Calculator
Class outline:

- Programming languages
- Parsing a language
- The Calculator language
- Evaluating a language
- Interactive interpreters
Programming languages
Levels of languages

High-level programming language
(Python, C++, JavaScript)

↓

Assembly language
(Hardware-specific)

↓

Machine language
(Hardware-specific)
Machine language

The language of the machine is all 1s and 0s, often specifying the action and the memory address to act on:

```
00000100 10000010  # Load data in 10000010
00000001 10000001  # Subtract data at 10000001
00000101 10000100  # Store result in 10000100
00001011 10000100  # Etc..
00001101 00010000
00010100 00000010
00000101 10000011
00001111 00000000
00010100 00000011
00000101 10000011
```

Code is executed directly by the hardware.
Assembly language

Assembly language was introduced for (slightly) easier programming.

<table>
<thead>
<tr>
<th>Machine code</th>
<th>Assembly code</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000100 10000010</td>
<td>LOD Y</td>
</tr>
<tr>
<td>00000001 10000001</td>
<td>SUB X</td>
</tr>
<tr>
<td>00000101 10000100</td>
<td>STO T1</td>
</tr>
<tr>
<td>00001011 10000100</td>
<td>CPL T1</td>
</tr>
<tr>
<td>00001101 00010000</td>
<td>JMZ 16</td>
</tr>
<tr>
<td>00010100 00000010</td>
<td>LOD #2</td>
</tr>
<tr>
<td>00000101 10000011</td>
<td>STO Z</td>
</tr>
<tr>
<td>00001111 00000000</td>
<td>HLT</td>
</tr>
<tr>
<td>00010100 000000011</td>
<td>LOD #3</td>
</tr>
<tr>
<td>00000101 10000011</td>
<td>STO Z</td>
</tr>
</tbody>
</table>
Assembly still has a 1:1 mapping with machine language, however.
Higher-level languages

Higher level languages:

- provide means of abstraction such as naming, function definition, and objects
- abstract away system details to be independent of hardware and operating system

```python
if x > y:
    z = 2
else:
    z = 3
```

Statements & expressions are either interpreted by another program or compiled (translated) into a lower-level language.
Compiled vs. interpreted

When a program is **compiled**, the source code is translated into machine code, and that code can be distributed and run repeatedly.

Source code → Compiler → Machine code → Output

When a program is **interpreted**, an interpreter runs the source code directly (without compiling it first).

Source code → Interpreter → Output
Compiled vs. interpreted

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Source code → Interpreter → Output

In its most popular implementation (CPython), Python programs are interpreted but have a compile step:

Source code → Compiler → Bytecode → Virtual Machine → Output
Phases of an interpreter/compiler

In order to either interpret or compile source code, a program must be written that understands that source code.

Typical phases of understanding:

Source code → Lexing → Parsing → Abstract Syntax Tree
Lexing & Parsing
Reading Scheme Lists

A Scheme list is written as elements in parentheses:

```
(<element_0>  <element_1>  ...  <element_n>)
```

Each `<element>` can be a combination or primitive.

```
(+  (* 3  (+ (* 2 4) (+ 3 5))))  (+ (- 10 7) 6))
```

The task of parsing a language involves turning a string representation of an expression into a structured object representing the expression.
# Parsing

A parser takes text and returns an expression object.

<table>
<thead>
<tr>
<th>Text</th>
<th>Lexical Analysis</th>
<th>Tokens</th>
<th>Syntactic Analysis</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>'(+ 1)'</td>
<td>→</td>
<td>'(, '+', 1)</td>
<td>→</td>
<td>Pair('+', Pair(1, ...))</td>
</tr>
<tr>
<td>' ( - 23)'</td>
<td>→</td>
<td>'(, '-', 23, ')'</td>
<td></td>
<td>printed as (+ 1 (- 23) (* 4 5.6))</td>
</tr>
<tr>
<td>' (* 4 5.6))'</td>
<td>→</td>
<td>'(, '*', 4, 5.6, ')</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lexical analysis

\[
' ( \ast \ 4 \ 5.6) )' \rightarrow '(', '\ast', 4, 5.6, ')', ')'
\]

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

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

• Tree-recursive process
• Balances parentheses
• Returns tree structure
• Processes multiple lines

In scheme_reader.py, each call to scheme_read consumes the input tokens for exactly one expression.

• Base case:
• Recursive case:
Syntactic analysis

\[ '(' , '+' , 1 , ... \rightarrow \text{Pair('+'}, \text{Pair(1, ...))} \]

- Tree-recursive process
- Balances parentheses
- Returns tree structure
- Processes multiple lines

In `scheme_reader.py`, each call to `scheme_read` consumes the input tokens for exactly one expression.

- Base case: symbols and numbers
- Recursive case:
Syntactic analysis

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

- Tree-recursive process
- Balances parentheses
- Returns tree structure
- Processes multiple lines

In `scheme_reader.py`, each call to `scheme_read` consumes the input tokens for exactly one expression.

- Base case: symbols and numbers
- Recursive case: read subexpressions and combine them
**Pair class**

The Pair class represents Scheme pairs and lists. A list is a pair whose second element is either pair or a list.

```python
class Pair:

s = Pair(1, Pair(2, Pair(3, nil)))
print(s)
len(s)
```

**Improper lists:**

```python
print(Pair(1, 2))
print(Pair(1, Pair(2, 3)))
len(Pair(1, Pair(2, 3)))
```
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print(s)  # (1 2 3)
len(s)    # 3

Improper lists:

print(Pair(1, 2))  # (1 . 2)
print(Pair(1, Pair(2, 3))) # (1 2 . 3)
len(Pair(1, Pair(2, 3))) Error!
The Calculator Language
What's in a language?

A programming language has:

- **Syntax**: The legal statements and expressions in the language
- **Semantics**: The execution/evaluation rule for those statements and expressions

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

- **Specification**: A document describing the precise syntax and semantics of the language
- **Canonical Implementation**: An interpreter or compiler for the language
Calculator language 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:

\((+ 1 2 3) (\div 3 (\times 4 5))\)

<table>
<thead>
<tr>
<th>Expression</th>
<th>Expression tree</th>
<th>Representation as pairs</th>
</tr>
</thead>
</table>
| (* 3
  (+ 4 5)
  (* 6 7 8)) | ![Expression tree](image) | ![Representation as pairs](image) |
Calculator language semantics

The value of a calculator expression is defined recursively.

- **Primitive**: A number evaluates to itself.
- **Call**: A call expression evaluates to its argument values combined by an operator.
  - `+`: Sum of the arguments
  - `*`: Product of the arguments
  - `-`: If one argument, negate it. If more than one, subtract the rest from the first.
  - `/`: If one argument, invert it. If more than one, divide the rest from the first.

<table>
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</thead>
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<tr>
<td>(+ 5</td>
<td></td>
</tr>
<tr>
<td>(* 2 3)</td>
<td></td>
</tr>
<tr>
<td>(* 2 5 5)</td>
<td></td>
</tr>
</tbody>
</table>
Evaluation
The eval function

The eval function computes the value of an expression.

It is a generic function that behaves according to the type of the expression (primitive or call).

### Implementation

```python
def calc_eval(exp):
    if isinstance(exp, (int, float)):
        return exp
    elif isinstance(exp, Pair):
        arguments = exp.rest.map(calc_eval)
        return calc_apply(exp.first, arguments)
    else:
        raise TypeError
```

### Language semantics

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

- A **call expression** evaluates... to its argument values combined by an operator
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: +, -, *, /

### Implementation

```python
def calc_apply(operator, args):
    if operator == '+':
        return reduce(add, args, 0)
    elif operator == '-':
        ...
    elif operator == '*':
        ...
    elif operator == '/':
        ...
    else:
        raise TypeError
```

### Language semantics

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Sum of the arguments</td>
</tr>
<tr>
<td>-</td>
<td></td>
</tr>
<tr>
<td>*</td>
<td></td>
</tr>
<tr>
<td>/</td>
<td></td>
</tr>
</tbody>
</table>
Interactive interpreters
REPL: Read-Eval-Print Loop

The user interface for many programming languages is an interactive interpreter

- Print a prompt
- Read text input from the user
- Parse the text input into an expression
- Evaluate the expression
- If any errors occur, report those errors, otherwise
- Print the value of the expression and repeat
Raising exceptions

Exceptions can be raised during lexical analysis, syntactic analysis, eval, and apply.

Example exceptions

• **Lexical analysis**: The token 2.3.4 raises `ValueError("invalid numeral")`

• **Syntactic analysis**: An extra ) raises `SyntaxError("unexpected token")`

• **Eval**: An empty combination raises `TypeError("() is not a number or call expression")`

• **Apply**: No arguments to - raises `TypeError("- requires at least 1 argument")`
Handling exceptions

An interactive interpreter prints information about each error.

A well-designed interactive interpreter should not halt completely on an error, so that the user has an opportunity to try again in the current environment.