Implementation

- There are two main classes of programming language implementations
  - Compilers
  - Interpreters

Compilers vs. Interpreters

Compilers vs Interpreters: What is the difference?

- Compilers translate high-level languages (Java, C, C++) into low-level languages (Java Byte Code, assembly language).
- Interpreters execute high-level languages directly (early versions of Lisp and Basic).

Note: Virtual machines can be considered interpreters for low-level languages; they directly execute a low-level language without first translating it.

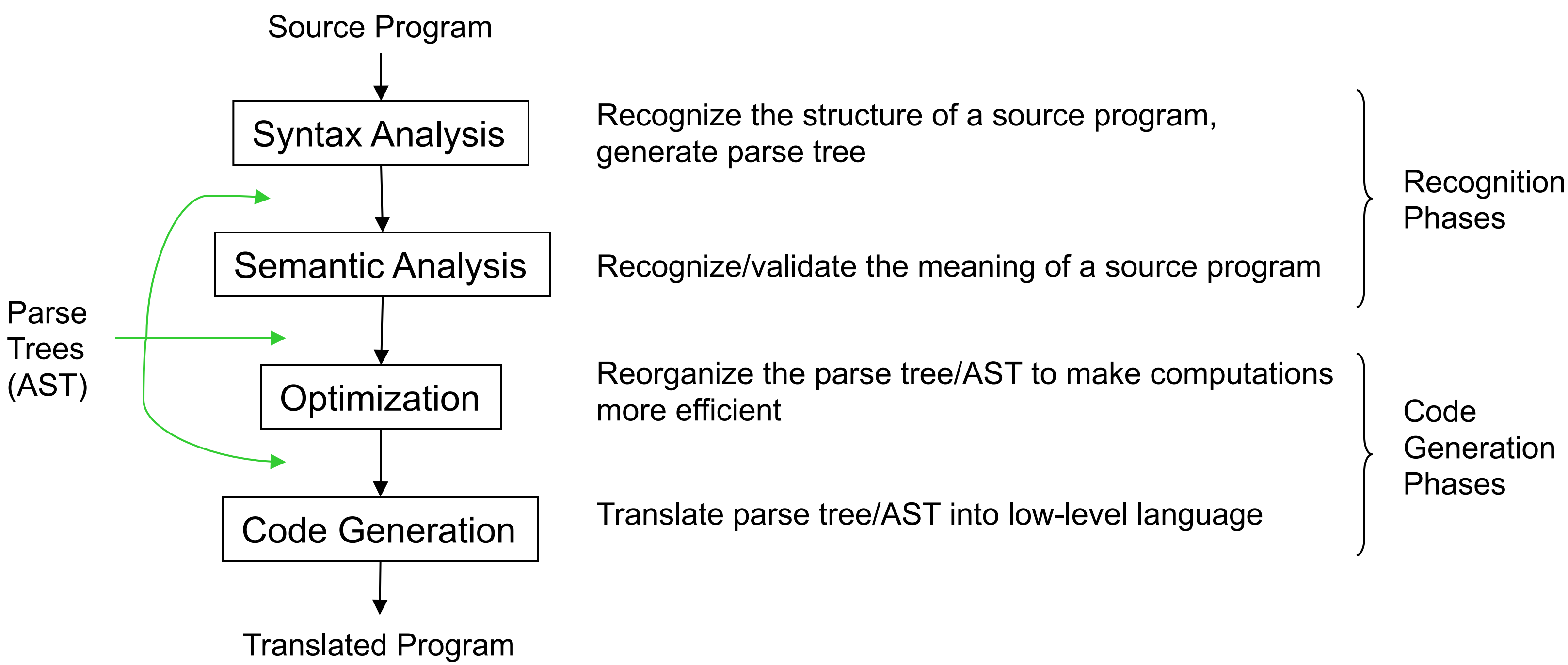
Compilers vs. Interpreters

- Why choose compilation over interpretation?
  - Compilers can generate very efficient code and, consequently, the compiled programs run faster than interpreted programs.

Compilers vs. Interpreters

- Why choose interpretation over compilation?
  - Responsive programming system – no compile/link step
  - Architecture independent – no code generation
  - Partial evaluation of a program
    - REPL – ‘read, evaluate, print, loop’
    - E.g. Python’s ‘>>>’ interface.

The Anatomy of a Compiler



Observations:

-Language definitions have two parts: syntax and semantics

-Compilers have two phases which deal with each of these language definition components: syntax analysis, semantic analysis.

Compilation Example

Assembly Language

```
load <address>,reg
load <value>,reg
store reg,<address>
add reg,reg,reg
sub reg,reg,reg
mul reg,reg,reg
```

Our machine has three registers: *r1, r2, r3*

consider: 3*2+5

Assembly Code:

```
load 3,r1
load 2,r2
mul r1,r2,r1
load 5,r2
add r1,r2,r1
```

Note: last argument to instructions is the target!

Interpreter Implementation

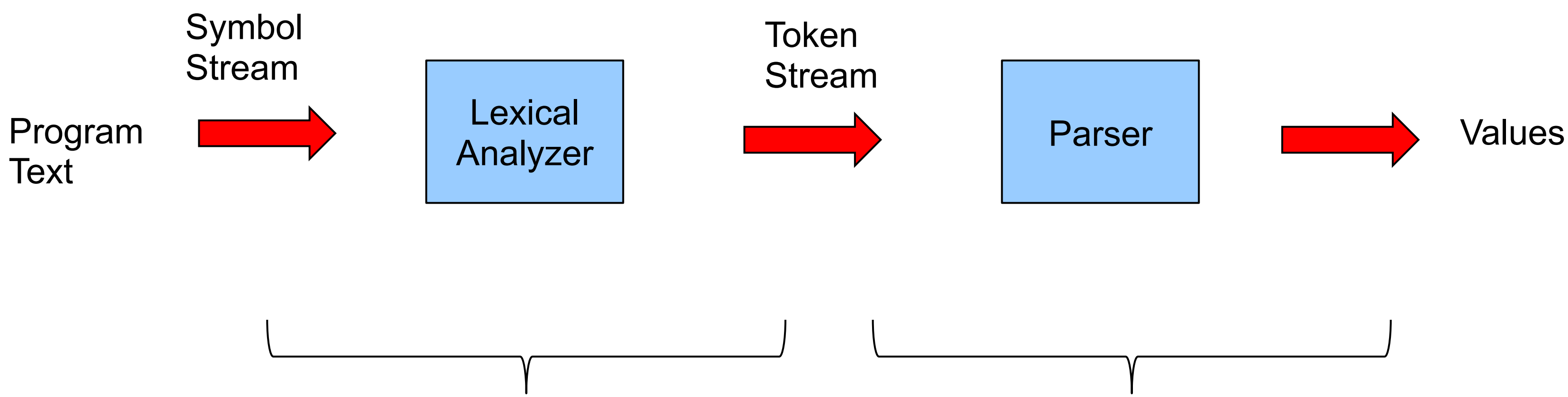
- A detailed look at an interpreter for a simple calculator language written in Asteroid.
- Here is the grammar for our language:

```
<expression>* ::= <expression> + <mulexp>
               |   <expression> - <mulexp>
               |   <mulexp>

<mulexp> ::= <mulexp> * <rootexp>
          |   <mulexp> / <rootexp>
          |   <rootexp>

<rootexp> ::= number | - <rootexp> | ( <expression> )
```

Interpreter Implementation

- Our implementation is based on something called *syntax-directed interpretation* – here interpretation of expressions happens as soon as they are recognized by the interpreter
- Other schemes exist where the interpreter first builds an intermediate representation of the program (similar to what we saw with the compiler) and then interprets this intermediate representation.
- Our interpreter architecture consists of 2 parts:
  - Lexer
  - Parser

Interpreter Implementation



Lexical Analysis:
Convert symbol stream into a token stream.

Syntax Analysis/Interpretation:
Make sure the sequence of tokens in the token stream conforms to the rules of the structure of the programming language and interpret the structures as soon as they are recognized.

The Lexer

- Turns an input stream into a token stream
- Provide a convenient interface to the token stream

```
lutz$ asteroid tokenizer.ast
tokenizing: (101+1)*2
[Token(lparen,(),Token(number,101),Token(add,+),Token(number,1),Token(rparen,)),Token(mul,*),Token(number,2)]
lutz$
```

The Lexer

- Convenient interface to the token stream

```
structure Lexer with
  data token_stream.

  function get
    with none do
      return this @token_stream @get().
    end

  function peek
    with none do
      return this @token_stream @peek().
    end

  function eof
    with none do
      return this @token_stream @eof().
    end

  function token_match
    with token_type do
      let token = this @token_stream @peek().
      if token @type == token_type do
        this @token_stream @get().
      else do
        throw Error("expected token "+token_type+" got "+token @type).
      end
    end

end -- structure
```

The Parser

- Here we use a parsing scheme called a "recursive descent parser"
- We derive the parser directly from the grammar.
- In this scheme we have one function for each non-terminal in the grammar.
- These function implement all the rules for the respective non-terminals.
- This gives rise to mutually recursive functions since most grammars are highly recursive.

The Parser

- In order to make this scheme work we need to rewrite our grammar slightly using an extended grammar notation called EBNF.
- Our grammar:

```
<expression>* ::= <expression> + <mulexp>
                |  <expression> - <mulexp>
                |  <mulexp>

<mulexp> ::= <mulexp> * <rootexp>
           |  <mulexp> / <rootexp>
           |  <rootexp>

<rootexp> ::= number | - <rootexp> | ( <expression> )
```

The Parser

- Becomes:

```
<expression>* ::= <mulexp> { ('+'  <mulexp>) | ('-' <mulexp>) }

<mulexp> ::= <rootexp> { ('*' <rootexp>) | ('/' <rootexp>) }

<rootexp> ::= number | '-' <rootexp> | '(' <expression> ')'
```

Notes: expressions written as **{*something*}** mean that ***something*** can **appear zero or more times** in the input. Also, we have put operator tokens in quotes in order to distinguish them from operators in the grammar language itself, e.g. parentheses.

Observation: we have replaced recursion in the grammar with the {…} operators. You should convince yourself that we are still parsing the same language.

The Parser

- Building the parser is now straight forward:
  - For each of the non-terminals we write a function that implements the rule(s)
  - The functions interface to the lexer to ask for tokens from the token stream as needed.
  - The functions also perform the interpretations of the operators as they are being recognized.

The Parser

<expression>* ::= <mulexp> { ('+' <mulexp>) | ('-' <mulexp>) }

```
function expression
  with lexer:%Lexer do
    let val = mulexp(lexer).
    loop do
      let token = lexer @peek().
      if not token do
        break.
      elif token @type == "add" do
        lexer @token_match("add").
        let val = val + mulexp(lexer).
      elif token @type == "sub" do
        lexer @token_match("sub").
        let val = val - mulexp(lexer)
      else do
        break.
      end
    end
    return val.
  end
```

Note: our calculator computations are in the parser.

The Parser

<mulexp> ::= <rootexp> { ('*' <rootexp>) | ('/' <rootexp>) }

```
function mulexp
  with lexer:%Lexer do
    let val = rootexp(lexer).
    if not lexer @peek() do
      return val.
    end
    loop do
      let token = lexer @peek().
      if not token do
        break.
      elif token @type == "mul" do
        lexer @token_match("mul").
        let val = val * rootexp(lexer).
      elif token @type == "div" do
        lexer @token_match("div").
        let val = val / rootexp(lexer)
      else do
        break.
      end
    end
    return val.
  end
```

The Parser

<rootexp> ::= number | '-' <rootexp> | '(' <expression> ')'

```
function rootexp
  with lexer:%Lexer do
    try
      let Token(type,val) = lexer @peek().
    catch _ do
      return none.
    end
    if type == "number" do
      lexer @token_match("number").
      return val.
    elif type == "sub" do
      lexer @token_match("sub").
      return - rootexp(lexer).
    elif type == "lparen" do
      lexer @token_match("lparen").
      let val = expression(lexer).
      lexer @token_match("rparen").
      return val.
    else do
      throw Error("syntax error at token "+val).
    end
  end
```

The Interpreter

- Putting it all together:
  - Read the input stream from stdin
  - Tokenize the input stream
  - Instantiate the lexer on the token stream
  - Call parser functions – start with start symbol.
  - Print out the computed value

The Interpreter

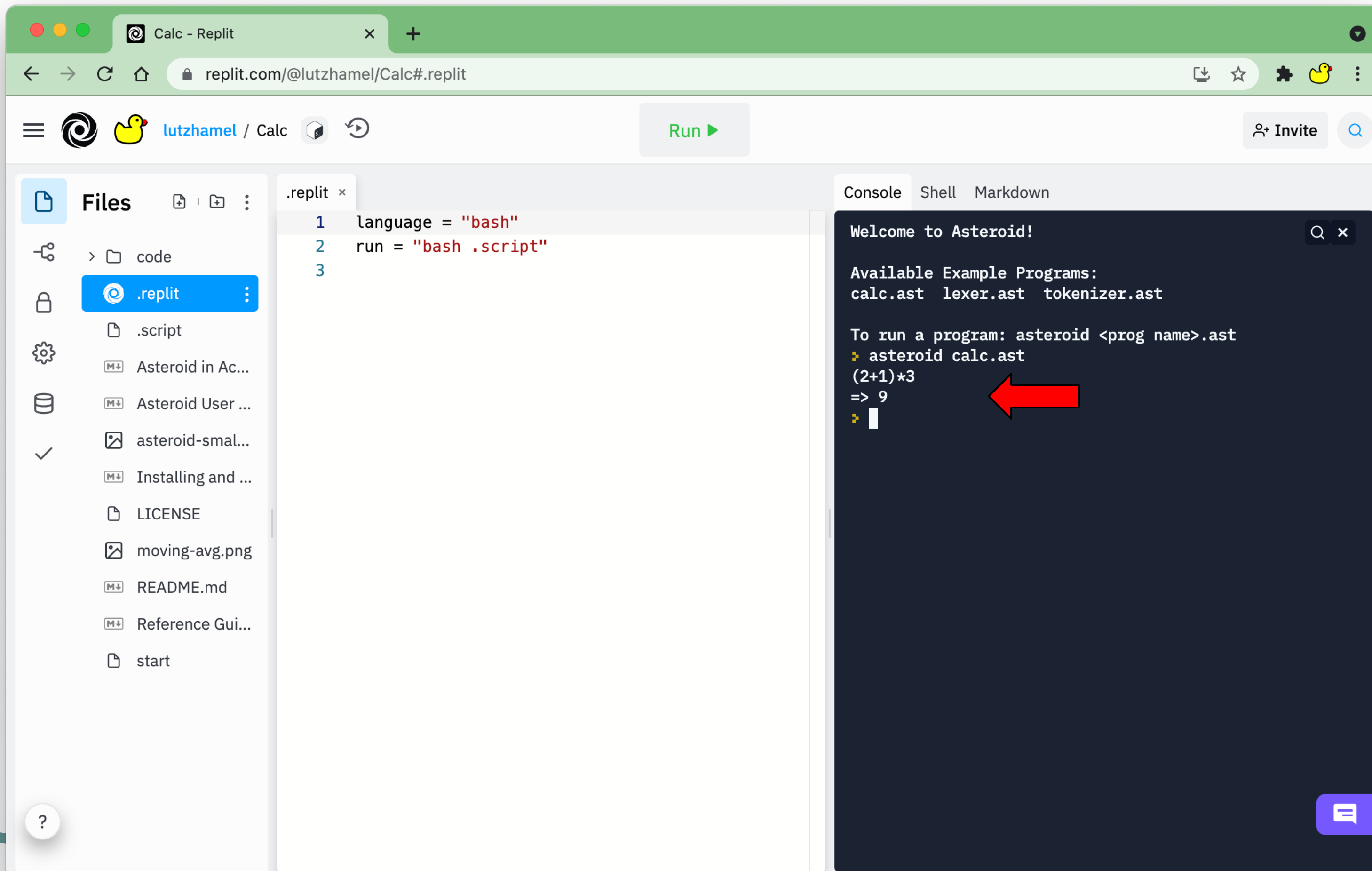
```
-- driver part of the script

-- tokenize input
let input = read().
let lexer = Lexer(tokenize(input)).

-- parse and interpret input
let val = expression(lexer).
if not (lexer @eof()) do
  throw Error("tokens still in input stream")
end

-- print out the final value of the parsed and i
println ("=> "+val).
```

Interpreter Code

- The code for the interpreter is available on repl.it:
  - https://repl.it/@lutzhamel/Calc

The Interpreter

Running the interpreter on a Unix-like system (repl.it shell):



Assignment: Translator

Problem: Build a simple translator from arithmetic expressions to a stack machine.

The translator accepts the same language as our calc language:

```
<expression>* ::= <mulexp> + <expression>
               |  <mulexp> - <expression>
               |  <mulexp>

<mulexp> ::= <rootexp> * <mulexp>
          |  <rootexp> / <mulexp>
          |  <rootexp>

<rootexp> ::= number | - <rootexp> | ( <expression> )
```

The translator generates the following stack machine language:

```
<comlist>*  ::= <command> <comlist> | <empty>
<command>   ::= add | sub | mul | push <number> | pop | print
<number>    ::= -- any valid integer --
```

Assignment: Translator

- Given the expression (1+2)*3 your translator should produce:

```
push 1
push 2
add
push 3
mul
print
```

- Note: it is assumed that the arithmetic commands pop the values off the stack that they use and push the result back onto the stack.
- Base your translator implementation on the calculator code given here: https://repl.it/@lutzhamel/Calc
- You can test drive you generated code with the stack machine given here: https://repl.it/@lutzhamel/Machine
- See Assignment #4 in BS