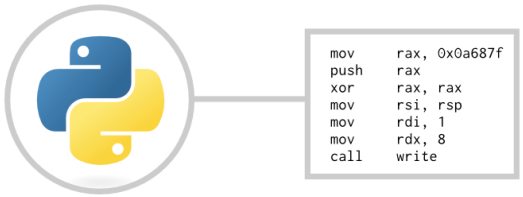
Writing your own programming language and compiler with Python

Marcelo Andrade Follow
Jun 29 · 7 min read



Introduction

After studying compilers and programming languages, I felt like internet tutorials and guides are way too complex for beginners or are missing some important parts about these topics.

★ Top highlight

My goal with this post is to help people that are seeking a way to start developing their first programming language/compiler.

Requirements

On this guide, I'll be using PLY as lexer and parser, and LLVMlite as low level intermediate language to do code generation with optimizations (if you don't know what I'm talking about, don't worry, I'll explain it later).

So, the requirements for this project are:

- Anaconda (way simpler to install LLVMlite through *conda* than *pip*)
- LLVMlite

```
$ conda install --channel=numba llvmlite
```

- RPLY (same as PLY but with a better API)

```
$ conda install -c conda-forge rply
```

- LLC (LLVM static compiler)
- GCC (or other linking tool)

Getting Started

"Where to begin?". This is the most common question when trying to create your programming language.

I'll start by defining my own language. Let's call it *TOY*, here's a simple example of a *TOY* program:

```
var x;
x := 4 + 4 * 2;
if (x > 3) {
    x := 2;
} else {
    x := 5;
}
print(x);
```

Although this example is really simple, it is not so easy to be implemented as a programming language. So let's start with a simpler example:

```
print(4 + 4 - 2);
```

But how do you formally describe a language grammar? It is way to hard to create all possible examples of a language to show everything it can do.

To do this, we do what is called an EBNF. It is a metalanguage to define with

To do this, we do what is called an EBNF. It is a metalanguage to define with one document, all possible grammar structures of a language. You can find most programming languages EBNFs easily.

To understand better how a EBNF grammar works, I recommend reading this post.

EBNF

Let's create a EBNF that describes the minimal possible functionality of *TOY*, only a sum operation. It will describe the following example:

```
4 + 2;
```

It's EBNF can be described as:

```
expression = number, "+", number, ";";
number = digit+;
digit = [0-9];
```

This example is way too simple to be useful as a programming language, so let's add some functionalities. The first one, is to be able to add as many numbers as you want, and the second one, is to to be able to subtract numbers as well.

Here's an example of our new programming language:

```
4 + 4 - 2;
```

And it's EBNF can be described as:

```
expression = number, { ("+"|"-"), number }, ";";
number = digit+;
digit = [0-9];
```

And finally, adding *print* to our programming language:

```
print(4 + 4 - 2);
```

We get to this EBNF:

```
program = "print", "(", expression, ")", ";";
expression = number, { ("+"|"-"), number } ;
number = digit+
digit = [0-9];
```

Now that we've defined our grammar, how do we translate it to code? So we can validate and understand a program? And after that, how can we compile it to a binary executable?

Compiler

A compiler is a program that turns a programming language into machine language or other languages. In this guide, I'm going to compile our programming language into LLVM IR and then into machine language.

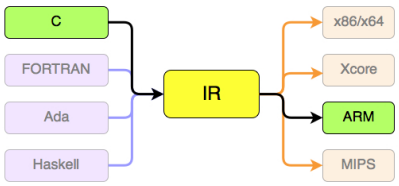


Diagram showing the process of compiling some programming languages, passing through an IR (Intermediate Representation).

Using LLVM, it is possible to optimize your compilation without learning compiling optimization, and LLVM has a really good library to work with compilers.

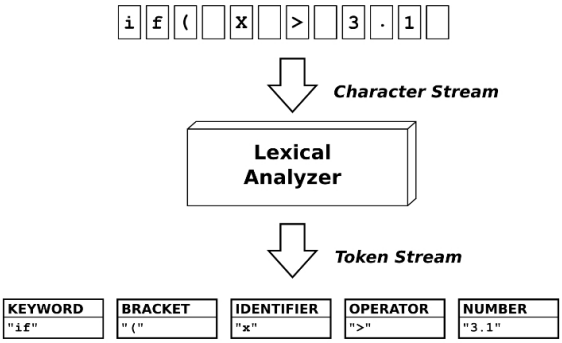
Our compiler can be divided into three components:

- Lexer
- Parser
- Code Generator

For the **Lexer** and **Parser** we'll be using RPLY, really similar to PLY: a Python library with lexical and parsing tools, but with a better API. And for the **Code Generator**, we'll use LLVMlite, a Python library for binding LLVM components.

Lexer

The first component of our compiler is the **Lexer**. It's role is to take the program as input and divide it into *Tokens*.



Lexer process of transforming a string into a list of tokens.

We use the minimal structures from our EBNF to define our tokens. For example, with the following input:

```
print(4 + 4 - 2);
```

Our Lexer would divide this string into this list of tokens:

```
Token('PRINT', 'print')
Token('OPEN_PAREN', '(')
Token('NUMBER', '4')
Token('SUM', '+')
Token('NUMBER', '4')
Token('SUB', '-')
Token('NUMBER', '2')
Token('CLOSE_PAREN', ')')
Token('SEMI_COLON', ';')
```

So, let's start coding our compiler. First, create a file named `lexer.py`. We'll define our tokens on this file. We'll only use *LexerGenerator* class from RPLY to create our Lexer.

```
from rply import LexerGenerator


class Lexer():
    def __init__(self):
        self.lexer = LexerGenerator()

    def _add_tokens(self):
        # Print
        self.lexer.add('PRINT', r'print')
        # Parenthesis
        self.lexer.add('OPEN_PAREN', r'\(')
        self.lexer.add('CLOSE_PAREN', r'\)')
        # Semi Colon
        self.lexer.add('SEMI_COLON', r'\;')
        # Operators
        self.lexer.add('SUM', r'\+')
        self.lexer.add('SUB', r'\-')
        # Number
        self.lexer.add('NUMBER', r'\d+')
        # Ignore spaces
        self.lexer.ignore('\s+')

    def get_lexer(self):
        self._add_tokens()
        return self.lexer.build()
```

lexer.py hosted with ❤ by GitHub — view raw

After this, create your main file named `main.py`. We'll combine all three compiler components on this file.

```
from lexer import Lexer

text_input = """
```

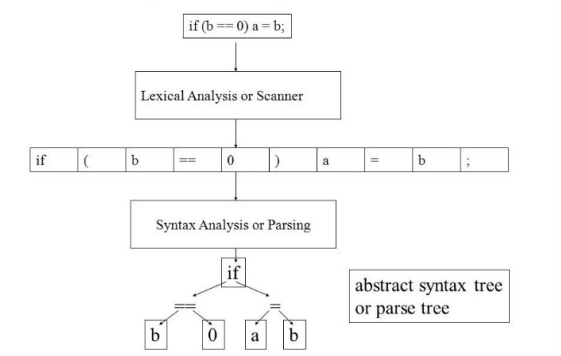
```
print(4 + 4 - 2);
"""

lexer = Lexer().get_lexer()
tokens = lexer.lex(text_input)

for token in tokens:
    print(token)
```

main1.py hosted with ❤ by GitHub view raw

If you run `$ python main.py` , the output of tokens will be the same as described above. You can change the name of your tokens if you want, but I recommend keeping the same to keep consistency with the **Parser**.

Parser

The second component in our compiler is the **Parser**. It's role is to do a syntax check of the program. It takes the list of tokens as input and create an AST as output. This concept is more complex than a list of tokens, so I highly recommend a little bit of research about Parsers and ASTs.



Lexical analysis followed by parsing to create the AST.

To implement our parser, we'll use the structure created with out EBNF as model. Luckly, RPLY's parser uses a format really similar to the EBNF to create it's parser, so it is really straightforward.

The most challenging is to attach the Parser with the AST, but when you get the idea, it becomes really mechanical.

First, create a new file named `ast.py` . It will contain all classes that are going to be called on the parser and create the AST.

```
class Number():
    def __init__(self, value):
        self.value = value

    def eval(self):
        return int(self.value)


class BinaryOp():
    def __init__(self, left, right):
        self.left = left
        self.right = right


class Sum(BinaryOp):
    def eval(self):
        return self.left.eval() + self.right.eval()


class Sub(BinaryOp):
    def eval(self):
        return self.left.eval() - self.right.eval()


class Print():
    def __init__(self, value):
        self.value = value

    def eval(self):
        print(self.value.eval())
```

ast1.py hosted with ❤ by GitHub view raw

Second, we need to create the parser. For that, we'll use *ParserGenerator* from RPLY. Create a file name `parser.py:`

```
from rply import ParserGenerator
from ast import Number, Sum, Sub, Print


class Parser():
    def __init__(self):
        self.pg = ParserGenerator(
            # A list of all token names accepted by the parser.
```

```
            ['NUMBER', 'PRINT', 'OPEN_PAREN', 'CLOSE_PAREN',
             'SEMI_COLON', 'SUM', 'SUB']
        )

    def parse(self):
        @self.pg.production('program : PRINT OPEN_PAREN expression CLOSE_PAREN SEMI_COLON')
        def program(p):
            return Print(p[2])

        @self.pg.production('expression : expression SUM expression')
        @self.pg.production('expression : expression SUB expression')
        def expression(p):
            left = p[0]
            right = p[2]
            operator = p[1]
            if operator.gettokentype() == 'SUM':
                return Sum(left, right)
            elif operator.gettokentype() == 'SUB':
                return Sub(left, right)

        @self.pg.production('expression : NUMBER')
        def number(p):
            return Number(p[0].value)

        @self.pg.error
        def error_handle(token):
            raise ValueError(token)

    def get_parser(self):
        return self.pg.build()
```

parser1.py hosted with ❤ by GitHub — view raw

And finally, we'll update our file `main.py` to combine **Parser** with **Lexer**.

```
from lexer import Lexer
from parser import Parser

text_input = """
print(4 + 4 - 2);
"""

lexer = Lexer().get_lexer()
tokens = lexer.lex(text_input)

pg = Parser()
pg.parse()
parser = pg.get_parser()
parser.parse(tokens).eval()
```

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Now, if you run `$ python main.py`, you'll see the output being the result of `print(4 + 4 - 2)`, which is equal to printing 6.

With these two components, we have a functional compiler that interprets *TOY* language with Python. However, it still doesn't create a machine language code and is not well optimized. To do this, we'll enter the most complex part of the guide, code generation with LLVM.

Code Generator

The third and last component of out compiler is the **Code Generator**. It's role is to transform the AST created from the parser into machine language or an IR. In this case, it's going to transform the AST into LLVM IR.

This component is the main reason whyI'm writing this post. There aren't good guides on how to implement code generation with LLVM on Python.

LLVM can be really complex to understand, so if you wish to fully understand what is going on, I recommend reading LLVMlite docs.

LLVMlite doesn't have a implementation to a `print` function, so you have to define your own.

So, to start, let's create a file named `codegen.py` that will contain the class `CodeGen`. This class is responsible to configure LLVM and create and save the IR code. We also declare the Print function on it.

```
from llvmlite import ir, binding


class CodeGen():
    def __init__(self):
        self.binding = binding
        self.binding.initialize()
        self.binding.initialize_native_target()
        self.binding.initialize_native_asmprinter()
        self._config_llvm()
        self._create_execution_engine()
        self._declare_print_function()

    def _config_llvm(self):
        # Config LLVM
        self.module = ir.Module(name=__file__)
        self.module.triple = self.binding.get_default_triple()
        func_type = ir.FunctionType(ir.VoidType(), [], False)
        base_func = ir.Function(self.module, func_type, name="main")
        block = base_func.append_basic_block(name="entry")
```

```
        self.builder = ir.IRBuilder(block)

    def _create_execution_engine(self):
        """
        Create an ExecutionEngine suitable for JIT code generation on
        the host CPU.  The engine is reusable for an arbitrary number of
        modules.
        """
        target = self.binding.Target.from_default_triple()
        target_machine = target.create_target_machine()
        # And an execution engine with an empty backing module
        backing_mod = binding.parse_assembly("")
        engine = binding.create_mcjit_compiler(backing_mod, target_machine)
        self.engine = engine

    def _declare_print_function(self):
        # Declare Printf function
        voidptr_ty = ir.IntType(8).as_pointer()
        printf_ty = ir.FunctionType(ir.IntType(32), [voidptr_ty], var_arg=True)
        printf = ir.Function(self.module, printf_ty, name="printf")
        self.printf = printf

    def _compile_ir(self):
        """
        Compile the LLVM IR string with the given engine.
        The compiled module object is returned.
        """
        # Create a LLVM module object from the IR
        self.builder.ret_void()
        llvm_ir = str(self.module)
        mod = self.binding.parse_assembly(llvm_ir)
        mod.verify()
        # Now add the module and make sure it is ready for execution
        self.engine.add_module(mod)
        self.engine.finalize_object()
        self.engine.run_static_constructors()
        return mod

    def create_ir(self):
        self._compile_ir()

    def save_ir(self, filename):
        with open(filename, 'w') as output_file:
            output_file.write(str(self.module))
```

codegen.py hosted with ❤ by GitHub — view raw

After this, let's update our `main.py` file to call `CodeGen` methods:

```
from lexer import Lexer
from parser import Parser
from codegen import CodeGen

fname = "input.toy"
with open(fname) as f:
    text_input = f.read()

lexer = Lexer().get_lexer()
tokens = lexer.lex(text_input)

codegen = CodeGen()

module = codegen.module
builder = codegen.builder
printf = codegen.printf

pg = Parser(module, builder, printf)
pg.parse()
parser = pg.get_parser()
parser.parse(tokens).eval()

codegen.create_ir()
codegen.save_ir("output.ll")
```

main3.py hosted with ❤ by GitHub — view raw

As you can see, I removed the input program from this file and created a new file called `input.toy` to simulate a external program. It's content is the same as the input described.

```
print(4 + 4 - 2);
```

Another change that was made is passing `module`, `builder` and `printf` objects to the Parser. This was made so we could pass this objects to the AST, where the LLVM AST is created. So, we change `parser.py` to receive these objects and pass them to the AST.

```
from rply import ParserGenerator
from ast import Number, Sum, Sub, Print

class Parser():
    def __init__(self, module, builder, printf):
        self.pg = ParserGenerator(
            # A list of all token names accepted by the parser.
            ['NUMBER', 'PRINT', 'OPEN_PAREN', 'CLOSE_PAREN',
             'SEMI_COLON', 'SUM', 'SUB']
        )
        self.module = module
        self.builder = builder
        self.printf = printf

    def parse(self):
        @self.pg.production('program : PRINT OPEN_PAREN expression CLOSE_PAREN SEMI_COLON')
```

```
        def program(p):
            return Print(self.builder, self.module, self.printf, p[2])

        @self.pg.production('expression : expression SUM expression')
        @self.pg.production('expression : expression SUB expression')
        def expression(p):
            left = p[0]
            right = p[2]
            operator = p[1]
            if operator.gettokentype() == 'SUM':
                return Sum(self.builder, self.module, left, right)
            elif operator.gettokentype() == 'SUB':
                return Sub(self.builder, self.module, left, right)

        @self.pg.production('expression : NUMBER')
        def number(p):
            return Number(self.builder, self.module, p[0].value)

        @self.pg.error
        def error_handle(token):
            raise ValueError(token)

    def get_parser(self):
        return self.pg.build()
```

parser2.py hosted with ❤ by GitHub — view raw

And finally, and most important, we change the `ast.py` to receive these objects and create the LLVM AST using LLVMlite methods.

```
from llvmlite import ir


class Number():
    def __init__(self, builder, module, value):
        self.builder = builder
        self.module = module
        self.value = value

    def eval(self):
        i = ir.Constant(ir.IntType(8), int(self.value))
        return i


class BinaryOp():
    def __init__(self, builder, module, left, right):
        self.builder = builder
        self.module = module
        self.left = left
        self.right = right


class Sum(BinaryOp):
    def eval(self):
        i = self.builder.add(self.left.eval(), self.right.eval())
        return i


class Sub(BinaryOp):
    def eval(self):
        i = self.builder.sub(self.left.eval(), self.right.eval())
        return i


class Print():
    def __init__(self, builder, module, printf, value):
        self.builder = builder
        self.module = module
        self.printf = printf
        self.value = value

    def eval(self):
        value = self.value.eval()

        # Declare argument list
        voidptr_ty = ir.IntType(8).as_pointer()
        fmt = "%i \n\0"
        c_fmt = ir.Constant(ir.ArrayType(ir.IntType(8), len(fmt)),
                            bytearray(fmt.encode("utf8")))
        global_fmt = ir.GlobalVariable(self.module, c_fmt.type, name="fstr")
        global_fmt.linkage = 'internal'
        global_fmt.global_constant = True
        global_fmt.initializer = c_fmt
        fmt_arg = self.builder.bitcast(global_fmt, voidptr_ty)

        # Call Print Function
        self.builder.call(self.printf, [fmt_arg, value])
```

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With these changes, our compiler is ready to transform a *TOY* program into an LLVM IR file `output.ll`. To compile this `.ll` file into a executable, we'll use LLC to create a object file `output.o`, and finally, GCC (you could use other linking programs) to create the final executable file.

```
$ llc -filetype=obj output.ll
$ gcc output.o -o output
```

And you can finally run your executable file compiled from the initial program.

```
$ ./output
```

Next Steps

After this guide, I hope you can understand an EBNF and the three basic concepts of a compiler. With this knowledge, you now can create your own programming language and write a optimized compiler to it with Python. I encourage you to go further and add new elements to your language and compiler, here are some ideas:

- Statements
- Variables
- New Binary Operators (Multiplication, Division)
- Unary Operators
- If Statement
- While Stametement

Feel free to send me any compiler projects. I'll be happy to help you with anything.

You can contact me at *marceloa1@al.insper.edu.br*

Hope you all enjoyed this post and got some love to programming languages and compilers!

You can see the final code on GitHub.

. . .

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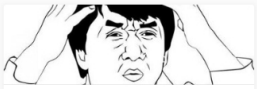

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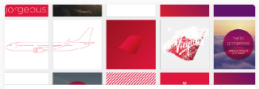

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to

too complex

43

Conversation with Marcelo Andrade.

Tyler Levasseur
Jul 2 · 1 min read

Very cool article! I keep getting stuck at the linking stage though. When I get to

gcc output.o -o output

I get the error:

/usr/bin/ld: output.o: relocation R_X86_64_32 against `.rodata' can not be used when making a shared object; recompile with -fPIC
/usr/bin/ld: final…

Read more...

5 1 response

Marcelo Andrade
Jul 4 · 1 min read

I was looking into this problem, and it seems that it is a problem with LLVM 6 and GCC (correct me if I'm wrong and this is not wrong case).

I couldn't find what causes it on this version on LLVM, but a solution I found was changing the linker to Clang.

Read more...

6 1 response

Conversation with Marcelo Andrade.

Shrek Wu
Jun 30 · 1 min read

llc command not found?

2 responses

Marcelo Andrade
Jun 30 · 1 min read

Have you installed LLC? I listed it on requirements section.

3 1 response

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