

## Dynamic Scope

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The way in which names are looked up in Scheme and Python is called lexical scope (or static scope) [You can see what names are in scope by inspecting the definition]

**Lexical scope:** The parent of a frame is the environment in which a procedure was *defined*

**Dynamic scope:** The parent of a frame is the environment in which a procedure was *called*

Special form to create dynamically scoped procedures ( $\mu$  special form only exists in Project 4 Scheme)

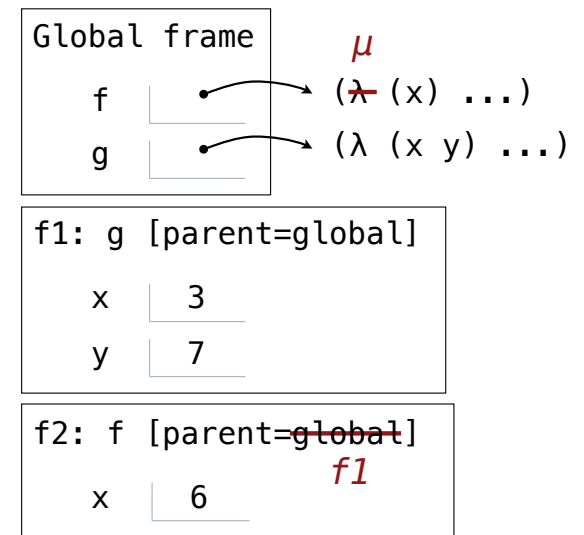
```
(define f (lambda  $\mu$  (x) (+ x y)))  
(define g (lambda (x y) (f (+ x x))))  
(g 3 7)
```

**Lexical scope:** The parent for f's frame is the global frame

*Error: unknown identifier: y*

**Dynamic scope:** The parent for f's frame is g's frame

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## Tail Recursion

## Functional Programming

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All functions are pure functions

No re-assignment and no mutable data types

Name-value bindings are permanent

Advantages of functional programming:

- The value of an expression is independent of the order in which sub-expressions are evaluated
- Sub-expressions can safely be evaluated in parallel or only on demand (lazily)
- **Referential transparency:** The value of an expression does not change when we substitute one of its subexpression with the value of that subexpression

But... no `for/while` statements! Can we make basic iteration efficient? Yes!

## Recursion and Iteration in Python

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In Python, recursive calls always create new active frames

`factorial(n, k)` computes:  $n! * k$

	<b>Time</b>	<b>Space</b>
<pre>def factorial(n, k):     if n == 0:         return k     else:         return factorial(n-1, k*n)</pre>	$\Theta(n)$	$\Theta(n)$
<pre>def factorial(n, k):     while n &gt; 0:         n, k = n-1, k*n     return k</pre>	$\Theta(n)$	$\Theta(1)$

## Tail Recursion

From the Revised<sup>7</sup> Report on the Algorithmic Language Scheme:

"Implementations of Scheme are required to be properly tail-recursive. This allows the execution of an iterative computation in constant space, even if the iterative computation is described by a syntactically recursive procedure."

```
(define (factorial n k)
  (if (zero? n) k
      (factorial (- n 1)
                  (* k n))))
```

Should use resources like

```
def factorial(n, k):
  while n > 0:
    n, k = n-1, k*n
  return k
```

How? Eliminate the middleman!

<b>Time</b>	<b>Space</b>
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$\Theta(n)$	$\Theta(1)$
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(Demo)

## Tail Calls

## Tail Calls

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A procedure call that has not yet returned is **active**. Some procedure calls are **tail calls**. A Scheme interpreter should support an **unbounded number** of active tail calls using only a **constant** amount of space.

A tail call is a call expression in a tail context:

- The last body sub-expression in a **lambda** expression
- Sub-expressions 2 & 3 in a tail context **if** expression
- All non-predicate sub-expressions in a tail context **cond**
- The last sub-expression in a tail context **and**, **or**, **begin**, or **let**

```
(define (factorial n k)
  (if (= n 0) k
      (factorial (- n 1)
                  (* k n))))
```



## Example: Length of a List

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```
(define (length s)
  (if (null? s) 0
      (+ 1 (length (cdr s)))))
```

Not a tail context

A call expression is not a tail call if more computation is still required in the calling procedure

Linear recursive procedures can often be re-written to use tail calls

```
(define (length-tail s)
  (define (length-iter s n)
    (if (null? s) n
        (length-iter (cdr s) (+ 1 n))))
  (length-iter s 0))
```

Recursive call is a tail call

## Eval with Tail Call Optimization

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The return value of the tail call is the return value of the current procedure call

Therefore, tail calls shouldn't increase the environment size

(Demo)

## Tail Recursion Examples

## Which Procedures are Tail Recursive?

Which of the following procedures run in constant space?  $\Theta(1)$

;; Compute the length of s.

```
(define (length s)
  (+ 1 (if (null? s)
           -1
           (length (cdr s)))))
```

;; Return the nth Fibonacci number.

```
(define (fib n)
  (define (fib-iter current k)
    (if (= k n)
        current
        (fib-iter (+ current
                     (fib (- k 1)))
                  (+ k 1))))
  (if (= 1 n) 0 (fib-iter 1 2)))
```

;; Return whether s contains v.

```
(define (contains s v)
  (if (null? s)
      false
      (if (= v (car s))
          true
          (contains (cdr s) v))))
```

;; Return whether s has any repeated elements.

```
(define (has-repeat s)
  (if (null? s)
      false
      (if (contains? (cdr s) (car s))
          true
          (has-repeat (cdr s)))))
```

## Map and Reduce

## Example: Reduce

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```
(define (reduce procedure s start)
  (if (null? s) start
      (reduce procedure
                (cdr s)
                (procedure start (car s)))))
```

Recursive call is a tail call

Space depends on what `procedure` requires

```
(reduce * '(3 4 5) 2)
```

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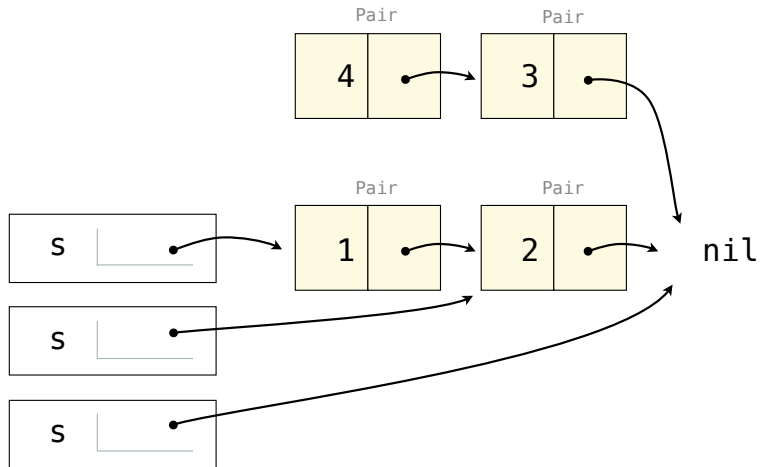
```
(reduce (lambda (x y) (cons y x)) '(3 4 5) '(2))
```

(5 4 3 2)

## Example: Map with Only a Constant Number of Frames

```
(define (map procedure s)
  (if (null? s)
      nil
      (cons (procedure (car s))
            (map procedure (cdr s))))))
```

```
(map (lambda (x) (- 5 x)) (list 1 2))
```



```
(define (map procedure s)
  (define (map-reverse s m)
    (if (null? s)
        m
        (map-reverse (cdr s)
                      (cons (procedure (car s))
                            m))))
  (reverse (map-reverse s nil)))
```

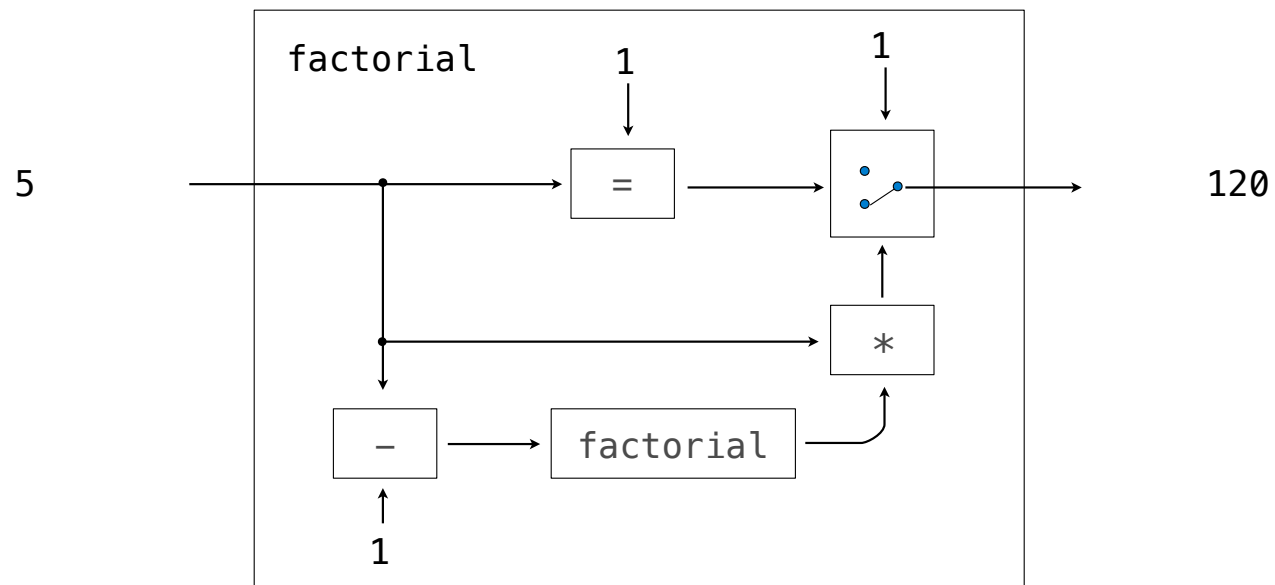
```
(define (reverse s)
  (define (reverse-iter s r)
    (if (null? s)
        r
        (reverse-iter (cdr s)
                      (cons (car s) r))))
  (reverse-iter s nil))
```

# General Computing Machines



## An Analogy: Programs Define Machines

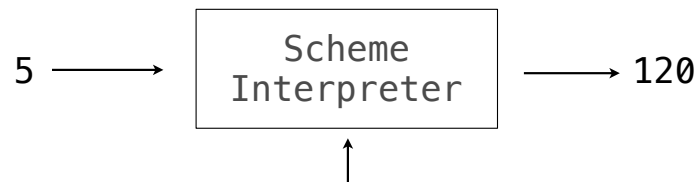
Programs specify the logic of a computational device



## Interpreters are General Computing Machine

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An interpreter can be parameterized to simulate any machine



```
(define (factorial n)
  (if (zero? n) 1 (* n (factorial (- n 1)))))
```

Our Scheme interpreter is a universal machine

A bridge between the data objects that are manipulated by our programming language and the programming language itself

Internally, it is just a set of evaluation rules