Interpreters

Translation

Problem:

Computers can only understand one language, binary (0s and 1s)

Humans can't really write a program using only 0s and 1s (not quickly anyways)

Solution:

Programming languages

Languages like Python, Java, C, etc are *translated* to 0s and 1s

This translation step comes in a couple forms:

- Compiled (pre-translated) - translate all at once and run later
- Interpreted (translated on-the-fly) - translate while the program is running

We'll focus on interpreted languages

Interpreters

An **interpreter** does 3 things:

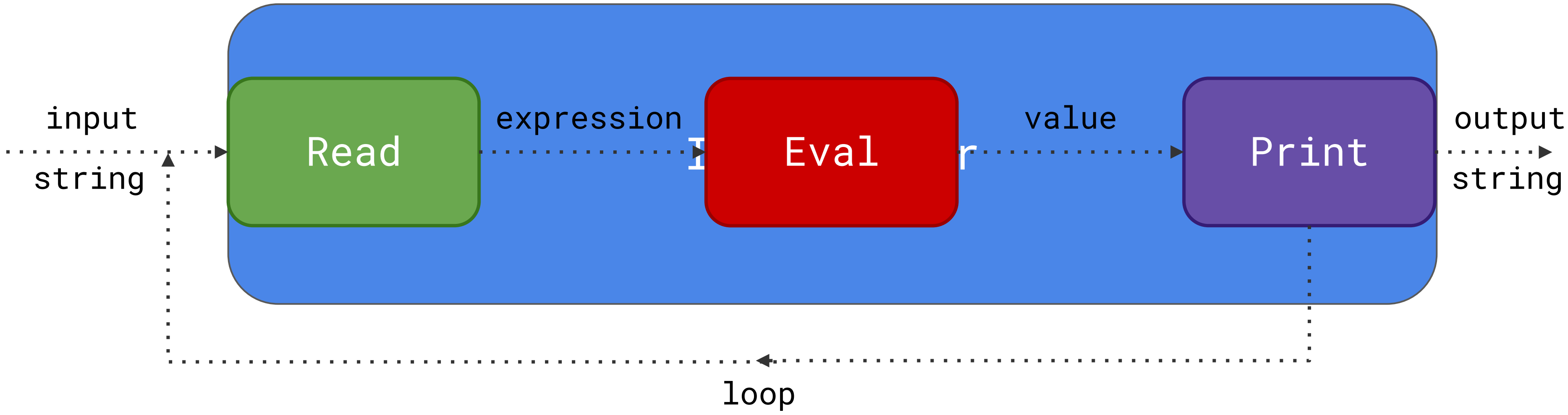
- **Reads** input from user in a specific programming language
- Translates input to be computer readable and **evaluates** the result
- **Prints** the result for the user

There are two languages involved:

- **Implemented language:** this is the language the user types in
- **Implementation language:** this is the language interpreter is implemented in

Implemented Language is translated into the **Implementation Language**

Read-Eval-Print Loop (REPL)



```
while True:
    exp = read()
    val = eval(exp)
    print(val)
```

Read

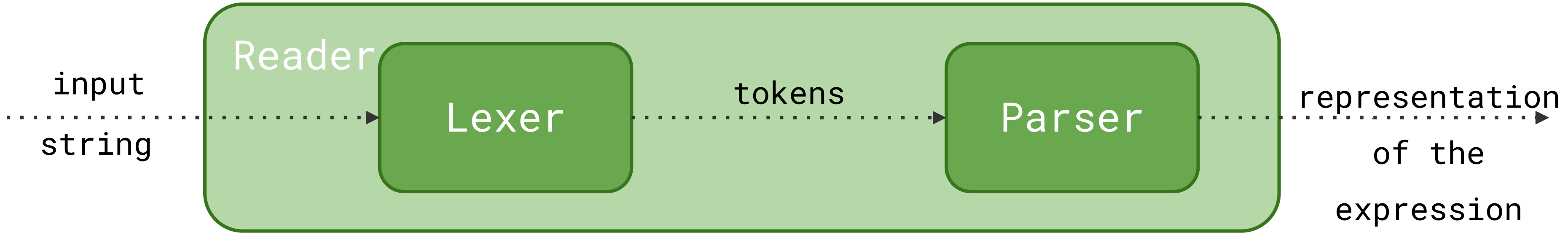
Reading Input

Lexical Analysis (Lexer): Turning the input into a collection of *tokens*

- A token: single input of the input string, e.g. literals, names, keywords, delimiters

Syntactic Analysis (Parser): Turning tokens into a representation of the expression in the implementing language

- The exact "representation" depends on the type of expression
- Types of Scheme Expressions: self-evaluating expressions, symbols, call expressions, special form expressions.



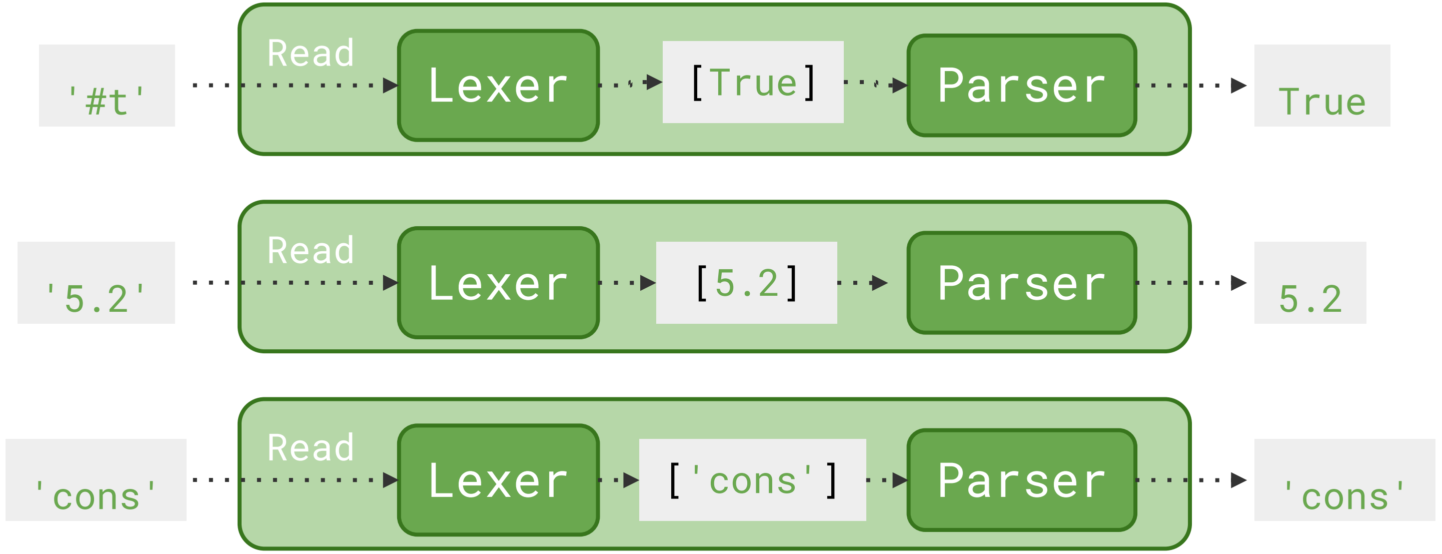
Representing Scheme Primitive Expressions

Self-Evaluating expressions *(booleans and numbers)*

Use Python booleans and Python numbers

Symbols

Use Python strings



Representing Combinations

```
(<operator> <operand1> <operand2> ...)
```

Combinations are just Scheme lists containing an operator and operands.

```
scm> (define expr '(+ 2 3)) ; Create the expression (+ 2 3)
expr
scm> (eval expr)            ; Evaluate the expression
5
scm> (car expr)             ; Get the operator
+
scm> (cdr expr)             ; Get the operands
(2 3)
```

```
>>> expr = ['+', 2, 3]  # Representation of (+ 2 3)
>>> expr[0]             # Get the operator
'+'
>>> expr[1:]            # Get the operands
[2, 3]
```

Works, but isn't an exact representation of Scheme lists.

Python Pairs

To accurately represent Scheme combinations as linked lists, let's write a `Pair` class in Python!

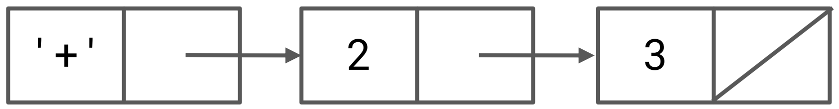
```
class Pair:
    def __init__(self, first, second):
        self.first = first
        self.second = second

    def __repr__(self):
        return 'Pair({0}, {1})'.format(
                    self.first, self.second)
```

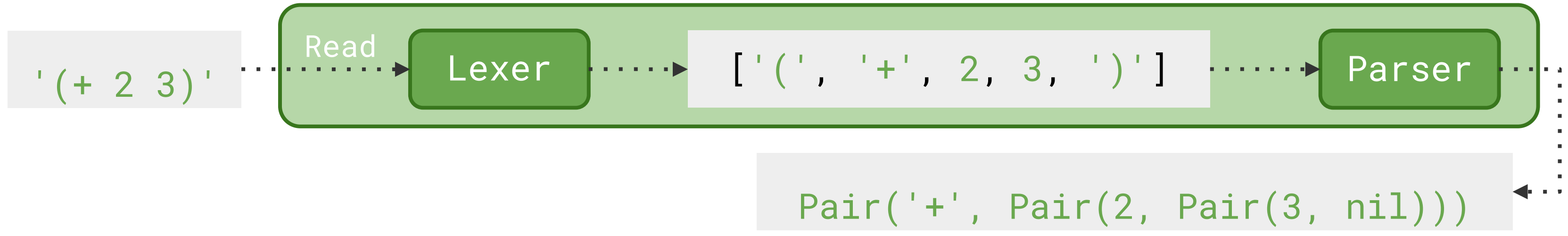
```
class nil:
    def __repr__(self):
        return 'nil'

nil = nil()
```

There is one instance of nil. No other instances can be created.

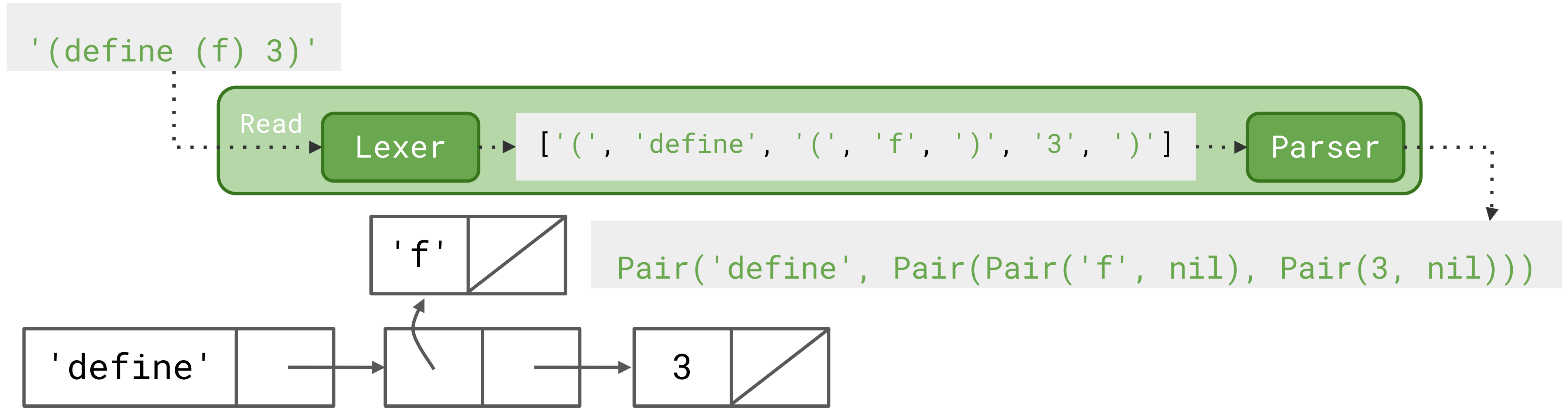
```
>>> expr = Pair('+', Pair(2, Pair(3, nil))) # Represent (+ 2 3)
>>> expr.first                              # Get the operator
'+'
>>> expr.second                             # Get the operands
Pair(2, Pair(3, nil))
```

Reading Combinations





```
'(+ 2 3)'
['(', '+', 2, 3, ')']
Pair('+', Pair(2, Pair(3, nil)))
```



```
'(define (f) 3)'
['(', 'define', '(', 'f', ')', '3', ')']
Pair('define', Pair(Pair('f', nil), Pair(3, nil)))
```

Special Case: quote

Recall that the quote special form can be invoked in two ways:

`(quote <expr>)`

```
scm> 'hello
hello
scm> (quote hello)
hello
```

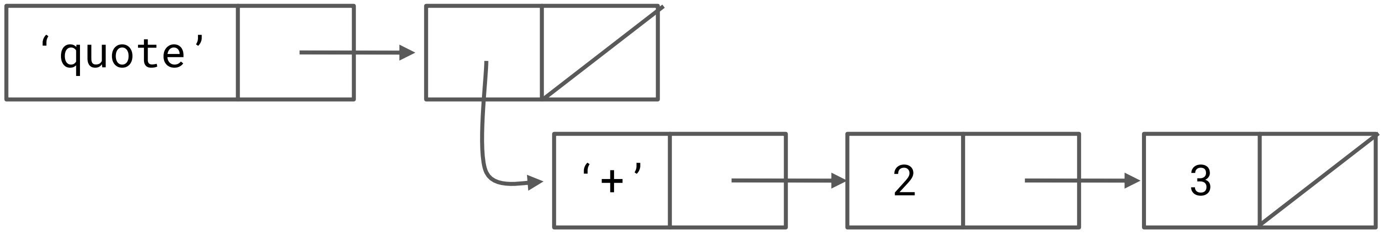
`'<expr>`

```
scm> '(1 2 3 4)
(1 2 3 4)
scm> (quote (1 2 3 4))
(1 2 3 4)
```

The special `'` syntax gets converted by the reader into a `quote` expression, which is a list with 2 elements:

`Pair('quote', Pair(<expr>, nil))`

`'(+ 2 3)`



`Pair('quote', Pair(Pair('+', Pair(2, Pair(3, nil))), nil))`

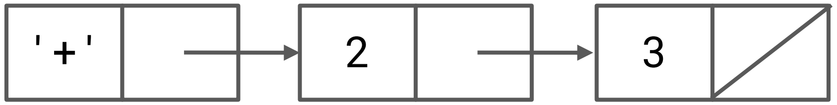
Check your understanding

How would each of the Scheme expressions below be represented in Python when read by our interpreter? If it would be a Pair object, write out the constructor call for that Pair and draw out the corresponding box-and-pointer diagram.

ex) `(+ 2 3)`

```
Pair('+', Pair(2, Pair(3, nil)))
```

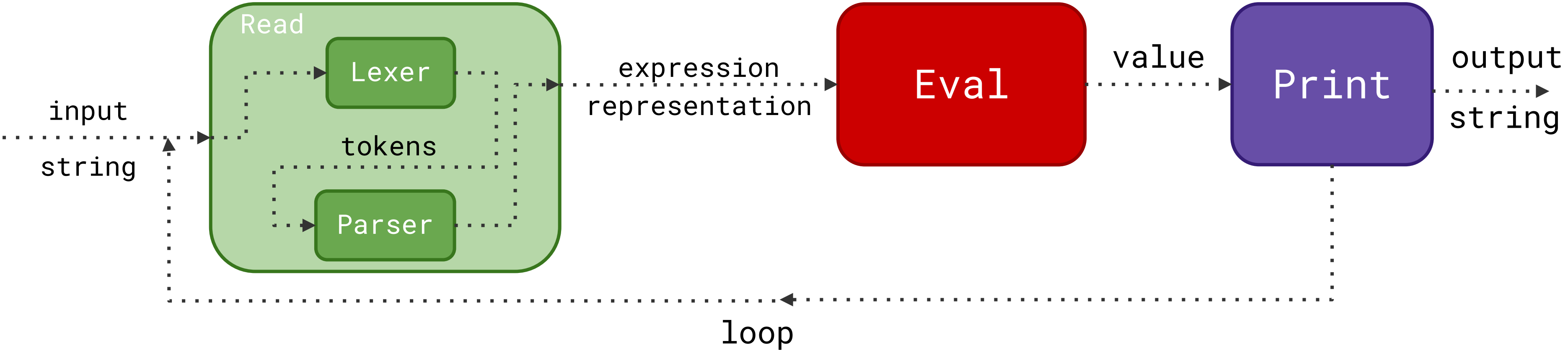
1) `4.67`
2) `#t`
3) `list`
4) `(cons 2 3)`
5) `(if (< x 0) 1 (+ x 1))`
6) `'hello`



Check your understanding (soln)

```
1) 4.67
   4.67

1) #t
   True

1) list
   'list'

1) (cons 2 3) ; lexer/parser does not care about this: 3 should be a pair
   Pair('cons', Pair(2, Pair(3, nil)))

1) (if (< x 0) 1 (+ x 1))
   Pair('if', Pair(Pair('<', Pair('x', Pair(0, nil))), Pair(1, Pair(Pair('+',
   Pair('x', Pair(1, nil))), nil))))

1) 'hello
   Pair('quote', Pair('hello', nil))
```

Read-Eval-Print Loop (REPL)

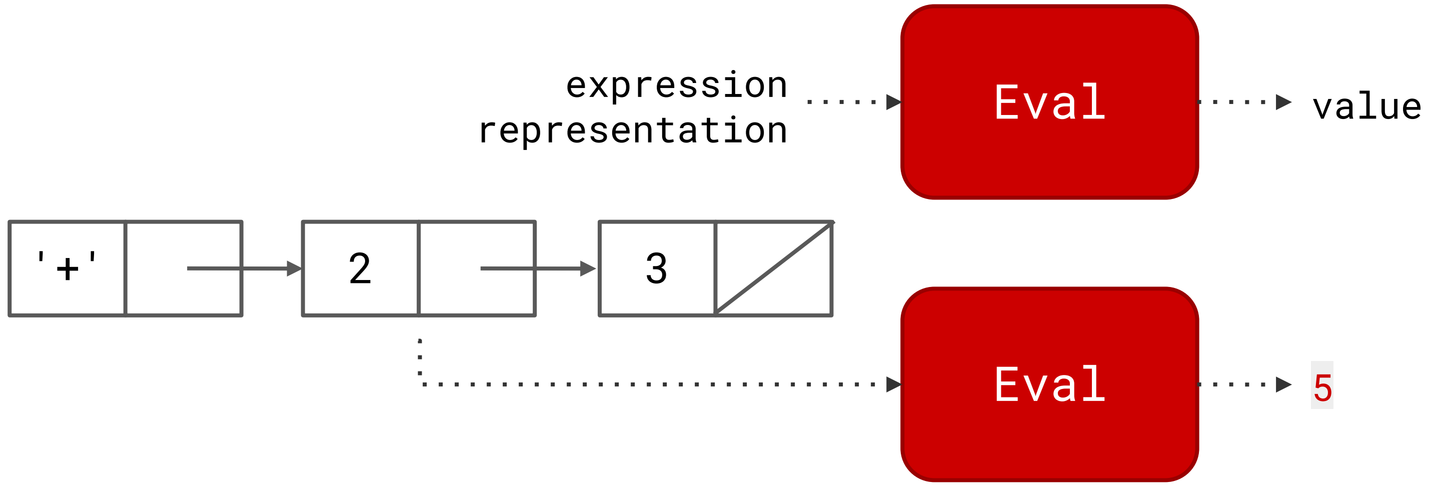


Eval

Evaluating Expression

Rules for evaluating an expression depends on the expression's type.

Types of Scheme expressions: self-evaluating expressions, symbols, call expressions, special form expressions

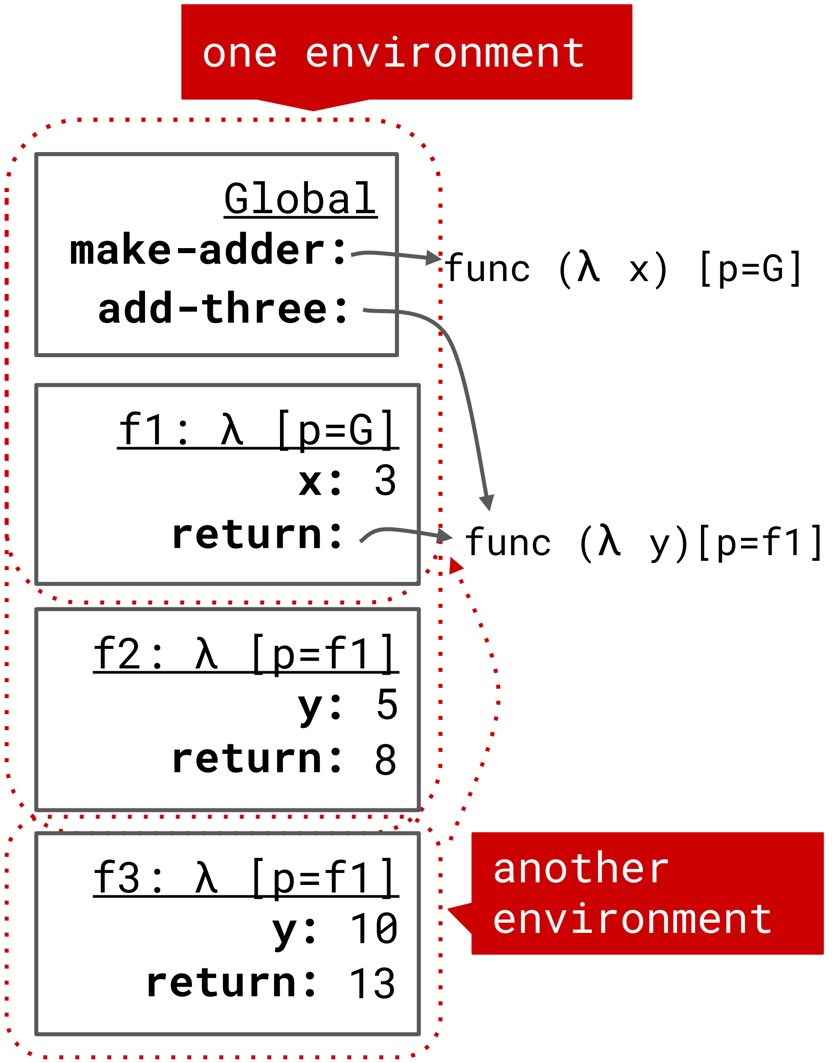


Eval takes in one argument besides the expression itself: the current environment.

Frames and Environments

When evaluating expressions, the current **environment** consists of the current frame, its parent frame, and all its ancestor frames until the Global Frame.

```
(define (make-adder x)
    (lambda (y) (+ x y)))

(define add-three (make-adder 3))

(add-three 5)

(add-three 10)
```



Frames in our interpreter

Frames are represented in our interpreter as instances of the **Frame** class

Each **Frame** instance has two instance attributes:

- **bindings**: a dictionary that binds Scheme symbols (Python strings) to Scheme values
- **parent**: the parent frame, another **Frame** instance

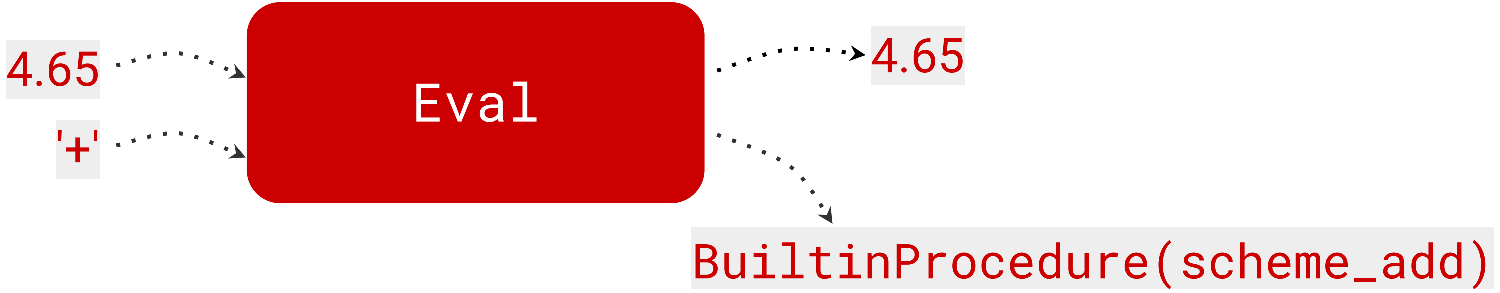
The evaluator needs to know the current environment, given as a single **Frame** instance, in order to look up names in expressions.

Evaluating primitive expressions

Self-evaluating expressions: These expressions evaluate to themselves.

Symbols:

1) Look in the current frame for the symbol. If it is found, return the value bound to it.
2) If it is not found in the current frame, look in the parent frame. If it is not found in the parent frame, look in its parent frame, and so on.
3) If the global frame is reached and the name is not found, raise a `SchemeError`.



Evaluating Combinations

`(<operator> <operand1> <operand2> …)`

The operator of a combination tells us whether it is a special form expression or a call expression.

If the operator is a symbol and is found in the dictionary of special forms, the combination is a special form.

- Each special form has special rules for evaluation.

Otherwise, the combination is a call expression.

First two steps are recursive calls to eval.

Step 1. Evaluate the operator to get a procedure.

Step 2. Evaluate all of the operands from left to right.

Step 3. Apply the procedure to the values of the operands.

How does apply work?

Types of Procedures

A **built-in procedure** is a procedure that is predefined in our Scheme interpreter, e.g. `+`, `list`, `modulo`, etc.

- Each built-in procedure has a corresponding Python function that performs the appropriate operation.
- In our interpreter -- instances of the `BuiltinProcedure` class

A **user-defined procedure** is a procedure defined by the user, either with a lambda expression or a define expression.

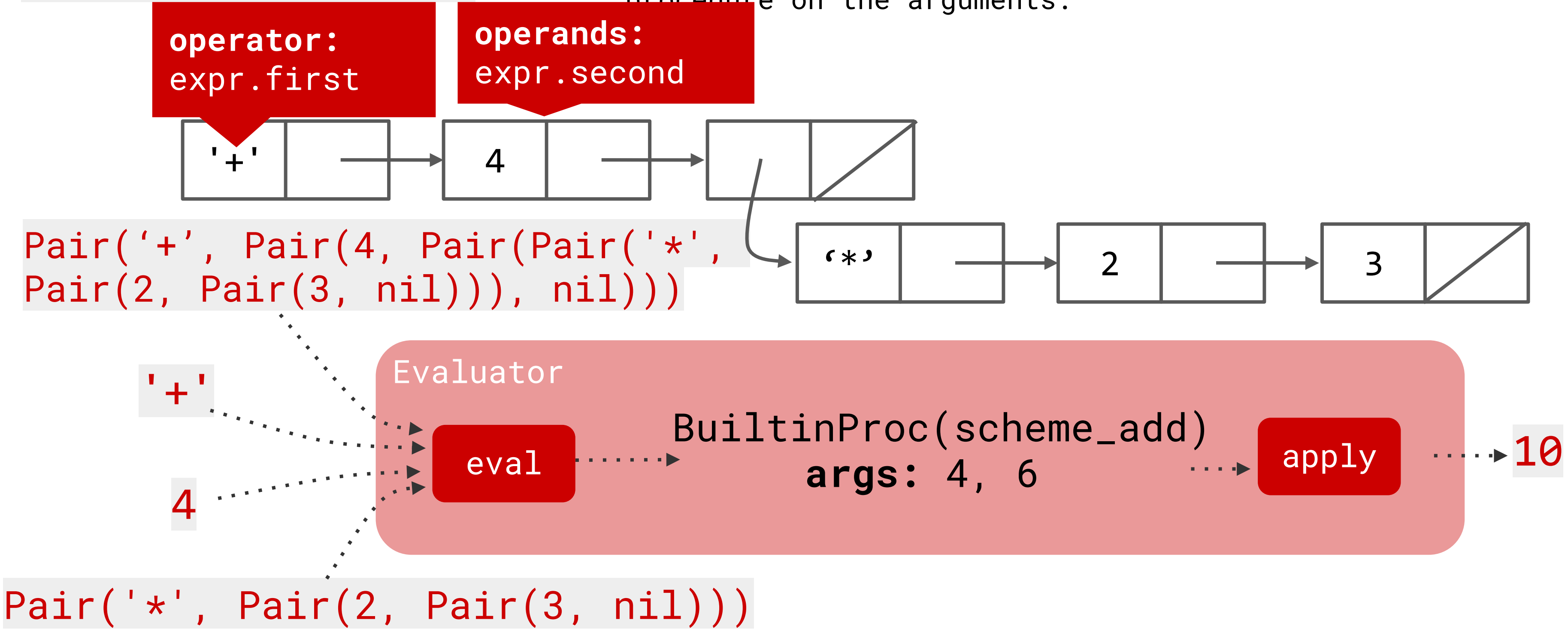
- Each user-defined procedure has
  1. a list of formal parameters
  2. a body (which is a Scheme list)
  3. a parent frame.
- In our interpreter -- instances of the `LambdaProcedure` class

Built-In Procedures

```
scm> (+ 4 (* 2 3))
10
```

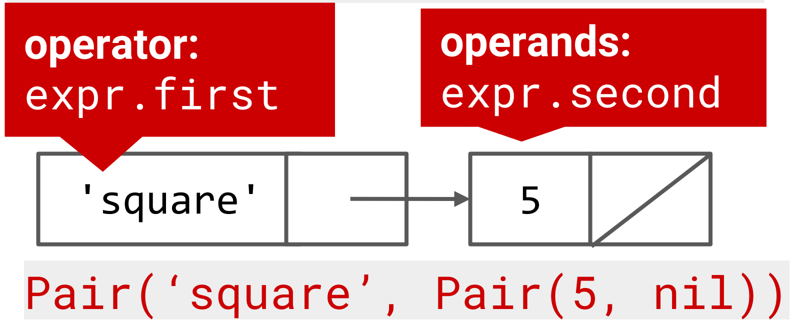
Applying built-in procedures:

- Call the Python function that implements the built-in procedure on the arguments.

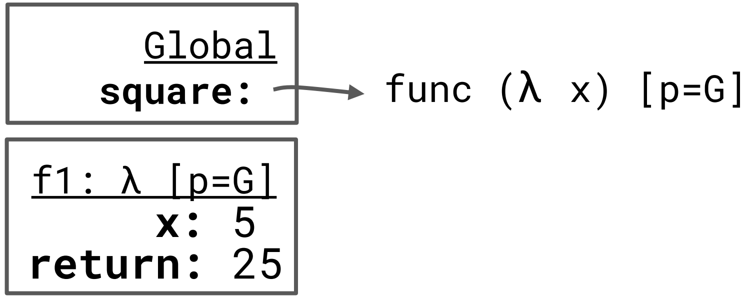


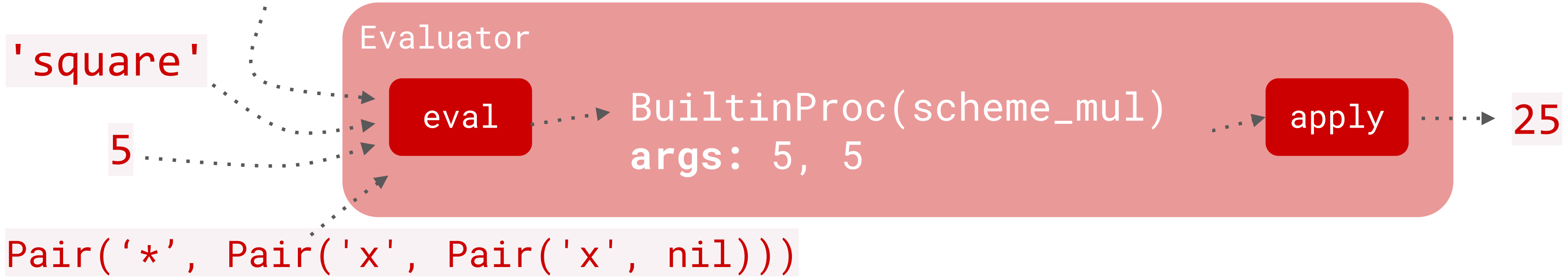
User-Defined Procedures

```
scm> (define (square x) (* x x))
square
scm> (square 5)
25
```



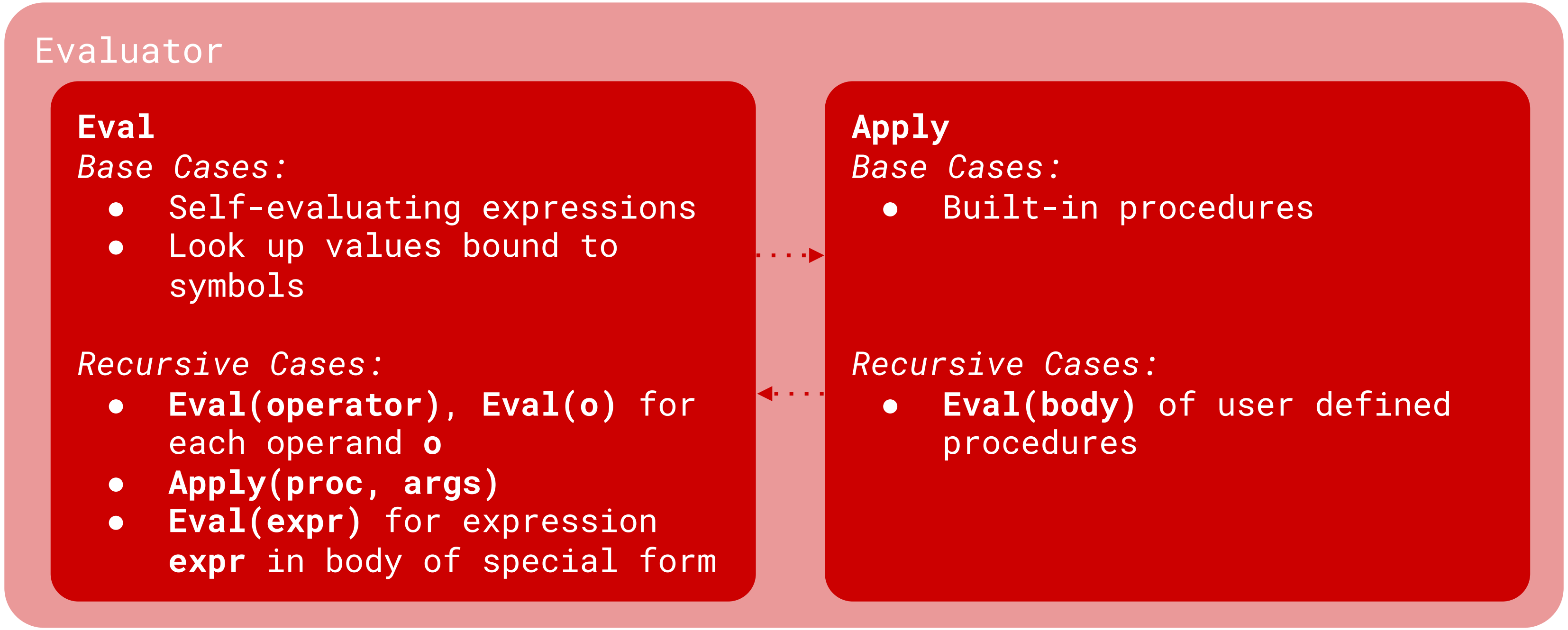
Applying user-defined procedures:
Step 1. Open a new frame whose parent is the parent frame of the procedure being applied.
Step 2. Bind the formal parameters of the procedure to the arguments in the new frame.
Step 3. Evaluate the body of the procedure in the new frame.





The evaluator

The evaluator consists of two *mutually-recursive* components:



Evaluator

Eval

Base Cases:

- Self-evaluating expressions
- Look up values bound to symbols

Recursive Cases:

- **Eval(operator)**, **Eval(o)** for each operand **o**
- **Apply(proc, args)**
- **Eval(expr)** for expression **expr** in body of special form

Apply

Base Cases:

- Built-in procedures

Recursive Cases:

- **Eval(body)** of user defined procedures

Counting eval/apply calls: built-in procedures

How many calls to eval and apply are made in order to evaluate this expression?

```
(+ 2 (* 4 1) 5)
```

- **eval**(Pair('+',
  Pair(2,
  Pair(Pair('*', Pair(4, Pair(1, nil))),
  Pair(5, nil)))))
  - **eval**('+')
  - **eval**(2)
  - **eval**(Pair('*', Pair(4, Pair(1, nil))))
    - **eval**('*')
    - **eval**(4)
    - **eval**(1)
    - **apply**(BuiltinProc(scheme_mul), [4, 1])
  - **eval**(5)
  - **apply**(BuiltinProc(scheme_add), [2, 4, 5])

# calls:
eval: 8
apply: 2

Counting eval/apply calls: user-defined procedures

How many calls to eval and apply are made in order to evaluate the second expression? (Assume the define expression has already been evaluated.)

```
(define (f x) (+ x 1))
(* (f 3) 2)
```

- **eval**(Pair('*',
  Pair(Pair('f', Pair(3, nil))
  Pair(2, nil))))
  - **eval**('*')
  - **eval**(Pair('f', Pair(3, nil)))
    - **eval**('f')
    - **eval**(3)
    - **apply**(λ, 3)
      - **eval**(Pair('+', Pair('x', Pair(1, nil))))
        - **eval**('+')
        - **eval**('x')
        - **eval**(1)
        - **apply**(BuiltinProc(scheme_add), [3, 1])
  - **eval**(2)
  - **apply**(BuiltinProc(scheme_mul), [4, 2])

# calls:
eval: 10
apply: 3