Announcements
Programming Languages
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def square(x):
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**Python 3 Byte Code**

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LOAD_FAST                0 (x)
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from dis import dis
dis(square)

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Metalinguistic Abstraction

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To create a new programming language, you either need a:

- **Specification**: A document that describes the precise syntax and semantics of the language.
- **Canonical Implementation**: An interpreter or compiler for the language.
Parsing
Reading Scheme Lists
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A Scheme list is written as elements in parentheses:
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(<element_0> <element_1> ... <element_n>)
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(Demo)

http://composingprograms.com/examples/scalc/scheme_reader.py.html
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A Parser takes text and returns an expression
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Parsing

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Text → Lexical analysis → Tokens → Expression
A Parser takes text and returns an expression.
A Parser takes text and returns an expression

Text

Lexical analysis

Tokens

Syntactic analysis

Expression

'( + 1'
' (− 23)'
' (* 4 5.6))'
A Parser takes text and returns an expression.

Text

Lexical analysis

Tokens

Syntactic analysis

Expression

'(+ 1'
'  (- 23)'
'  (* 4 5.6))'
A Parser takes text and returns an expression.
A Parser takes text and returns an expression

- Text: `(+ 1
  (- 23)
  (* 4 5.6))`
- Lexical analysis: tokens: `(', '+', 1, '(', '-', 23, ')', '(', '−', 23, ')', '(', '*', 4, 5.6, ')')`
- Syntactic analysis: expression: `(+ 1, (- 23), (* 4 5.6))`
Parsing

A Parser takes text and returns an expression

Text: 

- (+ 1)
- (- 23)
- (* 4 5.6)

Lexical analysis:

- '('
- '+'
- '1'
- '(-'
- '23, '
- ')

Tokens:

- '('
- '+', 1
- '(-', '23, ')

Syntactic analysis:

- '('
- '+', 1
- '(-', '23, ')

Expression:
A Parser takes text and returns an expression

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Tokens

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Text | Lexical analysis | Tokens | Syntactic analysis | Expression
---|------------------|--------|-------------------|--------
'+ 1' | '(' '+', 1 | '(' '+', 1 | '(' '+', 1 | '(' '+', 1 |
'(- 23)' | '(' '-', 23, ')' | '(' '-', 23, ')' | '(' '-', 23, ')' | '(' '-', 23, ')' |
'(* 4 5.6)' | '(' '*', 4, 5.6, ')' | '(' '*', 4, 5.6, ')' | '(' '*', 4, 5.6, ')' | '(' '*', 4, 5.6, ')' |
Parsing

A Parser takes text and returns an expression

- **Lexical analysis**
- **Tokens**
- **Syntactic analysis**
- **Expression**

- Iterative process

\[ (+ 1) \]
\[ (- 23) \]
\[ (* 4 \ 5.6) \]

\[ (', '+', 1) \]
\[ (', '-', 23, ') \]
\[ (', '*', 4, 5.6, '), ') \]
Parsing

A Parser takes text and returns an expression

- Lexical analysis
  - Tokens
  - Syntactic analysis

- Iterative process
- Checks for malformed tokens
A Parser takes text and returns an expression

### Lexical Analysis

- '(+ 1)
- '(- 23)
- '(* 4 5.6)

### Syntactic Analysis

- '(, '+', 1
- '(, '-', 23, ')
- '(, '*', 4, 5.6, ')', ')

- Iterative process
- Checks for malformed tokens
- Determines types of tokens
A Parser takes text and returns an expression

• Iterative process
• Checks for malformed tokens
• Determines types of tokens
• Processes one line at a time
A Parser takes text and returns an expression.

- **Lexical analysis**
  - Iterative process
  - Checks for malformed tokens
  - Determines types of tokens
  - Processes one line at a time

- **Tokens**
  - Tokens are broken into smaller units.

- **Syntactic analysis**
  - Converts tokens into a meaningful expression.
Parsing

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**Lexical analysis**
- Iterative process
- Checks for malformed tokens
- Determines types of tokens
- Processes one line at a time

**Syntactic analysis**
- Tree-recursive process

- Printed as:

```
(+ 1 (- 23) (* 4 5.6))
```

Text:
- '(+ 1'
- '(- 23)'
- '(* 4 5.6))'

Tokens:
- '(' '+', 1
- '(-, '+', 23, ')''
- '(*, '+', 4, 5.6, ')', ')''

Expression:
- Pair('+', Pair(1, ...))

```
A Parser takes text and returns an expression

- Iterative process
- Checks for malformed tokens
- Determines types of tokens
- Processes one line at a time

• Tree-recursive process
• Balances parentheses

Text

Lexical analysis

Tokens

Syntactic analysis

Expression

'(+ 1
   (- 23)
   (* 4 5.6))'

Pair('+', Pair(1, ...))

printed as

(+ 1 (- 23) (* 4 5.6))
A Parser takes text and returns an expression

Lexical analysis

Syntax analysis

Text

Tokens

Expression

- Iterative process
- Checks for malformed tokens
- Determines types of tokens
- Processes one line at a time

- Tree-recursive process
- Balances parentheses
- Returns tree structure
A Parser takes text and returns an expression

<table>
<thead>
<tr>
<th>Text</th>
<th>Lexical analysis</th>
<th>Tokens</th>
<th>Syntactic analysis</th>
<th>Expression</th>
</tr>
</thead>
</table>
| '(+ 1'  
  '(' - 23)'  
  '(* 4 5.6)')' | (', '+', 1  
                  '(, '-', 23, ')')  
                  '(' (*', 4, 5.6, ')', ')' | Pair('+', Pair(1, ...))  
  *printed as*  
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- Iterative process
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**Recursive call:** scheme_read sub-expressions and combine them.
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\[ '(', '+', 1, '(' , '-', 23, ')', '(' , '*', 4, 5.6, ')', ')' \]

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```
'(, '+', 1, '(, '-', 23, ')', '(, '*', 4, 5.6, ')', ')
```

Base case: symbols and numbers

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'(, '+', 1, '(, '-', 23, ')'), '(, '*', 4, 5.6, ')', ')
```

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**Recursive call:** scheme_read sub-expressions and combine them
**Syntactic Analysis**

Syntactic analysis identifies the hierarchical structure of an expression, which may be nested.

Each call to `scheme_read` consumes the input tokens for exactly one expression:

```
'( '+', 1, '( '+', '−', 23, ')', '( '+', '∗', 4, 5.6, ')', ')
```

*Base case:* symbols and numbers

*Recursive call:* `scheme_read` sub-expressions and combine them
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Each call to scheme_read consumes the input tokens for exactly one expression.

'(', '+', 1, '(, '-', 23, ')', '(, '*', 4, 5.6, ')', ')

Base case: symbols and numbers

Recursive call: scheme_read sub-expressions and combine them.
Syntactic Analysis

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Each call to scheme_read consumes the input tokens for exactly one expression.

```latex
'( ', '+', 1, '(', '−', 23, ')', '(', '*', 4, 5.6, ')', ')
```

**Base case:** symbols and numbers

**Recursive call:** scheme_read sub-expressions and combine them

(Demo)
Scheme-Syntax Calculator

(Demo)
The Pair Class

The Pair class represents Scheme pairs and lists. A list is a pair whose second element is either a list or nil.
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class Pair:
    """A Pair has two instance attributes: first and second.

    For a Pair to be a well-formed list, second is either a well-formed list or nil.
    Some methods only apply to well-formed lists.
    """
    def __init__(self, first, second):
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(1 2 3)
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(1 . 2)
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(1 2 . 3)
>>> len(Pair(1, Pair(2, 3)))
Traceback (most recent call last):
  ...TypeError: length attempted on improper list
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Scheme expressions are represented as Scheme lists! Source code is data
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(Demo)
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A primitive expression is a number: 2 -4 5.6

A call expression is a combination that begins with an operator (+, -, *, /) followed by 0 or more expressions: (+ 1 2 3) (/ 3 (+ 4 5))
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Expressions are represented as Scheme lists (Pair instances) that encode tree structures.

**Expression**

\[
(* 3 \\
  (+ 4 5) \\
  (* 6 7 8))
\]
Calculator Syntax

The Calculator language has primitive expressions and call expressions. (That's it!)

A primitive expression is a number: 2 -4 5.6

A call expression is a combination that begins with an operator (+, -, *, /) followed by 0 or more expressions: (+ 1 2 3) (/ 3 (+ 4 5))

Expressions are represented as Scheme lists (Pair instances) that encode tree structures.
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**Calculator Semantics**

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+: Sum of the arguments
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**Expression**

```
(+ 5
  (* 2 3)
  (* 2 5 5))
```
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![Expression Tree](attachment:expression_tree.png)
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---

**Expression**

\[
(+ 5 \\
(* 2 3) \\
(* 2 5 5))
\]

**Expression Tree**

```
  +
 /\ 
 /  \ 
5  6
/  /\ 
* 2 3  * 2 5 5
```

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```
Expression  |  Expression Tree
-----------|------------------
(+ 5  (* 2 3)  (* 2 5 5)) | + 5 6 50
```

```
          +
         /  
        6   50
       /   /  
      *   *   
     2   3   5 5
```
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**Expression**

\[ (+ 5 \text{\footnotesize \begin{align} &(* 2 3) \\ &(* 2 5 5)) \end{align}} \]

**Expression Tree**

```
+ 5
  /\ 6
  /\ 3
  /\ 2
  /\ 5
    /\ 5
```
Evaluation
The Eval Function
The Eval Function

The eval function computes the value of an expression, which is always a number.
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It is a generic function that dispatches on the type of the expression (primitive or call).
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<table>
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<th>Implementation</th>
<th>Language Semantics</th>
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The Eval Function

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It is a generic function that dispatches on the type of the expression (primitive or call).

---

**Implementation**

```python
def calc_eval(exp):
    if type(exp) in (int, float):
        return exp
    elif isinstance(exp, Pair):
        arguments = exp.second.map(calc_eval)
        return calc_apply(exp.first, arguments)
    else:
        raise TypeError
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#### Language Semantics

A number evaluates...
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### Language Semantics

- **A number evaluates...**
  - to itself

- **A call expression evaluates...**
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  - to its argument values
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**Language Semantics**

- **A number evaluates...**
  to itself

- **A call expression evaluates...**
  to its argument values
  combined by an operator
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*to itself*

*A call expression evaluates...*  
*to its argument values combined by an operator*
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**Language Semantics**

- **A number evaluates...**
  - to itself
- **A call expression evaluates...**
  - to its argument values combined by an operator

Recursive call returns a number for each operand

A Scheme list of numbers

'+', '-', '*', '/'
Applying Built-in Operators
Applying Built-in Operators

The apply function applies some operation to a (Scheme) list of argument values
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In calculator, all operations are named by built-in operators: +, -, *, /.
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<tbody>
<tr>
<td>def calc_apply(operator, args):</td>
<td></td>
</tr>
<tr>
<td>if operator == '+':</td>
<td></td>
</tr>
<tr>
<td>return reduce(add, args, 0)</td>
<td></td>
</tr>
<tr>
<td>elif operator == '-':</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>elif operator == '*':</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>elif operator == '/':</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>else:</td>
<td></td>
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<td>raise TypeError</td>
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## Applying Built-in Operators

The apply function applies some operation to a (Scheme) list of argument values.

In calculator, all operations are named by built-in operators: `+`, `−`, `∗`, `/.

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<tbody>
<tr>
<td><code>def calc_apply(operator, args):</code></td>
<td><code>-:</code></td>
</tr>
<tr>
<td><code>    if operator == '+':</code></td>
<td><code>+:</code></td>
</tr>
<tr>
<td><code>        return reduce(add, args, 0)</code></td>
<td></td>
</tr>
<tr>
<td><code>    elif operator == '-':</code></td>
<td></td>
</tr>
<tr>
<td><code>        ...</code></td>
<td></td>
</tr>
<tr>
<td><code>    elif operator == '*':</code></td>
<td></td>
</tr>
<tr>
<td><code>        ...</code></td>
<td></td>
</tr>
<tr>
<td><code>    elif operator == '/':</code></td>
<td></td>
</tr>
<tr>
<td><code>        ...</code></td>
<td></td>
</tr>
<tr>
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def calc_apply(operator, args):
    if operator == '+':
        return reduce(add, args, 0)
    elif operator == '-':
        ...
    elif operator == '*':
        ...
    elif operator == '/':
        ...
    else:
        raise TypeError
```

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<td><code>def calc_apply(operator, args):</code></td>
<td><code>+: Sum of the arguments</code></td>
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<tr>
<td><code>    if operator == '+':</code></td>
<td></td>
</tr>
<tr>
<td><code>        return reduce(add, args, 0)</code></td>
<td></td>
</tr>
<tr>
<td><code>    elif operator == '-':</code></td>
<td></td>
</tr>
<tr>
<td><code>        ...</code></td>
<td></td>
</tr>
<tr>
<td><code>    elif operator == '*':</code></td>
<td></td>
</tr>
<tr>
<td><code>        ...</code></td>
<td></td>
</tr>
<tr>
<td><code>    elif operator == '/':</code></td>
<td></td>
</tr>
<tr>
<td><code>        ...</code></td>
<td></td>
</tr>
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</tr>
<tr>
<td>return reduce(add, args, 0)</td>
<td>*: Sum of the arguments</td>
</tr>
<tr>
<td>elif operator == '-':</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>elif operator == '*':</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>-</td>
<td></td>
</tr>
<tr>
<td>*</td>
<td></td>
</tr>
<tr>
<td>/</td>
<td></td>
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Interactive Interpreters
Read-Eval-Print Loop
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The user interface for many programming languages is an interactive interpreter.
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(Demo)
Raising Exceptions
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Exceptions are raised within lexical analysis, syntactic analysis, eval, and apply.
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Example exceptions
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