CS46K Programming Languages

Structure and Interpretation of Computer Programs

Chapter 10B Interpreter Design – Read Evaluate Print Loop

LECTURE 15: VIRTUAL MACHINE

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Objectives

- What are REPL Loop and Python Virtual Machine?
- REPL Console Design
- Implementation of a REPL Console
- Virtual Machine Model
- Integration

Python Virtual Machine

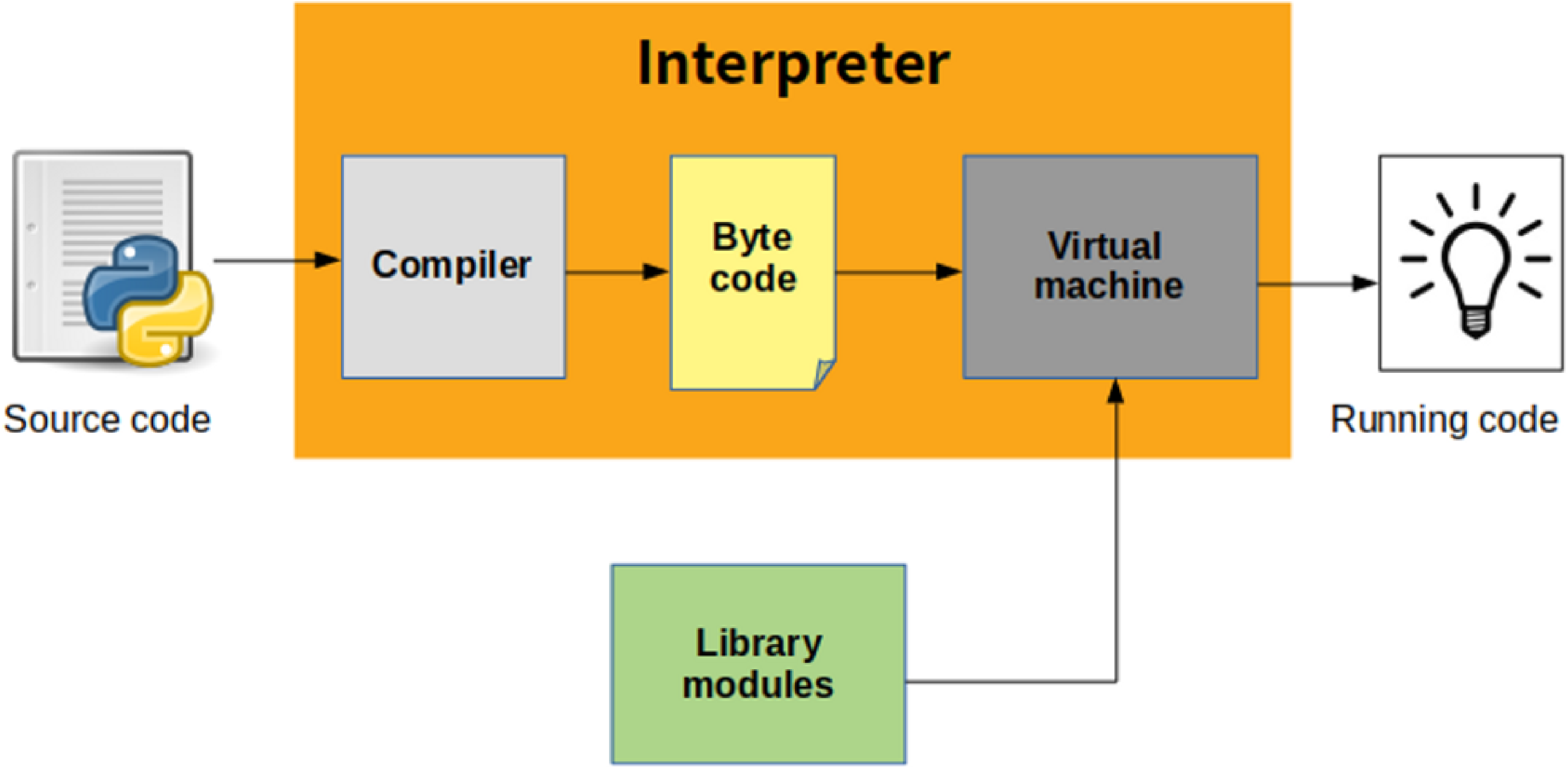
SECTION 1

Is Python an Interpreted language?

- Almost all Python introduction will tell you that Python is an interpreted language compare with compile language like **C/C++**.
- In Python, the interpreter will read your code line by line and execute it in a call stack. While in C, the compiler will check grammar, translate to assembly code, then compile and link them together to binary machine code.

Is Python an Interpreted language?

- Is that all true? if Python is interpreted line by line, how it is executed? I want to find out the detail behind it.
- And what I found? Python is not a pure interpretation language, it is very much like Java, a compile and interpretation language. Before Python Interpreter take over the execution, a Python program will goes through, lexing, parsing and then, compiling.


Interpreter
Source code
Compiler
Byte code
Virtual machine
Running code
Library modules

Is Python an Interpreted language?

- Yes, compiling, I did not make a mistake here, There IS a compiling stage.
- Lexing, will identify the keywords and tokenize all “element”s of your program. Its result is a Concrete Syntax Tree(CST) or parser tree.
- Next, Parser will check the sequence order and grammar to see if there any statement break the rule. And return an simpler Abstract Syntax Tree(AST) or syntax tree.
- Finally, Compiler will transform the syntax tree to python bytecode. The compiled bytecode will be cached in .pyc files so that make the second run faster. (this reminds me of .jar file in Java and IL .dll file in C#).

Is Python an Interpreted language?

- One difference compare with Java/C# is that the cached .pyc file is for performance purpose only. If Python interpreter don't see the .pyc file, it will compile the script on the fly.

Anatomy a Python program

SECTION 2

Anatomy a Python program

- Now, let’s take a look at a Python function.

```
def add(a,b):
    return a+b
```

- To view its compiled bytecode.

```
print(add.__code__.co_code)
```

- It will return this. the bytecode will be interpreted(aka run) by Python Interpreter.

```
b'|\x00|\x01\x17\x00S\x00'
```

Anatomy a Python program

- A pretty strange binary array. Hm,we can transform it to a more readable form by list() function.

```
print(list(add.__code__.co_code))
```

- It will print out:

```
[124, 0, 124, 1, 23, 0, 83, 0]
```

Anatomy a Python program

- From this numbers array, we still don’t know anything meaningful. Python provides a package called dis for revealing the meaning of these numbers.

```
import dis
dis.opname[124]
```

- The first number 124 means “LOAD_FAST”. Another function dis() can help output all readable bytecode.

```
def add(a,b):
    return a+b
import dis
dis.dis(add)
```

Anatomy a Python program

- The dis() will print out all readable bytecode like this:

```
2           0 LOAD_FAST                0 (a)
            2 LOAD_FAST                1 (b)
            4 BINARY_ADD
            6 RETURN_VALUE
```

- The 1st column represent the line number of original code; The 2nd column is the index number of original bytecode array; The 3rd column is the friendly name of the operation; The 4th column is the argument index; the 5th column, the one with () is the hint of the argument.

Anatomy a Python program

- Looks like an assembly language, right? The LOAD_FAST instruction load the value of a and b to data stack (it is just a stack, but for storing data). The BINARY_ADD instruction pop out the top 2 numbers from stack and add them together, then push the addition result back to stack. Finally, the RETURN_VALUE instructor will pop the data out of the stack, and send to the next "Frame" in frame stack(a stack, for storing calling frames).

Make one of my own Mini-Python interpreter

SECTION 3

Make one of my own Mini-Python interpreter

- Now, I have a Python program as shown below, and I am aiming to build one of my own Python interpreter(by Python) to execute it.

```
def add(a,b):
    return a+b
print(add(5,7))
```

Make one of my own Mini-Python interpreter

- After lexing, parsing and compiling, Suppose that we get bytecode like this(it is simplified, real python bytecode will contains more)

```
2           0 LOAD_FAST                0 (a)
            2 LOAD_FAST                1 (b)
            4 BINARY_ADD
            6 RETURN_VALUE
3           8 PRINT_VALUE
```

Make one of my own Mini-Python interpreter

- Transform it to a Python dictionary for easier process.

```
execution_bytecode = {
    "instructions": [("LOAD_FAST", 0),  # the first number
                     ("LOAD_FAST", 1),  # the second number
                     ("BINARY_ADD", None),
                     ("RETURN_VALUE",None),
                     ("PRINT_VALUE", None)],
    "numbers": [5, 7]
}
```

- Python using a stack based interpreter, all data manipulation will happen inside of a data stack.

A__PY_Interpreter.py

```
class AZ_PY_Interpreter:
    def __init__(self):
        self.stack = []
    def LOAD_FAST(self,number):
        self.stack.append(number)
    def PRINT_VALUE(self):
        answer = self.stack.pop()
        print(answer)
    def BINARY_ADD(self):
        first_num = self.stack.pop()
        second_num = self.stack.pop()
        total = first_num + second_num
        self.stack.append(total)
    def run_code(self, what_to_execute):
        instructions = what_to_execute["instructions"]
        numbers = what_to_execute["numbers"]
        for each_step in instructions:
            instruction, argument = each_step
            if instruction == "LOAD_FAST":
                number = numbers[argument]
                self.LOAD_FAST(number)
            elif instruction == "BINARY_ADD":
                self.BINARY_ADD()
            elif instruction == "PRINT_VALUE":
                self.PRINT_VALUE()
```

Running the Byte Code

A__PY_Interpreter.py

```
execution_bytecode = {
    "instructions": [("LOAD_FAST", 0),  # the first number
                     ("LOAD_FAST", 1),  # the second number
                     ("BINARY_ADD", None),
                     ("RETURN_VALUE",None),
                     ("PRINT_VALUE", None)],
    "numbers": [5, 7]
}
my_python = AZ_PY_Interpreter()
my_python.run_code(execution_bytecode)
```

Running the Byte Code

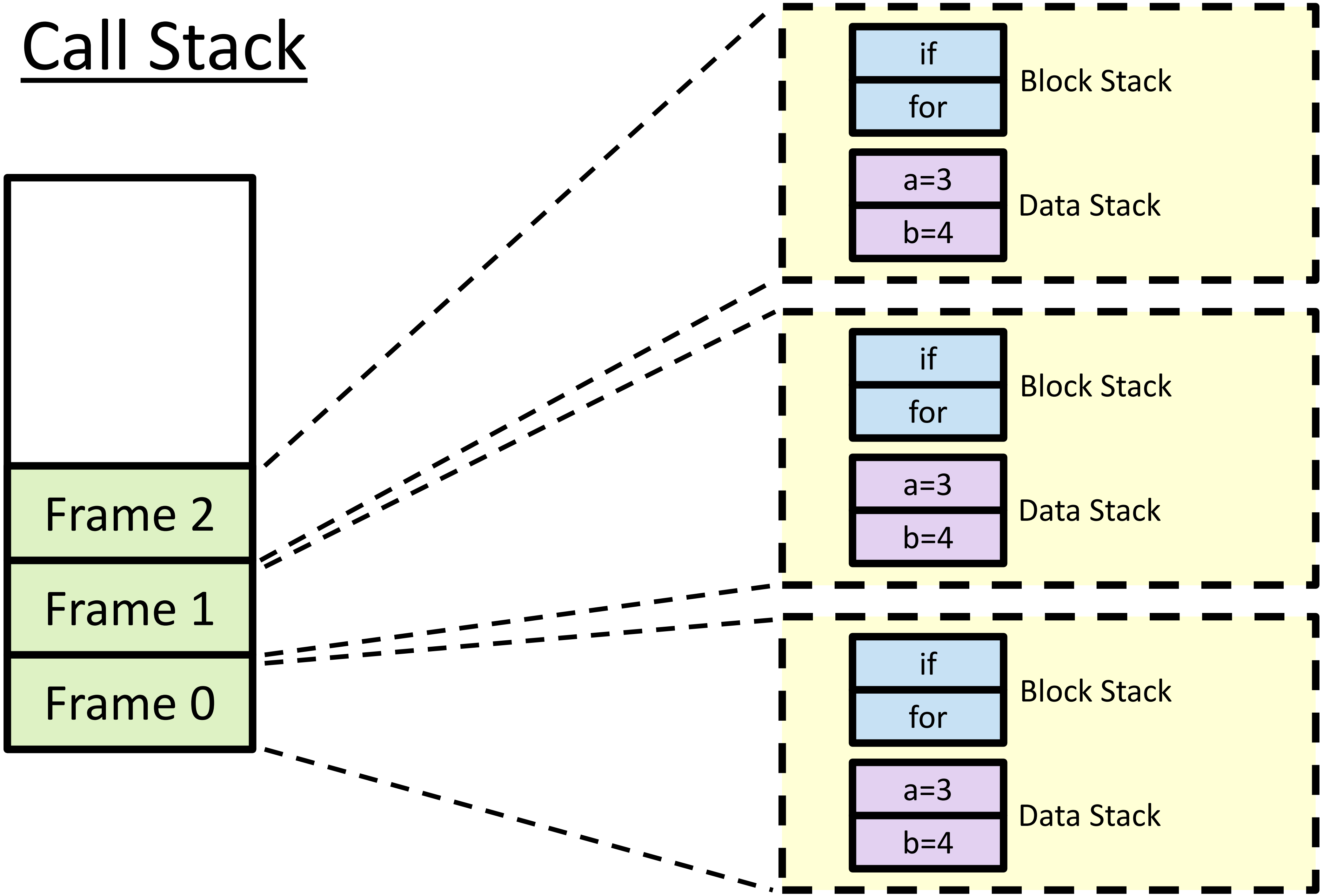
```
[Running] python -u "c:\Eric_Chou\Lewis University\CS 46K SIPC
12


[Done] exited with code=0 in 0.103 seconds
```

The Python Interpreter Stack

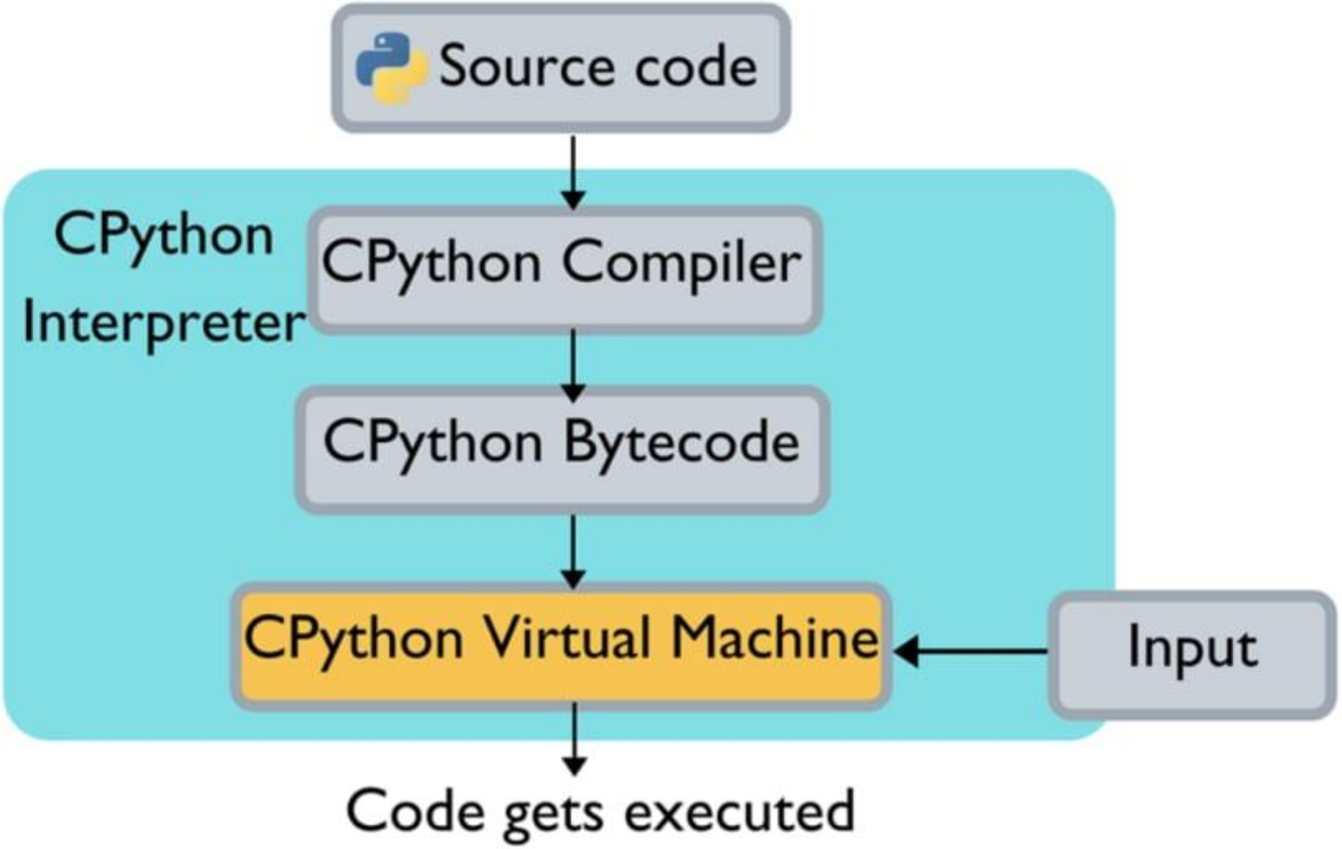
- Note that I ignored the RETURN_VALUE instruction implementation, because this involves Frames operation. and the above tiny interpreter involves only data stack.
- In real Python interpreter, there are three types of stack, that works together to execute all Python code. These three stacks are Call Stack, Block Stack and Data stack.
- Block stack is where store the Python operators like if, for, and while loops. Call Stack is where store the calling context, the context usually called "Frame", each frame has its own Block Stack and Data Stack.

Call Stack


Frame 2
Frame 1
Frame 0
if
for
Block Stack
a=3
b=4
Data Stack
if
for
Block Stack
a=3
b=4
Data Stack
if
for
Block Stack
a=3
b=4
Data Stack

The Python Interpreter Stack

- For example, in a recursive program, the main code will recursively call function 10 times, then there will 11 frames in the call stack. The one additional frame is for the context that you started from.



Python Virtual Machine ByteCode

HTTPS://DOCS.PYTHON.ORG/2.4/LIB/BYTECODES.HTML

Python as a Dynamically Typed Language

SECTION 4

Python as a Dynamically Typed Language

- In my previous article The Weird Parts That Make Python Cool, I mentioned that Python is not type-free language. But Python is not either static typed language. People usually describe Python as a dynamically typed language. Why? because, before the Python interpreter actually run the code, no body knows which type of data it is going to process.

Python as a Dynamically Typed Language

- For example, you defined a mod function

```
def mod(a,b):
        return a%b
```

- You call the function like this print(mod(7,4)) will give you perfect answer: 3
- What if you call this function with string arguments? mod("hello","world"). Python will throw out error. Now, what if you call like this?

```
mod("he%s","llo python")
```

Python as a Dynamically Typed Language

- You get A result, no error message, no exception!

```
hello python
```

- This dynamic feature bring some troubles in real life programming, My colleague Alex's comment reflect the fact:
- Yeah, it gets annoying to write and use functions that take specific object types as arguments, you have to write all these runtime checks that the compiler would do for you in a static language. — Alex Kyllo
- To write a good Python function require us to be careful and check more.

One additional note about dis module

- In the above sample, I use the dis package to show the bytecode of a function inside of a program, what if you want to check a whole python file? Here is the way to go.

```
import dis
code = '''
def add(a,b):
    return a+b
add(5,7)'''
co = dis.dis(code)
print(co)
```

One additional note about dis module

- With the dis module, you can dig into the python details, say, what is the difference between a list comprehensives and a traditional loop?

A Python Interpreter Written in Python

Introduction

SECTION 5

Introduction

- **Byterun** is a Python interpreter implemented in Python. Through my work on Byterun, I was surprised and delighted to discover that the fundamental structure of the Python interpreter fits easily into the 500-line size restriction.
- This chapter will walk through the structure of the interpreter and give you enough context to explore it further.
- The goal is not to explain everything there is to know about interpreters—like so many interesting areas of programming and computer science, you could devote years to developing a deep understanding of the topic.

Introduction

- **Byterun** was written by Ned Batchelder and myself, building on the work of Paul Swartz.
- Its structure is similar to the primary implementation of Python, CPython, so understanding Byterun will help you understand interpreters in general and the CPython interpreter in particular.
- (If you don't know which Python you're using, it's probably CPython.) Despite its short length, Byterun is capable of running most simple Python programs.

A Python Interpreter

- Before we begin, let's narrow down what we mean by "a Python interpreter". The word "interpreter" can be used in a variety of different ways when discussing Python. Sometimes interpreter refers to the Python REPL, the interactive prompt you get by typing python at the command line. Sometimes people use "the Python interpreter" more or less interchangeably with "Python" to talk about executing Python code from start to finish. In this chapter, "interpreter" has a more narrow meaning: it's the last step in the process of executing a Python program.

A Python Interpreter

- Before the interpreter takes over, Python performs three other steps: lexing, parsing, and compiling. Together, these steps transform the programmer's source code from lines of text into structured code objects containing instructions that the interpreter can understand. The interpreter's job is to take these code objects and follow the instructions.

A Python Interpreter

- You may be surprised to hear that compiling is a step in executing Python code at all. Python is often called an "interpreted" language like Ruby or Perl, as opposed to a "compiled" language like C or Rust. However, this terminology isn't as precise as it may seem. Most interpreted languages, including Python, do involve a compilation step. The reason Python is called "interpreted" is that the compilation step does relatively less work (and the interpreter does relatively more) than in a compiled language. As we'll see later in the chapter, the Python compiler has much less information about the behavior of a program than a C compiler does.

A Python Python Interpreter

- Byterun is a Python interpreter written in Python. This may strike you as odd, but it's no more odd than writing a C compiler in C. (Indeed, the widely used C compiler gcc is written in C.) You could write a Python interpreter in almost any language.

A Python Python Interpreter

- Writing a Python interpreter in Python has both advantages and disadvantages. The biggest disadvantage is **speed**: executing code via Byterun is much slower than executing it in CPython, where the interpreter is written in C and carefully optimized.
- However, Byterun was designed originally as **a learning exercise**, so speed is not important to us.
- The biggest advantage to using Python is that we can more easily implement just the interpreter, and not the rest of the Python run-time, particularly the object system. For example, Byterun can fall back to "real" Python when it needs to create a class.

A Python Python Interpreter

- Another advantage is that Byterun is **easy to understand**, partly because it's written in a high-level language (Python!) that many people find easy to read. (We also exclude interpreter optimizations in Byterun—once again favoring clarity and simplicity over speed.)

A Python Interpreter Written in Python

Building an Interpreter

SECTION 6

Building an Interpreter

- Before we start to look at the code of Byterun, we need some higher-level context on the structure of the interpreter. How does the Python interpreter work?
- The Python interpreter is a virtual machine, meaning that it is software that emulates a physical computer. This particular virtual machine is a stack machine: it manipulates several stacks to perform its operations (as contrasted with a register machine, which writes to and reads from particular memory locations).

Building an Interpreter

- The Python interpreter is a bytecode interpreter: its input is instruction sets called bytecode. When you write Python, the lexer, parser, and compiler generate code objects for the interpreter to operate on. Each code object contains a set of instructions to be executed—that's the bytecode—plus other information that the interpreter will need. Bytecode is an intermediate representation of Python code: it expresses the source code that you wrote in a way the interpreter can understand. It's analogous to the way that assembly language serves as an intermediate representation between C code and a piece of hardware.

A Tiny Interpreter

- To make this concrete, let's start with a very minimal interpreter. This interpreter can only add numbers, and it understands just three instructions. All code it can execute consists of these three instructions in different combinations. The three instructions are these:
  - LOAD_VALUE
  - ADD_TWO_VALUES
  - PRINT_ANSWER
- Since we're not concerned with the lexer, parser, and compiler in this chapter, it doesn't matter how the instruction sets are produced. You can imagine writing 7 + 5 and having a compiler emit a combination of these three instructions. Or, if you have the right compiler, you can write Lisp syntax that's turned into the same combination of instructions. The interpreter doesn't care. All that matters is that our interpreter is given a well-formed arrangement of the instructions.

A Tiny Interpreter

- Suppose that

```
7 + 5
```

produces this instruction set:

```
what_to_execute = {
    "instructions": [("LOAD_VALUE", 0),  # the first number
                     ("LOAD_VALUE", 1),  # the second number
                     ("ADD_TWO_VALUES", None),
                     ("PRINT_ANSWER", None)],
    "numbers": [7, 5] }
```

A Tiny Interpreter

- The Python interpreter is a stack machine, so it must manipulate stacks to add two numbers (Figure 12.1.) The interpreter will begin by executing the first instruction, LOAD_VALUE, and pushing the first number onto the stack. Next it will push the second number onto the stack. For the third instruction, ADD_TWO_VALUES, it will pop both numbers off, add them together, and push the result onto the stack. Finally, it will pop the answer back off the stack and print it.

A stack machine

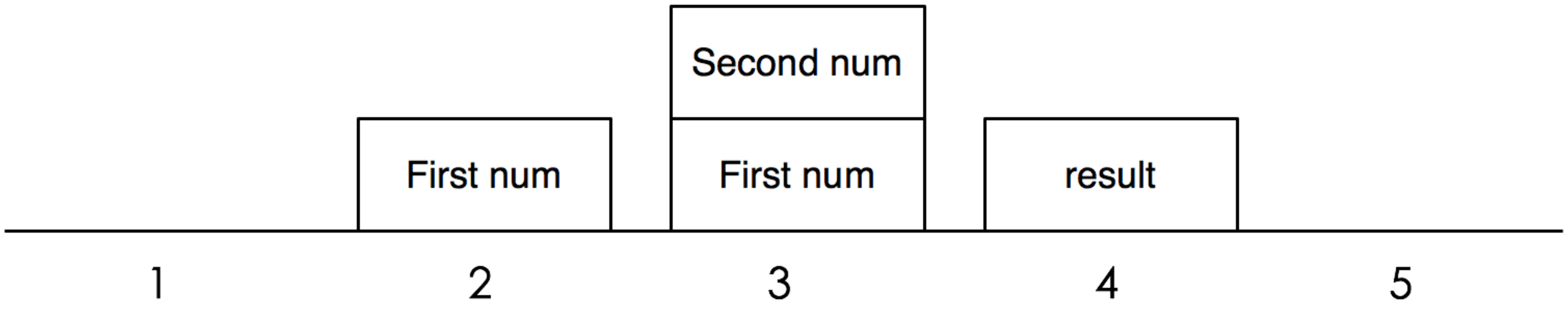


Figure 12.1 - A stack machine

A stack machine

- The LOAD_VALUE instruction tells the interpreter to push a number on to the stack, but the instruction alone doesn't specify which number. Each instruction needs an extra piece of information, telling the interpreter where to find the number to load. So our instruction set has two pieces: the instructions themselves, plus a list of constants the instructions will need. (In Python, what we're calling "instructions" is the bytecode, and the "what to execute" object below is the code object.)

A stack machine

- Why not just put the numbers directly in the instructions? Imagine if we were adding strings together instead of numbers. We wouldn't want to have the strings stuffed in with the instructions, since they could be arbitrarily large. This design also means we can have just one copy of each object that we need, so for example to add 7 + 7, "numbers" could be just [7].

A stack machine

- You may be wondering why instructions other than ADD_TWO_VALUES were needed at all. Indeed, for the simple case of adding two numbers, the example is a little contrived. However, this instruction is a building block for more complex programs. For example, with just the instructions we've defined so far, we can already add together three values—or any number of values—given the right set of these instructions. The stack provides a clean way to keep track of the state of the interpreter, and it will support more complexity as we go along.
- Now let's start to write the interpreter itself. The interpreter object has a stack, which we'll represent with a list. The object also has a method describing how to execute each instruction. For example, for LOAD_VALUE, the interpreter will push the value onto the stack.

Interpreter.py

```python
class Interpreter:
    def __init__(self):
        self.stack = []

    def LOAD_VALUE(self, number):
        self.stack.append(number)

    def PRINT_ANSWER(self):
        answer = self.stack.pop()
        print(answer)

    def ADD_TWO_VALUES(self):
        first_num = self.stack.pop()
        second_num = self.stack.pop()
        total = first_num + second_num
        self.stack.append(total)
```

A stack machine

- These three functions implement the three instructions our interpreter understands. The interpreter needs one more piece: a way to tie everything together and actually execute it. This method, run_code, takes the what_to_execute dictionary defined above as an argument. It loops over each instruction, processes the arguments to that instruction if there are any, and then calls the corresponding method on the interpreter object.

Interpreter.py

```python
def run_code(self, what_to_execute):
    instructions = what_to_execute["instructions"]
    numbers = what_to_execute["numbers"]
    for each_step in instructions:
        instruction, argument = each_step
        if instruction == "LOAD_VALUE":
            number = numbers[argument]
            self.LOAD_VALUE(number)
        elif instruction == "ADD_TWO_VALUES":
            self.ADD_TWO_VALUES()
        elif instruction == "PRINT_ANSWER":
            self.PRINT_ANSWER()
```

A stack machine

- To test it out, we can create an instance of the object and then call the run_code method with the instruction set for adding 7 + 5 defined above.

```
interpreter = Interpreter()
interpreter.run_code(what_to_execute)
```

- Sure enough, it prints the answer: 12.

A stack machine

- Although this interpreter is quite limited, this process is almost exactly how the real Python interpreter adds numbers. There are a couple of things to note even in this small example.
- First of all, some instructions need arguments. In real Python bytecode, about half of instructions have arguments. The arguments are packed in with the instructions, much like in our example. Notice that the arguments to the instructions are different than the arguments to the methods that are called.
- Second, notice that the instruction for ADD_TWO_VALUES did not require any arguments. Instead, the values to be added together were popped off the interpreter's stack. This is the defining feature of a stack-based interpreter.

A stack machine

- Remember that given valid instruction sets, without any changes to our interpreter, we can add more than two numbers at a time. Consider the instruction set below. What do you expect to happen? If you had a friendly compiler, what code could you write to generate this instruction set?

```
what_to_execute = {
    "instructions": [("LOAD_VALUE", 0),
                     ("LOAD_VALUE", 1),
                     ("ADD_TWO_VALUES", None),
                     ("LOAD_VALUE", 2),
                     ("ADD_TWO_VALUES", None),
                     ("PRINT_ANSWER", None)],
    "numbers": [7, 5, 8] }
```

- At this point, we can begin to see how this structure is extensible: we can add methods on the interpreter object that describe many more operations (as long as we have a compiler to hand us well-formed instruction sets).

Variables

- Next let's add variables to our interpreter. Variables require an instruction for storing the value of a variable, STORE_NAME; an instruction for retrieving it, LOAD_NAME; and a mapping from variable names to values. For now, we'll ignore namespaces and scoping, so we can store the variable mapping on the interpreter object itself. Finally, we'll have to make sure that what_to_execute has a list of the variable names, in addition to its list of constants.

Variables

```
>>> def s():
...     a = 1
...     b = 2
...     print(a + b)
# a friendly compiler transforms `s` into:
    what_to_execute = {
        "instructions": [("LOAD_VALUE", 0),
                         ("STORE_NAME", 0),
                         ("LOAD_VALUE", 1),
                         ("STORE_NAME", 1),
                         ("LOAD_NAME", 0),
                         ("LOAD_NAME", 1),
                         ("ADD_TWO_VALUES", None),
                         ("PRINT_ANSWER", None)],
        "numbers": [1, 2],
        "names":   ["a", "b"] }
```

Variables

- Our new implementation is below. To keep track of what names are bound to what values, we'll add an environment dictionary to the __init__ method. We'll also add STORE_NAME and LOAD_NAME. These methods first look up the variable name in question and then use the dictionary to store or retrieve its value.
- The arguments to an instruction can now mean two different things: They can either be an index into the "numbers" list, or they can be an index into the "names" list. The interpreter knows which it should be by checking what instruction it's executing. We'll break out this logic—and the mapping of instructions to what their arguments mean—into a separate method.

Interpreter2.py

```python
class Interpreter:
    def __init__(self):
        self.stack = []
        self.environment = {}
    def STORE_NAME(self, name):
        val = self.stack.pop()
        self.environment[name] = val
    def LOAD_NAME(self, name):
        val = self.environment[name]
        self.stack.append(val)
    def LOAD_VALUE(self, number):
        self.stack.append(number)
    def PRINT_ANSWER(self):
        answer = self.stack.pop()
        print(answer)
    def ADD_TWO_VALUES(self):
        first_num = self.stack.pop()
        second_num = self.stack.pop()
        total = first_num + second_num
        self.stack.append(total)
```

Interpreter2.py

```
def parse_argument(self, instruction, argument, what_to_execute):
    """ Understand what the argument to each instruction means."""
    numbers = ["LOAD_VALUE"]
    names = ["LOAD_NAME", "STORE_NAME"]

    if instruction in numbers:
        argument = what_to_execute["numbers"][argument]
    elif instruction in names:
        argument = what_to_execute["names"][argument]

    return argument
```

Interpreter2.py

```python
def run_code(self, what_to_execute):
    instructions = what_to_execute["instructions"]
    for each_step in instructions:
        instruction, argument = each_step
        argument = self.parse_argument(instruction, argument, what_to_execute)

        if instruction == "LOAD_VALUE":
            self.LOAD_VALUE(argument)
        elif instruction == "ADD_TWO_VALUES":
            self.ADD_TWO_VALUES()
        elif instruction == "PRINT_ANSWER":
            self.PRINT_ANSWER()
        elif instruction == "STORE_NAME":
            self.STORE_NAME(argument)
        elif instruction == "LOAD_NAME":
            self.LOAD_NAME(argument)
```

Variables

- Even with just five instructions, the run_code method is starting to get tedious. If we kept this structure, we'd need one branch of the if statement for each instruction. Here, we can make use of Python's dynamic method lookup. We'll always define a method called FOO to execute the instruction called FOO, so we can use Python's getattr function to look up the method on the fly instead of using the big if statement. The run_code method then looks like this:

Interpreter2.py

```
def execute(self, what_to_execute):
    instructions = what_to_execute["instructions"]
    for each_step in instructions:
        instruction, argument = each_step
        argument = self.parse_argument(instruction, argument, what_to_execute)
        bytecode_method = getattr(self, instruction)
        if argument is None:
            bytecode_method()
        else:
            bytecode_method(argument)
```

Run the New Interpreter

Interpreter2.py

```
interpreter = Interpreter()
what_to_execute = {
        "instructions": [("LOAD_VALUE", 0),
                         ("STORE_NAME", 0),
                         ("LOAD_VALUE", 1),
                         ("STORE_NAME", 1),
                         ("LOAD_NAME", 0),
                         ("LOAD_NAME", 1),
                         ("ADD_TWO_VALUES", None),
                         ("PRINT_ANSWER", None)],
        "numbers": [1, 2],
        "names":   ["a", "b"]
}
interpreter.run_code(what_to_execute)
```

Result:

```
[Running] python -u "c:\Eric_Chou\Lewis University\CS 46K SIPC
Execute:

>>> def s():
...     a = 1
...     b = 2
...     print(a + b)

3

[Done] exited with code=0 in 0.148 seconds
```

A Python Interpreter Written in Python

Real Python Bytecode

SECTION 7

Real Python Bytecode

- At this point, we'll abandon our toy instruction sets and switch to real Python bytecode. The structure of bytecode is similar to our toy interpreter's verbose instruction sets, except that it uses one byte instead of a long name to identify each instruction. To understand this structure, we'll walk through the bytecode of a short function. Consider the example below:

```
>>> def cond():
...     x = 3
...     if x < 5:
...         return 'yes'
...     else:
...         return 'no'
...
```

Real Python Bytecode

- Python exposes a boatload of its internals at run time, and we can access them right from the REPL. For the function object cond, cond.__code__ is the code object associated it, and cond.__code__.co_code is the bytecode. There's almost never a good reason to use these attributes directly when you're writing Python code, but they do allow us to get up to all sorts of mischief—and to look at the internals in order to understand them.

```
>>> cond.__code__.co_code  # the bytecode as raw bytes
b'd\x01\x00}\x00\x00|\x00\x00d\x02\x00k\x00\x00r\x16\x00d\x03\x00Sd\x04\x00Sd\x00\x00S'

>>> list(cond.__code__.co_code)  # the bytecode as numbers
[100, 1, 0, 125, 0, 0, 124, 0, 0, 100, 2, 0, 107, 0, 0, 114, 22, 0, 100, 3, 0, 83, 100, 4, 0, 83, 100, 0, 0, 83]
```

Real Python Bytecode

- When we just print the bytecode, it looks unintelligible—all we can tell is that it's a series of bytes. Luckily, there's a powerful tool we can use to understand it: the dis module in the Python standard library.
- dis is a bytecode disassembler. A disassembler takes low-level code that is written for machines, like assembly code or bytecode, and prints it in a human-readable way. When we run **`dis.dis`**, it outputs an explanation of the bytecode it has passed.

Real Python Bytecode

```
>>> dis.dis(cond)
  2           0 LOAD_CONST               1 (3)
              3 STORE_FAST               0 (x)

  3           6 LOAD_FAST                0 (x)
              9 LOAD_CONST               2 (5)
             12 COMPARE_OP               0 (<)
             15 POP_JUMP_IF_FALSE       22

  4          18 LOAD_CONST               3 ('yes')
             21 RETURN_VALUE

  6     >>   22 LOAD_CONST               4 ('no')
             25 RETURN_VALUE
             26 LOAD_CONST               0 (None)
             29 RETURN_VALUE
```

Real Python Bytecode

- What does all this mean? Let's look at the first instruction LOAD_CONST as an example. The number in the first column (2) shows the line number in our Python source code. The second column is an index into the bytecode, telling us that the LOAD_CONST instruction appears at position zero. The third column is the instruction itself, mapped to its human-readable name. The fourth column, when present, is the argument to that instruction. The fifth column, when present, is a hint about what the argument means.

Real Python Bytecode

- Consider the first few bytes of this bytecode: [100, 1, 0, 125, 0, 0]. These six bytes represent two instructions with their arguments. We can use dis.opname, a mapping from bytes to intelligible strings, to find out what instructions 100 and 125 map to:

```
>>> dis.opname[100]
'LOAD_CONST'
>>> dis.opname[125]
'STORE_FAST'
```

Real Python Bytecode

- The second and third bytes—1, 0—are arguments to LOAD_CONST, while the fifth and sixth bytes—0, 0—are arguments to STORE_FAST. Just like in our toy example, LOAD_CONST needs to know where to find its constant to load, and STORE_FAST needs to find the name to store. (Python's LOAD_CONST is the same as our toy interpreter's LOAD_VALUE, and LOAD_FAST is the same as LOAD_NAME.) So these six bytes represent the first line of code, x = 3. (Why use two bytes for each argument? If Python used just one byte to locate constants and names instead of two, you could only have 256 names/constants associated with a single code object. Using two bytes, you can have up to 256 squared, or 65,536.)

Conditionals and Loops

- So far, the interpreter has executed code simply by stepping through the instructions one by one. This is a problem; often, we want to execute certain instructions many times, or skip them under certain conditions. To allow us to write loops and if statements in our code, the interpreter must be able to jump around in the instruction set. In a sense, Python handles loops and conditionals with GOTO statements in the bytecode! Look at the disassembly of the function cond again:

Conditionals and Loops

```
>>> dis.dis(cond)
  2           0 LOAD_CONST               1 (3)
              3 STORE_FAST               0 (x)

  3           6 LOAD_FAST                0 (x)
              9 LOAD_CONST               2 (5)
             12 COMPARE_OP               0 (<)
             15 POP_JUMP_IF_FALSE       22

  4          18 LOAD_CONST               3 ('yes')
             21 RETURN_VALUE

  6     >>   22 LOAD_CONST               4 ('no')
             25 RETURN_VALUE
             26 LOAD_CONST               0 (None)
             29 RETURN_VALUE
```

Conditionals and Loops

- The conditional if x < 5 on line 3 of the code is compiled into four instructions: LOAD_FAST, LOAD_CONST, COMPARE_OP, and POP_JUMP_IF_FALSE. x < 5 generates code to load x, load 5, and compare the two values. The instruction POP_JUMP_IF_FALSE is responsible for implementing the if. This instruction will pop the top value off the interpreter's stack. If the value is true, then nothing happens. (The value can be "truthy"—it doesn't have to be the literal True object.) If the value is false, then the interpreter will jump to another instruction.

Conditionals and Loops

- The instruction to land on is called the jump target, and it's provided as the argument to the POP_JUMP instruction. Here, the jump target is 22. The instruction at index 22 is LOAD_CONST on line 6. (dis marks jump targets with >>.) If the result of x < 5 is False, then the interpreter will jump straight to line 6 (return "no"), skipping line 4 (return "yes"). Thus, the interpreter uses jump instructions to selectively skip over parts of the instruction set.

Conditionals and Loops

- Python loops also rely on jumping. In the bytecode below, notice that the line while x < 5 generates almost identical bytecode to if x < 10. In both cases, the comparison is calculated and then POP_JUMP_IF_FALSE controls which instruction is executed next. At the end of line 4—the end of the loop's body—the instruction JUMP_ABSOLUTE always sends the interpreter back to instruction 9 at the top of the loop. When x < 5 becomes false, then POP_JUMP_IF_FALSE jumps the interpreter past the end of the loop, to instruction 34.

Conditionals and Loops

```
>>> def loop():
...         x = 1
...         while x < 5:
...             x = x + 1
...         return x
...
```

Conditionals and Loops

```
>>> dis.dis(loop)
  2           0 LOAD_CONST               1 (1)
              3 STORE_FAST               0 (x)

  3           6 SETUP_LOOP              26 (to 35)
        >>    9 LOAD_FAST                0 (x)
             12 LOAD_CONST               2 (5)
             15 COMPARE_OP               0 (<)
             18 POP_JUMP_IF_FALSE       34

  4          21 LOAD_FAST                0 (x)
             24 LOAD_CONST               1 (1)
             27 BINARY_ADD
             28 STORE_FAST               0 (x)
             31 JUMP_ABSOLUTE            9
        >>   34 POP_BLOCK

  5     >>   35 LOAD_FAST                0 (x)
             38 RETURN_VALUE
```

Explore Bytecode

- I encourage you to try running dis.dis on functions you write. Some questions to explore:
  - What's the difference between a for loop and a while loop to the Python interpreter?
  - How can you write different functions that generate identical bytecode?
  - How does elif work? What about list comprehensions?

A Python Interpreter Written in Python

Frames

SECTION 8

Frames

- So far, we've learned that the Python virtual machine is a stack machine. It steps and jumps through instructions, pushing and popping values on and off a stack. There are still some gaps in our mental model, though. In the examples above, the last instruction is RETURN_VALUE, which corresponds to the return statement in the code. But where does the instruction return to?

Frames

- To answer this question, we must add a layer of complexity: the frame. A frame is a collection of information and context for a chunk of code. Frames are created and destroyed on the fly as your Python code executes. There's one frame corresponding to each call of a function—so while each frame has one code object associated with it, a code object can have many frames. If you had a function that called itself recursively ten times, you'd have eleven frames—one for each level of recursion and one for the module you started from. In general, there's a frame for each scope in a Python program. For example, each module, each function call, and each class definition has a frame.

Frames

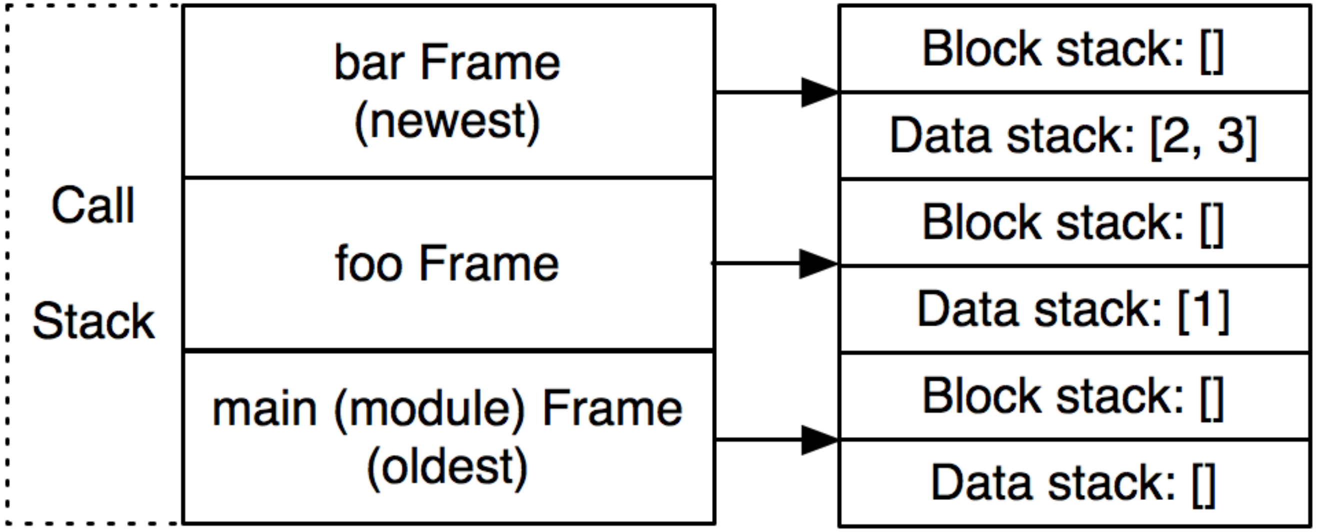
- Frames live on the call stack, a completely different stack from the one we've been discussing so far. (The call stack is the stack you're most familiar with already—you've seen it printed out in the tracebacks of exceptions. Each line in a traceback starting with "File 'program.py', line 10" corresponds to one frame on the call stack.) The stack we've been examining—the one the interpreter is manipulating while it executes bytecode—we'll call the data stack. There's also a third stack, called the block stack. Blocks are used for certain kinds of control flow, particularly looping and exception handling. Each frame on the call stack has its own data stack and block stack.

Frames

- Let's make this concrete with an example. Suppose the Python interpreter is currently executing the line marked 3 below. The interpreter is in the middle of a call to foo, which is in turn calling bar. The diagram shows a schematic of the call stack of frames, the block stacks, and the data stacks. (This code is written like a REPL session, so we've first defined the needed functions.) At the moment we're interested in, the interpreter is executing foo(), at the bottom, which then reaches into the body of foo and then up into bar.

Frames

```
>>> def bar(y):
...     z = y + 3      # <--- (3) ... and the interpreter is here.
...     return z
...
>>> def foo():
...     a = 1
...     b = 2
...     return a + bar(b) # <--- (2) ... which is returning a call to bar ...
...
>>> foo()              # <--- (1) We're in the middle of a call to foo ...
3
```


Call
Stack
bar Frame
(newest)
foo Frame
main (module) Frame
(oldest)
Block stack: []
Data stack: [2, 3]
Block stack: []
Data stack: [1]
Block stack: []
Data stack: []

Call Stack

Call Stack

- At this point, the interpreter is in the middle of the function call to bar. There are three frames on the call stack: one for the module level, one for the function foo, and one for bar (Figure 12.2.) Once bar returns, the frame associated with it is popped off the call stack and discarded.

- The bytecode instruction RETURN_VALUE tells the interpreter to pass a value between frames. First it will pop the top value off the data stack of the top frame on the call stack. Then it pops the entire frame off the call stack and throws it away. Finally, the value is pushed onto the data stack on the next frame down.

Call Stack

- When Ned Batchelder and I were working on Byterun, for a long time we had a significant error in our implementation. Instead of having one data stack on each frame, we had just one data stack on the entire virtual machine. We had dozens of tests made up of little snippets of Python code which we ran through Byterun and through the real Python interpreter to make sure the same thing happened in both interpreters. Nearly all of these tests were passing. The only thing we couldn't get working was generators. Finally, reading the CPython code more carefully, we realized the mistake2. Moving a data stack onto each frame fixed the problem.

Call Stack

- Looking back on this bug, I was amazed at how little of Python relied on each frame having a different data stack. Nearly all operations in the Python interpreter carefully clean up the data stack, so the fact that the frames were sharing the same stack didn't matter. In the example above, when bar finishes executing, it'll leave its data stack empty. Even if foo shared the same stack, the values would be lower down. However, with generators, a key feature is the ability to pause a frame, return to some other frame, and then return to the generator frame later and have it be in exactly the same state that you left it.

A Python Interpreter Written in Python

Byterun

SECTION 9

Byterun

We now have enough context about the Python interpreter to begin examining Byterun.

There are four kinds of objects in Byterun:

- A VirtualMachine class, which manages the highest-level structure, particularly the call stack of frames, and contains a mapping of instructions to operations. This is a more complex version of the Intepreter object above.
- A Frame class. Every Frame instance has one code object and manages a few other necessary bits of state, particularly the global and local namespaces, a reference to the calling frame, and the last bytecode instruction executed.

Byterun

- A Function class, which will be used in place of real Python functions. Recall that calling a function creates a new frame in the interpreter. We implement Function so that we control the creation of new Frames.
- A Block class, which just wraps the three attributes of blocks. (The details of blocks aren't central to the Python interpreter, so we won't spend much time on them, but they're included here so that Byterun can run real Python code.)

The VirtualMachine Class

- Only one instance of VirtualMachine will be created each time the program is run, because we only have one Python interpreter. VirtualMachine stores the call stack, the exception state, and return values while they're being passed between frames. The entry point for executing code is the method run_code, which takes a compiled code object as an argument. It starts by setting up and running a frame. This frame may create other frames; the call stack will grow and shrink as the program executes. When the first frame eventually returns, execution is finished.

VirtualMachine.py

```python
class VirtualMachineError(Exception):
    pass

class VirtualMachine(object):
    def __init__(self):
        self.frames = []    # The call stack of frames.
        self.frame = None   # The current frame.
        self.return_value = None
        self.last_exception = None

    def run_code(self, code, global_names=None, local_names=None):
        """ An entry point to execute code using the virtual machine."""
        frame = self.make_frame(code, global_names=global_names,
                                local_names=local_names)
        self.run_frame(frame)
```

The Frame Class

- Next we'll write the Frame object. The frame is a collection of attributes with no methods. As mentioned above, the attributes include the code object created by the compiler; the local, global, and builtin namespaces; a reference to the previous frame; a data stack; a block stack; and the last instruction executed. (We have to do a little extra work to get to the builtin namespace because Python treats this namespace differently in different modules; this detail is not important to the virtual machine.)

Frame.py

```python
class Frame(object):
    def __init__(self, code_obj, global_names, local_names, prev_frame):
        self.code_obj = code_obj
        self.global_names = global_names
        self.local_names = local_names
        self.prev_frame = prev_frame
        self.stack = []
        if prev_frame:
            self.builtin_names = prev_frame.builtin_names
        else:
            self.builtin_names = local_names['__builtins__']
            if hasattr(self.builtin_names, '__dict__'):
                self.builtin_names = self.builtin_names.__dict__

        self.last_instruction = 0
        self.block_stack = []
```

The Frame Class

- Next, we'll add frame manipulation to the virtual machine. There are three helper functions for frames: one to create new frames (which is responsible for sorting out the namespaces for the new frame) and one each to push and pop frames on and off the frame stack. A fourth function, run_frame, does the main work of executing a frame. We'll come back to this soon.

```python
# Frame manipulation
def make_frame(self, code, callargs={}, global_names=None, local_names=None):
    if global_names is not None and local_names is not None:
        local_names = global_names
    elif self.frames:
        global_names = self.frame.global_names
        local_names = {}
    else:
        global_names = local_names = {
            '__builtins__': __builtins__,
            '__name__': '__main__',
            '__doc__': None,
            '__package__': None,
        }
    local_names.update(callargs)
    frame = Frame(code, global_names, local_names, self.frame)
    return frame
def push_frame(self, frame):
    self.frames.append(frame)
    self.frame = frame
def pop_frame(self):
    self.frames.pop()
    if self.frames:
        self.frame = self.frames[-1]
    else:
        self.frame = None
def run_frame(self):
    pass
    # we'll come back to this shortly
```

VirtualMachine.py

The Function Class

- The implementation of the Function object is somewhat twisty, and most of the details aren't critical to understanding the interpreter. The important thing to notice is that calling a function—invoking the __call__ method—creates a new Frame object and starts running it.

Function.py

```python
class Function(object):
    """
    Create a realistic function object, defining the things the interpreter expects.
    """
    __slots__ = [
        'func_code', 'func_name', 'func_defaults', 'func_globals',
        'func_locals', 'func_dict', 'func_closure',
        '__name__', '__dict__', '__doc__',
        '_vm', '_func',
    ]

    def __init__(self, name, code, globs, defaults, closure, vm):
        """You don't need to follow this closely to understand the interpreter."""
        self._vm = vm
        self.func_code = code
        self.func_name = self.__name__ = name or code.co_name
        self.func_defaults = tuple(defaults)
        self.func_globals = globs
        self.func_locals = self._vm.frame.f_locals
        self.__dict__ = {}
        self.func_closure = closure
        self.__doc__ = code.co_consts[0] if code.co_consts else None
```

Function.py

```python
        # Sometimes, we need a real Python function.  This is for that.
        kw = {
            'argdefs': self.func_defaults,
        }
        if closure:
            kw['closure'] = tuple(make_cell(0) for _ in closure)
        self._func = types.FunctionType(code, globs, **kw)
    def __call__(self, *args, **kwargs):
        """When calling a Function, make a new frame and run it."""
        callargs = inspect.getcallargs(self._func, *args, **kwargs)
        # Use callargs to provide a mapping of arguments: values to pass into the new
        # frame.
        frame = self._vm.make_frame(
            self.func_code, callargs, self.func_globals, {}
        )
        return self._vm.run_frame(frame)

def make_cell(value):
    """Create a real Python closure and grab a cell."""
    # Thanks to Alex Gaynor for help with this bit of twistiness.
    fn = (lambda x: lambda: x)(value)
    return fn.__closure__[0]
```

The VirtualMachine Class

- Next, back on the VirtualMachine object, we'll add some helper methods for data stack manipulation. The bytecodes that manipulate the stack always operate on the current frame's data stack. This will make our implementations of POP_TOP, LOAD_FAST, and all the other instructions that touch the stack more readable.

VirtualMachine.py

```python
# Data stack manipulation
def top(self):
    return self.frame.stack[-1]

def pop(self):
    return self.frame.stack.pop()

def push(self, *vals):
    self.frame.stack.extend(vals)

def popn(self, n):
    """Pop a number of values from the value stack.
    A list of `n` values is returned, the deepest value first.
    """
    if n:
        ret = self.frame.stack[-n:]
        self.frame.stack[-n:] = []
        return ret
    else:
        return []
```

The VirtualMachine Class

- Before we get to running a frame, we need two more methods.
- The first, parse_byte_and_args, takes a bytecode, checks if it has arguments, and parses the arguments if so. This method also updates the frame's attribute last_instruction, a reference to the last instruction executed. A single instruction is one byte long if it doesn't have an argument, and three bytes if it does have an argument; the last two bytes are the argument. The meaning of the argument to each instruction depends on which instruction it is. For example, as mentioned above, for POP_JUMP_IF_FALSE, the argument to the instruction is the jump target. For BUILD_LIST, it is the number of elements in the list. For LOAD_CONST, it's an index into the list of constants.

The VirtualMachine Class

- Some instructions use simple numbers as their arguments. For others, the virtual machine has to do a little work to discover what the arguments mean. The dis module in the standard library exposes a cheatsheet explaining what arguments have what meaning, which makes our code more compact. For example, the list dis.hasname tells us that the arguments to LOAD_NAME, IMPORT_NAME, LOAD_GLOBAL, and nine other instructions have the same meaning: for these instructions, the argument represents an index into the list of names on the code object.

The VirtualMachine Class

- The next method is dispatch, which looks up the operations for a given instruction and executes them. In the CPython interpreter, this dispatch is done with a giant switch statement that spans 1,500 lines! Luckily, since we're writing Python, we can be more compact. We'll define a method for each byte name and then use getattr to look it up. Like in the toy interpreter above, if our instruction is named FOO_BAR, the corresponding method would be named byte_FOO_BAR.
- For the moment, we'll leave the content of these methods as a black box. Each bytecode method will return either None or a string, called why, which is an extra piece of state the interpreter needs in some cases. These return values of the individual instruction methods are used only as internal indicators of interpreter state—don't confuse these with return values from executing frames.

VirtualMachine.py

```python
def dispatch(self, byte_name, argument):
    """ Dispatch by bytename to the corresponding methods.
    Exceptions are caught and set on the virtual machine."""

    # When later unwinding the block stack,
    # we need to keep track of why we are doing it.
    why = None
    try:
        bytecode_fn = getattr(self, 'byte_%s' % byte_name, None)
        if bytecode_fn is None:
            if byte_name.startswith('UNARY_'):
                self.unaryOperator(byte_name[6:])
            elif byte_name.startswith('BINARY_'):
                self.binaryOperator(byte_name[7:])
            else:
                raise VirtualMachineError(
                    "unsupported bytecode type: %s" % byte_name
                )
        else:
            why = bytecode_fn(*argument)
    except:
        # deal with exceptions encountered while executing the op.
        self.last_exception = sys.exc_info()[:2] + (None,)
        why = 'exception'

    return why
```

```python
def run_frame(self, frame):
    """Run a frame until it returns (somehow).
    Exceptions are raised, the return value is returned.
    """
    self.push_frame(frame)
    while True:
        byte_name, arguments = self.parse_byte_and_args()

        why = self.dispatch(byte_name, arguments)

        # Deal with any block management we need to do
        while why and frame.block_stack:
            why = self.manage_block_stack(why)

        if why:
            break

    self.pop_frame()

    if why == 'exception':
        exc, val, tb = self.last_exception
        e = exc(val)
        e.__traceback__ = tb
        raise e

    return self.return_value
```

The Block Class

- Before we implement the methods for each bytecode instruction, we'll briefly discuss blocks. A block is used for certain kinds of flow control, specifically exception handling and looping. The block is reponsible for making sure that the data stack is in the appropriate state when the operation is finished. For example, in a loop, a special iterator object remains on the stack while the loop is running, but is popped off when it is finished. The interpreter must keep track of whether the loop is continuing or is finished.

The Block Class

- To keep track of this extra piece of information, the interpreter sets a flag to indicate its state. We implement this flag as a variable called why, which can be None or one of the strings "continue", "break", "exception", or "return". This indicates what kind of manipulation of the block stack and data stack should happen. To return to the iterator example, if the top of the block stack is a loop block and the why code is continue, the iterator object should remain on the data stack, but if the why code is break, it should be popped off.

The Block Class

- The precise details of block manipulation are rather fiddly, and we won't spend more time on this, but interested readers are encouraged to take a careful look.

```
Block = collections.namedtuple("Block",
                               "type, handler,
                               stack_height")
```

VirtualMachine.py

```python
# Block stack manipulation
def push_block(self, b_type, handler=None):
    stack_height = len(self.frame.stack)
    self.frame.block_stack.append(Block(b_type, handler, stack_height))

def pop_block(self):
    return self.frame.block_stack.pop()

def unwind_block(self, block):
    """Unwind the values on the data stack corresponding to a given block."""
    if block.type == 'except-handler':
        # The exception itself is on the stack as type, value, and traceback.
        offset = 3
    else:
        offset = 0

    while len(self.frame.stack) > block.level + offset:
        self.pop()

    if block.type == 'except-handler':
        traceback, value, exctype = self.popn(3)
        self.last_exception = exctype, value, traceback
```

VirtualMachine.py

```python
def manage_block_stack(self, why):
    """ """
    frame = self.frame
    block = frame.block_stack[-1]
    if block.type == 'loop' and why == 'continue':
        self.jump(self.return_value)
        why = None
        return why

    self.pop_block()
    self.unwind_block(block)

    if block.type == 'loop' and why == 'break':
        why = None
        self.jump(block.handler)
        return why

    if (block.type in ['setup-except', 'finally'] and why == 'exception'):
        self.push_block('except-handler')
        exctype, value, tb = self.last_exception
        self.push(tb, value, exctype)
        self.push(tb, value, exctype) # yes, twice
        why = None
        self.jump(block.handler)
        return why
```

```python
elif block.type == 'finally':
    if why in ('return', 'continue'):
        self.push(self.return_value)

    self.push(why)

    why = None
    self.jump(block.handler)
    return why
return why
```

A Python Interpreter Written in Python

The Instructions

SECTION 10

The Instructions

- All that's left is to implement the dozens of methods for instructions. The actual instructions are the least interesting part of the interpreter, so we show only a handful here, but the full implementation is available on GitHub.
- (Enough instructions are included here to execute all the code samples that we disassembled above.)

VirtualMachine.py

```python
def byte_LOAD_CONST(self, const):
    self.push(const)

def byte_POP_TOP(self):
    self.pop()

## Names
def byte_LOAD_NAME(self, name):
    frame = self.frame
    if name in frame.f_locals:
        val = frame.f_locals[name]
    elif name in frame.f_globals:
        val = frame.f_globals[name]
    elif name in frame.f_builtins:
        val = frame.f_builtins[name]
    else:
        raise NameError("name '%s' is not defined" % name)
    self.push(val)
```

VirtualMachine.py

```python
def byte_STORE_NAME(self, name):
    self.frame.f_locals[name] = self.pop()
def byte_LOAD_FAST(self, name):
    if name in self.frame.f_locals:
        val = self.frame.f_locals[name]
    else:
        raise UnboundLocalError(
            "local variable '%s' referenced before assignment" % name
        )
    self.push(val)
def byte_STORE_FAST(self, name):
    self.frame.f_locals[name] = self.pop()
def byte_LOAD_GLOBAL(self, name):
    f = self.frame
    if name in f.f_globals:
        val = f.f_globals[name]
    elif name in f.f_builtins:
        val = f.f_builtins[name]
    else:
        raise NameError("global name '%s' is not defined" % name)
    self.push(val)
```

```python
## Operators
BINARY_OPERATORS = {
    'POWER':    pow,
    'MULTIPLY': operator.mul,
    'FLOOR_DIVIDE': operator.floordiv,
    'TRUE_DIVIDE':  operator.truediv,
    'MODULO':   operator.mod,
    'ADD':      operator.add,
    'SUBTRACT': operator.sub,
    'SUBSCR':   operator.getitem,
    'LSHIFT':   operator.lshift,
    'RSHIFT':   operator.rshift,
    'AND':      operator.and_,
    'XOR':      operator.xor,
    'OR':       operator.or_,
}

def binaryOperator(self, op):
    x, y = self.popn(2)
    self.push(self.BINARY_OPERATORS[op](x, y))
```

VirtualMachine.py

```python
COMPARE_OPERATORS = [
    operator.lt,
    operator.le,
    operator.eq,
    operator.ne,
    operator.gt,
    operator.ge,
    lambda x, y: x in y,
    lambda x, y: x not in y,
    lambda x, y: x is y,
    lambda x, y: x is not y,
    lambda x, y: issubclass(x, Exception) and issubclass(x, y),
]

def byte_COMPARE_OP(self, opnum):
    x, y = self.popn(2)
    self.push(self.COMPARE_OPERATORS[opnum](x, y))
```

```python
## Attributes and indexing
def byte_LOAD_ATTR(self, attr):
    obj = self.pop()
    val = getattr(obj, attr)
    self.push(val)

def byte_STORE_ATTR(self, name):
    val, obj = self.popn(2)
    setattr(obj, name, val)

## Building
def byte_BUILD_LIST(self, count):
    elts = self.popn(count)
    self.push(elts)

def byte_BUILD_MAP(self, size):
    self.push({})

def byte_STORE_MAP(self):
    the_map, val, key = self.popn(3)
    the_map[key] = val
    self.push(the_map)
```

```python
def byte_LIST_APPEND(self, count):
    val = self.pop()
    the_list = self.frame.stack[-count] # peek
    the_list.append(val)

## Jumps
def byte_JUMP_FORWARD(self, jump):
    self.jump(jump)

def byte_JUMP_ABSOLUTE(self, jump):
    self.jump(jump)

def byte_POP_JUMP_IF_TRUE(self, jump):
    val = self.pop()
    if val:
        self.jump(jump)

def byte_POP_JUMP_IF_FALSE(self, jump):
    val = self.pop()
    if not val:
        self.jump(jump)
```

```python
## Blocks
def byte_SETUP_LOOP(self, dest):
    self.push_block('loop', dest)

def byte_GET_ITER(self):
    self.push(iter(self.pop()))

def byte_FOR_ITER(self, jump):
    iterobj = self.top()
    try:
        v = next(iterobj)
        self.push(v)
    except StopIteration:
        self.pop()
        self.jump(jump)

def byte_BREAK_LOOP(self):
    return 'break'

def byte_POP_BLOCK(self):
    self.pop_block()
```

```
## Functions
def byte_MAKE_FUNCTION(self, argc):
    name = self.pop()
    code = self.pop()
    defaults = self.popn(argc)
    globs = self.frame.f_globals
    fn = Function(name, code, globs, defaults, None, self)
    self.push(fn)

def byte_CALL_FUNCTION(self, arg):
    lenKw, lenPos = divmod(arg, 256) # KWargs not supported here
    posargs = self.popn(lenPos)

    func = self.pop()
    frame = self.frame
    retval = func(*posargs)
    self.push(retval)

def byte_RETURN_VALUE(self):
    self.return_value = self.pop()
    return "return"
```

A Python Interpreter Written in Python

Dynamic Typing: What the Compiler Doesn't Know

SECTION 11

Dynamic Typing: What the Compiler Doesn't Know

One thing you've probably heard is that Python is a "dynamic" language—particularly that it's "dynamically typed". The work we've done to this point sheds some light on this description.

One of the things "dynamic" means in this context is that a lot of work is done at run time. We saw earlier that the Python compiler doesn't have much information about what the code actually does. For example, consider the short function mod below. mod takes two arguments and returns the first modulo the second. In the bytecode, we see that the variables a and b are loaded, then the bytecode BINARY_MODULO performs the modulo operation itself.

Dynamic Typing: What the Compiler Doesn't Know

```
>>> def mod(a, b):
...     return a % b
>>> dis.dis(mod)
  2           0 LOAD_FAST                0 (a)
              3 LOAD_FAST                1 (b)
              6 BINARY_MODULO
              7 RETURN_VALUE
>>> mod(19, 5)
4
```

Dynamic Typing: What the Compiler Doesn't Know

- Calculating 19 % 5 yields 4—no surprise there. What happens if we call it with different arguments?

```
>>> mod("by%sde", "teco")
'bytecode'
```

- What just happened? You've probably seen this syntax before, but in a different context:

```
>>> print("by%sde" % "teco")
bytecode
```

Dynamic Typing: What the Compiler Doesn't Know

- Using the symbol % to format a string for printing means invoking the instruction BINARY_MODULO. This instruction mods together the top two values on the stack when the instruction executes—regardless of whether they're strings, integers, or instances of a class you defined yourself. The bytecode was generated when the function was compiled (effectively, when it was defined) and the same bytecode is used with different types of arguments.

Dynamic Typing: What the Compiler Doesn't Know

- The Python compiler knows relatively little about the effect the bytecode will have. It's up to the interpreter to determine the type of the object that BINARY_MODULO is operating on and do the right thing for that type. This is why Python is described as dynamically typed: you don't know the types of the arguments to this function until you actually run it. By contrast, in a language that's statically typed, the programmer tells the compiler up front what type the arguments will be (or the compiler figures them out for itself).

Dynamic Typing: What the Compiler Doesn't Know

- The compiler's ignorance is one of the challenges to optimizing Python or analyzing it statically—just looking at the bytecode, without actually running the code, you don't know what each instruction will do! In fact, you could define a class that implements the __mod__ method, and Python would invoke that method if you use % on your objects. So BINARY_MODULO could run any code at all!

- Just looking at the following code, the first calculation of a % b seems wasteful.

```
def mod(a,b):
    a % b
    return a %b
```

Dynamic Typing: What the Compiler Doesn't Know

- Unfortunately, a static analysis of this code—the kind of you can do without running it—can't be certain that the first a % b really does nothing. Calling __mod__ with % might write to a file, or interact with another part of your program, or do literally anything else that's possible in Python. It's hard to optimize a function when you don't know what it does! In Russell Power and Alex Rubinsteyn's great paper "How fast can we make interpreted Python?", they note, "In the general absence of type information, each instruction must be treated as INVOKE_ARBITRARY_METHOD."

A Python Interpreter Written in Python

Conclusion

SECTION 12

Conclusion

- Byterun is a compact Python interpreter that's easier to understand than CPython. Byterun replicates CPython's primary structural details: a stack-based interpreter operating on instruction sets called bytecode. It steps or jumps through these instructions, pushing to and popping from a stack of data. The interpreter creates, destroys, and jumps between frames as it calls into and returns from functions and generators. Byterun shares the real interpreter's limitations, too: because Python uses dynamic typing, the interpreter must work hard at run time to determine the correct behavior of a program.

Conclusion

- I encourage you to disassemble your own programs and to run them using Byterun. You'll quickly run into instructions that this shorter version of Byterun doesn't implement. The full implementation can be found at https://github.com/nedbat/byterun—or, by carefully reading the real CPython interpreter's ceval.c, you can implement it yourself!

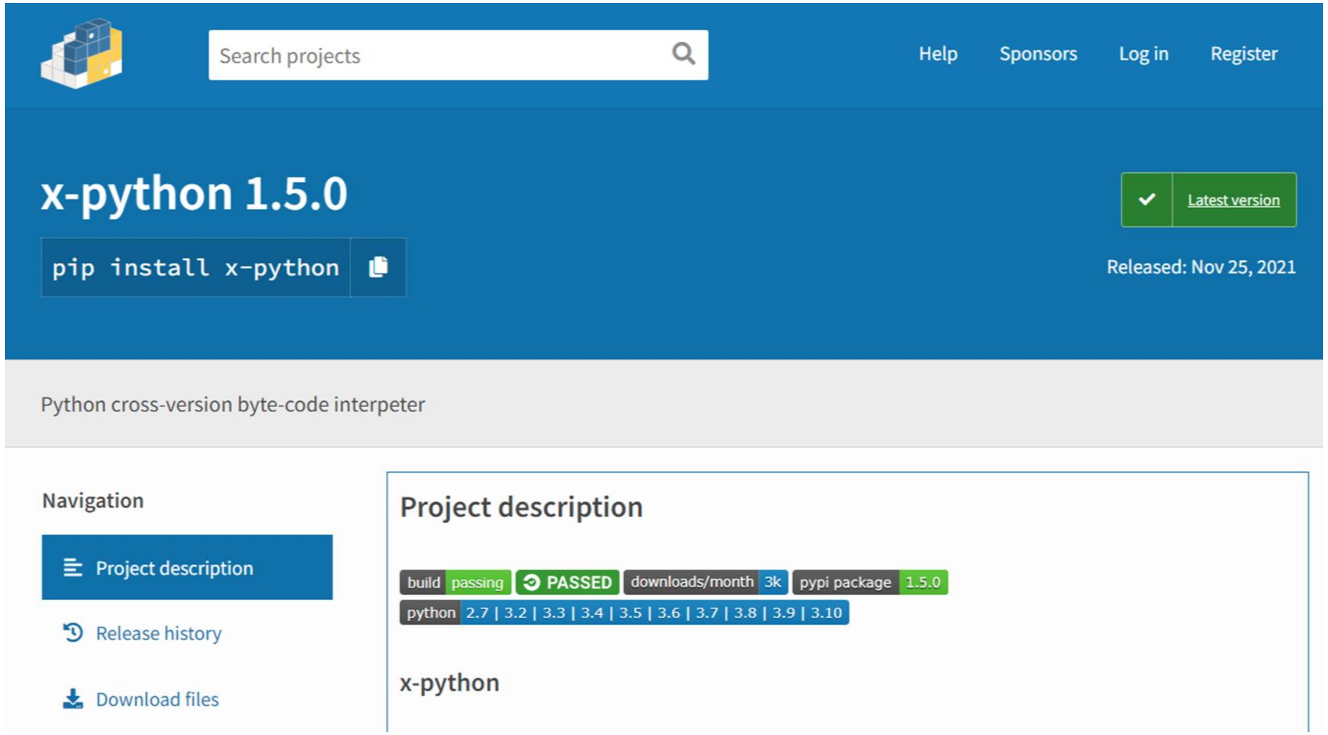
X-Python

SECTION 13

x-python

- This is a CPython **bytecode** interpreter written Python.
- You can use this to:
  - Learn about how the internals of CPython works since this models that
  - Experiment with additional opcodes, or ways to change the run-time environment
  - Use as a sandboxed environment for trying pieces of execution
  - Have one Python program that runs multiple versions of Python bytecode.
  - Use in a dynamic fuzzer or in coholic execution for analysis

x-python Installation



```
C:\Eric_Chou\Lewis University\CS 46K SIPC\PyDev\Lecture 15\x-python>pip install x-python
Collecting x-python
  Downloading https://files.pythonhosted.org/packages/85/aa/15badbc5f609bbb324136e2747b39c8ad095a187095
27b5fe4a1b55a2f7f/x_python-1.5.0-py36-none-any.whl (108kB)
    100% |████████████████████████████████| 112kB 755kB/s
Requirement already satisfied: six in c:\users\ericc\appdata\roaming\python\python36\site-packages (fro
m x-python) (1.11.0)
Collecting xdis<6.1.0,>=6.0.3 (from x-python)
  Downloading https://files.pythonhosted.org/packages/15/0f/d689434bb726cf9495ac59343f5b748367c30bdbef8
4222bd140a7348c80/xdis-6.0.3-py36-none-any.whl (134kB)
    100% |████████████████████████████████| 143kB 1.1MB/s
Requirement already satisfied: click in c:\python\python36\lib\site-packages (from x-python) (7.1.2)
Installing collected packages: xdis, x-python
Successfully installed x-python-1.5.0 xdis-6.0.3
You are using pip version 18.1, however version 21.3.1 is available.
You should consider upgrading via the 'python -m pip install --upgrade pip' command.

C:\Eric_Chou\Lewis University\CS 46K SIPC\PyDev\Lecture 15\x-python>
```

Demo Program

a.py

```
a = 3
b = 4
print(a+b)
```

a.py

```
xpython -v a.py
```

run_a.bat

Demo Program

a.py

```
C:\Eric_Chou\Lewis University\CS 46K SIPC\PyDev\Lecture 15\x-python>xpython -v a.py
INFO:xpython.vm:L. 1    @  0: LOAD_CONST 3
INFO:xpython.vm:        @  2: STORE_NAME (3) a
INFO:xpython.vm:L. 2    @  4: LOAD_CONST 4
INFO:xpython.vm:        @  6: STORE_NAME (4) b
INFO:xpython.vm:L. 3    @  8: LOAD_NAME print
INFO:xpython.vm:        @ 10: LOAD_NAME a
INFO:xpython.vm:        @ 12: LOAD_NAME b
INFO:xpython.vm:        @ 14: BINARY_ADD (3, 4)
INFO:xpython.vm:        @ 16: CALL_FUNCTION (print) [1 positional argument] 1
7
INFO:xpython.vm:        @ 18: POP_TOP
INFO:xpython.vm:        @ 20: LOAD_CONST None
INFO:xpython.vm:        @ 22: RETURN_VALUE (None)

C:\Eric_Chou\Lewis University\CS 46K SIPC\PyDev\Lecture 15\x-python>
```

Demo Program
gcd.py

gcd.py

```
def gcd(m, n):
    if (n==0): return m
    return gcd(n, m%n)

print(gcd(36, 48))
```

```
C:\Eric_Chou\Lewis University\CS 46K SIPC\PyDev\Lecture 15\x-python>xpython -v gcd.py > b.
txt
INFO:xpython.vm:L. 1   @  0: LOAD_CONST <code object gcd at 0x000001E648476C00, file "gcd.
py", line 1>
INFO:xpython.vm:       @  2: LOAD_CONST gcd
INFO:xpython.vm:       @  4: MAKE_FUNCTION (gcd) [Neither defaults, keyword-only args, ann
otations, nor closures] 0
INFO:xpython.vm:       @  6: STORE_NAME (<Function gcd at 0x1e64898e368>) gcd
INFO:xpython.vm:L. 5   @  8: LOAD_NAME print
INFO:xpython.vm:       @ 10: LOAD_NAME gcd
INFO:xpython.vm:       @ 12: LOAD_CONST 36
INFO:xpython.vm:       @ 14: LOAD_CONST 48
INFO:xpython.vm:       @ 16: CALL_FUNCTION (gcd) [2 positional arguments] 2
INFO:xpython.vm:    L. 2   @  0: LOAD_FAST n
INFO:xpython.vm:           @  2: LOAD_CONST 0
INFO:xpython.vm:           @  4: COMPARE_OP (48, 0) ==
INFO:xpython.vm:           @  6: POP_JUMP_IF_FALSE 12
INFO:xpython.vm:    L. 3   @ 12: LOAD_GLOBAL gcd
INFO:xpython.vm:           @ 14: LOAD_FAST n
INFO:xpython.vm:           @ 16: LOAD_FAST m
INFO:xpython.vm:           @ 18: LOAD_FAST n
INFO:xpython.vm:           @ 20: BINARY_MODULO (36, 48)
INFO:xpython.vm:           @ 22: CALL_FUNCTION (gcd) [2 positional arguments] 2
INFO:xpython.vm:                L. 2   @  0: LOAD_FAST n
INFO:xpython.vm:                       @  2: LOAD_CONST 0
INFO:xpython.vm:                       @  4: COMPARE_OP (0, 0) ==
INFO:xpython.vm:                       @  6: POP_JUMP_IF_FALSE 12
INFO:xpython.vm:                L. 2   @  8: LOAD_FAST m
INFO:xpython.vm:                       @ 10: RETURN_VALUE (12)
INFO:xpython.vm:                   @ 24: RETURN_VALUE (12)
INFO:xpython.vm:               @ 24: RETURN_VALUE (12)
INFO:xpython.vm:           @ 24: RETURN_VALUE (12)
INFO:xpython.vm:       @ 18: CALL_FUNCTION (print) [1 positional argument] 1
INFO:xpython.vm:       @ 20: POP_TOP
INFO:xpython.vm:       @ 22: LOAD_CONST None
INFO:xpython.vm:       @ 24: RETURN_VALUE (None)

C:\Eric_Chou\Lewis University\CS 46K SIPC\PyDev\Lecture 15\x-python>
```

End of Chapter 10B