

Programming Abstractions

Week 9-1: Dynamic Bindings and Parameter Passing

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```
(define f
  (let ([x 1]
        [y 2])
    (λ (z) (if z x y))))
```

What is the value of `(f 10)`?

- A. This is a run-time error because 10 isn't a boolean
- B. This is some other sort of error
- C. 1
- D. 2
- E. None of the above

Dynamic binding vs. lexical binding

Scope of a declaration

The scope of a declaration is the portion of the expression or program to which that declaration applies

Lexical binding

- ▶ Scope of a variable is determined by textual layout of the program
- ▶ C, Java, Scheme/Racket use lexical binding

Dynamic binding

- ▶ Scope of a variable is determined by most recent *runtime* declaration
- ▶ Bash and classic Lisp use dynamic binding

What is the value of **y** in the body of (f 2)

```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

With lexical (also called static) binding: **y** is 3

- ▶ The value of **y** comes from the closest lexical binding of **y**, namely [y 3]

With dynamic binding: **y** is 17

- ▶ The value of **y** comes from the most-recent *run-time* binding of **y**, namely [y 17]

Lambdas in a lexically-scoped language

A lambda expression evaluates to a closure which is a triple containing

- ▶ the environment at the time the lambda is evaluated
- ▶ the parameters
- ▶ the body of the lambda

When we apply the closure to argument expressions

- ▶ we evaluate the arguments in the current environment
- ▶ extend the **closure's** environment with bindings of parameters to argument values
- ▶ evaluate the closure's body in the new environment

Lexical binding example

```
(let ([y 3])  
  (let ([f ( $\lambda$  (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

Lexical binding example

```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

Variable	Value
y	3

Lexical binding example

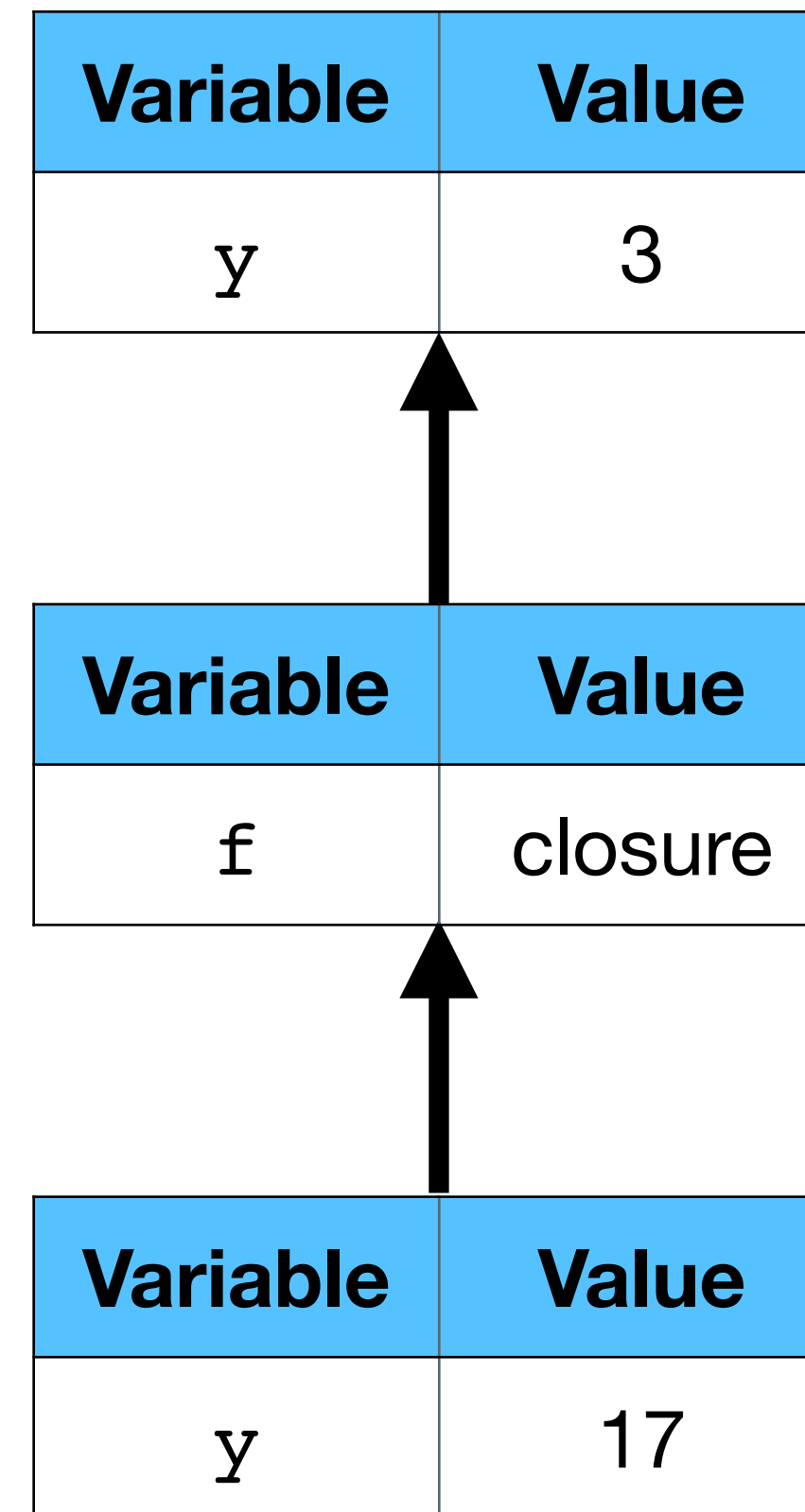
```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

Variable	Value
y	3

Variable	Value
f	closure

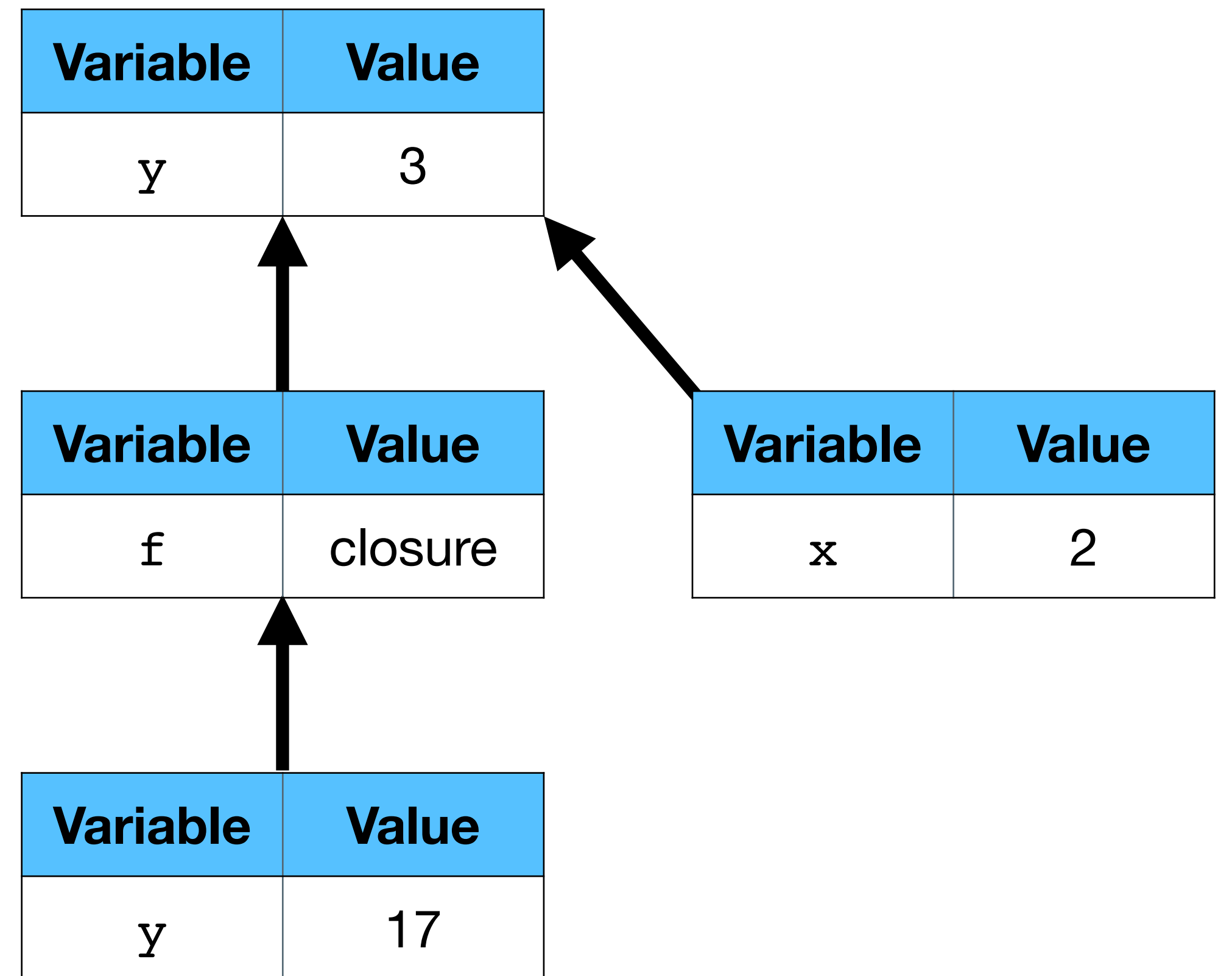
Lexical binding example

```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```



Lexical binding example

```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```



Lambdas in a dynamically-scoped language

A lambda expression evaluates to a procedure which is just a pair containing

- ▶ the parameters
- ▶ the body of the lambda

When we apply the procedure to argument expressions

- ▶ we evaluate the arguments in the current environment
- ▶ extend the **current** environment with bindings of parameters to argument values
- ▶ evaluate the lambda's body in the new environment

Dynamic binding example

```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

Dynamic binding example

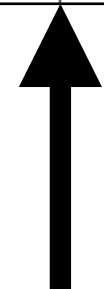
```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

Variable	Value
y	3

Dynamic binding example

```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

Variable	Value
y	3



Variable	Value
f	procedure

Dynamic binding example

```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

Variable	Value
y	3

Variable	Value
f	procedure

Variable	Value
y	17



Dynamic binding example

```
(let ([y 3])  
  (let ([f (λ (x) (+ x y))])  
    (let ([y 17])  
      (f 2))))
```

Variable	Value
y	3

Variable	Value
f	procedure

Variable	Value
y	17

Variable	Value
x	2



```
(let* ([x 10]
       [f (λ (x) (+ x x))])
  (f (- x 5)))
```

What is the value of this expression assuming lexical binding? What about dynamic binding?

A. Lexical: 10
Dynamic: 10

B. Lexical: 10
Dynamic: 20

C. Lexical: 20
Dynamic: 10

D. Lexical: 20
Dynamic: 20

E. None of the above

```
(let* ([x 10]
       [f (λ (y) (+ x y))])
      (f (- x 5)))
```

What is the value of this expression assuming lexical binding? What about dynamic binding?

A. Lexical: 15
Dynamic: 15

B. Lexical: 15
Dynamic: 10

C. Lexical: 10
Dynamic: 15

D. Lexical: Error
Dynamic: 10

E. None of the above

```
(define f
  (let ([z 100])
    (λ (x) (+ x z))))
```

```
(let ([z 10])
  (f 2))
```

- A. Lexical: 12
Dynamic: 12
- B. Lexical: 12
Dynamic: 102
- C. Lexical: 102
Dynamic: 12

What is the value of this let expression assuming lexical binding? What about dynamic binding?

- D. Lexical: 102
Dynamic: 102
- E. None of the above

Why was dynamic binding ever used?

It's easy to implement

- Dynamic binding was understood several years before static binding

It made sense to some people that $(\lambda (x) (+ x y))$ should use whatever the latest version of y is

Why do we now use lexical binding?

Most languages are derived from Algol-60 which used lexical binding

Compilers can use lexical addresses known at compile time for all variable references

Code from lexically-bound languages is easier to verify

- ▶ E.g., in Racket, we can ensure a variable is declared before it is used *before* we run the program
- ▶ It makes more sense to most people

Python example

```
def fun(x):  
    return lambda y: x + y  
  
def main():  
    f = fun(10)  
    print(f(7))          # Prints 17  
    x = 20  
    print(f(7))          # Prints 17  
  
main()
```

Bash example

```
1 #!/bin/bash
2
3 x=0
4
5 setx() {
6     x=$1
7 }
8
9 printx() {
10     echo "${x}"
11 }
12
```

```
13 main() {
14     printx # prints 0
15     setx 10
16     printx # prints 10
17     local x=25
18     printx # prints 25!
19     setx 100
20     printx # prints 100!
21 }
22
23 main
24 printx # prints 10
```


Parameter-passing mechanisms

Three mechanisms

Pass by value

- Arguments are evaluated in the caller's environment
- Argument values are bound to parameters

Pass by reference

- Arguments must be variables
- Addresses of arguments are bound to the parameters

Pass by name

- Arguments are not evaluated
- The text of the arguments is passed to the function and replace the parameters in the function's body

Aside: Mutation and sequencing

To see the difference between pass by value and pass by reference, we need to be able to mutate (modify) variables

In Scheme, `(set! var value)`

```
(let ([v 10])  
  (begin (displayln v) ; prints 10  
         (set! v 20)  
         (displayln v))) ; prints 20
```

`(begin exp1 ... expn)`

- ▶ Evaluates each expression and returns the value of the final one
- ▶ The other $n-1$ expressions are only useful for their *side effects* like printing or modifying variables
- ▶ `begin` isn't actually needed here, `let` allows multi-expression bodies

Pass by value vs. by reference

```
(let ([v 0]
      [f (λ (x) (set! x 34))])
  (f v)
  v)
```

Pass by value

- ▶ When evaluating `(f v)`, `x` is initially bound to 0
- ▶ The `(set! x 34)` sets the value of `x` to 34; `v` remains bound to 0
- ▶ The final `v` evaluates 0 and thus the whole expression evaluates to 0

Pass by reference

- ▶ When evaluating `(f v)`, `x` and `v` refer to the same variable with value 0
- ▶ The `(set! x 34)` sets the value of that variable to 34
- ▶ The final `v` (and the whole expression) evaluates to 34

```
(define (f x y)
  (let ([z x])
    (set! x (* y 2))
    (set! y (* z 3))))
(let ([a 1] [b 2])
  (f a b)
  (list a b))
```

What is the value of the let expression assuming pass by value? What about pass by reference?

A. Value: ' (1 2)

Reference: ' (1 2)

B. Value: ' (1 2)

Reference: ' (4 3)

C. Value: ' (4 3)

Reference ' (1 2)

D. Value: ' (1 2)

Reference: ' (4 12)

Pass by reference in Scheme (sort of)

We create a box which holds a value

The value of the box itself is the address of the variable and can be passed to functions

The value inside the box can be mutated

```
(let ([v (box 0)]  
      [f (λ (x) (set-box! x 34))])  
  (f v)  
  (unbox v)) ; Returns 34
```

Pass by value vs name

Pass by value

```
(let* ([v 0]
      [f (λ (x) ; Don't need begin in λ body
          (set! v (+ v 1))
          x)])
  (f (+ v 5)))
```

Pass by value

- ▶ `f` is called with value 5 so `x` is bound to 5
- ▶ `v` is set to 1
- ▶ `x` is returned

Pass by value vs name

Pass by name

```
(let* ([v 0]
       [f (λ (x) ; Don't need begin in λ body
            (set! v (+ v 1))
            x)])
  (f (+ v 5)))
```

Pass by name

- ▶ The text of `f`'s body becomes the two expressions (by replacing `x` with the text of the argument)

```
(set! v (+ v 1))
```

```
(+ v 5)
```

- ▶ `v` is set to 1 and then 6 is returned

Pass by name in Scheme: macros

```
(define-syntax-rule (name param1 ... paramn) body)
```

We can create macros where the arguments are substituted textually for the parameters (we'll probably discuss this more later in the semester)

```
(let ([v 0])
  (define-syntax-rule (f x)
    (begin
      (set! v (+ v 1))
      x))
  (f (+ v 5)))
```

This isn't quite the same as pass by name because Scheme macros don't allow free variables (here, `v` always refers to the `v` in the `let` expression)

Pass by x

Pass by value

- ▶ Easiest to understand and most common
- ▶ Used by Scheme, Java, C, Python, Bash, and most other languages

Pass by reference

- ▶ Allows modifying passed in variables which can be useful in languages that don't support returning multiple values
- ▶ Supported by C++, C#, Rust, and others

Pass by name

- ▶ Least common mechanism and by far the most difficult to reason about
- ▶ Used by macro languages like TeX, m4, and C's preprocessor
- ▶ Macro constructs in languages like Scheme and Rust

Pass by name in TeX

TeX is a macro language for writing documents

```
1 \def\work#1#2{%
2   All work and no play makes #1 a dull #2.\par
3 }
4 \def\sad#1#2dull{%
5   #1 a sad%
6 }
7 \work{Jack}{boy}
8 \work{\sad{Steve}}{professor}
9 \bye
```

All work and no play makes Jack a dull boy.

All work and no play makes Steve a sad professor.

Pass by name in the C preprocessor

```
1 #include <stdio.h>
2
3 #define swap(x, y) \
4     int tmp = x; \
5     x = y; \
6     y = tmp
7
8 int main() {
9     int arr[5] = {4, 4, 4, 4, 4};
10    int idx = 2;
11    swap(idx, arr[idx]);
12    printf("%d\n", idx);
13    printf("{%d, %d, %d, %d, %d}\n",
14           arr[0], arr[1], arr[2], arr[3], arr[4]);
15    return 0;
16 }
```

swap sets `idx` to 4 and then `arr[4]` to 2, `arr[2]` is unchanged!

Rust

```
1 fn by_value(mut x: u32) {
2     x += 1;
3 }
4
5 fn by_ref(x: &mut u32) {
6     *x += 1;
7 }
8
```

Prints

0
1
7

```
9 fn main() {
10     let mut v = 0;
11
12     macro_rules! by_name {
13         ($x:stmt) => {
14             v += 1;
15             $x
16         }
17     }
18
19     by_value(v);
20     println!("{}", v);
21     by_ref(&mut v);
22     println!("{}", v);
23     by_name!(v += 5);
24     println!("{}", v);
25 }
```

Implementing pass by reference

MiniScheme implements pass-by-value (or will, once you implement lambdas in the next homework)

We can make it pass-by reference by

- ▶ storing each value in a box;
- ▶ when calling functions, do not unbox the values, but pass the boxes as normal;
- ▶ unbox when performing primitive procedures

Implementing pass by name

We can make MiniScheme pass by name via function re-writing

- ▶ Don't evaluate arguments at all
- ▶ In `(apply-proc p args)`, rewrite the procedure's body (which is a parse tree) replacing each use of a parameter with the parse tree for the corresponding argument