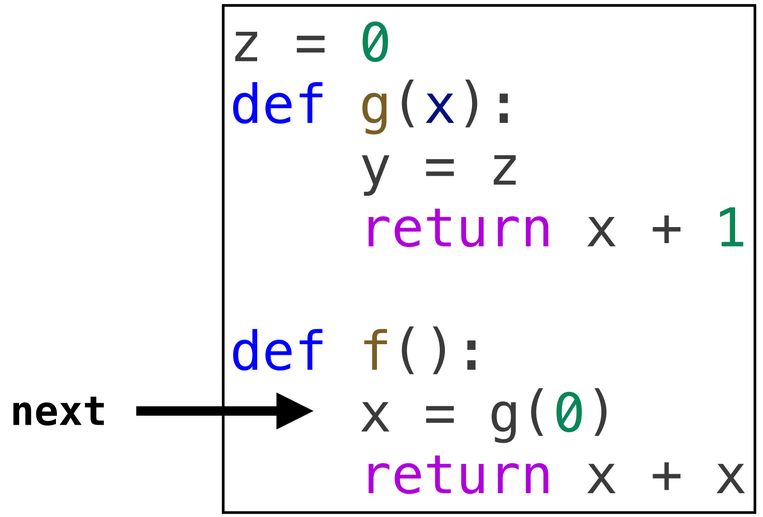
- create an **activation record** for the callee
  - *where do we put the info the callee needs to run?*



activation record for call to g

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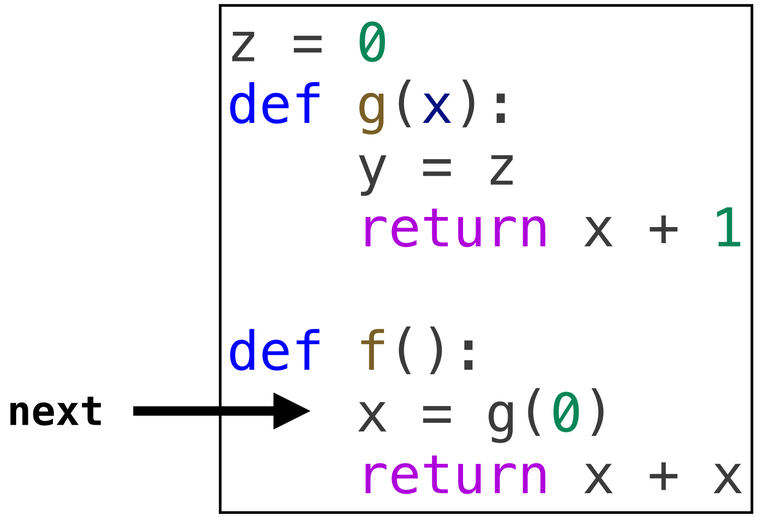
- link **formal parameters** with **actual parameters** (possibly within the activation record)



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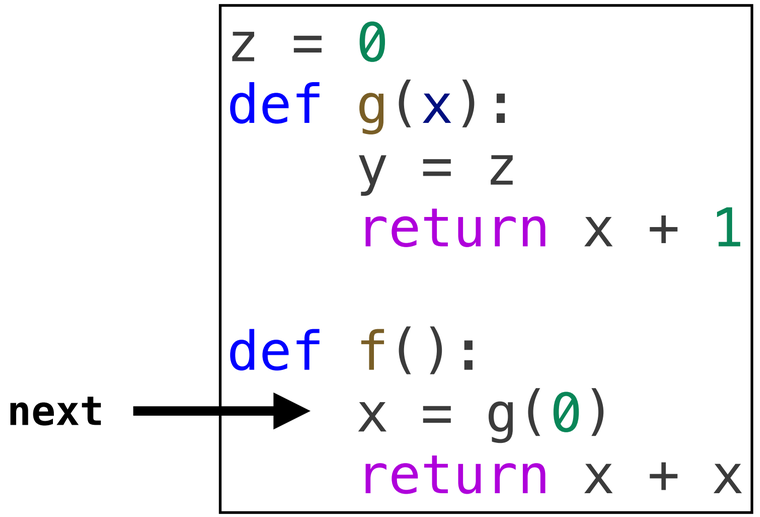

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parameter x is 0

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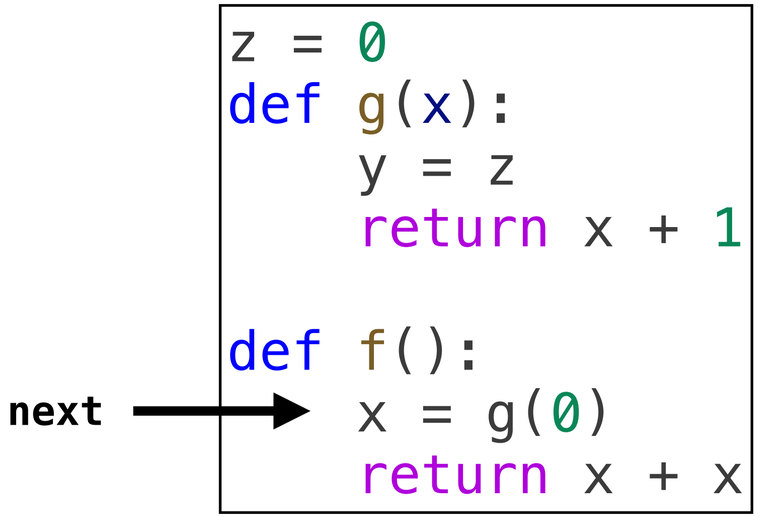
- save the **execution status** of the caller (possibly within the activation record)



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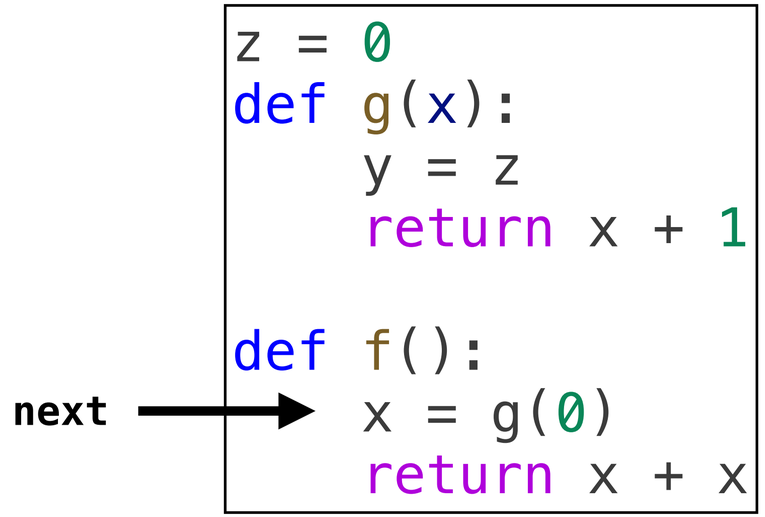
  - *what are we applying the function to?*
- save the **execution status** of the caller (possibly within the activation record)
  - *how much of the caller function have we already executed? Where to do we need to **return** to?*



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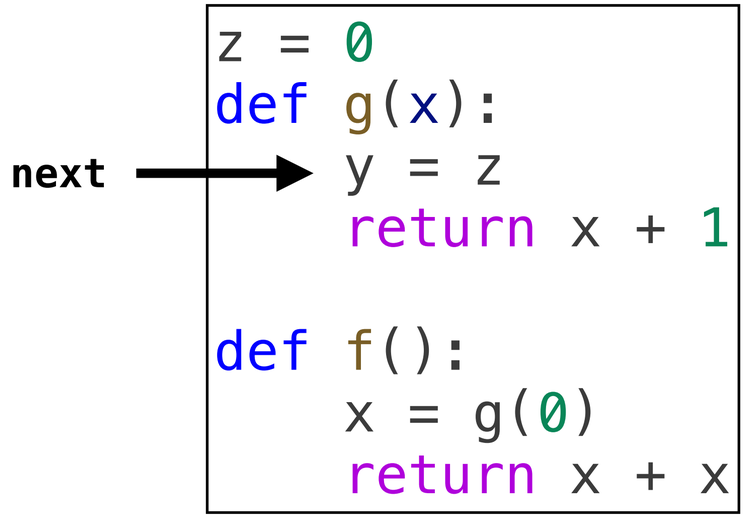
During Control

- Update local bindings in the activation record of the function
- Fetch bindings in the environment possibly by looking at the activation records of enclosing scopes



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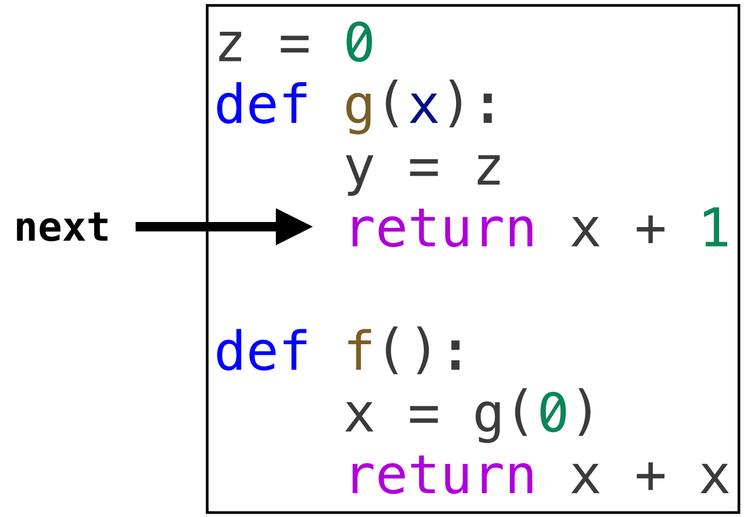
y is set to the value of z (0)

Before Returning Control to the Caller



activation record for call to g

parameter x is 0

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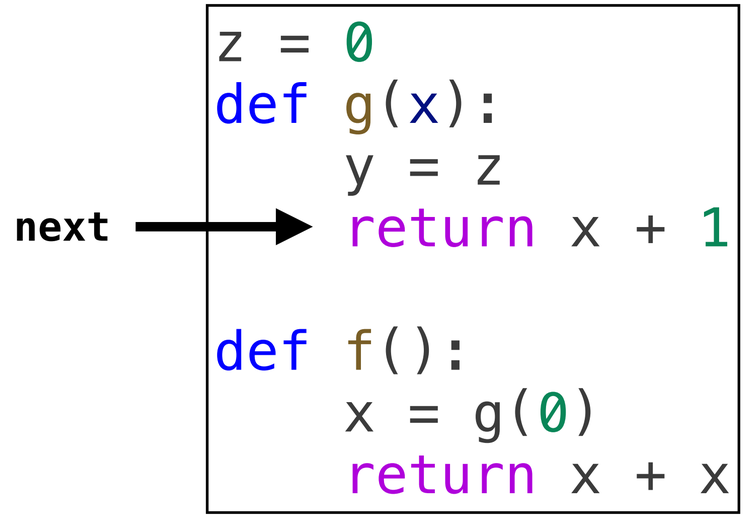

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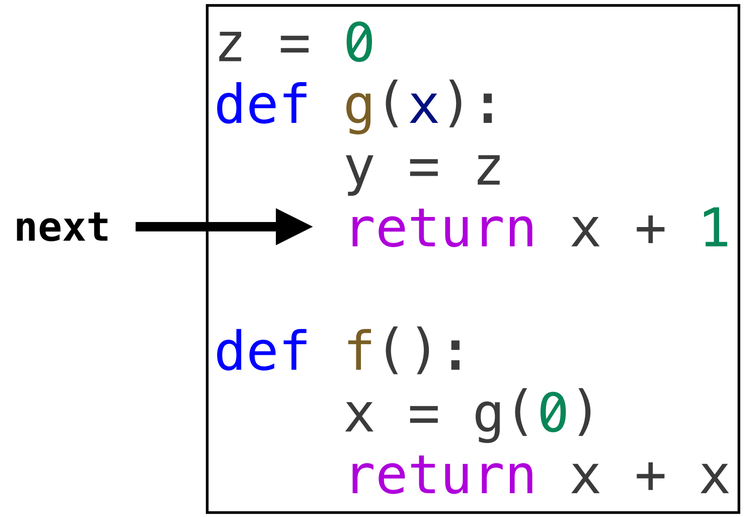

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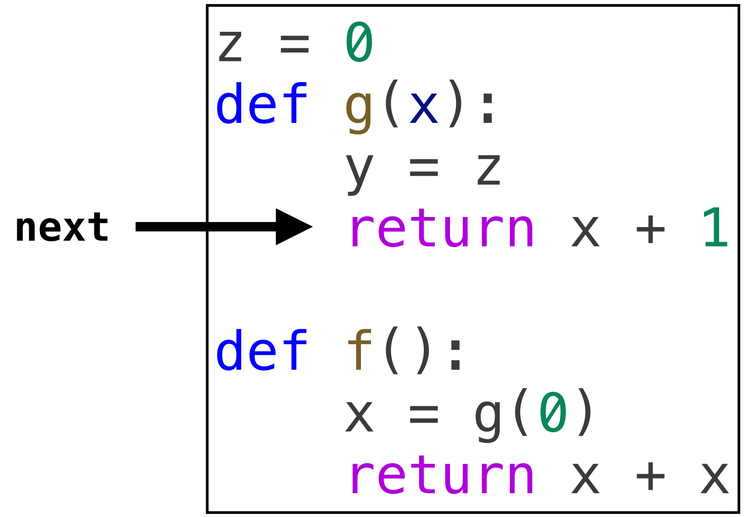
  - *What value does this function return?*
- Discard the activation record of the callee



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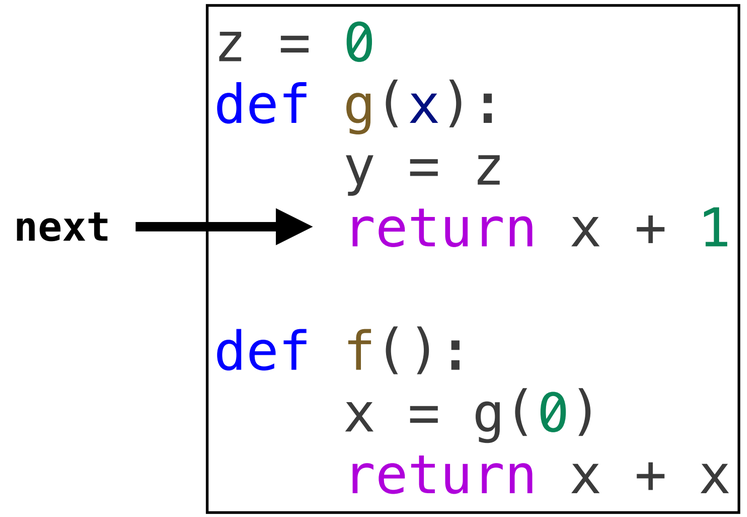

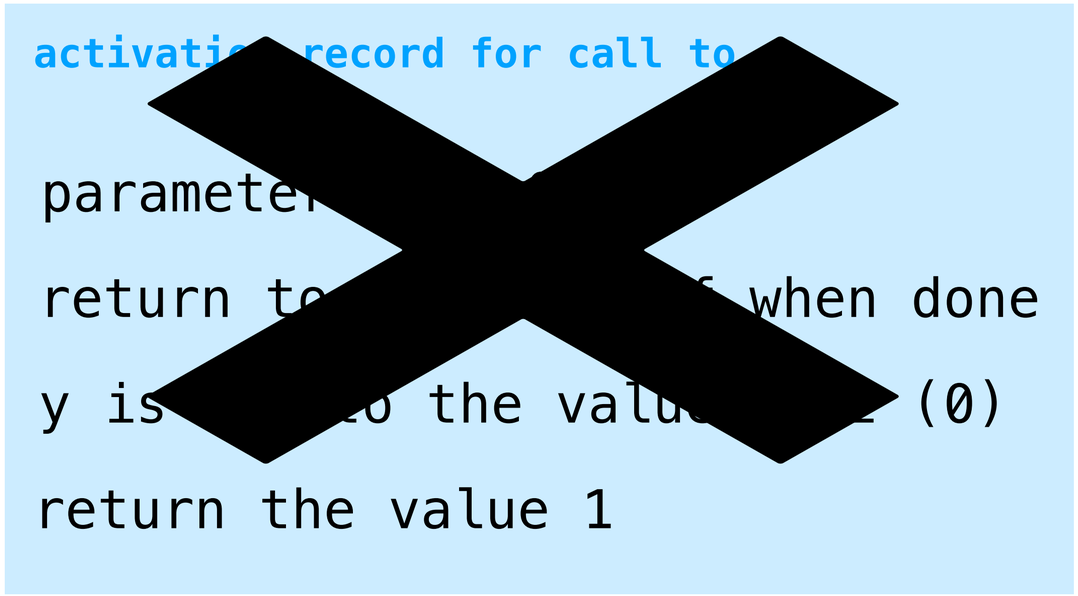

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- Set the return value of the function (possibly in the activation record)
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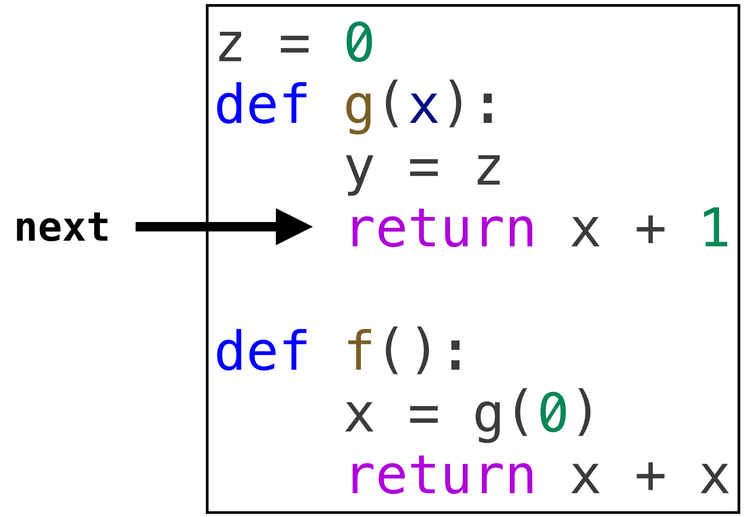

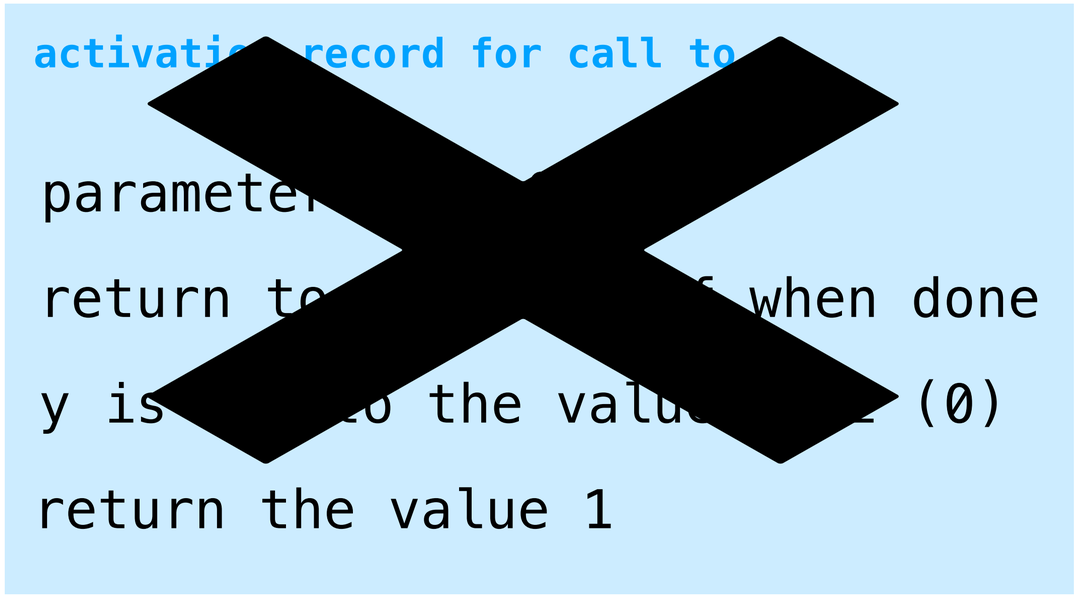

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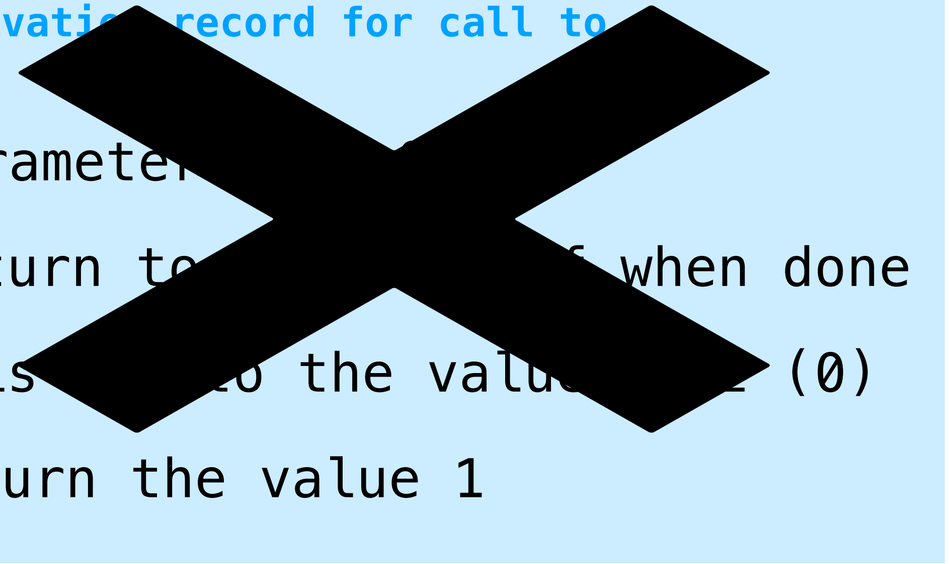
- Set the return value of the function (possibly in the activation record)
  - *What value does this function return?*
- Discard the activation record of the callee
  - *Make sure local variables are no longer in scope*
- Restore the activation record of the caller
  - *Continue running the code of the caller*

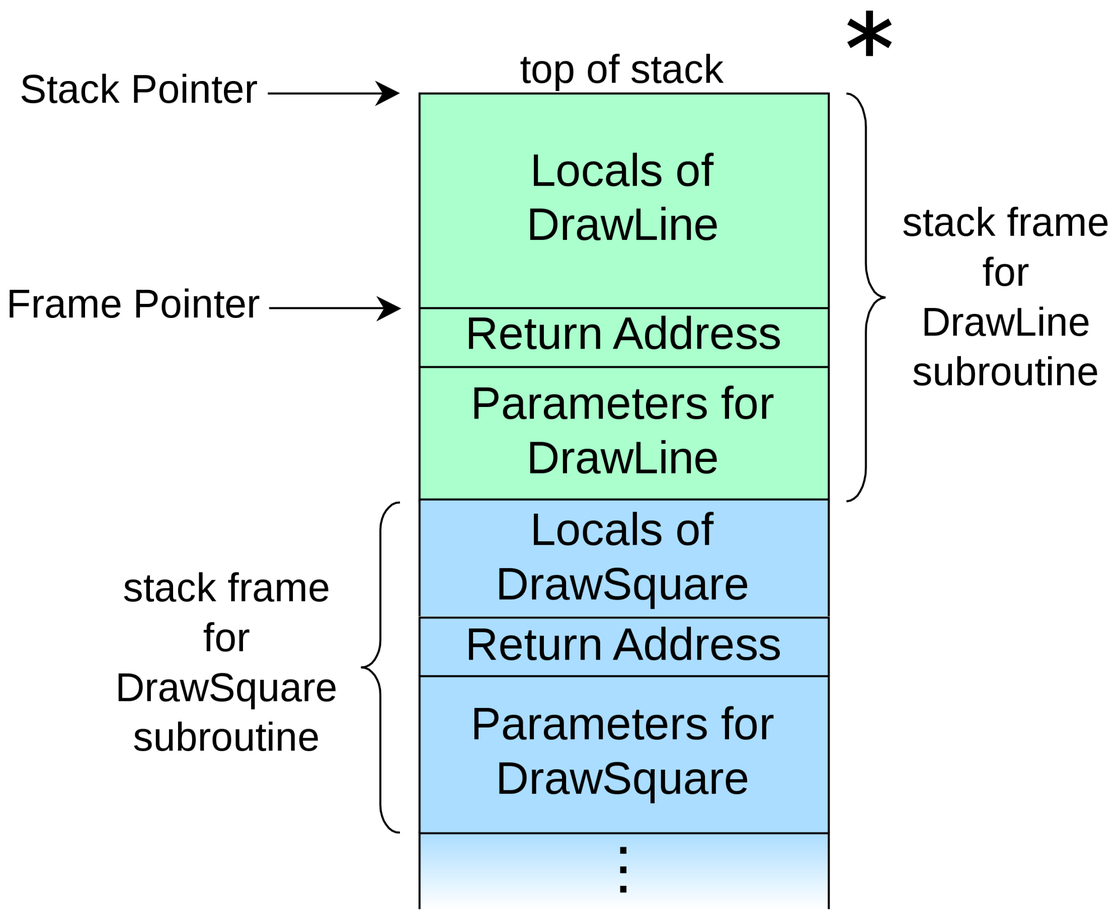
```
z = 0
def g(x):
    y = z
    return x + 1

def f():
    x = g(0)
    return x + x
```

next →



Activation Records



*since this is not a compilers course we will use this as a conceptual framework instead of an actual implementation guideline

https://commons.wikimedia.org/wiki/File:Call_stack_layout.svg

Activation Records

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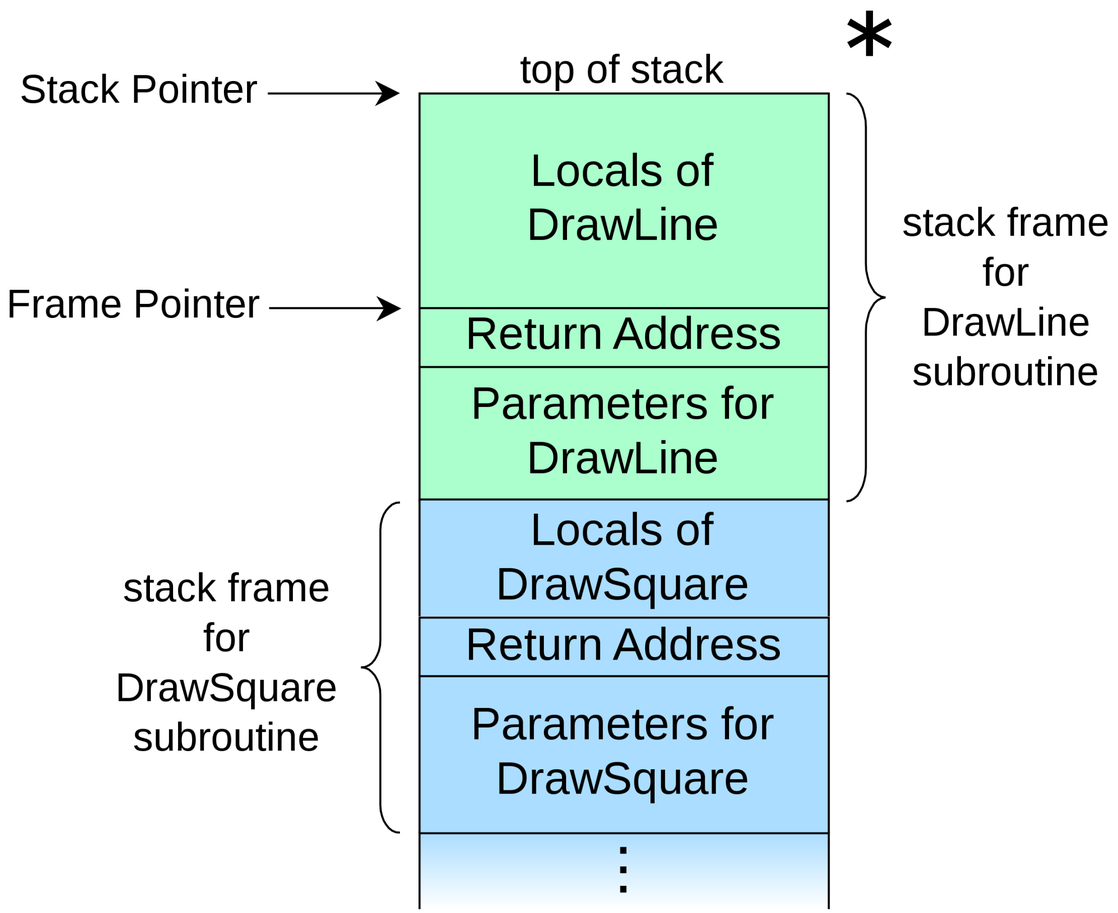

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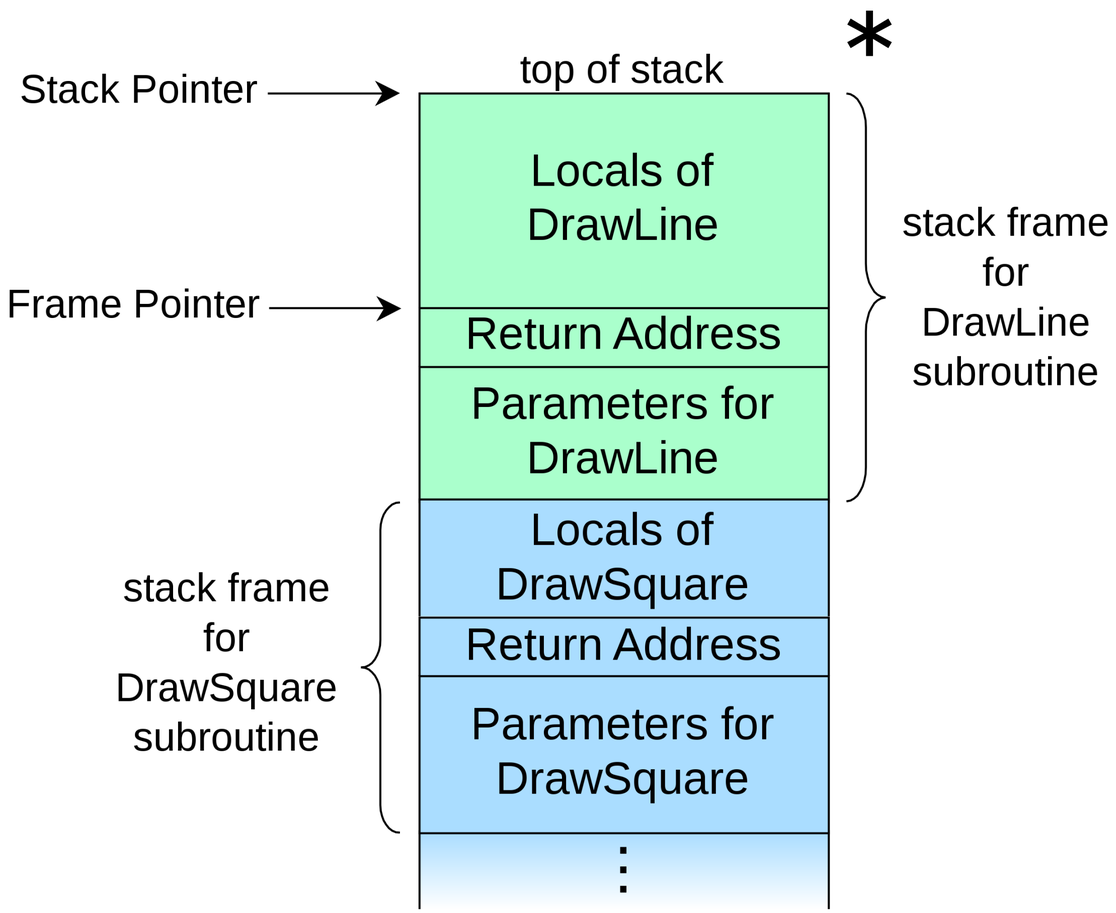

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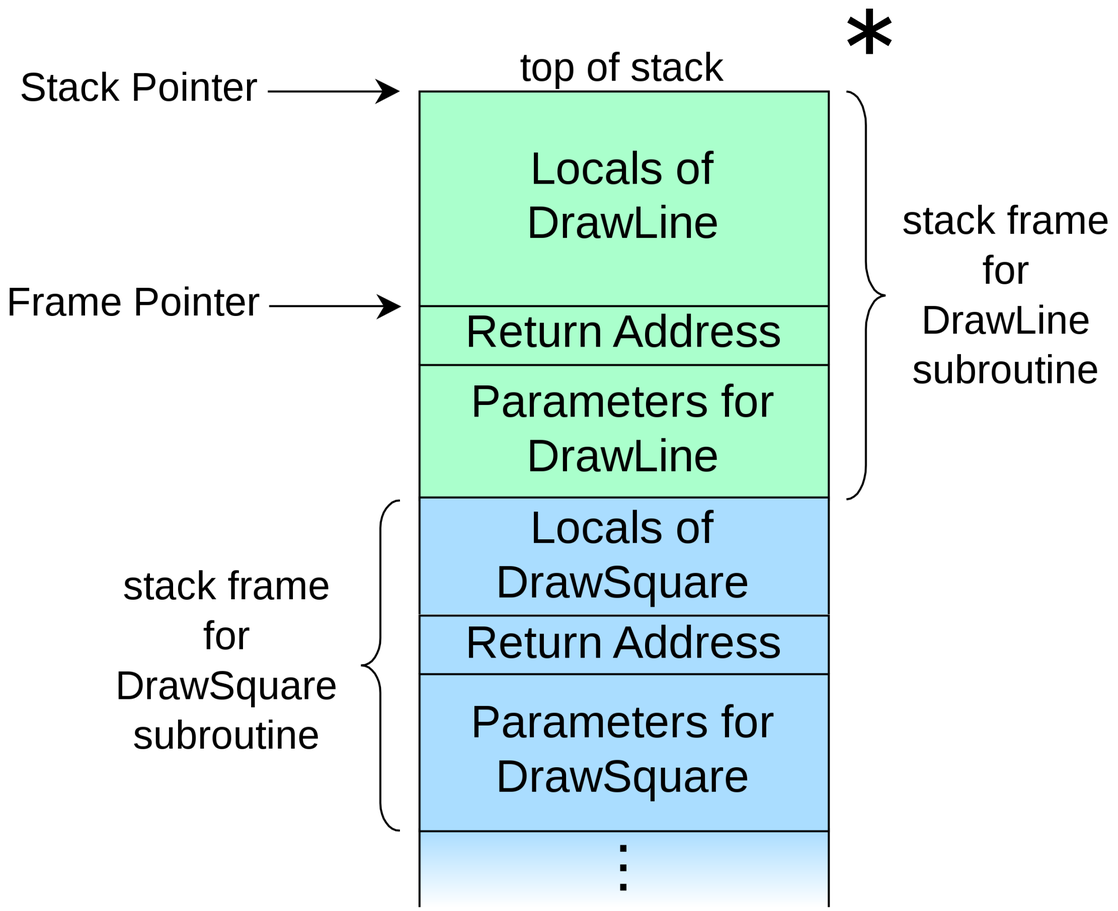

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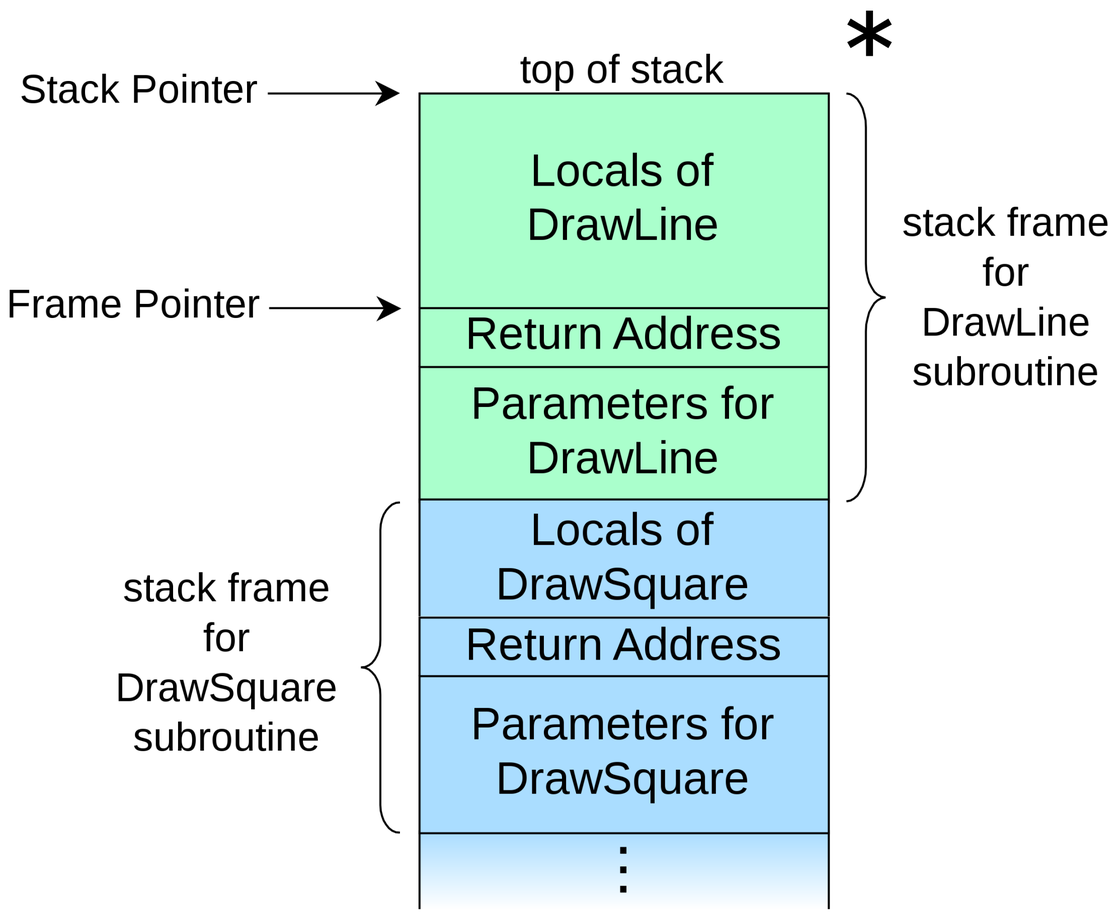
- local variables created during execution
- information about enclosing subroutines (e.g., activation records of other subroutines when nesting is allowed)



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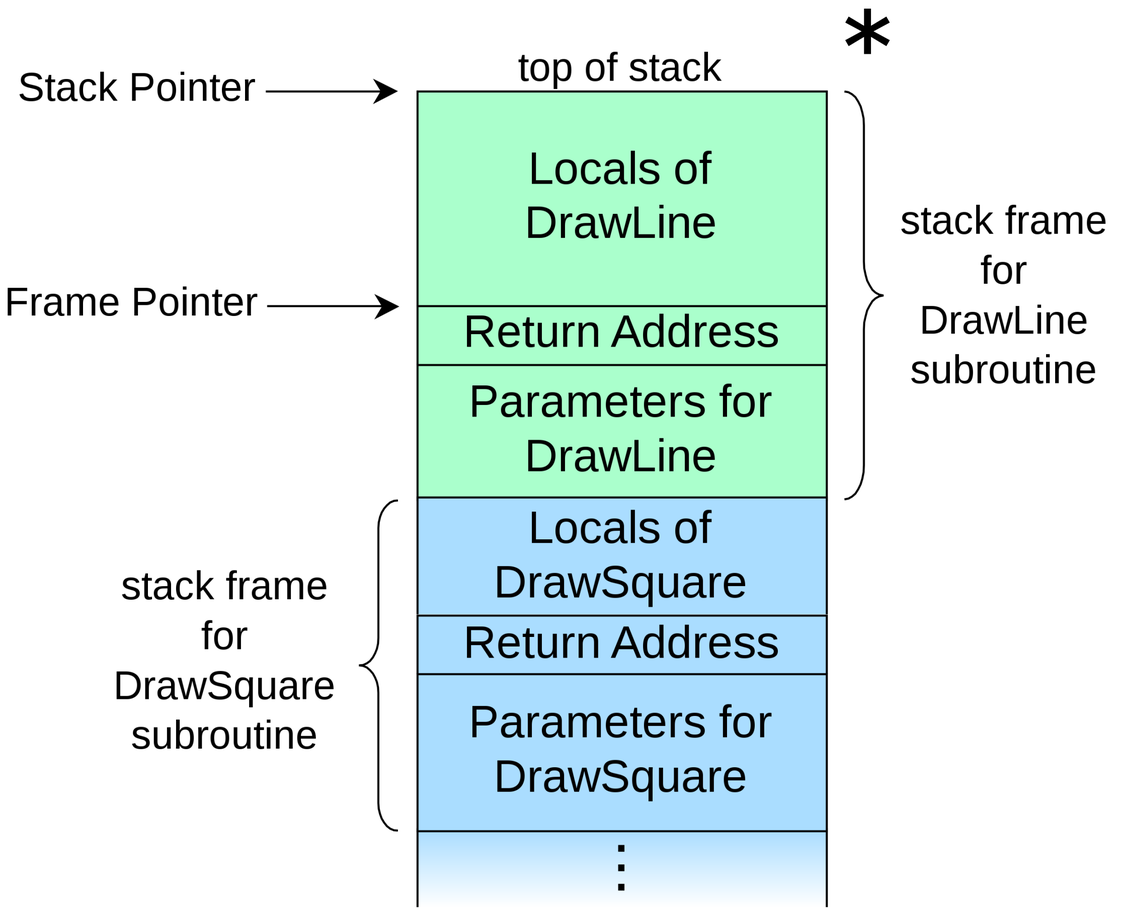

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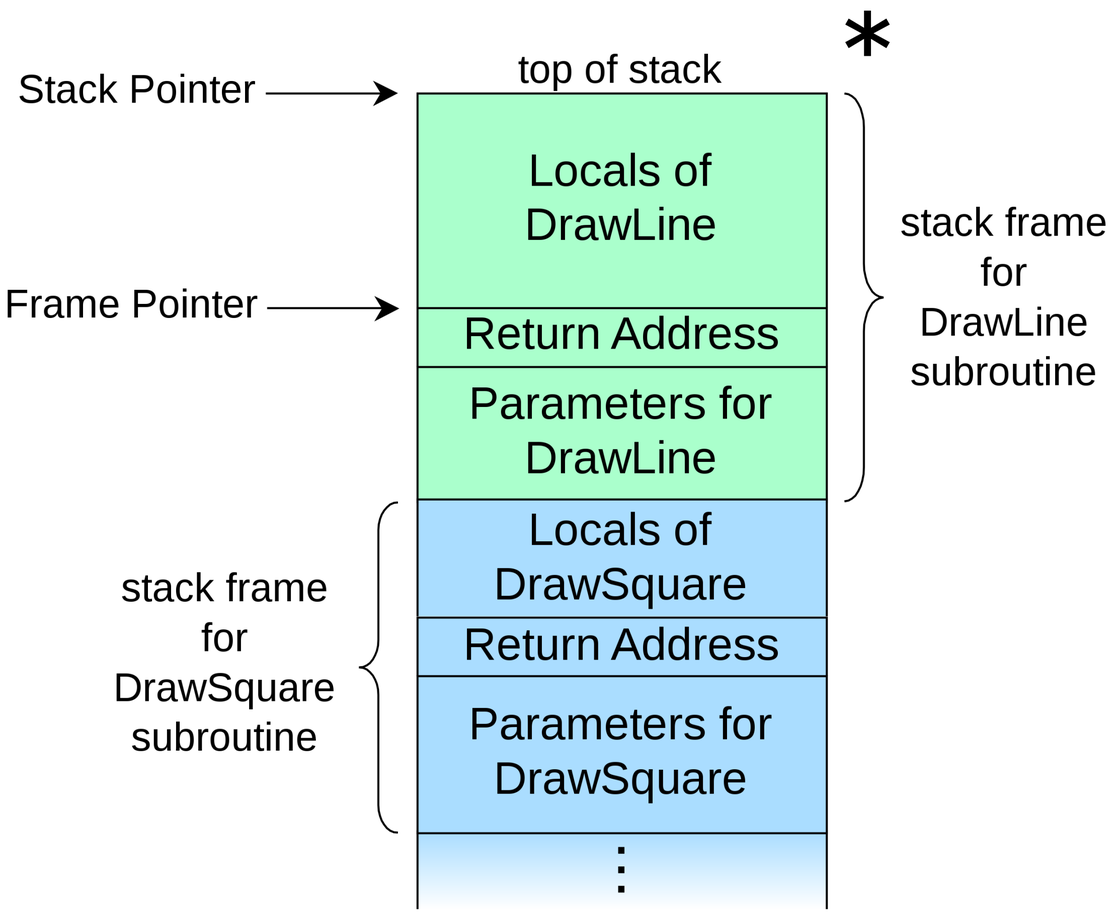
- information about enclosing subroutines (e.g., activation records of other subroutines when nesting is allowed)
- the caller location for returning
- possibly a return value



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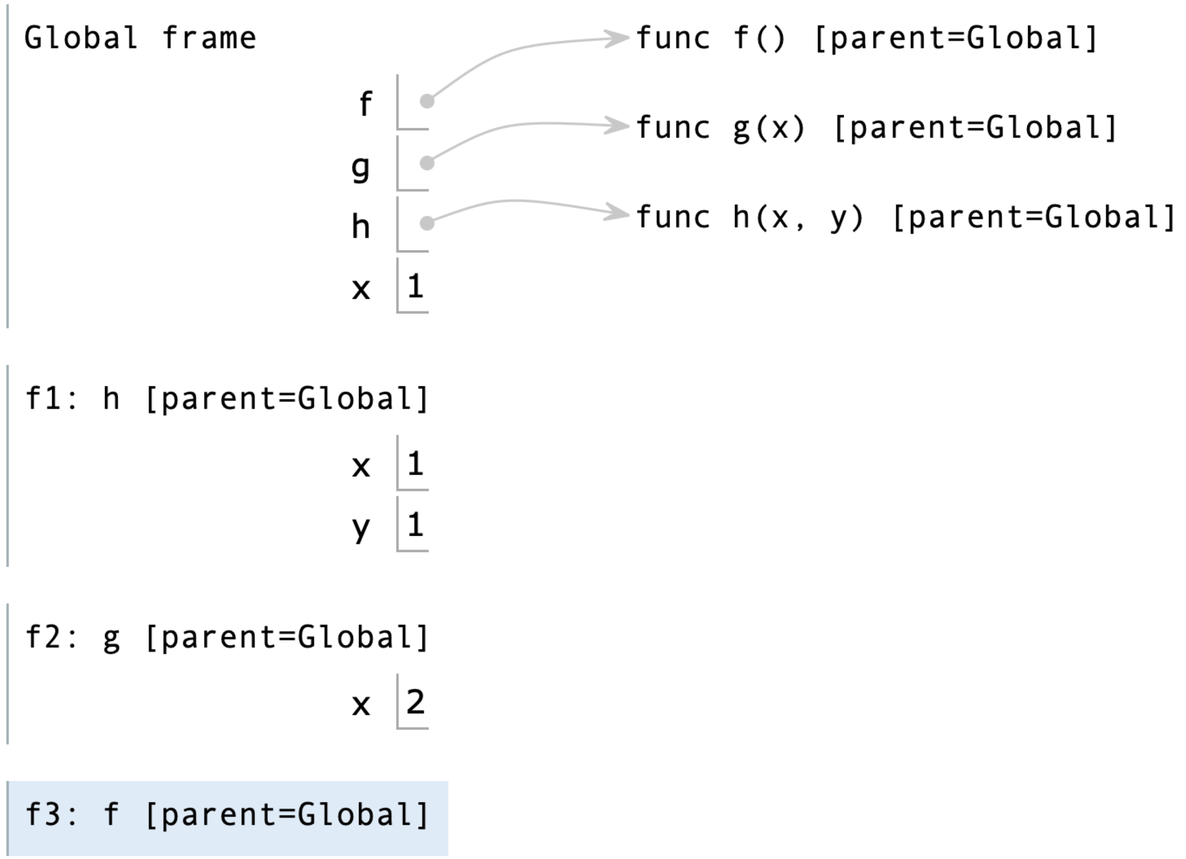
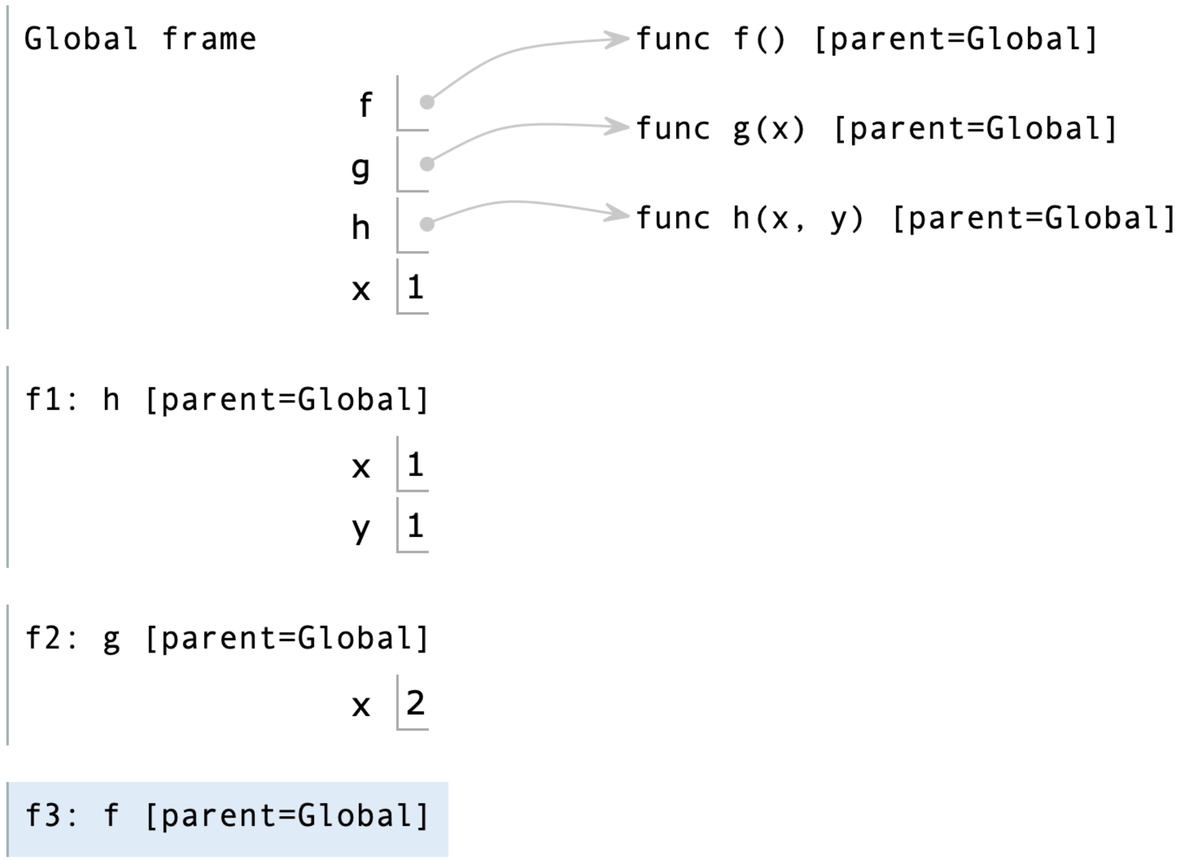
The Call Stack



The Call Stack

The **call stack** is a data structure for maintaining subroutine calls



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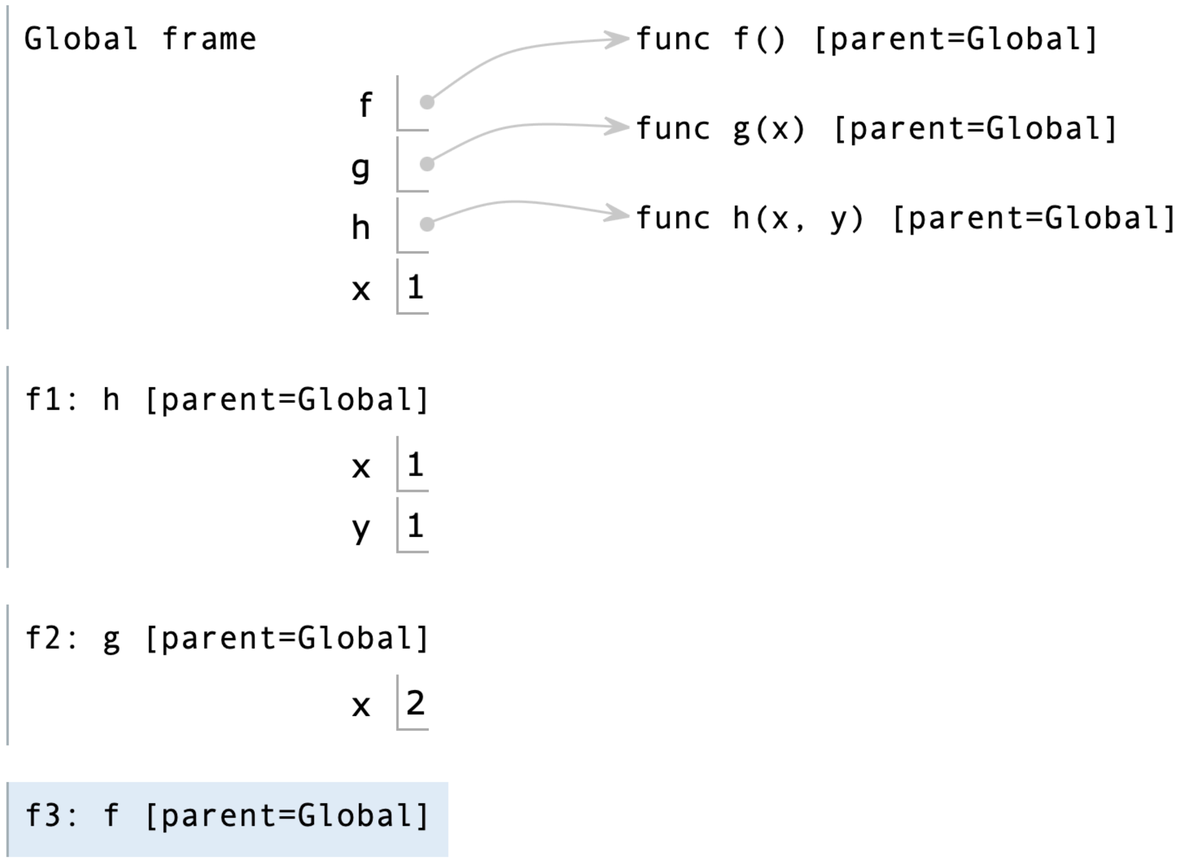
The **call stack** is a data structure for maintaining subroutine calls

It is a stack of activation records which are pushed when a function is called, and popped when a function returns



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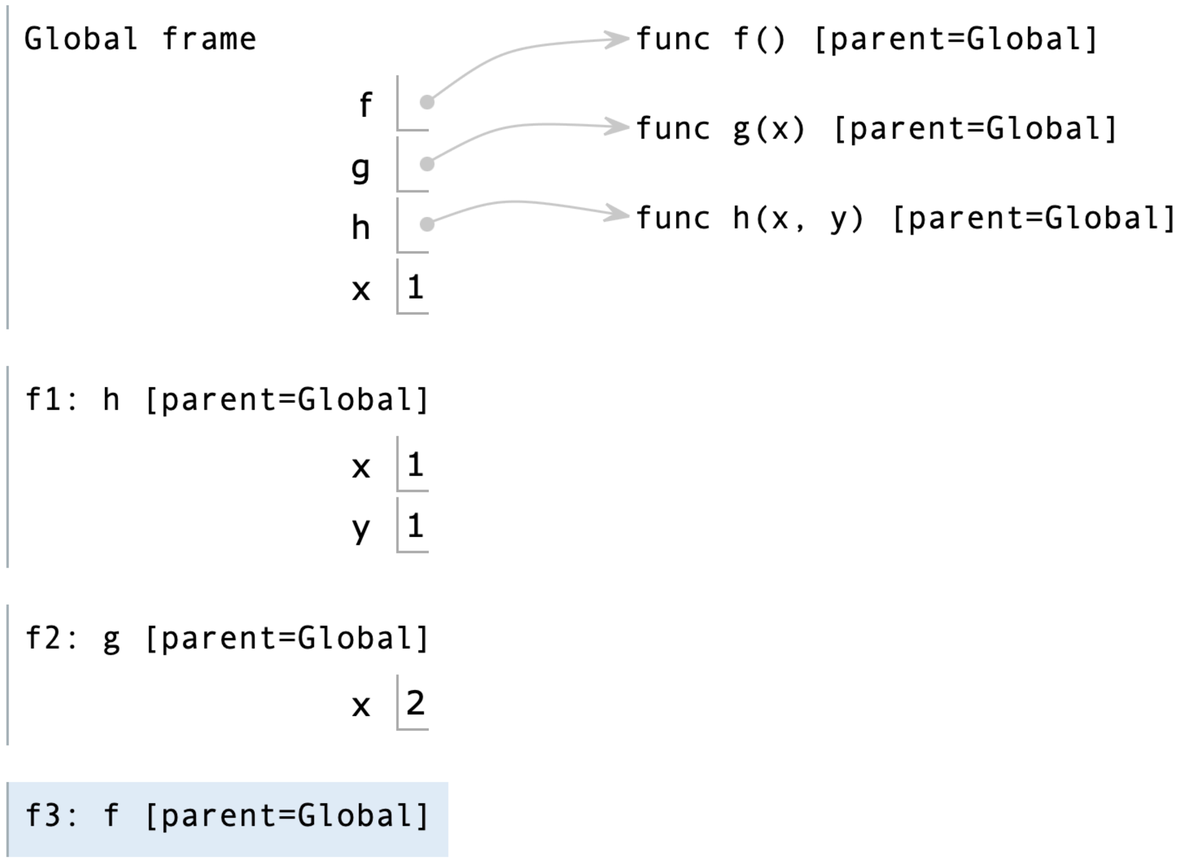

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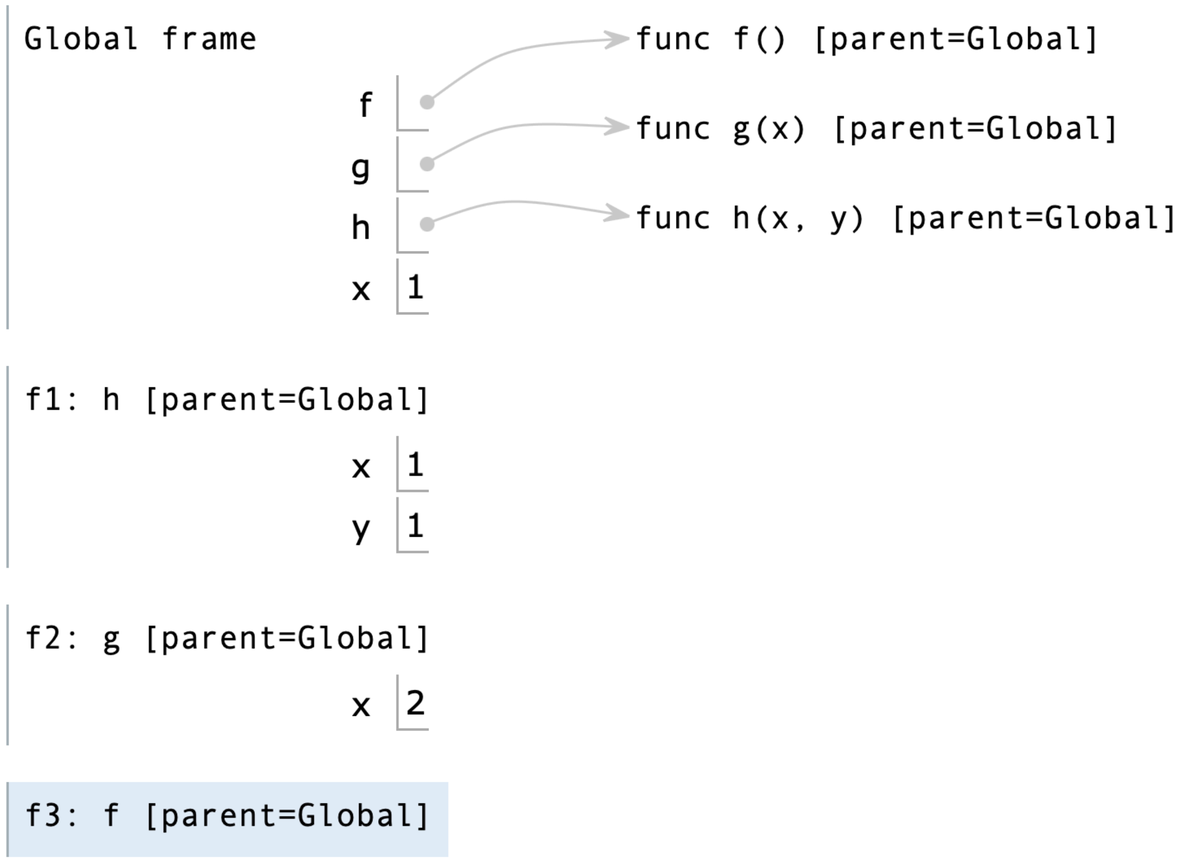
Question. *Why a stack?*



demo

(python tutor, example-1.py)

An Aside: Stack Overflow

Recursive functions have the potential to add *many* activation records to the call stack.

Stack overflow occurs when the activation records created by a sequence of function calls do not fit on the call stack.

Python

```python
def fact(n):
  if n == 0:
    return 1
  return fact(n - 1) * n
```

Our Language

```
(fact): ▷ n
  (if) 0 n = ?
    1 Return ;
  (else)
    -1 n + fact # n *
    Return ;
; ▷ fact
```

demo

(python tutor, example-2.py)

Understanding Check

```python
def f(x):
    if x == 0:
        return 1
    return f(x // 4) + f(x // 2)

f(16)
```

Python

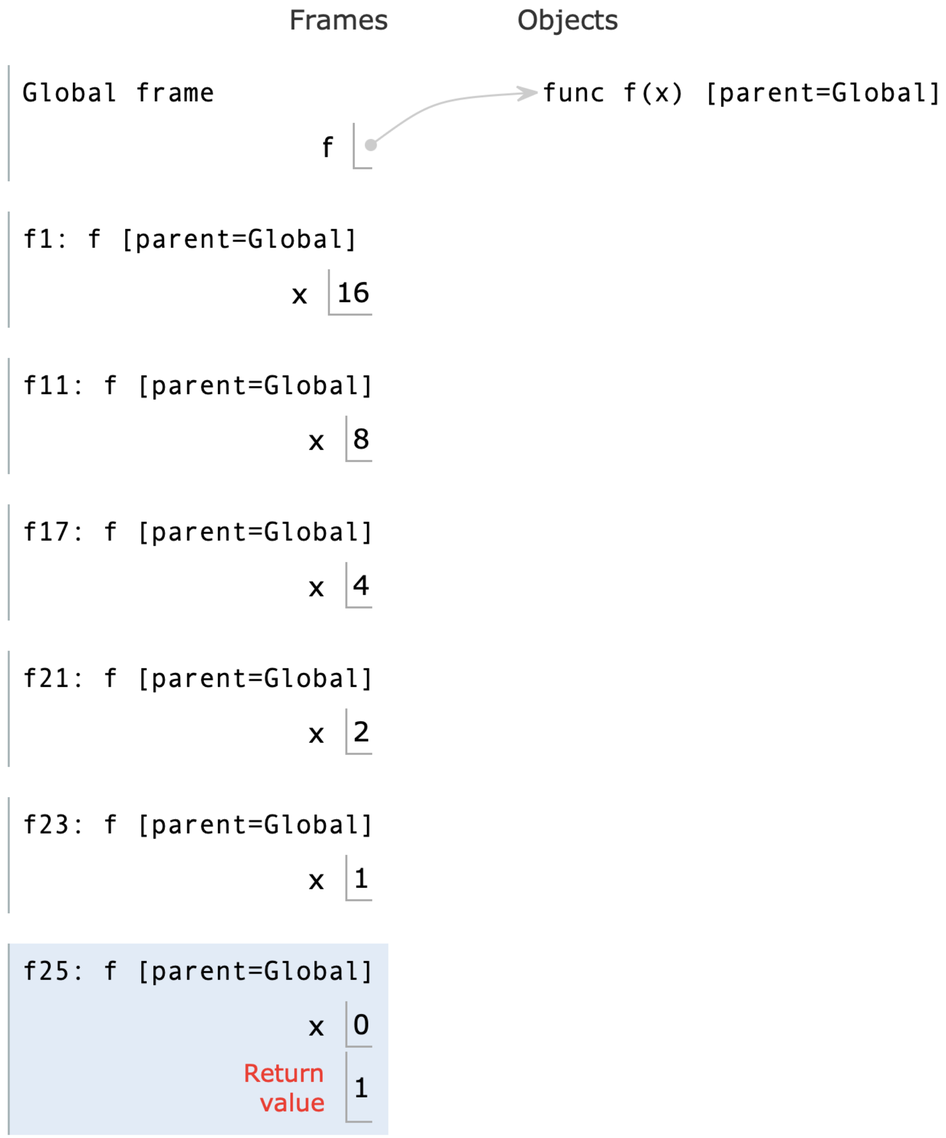
```
(f): ▷ x
  (if) 0 x = ?
    1 Return ;
  (else)
    4 x / f # ▷ a
    2 x / f # ▷ b
    a b + Return
  ;
; ▷ f

16 f #
```

Our Language

What is the maximum number of activation records on the call stack during the execution of this program (including the global frame)?

Answer

7


Frames
Objects
Global frame
f
func f(x) [parent=Global]
f1: f [parent=Global]
x
16
f11: f [parent=Global]
x
8
f17: f [parent=Global]
x
4
f21: f [parent=Global]
x
2
f23: f [parent=Global]
x
1
f25: f [parent=Global]
x
0
Return value
1

The Environment

Motivation

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What variables are in scope? How do we access them? Are variables mutable?

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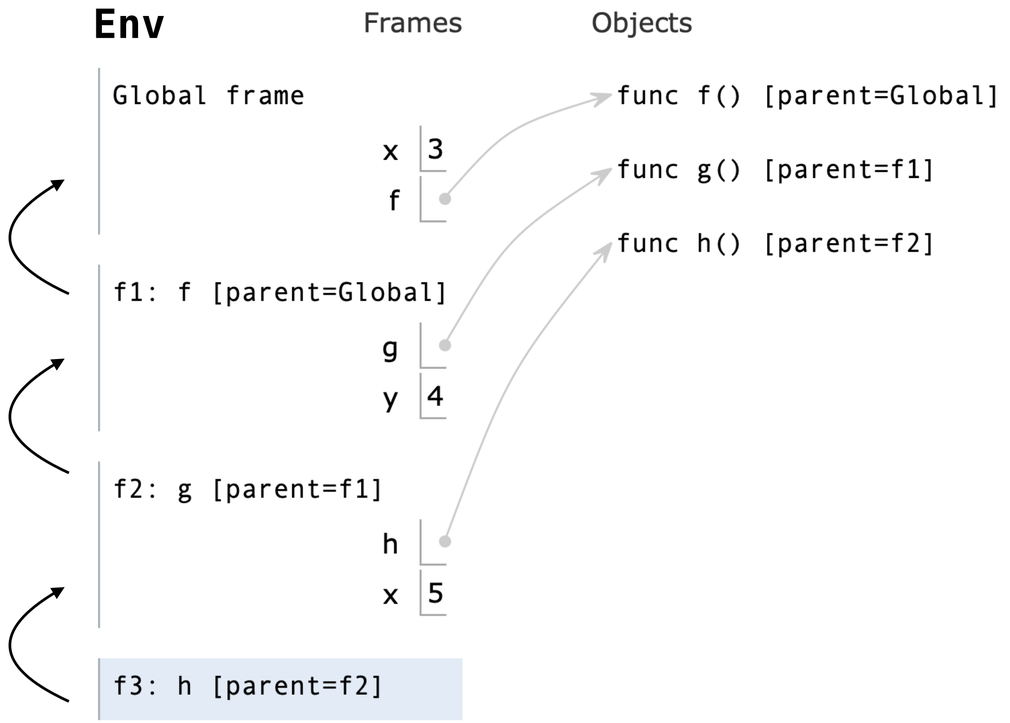
We will consider two cases in this course:

» Locally Mutable (Project 2)

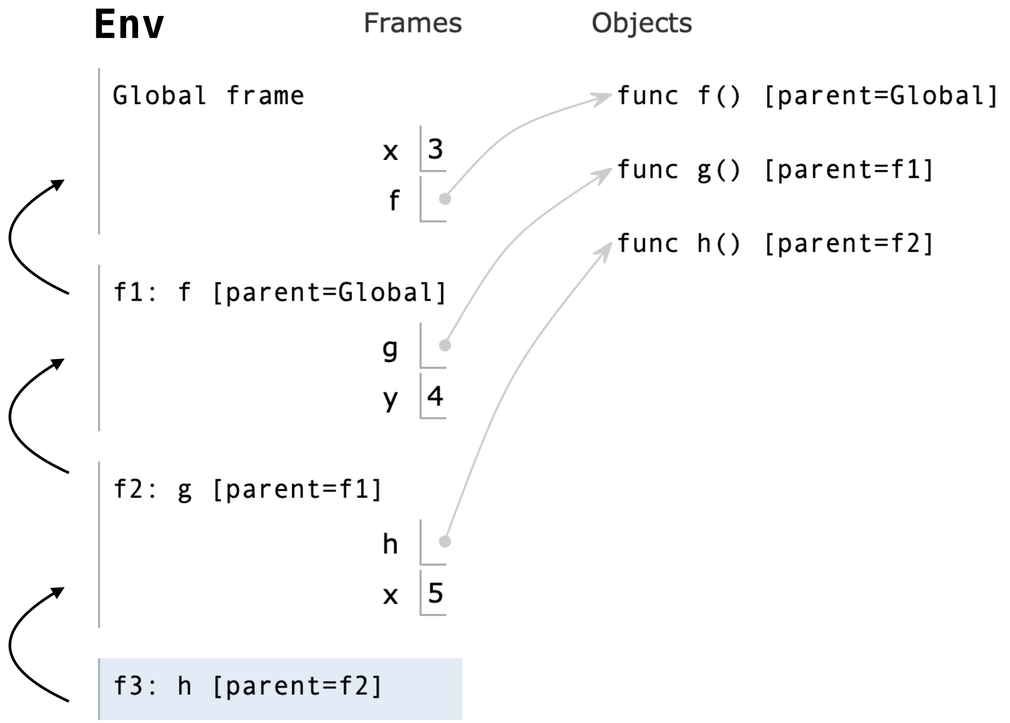
» Always immutable (e.g., let-bindings) (Project 3)

Fetching from the Environment



Fetching from the Environment

`fetch(Env, x)` algorithm:



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fetch(Env, x) algorithm:

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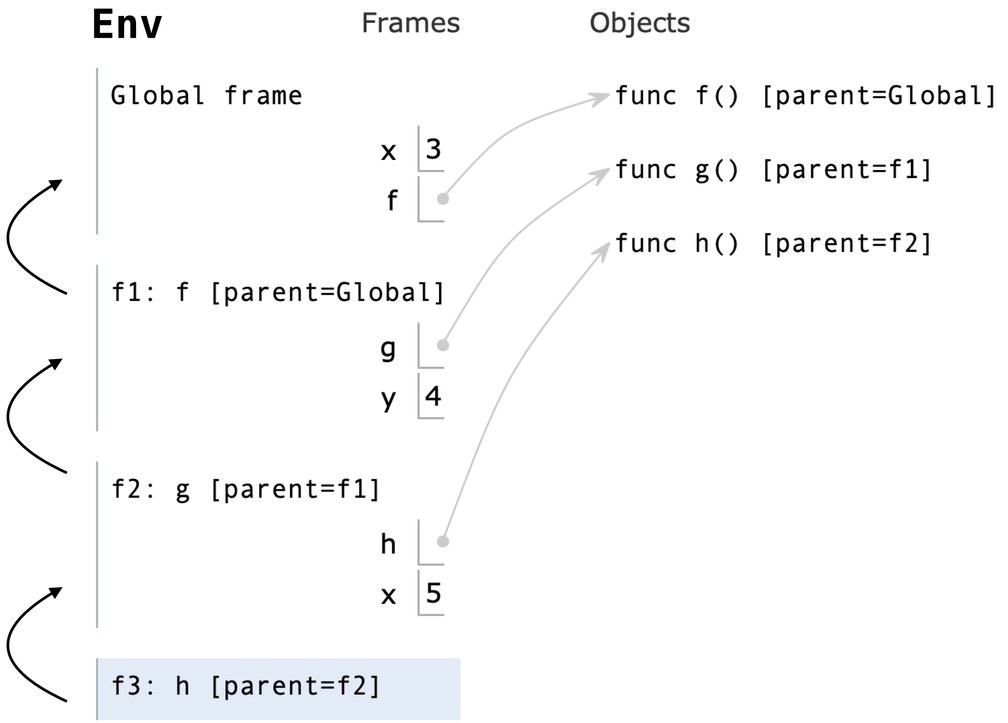

Fetching from the Environment

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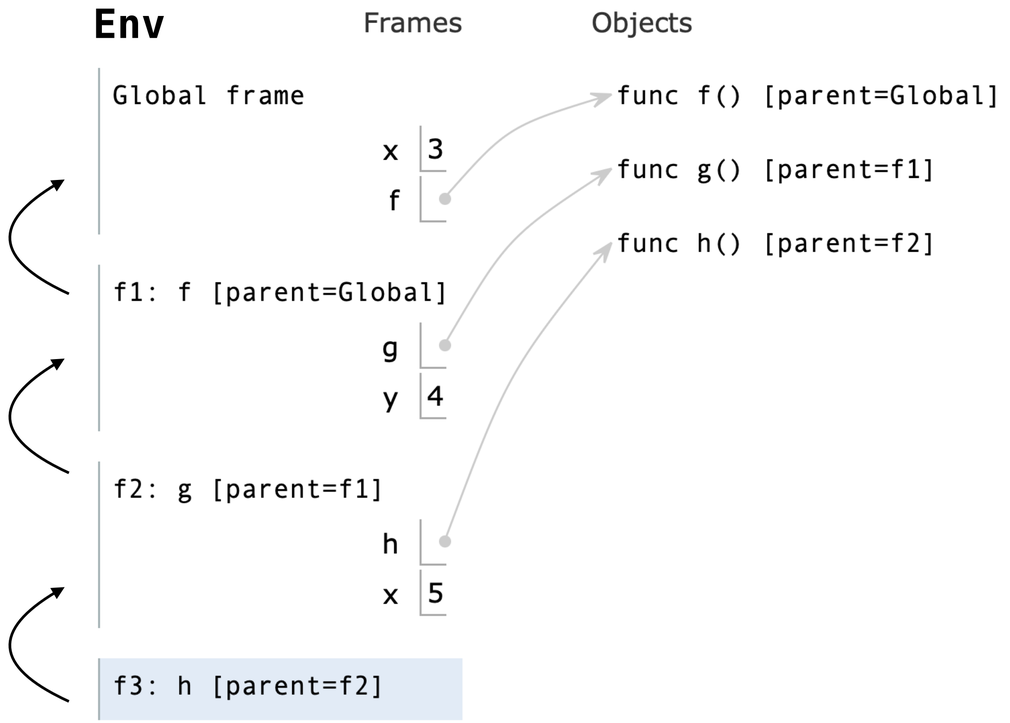
» Check locally (within the activation record of the called function)

» If failed, check record of enclosing subroutine (the activation record for the function where the called function was defined)



Fetching from the Environment

fetch(Env, x) algorithm:

- Check locally (within the activation record of the called function)
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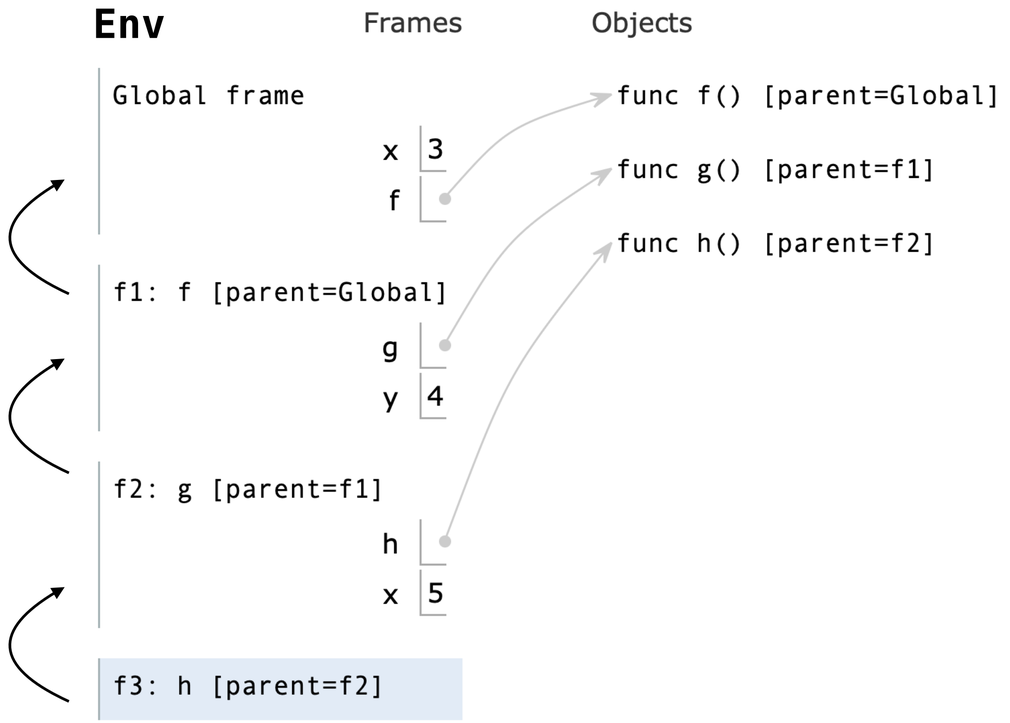
- Repeat until you get to the global frame. Fail if you did not find a binding



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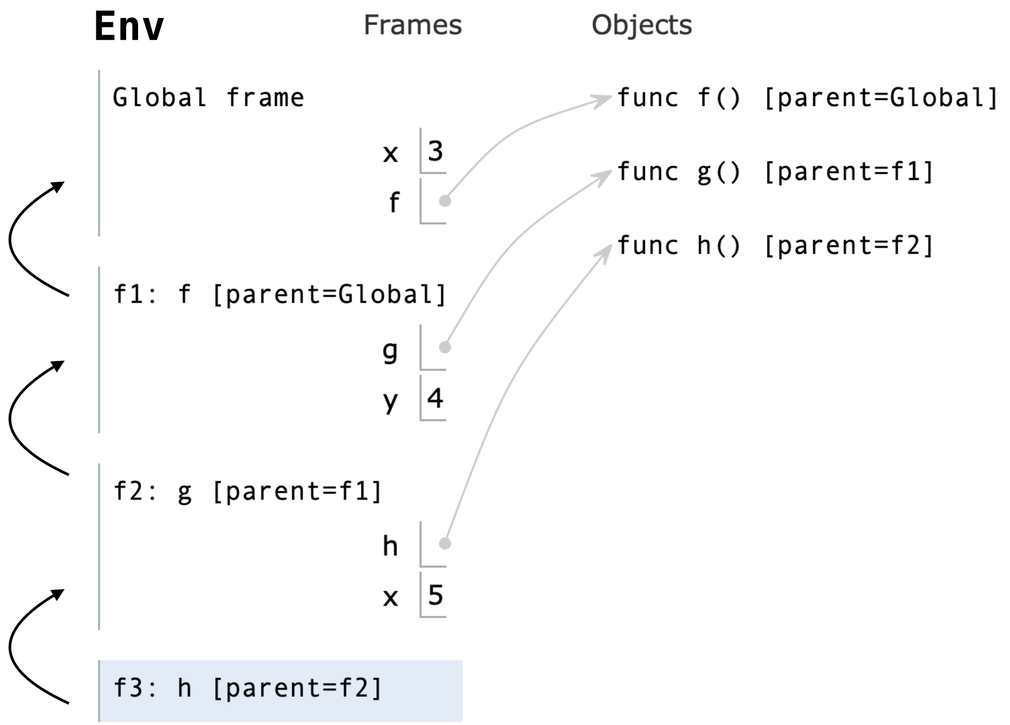
Each record has a way to get to the record in which the callee was defined.



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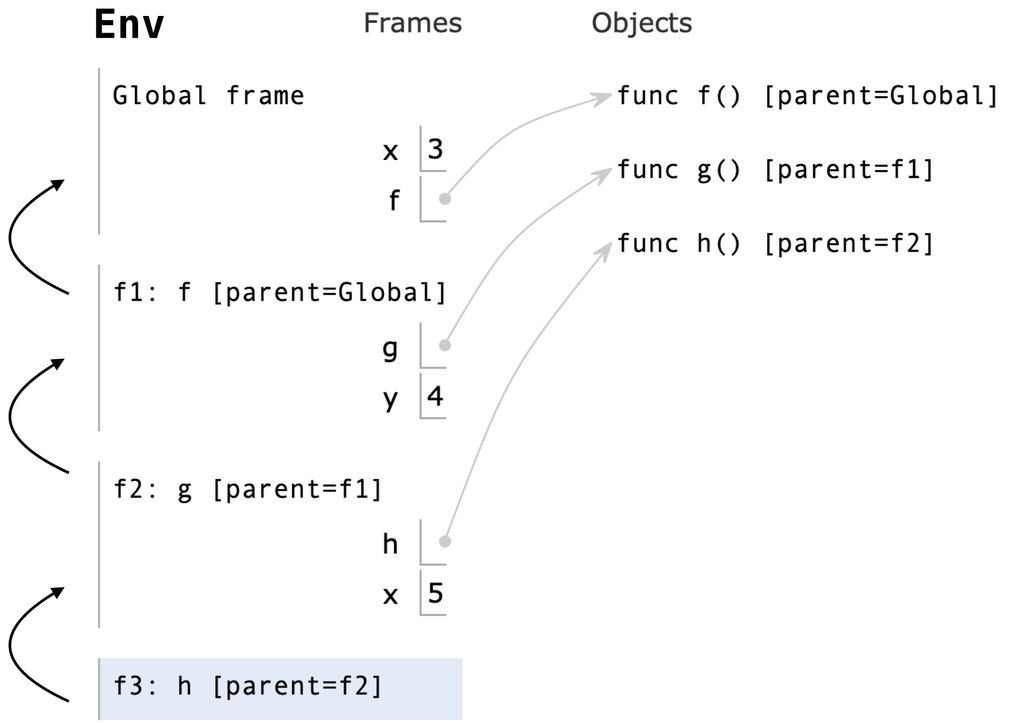

what is the value of x?

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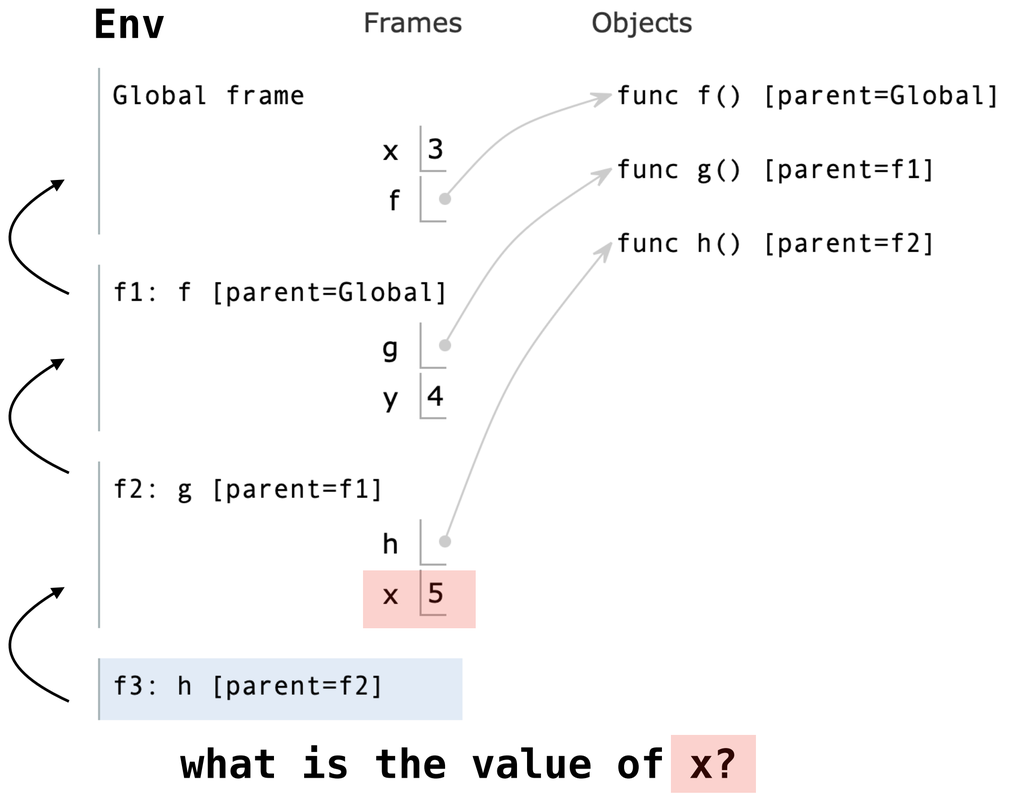

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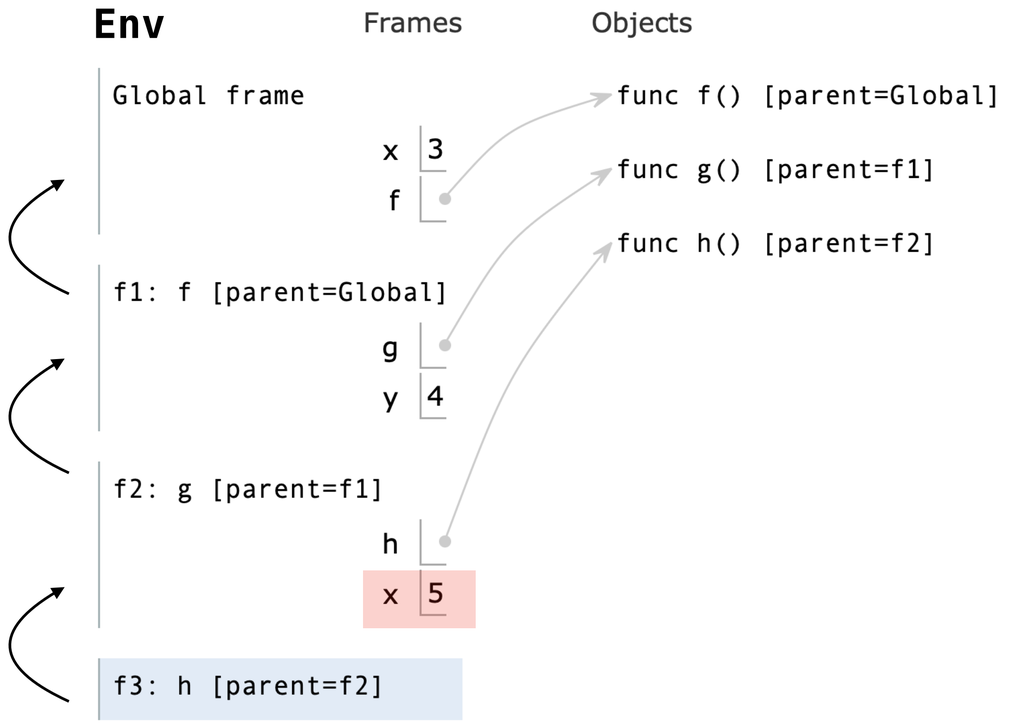

what is the value of x?

what is the value of y?

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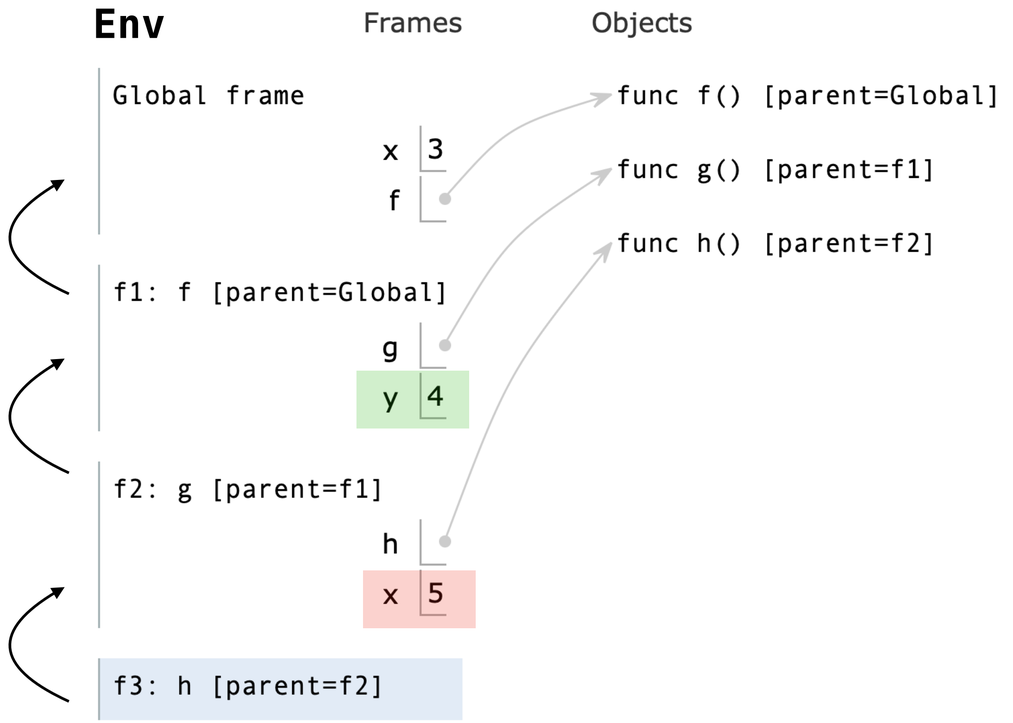

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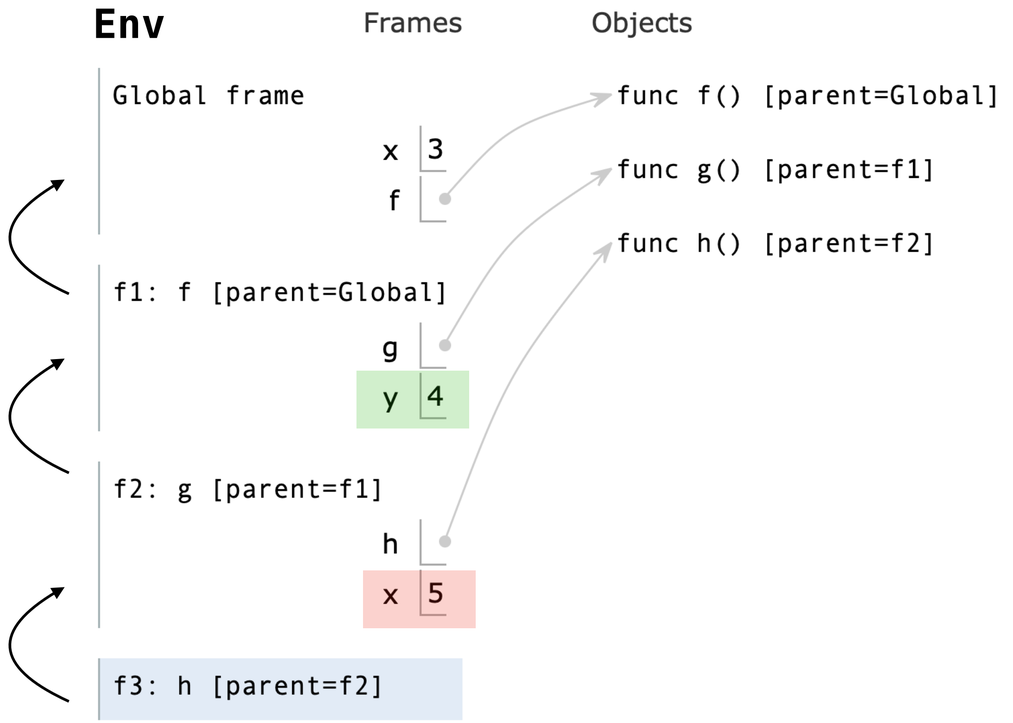

what is the value of x?

what is the value of y?

Take the first binding you see, going to higher nestings.

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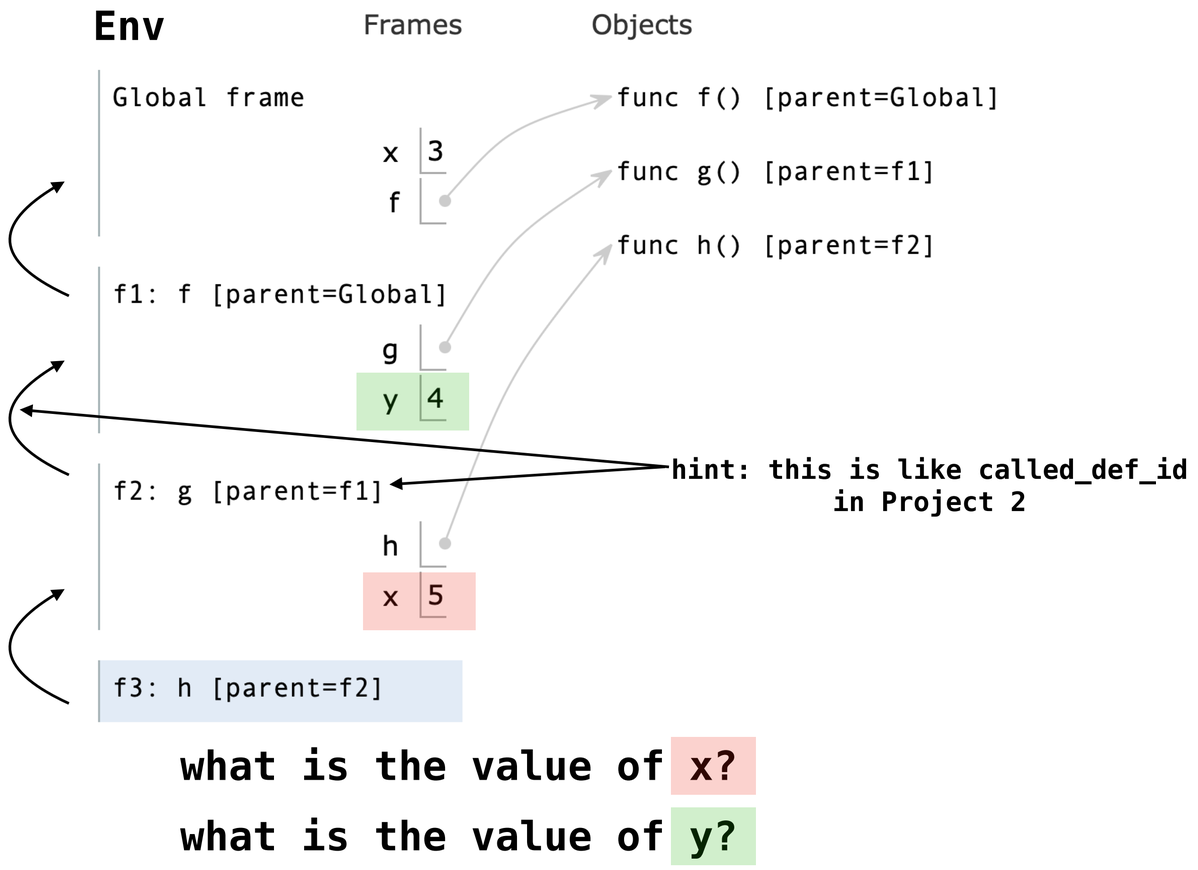


what is the value of x?

what is the value of y?

Take the first binding you see, going to higher nestings.

demo

(python tutor, example-5.py)

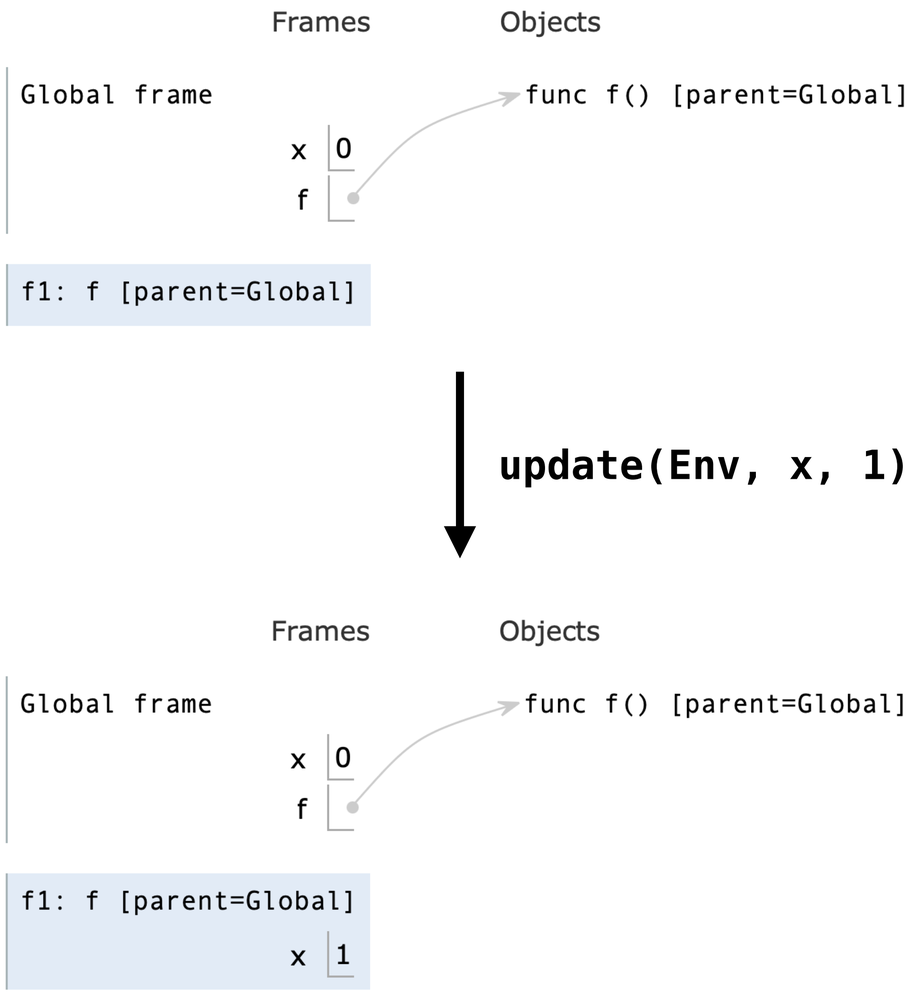
Updating the Environment

update(Env, x, v) algorithm:

» add the binding (x, v) to the topmost activation stack, rebinding if it already exists

updates always shadow existing assignments in lower records

Note. Its up to you if you want to use mutating or non-mutating updates, but think about what will happen with while loops...



demo

(python tutor, example-6.py)

A Note on Nested Subroutines

```python
def f():
    def g():
        return x

    x = 1
    y = g()
    x = 2
    z = g()
    return y == z


out = f()
```

Python

```
(f):
  (g):
    x Return
  ; ▷ g
  1 ▷ x
  g # ▷ y
  2 ▷ x
  g # ▷ z
  y z = Return
; ▷ f

f # ▷ out
```

Our Language

One important consequence of variables being mutable is that mutating variables should change the behavior of functions which use them.

Important. This is not dynamic scoping, x is in (lexical) scope for g.

demo

(python tutor, example-4.py)

Understanding Check

```python
def f():
    x = 0
    print(x)

def g():
    print(x)

x = 1
f()
g()
```

Python

```
(f):
  0 ▷ x
  x .
; ▷ f

(g): x . ; ▷ g

1 ▷ x
f #
g #
```

Our Language

What does this print under dynamic scoping?
under lexical scoping?

Answer

Dynamic:

0
1

Lexical:

1
1

```
(f):
  0 ▷ x
  x .
; ▷ f

(g): x . ; ▷ g

1 ▷ x
f #
g #
```

Closures

Recall: Higher-Order Programming

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(In OCaml and in our Toy Language)

There's some trickiness to this...

demo

(python tutor, example-3.py)

Closures

```
(Env, P, ...)
```

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A **closure** is a subroutine together with an environment and other data which may be useful for executing the function (name, pointer to activation record where the function is defined

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A **closure** is a subroutine together with an environment and other data which may be useful for executing the function (name, pointer to activation record where the function is defined

Env contains captured bindings, the bindings which were defined in records that don't exist when the function is called

(This is only a problem is the function is returned because that is when the defining record is discarded)

demo

(python tutor, example-3.py)

An Aside: Nonlocal Updates

In our language, updates always binds variables locally, shadowing preexisting bindings (same with "vanilla" python)

In some languages, we can update the variables nonlocally, this makes for more complicated semantics.

Closures are not enough for this.

demo

(python tutor, example-7.py)

reminder: we are not implementing this

Understanding Check

```
def f():
    x = 0
    def g():
        x = x + 1
        print(x)
    return g

h = f()
h()
h()
```

Python

```
(f):
  0 ▷ x
  (g):
    1 x + ▷ x
    x .
  ; ▷ g
; ▷ f
f # ▷ h
h #
h #
```

Our Language

What do these programs print (according to the semantics we've described so far)?

Answer

They both print:

1
1

(you should try to understand why this is the case from the level of semantics of Project 2)

Example from Project 2 (If there's time)

```
0 ▷ x
(f):
  1 ▷ x
  2 ▷ z
; ▷ f
f #
```