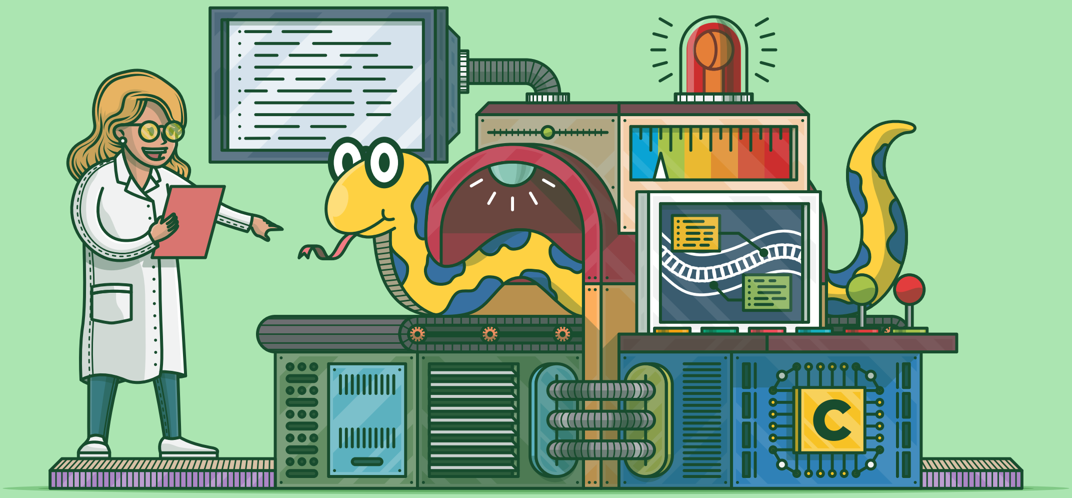
Real Python

CPYTHON INTERNALS



YOUR GUIDE TO THE PYTHON 3 INTERPRETER

FIRST EDITION

BY ANTHONY SHAW AND THE REALPYTHON.COM TUTORIAL TEAM

CPython Internals: Your Guide to the Python 3 Interpreter

Anthony Shaw

CPython Internals: Your Guide to the Python 3 Interpreter

Anthony Shaw

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This is an Early Access version of "CPython Internals: Your Guide to the Python 3 Interpreter"

With your help we can make this book even better:

At the end of each section of the book you'll find a "magical" feedback link. Clicking the link takes you to an **online feedback form** where you can share your thoughts with us.

Please feel free to be as terse or detailed as you see fit. All feedback is stored anonymously, but you can choose to leave your name and contact information so we can follow up or mention you on our "Thank You" page.

We use a different feedback link for each section, so we'll always know which part of the book your notes refer to.

Thank you for helping us make this book an even more valuable learning resource for the Python community.

— Anthony Shaw

What Readers Say About *CPython Internals: Your Guide to the Python 3 Interpreter*

"A comprehensive walkthrough of the Python internals, a topic which surprisingly has almost no good resource, in an easy-to-understand manner for both beginners as well as advanced Python users."

— **Abhishek Sharma**, Data Scientist

"The 'Parallelism and Concurrency' chapter is one of my favorites. I had been looking to get an in depth understanding around this topic and I found your book extremely helpful.

Of course, after going over that chapter I couldn't resist the rest. I am eagerly looking forward to have my own printed copy once it's out!

I had gone through your 'Guide to CPython Source code' article previously which got me interested in finding out more about the internals.

There are a ton of books on Python which teach the language, but I haven't really come across anything that would go about explaining the internals to those curious minded.

And while I teach Python to my daughter currently, I have this book added in her must-read list. She's currently studying Information Systems at Georgia State University."

— **Milan Patel**, Vice President at (a major investment bank)

"What impresses me the most about Anthony's book is how it puts all the steps for making changes to the CPython code base in an easy to follow sequence. It really feels like a 'missing manual' of sorts.

Diving into the C underpinnings of Python was a lot of fun and it cleared up some longstanding questions marks for me. I found the chapter about CPython's memory allocator especially enlightening.

CPython Internals is a great (and unique) resource for anybody looking to take their knowledge of Python to a deeper level."

— **Dan Bader**, Author of *Python Tricks* and Editor-in-Chief at Real Python

"This book helped me to better understand how lexing and parsing works in Python. It's my recommended source if you want to understand it."

— **Florian Dahlitz**, Pythonista

Acknowledgements

Thank you to my wife, Verity, for her support and patience. Without her this wouldn't be possible.

Thank you to everyone who has supported me on this journey.

– Anthony Shaw

About the Author

Anthony Shaw is an avid Pythonista and Fellow of the Python Software Foundation.

Anthony has been programming since the age of 12 and found a love for Python while trapped inside a hotel in Seattle, Washington, 15 years later. After ditching the other languages he'd learned, Anthony has been researching, writing about, and creating courses for Python ever since.

Anthony also contributes to small and large Open Source projects, including CPython, as well as being a member of the Apache Software Foundation.

Anthony's passion lies in understanding complex systems, then simplifying them, and teaching them to people.

About the Review Team

Jim Anderson has been programming for a long time in a variety of languages. He has worked on embedded systems, built distributed build systems, done off-shore vendor management, and sat in many, many meetings.

Contents

Foreword

> *"A programming language created by a community fosters happiness in its users around the world."*
>
> — Guido van Rossum, King's Day Speech 2016

I love building tools that help us learn, empower us to create, and move us to share knowledge and ideas with others. I feel humbled, thankful, and proud when I hear how these tools and Python are helping you to solve real-world problems, like climate change or Alzheimer's.

Through my "four decades" love of programming and problem solving, I have spent time learning, writing a lot of code, and sharing my ideas with others. I've seen profound changes in technology as the world progressed from mainframes to cell phone service to the wide-ranging wonders of the web and cloud computing. All of these technologies, including Python, have one thing in common.

At one moment, these successful innovations were nothing more than an idea. The creators, like Guido, had to take risks and leaps of faith to move forward. Dedication, learning through trial and error and working through many failures together built a solid foundation for success and growth.

CPython Internals will take you on a journey to explore the wildly successful language, **Python**. The book serves as a guidebook for learning how CPython is created under the hood. It will give you a glimpse of how the core developers crafted the language. Python's strengths include its readability and a welcoming community dedicated to education. Anthony embraces these strengths when explaining CPython, encouraging you to read the source, and sharing the building blocks of the language with you.

Why do I want to share Anthony's *CPython Internals* with you? It's the book that I wish existed years ago when I started my Python journey. More importantly, I believe we, as members of the Python community, have a unique opportunity – to put our expertise to work to help solve the complex real-world problems facing us. I'm confident after reading this book your skills will grow and you will be able solve even more complex problems that can improve our world.

It's my hope that Anthony motivates you to learn more about Python, inspire you to build innovative things, and give you confidence to share your creations with the world.

> *"Now is better than Never."*
>
> — Tim Peters, The Zen of Python

Let's follow Tim's wisdom and get started now.

Warmly,

— **Carol Willing**, CPython Core Developer & Member of the CPython Steering Council

Introduction

Are there certain parts of Python that just seem magic? Like how dictionaries are so much faster than looping over a list to find an item. How does a generator remember the state of the variables each time it yields a value, and why do you never have to allocate memory like other languages? It turns out, CPython, the most popular Python runtime is written in human-readable C and Python code.

CPython abstracts the complexities of the underlying C platform and your Operating System. It makes threading straightforward and cross-platform. It takes the pain of memory management in C and makes it simple. CPython gives the developer writing Python code the platform to write scalable and performant applications. At some stage in your progression as a Python developer, you need to understand how CPython works. These abstractions are not perfect, and they are leaky.

Once you understand how CPython works, you can optimize your applications and fully leverage its power. This book will explain the concepts, ideas, and technicalities of CPython.

In this book you'll cover the major concepts behind the internals of CPython, and learn how to:

- Read and navigate the source code
- Compile CPython from source code
- Make changes to the Python syntax and compile them into your version of CPython

- Navigate and comprehend the inner workings of concepts like lists, dictionaries, and generators
- Master CPython's memory management capabilities
- Scale your Python code with parallelism and concurrency
- Modify the core types with new functionality
- Run the test suite
- Profile and benchmark the performance of your Python code and runtime
- Debug C and Python code like a professional
- Modify or upgrade components of the CPython library to contribute them to future versions

Take your time for each chapter and make sure you try out the demos and the interactive elements. You can feel a sense of achievement that you grasp the core concepts of Python that can make you a better Python programmer.

How to Use This Book

This book is all about learning by doing, so be sure to set up your IDE early in the book using the instructions, downloading the code, and writing the examples.

For the best results, we recommend that you avoid copying and pasting the code examples. The examples in this book took many iterations to get right, and they may also contain bugs.

Making mistakes and learning how to fix them is part of the learning process. You might discover better ways to implement the examples, try changing them, and seeing what effect it has.

With enough practice, you will master this material—and have fun along the way!

How skilled do I need to be in Python to use this book? This book is aimed at Intermediate to Advanced Python developers. Every effort has been taken to show code examples, but some intermediate Python techniques will be used throughout the book.

Do I need to know C to use this book? You do not need to be proficient in C to use this book. If you are new to C, check out *Appendix 1: Introduction to C for Python Programmers* at the back of this book for a quick introduction.

How long will it take to finish this book? I don't recommend rushing this book. Try reading a chapter at a time, trying the examples after each chapter and exploring the code simultaneously. Once you've finished the book, it will make a great reference guide for you to come back to in time.

Won't the content in this book be out of date really quickly? Python has been around for over 30 years. Some parts of the CPython code haven't been touched since they were originally written. Many of the principles in this book have been the same for ten or more years. In fact, whilst writing this book, I discovered many lines of code written by Guido van Rossum (the author of Python) and untouched since version 1.

The skills you'll learn in this book will help you read and understand current and future versions of CPython. Change is constant, and your expertise is something you can develop along the way.

Some of the concepts in this book are brand-new; some are even experimental. While writing this book, I came across issues in the source code and bugs in CPython. Then, they got fixed or improved. That's part of the wonder of CPython as a flourishing open-source project.

Bonus Material & Learning Resources

Online Resources

This book comes with a number of free bonus resources that you can access at realpython.com/cpython-internals/resources/. On this web page, you can also find an errata list with corrections maintained by the Real Python team.

Code Samples

The examples and sample configurations throughout this book will be marked with a header denoting them as part of the `cpython-book-samples` folder.

cpython-book-samples ▸ 01 ▸ example.py

```
import this
```

You can download the code samples at realpython.com/cpython-internals/resources/.

Code Licenses

The example Python scripts associated with this book are licensed under a Creative Commons Public Domain (CC0) License. This means that you're welcome to use any portion of the code for any purpose in your own programs.

CPython is licensed under the PSF 2 license. Snippets and samples of CPython source code used in this book are done so under the license of the PSF 2.0 license terms.

> **Note**
>
> The code found in this book has been tested with Python 3.9.0b5 on Windows 10, macOS 10.15, and Linux.

Formatting Conventions

Code blocks will be used to present example code:

```
# This is Python code:
print("Hello world!")
```

Operating System agnostic commands follow the Unix-style format:

```
$ # This is a terminal command:
$ python hello-world.py
```

The `$` is not part of the command.

Windows-specific commands have the Windows command line format:

```
> python hello-world.py
```

The `>` is not part of the command.

Bold text will be used to denote a new or important term.

Notes and Important/Warning boxes appear as follows:

Note

This is a note filled in with placeholder text. The quick brown fox jumps over the lazy dog. The quick brown Python slithers over the lazy hog.

Important

This is a warning also filled in with placeholder text. The quick brown fox jumps over the lazy dog. The quick brown Python slithers over the lazy hog.

Any references to a file within the CPython source code will be shown like this:

path ▸ to ▸ file.py

Shortcuts or menu commands will be given in sequence, like this:

File › Other › Option

Keyboard commands and shortcuts will be given for both macOS and

Windows:

CTRL + SPACE

Feedback & Errata

We welcome ideas, suggestions, feedback, and the occasional rant. Did you find a topic confusing? Did you find an error in the text or code? Did we leave out a topic you would love to know more about?

We're always looking to improve our teaching materials. Whatever the reason, please send in your feedback at the link below:

realpython.com/cpython-internals/feedback

About Real Python

At Real Python, you'll learn real-world programming skills from a community of professional Pythonistas from all around the world.

The realpython.com website launched in 2012 and currently helps more than two million Python developers each month with books, programming tutorials, and other in-depth learning resources.

Here's where you can find Real Python on the web:

- realpython.com
- @realpython on Twitter
- The Real Python Email Newsletter

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Getting the CPython Source Code

When you type `python` at the console or install a Python distribution from python.org, you are running **CPython**. CPython is one of many Python implementations, maintained and written by different teams of developers. Some alternatives you may have heard of are PyPy, Cython, and Jython.

The unique thing about CPython is that it contains both a runtime and the shared language specification that all other Python implementations use. CPython is the "official" or reference implementation of Python.

The Python language specification is the document that describes the Python language. For example, it says that `assert` is a reserved keyword, and that `[]` is used for indexing, slicing, and creating empty lists.

Think about what you expect to be inside the Python distribution:

- When you type `python` without a file or module, it gives an interactive prompt (REPL).
- You can import built-in modules from the standard library like `json`, `csv`, and `collections`.
- You can install packages from the internet using `pip`.
- You can test your applications using the built-in `unittest` library.

These are all part of the CPython distribution. There's a lot more than just a compiler.

In this book, we'll explore the different parts of the CPython distribution:

- The language specification
- The compiler
- The standard library modules
- The core types
- The test suite

What's in the Source Code?

> **Note**
>
> This book targets version 3.9.0b5 of the CPython source code.

The CPython source distribution comes with a whole range of tools, libraries, and components. We'll explore those in this book.

To download a copy of the CPython source code, you can use `git` to pull the latest version:

```
$ git clone https://github.com/python/cpython
$ cd cpython
```

We are using version 3.9.0b5 throughout this book. Check out that version and create a local branch from it:

```
$ git checkout tags/v3.9.0b5 -b v3.9.0b5
```

> **Important**
>
> Switching to the v3.9.0b5 version is an important step. The master branch changes on an hourly basis. Many of the examples and exercises in this book are unlikely to work on master.

> **Note**
>
> If you don't have Git available, you can install it from git-scm.com. Alternatively, you can download the CPython source in a ZIP file directly from the GitHub website.
>
> If you download the source as a ZIP file, it won't contain any history, tags or branches.

Inside of the newly downloaded `cpython` directory, you will find the following subdirectories:

cpython/

Doc	Source for the documentation
Grammar	The computer-readable language definition
Include	The C header files
Lib	Standard library modules written in Python
Mac	macOS support files
Misc	Miscellaneous files
Modules	Standard library modules written in C
Objects	Core types and the object model
Parser	The Python parser source code
PC	Windows build support files for older versions of Windows
PCBuild	Windows build support files
Programs	Source code for the 'python' executable and other binaries
Python	The CPython interpreter source code
Tools	Standalone tools useful for building or extending CPython
m4	Custom scripts to automate configuration of the makefile

Next, you can set up your development environment.

Leave feedback on this section »

Setting up Your Development Environment

Throughout this book, you'll be working with C and Python code. It's going to be essential to have your development environment configured to support both languages.

The CPython source code is about 65% Python (the tests are a significant part), 24% C, and the remainder a mix of other languages.

IDE or Editor?

If you haven't yet decided which development environment to use, there is one decision to make first, whether to use an Integrated Development Environment (IDE) or code editor.

- An **IDE** targets a specific language and toolchain. Most IDEs have integrated testing, syntax checking, version control, and compilation.
- A **code editor** enables you to edit code files, regardless of language. Most code editors are simple text editors with syntax highlighting.

Because of their full-featured nature, IDEs often consume more hardware resources. So if you have limited RAM (less than 8GB), a code editor is recommended. IDEs also take longer to start-up. If you want to edit a file quickly, a code editor is a better choice.

There are 100's of editors and IDEs available for free or at a cost, here are some commonly used IDEs and Editors that would suit CPython development:

Application	Style	Supports
Microsoft VS Code	Editor	Windows, macOS and Linux
Atom	Editor	Windows, macOS and Linux
Sublime Text	Editor	Windows, macOS and Linux
Vim	Editor	Windows, macOS and Linux
Emacs	Editor	Windows, macOS and Linux
Microsoft Visual Studio	IDE (C, Python, and others)	Windows*
PyCharm by JetBrains	IDE (Python and others)	Windows, macOS and Linux
CLion by JetBrains	IDE (C and others)	Windows, macOS and Linux

* A version of Visual Studio is available for Mac, but does not support Python Tools for Visual Studio, nor C compilation.

To aid the development of CPython, you will explore the setup steps for:

- Microsoft Visual Studio
- Microsoft Visual Studio Code
- JetBrains CLion
- Vim

Skip ahead to the section for your chosen application, or read all of them if you want to compare.

Setting up Visual Studio

The newest version of Visual Studio, Visual Studio 2019, has builtin support for Python and the C source code on Windows. I recommend it for this book. If you already have Visual Studio 2017 installed, that would also work.

> **Note**
>
> None of the paid features are required for compiling CPython or this book. You can use the free, Community edition of Visual Studio.
>
> The Profile-Guided-Optimization build profile requires the Professional Edition or higher.

Visual Studio is available for free from Microsoft's Visual Studio website.

Once you've downloaded the Visual Studio installer, you'll be asked to select which components you want to install. The bare minimum for this book is:

- The **Python Development** workload
- The optional **Python native development tools**
- Python 3 64-bit (3.7.2) (can be deselected if you already have Python 3.7 installed)

Deselect any other optional features if you want to be more conscientious with disk space.

The installer will then download and install all of the required components. The installation could take an hour, so you may want to read on and come back to this section.

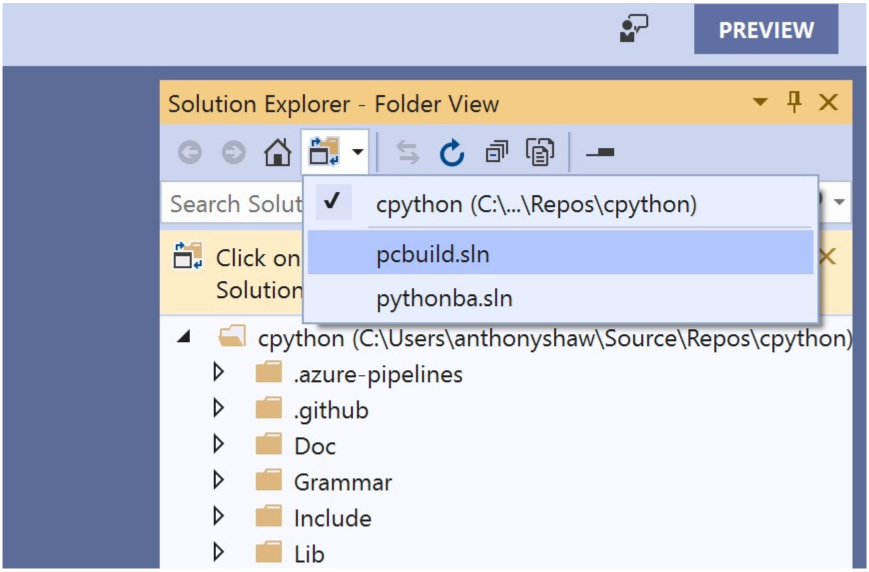
Once the installer has completed, click the Launch button to start Visual Studio. You will be prompted to sign in. If you have a Microsoft account, you can log in, or skip that step.

You will now be prompted to Open a Project. You can clone CPython's Git repository directly from Visual Studio by choosing the Clone or check out code option.

For the Repository Location, enter `https://github.com/python/cpython`, choose your Local path, and select Clone.

Visual Studio will then download a copy of CPython from GitHub using the version of Git bundled with Visual Studio. This step also saves you the hassle of having to install Git on Windows. The download may take 10 minutes.

Once the project has downloaded, you need to point Visual Studio to the `PCBuild` ▸ `pcbuild.sln` Solution file, by clicking on Solutions and Projects » pcbuild.sln:



Now that you have Visual Studio configured and the source code downloaded, you can compile CPython on Windows by following the steps in the next chapter.

Setting up Visual Studio Code

Microsoft Visual Studio Code is an extensible code-editor with an online marketplace of plugins.

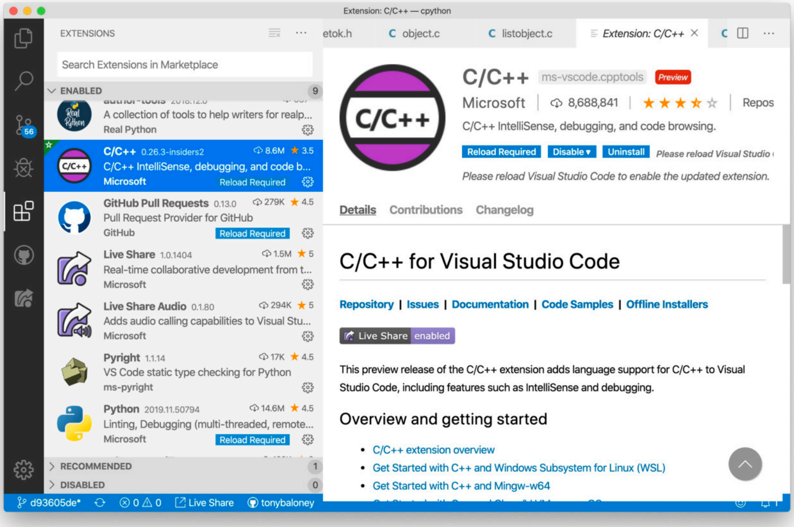
It makes an excellent choice for working with CPython as it supports both C and Python, with an integrated Git interface.

Installing

Visual Studio Code, or sometimes known as "VS Code," is available with a simple installer at code.visualstudio.com.

Out-of-the-box, VS Code will have required code editing capabilities but becomes more powerful once you have installed extensions.

The Extensions panel is available by selecting View > Extensions from the top menu:



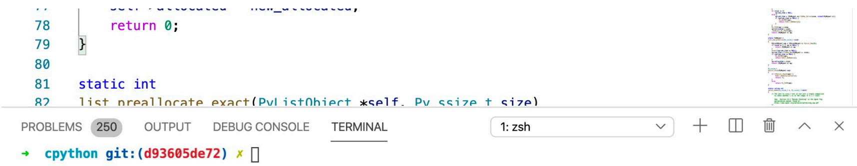
Inside the extensions panel, you can search for extensions by name or by their unique identifier, e.g., '`ms-vscode.cpptools`.' In some cases, there are many plugins with similar names, so to be sure you're installing the right one, use the unique identifier.

Recommended Extensions for This Book

- C/C++ (`ms-vscode.cpptools`) Provides support for C/C++, including IntelliSense, debugging and code highlighting.
- Python (`ms-python.python`) Provides rich Python support for editing, debugging, and reading Python code.
- Restructured Text (`lextudio.restructuredtext`) Provides rich support for reStructuredText, the format used in the CPython documentation.
- Task Explorer (`spmeesseman.vscode-taskexplorer`) Adds a "Task Explorer" panel inside the Explorer tab, making it easier to launch *make* tasks.

Once you have installed these extensions, you will need to reload the editor.

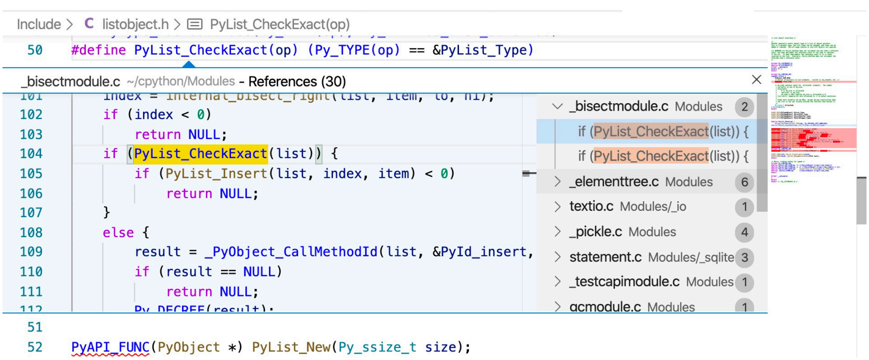
Because many of the tasks in this book require a command-line, you can add an integrated Terminal into VS Code by selecting Terminal > New Terminal and a terminal will appear below the code editor:



Using the Advanced Code Navigation (IntelliSense)

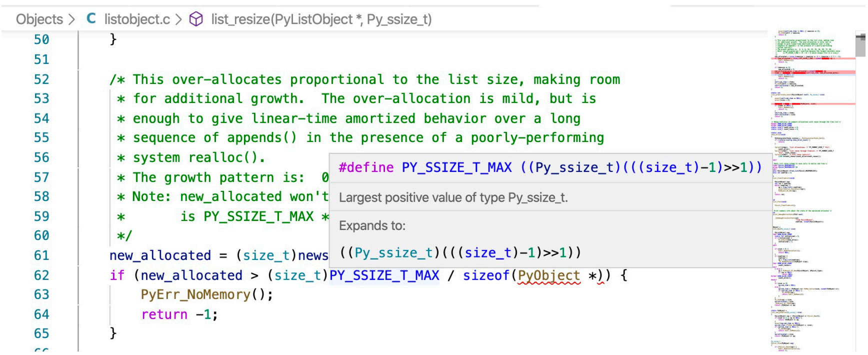
With the plugins installed, you can perform some advanced code navigation.

For example, if you right-click on a function call in a C file and select Go to References it will find other references in the codebase to that function:



Go to References is very useful for discovering the proper calling form for a function.

By clicking or hovering over a C Macro, the editor will expand that Macro to the compiled code:



To jump to the definition of a function, hover over any call to it and press cmd + click on macOS and ctrl + click on Linux and Windows.

Configuring the Task and Launch Files

VS Code creates a folder, `.vscode` in the Workspace Directory. Inside this folder, you can create:

- `tasks.json` for shortcuts to commands that execute your project
- `launch.json` to configure the debugger (see the chapter on Debugging)
- other plugin-specific files

Create a `tasks.json` file inside the `.vscode` directory. If it doesn't exist, create it now. This `tasks.json` will get you started:

`cpython-book-samples▸11▸tasks.json`

```
{
    "version": "2.0.0",
    "tasks": [
        {
            "label": "build",
            "type": "shell",
            "group": {
                "kind": "build",
                "isDefault": true
            },
            "windows":{
                "command": "PCBuild\build.bat",
                "args": ["-p x64 -c Debug"]
            },
            "linux":{
                "command": "make -j2 -s"
            },
            "osx":{
                "command": "make -j2 -s"
            }
        }
    ]
}
```

With the `Task Explorer` plugin, you will see a list of your configured tasks inside the **vscode** group:

In the next chapter, you will learn more about the build process for compiling CPython.

Setting up JetBrains CLion

JetBrains make an IDE for Python, called PyCharm, as well as an IDE for C/C++ development called CLion.

CPython has both C and Python code. You cannot install C/C++ support into PyCharm, but CLion comes bundled with Python support.

> **Important**
>
> Makefile support is only available in versions of CLion 2020.2 and above.

> **Important**
>
> This step requires that you have generated a `Makefile` by running `configure` and compiled CPython. Please read Compiling CPython for your Operating System and return to this chapter.

After compiling CPython for the first time, you will have a `Makefile` in the root of the source directory. Open CLion and choose Open or Import from the Welcome Screen. Navigate to the source directory and select the `Makefile` and press `Open`.

CLion will prompt whether you want to open the directory, or import the Makefile as a new project. Select Open as Project to import as a project.

CLion will prompt which make target to run before importing. Leave at the default option, `clean`, and continue.

Next, check that you can build the CPython executable from CLion. From the top menu, select Build > Build Project. In the status bar, you should see a progress bar for the project building:

Once this task is complete, you can target the compiled binary as a

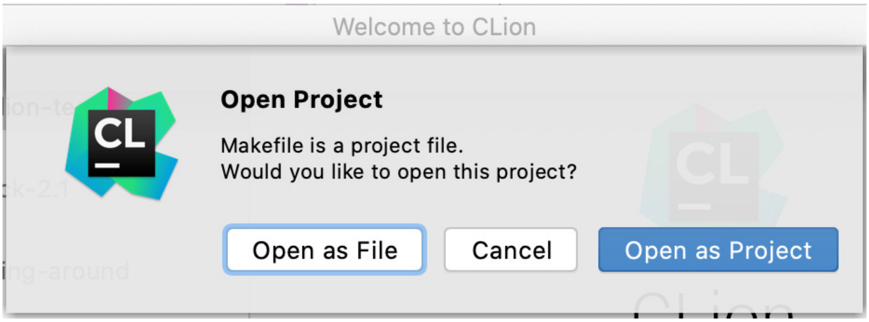


Figure 0.1: clion-open-makefile-project

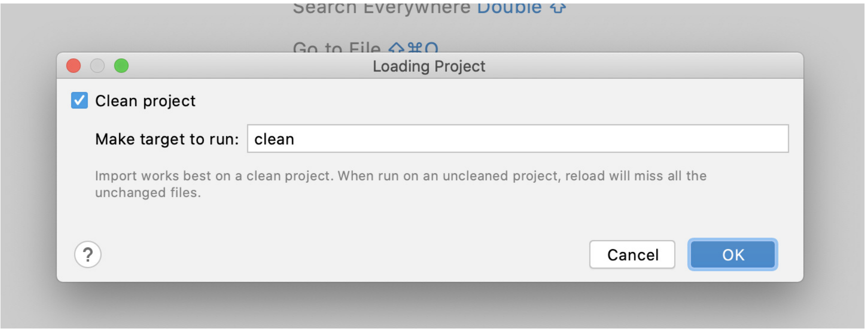


Figure 0.2: clion-loading-project

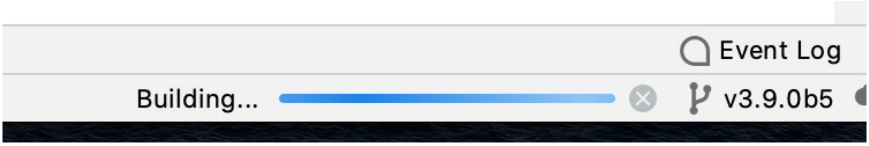


Figure 0.3: clion-build-progress

Run/Debug Configuration. Select Run > Edit Configurations... to open the "Run/Debug Configurations" window. Inside this window select + > Makefile Application

- Set the `Name` to `cpython`
- Leave `all` as the build target
- For the executable, select the dropdown and choose Select Other find the compiled CPython binary in the source directory. It will be called `python` or `python.exe`.
- Enter any program arguments you wish to always have, e.g., `-X dev` to enable development mode. These flags are covered later in Setting Runtime Configuration with the Command Line.
- Set the Working Directory to the CLion macro `$ProjectFileDir$`

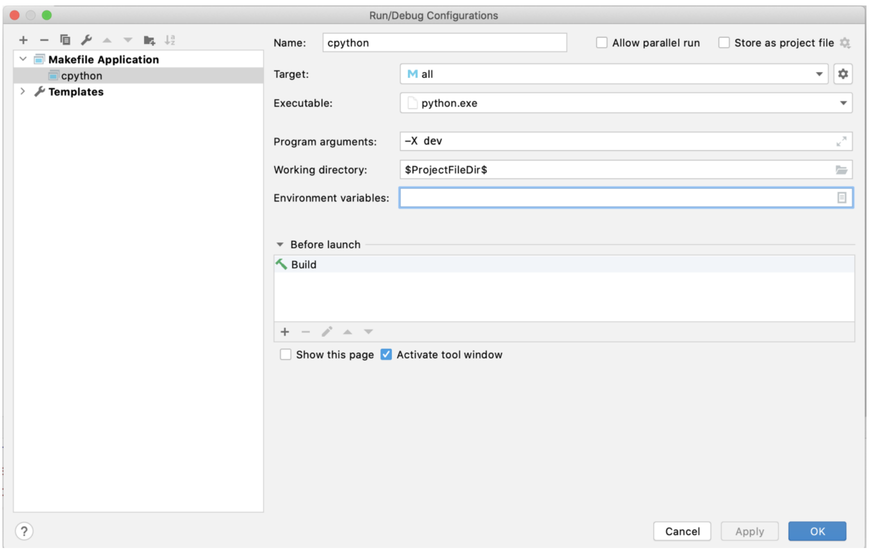


Figure 0.4: clion-run-configuration2

Click Ok to add this configuration. You can repeat this step as many times as you like for any of the CPython make targets. See CPython's Make Targets for a full reference.

The `cpython` build configuration will now be available in the top-right of the CLion window:

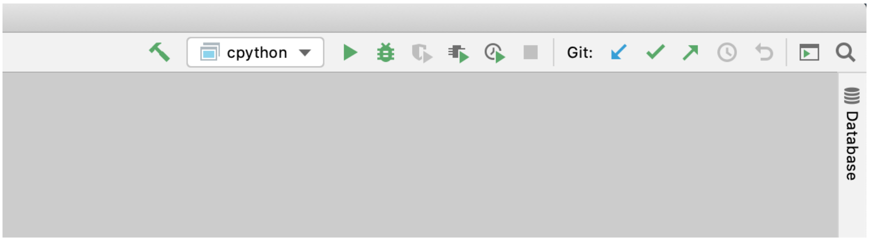


Figure 0.5: clion-run-configuration

To test it out, click the run arrow, or select the Run › Run 'cpython' item from the top menu. You should now see the REPL at the bottom of the CLion window:

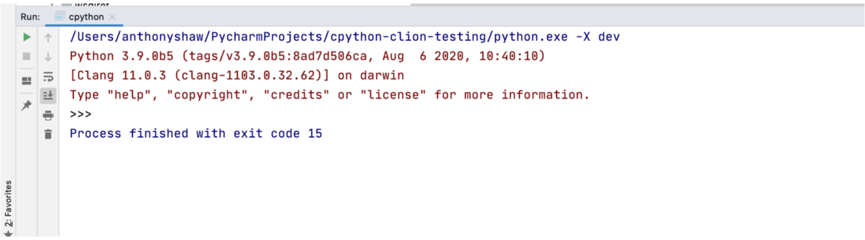
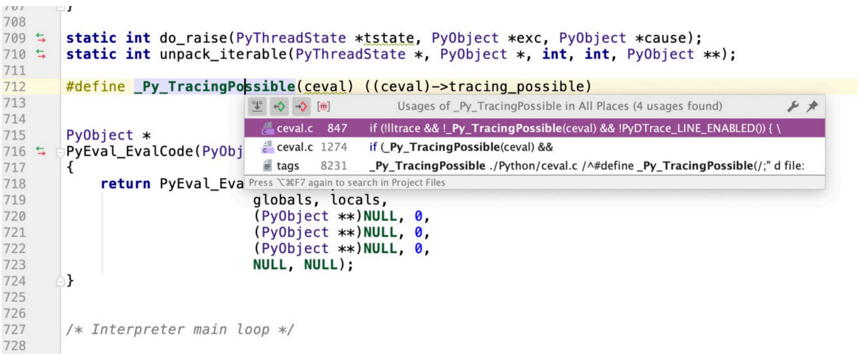


Figure 0.6: clion-running-repl

Great! Now you can make changes and quickly try them out by clicking Build and Run. If you put any breakpoints in the C code, make sure you choose `Debug` instead of `Run`.

Within the code editor, the shortcut cmd + click on macOS, and ctrl + click on Windows and Linux will give in-editor navigation features:



Setting up Vim

Vim is a powerful console-based text editor. Use Vim with your hands resting on the keyboard home keys. The shortcuts and commands are within reach for fast development.

> **Note**
>
> On most Linux distributions and within the macOS Terminal, `vi` is an alias for `vim`. I'll use the `vim` command, but if you have the alias, `vi` will also work.

Out of the box, Vim has only basic functionality, little more than a text editor like Notepad. With some configuration and extensions, Vim can become powerful for both Python and C editing. Vim's extensions are in various locations, like GitHub. To ease the configuration and installation of plugins from GitHub, you can install a plugin manager, like Vundle.

To install Vundle, run this command at the terminal:

```
$ git clone https://github.com/VundleVim/Vundle.vim.git \
   ~/.vim/bundle/Vundle.vim
```

Once Vundle is downloaded, you need to configure Vim to load the Vundle engine.

We will install two plugins:

- vim-fugitive A status bar for Git with shortcuts for many Git tasks.
- tagbar A pane for making it easier to jump to functions, methods, and classes.

To install these plugins, first change the contents of your vim configuration file, (normally `HOME ▸ .vimrc`) to include the following lines:

cpython-book-samples ▸ 11 ▸ .vimrc

```
syntax on
set nocompatible              " be iMproved, required
filetype off                  " required

" set the runtime path to include Vundle and initialize
set rtp+=~/.vim/bundle/Vundle.vim
call vundle#begin()

" let Vundle manage Vundle, required
Plugin 'VundleVim/Vundle.vim'

" The following are examples of different formats supported.
" Keep Plugin commands between vundle#begin/end.
" plugin on GitHub repo
Plugin 'tpope/vim-fugitive'
Plugin 'majutsushi/tagbar'
" All of your Plugins must be added before this line
call vundle#end()            " required
filetype plugin indent on    " required
" Open tagbar automatically in C files, optional
autocmd FileType c call tagbar#autoopen(0)
" Open tagbar automatically in Python files, optional
autocmd FileType python call tagbar#autoopen(0)
" Show status bar, optional
set laststatus=2
" Set status as git status (branch), optional
```

```
set statusline=%{FugitiveStatusline()}
```

To download and install these plugins, run:

```
$ vim +PluginInstall +qall
```

You should see output for the download and installation of the plugins specified in the configuration file.

When editing or exploring the CPython source code, you will want to jump between methods, functions, and macros quickly. Only using text search won't determine a call to a function, or its definition, versus the implementation. An application called ctags will index source files across a multitude of languages into a plaintext database.

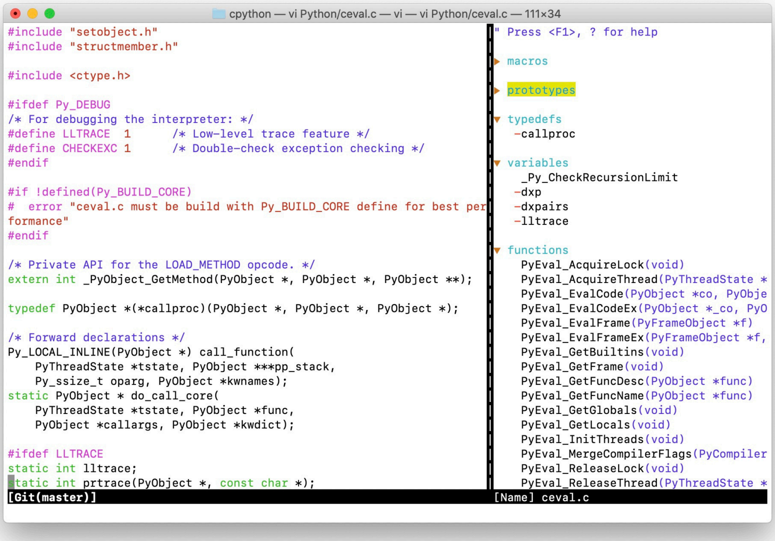
To index CPython's headers for all the C files, and Python files in the standard library, run:

```
$./configure
$ make tags
```

When you open `vim` now, for example editing the `Python`▸`ceval.c` file:

```
$ vim Python/ceval.c
```

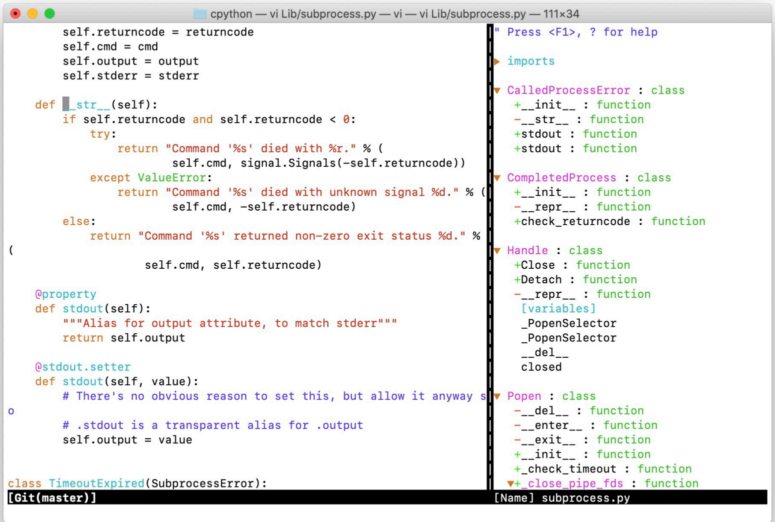
You will see the Git status at the bottom and the functions, macros, and variables on the right-hand pane:



When editing Python files, such as the `Lib▸subprocess.py`:

```
$ vim Lib/subprocess.py
```

The tagbar will show imports, classes, methods, and functions:



Within `vim` you can switch between tabs as CTRL+W, L to move to the right-hand pane, using the arrow keys to move up and down between the tagged functions. Press enter to skip to any function implementation. To move back to the editor pane press CTRL+W, H

See Also

Check out vim adventures for a fun way to learn and memorize the vim commands.

Conclusion

If you're still undecided about which environment to use, you don't need to make a decision right here and now. I used multiple environments while writing this book and working on changes to CPython. A critical feature for productivity is debugging, so having a reliable debugger that you can use to explore the runtime and understand bugs will save a lot of time. Especially if you're used to relying on `print()`

functions for debugging in Python, that approach doesn't work in C. You will cover Debugging in full later in this book.

Leave feedback on this section »

Compiling CPython

Now that you have CPython downloaded a development environment and configured it, you can compile the CPython source code into an executable interpreter.

Unlike Python files, C source code must be recompiled each time it changes. So you'll probably want to bookmark this chapter and memorize some of the steps because you'll be repeating them a lot.

In the previous chapter, you saw how to set up your development environment, with an option to run the "Build" stage, which recompiles CPython. Before the build steps work, you require a C compiler, and some build tools. The tools used depend on the Operating System you're using, so skip ahead to the section for your Operating System.

Note

If you're concerned that any of these steps will interfere with your existing CPython installations, don't worry. The CPython source directory behaves like a virtual environment.

For compiling CPython, modifying the source, and the standard library, this all stays within the sandbox of the source directory.

If you want to install your custom version, this step is covered in this chapter.

Compiling CPython on macOS

Compiling CPython on macOS requires some additional applications and libraries. You will first need the essential C compiler toolkit. "Command Line Development Tools" is an app that you can update in macOS through the App Store. You need to perform the initial installation on the terminal.

Note

To open up a terminal in macOS, go to Applications > Other > Terminal. You will want to save this app to your Dock, so right-click the Icon and select Keep in Dock

Within the terminal, install the C compiler and toolkit by running the following:

```
$ xcode-select --install
```

This command will pop up with a prompt to download and install a set of tools, including Git, Make, and the GNU C compiler.

You will also need a working copy of OpenSSL to use for fetching packages from the PyPi.org website. If you later plan on using this build to install additional packages, SSL validation is required.

The simplest way to install OpenSSL on macOS is by using Homebrew.

Note

If you don't have Homebrew, you can download and install Homebrew directly from GitHub with the following command:

```
$ /usr/bin/ruby -e "$(curl -fsSL \
 https://raw.githubusercontent.com/Homebrew/install/master/install)"
```

Once you have Homebrew installed, you can install the dependencies for CPython with the `brew install` command:

```
$ brew install openssl xz zlib gdbm sqlite
```

Now that you have the dependencies, you can run the `configure` script. Homebrew has a command `brew --prefix [package]` that will give the directory where the package is installed. You will enable support for SSL by compiling the location that Homebrew uses.

The flag `--with-pydebug` enables debug hooks. Add this if you intend on debugging for development or testing purposes. Debugging CPython is covered extensively in the Debugging chapter.

The configuration stage only needs to be run once, also specifying the location of the zlib package:

```
$ CPPFLAGS="-I$(brew --prefix zlib)/include" \
 LDFLAGS="-L$(brew --prefix zlib)/lib" \
 ./configure --with-openssl=$(brew --prefix openssl) --with-pydebug
```

Running `configure` will generate a `Makefile` in the root of the repository that you can use to automate the build process.

You can now build the CPython binary by running:

```
$ make -j2 -s
```

See Also

For more help on the options for `make`, see section A Quick Primer on Make.

During the build, you may receive some errors. In the build the summary, `make` will notify you that not all packages were built. For example, `ossaudiodev`, `spwd`, and `_tkinter` would fail to build with this set of instructions. That's okay if you aren't planning on developing against those packages. If you are, then check out the official dev guide website for more information.

The build will take a few minutes and generate a binary called `python.exe`. Every time you make changes to the source code, you will need to rerun `make` with the same flags. The `python.exe` binary is the debug binary of CPython. Execute `python.exe` to see a working REPL:

```
$ ./python.exe
Python 3.9.0b5 (tags/v3.9.0b5:8ad7d50, Jul 21 2020, 10:00:00)
[Clang 10.0.1 (clang-1001.0.46.4)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>>
```

Important

Yes, that's right, the macOS build has a file extension for `.exe`. This extension is *not* because it's a Windows binary! Because macOS has a case-insensitive filesystem and when working with the binary, the developers didn't want people to accidentally refer to the directory `Python/` so `.exe` was appended to avoid ambiguity. If you later run `make install` or `make altinstall`, it will rename the file back to `python` before installing it into your system.

Compiling CPython on Linux

To compile CPython on Linux, you first need to download and install `make`, `gcc`, `configure`, and `pkgconfig`.

For Fedora Core, RHEL, CentOS, or other yum-based systems:

```
$ sudo yum install yum-utils
```

For Debian, Ubuntu, or other `apt`-based systems:

```
$ sudo apt install build-essential
```

Then install some additional required packages.

For Fedora Core, RHEL, CentOS or other `yum`-based systems:

```
$ sudo yum-builddep python3
```

For Debian, Ubuntu, or other `apt`-based systems:

```
$ sudo apt install libssl-dev zlib1g-dev libncurses5-dev \
  libncursesw5-dev libreadline-dev libsqlite3-dev libgdbm-dev \
  libdb5.3-dev libbz2-dev libexpat1-dev liblzma-dev libffi-dev
```

Now that you have the dependencies, you can run the `configure` script, optionally enabling the debug hooks `--with-pydebug`:

```
$ ./configure --with-pydebug
```

Next, you can build the CPython binary by running the generated `Makefile`:

```
$ make -j2 -s
```

See Also

For more help on the options for `make`, see section A Quick Primer on Make.

Review the output to ensure that there weren't issues compiling the `_ssl` module. If there were, check with your distribution for instructions on installing the headers for OpenSSL.

During the build, you may receive some errors. In the build the summary, `make` will notify you that not all packages were built. That's okay if you aren't planning on developing against those packages. If you are, then check out the package details for required libraries.

The build will take a few minutes and generate a binary called `python`. This is the debug binary of CPython. Execute `./python` to see a working REPL:

```
$ ./python
Python 3.9.0b5 (tags/v3.9.0b5:8ad7d50, Jul 21 2020, 10:00:00)
[Clang 10.0.1 (clang-1001.0.46.4)] on Linux
```

```
Type "help", "copyright", "credits" or "license" for more information.
>>>
```

Installing a Custom Version

From your source repository, if you're happy with your changes and want to use them inside your system, you can install it as a custom version.

For macOS and Linux, you can use the `altinstall` command, which won't create symlinks for `python3` and install a standalone version:

```
$ make altinstall
```

For Windows, you have to change the build configuration from `Debug` to `Release`, then copy the packaged binaries to a directory on your computer which is part of the system path.

A Quick Primer on Make

As a Python developer, you might not have come across `make` before, or perhaps you have but haven't spent much time with it. For C, C++, and other compiled languages, the number of commands you need to execute to load, link, and compile your code in the right order can be very long. When compiling applications from source, you need to link any external libraries in the system. It would be unrealistic to expect the developer to know the locations of all of these libraries and copy+paste them into the command line, so `make` and `configure` are commonly used in C/C++ projects to automate the creation of a build script. When you executed `./configure`, `autoconf` searched your system for the libraries that CPython requires and copied their paths into `Makefile`.

The generated `Makefile` is similar to a shell script, broken into sections called **"targets."**

Take the `docclean` target as an example. This target deletes some generated documentation files using the `rm` command.

```
docclean:
    -rm -rf Doc/build
    -rm -rf Doc/tools/sphinx Doc/tools/pygments Doc/tools/docutils
```

To execute this target, run `make docclean`. `docclean` is a simple target as it only runs two commands.

The convention for executing any make target is:

```
$ make [options] [target]
```

If you call `make` without specifying a target, `make` will run the default target. The default target is the first target specified in the `Makefile`. For CPython, this is the `all` target which compiles all parts of CPython.

Make has many options, so here are the ones I think you'll find useful throughout this book:

Option	Use
`-d, --debug[=FLAGS]`	Print various types of debugging information
`-e, --environment-overrides`	Environment variables override makefiles
`-i, --ignore-errors`	Ignore errors from commands
`-j [N], --jobs[=N]`	Allow N jobs at once (infinite jobs otherwise)
`-k, --keep-going`	Keep going when some targets can't be made
`-l [N], --load-average[=N]`	Only start multiple jobs if load < N
`--max-load[=N]`	
`-n, --dry-run`	Print commands instead of running them.
`-s, --silent`	Don't echo commands.
`-S, --stop`	Turns off `-k`.

In the next section and throughout the book, I'm going to ask you to run `make` with the options:

```
$ make -j2 -s [target]
```

The `-j2` flag allows `make` to run 2 jobs simultaneously. If you have 4 or more cores, you can change this to 4 or larger and the compilation will complete faster. The `-s` flag stops the `Makefile` from printing every command it runs to the console. If you want to see what is happening, remove the `-s` flag.

CPython’s Make Targets

For both Linux and macOS, you will find yourself needing to clean up files, build, or to refresh configuration.

There are a number of useful make targets built into CPython’s Makefile:

Build Targets

Target	Purpose
`all` (default)	Build the compiler, libraries and modules
`profile-opt`	Compile the Python binary with profile guided optimization
`clinic`	Run “Argument Clinic” over all source files
`sharedmods`	Build the shared modules
`regen-all`	Regenerate all generated files

Test Targets

Target	Purpose
`test`	Run a basic set of regression tests
`testall`	Run the full test suite twice - once without .pyc files, and once with
`quicktest`	Run a faster set of regression tests, excluding the tests that take a long time
`testuniversal`	Run the test suite for both architectures in a Universal build on OSX
`coverage`	Compile and run tests with gcov
`coverage-lcov`	Create coverage HTML reports

Cleaning Targets

The primary clean targets are `clean`, `clobber` and `distclean`. The `clean` target is for generally removing compiled and cached libraries and pyc files. If you find that `clean` doesn't do the job, try `clobber`. For completely cleaning out an environment before distribution, run the `distclean` target.

Target	Purpose
`check-clean-src`	Check that the source is clean when building out of source
`cleantest`	Remove "test_python_*" directories of previous failed test jobs
`clean`	Remove pyc files, compiled libraries and profiles
`pycremoval`	Remove pyc files
`docclean`	Remove built documentation in Doc/
`profile-removal`	Remove any optimization profiles
`clobber`	Same as `clean`, but also removes libraries, tags, configurations and builds
`distclean`	Same as `clobber`, but also removes anything generated from source, e.g. Makefile

Installation Targets

There are two flavors for the installation targets, the default version, e.g. `install` and the `alt` version, e.g. `altinstall`. If you want to install the compiled version onto your computer, but don't want it to become the default Python 3 installation, use the `alt` version of the commands.

After installing using `make install`, the command `python3` will now link to your compiled binary.
Whereas, using `make altinstall`, only `python$(VERSION)` will be installed and the existing link for `python3` will remain intact.

Target	Purpose
`install`	Installs shared libraries, binaries and documentation. Will run `commoninstall`, `bininstall` and `maninstall`
`bininstall`	Installs all the binaries, e.g. `python`, `idle`, `2to3`
`altinstall`	Installs shared libraries, binaries and documentation with the version suffix

Target	Purpose
`maninstall`	Install the manuals
`altmaninstall`	Install the versioned manuals
`altbininstall`	Install the `python` interpreter, with the version affixed, e.g. `python3.9`
`commoninstall`	Install shared libraries and modules
`libinstall`	Install shared libraries
`sharedinstall`	Dynamically loaded modules

Miscellaneous Targets

Target	Purpose
`python-config`	Generate the `python-config` script
`recheck`	Rerun configure with the same options as it was run last time
`autoconf`	Regenerate configure and pyconfig.h.in
`tags`	Create a tags file for vi
`TAGS`	Create a tags file for emacs
`smelly`	Check that exported symbols start `Py` or `_Py` (see PEP7)

Compiling CPython on Windows

There are two ways to compile the CPython binaries and libraries from Windows.

The first is to compile from the command line, this still requires the Microsoft Visual C++ compiler, which comes with Visual Studio. The second is to open the `PCBuild` ▸ `pcbuild.sln` from Visual Studio and build directly.

Installing the Dependencies

For either the command line compile script or the Visual Studio solution, you need to install several external tools, libraries, and C headers.

Inside the `PCBuild` folder there is a `.bat` file that automates this for you.

Open up a command-line prompt inside `PCBuild` and execute `PCBuild▸get_externals.bat`:

```
 > get_externals.bat
Using py -3.7 (found 3.7 with py.exe)
Fetching external libraries...
Fetching bzip2-1.0.6...
Fetching sqlite-3.28.0.0...
Fetching xz-5.2.2...
Fetching zlib-1.2.11...
Fetching external binaries...
Fetching openssl-bin-1.1.1d...
Fetching tcltk-8.6.9.0...
Finished.
```

Now you can compile from the command line or Visual Studio.

Compiling From the Command Line

To compile from the command line, you need to select the CPU architecture you want to compile against. The default is win32, but the chances are you want a 64-bit (`amd64`) binary.

If you do any debugging, the debug build comes with the ability to attach breakpoints in the source code. To enable the debug build, you add `-c Debug` to specify the Debug configuration.

By default, `build.bat` will fetch external dependencies, but because we've already done that step, it will print a message skipping downloads:

```
> build.bat -p x64 -c Debug
```

This command will produce the Python binary `PCbuild▸amd64▸python_d.exe`. Start that binary directly from the command line:

```
> amd64\python_d.exe

Python 3.9.0b5 (tags/v3.9.0b5:8ad7d50, Jul 21 2020, 10:00:00)
```

```
 [MSC v.1922 64 bit (AMD64)] on win32
Type "help", "copyright", "credits" or "license" for more information.
>>>
```

You are now inside the REPL of your compiled CPython binary.

To compile a release binary:

```
> build.bat -p x64 -c Release
```

This command will produce the binary `PCbuild` ▸ `amd64` ▸ `python.exe`.

Note

The suffix `_d` specifies that CPython was built in the `Debug` configuration.

The released binaries on python.org are compiled in the Profile-Guided-Optimization (PGO) configuration. See the Profile-Guided-Optimization (PGO) section at the end of this chapter for more details on PGO.

Arguments

The following arguments are available in `build.bat`:

Flag	Purpose	Expected Value
`-p`	Build platform CPU architecture	`x64`, `Win32` (default), `ARM`, `ARM64`
`-c`	Build configuration	`Release` (default), `Debug`, `PGInstrument` or `PGUpdate`
`-t`	Build target	`Build` (default), `Rebuild`, `Clean`, `CleanAll`

Flags

Here are some optional flags you can use for `build.bat`. For a full list, run `build.bat -h`.

Flag	Purpose
`-v`	Verbose mode. Show informational messages during build
`-vv`	Very verbose mode. Show detailed messages during build
`-q`	Quiet mode. Only show warning and errors during build
`-e`	Download and install external dependencies (default)
`-E`	**Don't** download and install external dependencies
`--pgo`	Build with profile-guided-optimization
`--regen`	Regenerate all grammar and tokens, used when you update the language

Compiling From Visual Studio

Inside the `PCBuild` folder is a Visual Studio project file, `PCBuild ▸ pcbuild.sln`, for building and exploring CPython source code.

When the Solution is loaded, it will prompt you to retarget the project's inside the Solution to the version of the C/C++ compiler you have installed. Visual Studio will also target the release of the Windows SDK you have installed.

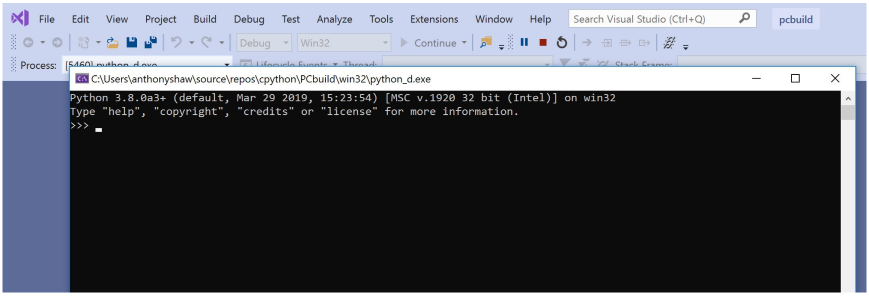
Ensure that you change the Windows SDK version to the newest installed version and the platform toolset to the latest version. If you missed this window, you can right-click on the Solution in the *Solutions and Projects* window and click *Retarget Solution*.

Navigate to Build › Configuration Manager and ensure the "Active solution configuration" is set to `Debug`, and the "Active Solution Platform" is set to `x64` for 64-bit CPU architecture or `win32` for 32-bit.

Next, build CPython by pressing CTRL + SHIFT + B, or choosing Build › Build Solution. If you receive any errors about the Windows SDK being missing, make sure you set the right targeting settings in the *Retarget Solution* window. You should also see *Windows Kits* inside your Start Menu, and *Windows Software Development Kit* inside of that menu.

The build stage could take 10 minutes or more the first time. Once the build completes, you may see a few warnings that you can ignore.

To start the debug version of CPython, press F5 and CPython will start in Debug mode straight into the REPL:

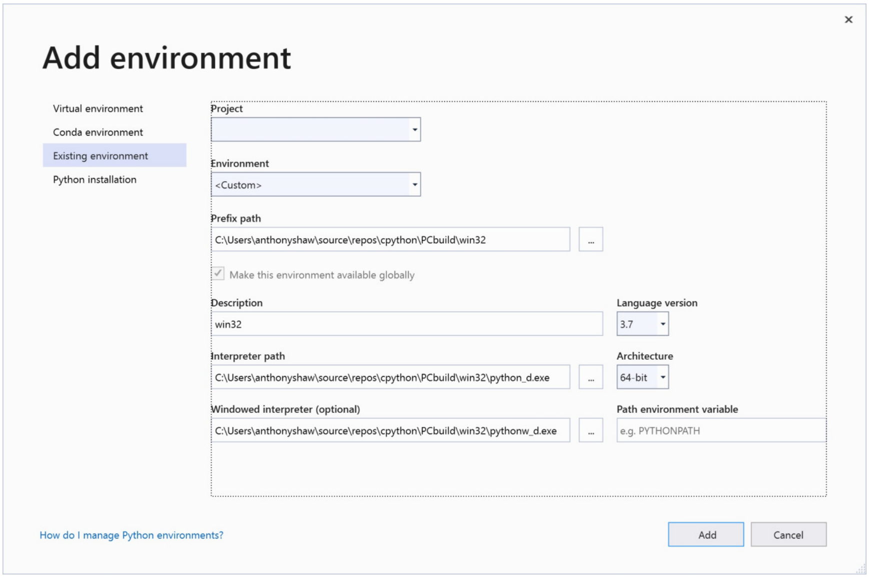


You can run the Release build by changing the build configuration from *Debug* to *Release* on the top menu bar and rerunning Build ▸ Build Solution. You now have both Debug and Release versions of the CPython binary within `PCBuild`▸`amd64`.

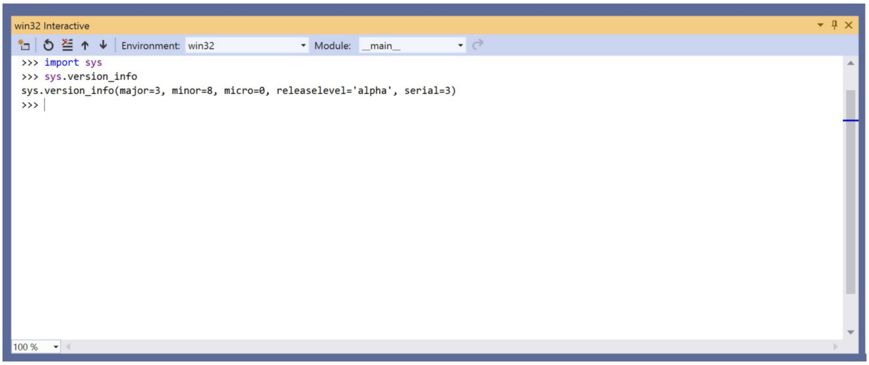
You can set up Visual Studio to be able to open a REPL with either the Release or Debug build by choosing Tools ▸ Python ▸ Python Environments from the top menu:

In the Python Environments panel, click *Add Environment* and then target the Debug or Release binary. The Debug binary will end in `_d.exe`. For example, `python_d.exe` and `pythonw_d.exe`. You will most likely want to use the debug binary as it comes with Debugging support in Visual Studio and will be useful for this book.

In the Add Environment window, target the `python_d.exe` file as the interpreter inside `PCBuild`▸`amd64` and the `pythonw_d.exe` as the windowed interpreter:

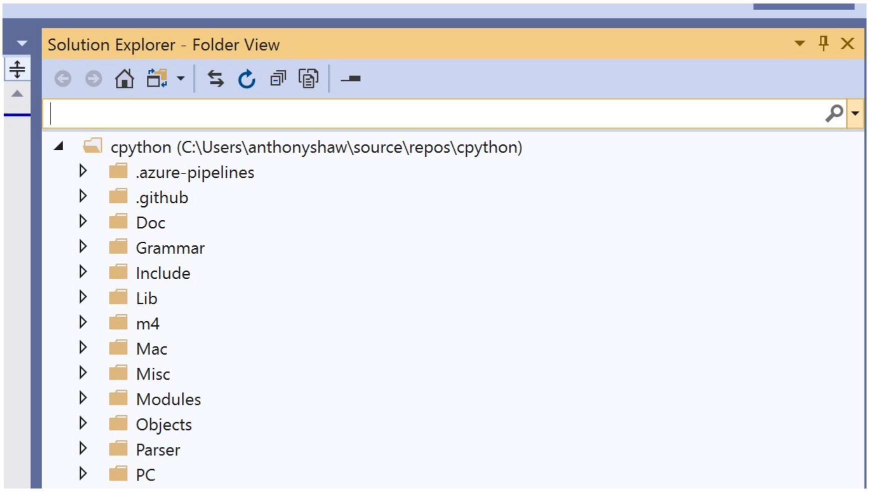


Start a REPL session by clicking `Open Interactive Window` in the Python Environments window and you will see the REPL for the compiled version of Python:



During this book, there will be REPL sessions with example commands. I encourage you to use the Debug binary to run these REPL sessions in case you want to put in any breakpoints within the code.

To make it easier to navigate the code, in the Solution View, click on the toggle button next to the Home icon to switch to Folder view:



Profile Guided Optimization

The macOS, Linux, and Windows build processes have flags for "PGO," or "Profile Guided Optimization." PGO is not something created by the Python team, but a feature of many compilers, including those used by CPython.

PGO works by doing an initial compilation, then profiling the application by running a series of tests. The profile created is then analyzed, and the compiler will make changes to the binary that would improve performance.

For CPython, the profiling stage runs `python -m test --pgo`, which executes the regression tests specified in `Lib` ▸ `test` ▸ `libregrtest` ▸ `pgo.py`. These tests have been specifically selected because they use a commonly used C extension module or type.

Note

The PGO process is time-consuming, so throughout this book I've excluded it from the list of recommended steps to keep your compilation time short. If you want to distribute a custom compiled version of CPython into a production environment, you should run `./configure` with the `--with-pgo` flag in Linux and macOS, and use the `--pgo` flag in `build.bat` on Windows.

Because the optimizations are specific to the platform and architecture that the profile was executed on, PGO profiles cannot be shared between Operating Systems or CPU architectures. The distributions of CPython on python.org have already been through PGO, so if you run a benchmark on a vanilla-compiled binary it will be slower than one downloaded from python.org.

The Windows, macOS and Linux profile-guided optimizations include these checks and improvements:

- **Function Inlining** - If a function is regularly called from another function, then it will be "inlined" to reduce the stack-size.
- **Virtual Call Speculation and Inlining** - If a virtual function call frequently targets a certain function, PGO can insert a conditionally executed direct call to that function. The direct call can then be inlined.
- **Register Allocation Optimization** - Based on profile data results, the PGO will optimize register allocation.
- **Basic Block Optimization** - Basic block optimization allows commonly executed basic blocks that temporally execute within a given frame to be placed in the same set of pages (locality). It minimizes the number of pages used, which minimizes memory overhead.
- **Hot-Spot Optimization** - Functions where the program spends the most execution time can be optimized for speed.
- **Function Layout Optimization** - After analyzing the call graph,

functions that tend to be along the same execution path are moved to the same section of the compiled application.

- **Conditional Branch Optimization** - PGO can look at a decision branch, like an `if..else if` or `switch` statement and spot the most commonly used path. For example, if there are 10 cases in a `switch` statement and one is used 95% of the time, then it will be moved to the top so that it will be executed immediately in the code path.
- **Dead-Spot Separation** - Code that isn't called during PGO is moved to a separate section of the application.

Conclusion

In this chapter, you've seen how to compile CPython source code into a working interpreter. You can use this knowledge throughout the book as you explore and adapt the source code.

You might need to repeat the compilation steps tens, or even hundreds of times when working with CPython. If you can adapt your development environment to create shortcuts for recompilation, it is better to do that now and save yourself a lot of time.

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The Python Language and Grammar

The purpose of a compiler is to convert one language into another. Think of a compiler like a translator. You would hire a translator to listen to you speaking in English and then speak in Japanese.

To accomplish this, the translator must understand the grammatical structures of the source and target languages.

Some compilers will compile into a low-level machine code, which can be executed directly on a system. Other compilers will compile into an intermediary language, to be executed by a virtual machine.

A consideration when choosing a compiler is the system portability requirements. Java and .NET CLR will compile into an Intermediary Language so that the compiled code is portable across multiple systems architectures. C, Go, C++, and Pascal will compile into an executable binary. This binary is built for the platform on which it was compiled.

Python applications are typically distributed as source code. The role of the Python interpreter is to convert the Python source code and execute it in one step. The CPython runtime does compile your code when it runs for the first time. This step is invisible to the regular user.

Python code is not compiled into machine code; it is compiled into a low-level intermediary language called **bytecode**. This bytecode is stored in `.pyc` files and cached for execution. If you run the same

Python application twice without changing the source code, it will be faster on the second execution. This is because it loads the compiled bytecode instead of recompiling each time.

Why CPython Is Written in C and Not Python

The **C** in CPython is a reference to the C programming language, implying that this Python distribution is written in the C language.

This statement is mostly true: the compiler in CPython is written in pure C. However, many of the standard library modules are written in pure Python or a combination of C and Python.

So Why Is the CPython Compiler Written in C and Not Python?

The answer is located in how compilers work. There are two types of compilers:

1. **Self-hosted compilers** are compilers written in the language they compile, such as the Go compiler. This is done by a process known as bootstrapping.
2. **Source-to-source compilers** are compilers written in another language that already has a compiler.

If you're writing a new programming language from scratch, you need an executable application to compile your compiler! You need a compiler to execute anything, so when new languages are developed, they're often written first in an older, more established language.

There are also tools available that can take a language specification and create a parser (topics you will cover in this chapter). Popular compiler-compilers include GNU Bison, Yacc, and ANTLR.

See Also

If you want to learn more about parsers, check out the lark project. Lark is a parser for context-free grammar written in Python.

An excellent example of compiler bootstrapping is the Go programming language. The first Go compiler was written in C, then once Go could be compiled, the compiler was rewritten in Go.

CPython kept its C heritage; many of the standard library modules, like the `ssl` module or the `sockets` module, are written in C to access low-level operating system APIs. The APIs in the Windows and Linux kernels for creating network sockets, working with the filesystem, or interacting with the display are all written in C.
It made sense for Python's extensibility layer to be focused on the C language. Later in this book, you will cover the Python Standard Library and the C modules.

There is a Python compiler written in Python called PyPy. PyPy's logo is an Ouroboros to represent the self-hosting nature of the compiler.

Another example of a cross-compiler for Python is Jython. Jython is written in Java and compiles from Python source code into Java bytecode. In the same way that CPython makes it easy to import C libraries and use them from Python, Jython makes it easy to import and reference Java modules and classes.

The first step of creating a compiler is to define the language. For example, this is not valid Python:

```
def my_example() <str> :
{
    void* result = ;
}
```

The compiler needs strict rules of the grammatical structure for the language before it tries to execute it.

Note

For the rest of this tutorial, `./python` will refer to the compiled version of CPython. However, the actual command will depend on your Operating System.

For Windows:

```
> python.exe
```

For Linux:

```
$ ./python
```

For macOS:

```
$ ./python.exe
```

The Python Language Specification

Contained within the CPython source code is the definition of the Python language. This document is the reference specification used by all the Python interpreters.

The specification is in both a human-readable and machine-readable format. Inside the documentation is a detailed explanation of the Python language. What is allowed and how each statement should behave.

Language Documentation

Located inside the `Doc` ▸ `reference` directory are reStructuredText explanations of each of the features in the Python language. These files form the official Python reference guide at docs.python.org/3/reference.

Inside the directory are the files you need to understand the whole language, structure, and keywords:

cpython/Doc/reference

compound_stmts.rst	Compound statements like if, while, for and function definitions
datamodel.rst	Objects, values and types
executionmodel.rst	The structure of Python programs
expressions.rst	The elements of Python expressions
grammar.rst	Python's core grammar (referencing Grammar/Grammar)
import.rst	The import system
index.rst	Index for the language reference
introduction.rst	Introduction to the reference documentation
lexical_analysis.rst	Lexical structure like lines, indentation, tokens and keywords
simple_stmts.rst	Simple statements like assert, import, return and yield
toplevel_components.rst	Description of the ways to execute Python, like scripts and modules

An Example

Inside `Doc` ▸ `reference` ▸ `compound_stmts.rst`, you can see a simple example defining the `with` statement.

The `with` statement has many forms, the simplest being the instantiation of a context-manager, and a nested block of code:

```python
with x():
   ...
```

You can assign the result to a variable using the `as` keyword:

```python
with x() as y:
   ...
```

You can also chain context managers together with a comma:

```python
with x() as y, z() as jk:
   ...
```

The documentation contains the human-readable specification of the language, and the machine-readable specification is housed in a single file, `Grammar` ▸ `python.gram`.

The Grammar File

Python's grammar file uses a Parsing Expression Grammar specification. In the grammar file you can use:

- `*` for repetition
- `+` for at-least-once repetition
- `[]` for optional parts
- `|` for alternatives
- `()` for grouping

As an example, think about how you would define a cup of coffee:

- It must have a cup
- It must include at least one shot of espresso and can contain multiple
- It can have milk, but it is optional
- There are many types of milk you can put into coffee, like full fat, skimmed and soy

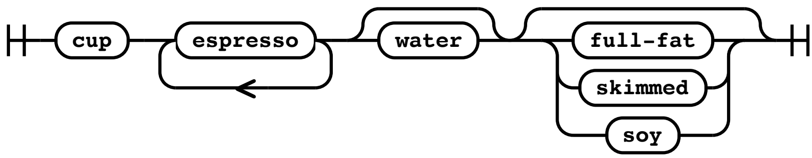
Defined in EBNF, a coffee order could look like this:

```
coffee: 'cup' ('espresso')+ ['water'] [milk]
milk: 'full-fat' | 'skimmed' | 'soy'
```

See Also

The CPython source code has two grammar files in 3.9.0b5. One legacy grammar, written in a context-notation called Backus-Naur Form (BNF).
BNF is not specific to Python and is often used as the notation for grammar in many other languages.

In this chapter, grammar is visualized with railroad diagrams. This diagram is the railroad diagram for the coffee statement:



In a railroad diagram, each possible combination must go in a line from left to right. Optional statements can be bypassed, and some statements can be formed as loops.

Example: While Statement

There are a few forms of the while statement. The simplest contains an expression, then the `:` terminal and a block of code:

```
while finished == True:
    do_things()
```

Alternatively, assignment expressions can be used. They are referred to as `named_expression` within the grammar. This is a new feature in Python 3.8.

```
while letters := read(document, 10):
    print(letters)
```

Optionally, while statements can be followed by an `else` statement and block:

```
while item := next(iterable):
    print(item)
else:
    print("Iterable is empty")
```

If you search for `while_stmt` in the grammar file, you can see the definition:

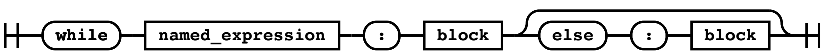
```
while_stmt[stmt_ty]:
    | 'while' a=named_expression ':' b=block c=[else_block] { _Py_While(a, b, c, EXTRA) }
```

Anything in quotes is a string literal, known as a terminal. Terminals are how keywords are recognized.

There are references to two other definitions in these two lines:

- **`block`** refers to a block of code with one or multiple statements
- **`named_expression`** refers to a simple expression or assignment expression

Visualized in a Railroad Diagram, the `while` statement looks like this:



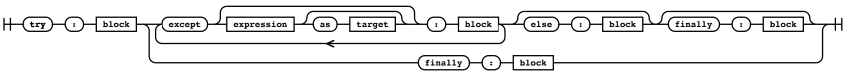
As a more complex example, the `try` statement is defined as:

```
try_stmt[stmt_ty]:
    | 'try' ':' b=block f=finally_block { _Py_Try(b, NULL, NULL, f, EXTRA) }
    | 'try' ':' b=block ex=except_block+ el=[else_block] f=[finally_block] { _Py_Try(b, e
except_block[excepthandler_ty]:
    | 'except' e=expression t=['as' z=target { z }] ':' b=block {
        _Py_ExceptHandler(e, (t) ? ((expr_ty) t)->v.Name.id : NULL, b, EXTRA) }
    | 'except' ':' b=block { _Py_ExceptHandler(NULL, NULL, b, EXTRA) }
finally_block[asdl_seq*]: 'finally' ':' a=block { a }
```

There are two uses of the try statement:

1. `try` with only a `finally` statement
2. `try` with one or many `except` clauses, followed by an optional `else`, then an optional `finally`

Or, visualized in a Railroad Diagram:



The `try` statement is a good example of a more complex structure.

If you want to understand the Python language in detail, the grammar is defined in `Grammar` ▸ `python.gram`.

The Parser Generator

The grammar file itself is never used by the Python compiler. Instead, a parser is created by a parser generator. If you make changes to the grammar file, you must regenerate the parser and recompile CPython.

The CPython Parser was rewritten in Python 3.9 from a Parser Table Automata (the `pgen` module) into a Context Grammar Parser. In Python 3.9, the old parser is available at the command-line by using the `-X oldparser` flag, and in Python 3.10 it is removed completely.

This book refers to the "new" parser, implemented in 3.9.

Regenerating Grammar

To see `pegen` in action, let's change part of the Python grammar. Search `Grammar` ▸ `python.gram` for `small_stmt` to see the definition of a small statements:

```
small_stmt[stmt_ty] (memo):
    | assignment
    | e=star_expressions { _Py_Expr(e, EXTRA) }
    | &'return' return_stmt
    | &('import' | 'from') import_stmt
    | &'raise' raise_stmt
    | 'pass' { _Py_Pass(EXTRA) }
    | &'del' del_stmt
    | &'yield' yield_stmt
```

```
    | &'assert' assert_stmt
    | 'break' { _Py_Break(EXTRA) }
    | 'continue' { _Py_Continue(EXTRA) }
    | &'global' global_stmt
    | &'nonlocal' nonlocal_stmt
```

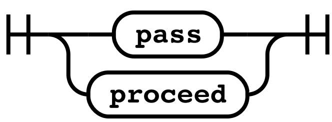
In particular, the line:

```
    | 'pass' { _Py_Pass(EXTRA) }
```

Is for the `pass` statement

Change that line to accept the terminal (keyword) `'pass'` or `'proceed'` as keywords by adding a choice, `|`, and the `proceed` literal:

```
    | ('pass'|'proceed') { _Py_Pass(EXTRA) }
```



Next, rebuild the grammar files. CPython comes with scripts to automate grammar regeneration.

On macOS and Linux, run the `make regen-pegen` target:

```
$ make regen-pegen
```

For Windows, bring up a command line from the `PCBuild` directory and run `build.bat` with the `--regen` flag:

```
> build.bat --regen
```

You should see an output showing that the new `Parser` ▸ `pegen` ▸ `parse.c` file has been regenerated.

With the regenerated parser table, when you recompile CPython, it will use the new syntax. Use the same compilation steps you used in the last chapter for your operating system.

If the code compiled successfully, you can execute your new CPython binary and start a REPL.

In the REPL, you can now try defining a function. Instead of using the `pass` statement, use the `proceed` keyword alternative that you compiled into the Python grammar:

```
 $ ./python

Python 3.9.0b5 (tags/v3.9.0b5:8ad7d50, Jul 21 2020, 10:00:00)
[Clang 10.0.1 (clang-1001.0.46.4)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> def example():
...    proceed
...
>>> example()
```

Congratulations, you've changed the CPython syntax and compiled your own version of CPython.

Next, we'll explore tokens and their relationship to grammar.

Tokens

Alongside the grammar file in the `Grammar` folder is the `Grammar` ▸ `Tokens` file, which contains each of the unique types found as leaf nodes in a parse tree. Each token also has a name and a generated unique ID. The names are used to make it simpler to refer to in the tokenizer.

Note

The `Grammar`▸`Tokens` file is a new feature in Python 3.8.

For example, the left parenthesis is called `LPAR`, and semicolons are called `SEMI`. You'll see these tokens later in the book:

```
LPAR                    '('
RPAR                    ')'
LSQB                    '['
RSQB                    ']'
COLON                   ':'
COMMA                   ','
SEMI                    ';'
```

As with the `Grammar` file, if you change the `Grammar`▸`Tokens` file, you need to rerun `pegen`.

To see tokens in action, you can use the `tokenize` module in CPython.

Note

The tokenizer written in Python is a utility module, the actual Python parser uses a different process for identifying tokens.

Create a simple Python script called `test_tokens.py`:

`cpython-book-samples`▸`13`▸`test_tokens.py`

```python
# Demo application
def my_function():
   proceed
```

Input the `test_tokens.py` file to a module built into the standard library called `tokenize`. You will see the list of tokens by line and character. Use the `-e` flag to output the exact token name:

```
$ ./python -m tokenize -e test_tokens.py
```

```
0,0-0,0:            ENCODING       'utf-8'
1,0-1,14:           COMMENT        '# Demo application'
1,14-1,15:          NL             '\n'
2,0-2,3:            NAME           'def'
2,4-2,15:           NAME           'my_function'
2,15-2,16:          LPAR           '('
2,16-2,17:          RPAR           ')'
2,17-2,18:          COLON          ':'
2,18-2,19:          NEWLINE        '\n'
3,0-3,3:            INDENT         '   '
3,3-3,7:            NAME           'proceed'
3,7-3,8:            NEWLINE        '\n'
4,0-4,0:            DEDENT         ''
4,0-4,0:            ENDMARKER      ''
```

In the output, the first column is the range of the line/column coordinates, the second column is the name of the token, and the final column is the value of the token.

In the output, the `tokenize` module has implied some tokens:

- The `ENCODING` token for `utf-8`
- A blank line at the end
- A `DEDENT` to close the function declaration
- An `ENDMARKER` to end the file

It is best practice to have a blank line at the end of your Python source files. If you omit it, CPython adds it for you.

The `tokenize` module is written in pure Python and is located in `Lib` ▸ `tokenize.py`.

To see a verbose readout of the C tokenizer, you can run Python with the `-d` flag. Using the `test_tokens.py` script you created earlier, run it with the following:

```
$ ./python -d test_tokens.py
```

```
> file[0-0]: statements? $
 > statements[0-0]: statement+
  > _loop1_11[0-0]: statement
   > statement[0-0]: compound_stmt
...
 + statements[0-10]: statement+ succeeded!
+ file[0-11]: statements? $ succeeded!
```

In the output, you can see that it highlighted `proceed` as a keyword. In the next chapter, we'll see how executing the Python binary gets to the tokenizer and what happens from there to execute your code.

To clean up your code, revert the change in `Grammar` ▸ `python.gram`, regenerate the grammar again, then clean the build, and recompile:

For macOS or Linux:

```
$ git checkout -- Grammar/python.gram
$ make regen-pegen
$ make -j2 -s
```

Or for Windows:

```
> git checkout -- Grammar/python.gram
> build.bat --regen
> build.bat -t CleanAll
> build.bat -t Build
```

Conclusion

In this chapter, you've been introduced to the Python grammar definitions and parser generator. In the next chapter, you'll expand on that knowledge to build a more complex syntax feature, an "almost-equals" operator.

In practice, changes to the Python grammar have to be carefully considered and discussed. There are two reasons for the level of scrutiny:

1. Having "too many" language features, or a complex grammar would change the ethos of Python being a simple and readable language
2. Changes to grammar introduce backward-incompatibilities, which create work for all developers

If a Python Core Developer proposes a change to the grammar, it must be proposed as a Python Enhancement Proposal (PEP). All PEPs are numbered and indexed on the PEP index. PEP 5 documents the guidelines for evolving the language and specifies that changes must be proposed in PEPs.

Members can also suggest changes to the language outside of the core development group through the python-ideas mailing list.

You can see the drafted, rejected, and accepted PEPs for future versions of CPython in the PEP index. Once a PEP has consensus, and the draft has been finalized, the Steering Council must accept or reject it. The mandate of the Steering Council, defined in PEP 13, states that they shall work to "Maintain the quality and stability of the Python language and CPython interpreter."

Leave feedback on this section »

Configuration and Input

Now that you've seen the Python grammar, its time to explore how code gets input into a state that can be executed.

There are many ways Python code can be run in CPython. Here are some of the most commonly used:

1. By running `python -c` and a Python string
2. By running `python -m` and the name of a module
3. By running `python [file]` with the path to a file that contains Python code
4. By piping Python code into the `python` executable over stdin, e.g., `cat [file] | python`
5. By starting a REPL and executing commands one at a time
6. By using the C API and using Python as an embedded environment

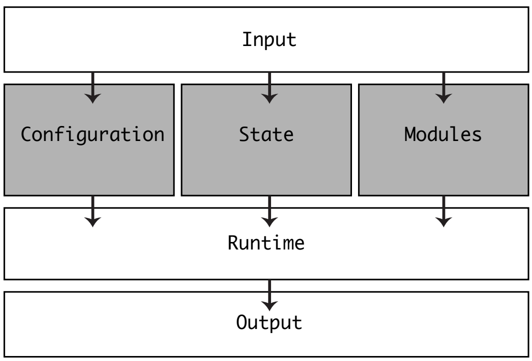
See Also

Python has so many ways to execute scripts; it can be a little overwhelming. Darren Jones has put together a great course at realpython.com on running Python scripts if you want to learn more.

To execute any Python code, the interpreter needs:

- A module to execute
- A state to hold information such as variables
- Configuration, such as which options are enabled

With these three components, the interpreter can execute code and provide an output:



Note

Similar to the PEP8 style guide for Python code, there is PEP7 for the CPython C code.

There are some naming standards for C source code:

- Use a `Py` prefix for public functions, never for static functions. The `Py_` prefix is reserved for global service routines like `Py_FatalError`. Specific groups of routines (like specific object type APIs) use a longer prefix, such as `PyString_` for string functions.
- Public functions and variables use MixedCase with underscores, like this: `PyObject_GetAttr()`, `Py_BuildValue()`, `PyExc_TypeError()`.
- Occasionally an "internal" function has to be visible to the loader. Use the `_Py` prefix for this, for example, `_PyObject_Dump()`.
- Macros should have a MixedCase prefix and then use upper case, for example `PyString_AS_STRING`, `Py_PRINT_RAW`.

Unlike PEP8, there are few tools for checking the compliance of PEP7. This task is instead done by the core developers as part of code reviews. As with any human-operated process, it isn't perfect so you will likely find code that does not adhere to PEP7.

The only bundled tool is a script called `smelly.py`, which you can execute using the `make smelly` target on Linux or macOS, or via the command line:

```
$ ./python Tools/scripts/smelly.py
```

This will raise an error for any symbols that are in `libpython` (the shared CPython library) that do not start `Py`, or `_Py`.

Configuration State

Before any Python code is executed, the CPython runtime first establishes the configuration of the runtime and any user-provided options.

The configuration of the runtime is in three data structures, defined in PEP587:

1. `PyPreConfig`, used for pre-initialization configuration
2. `PyConfig`, used for the runtime configuration
3. The compiled configuration of the CPython interpreter

Both data structures are defined in `Include ▸ cpython ▸ initconfig.h`.

Pre-Initialization Configuration

The pre-initialization configuration is separate to the runtime configuration as it's properties relate to the Operating System or user environment.

The three primary functions of the `PyPreConfig` are:

- Setting the Python memory allocator
- Configuring the LC_CTYPE locale
- Setting the UTF-8 mode (PEP540)

The `PyPreConfig` type contains the following fields; all of type `int`:

Name	Purpose
`allocator`	Name of the memory allocator (e.g. `PYMEM_ALLOCATOR_MALLOC`). Run `./configure --help` for more information on the memory allocator
`configure_locale`	Set the LC_CTYPE locale to the user preferred locale. If equal to 0, set `coerce_c_locale` and `coerce_c_locale_warn` to 0
`coerce_c_locale`	If equal to 2, coerce the C locale; if equal to 1, read the LC_CTYPE locale to decide if it should be coerced
`coerce_c_locale_warn`	If non-zero, emit a warning if the C locale is coerced
`dev_mode`	See PyConfig.dev_mode

Name	Purpose
`isolated`	Enable isolated mode: sys.path contains neither the script's directory nor the user's site-packages directory
`legacy_windows_fs_encoding`	(_Windows only_) If non-zero, disable UTF-8 Mode, set the Python filesystem encoding to **mbcs**
`parse_argv`	If non-zero, Py_PreInitializeFromArgs() and Py_PreInitializeFromBytesArgs() parse from command line arguments
`use_environment`	See PyConfig.use_environment
`utf8_mode`	If non-zero, enable the UTF-8 mode

Related Source Files

The source files relating to `PyPreConfig` are:

File	Purpose
`Python ▸ initconfig.c`	Loads the configuration from the system environment and merges it with any command line flags
`Include ▸ cpython ▸ initconfig.h`	Defines the initialization configuration data structure

Runtime Configuration Data Structure

The second stage configuration is the runtime configuration. The runtime configuration data structure in `PyConfig` includes values, such as:

- Runtime flags for modes like debug and optimized
- The mode of execution, e.g. script file, stdin or a module
- Extended options, specified by `-X <option>`
- Environment variables for runtime settings

The configuration data is used by the CPython runtime to enable and disable features.

Setting Runtime Configuration with the Command Line

Python also comes with several Command Line Interface Options.

As an example, CPython has a mode called **verbose mode**. This is primarily aimed at developers for debugging CPython.

In Python you can enable verbose mode with the `-v` flag. In verbose mode, Python will print messages to the screen when modules are loaded:

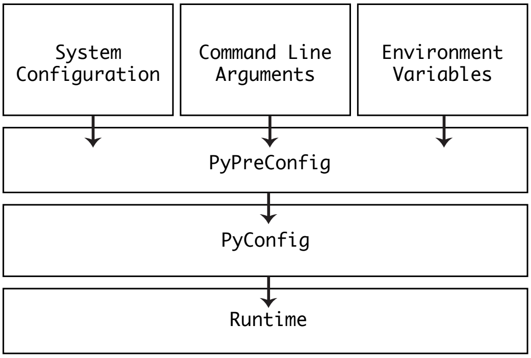
```
 $ ./python -v -c "print('hello world')"


# installing zipimport hook
import zipimport # builtin
# installed zipimport hook
...
```

You will see a hundred lines or more with all the imports of your user site-packages and anything else in the system environment.

Because runtime configuration can be set in several ways, configuration settings have levels of precedence over each other. The order of precedence for verbose mode is:

1. The default value for `config->verbose` is hardcoded to `-1` in the source code.
2. The environment variable `PYTHONVERBOSE` is used to set the value of `config->verbose`.
3. If the environment variable does not exist, then the default value of `-1` will remain.
4. In `config_parse_cmdline()` within `Python` ▸ `initconfig.c`, the command line flag is used to set the value, if provided.
5. This value is copied to a global variable, `Py_VerboseFlag` by `_Py_GetGlobalVariablesAsDict()`.

All `PyConfig` values follow the same sequence and order of precedence:



Viewing Runtime Flags

CPython interpreters have a set of runtime flags. These flags are advanced features used for toggling CPython specific behaviors. Within a Python session, you can access the runtime flags, like verbose mode and quiet mode, by using the `sys.flags` named tuple. All `-X` flags are available inside the `sys._xoptions` dictionary:

```
$ ./python -X dev -q

>>> import sys
>>> sys.flags
sys.flags(debug=0, inspect=0, interactive=0, optimize=0,
 dont_write_bytecode=0, no_user_site=0, no_site=0,
 ignore_environment=0, verbose=0, bytes_warning=0,
 quiet=1, hash_randomization=1, isolated=0,
 dev_mode=True, utf8_mode=0)

>>> sys._xoptions
{'dev': True}
```

Build Configuration

As well as the runtime configuration in `Python` ▸ `cpython` ▸ `initconfig.h`, there is also a build configuration. This is located inside `pyconfig.h` in the root folder. This file is created dynamically in the `./configure` step in the build process for macOS/Linux, or by `build.bat` in Windows.

You can see the build configuration by running:

```
 $ ./python -m sysconfig

Platform: "macosx-10.15-x86_64"
Python version: "3.9"
Current installation scheme: "posix_prefix"

Paths:
    data = "/usr/local"
    include = "/Users/anthonyshaw/CLionProjects/cpython/Include"
    platinclude = "/Users/anthonyshaw/CLionProjects/cpython"
...
```

Build configuration properties are compile-time values used to select additional modules to be linked into the binary. For example, debuggers, instrumentation libraries, and memory allocators are all set at compile time.

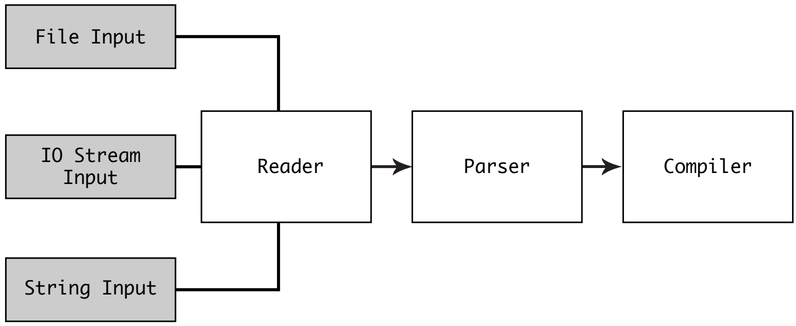
With the three configuration stages, the CPython interpreter can now take input and process text into executable code.

Building a Module From Input

Before any code can be executed, it must be compiled into a module from an input. As discussed before, inputs can vary in type:

- Local files and packages
- I/O Streams, e.g., stdin or a memory pipe
- Strings

Inputs are read and then passed to the parser, and then the compiler.



Due to this flexibility, a large portion of the CPython source code is dedicated to processing inputs to the CPython parser.

Related Source Files

There are two main files dealing with the command line interface:

File	Purpose
`Lib ▸ runpy.py`	Standard Library module for importing Python modules and executing them
`Modules ▸ main.c`	Functions wrapping the execution of external code, e.g. from a file, module, or input stream
`Programs ▸ python.c`	The entry point for the `python` executable for Windows, Linux and macOS. Only serves as a wrapper for `Modules/main.c`.
`Python ▸ pythonrun.c`	Functions wrapping the internal C APIs for processing inputs from the command line

Reading Files/Input

Once CPython has the runtime configuration and the command line arguments, it can load the code it needs to execute.
This task is handled by the `pymain_main()` function inside `Modules ▸ main.c`.

Depending on the newly created `PyConfig` instance, CPython will now execute code provided via several options.

Input String From the Command Line

CPython can execute a small Python application at the command line with the `-c` option. For example to execute `print(2 ** 2)`:

```
$ ./python -c "print(2 ** 2)"

4
```

The `pymain_run_command()` function is executed inside `Modules ▸ main.c` taking the command passed in `-c` as an argument in the C type `wchar_t*`.

Note

The `wchar_t*` type is often used as a low-level storage type for Unicode data across CPython as the size of the type can store UTF8 characters.

When converting the `wchar_t*` to a Python string, the `Objects ▸ unicodeobject.c` file has a helper function `PyUnicode_FromWideChar()` that returns Unicode string. The encoding to UTF8 is then done by `PyUnicode_AsUTF8String()`.

Python Unicode Strings are covered in depth in the Unicode String Type section of the Objects and Types chapter.

Once this is complete, `pymain_run_command()` will then pass the Python bytes object to `PyRun_SimpleStringFlags()` for execution.

The `PyRun_SimpleStringFlags()` function is part of `Python ▸ pythonrun.c`. Its purpose is to turn a string into a Python module and then send it on to be executed. A Python module needs to have an entry-point, (`__main__`), to be executed as a standalone module. `PyRun_SimpleStringFlags()` creates the entry point implicitly.

Once `PyRun_SimpleStringFlags()` has created a module and a dictionary, it calls `PyRun_StringFlags()`. `PyRun_SimpleStringFlags()` creates a fake filename and then calls the Python parser to create an AST from the string and return a module.

> **Note**
>
> Python modules are the data structure used to hand parsed code onto the compiler. The C structure for a Python module is `mod_ty` and is defined in `Include▸Python-ast.h`.

Input with a Local Module

Another way to execute Python commands is by using the `-m` option with the name of a module. A typical example is `python -m unittest` to run the unittest module in the standard library.

Being able to execute modules as scripts was initially proposed in PEP 338. The standard for explicit relative imports was defined in PEP366.

The use of the "`-m`" flag implies that within the module package, you want to execute whatever is inside the entry point (`__main__`). It also implies that you want to search `sys.path` for the named module.

This search mechanism in the import library (`importlib`) is why you don't need to remember where the `unittest` module is stored on your filesystem.

CPython imports a standard library module, `runpy` and executes it using `PyObject_Call()`. The import is done using the C API function `PyImport_ImportModule()`, found within the `Python▸import.c` file.

Note

In Python, if you had an object and wanted to get an attribute, you could call `getattr()`. In the C API, this call is `PyObject_GetAttrString()`, which is found in `Objects ▸ object.c`. If you wanted to run a callable, you would give it parentheses, or you can run the `__call__()` property on any Python object. The `__call__()` method is implemented inside `Objects ▸ object.c`:

```
>>> my_str = "hello world!"
>>> my_str.upper()
'HELLO WORLD!'
>>> my_str.upper.__call__()
'HELLO WORLD!'
```

The `runpy` module is written in pure Python and located in `Lib ▸ runpy.py`.

Executing `python -m <module>` is equivalent to running `python -m runpy <module>`. The `runpy` module was created to abstract the process of locating and executing modules on an Operating System.

`runpy` does a few things to run the target module:

- Calls `__import__()` for the module name you provided
- Sets `__name__` (the module name) to a namespace called `__main__`
- Executes the module within the `__main__` namespace

The `runpy` module also supports executing directories and zip files.

Input From a Script File or Standard Input

If the first argument to `python` was a filename, such as `python test.py`, then CPython will open a filehandle, and pass the handle to `PyRun_SimpleFileExFlags()`, inside `Python ▸ pythonrun.c`.

There are three paths this function can take:

1. If the file path is a `.pyc` file, it will call `run_pyc_file()`.
2. If the file path is a script file (`.py`) it will run `PyRun_FileExFlags()`.
3. If the file path is `stdin` because the user ran `command | python`, then treat `stdin` as a filehandle and run `PyRun_FileExFlags()`.

For `stdin` and basic script files, CPython will pass the filehandle to `PyRun_FileExFlags()` located in the `Python` ▸ `pythonrun.c` file.

The purpose of `PyRun_FileExFlags()` is similar to `PyRun_SimpleStringFlags()`. CPython will load the filehandle into `PyParser_ASTFromFileObject()`.

Identical to `PyRun_SimpleStringFlags()`, once `PyRun_FileExFlags()` has created a Python module from the file, it sent it to `run_mod()` to be executed.

Input From Compiled Bytecode

If the user runs `python` with a path to a `.pyc` file, then instead of loading the file as a plain text file and parsing it, CPython will assume that the `.pyc` file contains a code object written to disk.

In `PyRun_SimpleFileExFlags()` there is a clause for the user providing a file path to a `.pyc` file.

The `run_pyc_file()` function inside `Python` ▸ `pythonrun.c` marshals the code object from the `.pyc` file by using a filehandle. The code object data structure on the disk is the CPython compiler's way to cache compiled code so that it doesn't need to parse it every time the script is called.

Note

Marshaling is a term for copying the contents of a file into memory and converting them to a specific data structure.

Once the code object has been marshaled to memory, it is sent to `run_eval_code_obj()`, which calls `Python` ▸ `ceval.c` to execute the code.

Conclusion

In this chapter, you've uncovered how Python's many configuration options are loaded and how code is input into the interpreter. Python's flexibility of input makes it a great tool for a range of applications, such as:

- Command-line utilities
- Long-running network applications, like web servers
- Short, composable scripts

Python's ability to set configuration properties in many ways causes complexity. For example, if you tested a Python application on Python 3.8, and it executed correctly. But in a different environment, it failed, you need to understand what settings were different in that environment. This means you'd need to inspect environment variables, runtime flags, and even the sys config properties. The compile-time properties found in sys config can be different amongst distributions of Python. For example, Python 3.8 downloaded from python.org for macOS has different default values than the Python 3.8 distribution found on Homebrew or the one found on the Anaconda distribution.

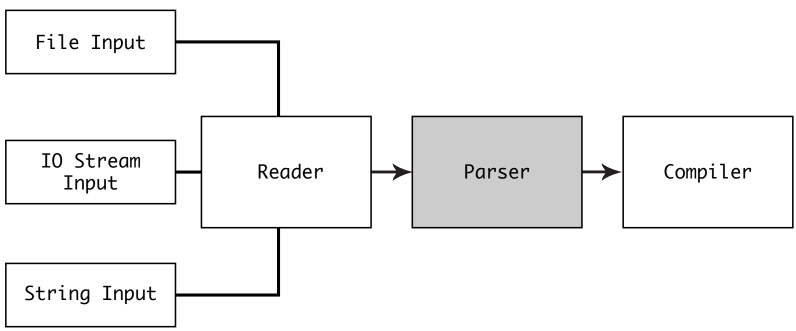
All of these input methods have an output of a Python module. In the next chapter, you will uncover how modules are created from the input.

Leave feedback on this section »

Lexing and Parsing with Syntax Trees

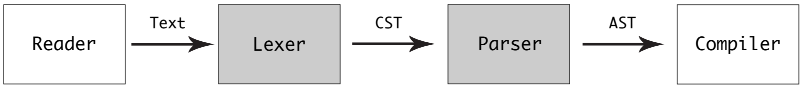
In the previous chapter, you explored how Python text is read from various sources. It needs to be converted into a structure that the compiler can use.

This stage is **parsing**:



In this chapter, you will explore how the text is parsed into logical structures that can be compiled.

There are two structures used to parse code in CPython, the **Concrete Syntax Tree** and the **Abstract Syntax Tree**.



The two parts of the parsing process are:

1. Creating a Concrete Syntax Tree using a **Parser-Tokenizer** (**Lexer**)
2. Creating an Abstract Syntax Tree from a Concrete Syntax Tree using a **Parser**

These two steps are common paradigms used in many programming languages.

Concrete Syntax Tree Generation

The Concrete Syntax Tree (CST) (or sometimes known as a **parse-tree**), is an ordered, rooted tree structure that represents code in a context-free grammar.

The CST is created from a **tokenizer** and **parser**. You explored the parser-generator in the chapter on **The Python Language and Grammar**. The output from the parser-generator is a Deterministic Finite Automaton (DFA) parsing table, describing the possible states of context-free grammar.

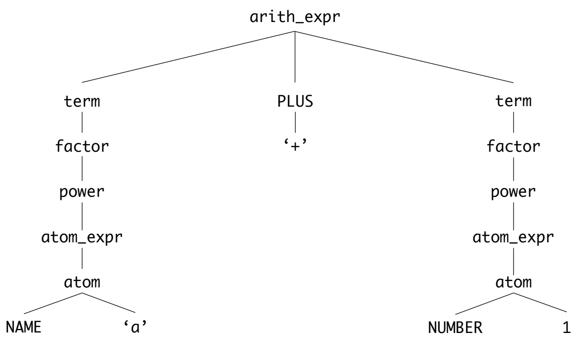
See Also

The original author of Python, Guido van Rossum is currently working on a contextual-grammar as an alternative to LL(1), the grammar used in CPython. The alternative is called Parser Expression Grammar, or PEG.

This will be available as an experimental feature in Python 3.9

In the grammar chapter, you explored some expression types, such as `if_stmt` and `with_stmt`. The Concrete Syntax Tree represents grammar symbols (like `if_stmt`) as branches, with tokens and terminals as leaf nodes.

For example, the arithmetic expression "`a + 1`" becomes the CST:



An arithmetic expression is represented here with three major branches, the left, operator, and right.

The parser iterates through tokens from an input stream and matches it against the possible states and tokens in the grammar to build a CST.

In `Grammar` ▸ `Grammar`, all of the symbols shown in the CST above are defined:

```
arith_expr: term (('+'|'-') term)*
term: factor (('*'|'@'|'/'|'%'|'//') factor)*
factor: ('+'|'-'|'~') factor | power
power: atom_expr ['**' factor]
atom_expr: [AWAIT] atom trailer*
atom: ('(' [yield_expr|testlist_comp] ')' |
       '[' [testlist_comp] ']' |
```

```
       '{' [dictorsetmaker] '}' |
       NAME | NUMBER | STRING+ | '...' | 'None' | 'True' | 'False')
```

In `Grammar` ▸ `Tokens`, the tokens are also defined:

```
ENDMARKER
NAME
NUMBER
STRING
NEWLINE
INDENT
DEDENT

LPAR                    '('
RPAR                    ')'
LSQB                    '['
RSQB                    ']'
COLON                   ':'
COMMA                   ','
SEMI                    ';'
PLUS                    '+'
MINUS                   '-'
STAR                    '*'
...
```

A `NAME` token represents the name of a variable, function, class, or module. Python's syntax doesn't allow a NAME to be:

- One of the reserved keywords, like `await` and `async`
- A numeric or other literal type

For example, if you tried to define a function named `1`, Python would raise a SyntaxError:

```
>>> def 1():
  File "<stdin>", line 1
    def 1():
        ^
SyntaxError: invalid syntax
```

A `NUMBER` is a particular token type to represent one of Python's many numeric values. Python has a special grammar for numbers, including:

- Octal values, e.g., `0o20`
- Hexadecimal values, e.g., `0x10`
- Binary values, e.g., `0b10000`
- Complex numbers, e.g., `10j`
- Floating-point numbers, e.g., `1.01`
- Underscores as commas, e.g., `1_000_000`

You can see compiled symbols and tokens using the `symbol` and `token` modules in Python:

```
 $ ./python
>>> import symbol
>>> dir(symbol)
['__builtins__', '__cached__', '__doc__', '__file__', '__loader__',
 '__name__', '__package__', '__spec__', '_main', '_name', '_value',
 'and_expr', 'and_test', 'annassign', 'arglist', 'argument',
 'arith_expr', 'assert_stmt', 'async_funcdef', 'async_stmt',
 'atom', 'atom_expr',
...
>>> import token
>>> dir(token)
['AMPER', 'AMPEREQUAL', 'AT', 'ATEQUAL', 'CIRCUMFLEX',
 'CIRCUMFLEXEQUAL', 'COLON', 'COMMA', 'COMMENT', 'DEDENT', 'DOT',
 'DOUBLESLASH', 'DOUBLESLASHEQUAL', 'DOUBLESTAR', 'DOUBLESTAREQUAL',
...
```

The CPython Parser-Tokenizer

Programming languages have different implementations for the Lexer. Some use a Lexer-Generator, as a complement to the Parser-Generator.

CPython has a Parser/Tokenizer module, written in C.

Related Source Files

The source files relating to the parser-tokenizer are:

File	Purpose
`Python▸pythonrun.c`	Executes the parser and the compiler from an input
`Parser▸parsetok.c`	The Parser and Tokenizer implementation
`Parser▸tokenizer.c`	Tokenizer implementation
`Parser▸tokenizer.h`	Header file for the Tokenizer Implementation, describes data models like token state
`Include▸token.h`	Declaration of token types, generated by `Tools▸scripts▸generate_token.py`
`Include▸node.h`	Parse tree node interface and macros for the tokenizer

Inputting Data Into the Parser From a File

The entry point for the parser-tokenizer, `PyParser_ASTFromFileObject()`, takes a file handle, compiler flags and a `PyArena` instance and converts the file object into a module. There are two steps:

1. Convert to a CST using `PyParser_ParseFileObject()`
2. Convert into a AST/module, using the AST function `PyAST_FromNodeObject()`

The `PyParser_ParseFileObject()` function has two important tasks:

1. Instantiate a tokenizer state `tok_state` using `PyTokenizer_FromFile()`
2. Convert the tokens into a CST (a list of `node`) using `parsetok()`

Parser-Tokenizer Flow

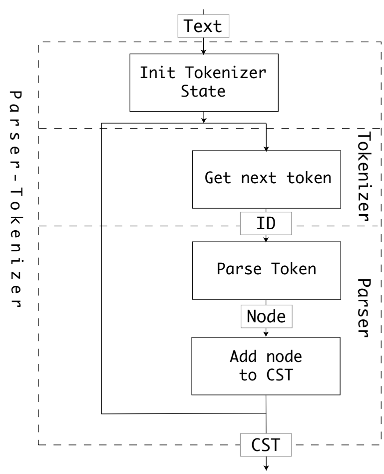
The parser-tokenizer takes text input and executes the tokenizer and parser in a loop until the cursor is at the end of the text (or a syntax error occurred).

Before execution, the parser-tokenizer establishes `tok_state`, a temporary data structure to store all state used by the tokenizer. The tokenizer state contains information such as the current cursor position and line.

The parser-tokenizer calls `tok_get()` to get the next token. The parser-tokenizer passes the resulting token ID to the parser, which uses the parser-generator DFA to create a node on the Concrete Syntax Tree.

`tok_get()` is one of the most complex functions in the whole CPython codebase. It has over 640 lines and includes decades of heritage with edge cases, new language features, and syntax.

The process of calling the tokenizer and parser in a loop can be shown as:



The CST root `node` returned by `PyParser_ParseFileObject()` is going to be essential for the next stage, converting a CST into an Abstract-Syntax-Tree (AST). The node type is defined in `Include▸node.h` as:

```
typedef struct _node {
    short               n_type;
    char                *n_str;
```

```
    int                 n_lineno;
    int                 n_col_offset;
    int                 n_nchildren;
    struct _node        *n_child;
    int                 n_end_lineno;
    int                 n_end_col_offset;
} node;
```

Since the CST is a tree of syntax, token IDs, and symbols, it would be difficult for the compiler to make quick decisions based on the Python language.

Before you jump into the AST, there is a way to access the output from the parser stage. CPython has a standard library module `parser`, which exposes the C functions with a Python API.

The output will be in the numeric form, using the token and symbol numbers generated by the `make regen-grammar` stage, stored in `Include ▸ token.h`:

```
>>> from pprint import pprint
>>> import parser
>>> st = parser.expr('a + 1')
>>> pprint(parser.st2list(st))
[258,
 [332,
  [306,
   [310,
    [311,
     [312,
      [313,
       [316,
        [317,
         [318,
          [319,
           [320,
            [321, [322, [323, [324, [325, [1, 'a']]]]]],
            [14, '+'],
            [321, [322, [323, [324, [325, [2, '1']]]]]]]]]]]]]]]]],
```

```
 [4, ''],
 [0, '']]
```

To make it easier to understand, you can take all the numbers in the `symbol` and `token` modules, put them into a dictionary and recursively replace the values in the output of `parser.st2list()` with the names of the tokens:

cpython-book-samples ▸ 21 ▸ lex.py

```python
import symbol
import token
import parser

def lex(expression):
    symbols = {v: k for k, v in symbol.__dict__.items()
               if isinstance(v, int)}
    tokens = {v: k for k, v in token.__dict__.items()
              if isinstance(v, int)}
    lexicon = {**symbols, **tokens}
    st = parser.expr(expression)
    st_list = parser.st2list(st)

    def replace(l: list):
        r = []
        for i in l:
            if isinstance(i, list):
                r.append(replace(i))
            else:
                if i in lexicon:
                    r.append(lexicon[i])
                else:
                    r.append(i)
        return r

    return replace(st_list)
```

You can run `lex()` with a simple expression, like `a + 1` to see how this is represented as a parser-tree:

```
>>> from pprint import pprint
>>> pprint(lex('a + 1'))

['eval_input',
 ['testlist',
  ['test',
   ['or_test',
    ['and_test',
     ['not_test',
      ['comparison',
       ['expr',
        ['xor_expr',
         ['and_expr',
          ['shift_expr',
           ['arith_expr',
            ['term',
             ['factor', ['power', ['atom_expr', ['atom',
['NAME', 'a']]]]]],
            ['PLUS', '+'],
            ['term',
             ['factor',
              ['power', ['atom_expr', ['atom', ['NUMBER',
'1']]]]]]]]]]]]]]]]],
 ['NEWLINE', ''],
 ['ENDMARKER', '']]
```

In the output, you can see the symbols in lowercase, such as `'arith_expr'` and the tokens in uppercase, such as `'NUMBER'`.

Abstract Syntax Trees

The next stage in the CPython interpreter is to convert the CST generated by the parser into something more logical that can be executed.

Concrete Syntax Trees are a very literal representation of the text in the code file. At this stage, it could be a number of languages. Python's basic grammatical structure has been interpreted, but you could not use the CST to establish functions, scopes, loops or any of the core

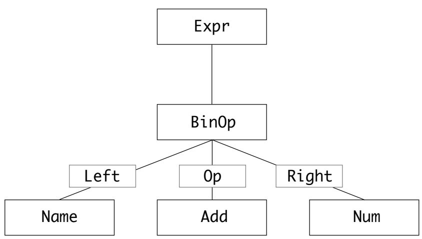
Python language features.

Before code is compiled, the CST needs to be converted into a higher-level structure that represents actual Python constructs. The structure is a representation of the CST, called an Abstract Syntax Tree (AST).

As an example, a binary operation in the AST is called a `BinOp` and is defined as a type of expression. It has three components:

- `left` - The left-hand part of the operation
- `op` - The operator, e.g., +, -, *
- `right` - The right-hand part of the expression

The AST for `a + 1` can be represented in an AST as:



ASTs are produced by the CPython parser process, but you can also generate them from Python code using the `ast` module in the Standard Library.

Before diving into the implementation of the AST, it would be useful to understand what an AST looks like for a simple piece of Python code.

Related Source Files

The source files relating to Abstract Syntax Trees are:

File	Purpose
Include▸Python-ast.h	Declaration of AST Node types, generated by Parser▸asdl_c.py
Parser▸Python.asdl	A list of AST Node Types and Properties in a domain-specific-language, **ASDL 5**
Python▸ast.c	The AST implementation

Using Instaviz to View Abstract Syntax Trees

Instaviz is a Python package written for this book. It displays ASTs and compiled code in a web interface.

To install `instaviz`, install the `instaviz` package from `pip`:

```
$ pip install instaviz
```

Then, open up a REPL by running `python` at the command line with no arguments. The function `instaviz.show()` takes a single argument of type `code object`.
You will cover code objects in the next chapter. For this example, define a function and use the name of the function as the argument value:

```
 $ python
>>> import instaviz
>>> def example():
       a = 1
       b = a + 1
       return b

>>> instaviz.show(example)
```

You'll see a notification on the command-line that a web server has started on port `8080`. If you were using that port for something else, you could change it by calling `instaviz.show(example, port=9090)` or another port number.

In the web browser, you can see the detailed breakdown of your function:

Code Object Properties

Field	Value
co_argcount	0
co_cellvars	()
co_code	64017d007c00640117007d017c015300
co_consts	(None, 1)
co_filename	test.py
co_firstlineno	4
co_freevars	()
co_kwonlyargcount	0
co_lnotab	b'\x00\x01\x04\x01\x08\x01'
co_name	foo
co_names	()
co_nlocals	2
co_stacksize	2
co_varnames	('a', 'b')

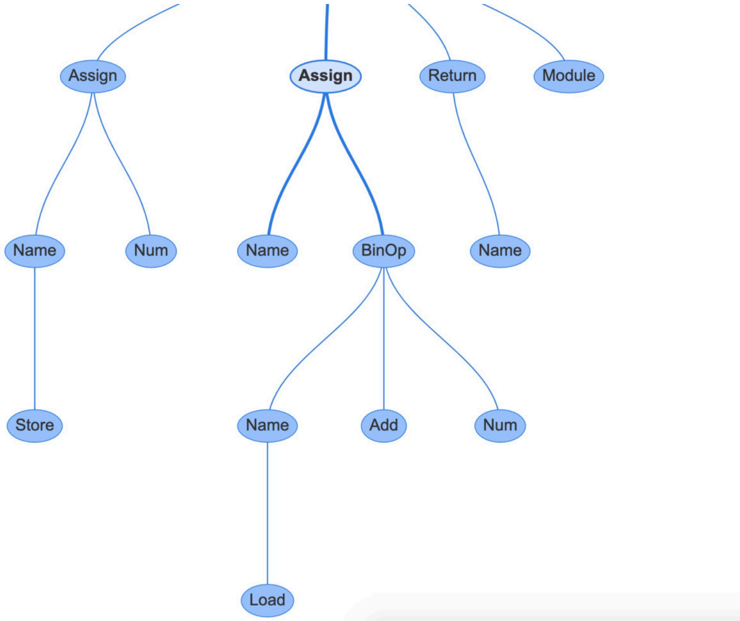
```
def foo():
    a = 1
    b = a + 1
    return b
```

Graph direction: Up-Down Down-Up Left-Right Right-Left

The bottom left graph is the function you declared in REPL, represented as an Abstract Syntax Tree. Each node in the tree is an AST type. They are found in the `ast` module, and all inherit from `_ast.AST`.

Some of the nodes have properties that link them to child nodes, unlike the CST, which has a generic child node property.

For example, if you click on the Assign node in the center, this links to the line `b = a + 1`:

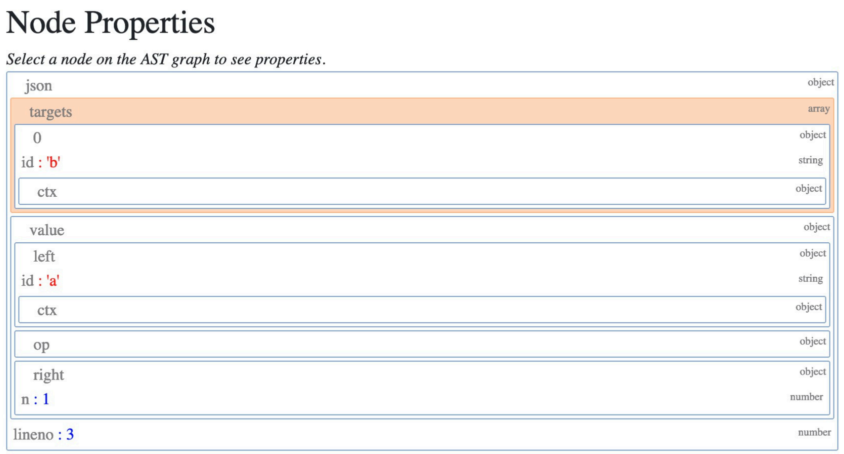


The **`assign`** node has two properties:

1. **`targets`** is a list of names to assign. It is a list because you can assign to multiple variables with a single expression using unpacking
2. **`value`** is the value to assign, which in this case is a `BinOp` statement, `a + 1`.

If you click on the `BinOp` statement, it shows the properties of relevance:

- **`left:`** the node to the left of the operator
- **`op:`** the operator, in this case, an `Add` node (`+`) for addition
- **`right:`** the node to the right of the operator



AST Compilation

Compiling an AST in C is not a straightforward task. The `Python ▸ ast.c` module has over 5000 lines of code.

There are a few entry points, forming part of the AST's public API. The AST API takes a node tree (CST), a filename, the compiler flags, and a memory storage area. The result type is `mod_ty` representing a Python module, defined in `Include ▸ Python-ast.h`.

`mod_ty` is a container structure for one of the five module types in Python:

1. `Module`
2. `Interactive`
3. `Expression`
4. `FunctionType`
5. `Suite`

The module types are all listed in `Parser ▸ Python.asdl`. You will see the module types, statement types, expression types, operators, and comprehensions all defined in this file. The names of the types in `Parser ▸ Python.asdl` relate to the classes generated by the AST and the same classes named in the `ast` standard module library:

```
-- ASDL's 5 builtin types are:
-- identifier, int, string, object, constant

module Python
{
    mod = Module(stmt* body, type_ignore *type_ignores)
        | Interactive(stmt* body)
        | Expression(expr body)
        | FunctionType(expr* argtypes, expr returns)
```

The AST module imports `Include▸Python-ast.h`, a file created automatically from `Parser▸Python.asdl` when regenerating grammar. The parameters and names in `Include▸Python-ast.h` correlate directly to those specified in `Parser▸Python.asdl`.

The `mod_ty` type is generated into `Include▸Python-ast.h` from the `Module` definition in `Parser▸Python.asdl`:

```c
enum _mod_kind {Module_kind=1, Interactive_kind=2, Expression_kind=3,
                 FunctionType_kind=4, Suite_kind=5};
struct _mod {
    enum _mod_kind kind;
    union {
        struct {
            asdl_seq *body;
            asdl_seq *type_ignores;
        } Module;

        struct {
            asdl_seq *body;
        } Interactive;

        struct {
            expr_ty body;
        } Expression;

```

```
        struct {
            asdl_seq *argtypes;
            expr_ty returns;
        } FunctionType;

        struct {
            asdl_seq *body;
        } Suite;

    } v;
};
```

The C header file and structures are there so that the `Python ▸ ast.c` program can quickly generate the structures with pointers to the relevant data.

The AST entry-point, `PyAST_FromNodeObject()`, is essentially a `switch` statement around the result from `TYPE(n)`. `TYPE()` is a macro used by the AST to determine what type a node in the concrete syntax tree is. The result of `TYPE()` will be either a symbol or token type. By starting at the root node, it can only be one of the module types defined as `Module`, `Interactive`, `Expression`, `FunctionType`.

- For `file_input`, the type should be a `Module`
- For `eval_input`, such as from a REPL, the type should be an `Expression`

For each type of statement, there is a corresponding `ast_for_xxx` C function in `Python ▸ ast.c`, which will look at the CST nodes to complete the properties for that statement.

One of the simpler examples is the power expression, i.e., `2**4` is 2 to the power of 4.

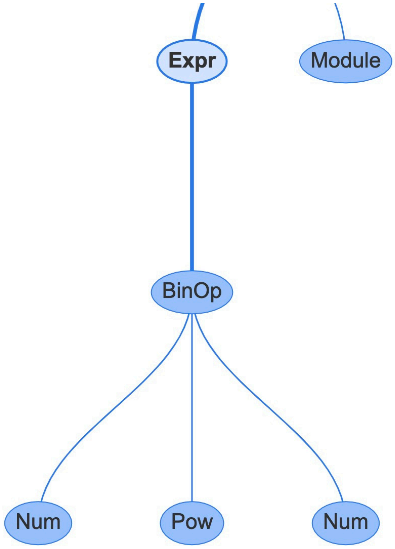
The `ast_for_power()` function will return a `BinOp` (binary operation) with the operator as `Pow` (power), the left hand of `e` (2), and the right hand of `f` (4):

`Python` ▸ `ast.c` line 2717

```
static expr_ty
ast_for_power(struct compiling *c, const node *n)
{
    /* power: atom trailer* ('**' factor)*
     */
    expr_ty e;
    REQ(n, power);
    e = ast_for_atom_expr(c, CHILD(n, 0));
    if (!e)
        return NULL;
    if (NCH(n) == 1)
        return e;
    if (TYPE(CHILD(n, NCH(n) - 1)) == factor) {
        expr_ty f = ast_for_expr(c, CHILD(n, NCH(n) - 1));
        if (!f)
            return NULL;
        e = BinOp(e, Pow, f, LINENO(n), n->n_col_offset,
                  n->n_end_lineno, n->n_end_col_offset, c->c_arena);
    }
    return e;
}
```

You can see the result of this if you send a short function to the `instaviz` module:

```
>>> def foo():
       2**4
>>> import instaviz
>>> instaviz.show(foo)
```



In the UI, you can also see the corresponding properties:

In summary, each statement type and expression has a corresponding `ast_for_*()` function to create it. The arguments are defined in `Parser` ▸ `Python.asdl` and exposed via the `ast` module in the standard library. If an expression or statement has children, then it will call the corresponding `ast_for_*` child function in a depth-first traversal.

Important Terms to Remember

- **Concrete Syntax Tree CST** A non-contextual tree representation of tokens and symbols
- **Parse-Tree** Another term for Concrete Syntax Tree
- **Abstract Syntax Tree** A contextual tree representation of Python's grammar and statements
- **Token** A type of symbol, e.g., "+"
- **Tokenizer** The process of converting text into tokens
- **Parser** A generic term of the process in converting text into a CST or AST

Example: Adding an Almost Equal Comparison Operator

To bring all this together, you can add a new piece of syntax to the Python language and recompile CPython to understand it.

A **comparison expression** will compare the values of two or more values. For example,

```
>>> a = 1
>>> b = 2
>>> a == b
False
```

The operator used in the comparison expression is called the **comparison operator**. Here are some comparison operators you may recognize:

- `<` Less than
- `>` Greater than
- `==` Equal to
- `!=` Not equal to

See Also

Rich comparisons in the data model were proposed for Python 2.1 in PEP207. The PEP contains context, history, and justification for custom Python types to implement comparison methods.

We will now add another comparison operator, called **almost equal**, represented by `~=` with the following behaviors:

- If you compare a float and an integer, it will cast the float into an integer and compare the result.
- If you compare two integers, it will use the normal equality operators.

Once implemented, this new operator should return the following in a REPL:

```
>>> 1 ~= 1
True
>>> 1 ~= 1.0
True
>>> 1 ~= 1.01
True
>>> 1 ~= 1.9
False
```

To add the new operator, you first need to update the CPython grammar.

In `Grammar` ▸ `python.gram`, the comparison operators are defined as a symbol, `comp_op`:

```
comparison[expr_ty]:
    | a=bitwise_or b=compare_op_bitwise_or_pair+ ...
    | bitwise_or
compare_op_bitwise_or_pair[CmpopExprPair*]:
    | eq_bitwise_or
```

```
    | noteq_bitwise_or
    | lte_bitwise_or
    | lt_bitwise_or
    | gte_bitwise_or
    | gt_bitwise_or
    | notin_bitwise_or
    | in_bitwise_or
    | isnot_bitwise_or
    | is_bitwise_or
eq_bitwise_or[CmpopExprPair*]: '==' a=bitwise_or ...
noteq_bitwise_or[CmpopExprPair*]:
    | (tok='!=' {_PyPegen_check_barry_as_flufl(p) ? NULL : tok}) a=bitwise_or ...
lte_bitwise_or[CmpopExprPair*]: '<=' a=bitwise_or ...
lt_bitwise_or[CmpopExprPair*]: '<' a=bitwise_or ...
gte_bitwise_or[CmpopExprPair*]: '>=' a=bitwise_or ...
gt_bitwise_or[CmpopExprPair*]: '>' a=bitwise_or ...
notin_bitwise_or[CmpopExprPair*]: 'not' 'in' a=bitwise_or ...
in_bitwise_or[CmpopExprPair*]: 'in' a=bitwise_or ...
isnot_bitwise_or[CmpopExprPair*]: 'is' 'not' a=bitwise_or ...
is_bitwise_or[CmpopExprPair*]: 'is' a=bitwise_or ...
```

Change the `compare_op_bitwise_or_pair` expression to also allow a new `ale_bitwise_or` pair:

```
compare_op_bitwise_or_pair[CmpopExprPair*]:
    | eq_bitwise_or
...
    | ale_bitwise_or
```

Define the new `ale_bitwise_or` expression, beneath the existing `isnot_bitwise_or` expression:

```
...
is_bitwise_or[CmpopExprPair*]: 'is' a=bitwise_or ...
ale_bitwise_or[CmpopExprPair*]: '~=' a=bitwise_or
    { _PyPegen_cmpop_expr_pair(p, AlE, a) }
```

This new type defines a named expression, `ale_bitwise_or`, that contains the `'~='` terminal.

The function call `_PyPegen_cmpop_expr_pair(p, AlE, a)` is an expression to get the a `cmpop` node from the AST, where the type is `AlE`.

Next, add a token to `Grammar` ▸ `Tokens`:

```
ATEQUAL                 '@='
RARROW                  '->'
ELLIPSIS                '...'
COLONEQUAL              ':='
# Add this line
ALMOSTEQUAL             '~='
```

To update the grammar and tokens in C, you now have to regenerate the headers:

On macOS/Linux:

```
$ make regen-token regen-pegen
```

On Windows, within the `PCBuild` directory:

```
> build.bat --regen
```

The tokenizer will be automatically updated by these steps. For example, open the `Parser/token.c` source and see how a case in the `PyToken_TwoChars()` function has changed:

```
    case '~':
        switch (c2) {
        case '=': return ALMOSTEQUAL;
        }
        break;
    }
```

If you recompile CPython at this stage and open a REPL, you can see that the tokenizer can successfully recognise the token, but the AST does not know how to handle it:

```
$ ./python
>>> 1 ~= 2
SystemError: invalid comp_op: ~=
```

This exception is raised by `ast_for_comp_op()` inside `Python` ▸ `ast.c` because it does not recognise `ALMOSTEQUAL` as a valid operator for a comparison statement.

`Compare` is an expression type defined in `Parser` ▸ `Python.asdl`, it has properties for the left expression, a list of operators, `ops`, and a list of expressions to compare to, `comparators`:

```
| Compare(expr left, cmpop* ops, expr* comparators)
```

Inside the `Compare` definition is a reference to the `cmpop` enumeration:

```
cmpop = Eq | NotEq | Lt | LtE | Gt | GtE | Is | IsNot | In | NotIn
```

This is a list of possible AST leaf nodes that can act as comparison operators. Ours is missing and needs to be added. Update the list of options to include a new type, `AlE` (**Al**most **E**qual):

```
cmpop = Eq | NotEq | Lt | LtE | Gt | GtE | Is | IsNot | In | NotIn | AlE
```

Next, regenerate the AST again to update the AST C header files:

```
$ make regen-ast
```

This will have updated the comparison operator, `_cmpop`, enum inside `Include/Python-ast.h` to include the `AlE` option:

```
typedef enum _cmpop { Eq=1, NotEq=2, Lt=3, LtE=4, Gt=5, GtE=6, Is=7,
                      IsNot=8, In=9, NotIn=10, AlE=11 } cmpop_ty;
```

The AST has no knowledge that the `ALMOSTEQUAL` token is equivalent to the `AlE` comparison operator. So you need to update the C code for the AST.

Navigate to `ast_for_comp_op()` in `Python` ▸ `ast.c`. Find the switch statement for the operator tokens. This returns one of the `_cmpop` enumeration values.

Add two lines, to catch the `ALMOSTEQUAL` token and return the `AlE` comparison operator:

`Python` ▸ `ast.c` line 1222

```
static cmpop_ty
ast_for_comp_op(struct compiling *c, const node *n)
{
    /* comp_op: '<'|'>'|'=='|'>='|'<='|'!='|'in'|'not' 'in'|'is'
               |'is' 'not'
    */
    REQ(n, comp_op);
    if (NCH(n) == 1) {
        n = CHILD(n, 0);
        switch (TYPE(n)) {
            case LESS:
                return Lt;
            case GREATER:
                return Gt;
            case ALMOSTEQUAL: // Add this line to catch the token
                return AlE;    // And this one to return the AST node
```

Now recompile CPython and open up a REPL to test the command:

```
>>> a = 1
>>> b = 1.0
>>> a ~= b
True
```

At this stage, the tokenizer and the AST can parse this code, but the compiler won't know how to handle the operator. To test the AST representation, use the `ast.parse()` function and explore the first operator in the expression:

```
>>> import ast
>>> m = ast.parse('1 ~= 2')
>>> m.body[0].value.ops[0]
```

```
<_ast.AlE object at 0x10a8d7ee0>
```

This is an instance of our `AlE` comparison operator type, so the AST has correctly parsed the code.

In the next chapter, you will learn about how the CPython compiler works, and revisit the almost-equal operator to build out its behavior.

Conclusion

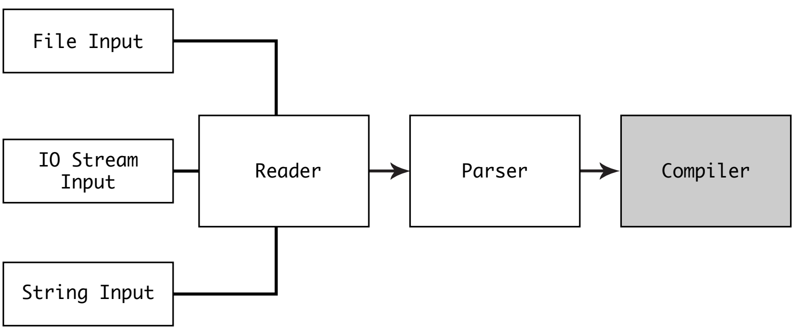
CPython's versatility and low-level execution API make it the ideal candidate for an embedded scripting engine. You will see CPython used in many UI applications, such as Game Design, 3D graphics, and system automation.

The interpreter process is flexible and efficient, and now you have an understanding of how it works you're ready to understand the compiler.

Leave feedback on this section »

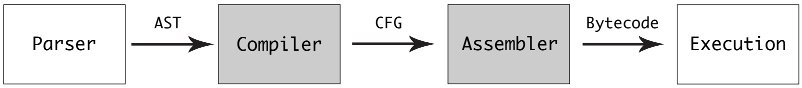
The Compiler

After completing the task of parsing, the interpreter has an AST with the operations, functions, classes, and namespaces of the Python code. The job of the **compiler** is to turn the AST into instructions the CPU could understand.



This compilation task is split into two components:

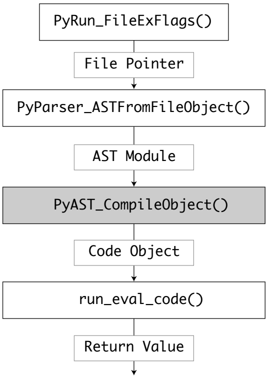
1. **Compiler** - Traverse the AST and create a **control-flow-graph** (CFG), which represents the logical sequence for execution
2. **Assembler** - Convert the nodes in the CFG to sequential, executable statements, known as **bytecode**



Important

Throughout this chapter, it is important to remember that the unit of compilation for CPython is a module. The compilation steps and process indicated in this chapter will happen once for each module in your project.

In this chapter, you will focus on the compilation of an AST module into a code object:



The `PyAST_CompileObject()` function is the main entry point to the CPython compiler. It takes a Python AST module as its primary argument, along with the name of the file, the globals, locals, and the `PyArena` all created earlier in the interpreter process.

> **Note**
>
> We're starting to get into the guts of the CPython compiler now, with decades of development and Computer Science theory behind it. Don't be put off by the size of it. Once you break down the compiler into logical steps, it is easier to understand.

Related Source Files

The source files relating to the compiler are:

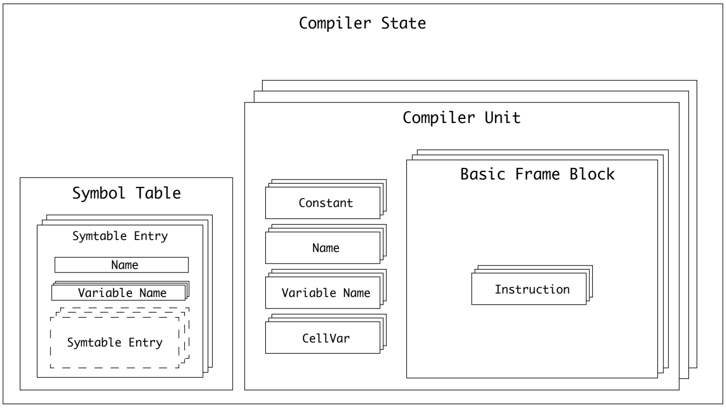
File	Purpose
`Python ▸ pythonrun.c`	Executes the parser and the compiler from an input
`Python ▸ compile.c`	The compiler implementation
`Include ▸ compile.h`	The compiler API and type definitions

Important Terms

This chapter refers to many terms that may be new to you:

- The **compiler state** is implemented as a container type, which contains one **symbol table**
- The Symbol Table contains many **variable names** and can optionally contain child symbol tables
- The compiler type contains many **compiler units**
- Each compiler unit can contain many names, variable names, constants and cell variables
- A compiler unit contains many **basic frame blocks**
- Basic frame blocks contains many **bytecode instructions**

The compiler state container and its components can be shown as:



Instantiating a Compiler

Before the compiler starts, a global compiler state is created. The compiler state, (`compiler`), struct contains properties used by the compiler to such as compiler flags, the stack, and the `PyArena`. It also contains links to other data structures, like the symbol table.

Field	Type	Purpose
`c_filename`	`PyObject *` (`str`)	A string of the filename being compiled
`c_st`	`symtable *`	The compiler's symbol table
`c_future`	`PyFutureFeatures *`	A pointer to module's `__future__`
`c_flags`	`PyCompilerFlags *`	Inherited compiler flags (*See compiler flags*)
`c_optimize`	`int`	Optimization level
`c_interactive`	`int`	1 if in interactive mode
`c_nestlevel`	`int`	Current nesting level
`c_do_not_emit_-bytecode`	`int`	The compiler won't emit any bytecode if this value is different from zero. This setting can be used to temporarily visit nodes without emitting bytecode to check only errors
`c_const_cache`	`PyObject *` (`dict`)	Python dict holding all constants, including names tuple

Field	Type	Purpose
`u`	`compiler_unit*`	Compiler state for current block
`c_stack`	`PyObject *` (list)	Python list holding compiler_unit pointers
`c_arena`	`PyArena *`	A pointer to the memory allocation arena

Inside `PyAST_CompileObject()`, the compiler state is instantiated:

- If the module does not have a docstring (`__doc__`) property, an empty one is created here, as with the `__annotations__` property.
- `PyAST_CompileObject()` sets the filename in the compiler state to the value passed. This function is later used for stack traces and exception handling.
- The memory allocation arena for the compiler is set to the one used by the interpreter. See the Custom Memory Allocators section in the Memory Management chapter for more information on memory allocators.
- Any future flags are configured before the code is compiled.

Future Flags and Compiler Flags

Before the compiler runs, there are two types of flags to toggle the features inside the compiler. These come from two places:

1. The configuration state, which contains environment variables and command-line flags. *See the chapter on Configuration State.*
2. The use of `__future__` statements inside the source code of the module.

Future Flags

Future flags are required because of the syntax or features in that specific module. For example, Python 3.7 introduced delayed evaluation of type hints through the `annotations` future flag:

```python
from __future__ import annotations
```

The code after this statement might use unresolved type hints, so the `__future__` statement is required. Otherwise, the module wouldn't import.

Reference of Future Flags in 3.9.0b5

As of 3.9.0b5, all but two of the future flags are mandatory and enabled automatically:

Import	Mandatory Since	Purpose
`nested_scopes`	2.2	Statically nested scopes (PEP227)
`generators`	2.3	Simple generators (PEP255)
`division`	3.0	Use the "true" division operator (PEP238)
`absolute_import`	3.0	Enable absolute imports (PEP328)
`with_statement`	2.6	Enable the with statement (PEP343)
`print_function`	3.0	Make `print` a function (PEP3105)
`unicode_literals`	3.0	Make `str` literals Unicode instead of bytes (PEP3112)
`barry_as_FLUFL`	N/A	Easter Egg (PEP401)
`generator_stop`	3.7	Enable `StopIteration` inside generators (PEP479)
`annotations`	4.0	Postponed evaluation of type annotations (PEP563)

Note

Many of the `__future__` flags were used to aid portability between Python 2 and 3. As Python 4.0 approaches, you may see more future flags added.

Compiler Flags

The other compiler flags are specific to the environment, so they might change the way the code executes or the way the compiler runs, but they shouldn't link to the source in the same way that `__future__` statements do.

One example of a compiler flag would be the `-O` flag for optimizing the use of `assert` statements. This flag disables any `assert` statements, which may have been put in the code for debugging purposes. It can also be enabled with the `PYTHONOPTIMIZE=1` environment variable setting.

Symbol Tables

Before the code is compiled, a **symbol table** is created by the `PySymtable_BuildObject()` API.

The purpose of the symbol table is to provide a list of namespaces, globals, and locals for the compiler to use for referencing and resolving scopes.

Related Source Files

The source files relating to the symbol table are:

File	Purpose
`Python ▸ symtable.c`	The symbol table implementation
`Include ▸ symtable.h`	The symbol table API definition and type definitions
`Lib ▸ symtable.py`	The `symtable` standard library module

Symbol Table Data Structure

The `symtable` structure should be one symtable instance for the compiler, so namespacing becomes essential.

For example, if you create a method called `resolve_names()` in one class and declare another method with the same name in another class. Inside the module, you want to be sure which one is called.

The symtable serves this purpose, as well as ensuring that variables declared within a narrow scope don't automatically become globals.

The symbol table struct, `symtable`, has the following fields:

Field	Type	Purpose
`st_filename`	`PyObject *` (`str`)	Name of the file being compiled
`st_cur`	`_symtable_entry *`	Current symbol table entry
`st_top`	`_symtable_entry *`	Symbol table entry for the module
`st_blocks`	`PyObject *` (`dict`)	Map of AST node addresses to symbol table entries
`st_stack`	`PyObject *` (`list`)	Stack of namespace info
`st_global`	`PyObject *` (`dict`)	Reference to the symbols in `st_top` (`st_top->ste_symbols`)
`st_nblocks`	`int`	Number of blocks used
`st_private`	`PyObject *` (`str`)	Name of current class or NULL
`st_future`	`PyFutureFeatures *`	Module's future features that affect the symbol table
`recursion_depth`	`int`	Current recursion depth
`recursion_limit`	`int`	Recursion limit before `RecursionError` is raised. Set by `Py_SetRecursionLimit()`

Using the `symtable` Standard Library Module

Some of the symbol table C API is exposed in Python via the `symtable` module in the standard library.

Using another module called `tabulate` (available on PyPi), you can create a script to print a symbol table. Symbol tables can be nested, so if a module contains a function or class, that will have a symbol table.

Create a script called `symviz.py` with a recursive `show()` function:

cpython-book-samples ▸ 30 ▸ symviz.py

```
import tabulate
import symtable

code = """
def calc_pow(a, b):
    return a ** b
a = 1
b = 2
c = calc_pow(a,b)
"""

_st = symtable.symtable(code, "example.py", "exec")


def show(table):
    print("Symtable {0} ({1})".format(table.get_name(),
                                      table.get_type()))
    print(
        tabulate.tabulate(
            [
                (
                    symbol.get_name(),
                    symbol.is_global(),
                    symbol.is_local(),
                    symbol.get_namespaces(),
                )
                for symbol in table.get_symbols()
            ],
            headers=["name", "global", "local", "namespaces"],
            tablefmt="grid",
        )
    )
    if table.has_children():
        [show(child) for child in table.get_children()]


show(_st)
```

Run `symviz.py` at the command-line to see the symbol tables for the example code:

```
(venv) ➜  instaviz git:(master) ✗ python symviz.py
Symtable top (module)
+----------+----------+---------+------------------------------------------------------+
| name     | global   | local   | namespaces                                           |
+==========+==========+=========+======================================================+
| calc_pow | False    | True    | [<Function SymbolTable for calc_pow in example.py>] |
+----------+----------+---------+------------------------------------------------------+
| a        | False    | True    | ()                                                   |
+----------+----------+---------+------------------------------------------------------+
| b        | False    | True    | ()                                                   |
+----------+----------+---------+------------------------------------------------------+
| c        | False    | True    | ()                                                   |
+----------+----------+---------+------------------------------------------------------+
Symtable calc_pow (function)
+--------+----------+---------+--------------+
| name   | global   | local   | namespaces   |
+========+==========+=========+==============+
| a      | False    | True    | ()           |
+--------+----------+---------+--------------+
| b      | False    | True    | ()           |
+--------+----------+---------+--------------+
```

Symbol Table Implementation

The implementation of symbol tables is in `Python` ▸ `symtable.c` and the primary interface is the `PySymtable_BuildObject()` function.

Similar to AST compilation covered in the last chapter, the `PySymtable_BuildObject()` function switches between the `mod_ty` possible types (Module, Expression, Interactive, Suite, FunctionType), and visits each of the statements inside them.

The Symbol Table will recursively explore the nodes and branches of the AST (of type `mod_ty`) and add entries to the symtable:

`Python` ▸ `symtable.c` line 261

```
struct symtable *
PySymtable_BuildObject(mod_ty mod, PyObject *filename,
                       PyFutureFeatures *future)
{
    struct symtable *st = symtable_new();
```

```
    asdl_seq *seq;
    int i;
    PyThreadState *tstate;
    int recursion_limit = Py_GetRecursionLimit();
...
    st->st_top = st->st_cur;
    switch (mod->kind) {
    case Module_kind:
        seq = mod->v.Module.body;
        for (i = 0; i < asdl_seq_LEN(seq); i++)
            if (!symtable_visit_stmt(st,
                        (stmt_ty)asdl_seq_GET(seq, i)))
                goto error;
        break;
    case Expression_kind:
        ...
    case Interactive_kind:
        ...
    case Suite_kind:
        ...
    case FunctionType_kind:
        ...
    }
    ...
}
```

For a module, `PySymtable_BuildObject()` will loop through each statement in the module and call `symtable_visit_stmt()`. The `symtable_visit_stmt()` is a huge `switch` statement with a case for each statement type (defined in `Parser ▸ Python.asdl`).

For each statement type, there is specific logic to that statement type. For example, a function definition (`FunctionDef_kind`) has particular logic for:

1. The current recursion depth against the recursion limit. If it has been exceeded a `RecursionError` is thrown.
2. The name of the function is added to the symbol table as a local

variable. In Python, functions are objects, so they can be passed as parameters or references.

3. Any non-literal default arguments to a function (non-keyword) are resolved from the symbol table.
4. Any non-literal default arguments to a function (keyword) are resolved from the symbol table.
5. Any type annotations for the arguments or the return type are resolved from the symbol table.
6. Any function decorators are resolved in sequence of definition.
7. The code block with the contents of the function is visited by `symtable_enter_block()`.
8. The arguments are visited and resolved.
9. The body of the function is visited and resolved.

Important

If you've ever wondered why Python's default arguments are mutable, the reason is in `symtable_visit_stmt()`. Argument defaults are a reference to the variable in the symtable. No extra work is done to copy any values to an immutable type.

As a preview, the C code for those steps in building a symtable for a function in `symtable_visit_stmt()`:

`Python` ▸ `symtable.c` line 1171

```
static int
symtable_visit_stmt(struct symtable *st, stmt_ty s)
{
    if (++st->recursion_depth > st->recursion_limit) {
        PyErr_SetString(PyExc_RecursionError,
           "maximum recursion depth exceeded during compilation");
        VISIT_QUIT(st, 0);
    }
```

```c
    switch (s->kind) {
    case FunctionDef_kind:
        if (!symtable_add_def(st, s->v.FunctionDef.name, DEF_LOCAL))
            VISIT_QUIT(st, 0);
        if (s->v.FunctionDef.args->defaults)
            VISIT_SEQ(st, expr, s->v.FunctionDef.args->defaults);
        if (s->v.FunctionDef.args->kw_defaults)
            VISIT_SEQ_WITH_NULL(st, expr,
             s->v.FunctionDef.args->kw_defaults);
        if (!symtable_visit_annotations(st, s, s->v.FunctionDef.args,
                                        s->v.FunctionDef.returns))
            VISIT_QUIT(st, 0);
        if (s->v.FunctionDef.decorator_list)
            VISIT_SEQ(st, expr, s->v.FunctionDef.decorator_list);
        if (!symtable_enter_block(st, s->v.FunctionDef.name,
                                  FunctionBlock, (void *)s, s->lineno,
                                  s->col_offset))
            VISIT_QUIT(st, 0);
        VISIT(st, arguments, s->v.FunctionDef.args);
        VISIT_SEQ(st, stmt, s->v.FunctionDef.body);
        if (!symtable_exit_block(st, s))
            VISIT_QUIT(st, 0);
        break;
    case ClassDef_kind: {
        ...
    }
    case Return_kind:
        ...
    case Delete_kind:
        ...
    case Assign_kind:
        ...
    case AnnAssign_kind:
        ...
```

Once the resulting symbol table has been created, it is passed on to the compiler.

Core Compilation Process

Now that the `PyAST_CompileObject()` has a compiler state, a symtable, and a module in the form of the AST, the actual compilation can begin.

The purpose of the core compiler is to:

1. Convert the state, symtable, and AST into a Control-Flow-Graph (CFG)
2. Protect the execution stage from runtime exceptions by catching any logic and code errors

Accessing the Compiler From Python

You can call the compiler in Python by calling the built-in function `compile()`. It returns a `code object`:

```
>>> co = compile('b+1', 'test.py', mode='eval')
<code object <module> at 0x10f222780, file "test.py", line 1>
```

The same as with the `symtable()` API, a simple expression should have a mode of `'eval'`, and a module, function, or class should have a mode of `'exec'`.

The compiled code can be found in the `co_code` property of the code object:

```
>>> co.co_code
b'e\x00d\x00\x17\x00S\x00'
```

There is also a `dis` module in the standard library, which disassembles the bytecode instructions. You can print them on the screen, or get a list of `Instruction` instances.

> **Note**
>
> The `Instruction` type in the `dis` module is a reflection of the `instr` type in the C API.

If you import `dis` and give the `dis()` function the code object's `co_code` property it disassembles it and prints the instructions on the REPL:

```
>>> import dis
>>> dis.dis(co.co_code)
          0 LOAD_NAME                0 (0)
          2 LOAD_CONST               0 (0)
          4 BINARY_ADD
          6 RETURN_VALUE
```

`LOAD_NAME`, `LOAD_CONST`, `BINARY_ADD`, and `RETURN_VALUE` are all bytecode instructions. They're called bytecode because, in binary form, they were a byte long. However, since Python 3.6 the storage format was changed to a `word`, so now they're technically wordcode, not bytecode.

The full list of bytecode instructions is available for each version of Python, and it does change between versions. For example, in Python 3.7, some new bytecode instructions were introduced to speed up execution of specific method calls.

In earlier chapters, you explored the `instaviz` package. This included a visualization of the code object type by running the compiler. It also displays the bytecode operations inside the code objects.

Execute instaviz again to see the code object and bytecode for a function defined on the REPL:

```
>>> import instaviz
>>> def example():
       a = 1
       b = a + 1
       return b
>>> instaviz.show(example)
```

Compiler C API

The entry point for AST module compilation, `compiler_mod()`, switches to different compiler functions depending on the module type. If you assume that `mod` is a `Module`, the module is compiled into the `c_stack` property as compiler units. Then `assemble()` is run to create a `PyCodeObject` from the compiler unit stack.

The new code object is returned back and sent on for execution by the interpreter, or cached and stored on disk as a `.pyc` file:

Python ▸ `compile.c` line 1820

```
static PyCodeObject *
compiler_mod(struct compiler *c, mod_ty mod)
{
    PyCodeObject *co;
    int addNone = 1;
    static PyObject *module;
    ...
    switch (mod->kind) {
    case Module_kind:
        if (!compiler_body(c, mod->v.Module.body)) {
            compiler_exit_scope(c);
            return 0;
        }
        break;
    case Interactive_kind:
        ...
    case Expression_kind:
        ...
    case Suite_kind:
        ...
    ...
    co = assemble(c, addNone);
    compiler_exit_scope(c);
    return co;
}
```

The `compiler_body()` function loops over each statement in the module and visits it:

Python ▸ `compile.c` line 1782

```
static int
compiler_body(struct compiler *c, asdl_seq *stmts)
{
    int i = 0;
    stmt_ty st;
    PyObject *docstring;
    ...
    for (; i < asdl_seq_LEN(stmts); i++)
        VISIT(c, stmt, (stmt_ty)asdl_seq_GET(stmts, i));
    return 1;
}
```

The statement type is determined through a call to the `asdl_seq_GET()` function, which looks at the AST node type.

Through a macro, `VISIT` calls a function in `Python` ▸ `compile.c` for each statement type:

```
#define VISIT(C, TYPE, V) {\
    if (!compiler_visit_ ## TYPE((C), (V))) \
        return 0; \
}
```

For a `stmt` (the generic type for a statement) the compiler will then call `compiler_visit_stmt()` and switch through all of the potential statement types found in `Parser` ▸ `Python.asdl`:

`Python` ▸ `compile.c` line 3375

```
static int
compiler_visit_stmt(struct compiler *c, stmt_ty s)
{
    Py_ssize_t i, n;

    /* Always assign a lineno to the next instruction for a stmt. */
    c->u->u_lineno = s->lineno;
    c->u->u_col_offset = s->col_offset;
    c->u->u_lineno_set = 0;

```

```
    switch (s->kind) {
    case FunctionDef_kind:
        return compiler_function(c, s, 0);
    case ClassDef_kind:
        return compiler_class(c, s);
    ...
    case For_kind:
        return compiler_for(c, s);
    ...
    }

    return 1;
}
```

As an example, the `For` statement in Python is:

```
for i in iterable:
    # block
else:  # optional if iterable is False
    # block
```

Or shown as a railroad diagram:

If the statement is a `For` type, `compiler_visit_stmt()` calls `compiler_for()`. There is an equivalent `compiler_*()` function for all of the statement and expression types. The more straightforward types create the bytecode instructions inline, some of the more complex statement types call other functions.

Instructions

Many of the statements can have sub-statements. A `for` loop has a body, but you can also have complex expressions in the assignment and the iterator.

The compiler emits **blocks** to the compiler state. These blocks contain a sequence of instructions. The instruction data structure has an opcode, arguments, the target block (if this is a jump instruction), and the line number of the statement.

Instruction Type

The instruction type, `instr`, is defined as:

Field	Type	Purpose
`i_jabs`	`unsigned`	Flag to specify this is a absolute jump instruction
`i_jrel`	`unsigned`	Flag to specify this is a relative jump instruction
`i_opcode`	`unsigned char`	Opcode number this instruction represents (see `Include`▸`Opcode.h`)
`i_oparg`	`int`	Opcode argument
`i_target`	`basicblock*`	Pointer to the `basicblock` target when `i_jrel` is true
`i_lineno`	`int`	Line number this instruction was created for

Jump Instructions

Jump instructions can either be absolute or relative. Jump instructions are used to "jump" from one instruction to another. Absolute jump instructions specify the exact instruction number in the compiled code object, whereas relative jump instructions specify the jump target relative to another instruction.

Basic Frame Blocks

A basic frame block (of type `basicblock`), contains the following fields:

Field	Type	Purpose
`b_list`	`basicblock *`	Each `basicblock` in a compilation unit is linked via `b_list` in the reverse order that the block are allocated
`b_iused`	`int`	Number of instructions used (`b_instr`)
`b_ialloc`	`int`	Length of instruction array (`b_instr`)
`b_instr`	`instr *`	Pointer to an array of instructions, initially `NULL`

Field	Type	Purpose
b_next	basicblock*	If b_next is non-NULL, it is a pointer to the next block reached by normal control flow
b_seen	unsigned	Used to perform a DFS of basicblocks. See assembly
b_return	unsigned	Is true if block returns a value (a RETURN_VALUE opcode is inserted)
b_-startdepth	int	Depth of stack upon entry of block, computed by stackdepth()
b_offset	int	Instruction offset for block, computed by assemble_jump_offsets()

Operations and Arguments

Depending on the type of operation, there are different arguments required. For example, ADDOP_JABS and ADDOP_JREL refer to "**ADD** **O**peration with **J**ump to a **REL**ative position" and "**ADD** **O**peration with **J**ump to an **ABS**olute position". The ADDOP_JREL and ADDOP_JABS macros which call `compiler_addop_j(struct compiler *c, int opcode, basicblock *b, int absolute)` and set the `absolute` argument to 0 and 1 respectively.

There are some other macros, like ADDOP_I calls `compiler_addop_i()` which add an operation with an integer argument, or ADDOP_O calls `compiler_addop_o()` which adds an operation with a PyObject argument.

Assembly

Once these compilation stages have completed, the compiler has a list of frame blocks, each containing a list of instructions and a pointer to the next block. The assembler performs a "depth-first-search" of the basic frame blocks and merges the instructions into a single bytecode sequence.

Assembler Data Structure

The assembler state struct, `assembler`, is declared in `Python ▸ compile.c`.

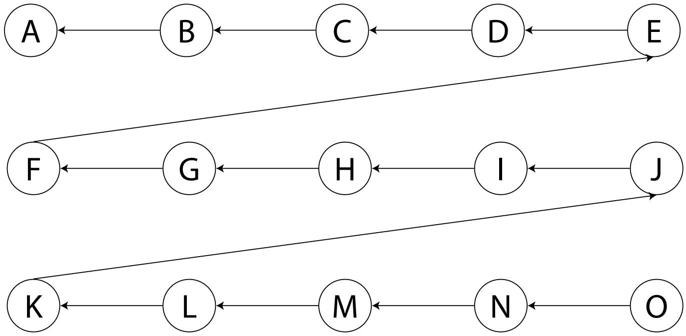
Field	Type	Purpose
a_bytecode	PyObject * (str)	String containing bytecode
a_offset	int	Offset into bytecode
a_nblocks	int	Number of reachable blocks
a_postorder	basicblock **	List of blocks in dfs postorder
a_lnotab	PyObject * (str)	String containing lnotab
a_lnotab_-off	int	Offset into lnotab
a_lineno	int	Last lineno of emitted instruction
a_lineno_-off	int	Bytecode offset of last lineno

Assembler Depth-First-Search Algorithm

The assembler uses a Depth-First-Search to traverse the nodes in the basic frame block graph. The DFS algorithm is not specific to CPython, but is a commonly used algorithm in graph traversal.

The CST and AST were both tree structures, whereas the compiler state is a graph structure, where the nodes are basic frame blocks containing instructions.

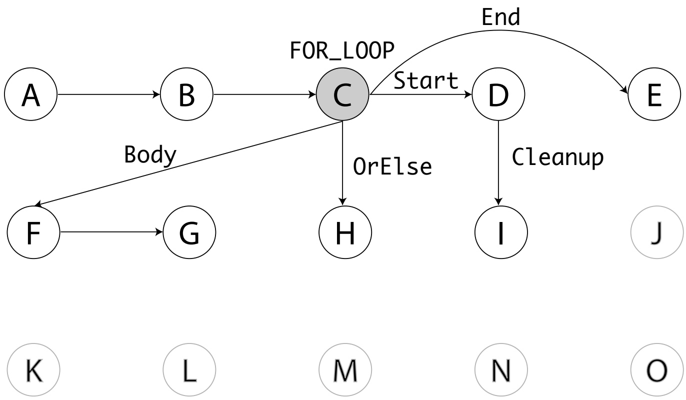
The basic frame blocks are linked by two graphs, one is in reverse order of creation (the `b_list` property of each block). A series of basic frame blocks arbitrarily named A-P would look like this:



The graph created from the `b_list` is used to sequentially visit every block in a compiler unit

The second graph uses the `b_next` property of each block. This list represents the control flow. Vertices in this graph are created by calls to `compiler_use_next_block(c, next)`, where `next` is the next block to draw a vertex to from the current block (`c->u->u_curblock`).

The `For` loop node graph might look something like this:



Both the sequential and control-flow graphs are used, but the control-flow graph is the one used by the DFS implementation.

Assembler C API

The assembler API has an entry point `assemble()`. The `assemble()` function has a few responsibilities:

- Calculate the number of blocks for memory allocation
- Ensure that every block that falls off the end returns `None` (This is why every function returns `None`, whether or not a `return` statement exists)
- Resolve any jump statements offsets that were marked as relative
- Call `dfs()` to perform a depth-first-search of the blocks
- Emit all the instructions to the compiler
- Call `makecode()` with the compiler state to generate the `PyCodeObject`

`Python` ▸ `compile.c` line 6010

```
static PyCodeObject *
assemble(struct compiler *c, int addNone)
{
    ...
    if (!c->u->u_curblock->b_return) {
        NEXT_BLOCK(c);
        if (addNone)
            ADDOP_LOAD_CONST(c, Py_None);
        ADDOP(c, RETURN_VALUE);
    }
    ...
    dfs(c, entryblock, &a, nblocks);

    /* Can't modify the bytecode after computing jump offsets. */
    assemble_jump_offsets(&a, c);

    /* Emit code in reverse postorder from dfs. */
```

```
    for (i = a.a_nblocks - 1; i >= 0; i--) {
        b = a.a_postorder[i];
        for (j = 0; j < b->b_iused; j++)
            if (!assemble_emit(&a, &b->b_instr[j]))
                goto error;
    }
    ...

    co = makecode(c, &a);
 error:
    assemble_free(&a);
    return co;
}
```

Depth-First-Search

The depth-first-search is performed by the `dfs()` function in `Python` ▸ `compile.c`, which follows the the `b_next` pointers in each of the blocks, marks them as seen by toggling `b_seen` and then adds them to the assemblers' `a_postorder` list in reverse order.

The function loops back over the assembler's post-order list and for each block, if it has a jump operation, recursively call `dfs()` for that jump:

`Python` ▸ `compile.c` line 5441

```
static void
dfs(struct compiler *c, basicblock *b, struct assembler *a, int end)
{
    int i, j;

    /* Get rid of recursion for normal control flow.
       Since the number of blocks is limited, unused space in a_postorder
       (from a_nblocks to end) can be used as a stack for still not ordered
       blocks. */
    for (j = end; b && !b->b_seen; b = b->b_next) {
        b->b_seen = 1;
```

```
        assert(a->a_nblocks < j);
        a->a_postorder[--j] = b;
    }
    while (j < end) {
        b = a->a_postorder[j++];
        for (i = 0; i < b->b_iused; i++) {
            struct instr *instr = &b->b_instr[i];
            if (instr->i_jrel || instr->i_jabs)
                dfs(c, instr->i_target, a, j);
        }
        assert(a->a_nblocks < j);
        a->a_postorder[a->a_nblocks++] = b;
    }
}
```

Once the assembler has assembled the graph into a CFG using DFS, the code object can be created.

Creating a Code Object

The task of `makecode()` is to go through the compiler state, some of the assembler's properties, and to put these into a `PyCodeObject` by calling `PyCode_New()`.

The variable names, constants are put as properties to the code object:

`Python` ▸ `compile.c` line 5893

```
static PyCodeObject *
makecode(struct compiler *c, struct assembler *a)
{
...

    consts = consts_dict_keys_inorder(c->u->u_consts);
    names = dict_keys_inorder(c->u->u_names, 0);
    varnames = dict_keys_inorder(c->u->u_varnames, 0);
...
    cellvars = dict_keys_inorder(c->u->u_cellvars, 0);
```

```
...
    freevars = dict_keys_inorder(c->u->u_freevars,
                                 PyTuple_GET_SIZE(cellvars));
...
    flags = compute_code_flags(c);
    if (flags < 0)
        goto error;

    bytecode = PyCode_Optimize(a->a_bytecode, consts,
                               names, a->a_lnotab);
...
    co = PyCode_NewWithPosOnlyArgs(
        posonlyargcount+posorkeywordargcount,
        posonlyargcount, kwonlyargcount, nlocals_int,
        maxdepth, flags, bytecode, consts, names,
        varnames, freevars, cellvars, c->c_filename,
        c->u->u_name, c->u->u_firstlineno, a->a_lnotab);
...
    return co;
}
```

You may also notice that the bytecode is sent to `PyCode_Optimize()` before it is sent to `PyCode_NewWithPosOnlyArgs()`. This function is part of the bytecode optimization process in `Python▸peephole.c`.

The peephole optimizer goes through the bytecode instructions and in certain scenarios, replace them with other instructions. For example, there is an optimizer that removes any unreachable instructions that follow a `return` statement.

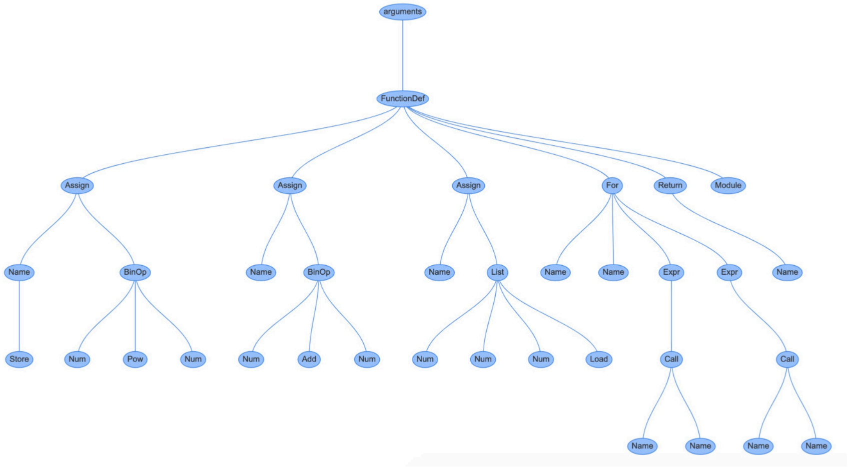
Using Instaviz to Show a Code Object

You can pull together all of the compiler stages with the instaviz module:

```
import instaviz


def foo():
```

```
    a = 2**4
    b = 1 + 5
    c = [1, 4, 6]
    for i in c:
        print(i)
    else:
        print(a)
    return c


instaviz.show(foo)
```

Will produce a large and complex AST graph:



You can see the bytecode instructions in sequence:

Disassembled Code

OpCode	Operation Name	Numeric Arg	Resolved Arg Value	Argument description	Index Offset	Starts Line	Is Jump Target?
100	LOAD_CONST	1	16	16	0	5	False
125	STORE_FAST	0	a	a	2	None	False
100	LOAD_CONST	2	6	6	4	6	False
125	STORE_FAST	1	b	b	6	None	False
100	LOAD_CONST	3	1	1	8	7	False
100	LOAD_CONST	4	4	4	10	None	False
100	LOAD_CONST	2	6	6	12	None	False
103	BUILD_LIST	3	3		14	None	False
125	STORE_FAST	2	c	c	16	None	False
120	SETUP_LOOP	28	48	to 48	18	8	False
124	LOAD_FAST	2	c	c	20	None	False
68	GET_ITER	None	None		22	None	False
93	FOR_ITER	12	38	to 38	24	None	True
125	STORE_FAST	3	i	i	26	None	False
116	LOAD_GLOBAL	0	print	print	28	9	False
124	LOAD_FAST	3	i	i	30	None	False
131	CALL_FUNCTION	1	1		32	None	False
1	POP_TOP	None	None		34	None	False
113	JUMP_ABSOLUTE	24	24		36	None	False
87	POP_BLOCK	None	None		38	None	True
116	LOAD_GLOBAL	0	print	print	40	11	False
124	LOAD_FAST	0	a	a	42	None	False
131	CALL_FUNCTION	1	1		44	None	False
1	POP_TOP	None	None		46	None	False
124	LOAD_FAST	2	c	c	48	12	True
83	RETURN_VALUE	None	None		50	None	False

The code object with the variable names, constants, and binary `co_code`:

Code Object Properties

Field	Value
co_argcount	0
co_cellvars	()
co_code	64017d0064027d0164036404640267037d02781c7c0244005d0c7d0374007c038301010071185700740074007c00830101007c025300
co_consts	(None, 16, 6, 1, 4)
co_filename	test.py
co_firstlineno	4
co_freevars	()
co_kwonlyargcount	0
co_lnotab	b'\x00\x01\x04\x01\x04\x01\n\x01\n\x01\x0c\x02\x08\x01'
co_name	foo
co_names	('print',)
co_nlocals	4
co_stacksize	3
co_varnames	('a', 'b', 'c', 'i')

Try it out with some other, more complex code that you have to learn more about CPython's compiler and code objects.

Example: Implementing the "Almost-Equal" Operator

After covering the compiler, bytecode instructions and the assembler, you can now modify CPython to support the "almost-equal" operator you compiled into the grammar in the last chapter.

First you have to add an internal `#define` for the `Py_AlE` operator, so it can be referenced inside the rich comparison functions for PyObject.

Open `Include ▸ object.h`, and locate the following `#define` statements:

```
/* Rich comparison opcodes */
#define Py_LT 0
#define Py_LE 1
#define Py_EQ 2
#define Py_NE 3
#define Py_GT 4
#define Py_GE 5
```

Add an additional value, `PyAlE` with a value of 6:

```
/* New Almost Equal comparator */
#define Py_AlE 6
```

Just underneath this expression is a macro `Py_RETURN_RICHCOMPARE`. Update this macro with a case statement for `Py_AlE`:

```
/*
 * Macro for implementing rich comparisons
 *
 * Needs to be a macro because any C-comparable type can be used.
 */
#define Py_RETURN_RICHCOMPARE(val1, val2, op)
    do {
        switch (op) {
        case Py_EQ: if ((val1) == (val2)) Py_RETURN_TRUE; Py_RETURN_FALSE;
        case Py_NE: if ((val1) != (val2)) Py_RETURN_TRUE; Py_RETURN_FALSE;
```

```
        case Py_LT: if ((val1) < (val2)) Py_RETURN_TRUE; Py_RETURN_FALSE;
        case Py_GT: if ((val1) > (val2)) Py_RETURN_TRUE; Py_RETURN_FALSE;
        case Py_LE: if ((val1) <= (val2)) Py_RETURN_TRUE; Py_RETURN_FALSE;
        case Py_GE: if ((val1) >= (val2)) Py_RETURN_TRUE; Py_RETURN_FALSE;
/* + */ case Py_AlE: if ((val1) == (val2)) Py_RETURN_TRUE; Py_RETURN_FALSE;
        default:
            Py_UNREACHABLE();
        }
    } while (0)
```

Inside `Objects▸object.c` there is a guard to check that the operator is within the range 0-5, because you added the value 6 you have to update that assertion:

`Objects▸object.c` line 709

```
PyObject *
PyObject_RichCompare(PyObject *v, PyObject *w, int op)
{
    PyThreadState *tstate = _PyThreadState_GET();

    assert(Py_LT <= op && op <= Py_GE);
```

Change that last line to:

```
assert(Py_LT <= op && op <= Py_AlE);
```

Next, you need to update the `COMPARE_OP` opcode to support `Py_AlE` as a value for the operator type.

First, edit `Objects▸object.c` and add `Py_AlE` into the `_Py_SwappedOp` list. This list is used for matching whether a custom class has one operator dunder method, but not the other.

For example, if you defined a class, `Coordinate`, you could define an equality operator by implementing the `__eq__` magic-method:

```
class Coordinate:
    def __init__(self, x, y):
```

```python
        self.x = x
        self.y = y

    def __eq__(self, other):
        if isinstance(other, Coordinate):
            return (self.x == other.x and self.y == other.y)
        return super(self, other).__eq__(other)
```

Even though you haven't implemented `__ne__` (not equal) for `Coordinate`, CPython assumes that the opposite of `__eq__` can be used.

```python
>>> Coordinate(1, 100) != Coordinate(2, 400)
True
```

Inside `Objects▸object.c`, locate the `_Py_SwappedOp` list and add `Py_AlE` to the end. Then add `"~="` to the end of the `opstrings` list:

```c
int _Py_SwappedOp[] = {Py_GT, Py_GE, Py_EQ, Py_NE, Py_LT, Py_LE, Py_AlE};

static const char * const opstrings[]
 = {"<", "<=", "==", "!=", ">", ">=", "~="};
```

Open `Lib/opcode.py` and edit the list of rich comparison operators:

```python
cmp_op = ('<', '<=', '==', '!=', '>', '>=')
```

Include the new operator at the end of the tuple:

```python
cmp_op = ('<', '<=', '==', '!=', '>', '>=', '~=')
```

The `opstrings` list is used for error messages, if rich comparison operators are not implemented on a class.

Next, you can update the compiler to handle the case of a `PyCmp_AlE` property in a `BinOp` node.

Open `Python▸compile.c` and find the `compiler_addcompare()` function:

`Python▸compile.c` line 2479

```
static int compiler_addcompare(struct compiler *c, cmpop_ty op)
{
    int cmp;
    switch (op) {
    case Eq:
        cmp = Py_EQ;
        break;
    case NotEq:
        cmp = Py_NE;
        break;
    case Lt:
        cmp = Py_LT;
        break;
    case LtE:
        cmp = Py_LE;
        break;
    case Gt:
        cmp = Py_GT;
        break;
    case GtE:
        cmp = Py_GE;
        break;
```

Next, add another `case` to this switch statement to pair the `AlE` AST `comp_op` enumeration with the `PyCmp_AlE` opcode comparison enumeration:

```
    case AlE:
        cmp = Py_AlE;
        break;
```

Next, recompile CPython and open up a REPL. You should see the almost-equal operator behave in the same way as the `==` operator:

```
 $ ./python
>>> 1 ~= 2
False
>>> 1 ~= 1
True
```

```
>>> 1 ~= 1.01
False
```

You can now program the behaviour of almost-equal to match the following scenario:

- `1 ~= 2` is `False`
- `1 ~= 1.01` is `True`, using floor-rounding

We can achieve this with some additional code. For now, you will cast both floats into integers and compare them.

CPython's API has many functions for dealing with PyLong (`int`) and `PyFloat` (`float`) types. This will be covered in the chapter on Objects and Types.

Locate the `float_richcompare()` in `Objects▸floatobject.c`, and under the `Compare:` goto definition add the following case:

`Objects▸floatobject.c` line 358

```
static PyObject*
float_richcompare(PyObject *v, PyObject *w, int op)
{
 ...
    case Py_GT:
        r = i > j;
        break;
    /* New Code START */
    case Py_AlE: {
        double diff = fabs(i - j);
        double rel_tol = 1e-9; // relative tolerance
        double abs_tol = 0.1;  // absolute tolerance
        r = (((diff <= fabs(rel_tol * j)) ||
                 (diff <= fabs(rel_tol * i))) ||
                (diff <= abs_tol));
        }
        break;
    }
```

```
    /* New Code END */
    return PyBool_FromLong(r);
```

This code will handle comparison of floating point numbers where the almost-equal operator has been used. It uses similar logic to `math.isclose()`, defined in PEP485, but with a hardcoded absolute tolerance of `0.1`.

Another safeguard that you need to change is in the evaluation loop, `Python` ▸ `ceval.c`. You will cover the evaluation loop in the next chapter. Search for the code snippet:

```
        case TARGET(COMPARE_OP): {
            assert(oparg <= Py_GE);
```

Change the assertion to:

```
assert(oparg <= Py_AlE);
```

After recompiling CPython again, open a REPL and test it out:

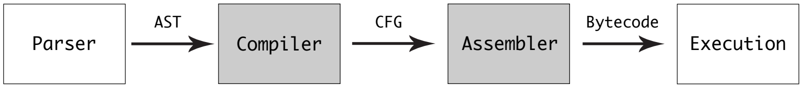
```
 $ ./python
>>> 1.0 ~= 1.01
True
>>> 1.02 ~= 1.01
True
>>> 1.02 ~= 2.01
False
>>> 1 ~= 1.01
True
>>> 1 ~= 1
True
>>> 1 ~= 2
False
>>> 1 ~= 1.9
False
>>> 1 ~= 2.0
False
>>> 1.1 ~= 1.101
```

```
True
```

In later chapters you will extend this implementation across other types.

Conclusion

In this chapter, you've explored how a parsed Python module is converted into a symbol table, a compilation state, and then a series of bytecode operations.



It is now the job of the CPython interpreter's core evaluation loop to execute those modules.

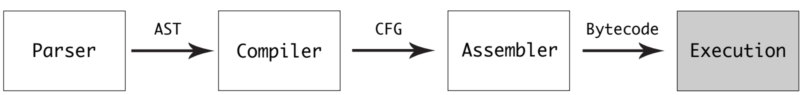
In the next chapter, you will explore how code objects are executed.

Leave feedback on this section »

The Evaluation Loop

So far, you have seen how Python code is parsed into an Abstract Syntax Tree and compiled into code objects. These code objects contain lists of discrete operations in the form of bytecode. There is one major thing missing for these code objects to be executed and come to life. They need input. In the case of Python, these inputs take the form of local and global variables. In this chapter, you will be introduced to a concept called a Value Stack, where variables are created, modified, and used by the bytecode operations in your compiled code objects.

Execution of code in CPython happens within a central loop, called the "evaluation loop." The CPython interpreter will evaluate and execute a code object, either fetched from the marshaled `.pyc` file, or the compiler:



In the evaluation loop, each of the bytecode instructions is taken and executed using a "Stack Frame" based system.

Note

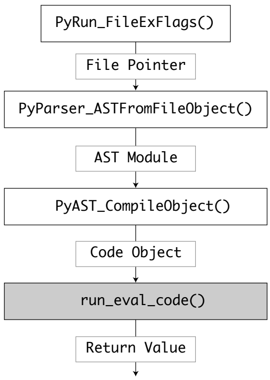
Stack Frames

Stack Frames are a data type used by many runtimes, not just Python. Stack Frames allow functions to be called and variables to be returned between functions. Stack Frames also contain arguments, local variables, and other stateful information.

A Stack Frame exists for every function call, and they are stacked in sequence. You can see CPython's frame stack anytime an exception is unhandled:

```
Traceback (most recent call last):
  File "example_stack.py", line 8, in <module>  <--- Frame
    function1()
  File "example_stack.py", line 5, in function1 <--- Frame
    function2()
  File "example_stack.py", line 2, in function2 <--- Frame
    raise RuntimeError
RuntimeError
```

When exploring the CPython compiler, you broke out just before the call to `run_eval_code_obj()`. In this next chapter, you will explore the interpreter API:



Related Source Files

The source files relating to the evaluation loop are:

File	Purpose
`Python ▸ ceval.c`	The core evaluation loop implementation
`Python ▸ ceval-gil.h`	The GIL definition and control algorithm

Important Terms

- The evaluation loop will take a **code object** and convert it into a series of **frame objects**
- The interpreter has at least one **thread**
- Each thread has a **thread state**
- Frame Objects are executed in a stack, called the **frame stack**
- Variables are referenced in a **value stack**

Constructing Thread State

Before a frame can be executed, it needs to be linked to a thread. CPython can have many threads running at any one time within a single interpreter. The **interpreter state** includes a linked-list of those threads.

CPython always has at least one thread and each thread has it's own state.

> **See Also**
>
> Threading is covered in more detail within the "Parallelism and Concurrency" chapter.

Thread State Type

The thread state type, `PyThreadState` has over 30 properties, including:

- A unique identifier
- A linked-list to the other thread states
- The interpreter state it was spawned by
- The currently executing frame
- The current recursion depth
- Optional tracing functions
- The exception currently being handled
- Any async exception currently being handled
- A stack of exceptions raised, when multiple exceptions have been raised (e.g. raise within an `except` block)
- A GIL counter
- Async generator counters

Related Source Files

The source files relating to the thread state are spread across many files:

File	Purpose
Python ▸ thread.c	The thread API implementation
Include ▸ threadstate.h	Some of the thread state API and types definition
Include ▸ pystate.h	The interpreter state API and types definition
Include ▸ pythread.h	The threading API
Include ▸ cpython ▸ pystate.h	Some of the thread and interpreter state API

Constructing Frame Objects

Compiled code objects are inserted into frame objects. Frame objects are a Python type, so they can be referenced from C, and from Python. Frame objects also contain other runtime data that is required for executing the instructions in the code objects. This data includes the local variables, global variables and builtin modules.

Frame Object Type

The frame object type is a `PyObject` with the following additional properties:

Field	Type	Purpose
`f_back`	`PyFrameObject *`	Pointer to the previous in the stack, or `NULL` if first frame
`f_code`	`PyCodeObject *`	Code Object to be executed
`f_builtins`	`PyObject *` (dict)	Symbol table for the `builtin` module
`f_globals`	`PyObject *` (dict)	global symbol table (PyDictObject
`f_locals`	`PyObject *`	Local symbol table (any mapping)
`f_valuestack`	`PyObject **`	Pointer to the last local
`f_stacktop`	`PyObject **`	Next free slot in `f_valuestack`
`f_trace`	`PyObject *`	Pointer to a custom tracing function. See section on frame tracing
`f_trace_lines`	`char`	Toggle for the custom tracing function to trace at line-level
`f_trace_opcodes`	`char`	Toggle for the custom tracing function to trace at an opcode level
`f_gen`	`PyObject *`	Borrowed reference to a generator, or `NULL`

Field	Type	Purpose
f_lasti	int	Last instruction, if called
f_lineno	int	Current line number
f_iblock	int	Index of this frame in f_blockstack
f_executing	char	Flag whether the frame is still executing
f_blockstack	PyTryBlock[]	Sequence of for, try, and loop blocks
f_localsplus	PyObject *[]	Union of locals + stack

Related Source Files

The source files relating to frame objects are:

File	Purpose
Objects ▸ frameobject.c	The frame object implementation and Python API
Include ▸ frameobject.h	The frame object API and type definition

Frame Object Initialization API

The API for Frame Object Initialization, `PyEval_EvalCode()` is the entry point for evaluating a code object

`PyEval_EvalCode()` is a wrapper around the internal function `_PyEval_EvalCode()`.

> **Note**
>
> `_PyEval_EvalCode()` is a complex function that defines many behaviours of both frame objects and the interpreter loop. It is an important function to understand as it can also teach you some principles of the CPython interpreter design.

In this section you will step through the logic in `_PyEval_EvalCode()`.

The `_PyEval_EvalCode()` function specifies many arguments:

- **tstate:** a `PyThreadState *` pointing to the thread state of the thread this code will be evaluated on

- **`_co`:** a `PyCodeObject*` containing the code to be put into the frame object
- **`globals`:** a `PyObject*` (`dict`) with variable names as keys and their values
- **`locals`:** a `PyObject*` (`dict`) with variable names as keys and their values

Note

In Python, local and global variables stored as a dictionary. You can access this dictionary with the builtin functions `locals()` and `globals()`:

```
>>> a = 1
>>> print(locals()['a'])
1
```

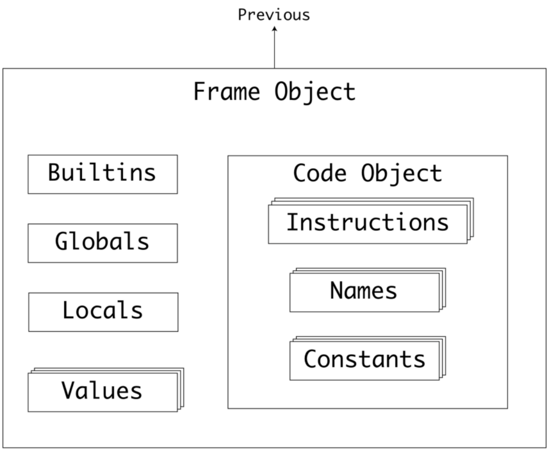
The other arguments are optional, and not used for the basic API:

- **`args`:** a `PyObject*` (`tuple`) with positional argument values in order, and `argcount` for the number of values
- **`kwnames`:** a list of keyword argument names
- **`kwargs`:** a list of keyword argument values, and `kwcount` for the number of them
- **`defs`:** a list of default values for positional arguments, and `defcount` for the length
- **`kwdefs`:** a dictionary with the default values for keyword arguments
- **`closure`:** a tuple with strings to merge into the code objects `co_freevars` field
- **`name`:** the name for this evaluation statement as a string
- **`qualname`:** the qualified name for this evaluation statement as a string

The call to `_PyFrame_New_NoTrack()` creates a new frame. This API is also available from the C API using `PyFrame_New()`. The `_PyFrame_New_-NoTrack()` function will create a new `PyFrameObject` by following these steps:

1. Set the frame `f_back` property to the thread state's last frame
2. Load the current builtin functions by setting the `f_builtins` property and loading the builtins module using `PyModule_GetDict()`
3. Set the `f_code` property to the code object being evaluated
4. Set the `f_valuestack` property to an empty value stack
5. Set the `f_stacktop` pointer to `f_valuestack`
6. Set the global property, `f_globals`, to the `globals` argument
7. Set the locals property, `f_locals`, to a new dictionary
8. Set the `f_lineno` to the code object's `co_firstlineno` property so that tracebacks contain line numbers
9. Set all the remaining properties to their default values

With the new `PyFrameObject` instance, the arguments to the frame object can be constructed:



Converting Keyword Parameters to a Dictionary

Function definitions can contain a `**kwargs` catch-all for keyword-arguments, for example:

```
def example(arg, arg2=None, **kwargs):
    print(kwargs['x'], kwargs['y'])  # this would resolve to a dictionary key
example(1, x=2, y=3)  # 2 3
```

In this scenario, a new dictionary is created, and the unresolved arguments are copied across. The `kwargs` name is then set as a variable in the local scope of the frame.

Converting Positional Arguments Into Variables

Each of the positional arguments (if provided) are set as local variables: In Python, function arguments are already local variables within the function body. When a positional argument is defined with a value, it is available within the function scope:

```
def example(arg1, arg2):
    print(arg1, arg2)
example(1, 2)  # 1 2
```

The reference counter for those variables is incremented, so the garbage collector won't remove them until the frame has evaluated (e.g. the function has finished and returned).

Packing Positional Arguments Into `*args`

Similar to `**kwargs`, a function argument prepended with a `*` can be set to catch all remaining positional arguments. This argument is a tuple and the `*args` name is set as a local variable:

```
def example(arg, *args):
    print(arg, args[0], args[1])

example(1, 2, 3)  # 1 2 3
```

Loading Keyword Arguments

If the function was called with keyword arguments and values, a dictionary is filled with any remaining keyword arguments passed by the caller that doesn't resolve to named arguments or positional arguments.

For example, the `e` argument was neither positional or named, so it is added to `**remaining`:

```
>>> def my_function(a, b, c=None, d=None, **remaining):
        print(a, b, c, d, remaining)

>>> my_function(a=1, b=2, c=3, d=4, e=5)
(1, 2, 3, 4, {'e': 5})
```

Note

Positional-only arguments are a new feature in Python 3.8. Introduced in PEP570, positional-only arguments are a way of stopping users of your API from using positional arguments with a keyword syntax.

For example, this simple function converts Fahrenheit to Celsius. Note, the use of `/` as a special argument separates positional-only arguments from the other arguments.

```
def to_celsius(fahrenheit, /, options=None):
    return (fahrenheit-32)*5/9
```

All arguments to the left of `/` must be called only as a positional argument, and arguments to the right can be called as either positional or keyword arguments:

```
>>> to_celsius(110)
```

Calling the function using a keyword argument to a positional-only argument will raise a `TypeError`:

```
>>> to_celsius(fahrenheit=110)
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
TypeError: to_celsius() got some positional-only arguments
 passed as keyword arguments: 'fahrenheit'
```

The resolution of the keyword argument dictionary values comes after the unpacking of all other arguments. The PEP570 positional-only arguments are shown by starting the keyword-argument loop at `co_posonlyargcount`. If the `/` symbol was used on the 3rd argument, the value of `co_posonlyargcount` would be `2`. `PyDict_SetItem()` is called for each remaining argument for adding it to the `locals` dictionary. When executing, each of the keyword arguments become scoped local variables.

If a keyword argument is defined with a value, that is available within this scope:

```python
def example(arg1, arg2, example_kwarg=None):
    print(example_kwarg)  # example_kwarg is already a local variable.
```

Adding Missing Positional Arguments

Any positional arguments provided to a function call that are not in the list of positional arguments are added to a `*args` tuple if this tuple does not exist, an exception is raised.

Adding Missing Keyword Arguments

Any keyword arguments provided to a function call that are not in the list of named keyword arguments are added to a `**kwargs` dictionary if this dictionary does not exist, an exception is raised.

Collapsing Closures

Any closure names are added to the code object's list of free variable names.

Creating Generators, Coroutines, and Asynchronous Generators

If the evaluated code object has a flag that it is a generator, coroutine, or async generator, then a new frame is created using one of the unique methods in the Generator, Coroutine, or Async libraries and the current frame is added as a property.

See Also

The APIs and implementation of generators, coroutines, and async frames are covered in the chapter on parallelism and concurrency

The new frame is then returned, and the original frame is not evaluated. The frame is only evaluated when the generator/coroutine/async method is called on to execute its target.

Lastly, `_PyEval_EvalFrame()` is called with the new frame.

Frame Execution

As covered earlier in the compiler and AST chapters, the code object contains a binary encoding of the bytecode to be executed. It also contains a list of variables and a symbol table.

The local and global variables are determined at runtime based on how that function, module, or block was called. This information is added to the frame by the `_PyEval_EvalCode()` function. There are other uses of frames, like the coroutine decorator, which dynamically generates a frame with the target as a variable.

The public API, `PyEval_EvalFrameEx()` calls the interpreter's configured frame evaluation function in the `eval_frame` property. Frame evaluation was made pluggable in Python 3.7 with PEP 523.

`_PyEval_EvalFrameDefault()` is the default function and the only option bundled with CPython.

Frames are executed in the main execution loop inside `_PyEval_EvalFrameDefault()`. This central function brings everything together and brings your code to life. It contains decades of optimization since even a single line of code can have a significant impact on performance for the whole of CPython.

Everything that gets executed in CPython goes through this function.

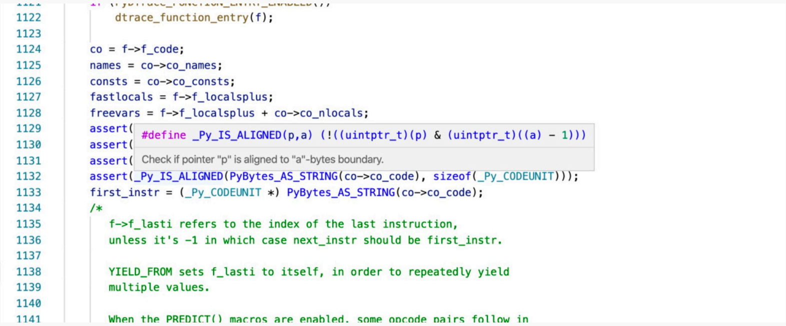
Note

Something you might notice when reading `Python` ▸ `ceval.c`, is how many times C macros have been used. C Macros are a way of having reusable code without the overhead of making function calls. The compiler converts the macros into C code and then compile the generated code.

If you want to see the expanded code, you can run `gcc -E` on Linux and macOS:

```
$ gcc -E Python/ceval.c
```

In Visual Studio Code, inline macro expansion shows once you have installed the official C/C++ extension:



In CLion, select a macro and press Alt + Space to peek into it's definition.

Frame Execution Tracing

You can step through frame execution in Python 3.7 and beyond by enabling the tracing attribute on the current thread. In the `PyFrameObject` type, there is a `f_trace` property, of type `PyObject *`. The value is expected to point to a Python function.

This code example sets the global tracing function to a function called `my_trace()` that gets the stack from the current frame, prints the disassembled opcodes to the screen, and some extra information for debugging:

cpython-book-samples ▸ 31 ▸ my_trace.py

```
import sys
import dis
import traceback
import io

def my_trace(frame, event, args):
    frame.f_trace_opcodes = True
    stack = traceback.extract_stack(frame)
    pad = "   "*len(stack) + "|"
    if event == 'opcode':
        with io.StringIO() as out:
            dis.disco(frame.f_code, frame.f_lasti, file=out)
            lines = out.getvalue().split('\n')
            [print(f"{pad}{l}") for l in lines]
    elif event == 'call':
        print(f"{pad}Calling {frame.f_code}")
    elif event == 'return':
        print(f"{pad}Returning {args}")
    elif event == 'line':
        print(f"{pad}Changing line to {frame.f_lineno}")
    else:
        print(f"{pad}{frame} ({event} - {args})")
    print(f"{pad}----------------------------------")
    return my_trace
sys.settrace(my_trace)

# Run some code for a demo
eval('"-".join([letter for letter in "hello"])')
```

The `sys.settrace()` function will set the current thread state default tracing function to the one provided. Any new frames created after this call will have `f_trace` set to this function.

This code snippet prints the code within each stack and points to the next operation before it is executed. When a frame returns a value, the return statement is printed:

```
➜  cpython git:(master) ✗ ./python.exe my_trace.py
    |Calling <code object <module> at 0x104cdc110, file "<string>", line 1>
    |-----------------------------------
    |Changing line to 1
    |-----------------------------------
    |  1 -->        0 LOAD_CONST               0 ('-')
             2 LOAD_METHOD              0 (join)
             4 LOAD_CONST               1 (<code object <listcomp> at 0x104cdcee0, file "<string>", line 1>)
             6 LOAD_CONST               2 ('<listcomp>')
             8 MAKE_FUNCTION            0
            10 LOAD_CONST               3 ('hello')
            12 GET_ITER
            14 CALL_FUNCTION            1
            16 CALL_METHOD              1
            18 RETURN_VALUE

    |-----------------------------------
    |  1            0 LOAD_CONST               0 ('-')
  -->        2 LOAD_METHOD              0 (join)
             4 LOAD_CONST               1 (<code object <listcomp> at 0x104cdcee0, file "<string>", line 1>)
             6 LOAD_CONST               2 ('<listcomp>')
             8 MAKE_FUNCTION            0
            10 LOAD_CONST               3 ('hello')
            12 GET_ITER
            14 CALL_FUNCTION            1
            16 CALL_METHOD              1
            18 RETURN_VALUE
```

The full list of possible bytecode instructions is available on the `dis` module documentation.

The Value Stack

Inside the core evaluation loop, a value stack is created. This stack is a list of pointers to `PyObject` instances. These could be values like variables, references to functions (which are objects in Python), or any other Python object.

Bytecode instructions in the evaluation loop will take input from the value stack.

Example Bytecode Operation, BINARY_OR

The binary operations that you have been exploring in previous chapters compile into a single instruction.

If you inserted an `or` statement in Python:

```python
if left or right:
    pass
```

The `or` operation would be compiled into a `BINARY_OR` instruction by the compiler:

```c
static int
binop(struct compiler *c, operator_ty op)
{
    switch (op) {
    case Add:
        return BINARY_ADD;
    ...
    case BitOr:
        return BINARY_OR;
```

In the evaluation loop, the case for a `BINARY_OR` will take two values from the value stack, the left, and right operation, then call `PyNumber_Or` against those 2 objects:

```c
    ...
    case TARGET(BINARY_OR): {
        PyObject *right = POP();
        PyObject *left = TOP();
        PyObject *res = PyNumber_Or(left, right);
        Py_DECREF(left);
        Py_DECREF(right);
        SET_TOP(res);
        if (res == NULL)
            goto error;
        DISPATCH();
    }
```

The result, `res`, is then set as the top of the stack, overriding the current top value.

Value Stack Simulations

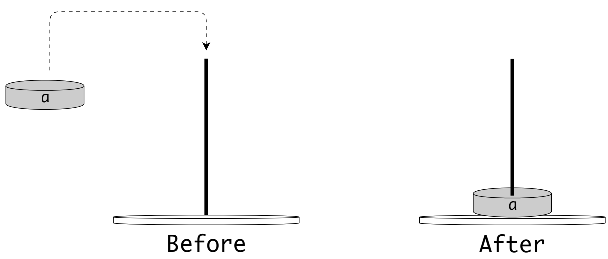
To understand the evaluation loop, you have to understand the value stack.

One way to think of the value stack is like a wooden peg on which you can stack cylinders. You would only add or remove one item at a time. This is done using the `PUSH(a)` macro, where `a` is a pointer to a `PyObject`.

For example, if you created a `PyLong` with the value 10 and pushed it onto the value stack:

```
PyObject *a = PyLong_FromLong(10);
PUSH(a);
```

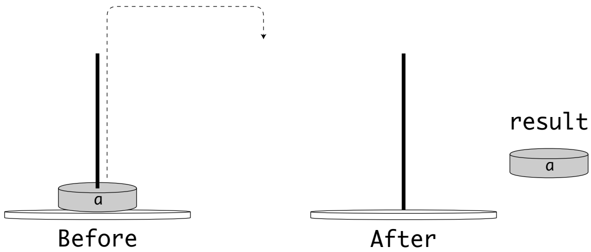
This action would have the following effect:



In the next operation, to fetch that value, you would use the `POP()` macro to take the top value from the stack:

```
PyObject *a = POP();  // a is PyLongObject with a value of 10
```

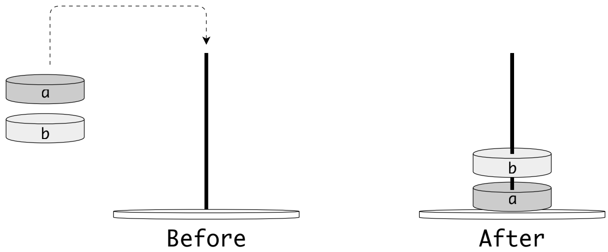
This action would return the top value and end up with an empty value stack:



If you were to add 2 values to the stack:

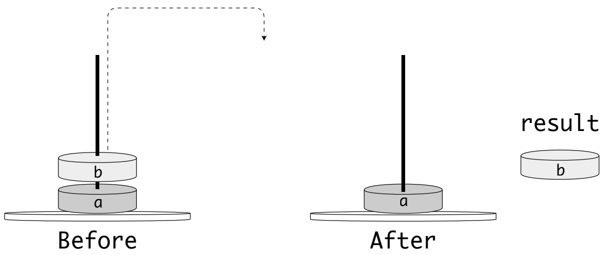
```
PyObject *a = PyLong_FromLong(10);
PyObject *b = PyLong_FromLong(20);
PUSH(a);
PUSH(b);
```

They would end up in the order in which they were added, so `a` would be pushed to the second position in the stack:



If you were to fetch the top value in the stack, you would get a pointer to `b` because it is at the top:

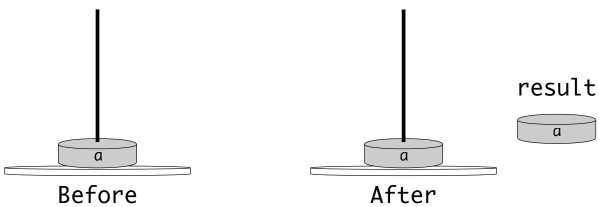
```
PyObject *val = POP(); // returns ptr to b
```



If you need to fetch the pointer to the top value in the stack without popping it, you can use the `PEEK(v)` operation, where `v` is the stack position:

```
PyObject *first = PEEK(0);
```

0 represents the top of the stack, 1 would be the second position:



The `DUP_TOP()` macro can be used to clone the value at the top of the stack:

```
DUP_TOP();
```

This action would copy the value at the top to form 2 pointers to the same object:

There is a rotation macro ROT_TWO that swaps the first and second values.

```
ROT_TWO();
```

Stack Effects

Each of the opcodes has a predefined **stack effect,** calculated by the `stack_effect()` function inside `Python`▸`compile.c`. This function returns the delta in the number of values inside the stack for each opcode. Stack effects can have a positive, negative, or zero value. Once the operation has been executed, if the stack effect (e.g., +1) does not match the delta in the value stack, an exception is raised to ensure there is no corruption to objects on the value stack.

Example: Adding an Item to a List

In Python, when you create a list, the `.append()` method is available on the list object:

```
my_list = []
my_list.append(obj)
```

In this example, `obj` is an object that you want to append to the end of the list.

There are 2 operations involved in this operation:

- `LOAD_FAST`, to load the object `obj` to the top of the value stack from the list of `locals` in the frame
- `LIST_APPEND` to add the object

First exploring `LOAD_FAST`, there are 5 steps:

1. The pointer to `obj` is loaded from `GETLOCAL()`, where the variable to load is the operation argument. The list of variable pointers is stored in `fastlocals`, which is a copy of the PyFrame attribute `f_localsplus`. The operation argument is a number, pointing to the index in the `fastlocals` array pointer. This means that the loading of a local is simply a copy of the pointer instead of having to look up the variable name.
2. If the variable no longer exists, an unbound local variable error is raised.
3. The reference counter for `value` (in our case, `obj`) is increased by 1.
4. The pointer to `obj` is pushed to the top of the value stack.
5. The `FAST_DISPATCH` macro is called, if tracing is enabled, the loop goes over again (with all the tracing). If tracing is not enabled, a `goto` is called to `fast_next_opcode`. The `goto` jumps back to the top of the loop for the next instruction.

```
...
    case TARGET(LOAD_FAST): {
        PyObject *value = GETLOCAL(oparg);              // 1.
        if (value == NULL) {
            format_exc_check_arg(
                PyExc_UnboundLocalError,
                UNBOUNDLOCAL_ERROR_MSG,
                PyTuple_GetItem(co->co_varnames, oparg));
            goto error;                                 // 2.
        }
        Py_INCREF(value);                               // 3.
        PUSH(value);                                    // 4.
        FAST_DISPATCH();                                // 5.
    }
...
```

The pointer to `obj` is now at the top of the value stack, and the next instruction, `LIST_APPEND`, is executed.

Many of the bytecode operations are referencing the base types, like `PyUnicode`, `PyNumber`. For example, `LIST_APPEND` appends an object to the end of a list. To achieve this, it pops the pointer from the value stack and returns the pointer to the last object in the stack. The macro is a shortcut for:

```
PyObject *v = (*--stack_pointer);
```

Now the pointer to `obj` is stored as `v`. The list pointer is loaded from `PEEK(oparg)`.

Then the C API for Python lists is called for `list` and `v`. The code for this is inside `Objects` ▸ `listobject.c`, which you go into in the chapter Objects and Types.

A call to `PREDICT` is made, which guesses that the next operation will be `JUMP_ABSOLUTE`. The `PREDICT` macro has compiler-generated `goto` statements for each of the potential operations' `case` statements. This means the CPU can jump to that instruction and not have to go through the loop again:

```
...
        case TARGET(LIST_APPEND): {
            PyObject *v = POP();
            PyObject *list = PEEK(oparg);
            int err;
            err = PyList_Append(list, v);
            Py_DECREF(v);
            if (err != 0)
                goto error;
            PREDICT(JUMP_ABSOLUTE);
            DISPATCH();
        }
...
```

Note

Opcode Predictions

Some opcodes come in pairs, making it possible to predict the second code when the first is run. For example, `COMPARE_OP` is often followed by `POP_JUMP_IF_FALSE` or `POP_JUMP_IF_TRUE`.

"Verifying the prediction costs a single high-speed test of a register variable against a constant. If the pairing was good, then the processor's own internal branch prediction has a high likelihood of success, resulting in a nearly zero-overhead transition to the next opcode. A successful prediction saves a trip through the eval-loop, including its unpredictable switch-case branch. Combined with the processor's internal branch prediction, a successful PREDICT has the effect of making the two opcodes run as if they were a single new opcode with the bodies combined."

If collecting opcode statistics, you have two choices:

1. Keep the predictions turned-on and interpret the results as if some opcodes had been combined
2. Turn off predictions so that the opcode frequency counter updates for both opcodes

Opcode prediction is disabled with threaded code since the latter allows the CPU to record separate branch prediction information for each opcode.

Some of the operations, such as `CALL_FUNCTION` and `CALL_METHOD`, have an operation argument referencing another compiled function. In these cases, another frame is pushed to the frame stack in the thread. The evaluation loop is then run for that function until the function completes. Each time a new frame is created and pushed onto the stack, the value of the frame's `f_back` is set to the current frame before the new one is created.

This nesting of frames is clear when you see a stack trace:

cpython-book-samples ▸ 31 ▸ example_stack.py

```python
def function2():
  raise RuntimeError

def function1():
  function2()

if __name__ == '__main__':
  function1()
```

Calling this on the command-line will give you:

```
 $ ./python example_stack.py

Traceback (most recent call last):
  File "example_stack.py", line 8, in <module>
    function1()
  File "example_stack.py", line 5, in function1
    function2()
  File "example_stack.py", line 2, in function2
    raise RuntimeError
RuntimeError
```

In `Lib ▸ traceback.py`, the `walk_stack()` function can be used to get trace backs:

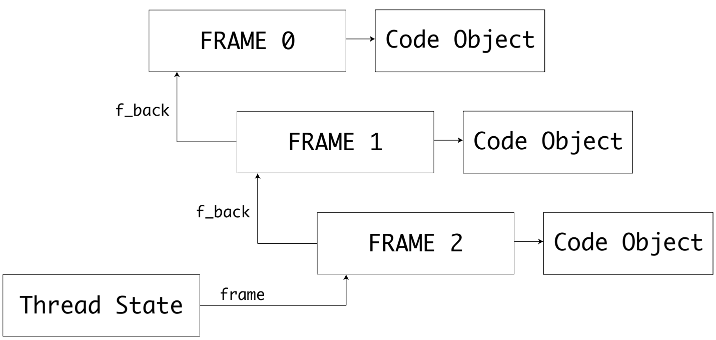
```python
def walk_stack(f):
    """Walk a stack yielding the frame and line number for each frame.

    This will follow f.f_back from the given frame. If no frame is given, the
    current stack is used. Usually used with StackSummary.extract.
    """
    if f is None:
        f = sys._getframe().f_back.f_back
    while f is not None:
        yield f, f.f_lineno
```

```
        f = f.f_back
```

The parent's parent (`sys._getframe().f_back.f_back`) is set as the frame, because you don't want to see the call to `walk_stack()` or `print_trace()` in the traceback. The `f_back` pointer is followed to the top of the call stack.

`sys._getframe()` is the Python API to get the `frame` attribute of the current thread.

Here is how that frame stack would look visually, with 3 frames each with its code object and a thread state pointing to the current frame:



Conclusion

In this chapter, you've been introduced to the "brain" of CPython. The core evaluation loop is the interface between compiled Python code and the underlying C extension modules, libraries, and system calls.

Some parts in this chapter have been glossed over as you'll go into them in upcoming chapters. For example, the CPython interpreter has a core evaluation loop, you can have multiple loops running at the same time. Whether that be in parallel or concurrently. CPython can have multiple evaluation loops running multiple frames on a system. In an upcoming chapter on Parallelism and Concurrency, you will see how the frame stack system is used for CPython to run on multiple core or CPUs. Also, CPython's frame object API enables frames to be paused and resumed in the form of asynchronous programming.

The loading of variables using a Value Stack needs memory allocation and management. For CPython to run effectively, it has to have a solid Memory Management process. In the next chapter, you'll explore that memory management process, and how it relates to the PyObject pointers used by the evaluation loop.

Leave feedback on this section »

Memory Management

The two most important parts of your computer are the memory and the CPU. One cannot work without the other, they must be utilized well, and they must be efficient.

When designing a programming language, the authors need to make a vital trade-off:-

"How should the user manage computer memory?"

There are many solutions to this question. It depends on how simple you want the interface to be, whether you want the language to be cross-platform, whether you value performance over stability.

The authors of Python have made those decisions for you and left you with some additional ones to make yourself. In this chapter, you will explore how C manages memory, since CPython is written in C. You'll look at two critical aspects to managing memory in Python - **reference counting** and **garbage collection**.

By the end of this chapter, you will understand how CPython allocates memory on the Operating System, how object memory is allocated and freed, and how CPython manages memory leaks.

Memory Allocation in C

In C, variables must have their memory allocated from the Operating System before they can be used.

There are three memory allocation mechanisms in C:

1. Static memory allocation, where memory requirements are calculated at compile time and allocated by the executable when it starts
2. Automatic memory allocation, where memory requirements for a scope (e.g., function) are allocated within the call stack when a frame is entered and freed once the frame is terminated
3. Dynamic memory allocation, where memory can be requested and allocated dynamically (i.e., at runtime) by calls to the memory allocation API

Static Memory Allocation in C

Types in C have a fixed size. The compiler will calculate the memory requirements for all static and global variables and then compile that requirement into the application.

For example:

```
static int number = 0;
```

You can see the size of a type in C by using the `sizeof()` function. On my system, a 64-bit macOS running GCC, an `int` is 4 bytes. Basic types in C can have different sizes depending on the architecture and compiler.

For cases of arrays, these are statically defined, for example, an array of 10 integers:

```
static int numbers[10] = {0,1,2,3,4,5,6,7,8,9};
```

The C compiler converts this statement into an allocation of `sizeof(int) * 10` bytes of memory.

The C compiler uses system calls to allocate memory. These system calls depend on the Operating System and are low-level functions to the Kernel to allocate memory from the system memory pages.

Automatic Memory Allocation in C

Similar to static memory allocation, automatic memory allocation will calculate the memory allocation requirements at compile-time.

This example application will convert 100 degrees Fahrenheit to Celsius:

cpython-book-samples ▸ 32 ▸ automatic.c

```c
#include <stdio.h>

static const double five_ninths = 5.0/9.0;

double celsius(double fahrenheit) {
    double c = (fahrenheit - 32) * five_ninths;
    return c;
}

int main() {
    double f = 100;
    printf("%f F is %f Cn", f, celsius(f));
    return 0;
}
```

Both static and dynamic memory allocation techniques are being used in the last example:

- The const value `five_ninths` is **statically** allocated because it has the `static` keyword
- The variable `c` within the function `celsius()` is allocated **automatically** when `celsius()` is called and freed when it is completed
- The variable `f` within the function `main()` is allocated **automatically** when `main()` is called and freed when it is completed
- The result of `celsius(f)` is implicitly allocated **automatically**
- The automatic memory requirements of `main()` are freed when the function completes

Dynamic Memory Allocation in C

In many cases, neither static nor automatic memory allocation is sufficient. For example- a program cannot calculate the size of the memory required at compile-time because it is a user-input defined.

In such cases, memory is allocated **dynamically**. Dynamic memory allocation works by calls to the C memory allocation APIs.

Operating Systems reserve a section of the system memory for dynamic allocation to processes. This section of memory is called a **heap**.

In this example, you will allocate memory dynamically to an array of Fahrenheit and Celsius values.

The application calculates the Celsius values corresponding to a user-specified number of Fahrenheit values:

cpython-book-samples ▸ 32 ▸ dynamic.c

```c
#include <stdio.h>
#include <stdlib.h>

static const double five_ninths = 5.0/9.0;

double celsius(double fahrenheit) {
    double c = (fahrenheit - 32) * five_ninths;
    return c;
}

int main(int argc, char** argv) {
    if (argc != 2)
        return -1;
    int number = atoi(argv[1]);
    double* c_values = (double*)calloc(number, sizeof(double));
    double* f_values = (double*)calloc(number, sizeof(double));
    for (int i = 0 ; i < number ; i++ ){
        f_values[i] = (i + 10) * 10.0 ;
```

```
        c_values[i] = celsius((double)f_values[i]);
    }
    for (int i = 0 ; i < number ; i++ ){
        printf("%f F is %f Cn", f_values[i], c_values[i]);
    }
    free(c_values);
    free(f_values);

    return 0;
}
```

If you execute this with the argument `4`, it will print:

```
100.000000 F is 37.777778 C
110.000000 F is 43.333334 C
120.000000 F is 48.888888 C
130.000000 F is 54.444444 C
```

This example uses dynamic memory allocation to allocate a block of memory from the heap that is then returned when it is no longer needed.

If any memory that is dynamically allocated is not freed, it will cause a memory leak.

Design of the Python Memory Management System

Being built on top of C, CPython has to use the constraints of **static**, **automatic**, and **dynamic** memory allocation.

There are some design aspects of the Python language that make those constraints even more challenging:

1. Python is a dynamically typed language. The size of variables cannot be calculated at compile-time
2. Most of Python's core types are dynamically sized. The `list` type can be of any size, `dict` can have any number of keys, even `int` is

dynamic. The user never has to specify the size of these types

3. Names in Python can be reused to values of different types, e.g.:

```
>>> a_value = 1
>>> a_value = "Now I'm a string"
>>> a_value = ["Now" , "I'm" "a", "list"]
```

To overcome these constraints, CPython relies heavily on dynamic memory allocation but adds safety-rails to automate the freeing of memory using the garbage collection and reference counting algorithms.

Instead of the Python developer having to allocate memory, Python Object memory is allocated automatically via a single, unified API.

This design requires that the entire CPython standard library and core modules (written in C) use this API.

Allocation Domains

CPython comes with three dynamic memory allocation domains:

1. **Raw Domain** - Used for allocation from the system heap. Used for large, or non-object related memory allocation
2. **Object Domain** - Used for allocation of all Python Object-related memory allocation
3. **PyMem Domain** - The same as `PYMEM_DOMAIN_OBJ`, exists for legacy API purposes

Each domain implements the same interface of functions:

- `_Alloc(size_t size)` - allocates memory of size, `size`, and returns a pointer
- `_Calloc(size_t nelem, size_t elsize)` - allocates memory of size
- `_Realloc(void *ptr, size_t new_size)` - reallocates memory to a new size

- `_Free(void *ptr)` - frees memory at `ptr` back to the heap

The `PyMemAllocatorDomain` enumeration represents the three domains in CPython as `PYMEM_DOMAIN_RAW`, `PYMEM_DOMAIN_OBJ`, and `PYMEM_DOMAIN_MEM`.

Memory Allocators

CPython uses two memory allocators:

1. The Operating System allocator (`malloc`) for the **Raw** memory domain
2. The CPython allocator (`pymalloc`) for the **PyMem** and **Object Memory** domains

> **Note**
>
> The CPython allocator, `pymalloc`, is compiled into CPython by default. You can remove it by recompiling CPython after setting `WITH_PYMALLOC = 0` in `pyconfig.h`. If you remove it, the PyMem and Object memory domain APIs will use the system allocator.

If you compiled CPython with debugging (`--with-pydebug` on macOS/Linux, or with the `Debug` target on Windows), then each of the memory allocation functions will go to a Debug implementation. For example, with debugging enabled, your memory allocation calls would execute `_PyMem_DebugAlloc()` instead of `_PyMem_Alloc()`.

The CPython Memory Allocator

The CPython memory allocator sits atop the system memory allocator and has its algorithm for allocation. This algorithm is similar to the system allocator, except that it is customized to CPython:

- Most of the memory allocation requests are small, fixed-size because `PyObject` is 16 bytes, `PyASCIIObject` is 42 bytes, `PyCompactUnicodeObject` is 72 bytes, and `PyLongObject` is 32 bytes.

- The pymalloc allocator only allocates memory blocks up to 256KB, anything larger is sent to the system allocator
- The pymalloc allocator uses the GIL instead of the system thread-safety check

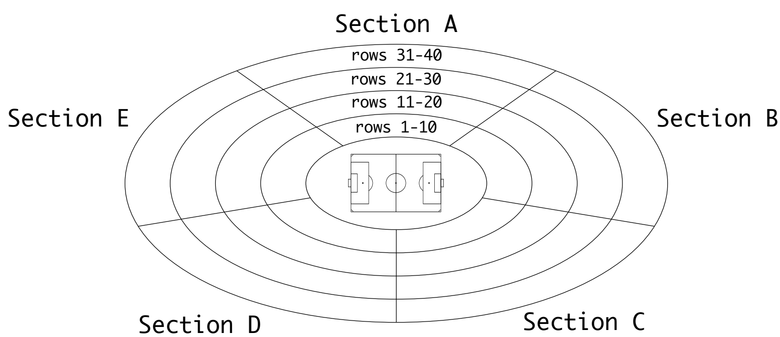
To help explain this situation, we're going to use a physical sports stadium as our analogy.

This is the stadium of "CPython FC," our fictional team.

To help manage crowds, CPython FC has implemented a system of breaking the stadium up into sections A-E, each with seating rows 1-40.

The rows at the front of the stadium (1-10) are the Premium seats, each taking up more space. So there can only be 80 seats per row.

At the back, from rows 31-40 are the Economy seats. There are 150 seats per row:



- Just like the stadium has seats, the pymalloc algorithm has memory "**blocks**"

- Just like seats can either be Premium, Regular or Economy, blocks are all of a range of fixed sizes. You can't bring your deckchair
- Just like seats of the same size are put into rows, blocks of the same size are put into sized pools
- A central register keeps a record of where blocks are and the number of blocks available in a pool, just as the stadium would allocate seating
- When a row in the stadium is full, the next row is used. When a pool of blocks is full, the next pool is used
- Pools are grouped into arenas, just like the stadium groups the rows into sections

There are some advantages to this strategy:

1. The algorithm is more performant for CPython's main use case-short-lived, small objects
2. The algorithm uses the GIL instead of system thread lock detection
3. The algorithm uses memory mapping (mmap) instead of heap allocation

Related Source Files

Source files related to the memory allocator are:

File	Purpose
`Include ▸ pymem.h`	PyMem Allocator API
`Include ▸ cpython ▸ pymem.h`	PyMem Memory Allocator Configuration API
`Include ▸ internal ▸ pycore_mem.h`	GC data structure and internal APIs
`Objects ▸ obmalloc.c`	Domain allocator implementations, and the `pymalloc` implementation

Important Terms

- Requested memory is matched to a **block** size

- Blocks of the same size are all put into the same **pool** of memory
- Pools are grouped into **arenas**

Blocks, Pools, and Arenas

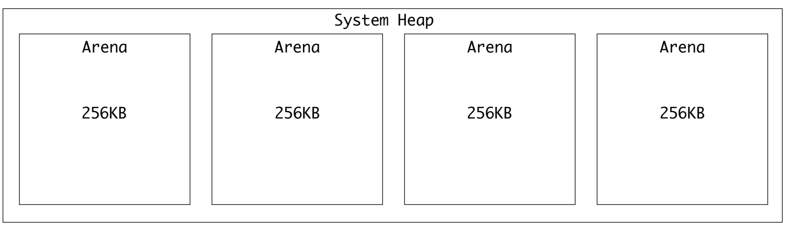
The largest group of memory is an arena. CPython creates arenas of 256KB to align with the system page size. A system page boundary is a fixed-length contiguous chunk of memory.

Even with modern, high-speed memory, contiguous memory will load faster than fragmented. It is beneficial to have contiguous memory.

Arenas

Arenas are allocated against the system heap, and with `mmap()` on systems supporting anonymous memory mappings. Memory mapping helps reduce heap fragmentation of the arenas.

This is the representation of 4 arenas within the system heap:



Arenas have the data struct `arenaobject`:

Field	Type	Purpose
`address`	`uintptr_t`	Memory address of the arena
`pool_address`	`block *`	Pointer to the next pool to be carved off for allocation
`nfreepools`	`uint`	The number of available pools in the arena: free pools + never-allocated pools
`ntotalpools`	`uint`	The total number of pools in the arena, whether or not available

Field	Type	Purpose
freepools	pool_header*	Singly-linked list of available pools
nextarena	arena_-object*	Next arena (see note)
prevarena	arena_-object*	Previous arena (see note)

Note

Arenas are linked together in a doubly-linked list inside the arena data structure, using the nextarena and prevarena pointers.

If this arena is **unallocated**, the nextarena member is used. The nextarena member links all unassociated arenas in the singly-linked unused_arena_objects global variable.

When this arena is associated with an allocated arena, with at least one available pool, both nextarena and prevarena are used in the doubly-linked usable_arenas list. This list is maintained in increasing order of nfreepools values.

Pools

Within an arena, pools are created for block sizes up to 512 bytes.

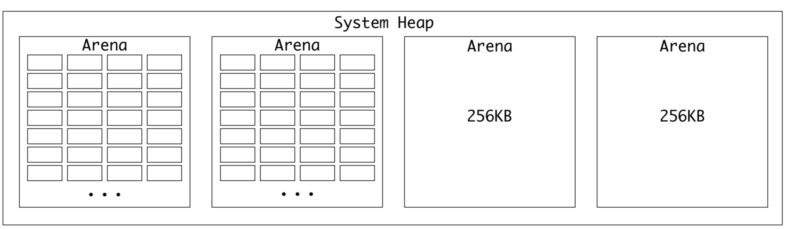
For 32-bit systems, the step is 8 bytes, so there are 64 classes:

Request in bytes	Size of allocated block	Size class index
1-8	8	0
9-16	16	1
17-24	24	2
25-32	32	3
...	...	...
497-504	504	62
505-512	512	63

For 64-bit systems, the step is 16 bytes, so there are 32 classes:

Request in bytes	Size of allocated block	Size class index
1-16	16	0
17-32	32	1
33-48	48	2
49-64	64	3
...	...	...
480-496	496	30
496-512	512	31

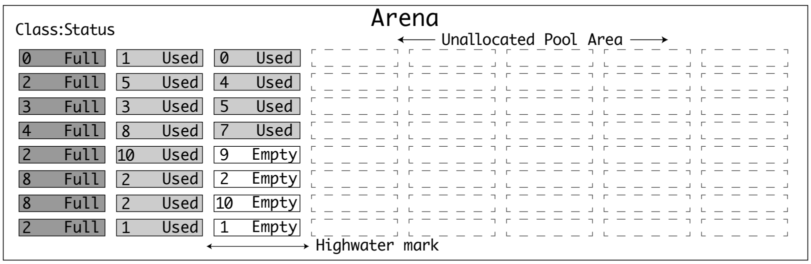
Pools are all 4096 bytes (4KB), so there are always 64 pools in an arena.



Pools are allocated on demand. When no available pools are available for the requested class size index, a new one is provisioned. Arenas have a "high water mark" to index how many pools have been provisioned.

Pools have three possible states,

1. **Full**: all available blocks in that pool are allocated
2. **Used**: the pool is allocated, and some blocks have been set, but it still has space
3. **Empty**: the pool is allocated, but no blocks have been set



Pools have the data structure `poolp`, which is a static allocation of the struct `pool_header`. The `pool_header` type has the following properties:

Field	Type	Purpose
`ref`	`uint`	Number of currently allocated blocks in this pool
`freeblock`	`block *`	Pointer to this pool's "free list" head
`nextpool`	`pool_header*`	Pointer to the next pool of this size class
`prevpool`	`pool_header*`	Pointer to the previous pool of this size class
`arenaindex`	`uint`	Singly-linked list of available pools
`szidx`	`uint`	Class size index of this pool
`nextoffset`	`uint`	Number of bytes to unused block
`maxnextoffset`	`uint`	Maximum number that `nextoffset` can be until pool is full

Each pool of a certain class size will keep a doubly-linked list to the next and previous pools of that class. When the allocation task happens, it is easy to jump between pools of the same class size within an arena by following this list.

Pool Tables

A register of the pools within an arena is called a **pool table**.

A pool table is a headed, circular, doubly-linked list of partially-used pools. The pool table is segmented by class size index, `i`. For an index of `i`, `usedpools[i + i]` points to the header of a list of all partially-used pools that have the size index for that class size.

Pool tables have some essential characteristics:

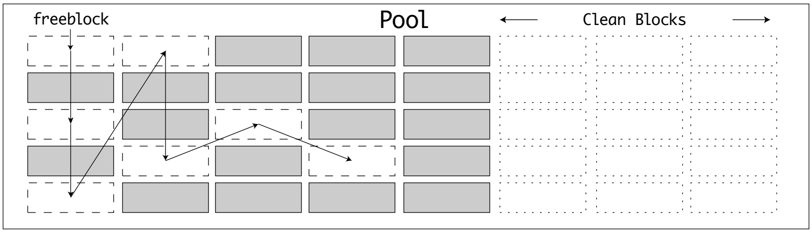
- When a pool becomes full, it is unlinked from its `usedpools[]` list.
- If a full block has a block freed, the pool back is put back in the used state. The newly freed pool is linked in at the front of the appropriate `usedpools[]` list so that the next allocation for its size class will reuse the freed block.
- On transition to empty, a pool is unlinked from its `usedpools[]` list, and linked to the front of its arena's singly-linked `freepools` list.

Blocks

Within a pool, memory is allocated into blocks. Blocks have the following characteristics:

- Within a pool, blocks of fixed class size can be allocated and freed.
- Available blocks within a pool are listed in the singly-linked list, `freeblock`.
- When a block is freed, it is inserted at the front of the `freeblock` list.
- When a pool is initialized, only the first two blocks are linked within the `freeblock` list.
- As long a pool is in the **used** state, there will be a block available for allocating.

A partially allocated pool with a combination of used, freed, and available blocks:



Block Allocation API

When a block of memory is requested by a memory domain that uses pymalloc, the pymalloc_alloc function will be called.

This function is a good place to insert a breakpoint and step through the code to test your knowledge of the blocks, pools, and arenas.

Objects ▸ obmalloc.c line 1590

```
static inline void*
pymalloc_alloc(void *ctx, size_t nbytes)
{
...
```

For a request of `nbytes = 30`, it is neither zero, nor below the SMALL_REQUEST_THRESHOLD of 512:

```
    if (UNLIKELY(nbytes == 0)) {
        return NULL;
    }
    if (UNLIKELY(nbytes > SMALL_REQUEST_THRESHOLD)) {
        return NULL;
    }
```

For a 64-bit system, the size class index is calculated as 1. This correlates to the 2nd class size index (17-32 bytes). The target pool is then `usedpools[1 + 1]` (`usedpools[2]`):

```
    uint size = (uint)(nbytes - 1) >> ALIGNMENT_SHIFT;
    poolp pool = usedpools[size + size];
    block *bp;
```

Next, a check is done to see if there is an available (`'used'`) pool for the class size index. If the freeblock list is at the end of the pool, then there are still clean blocks available in that pool. `pymalloc_pool_extend()` is called to extend the `freeblock` list:

```
    if (LIKELY(pool != pool->nextpool)) {
        /*
         * There is a used pool for this size class.
         * Pick up the head block of its free list.
         */
        ++pool->ref.count;
        bp = pool->freeblock;
        assert(bp != NULL);

        if (UNLIKELY((pool->freeblock = *(block **)bp) == NULL)) {
            // Reached the end of the free list, try to extend it.
            pymalloc_pool_extend(pool, size);
        }
    }
```

If there were no available pools, a new pool is created and the first block is returned. The `allocate_from_new_pool()` function adds the new pool to the `usedpools` list automatically:

```
    else {
        /* There isn't a pool of the right size class immediately
         * available:  use a free pool.
         */
        bp = allocate_from_new_pool(size);
    }

    return (void *)bp;
}
```

Finally, the new block address is returned.

Using the Python Debug API

The `sys` module contains an internal function, `_debugmallocstats()`, to get the number of blocks in use for each of the class size pools. It will also print the number of arenas allocated, reclaimed, and the total number of blocks used.

You can use this function to see the running memory usage:

```
 $ ./python -c "import sys; sys._debugmallocstats()"

Small block threshold = 512, in 32 size classes.

class   size   num pools   blocks in use  avail blocks
-----   ----   ---------   -------------  ------------
    0     16           1             181            72
    1     32           6             675            81
    2     48          18            1441            71
...
 2 free 18-sized PyTupleObjects * 168 bytes each =                 336
 3 free 19-sized PyTupleObjects * 176 bytes each =                 528
```

The output shows the class index size table, the allocations, and some additional statistics.

The Object and PyMem Memory Allocation Domains

CPython's object memory allocator is the first of the three domains that you will explore.

The purpose of the Object memory allocator is to allocate memory related to Python Objects, such as:

- New Object Headers
- Object data, such as dictionary keys and values, or list items

The allocator is also used for the compiler, AST, parser and evaluation loop.

An excellent example of the Object memory allocator being used is the `PyLongObject` (`int`) type constructor, `PyLong_New()`.

- When a new `int` is constructed, memory is allocated from the Object Allocator.
- The size of the request is the size of the `PyLongObject` struct, plus the amount of memory required to store the digits.

Python longs are not equivalent to C's `long` type. They are a *list* of digits.

The number `12378562834` in Python would be represented as the list of digits `[1,2,3,7,8,5,6,2,8,3,4]`.

This memory structure is how Python can deal with huge numbers without having to worry about 32 or 64-bit integer constraints.

Take a look at the `PyLong` constructor to see an example of object memory allocation:

```
PyLongObject *
_PyLong_New(Py_ssize_t size)
{
    PyLongObject *result;
    ...
    if (size > (Py_ssize_t)MAX_LONG_DIGITS) {
        PyErr_SetString(PyExc_OverflowError,
                        "too many digits in integer");
        return NULL;
    }
    result = PyObject_MALLOC(offsetof(PyLongObject, ob_digit) +
                             size*sizeof(digit));
    if (!result) {
        PyErr_NoMemory();
        return NULL;
    }
```

```
    return (PyLongObject*)PyObject_INIT_VAR(result, &PyLong_Type, size);
}
```

If you were to call `_PyLong_New(2)`, it would calculate:

Value	Bytes
sizeof(digit)	4
size	2
header offset	26
Total	**32**

A call to `PyObject_MALLOC()` would be made with a `size_t` value of 32.

On my system, the maximum number of digits in a long, `MAX_LONG_DIGITS`, is `2305843009213693945` (a very, very big number). If you ran `_PyLong_New(2305843009213693945)` it would call `PyObject_MALLOC()` with a `size_t` of `9223372036854775804` bytes, or 8,589,934,592 Gigabytes (more RAM than I have available).

Using the `tracemalloc` Module

The `tracemalloc` in the standard library can be used to debug memory allocation through the Object Allocator. It provides information on where an object was allocated, and the number of memory blocks allocated.

As a debug tool, it is beneficial to calculate the amount of memory consumed by running your code or detect memory leaks.

To enable memory tracing, you should start Python with the `-X tracemalloc=1`, where `1` is the number of frames deep you want to trace. Alternatively, you can enable memory tracing using the `PYTHONTRACEMALLOC=1` environment variable. `1` is the number of frames deep you want to trace and can be replaced with any integer.

You can use the `take_snapshot()` function to create a snapshot instance, then compare multiple snapshots using `compare_to()`.

Create an example `tracedemo.py` file to see this in action:

cpython-book-samples ▸ 32 ▸ tracedemo.py

```
import tracemalloc

tracemalloc.start()

def to_celsius(fahrenheit, /, options=None):
    return (fahrenheit-32)*5/9

values = range(0, 100, 10)  # values 0, 10, 20, ... 90

for v in values:
    c = to_celsius(v)

after = tracemalloc.take_snapshot()

tracemalloc.stop()
after = after.filter_traces([tracemalloc.Filter(True, '**/tracedemo.py')])
stats = after.statistics('lineno')

for stat in stats:
    print(stat)
```

Executing this will print a list of the memory used by line, from highest to lowest:

```
$ ./python -X tracemalloc=2 tracedemo.py

/Users/.../tracedemo.py:5: size=712 B, count=2, average=356 B
/Users/.../tracedemo.py:13: size=512 B, count=1, average=512 B
/Users/.../tracedemo.py:11: size=480 B, count=1, average=480 B
/Users/.../tracedemo.py:8: size=112 B, count=2, average=56 B
/Users/.../tracedemo.py:6: size=24 B, count=1, average=24 B
```

The line with the highest memory consumption was `return (fahrenheit-32)*5/9` (the actual calculation).

The Raw Memory Allocation Domain

The Raw Memory Allocation domain is used either directly, or when the other two domains are called with a request size over 512 KB.

It takes the request size, in bytes, and calls `malloc(size)`.

If the size argument is 0, some systems will return NULL for malloc(0), which would be treated as an error.
Some platforms would return a pointer with no memory behind it, which would break pymalloc. To solve these problems, `_PyMem_RawMalloc()` will add an extra byte before calling `malloc()`.

Important

By default, the PyMem Domain allocators will use the Object Allocators. `PyMem_Malloc()` and `PyObject_Malloc()` will have the same execution path.

Custom Domain Allocators

CPython also allows for the allocation implementation for any of the three domains to be overridden. If your system environment required bespoke memory checks or algorithms for memory allocation, then you can plug a new set of allocation functions into the runtime.

`PyMemAllocatorEx` is a `typedef` struct with members for all of the methods you would need to implement to override the allocator:

```
typedef struct {
    /* user context passed as the first argument to the 4 functions */
    void *ctx;

    /* allocate a memory block */
    void* (*malloc) (void *ctx, size_t size);

    /* allocate a memory block initialized by zeros */
```

```
    void* (*calloc) (void *ctx, size_t nelem, size_t elsize);

    /* allocate or resize a memory block */
    void* (*realloc) (void *ctx, void *ptr, size_t new_size);

    /* release a memory block */
    void (*free) (void *ctx, void *ptr);
} PyMemAllocatorEx;
```

The API method `PyMem_GetAllocator()` is available to get the existing implementation:

```
PyMemAllocatorEx * existing_obj;
PyMem_GetAllocator(PYMEM_DOMAIN_OBJ, existing_obj);
```

Important

There are some important design tests for custom allocators:

- The new allocator must return a distinct non-NULL pointer when requesting zero bytes
- For the PYMEM_DOMAIN_RAW domain, the allocator must be thread-safe

If you implemented functions `My_Malloc`, `My_Calloc`, `My_Realloc` and `My_Free` implementing the signatures in `PyMemAllocatorEx`, you could override the allocator for any domain, e.g., the `PYMEM_DOMAIN_OBJ` domain:

```
PyMemAllocatorEx my_allocators =
    {NULL, My_Malloc, My_Calloc, My_Realloc, My_Free};
PyMem_SetAllocator(PYMEM_DOMAIN_OBJ, &my_allocators);
```

Custom Memory Allocation Sanitizers

Memory allocation sanitizers are an additional algorithm placed between the system call to allocate memory, and the kernel function to allocate the memory on the system. They are used for environments that require specific stability constraints, very high security, or for debugging memory allocation bugs.

CPython can be compiled using several memory sanitizers. These are part of the compiler libraries, not something developed for CPython.

They typically slow down CPython significantly and cannot be combined. They generally are for use in debugging scenarios or systems where preventing corrupt memory access is critical.

Address Sanitizer

Address Sanitizer is a "fast" memory error detector. It can detect many runtime memory-related bugs:

- Out-of-bounds accesses to heap, stack, and globals
- Memory being used after it has been freed
- Double-free, invalid free

It can be enabled by running:

```
$ ./configure --with-address-sanitizer ...
```

Important

Address Sanitizer would slow down applications by up to 2x and consume up to 3x more memory.

Address Sanitizer is supported on:

- Linux
- macOS
- NetBSD
- FreeBSD

See the official documentation for more information.

Memory Sanitizer

Memory Sanitizer is a detector of uninitialized reads. If an address space is addressed before it has been initialized (allocated), then the process is stopped before the memory can be read.

It can be enabled by running:

```
$ ./configure --with-memory-sanitizer ...
```

> **Important**
>
> Memory Sanitizer would slow down applications by up to 2x and consume up to 2x more memory.

Memory Sanitizer is supported on:

- Linux
- NetBSD
- FreeBSD

See the official documentation for more information.

Undefined Behavior Sanitizer

Undefined Behavior Sanitizer is a "fast" undefined behavior detector. It can catch various kinds of undefined behavior during execution, for example:

- Using misaligned or null pointer
- Signed integer overflow
- Conversion to, from, or between floating-point types which would overflow the destination

It can be enabled by running:

```
$ ./configure --with-undefined-behavior-sanitizer ...
```

Undefined Behavior Sanitizer is supported on:

- Linux
- macOS
- NetBSD
- FreeBSD

See the official documentation for more information.

The Undefined Behavior Sanitizer has many configurations, using `--with-undefined-behavior-sanitizer` will set the `undefined` profile. To use another profile, e.g., `nullability`, run `./configure` with the custom CFLAGS:

```
$ ./configure CFLAGS="-fsanitize=nullability"
    LDFLAGS="-fsanitize=nullability"
```

The PyArena Memory Arena

Throughout this book, you will see references to a `PyArena` object.

The `PyArena` is a separate arena allocation API used for the compiler, frame evaluation, and other parts of the system not run from Python's Object allocation API. The PyArena also has its own list of allocated objects within the arena structure. Memory allocated by the `PyArena` is not a target of the garbage collector.

When memory is allocated in a `PyArena` instance, it will capture a running total of the number of blocks allocated, then call `PyMem_Alloc`.

Allocation requests to the `PyArena` use the Object Allocator for blocks <= 512KB, or the Raw Allocator for blocks > 256KB.

Related Files

File	Purpose
Include ▸ pyarena.h	The PyArena API and type definitions
Python ▸ pyarena.c	The PyArena implementation

Reference Counting

As you have explored so far in this chapter, CPython is built on C's Dynamic Memory Allocation system. Memory requirements are determined at runtime, and memory is allocated on the system using the `PyMem` APIs.

For the Python developer, this system has been abstracted and simplified. Developers don't have to worry (too much) about allocating and free'ing memory.

To achieve simple memory management, Python adopts two strategies for managing the memory allocated by objects:

1. Reference Counting
2. Garbage Collection

Creating Variables in Python

To create a variable in Python, you have to assign a value to a *uniquely* named variable. For example:

```
my_variable = ['a', 'b', 'c']
```

When a **value** is assigned to a **variable** in Python, the **name** of the variable is checked within the locals and globals scope to see if it already exists.

In the example, `my_variable` is not already within any `locals()` or `globals()` dictionary. A new `list` object is created, and a pointer is stored in the `locals()` dictionary. There is now one **reference** to `my_variable`. The list object's memory should not be freed while there are valid references to it. If memory were freed, the `my_variable` pointer would point to invalid memory space, and CPython would crash.

Throughout the C source code for CPython, you will see calls to `Py_INCREF()` and `Py_DECREF()`.

These macros are the primary API for incrementing and decrementing references to Python objects. Whenever something depends on a value, the reference count increases, when that dependency is no longer valid, the reference count decreases.
If a reference count reaches zero, it is assumed that it is no longer needed, and it is automatically freed.

Incrementing References

Every instance of `PyObject` has a property `ob_refcnt`. This property is a counter of the number of references to that object.

References to an object are incremented under many scenarios. In the CPython code base, there are over 3000 calls to `Py_INCREF()`. The most frequent calls are when an object is:

- assigned to a variable name
- referenced as a function or method argument
- returned, or yielded from a function

The logic behind the `Py_INCREF` macro is simple. It increments the `ob_refcnt` value by 1:

```
static inline void _Py_INCREF(PyObject *op)
{
    _Py_INC_REFTOTAL;
    op->ob_refcnt++;
}
```

If CPython is compiled in debug mode, `_Py_INC_REFTOTAL` will increment a global reference counter, `_Py_RefTotal`.

Note

You can see the global reference counter by adding the `-X showrefcount` flag when running CPython:

```
$ ./python -X showrefcount -c "x=1; x+=1; print(f'x is {x}')"
x is 2
[18497 refs, 6470 blocks]
```

The first number in brackets is the number of references made during the process, and the second is the number of allocated blocks.

Decrementing References

References to an object are decremented when a variable falls outside of the scope in which it was declared. Scope in Python can refer to a function or method, a comprehension, or a lambda. These are some of the more literal scopes, but there are many other implicit scopes, like passing variables to a function call.

The `Py_DECREF()` function is more complex than `Py_INCREF()` because it also handles the logic of a reference count reaching 0, requiring the object memory to be freed:

```
static inline void _Py_DECREF(
#ifdef Py_REF_DEBUG
    const char *filename, int lineno,
#endif
    PyObject *op)
{
    _Py_DEC_REFTOTAL;
    if (--op->ob_refcnt != 0) {
#ifdef Py_REF_DEBUG
        if (op->ob_refcnt < 0) {
            _Py_NegativeRefcount(filename, lineno, op);
        }
#endif
```

```
    }
    else {
        _Py_Dealloc(op);
    }
}
```

Inside `Py_DECREF()`, when the reference counter (`ob_refcnt`) value becomes 0, the object destructor is called via `_Py_Dealloc(op)`, and any allocated memory is freed.

As with `Py_INCREF()`, there are some additional functions when CPython has been compiled in debug mode.

For an increment, there should be an equivalent decrement operation.

If a reference count becomes a negative number, this indicates an imbalance in the C code. An attempt to decrement references to an object that has no references will give this error message:

```
<file>:<line>: _Py_NegativeRefcount: Assertion failed:
    object has negative ref count
Enable tracemalloc to get the memory block allocation traceback

object address  : 0x109eaac50
object refcount : -1
object type     : 0x109cadf60
object type name: <type>
object repr     : <refcnt -1 at 0x109eaac50>
```

When making changes to the behavior of an operation, the Python language, or the compiler, you must carefully consider the impact on object references.

Reference Counting in Bytecode Operations

A large portion of the reference counting in the Python happens within the bytecode operations in `Python▸ceval.c`.

Take this example, how many references do you think there are to `y`?

```python
y = "hello"

def greet(message=y):
    print(message.capitalize() + " " + y)

messages = [y]

greet(*messages)
```

At a glance, `y` is immediately referenced by:

1. `y` is a variable in the top-level scope
2. `y` is referenced as a default value for the keyword argument `message`
3. `y` is referenced inside the `greet()` function
4. `y` is an item in the `messages` list

Run this code with an additional snippet:

```python
import sys
print(sys.getrefcount(y))
```

The total references to `y` is 6.

Instead of the logic for incrementing and decrementing references sitting within a central function that has to cater for all these cases (and more!), the logic is split into small parts.

A bytecode operation should have a determining impact on the reference counter for the objects that it takes as arguments.

For example, in the frame evaluation loop, the `LOAD_FAST` operation loads the object with a given name and pushes it to the top of the value stack. Once the variable name, which is provided in the `oparg`, has been resolved using `GETLOCAL()` the reference counter is incremented:

```c
        case TARGET(LOAD_FAST): {
            PyObject *value = GETLOCAL(oparg);
```

```
            if (value == NULL) {
                format_exc_check_arg(tstate, PyExc_UnboundLocalError,
                                     UNBOUNDLOCAL_ERROR_MSG,
                                     PyTuple_GetItem(co->co_varnames, oparg));
                goto error;
            }
            Py_INCREF(value);
            PUSH(value);
            FAST_DISPATCH();
        }
```

A `LOAD_FAST` operation is compiled by many AST nodes that have operations.

For example, if you were to assign two variables `a` and `b`, then create third, `c` from the result of multiplying them:

```
a = 10
b = 20
c = a * b
```

In the third operation, `c = a * b`, the right-hand side expression, `a * b`, would be assembled into three operations:

1. `LOAD_FAST`, resolving the variable `a` and pushing it to the value stack then incrementing the references to `a` by 1
2. `LOAD_FAST`, resolving the variable `b` and pushing it to the value stack then incrementing the references to `b` by 1
3. `BINARY_MULTIPLY`

The binary multiply operator, `BINARY_MULTIPLY` knows that references to the left and right variables in the operation have been loaded to the first and second positions in the value stack. It is also implied that the `LOAD_FAST` operation incremented its reference counters.

In the implementation of the `BINARY_MULTIPLY` operation, the references to both `a` (`left`) and `b` (`right`) are decremented once the result has been calculated.

```
        case TARGET(BINARY_MULTIPLY): {
            PyObject *right = POP();
            PyObject *left = TOP();
            PyObject *res = PyNumber_Multiply(left, right);
>>>         Py_DECREF(left);
>>>         Py_DECREF(right);
            SET_TOP(res);
            if (res == NULL)
                goto error;
            DISPATCH();
        }
```

The resulting number, `res`, will have a reference count of 1 before it is set as the top of the value stack.

Conclusion

CPython's reference counter has the benefits of being simple, fast, and efficient.

The biggest drawback of the reference counter is that it needs to cater for, and carefully balance, the effect of every operation.

As you just saw, a bytecode operation increments the counter, and it is assumed that an equivalent operation will decrement it properly. What happens if there's an unexpected error? Have all possible scenarios been tested?

Everything discussed so far is within the realm of the CPython runtime. The Python developer has little to no control over this behavior.

There is also a significant flaw in the reference counting approach–**cyclical references**.

Take this Python example:

```python
x = []
x.append(x)
del x
```

The reference count for `x` is still 1 because it referred to itself.

To cater to this complexity, and resolve some of these memory leaks, CPython has a second memory management mechanism, **Garbage Collection**.

Garbage Collection

How often does your garbage get collected? Weekly or fortnightly?

When you're finished with something, you discard it and throw it in the trash. But that trash won't get collected straight away. You need to wait for the garbage trucks to come and pick it up.

CPython has the same principle, using a garbage collection algorithm. CPython's garbage collector is **enabled** by default, happens in the background, and works to deallocate memory that's been used for objects which no longer exist.

Because the garbage collection algorithm is a lot more complicated than the reference counter, it doesn't happen all the time. If it did, it would consume a vast amount of CPU resources. The garbage collection runs periodically after a set number of operations.

Related Source Files

Source files related to the garbage collector are:

File	Purpose
`Modules` ▸ `gcmodule.c`	The Garbage Collection module and algorithm implementation
`Include` ▸ `internal` ▸ `pycore_mem.h`	The GC data structure and internal APIs

The GC Design

As you uncovered in the previous section, every Python object retains a counter of the number of references to it. Once that counter reaches

0, the object is finalized, and the memory is freed.

Many of the Python **container types**, like lists, tuples, dictionaries, and sets, could result in cyclical references. The reference counter is an insufficient mechanism to ensure that objects which are no longer required are freed. While creating cyclical references in containers should be avoided, there are many examples within the standard library and the core interpreter.

Here is another common example, where a container type (`class`) can refer to itself:

cpython-book-samples ▸ 32 ▸ user.py

```python
__all__ = ['User']

class User(BaseUser):
    name: 'str' = ""
    login: 'str' = ""

    def __init__(self, name, login):
        self.name = name
        self.login = login
        super(User).__init__()

    def __repr__(self):
        return ""

class BaseUser:
    def __repr__(self):
        # This creates a cyclical reference
        return User.__repr__(self)
```

In this example, the instance of `User` links to the `BaseUser` type, which references back to the instance of `User`.

The goal of the garbage collector is to find **unreachable** objects and mark them as garbage.

Some GC algorithms, like mark-and-sweep, or stop-and-copy start at the root of the system and explore all *reachable* objects. This is hard to do in CPython because C extension modules can define and store their own objects. You could not easily determine all objects by simply looking at `locals()` and `globals()`.

For long-running processes, or large data processing tasks, running out of memory would cause a significant issue.

Instead, the CPython garbage collector leverages the existing reference counter and a custom garbage collector algorithm to find all *unreachable* objects. Because the reference counter is already in place, the role of the CPython garbage collector is to look for cyclical references in certain container types.

Container Types Included in GC

The Garbage Collector will look for types that have the flag `Py_TPFLAGS_HAVE_GC` set in their type definition.
You will cover type definitions in the chapter Objects in CPython.

Types that are marked for garbage collection are:

- Class, Method and Function objects
- Cell Objects
- Byte arrays, Byte, and Unicode strings
- Dictionaries
- Descriptor Objects, used in attributes
- Enumeration Objects
- Exceptions
- Frame Objects
- Lists, Tuples, Named Tuples and Sets
- Memory Objects
- Modules and Namespaces

- Type and Weak Reference Objects
- Iterators and Generators
- Pickle Buffers

Wondering what's missing? Floats, Integers, Boolean, and `NoneType` are not marked for garbage collection.

Custom types written with C extension models can be marked as requiring GC using the GC C-API.

Untrackable Objects and Mutability

The GC will track certain types for changes in their properties to determine which are unreachable.

Some container instances are not subject to change because they are immutable, so the API provides a mechanism for "untracking." The fewer objects there are to be tracked by the GC, the faster and more efficient the GC is.

An excellent example of untrackable objects is tuples. Tuples are immutable. Once you create them, they cannot be changed. However, tuples can contain mutable types, like lists and dictionaries.

This design in Python creates many side-effects, one of which is the GC algorithm. When a tuple is created, unless it is empty, it is marked for tracking. When the GC runs, every tuple looks at its contents to see if it only contains immutable (untracked) instances. This step is completed in `_PyTuple_MaybeUntrack()`. If the tuple determines that it only contains immutable types, like booleans and integers, it will remove itself from the GC tracking by calling `_PyObject_GC_UNTRACK()`.

Dictionaries are empty when they are created and untracked. When an item is added to a dictionary, if it is a tracked object, the dictionary will request itself to be tracked by the GC.

You can see if any object is being tracked by calling `gc.is_tracked(obj)`.

Garbage Collection Algorithm

See Also

The CPython core development team has written a detailed guide on the GC algorithm.

Initialization

The `PyGC_Collect()` entry-point follows five steps to start, and stop the garbage collector.

1. Get the Garbage Collection state, `GCState` from the interpreter
2. Check to see if the GC is enabled
3. Check to see if the GC is already running
4. Run the collection function, `collect()` with progress callbacks
5. Mark the GC as completed

When the collection stage is run and completed, callback methods can be user-specified by the `gc.callbacks` list. Callbacks should have a method signature `f(stage: str, info: dict)`:

```
Python 3.9.0b5 (tags/v3.9.0b5:8ad7d50, Jul 21 2020, 10:00:00)
[Clang 6.0 (clang-600.0.57)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> import gc
>>> def gc_callback(phase, info):
...  print(f"GC phase:{phase} with info:{info}")
...
>>> gc.callbacks.append(gc_callback)
>>> x = []
>>> x.append(x)
>>> del x
>>> gc.collect()
GC phase:start with info:{'generation': 2, 'collected': 0, 'uncollectable': 0}
GC phase:stop with info:{'generation': 2, 'collected': 1, 'uncollectable': 0}
1
```

The Collection Stage

In the main GC function, `collect()` targets a particular generation. There are 3 generations in CPython. Before you understand the purpose of the generations, it's important to understand the collection algorithm.

For each collection, the GC will use a doubly-linked list of type `PyGC_HEAD`.

So that the GC doesn't have to "find" all container types, all container types that are a target for the GC have an additional header. This header links them all together in a doubly-linked list. When one of these container types is created, it adds itself to the list, and when it is destroyed, it removes itself.

You can see an example of this in the `cellobject.c` type:

`Objects` ▸ `cellobject.c` line 7

```
PyObject *
PyCell_New(PyObject *obj)
{
    PyCellObject *op;

    op = (PyCellObject *)PyObject_GC_New(PyCellObject, &PyCell_Type);
    if (op == NULL)
        return NULL;
    op->ob_ref = obj;
    Py_XINCREF(obj);

>>  _PyObject_GC_TRACK(op);
    return (PyObject *)op;
}
```

Because cells are mutable, the object is marked to be tracked by a call to `_PyObject_GC_TRACK()`.

When cell objects are deleted, the `cell_dealloc()` function is called. This function takes three steps:

1. The destructor tells the GC to stop tracking this instance by calling `_PyObject_GC_UNTRACK()`. Because it has been destroyed, it's contents don't need to be checked for changes in subsequent collections.
2. `Py_XDECREF` is a standard call in any destructor to decrement the reference counter. The reference counter for an object is initialized to 1, so this counters that operation.
3. The `PyObject_GC_Del()` will remove this object from the GC linked-list by calling `gc_list_remove()` and then free the memory with `PyObject_FREE()`.

`Objects` ▸ `cellobject.c` line 79

```
static void
cell_dealloc(PyCellObject *op)
{
    _PyObject_GC_UNTRACK(op);
    Py_XDECREF(op->ob_ref);
    PyObject_GC_Del(op);
}
```

When a collection starts, it will merge younger generations into the current. For example, if you are collecting the second generation, when it starts collecting, it will merge the first generation's objects into the GC list using `gc_list_merge()`.

The GC will then determine unreachable objects in the `young` (currently targeted) generation.

The logic for determining unreachable objects is located in `deduce_unreachable()`. It follows these stages:

1. For every object in the generation, copy the reference count value `ob->ob_refcnt` to `ob->gc_ref`.
2. For every object, subtract internal (cyclical) references from `gc_refs` to determine how many objects can be collected by the GC. If `gc_refs` ends up equal to 0, that means it is unreachable.
3. Create a list of unreachable objects and add every object that met

the criteria in (2) to it.

4. Remove every object that met the criteria in (2) from the generation list.

There is no single method for determining cyclical references. Each type must define a custom function with signature `traverseproc` in the `tp_traverse` slot. To complete task (2), the `deduce_unreachable()` function will call the traversal function for every object within a `subtract_refs()` function.
It is expected that the traversal function will run the callback `visit_decref()` for every item it contains:

`Modules` ▸ `gcmodule.c` line 462

```
static void
subtract_refs(PyGC_Head *containers)
{
    traverseproc traverse;
    PyGC_Head *gc = GC_NEXT(containers);
    for (; gc != containers; gc = GC_NEXT(gc)) {
        PyObject *op = FROM_GC(gc);
        traverse = Py_TYPE(op)->tp_traverse;
        (void) traverse(FROM_GC(gc),
                       (visitproc)visit_decref,
                       op);
    }
}
```

The traversal functions are kept within each object's source code in `Objects`. For example, the `tuple` type's traversal, `tupletraverse()` calls `visit_decref()` on all of it's items. The dictionary type, will call `visit_decref()` on all keys and values.

Any object which did not end up being moved to the `unreachable` list graduates to the next generation.

Freeing Objects

Once unreachable objects have been determined, they can be (carefully) freed following these stages.

The approach depends on whether the type implements the old or the new finalizer slot:

1. If an object has defined a finalizer in the legacy `tp_del` slot, it cannot safely be deleted and is marked as `uncollectable`. These are added to the `gc.garbage` list for the developer to destroy manually.
2. If an object has defined a finalizer in the `tp_finalize` slot, mark the objects as finalized to avoid calling them twice.
3. If an object in (2) has been "resurrected" by being initialized again, the GC reruns the collection cycle.
4. For all objects, call the `tp_clear` slot. This slot changes the reference count, `ob_refcnt`, to 0, triggering the freeing of memory.

Generational GC

Generational garbage collection is a technique based on the observation that most (80%+) objects are destroyed shortly after being created.

CPython's GC uses three generations that have thresholds to trigger their collections. The youngest generation (`0`) has a high threshold to avoid the collection loop being run too frequently. If an object survives the GC, it will move to the second generation, and then the third.

In the collection function, a single generation is targeted, and it merges younger generations into it before execution. For this reason, if you run `collect()` on generation `1`, it will collect generation `0`. Likewise, running collect on generation `2` will `collect()` generations `0` and `1`.

When objects are instantiated, the generational counters are incremented. When the counter reaches a user-defined threshold, `collect()` is automatically run.

Using the GC API From Python

CPython's standard library comes with a Python module to interface with the arena and the garbage collector, the `gc` module. Here's how to use the `gc` module in debug mode:

```
>>> import gc
>>> gc.set_debug(gc.DEBUG_STATS)
```

This will print the statistics whenever the garbage collector is run:

```
gc: collecting generation 2...
gc: objects in each generation: 3 0 4477
gc: objects in permanent generation: 0
gc: done, 0 unreachable, 0 uncollectable, 0.0008s elapsed
```

You use the `gc.DEBUG_COLLECTABLE` to discover when items are collected for garbage. When you combine this with the `gc.DEBUG_SAVEALL` debug flag, it will move items to a list, `gc.garbage` once they have been collected:

```
>>> import gc
>>> gc.set_debug(gc.DEBUG_COLLECTABLE | gc.DEBUG_SAVEALL)
>>> z = [0, 1, 2, 3]
>>> z.append(z)
>>> del z
>>> gc.collect()
gc: collectable <list 0x10d594a00>
>>> gc.garbage
[[0, 1, 2, 3, [...]]]
```

You can get the threshold after which the garbage collector is run by calling `get_threshold()`:

```
>>> gc.get_threshold()
(700, 10, 10)
```

You can also get the current threshold counts:

```
>>> gc.get_count()
(688, 1, 1)
```

Lastly, you can run the collection algorithm manually for a generation, and it will return the collected total:

```
>>> gc.collect(0)
24
```

If you don't specify a generation, it will default to `2`, which merges generations `0` and `1`:

```
>>> gc.collect()
20
```

Conclusion

In this chapter, you've been shown how CPython allocates, manages, and frees memory. These operations happen 1000s of times during the lifecycle of even the simplest Python script. The reliability and scalability of CPython's Memory Management system are what enables it to scale from a 2-line script all the way to run some of the world's biggest websites.

The Object and Raw Memory Allocation systems you've been shown in this chapter will come in useful if you develop C extension modules. C extension modules require an intimate knowledge of CPython's Memory Management system. Even a single missing `Py_INCREF()` can cause a memory leak or system crash.

When working with pure Python code, knowledge of the GC is useful if you're designing long-running Python code. For example, if you designed a single function that executes over hours, days, or even longer. This function would need to carefully manage its memory within the constraints of the system on which it's executing. You can use some of the techniques learned in this chapter to control and tweak the GC generations to better optimize your code and its memory footprint.

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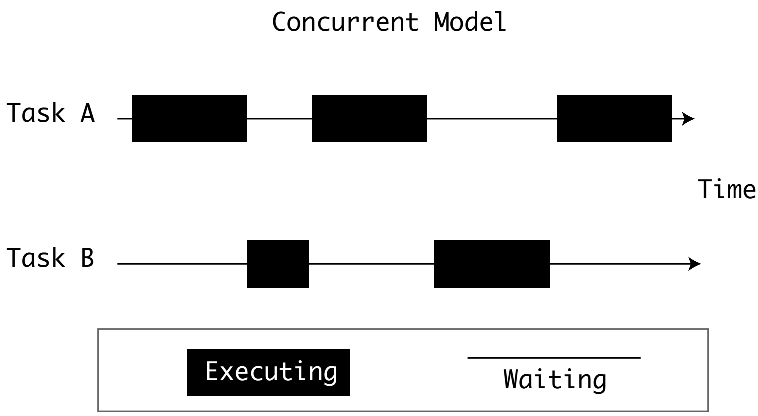
Parallelism and Concurrency

The first computers were designed to do one thing at a time. A lot of their work was in the field of computational mathematics. As time went on, computers are needed to process inputs from a variety of sources. Some input as far away as distant galaxies. The consequence of this is that computer applications spend a lot of time idly waiting for responses. Whether they be from a bus, an input, memory, computation, an API, or a remote resource.

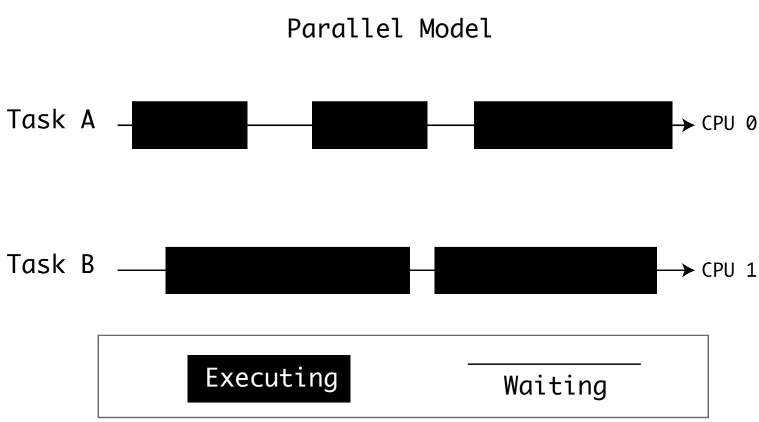
Another progression in computing was the move in Operating Systems away from a single-user terminal, to a multitasking Operating System. Applications needed to run in the background to listen and respond on the network and process inputs such as the mouse cursor. Multitasking was required way before modern multiple-core CPUs, so Operating Systems long could share the system resources between multiple processes.

At the core of any Operating System is a registry of running processes. Each process will have an owner, and it can request resources, like memory or CPU. In the last chapter, you explored memory allocation. For a CPU, the process will request CPU time in the form of operations to be executed. The Operating System controls which process is using the CPU. It does this by allocating "CPU Time" and scheduling processes by a priority:



A single process may need to do multiple things at once. For example, if you use a word processor, it needs to check your spelling while you're typing. Modern applications accomplish this by running multiple threads, concurrently, and handling their own resources.

Concurrency is an excellent solution to dealing with multitasking, but CPUs have their limits. Some high-performance computers deploy either multiple CPUs or multiple cores to spread tasks. Operating Systems provide a way of scheduling processes across multiple CPUs:



In summary,

- To have **parallelism**, you need multiple computational units. Computational units can be CPUs or Cores.
- To have **concurrency**, you need a way of scheduling tasks so that idle ones don't lock the resources.

Many parts of CPython's design abstract the complexity of Operating Systems to provide a simple API for developers. CPython's approach to parallelism and concurrency is no exception.

Models of Parallelism and Concurrency

CPython offers many approaches to Parallelism and Concurrency. Your choice depends on several factors. There are also overlapping use cases across models as CPython has evolved.

You may find that for a particular problem, there are two or more concurrency implementations to choose from. Each with their own pros and cons.

The four bundled models with CPython are:

Approach	Module	Concurrent	Parallel
Threading	`threading`	Yes	No
Multiprocessing	`multiprocessing`	Yes	Yes
Async	`asyncio`	Yes	No
Subinterpreters	`subinterpreters`	Yes	Yes

The Structure of a Process

One of the tasks for an Operating System, like Windows, macOS, or Linux, is to control the running processes. These processes could be UI applications like a browser or IDE. They could also be background processes, like network services or OS services.

To control these processes, the OS provides an API to start a new process. When a process is created, it is registered by the Operating System so that it knows which processes are running. Processes are given a unique ID (PID). Depending on the Operating System, they have other properties.

POSIX processes have a minimum set of properties, registered in the Operating System:

- Controlling Terminal
- Current Working Directory
- Effective Group ID, Effective User ID
- File Descriptors, File Mode Creation Mask
- Process Group ID, Process ID
- Real Group ID, Real User ID
- Root Directory

You can see these attributes for running processes in macOS or Linux by running the `ps` command.

See Also

The IEEE POSIX Standard (1003.1-2017) defines the interface and standard behaviors for processes and threads.

Windows has a similar list of properties but sets its own standard. The Windows file permissions, directory structures, and process registry are very different from POSIX. Windows processes, represented by `Win32_Process`, can be queried in WMI, the Windows Management Interface runtime, or by using the Task Manager.

Once a process is started on an Operating System, it is given:

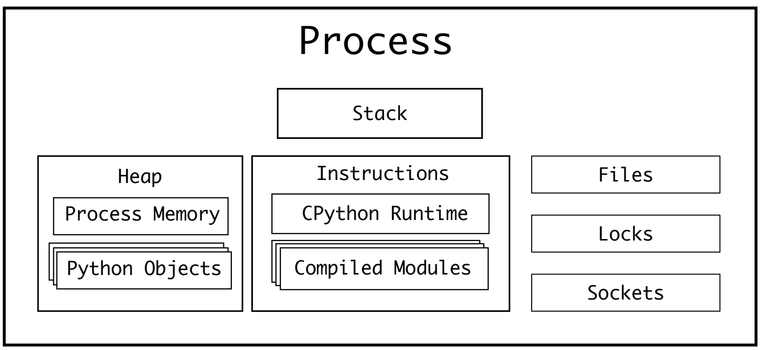
- A **Stack** of memory for calling subroutines
- A **Heap** (see Dynamic Memory Allocation in C)

- Access to **Files**, **Locks**, and **Sockets** on the Operating System

The CPU on your computer also keeps additional data when the process is executing, such as :

- **Registers** holding the current instruction being executed or any other data needed by the process for that instruction
- An **Instruction Pointer**, or **Program Counter** indicating which instruction in the program sequence is being executed

The CPython process comprises of the compiled CPython interpreter, and the compiled modules. These modules are loaded at runtime and converted into instructions by the CPython Evaluation Loop:



The program register and program counter point to a **single** instruction in the process. This means that only one instruction can be executing at any one time.

For CPython, this means that only one Python bytecode instruction can be executing at any one time.

There are two main approaches to allowing parallel execution of instructions in a process:

1. Fork another process

2. Spawn a thread

Now that you have reviewed what makes up a process. Next, you can explore forking and spawning child processes.

Multi-Process Parallelism

POSIX systems provide an API for any process to **fork** a child process.

Forking processes is a low-level API call to the Operating System that can be made by any running process.

When this call is made, the OS will clone all the attributes of the currently running process and create a new process.

This clone operation includes the heap, register, and counter position of the parent process. The child process can read any variables from the parent process at the time of forking.

Forking a Process in POSIX

As an example, take the Fahrenheit to Celcius example application used at the beginning of Dynamic Memory Allocation in C. Adapt it to spawn a child process for each Fahrenheit value instead of calculating them in sequence.

This is accomplished by using the `fork()` function. Each child process will continue operating from that point:

cpython-book-samples ▸ 33 ▸ thread_celcius.c

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

static const double five_ninths = 5.0/9.0;

double celsius(double fahrenheit){
```

```
    return (fahrenheit - 32) * five_ninths;
}

int main(int argc, char** argv) {
    if (argc != 2)
        return -1;
    int number = atoi(argv[1]);
    for (int i = 1 ; i <= number ; i++ ) {
        double f_value = 100 + (i*10);
        pid_t child = fork();
        if (child == 0) { // Is child process
            double c_value = celsius(f_value);
            printf("%f F is %f C (pid %d)n", f_value, c_value, getpid());
            exit(0);
        }
    }
    printf("Spawned %d processes from %dn", number, getpid());
    return 0;
}
```

Running this on the command-line would give an output similar to:

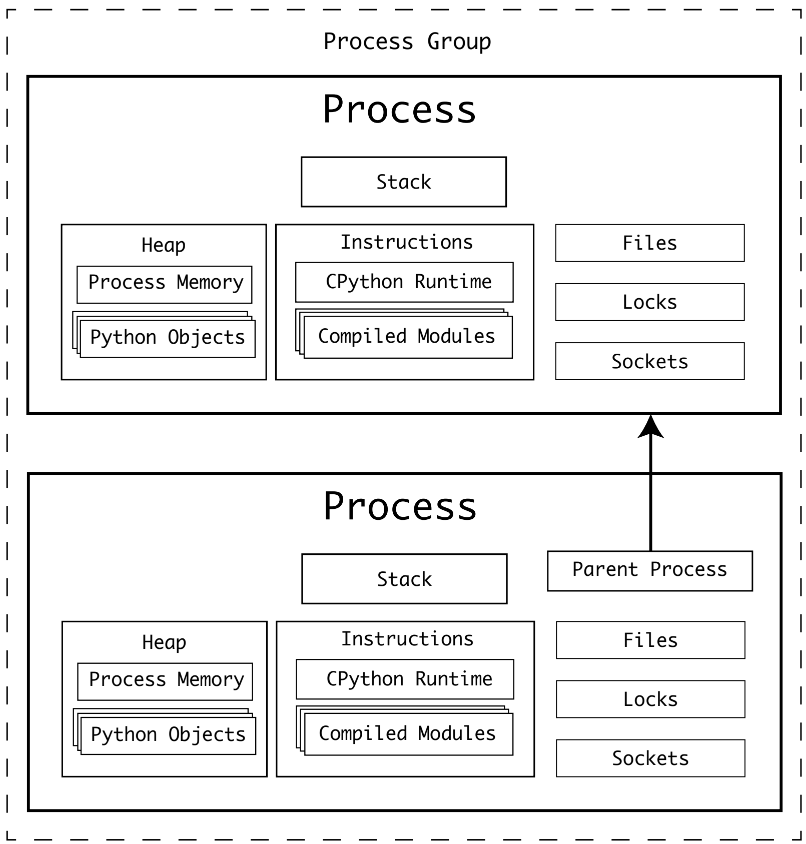
```
 $ ./thread_celcius 4
110.000000 F is 43.333333 C (pid 57179)
120.000000 F is 48.888889 C (pid 57180)
Spawned 4 processes from 57178
130.000000 F is 54.444444 C (pid 57181)
140.000000 F is 60.000000 C (pid 57182)
```

The parent process (57178), spawned 4 processes. For each child process, it continued at the line `child = fork()`, where the resulting value of `child` is 0. It then completes the calculation, prints the value, and exits the process.

Finally, the parent process outputs how many processes it spawned, and it's own PID.

The time taken for the 3rd and 4th child processes to complete was longer than it took for the parent process to complete. This is why the parent process prints the final output before the 3rd and 4th print their own.

A parent process can exit, with its own exit code before a child process. Child Processes will be added to a Process Group by the Operating System, making it easier to control all related processes:



The biggest downside with this approach to parallelism is that the child process is a complete copy of the parent process.

In the case of CPython, this means you would have 2 CPython interpreters running, and both would have to load the modules and all the libraries. It creates significant overhead. Using multiple processes makes sense when the overhead of forking a process is outweighed by the size of the task being completed.

Another major downside of forked processes is that they have a separate, isolated, heap from the parent process. This means that the child process cannot write to the memory space of the parent process. When creating the child process, the parent's heap becomes available to the child process. To send information back to the parent, some form of Inter-Process-Communication (IPC) must be used.

> **Note**
>
> The `os` module offers a wrapper around the `fork()` function.

Multi-Processing in Windows

So far, you've been reading the POSIX model. Windows doesn't provide an equivalent to `fork()`, and Python *should* (as best as possible) have the same API across Linux, macOS, and Windows.

To overcome this, the `CreateProcessW()` API is used to spawn another `python.exe` process with a `-c` command-line argument.

This step is known as "spawning," a process and is also available on POSIX. You'll see references to it throughout this chapter.

The `multiprocessing` Package

CPython provides an API on top of the Operating System process forking API. This API makes it simple to create multi-process parallelism in Python.

This API is available from the `multiprocessing` package. This package provides expansive capabilities for pooling processes, queues, forking, creating shared memory heaps, connecting processes together, and more.

Related Source Files

Source files related to multiprocessing are:

File	Purpose
`Lib ▸ multiprocessing`	Python Source for the `multiprocessing` package
`Modules ▸ _posixsubprocess.c` |	C extension module wrapping the POSIX `fork()` syscall
`Modules ▸ _winapi.c` |	C extension module wrapping the Windows Kernel APIs
`Modules ▸ _multiprocessing` |	C extension module used by the `multiprocessing` package
`PC ▸ msvcrtmodule.c`	A Python interface to the Microsoft Visual C Runtime Library

Spawning and Forking Processes

The multiprocessing package offers three methods to start a new parallel process.

1. Forking an Interpreter (on POSIX only)
2. Spawning a new Interpreter process (on POSIX and Windows)
3. Running a Fork Server, where a new process is created which then forks any number of processes (on POSIX only)

Note

For Windows and macOS, the default start method is Spawning. For Linux, the default is Forking. You can override the default method using the `multiprocessing.set_start_method()` function.

The Python API for starting a new process takes a callable, `target`, and a tuple of arguments, `args`.

Take this simple example of spawning a new process to convert Fahrenheit to Celcius:

cpython-book-samples ▸ 33 ▸ spawn_process_celcius.py

```
import multiprocessing as mp
import os

def to_celcius(f):
    c = (f - 32) * (5/9)
    pid = os.getpid()
    print(f"{f}F is {c}C (pid {pid})")

if __name__ == '__main__':
    mp.set_start_method('spawn')
    p = mp.Process(target=to_celcius, args=(110,))
    p.start()
```

While you can start a single process, the `multiprocessing` API assumes you want to start multiple. There are convenience methods for spawning multiple processes and feeding them sets of data. One of those methods is the `Pool` class.

The previous example can be expanded to calculate a range of values in separate Python interpreters:

cpython-book-samples ▸ 33 ▸ pool_process_celcius.py

```
import multiprocessing as mp
import os

def to_celcius(f):
    c = (f - 32) * (5/9)
    pid = os.getpid()
    print(f"{f}F is {c}C (pid {pid})")

if __name__ == '__main__':
    mp.set_start_method('spawn')
    with mp.Pool(4) as pool:
        pool.map(to_celcius, range(110, 150, 10))
```

Note that the output shows the same PID. Because the CPython interpreter process has a signification overhead, the `Pool` will consider each process in the pool a "worker." If a worker has completed, it will be reused. If you replace the line:

```
    with mp.Pool(4) as pool:
```

with:

```
    with mp.Pool(4, maxtasksperchild=1) as pool:
```

Thie previous multiprocessing example will print something similar to:

```
 $ python pool_process_celcius.py
110F is 43.333333333333336C (pid 5654)
120F is 48.88888888888889C (pid 5653)
130F is 54.44444444444445C (pid 5652)
140F is 60.0C (pid 5655)
```

The output shows the process IDs of the newly spawned processes and the calculated values.

Creation of Child Processes

Both of these scripts will create a new Python interpreter process and pass data to it using `pickle`.

> **See Also**
>
> The `pickle` module is a serialization package used for serializing Python objects. Davide Mastromatteo has written a great write up of the pickle module at realpython.com.

For POSIX systems, the creation of the subprocess by the `multiprocessing` module is equivalent to this command:

```
$ python -c 'from multiprocessing.spawn import spawn_main;
    spawn_main(tracker_fd=<i>, pipe_handle=<j>)' --multiprocessing-fork
```

Where `<i>` is the filehandle descriptor, and `<j>` is the pipe handle descriptor.

For Windows systems, the parent PID is used instead of a tracker file descriptor:

```
> python.exe -c 'from multiprocessing.spawn import spawn_main;
    spawn_main(parent_pid=<k>, pipe_handle=<j>)' --multiprocessing-fork
```

Where `<k>` is the parent PID and `<j>` is the pipe handle descriptor.

Piping Data to the Child Process

When the new child process has been instantiated on the OS, it will wait for initialization data from the parent process.

The parent process writes 2 objects to a pipe file stream. The pipe file stream is a special IO stream used to send data between processes on the command line.

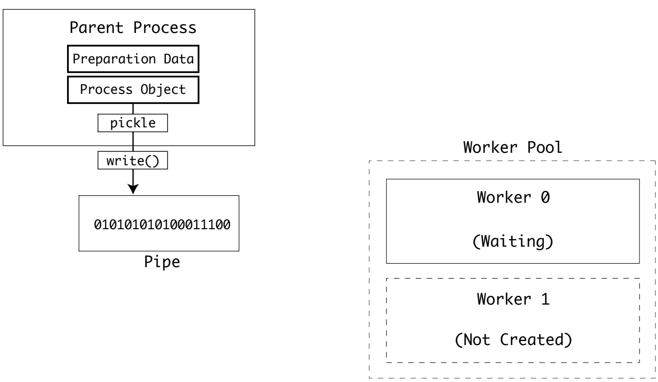
The first object written by the parent process is the **preparation data** object. This object is a dictionary containing some information about the parent, such as the executing directory, the start method, any special command-line arguments, and the `sys.path`. You can see an example of what is generated by running `multiprocessing.spawn.get_preparation_data(name)`:

```
>>> import multiprocessing.spawn
>>> import pprint
>>> pprint.pprint(multiprocessing.spawn.get_preparation_data("example"))
{'authkey': b'x90xaa_x22[x18rixbcag]x93xfexf5xe5@[wJx99p#x00'
            b'xcexd4)1j.xc3c',
 'dir': '/Users/anthonyshaw',
 'log_to_stderr': False,
 'name': 'example',
 'orig_dir': '/Users/anthonyshaw',
 'start_method': 'spawn',
 'sys_argv': [''],
 'sys_path': [
```

```
    '/Users/anthonyshaw',
    ]}
```

The second object written is the `BaseProcess` child class instance. Depending on how multiprocessing was called and which Operating System is being used, one of the child classes of `BaseProcess` will be the instance serialized.

Both the preparation data and process object are serialized using the `pickle` module and written to the parent process' pipe stream:



Note

The POSIX implementation of the child process spawning and serialization process is located in `Lib` ▸ `multiprocessing` ▸ `popen_spawn_posix.py`. The Windows implementation is located in `Lib` ▸ `multiprocessing` ▸ `popen_spawn_win32.py`.

Executing the Child Process

The entry point of the child process, `multiprocessing.spawn.spawn_main()` takes the argument `pipe_handle` and either `parent_pid` for Windows or `tracked_fd` for POSIX:

```
def spawn_main(pipe_handle, parent_pid=None, tracker_fd=None):
    '''
    Run code specified by data received over pipe
    '''
    assert is_forking(sys.argv), "Not forking"
```

For Windows, the function will call the `OpenProcess` API of the parent PID.

This process object is used to create a filehandle, `fd`, of the parent process pipe:

```
    if sys.platform == 'win32':
        import msvcrt
        import _winapi

        if parent_pid is not None:
            source_process = _winapi.OpenProcess(
                _winapi.SYNCHRONIZE | _winapi.PROCESS_DUP_HANDLE,
                False, parent_pid)
        else:
            source_process = None
        new_handle = reduction.duplicate(pipe_handle,
                                         source_process=source_process)
        fd = msvcrt.open_osfhandle(new_handle, os.O_RDONLY)
        parent_sentinel = source_process
```

For POSIX, the `pipe_handle` becomes the file descriptor, `fd`, and is duplicated to become the `parent_sentinel` value:

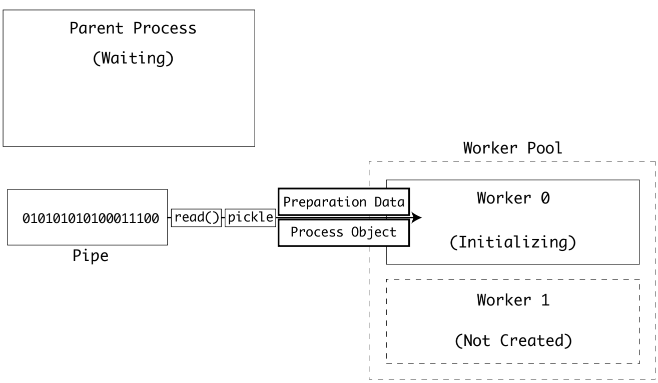
```
    else:
        from . import resource_tracker
        resource_tracker._resource_tracker._fd = tracker_fd
        fd = pipe_handle
        parent_sentinel = os.dup(pipe_handle)
```

Next, the `_main()` function is called with the parent pipe file handle, `fd`, and the parent process sentinel, `parent_sentinel`. Whatever the return value of `_main()` is becomes the exit code for the process and the interpreter is terminated:

```
exitcode = _main(fd, parent_sentinel)
sys.exit(exitcode)
```

The `_main()` function is called with the file descriptor of the parent processes pipe and the parent sentinel for checking if the parent process has exited whilst executing the child.

The main function deserialises the binary data on the `fd` byte stream. Remember, this is the `pipe` file handle. The deserialization happens using using same `pickle` library that the parent process used:



The first value is a `dict` containing the preparation data. The second value is an instance of `SpawnProcess` which is then used at the instance to call `_bootstrap()` upon:

```python
def _main(fd, parent_sentinel):
    with os.fdopen(fd, 'rb', closefd=True) as from_parent:
        process.current_process()._inheriting = True
        try:
            preparation_data = reduction.pickle.load(from_parent)
            prepare(preparation_data)
            self = reduction.pickle.load(from_parent)
```

```
        finally:
            del process.current_process()._inheriting
    return self._bootstrap(parent_sentinel)
```

The `_bootstrap()` function handles the instantiation of a `BaseProcess` instance from the deserialized data, and then the target function is called with the arguments and keyword arguments. This final task is completed by `BaseProcess.run()`:

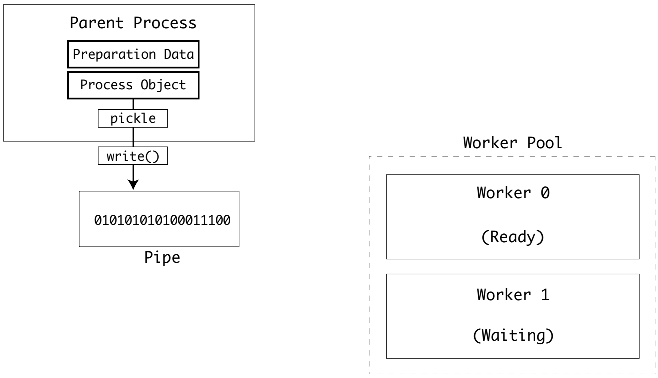
```
    def run(self):
        '''
        Method to be run in sub-process; can be overridden in sub-class
        '''
        if self._target:
            self._target(*self._args, **self._kwargs)
```

The exit code of `self._bootstrap()` is set as the exit code, and the child process is terminated.

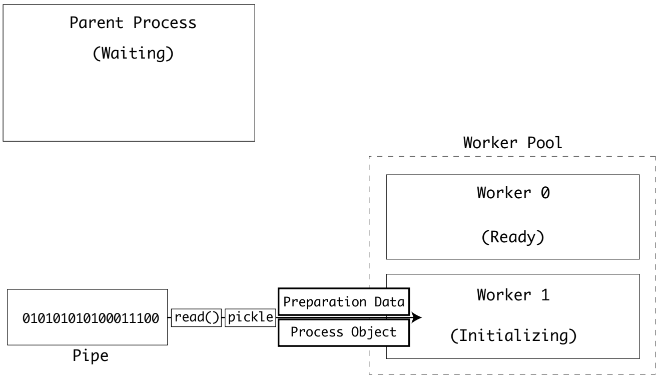
This process allows the parent process to serialize the module and the executable function. It also allows the child process to deserialize that instance, execute the function with arguments, and return.

It does not allow for the exchanging of data once the child process has started. This task is done using the extension of the `Queue` and `Pipe` objects.

If processes are being created in a pool, the first process will be ready and in a waiting state. The parent process repeats the process and sends the data to the next worker:



The next worker receives the data and initializes its state and runs the target function:



To share any data beyond initialization, queues and pipes must be used.

Exchanging Data with Queues and Pipes

In the previous section you saw how child processes are spawned, and then the pipe is used as a serialization stream to tell the child process what function to call with arguments.

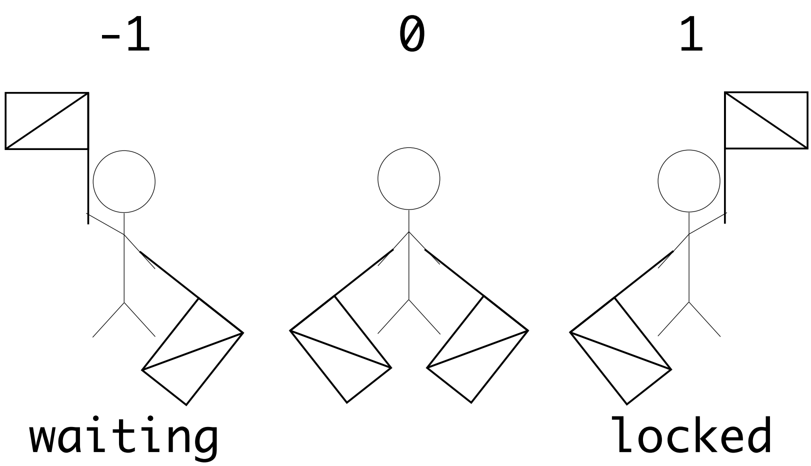
There is two types of communication between processes, depending on the nature of the task.

Semaphores

Many of the mechanisms in multiprocessing use **semaphores** as a way of signaling that resources are locked, being waited on, or not used. Operating Systems use binary semaphores as a simple variable type for locking resources, like files, sockets, and other resources.

If one process is writing to a file or a network socket, you don't want another process to suddenly start writing to the same file. The data would become corrupt instantly. Instead, Operating Systems put a "lock" on resources using a semaphore. Processes can also signal that they are waiting for that lock to be released so that when it is, they get a message to say it is ready and they can start using it.

Semaphores (in the real world) are a signaling method using flags, so the states for a resource of waiting, locked and not-used would look like:



The semaphore API is different between Operating Systems, so there is an abstraction class, `multiprocessing.synchronize.Semaphore`.

Semaphores are used by CPython for multiprocessing because they are both thread-safe and process-safe. The Operating System handles any potential deadlocks of reading or writing to the same semaphore.

The implementation of these semaphore API functions is located in a C extension module `Modules ▸ _multiprocessing ▸ semaphore.c`. This extension module offers a single method for creating, locking, releasing semaphores, and other operations.

The call to the Operating System is through a series of Macros, which are compiled into different implementations depending on the Operating System platform. For Windows, the `<winbase.h>` API functions for semaphores are used:

```
#define SEM_CREATE(name, val, max) CreateSemaphore(NULL, val, max, NULL)
#define SEM_CLOSE(sem) (CloseHandle(sem) ? 0 : -1)
#define SEM_GETVALUE(sem, pval) _GetSemaphoreValue(sem, pval)
#define SEM_UNLINK(name) 0
```

For POSIX, the macros use the `<semaphore.h>` API is used:

```
#define SEM_CREATE(name, val, max) sem_open(name, O_CREAT | O_EXCL, 0600, val)
#define SEM_CLOSE(sem) sem_close(sem)
#define SEM_GETVALUE(sem, pval) sem_getvalue(sem, pval)
#define SEM_UNLINK(name) sem_unlink(name)
```

Queues

Queues are a great way of sending small data to and from multiple processes.

If you adapt the multiprocessing example before to use a `multiprocessing Manager()` instance, and create two queues:

1. `inputs` to hold the input Fahrenheit values
2. `outputs` to hold the resulting Celcius values

Change the pool size to `2` so that there are two workers:

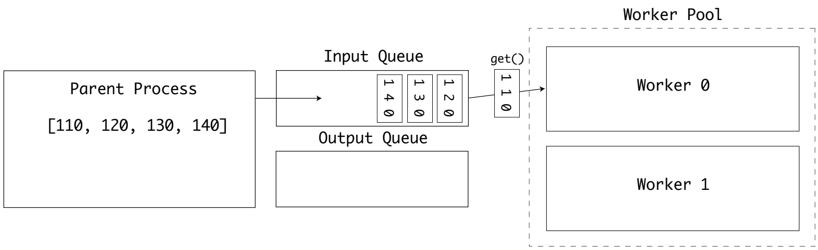
cpython-book-samples ▸ 33 ▸ pool_queue_celcius.py

```python
import multiprocessing as mp

def to_celcius(input: mp.Queue, output: mp.Queue):
    f = input.get()
    # time-consuming task ...
    c = (f - 32) * (5/9)
    output.put(c)

if __name__ == '__main__':
    mp.set_start_method('spawn')
    pool_manager = mp.Manager()
    with mp.Pool(2) as pool:
        inputs = pool_manager.Queue()
        outputs = pool_manager.Queue()
        input_values = list(range(110, 150, 10))
        for i in input_values:
            inputs.put(i)
            pool.apply(to_celcius, (inputs, outputs))

        for f in input_values:
            print(outputs.get(block=False))
```

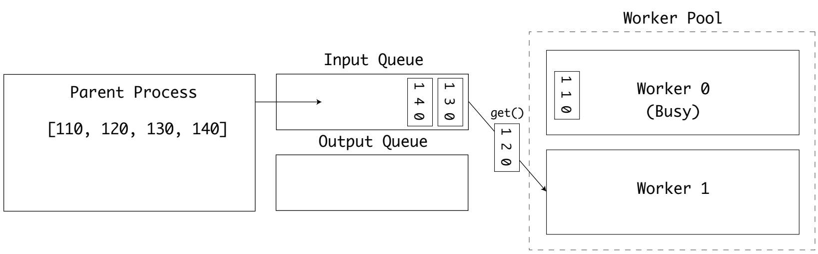
This would print the list of tuples returned to the `results` queue:

```
$ python pool_queue_celcius.py
43.333333333333336
48.88888888888889
54.44444444444445
60.0
```

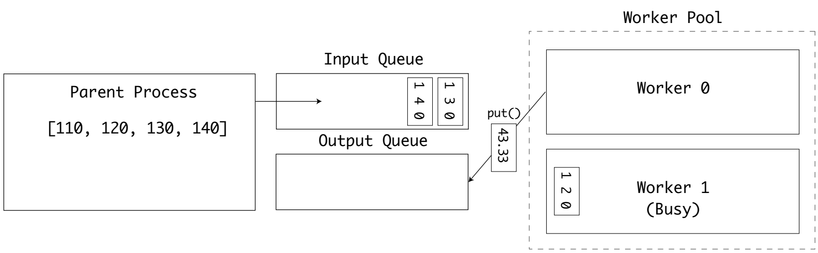
The parent process first puts the input values onto the input queue. The first worker then takes an item from the queue. Each time an item is taken from the queue using `.get()`, a semaphore lock is used on the queue object:



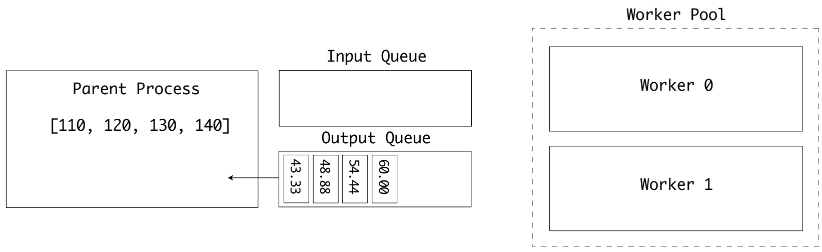
While this worker is busy, the second worker then takes another value from the queue:



The first worker has completed its calculation and puts the resulting value onto the result queue:



Two queues are in use to separate the input and output values. Eventually, all input values have been processed, and the output queue is full. The values are then printed by the parent process:

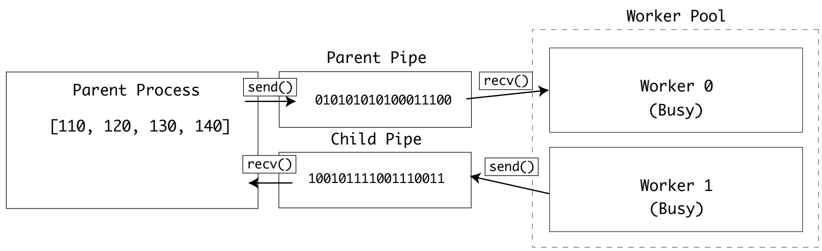


This example shows how a pool of workers could receive a queue of small, discreet values and process them in parallel to send the resulting data back to the host process. In practice, converting Celcius to Fahrenheit is a small, trivial calculation unsuited for parallel execution. If the worker process were doing another CPU-intensive calculation, this would provide significant performance improvement on a multi-CPU or multi-core computer.

For streaming data instead of discrete queues, pipes can be used instead.

Pipes

Within the `multiprocessing` package, there is a type `Pipe`. Instantiating a Pipe returns two connections, a parent and a child. Both can send and receive data:



In the queue example, a lock is implicitly placed on the queue when data is sent and received. Pipes do not have that behavior, so you have to be careful that two processes do not try and write to the same pipe at the same time.

If you adapt the last example to work with a pipe, it will require changing the `pool.apply()` to `pool.apply_async()`. This changes the execution of the next process to a non-blocking operation:

cpython-book-samples ▸ 33 ▸ pool_pipe_celcius.py

```
import multiprocessing as mp

def to_celcius(child_pipe: mp.Pipe, parent_pipe: mp.Pipe):
    f = parent_pipe.recv()
    # time-consuming task ...
    c = (f - 32) * (5/9)
    child_pipe.send(c)

if __name__ == '__main__':
    mp.set_start_method('spawn')
    pool_manager = mp.Manager()
    with mp.Pool(2) as pool:
        parent_pipe, child_pipe = mp.Pipe()
        results = []
        for i in range(110, 150, 10):
            parent_pipe.send(i)
            pool.apply_async(to_celcius, args=(child_pipe, parent_pipe))
            print(child_pipe.recv())
        parent_pipe.close()
        child_pipe.close()
```

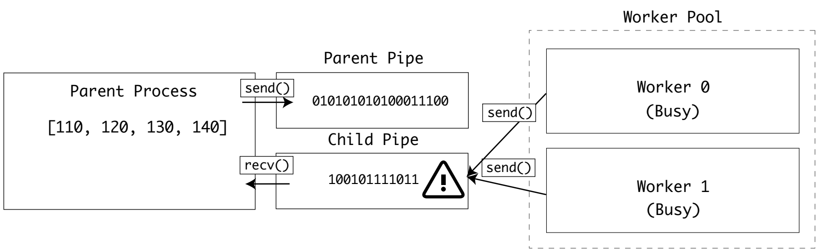
In this example, there is a risk of two or more processes trying to read from the parent pipe at the same time on the line:

```
    f = parent_pipe.recv()
```

There is also a risk of two or more processes trying to write to the child pipe at the same time.

```
    child_pipe.send(c)
```

If this situation occurs, data would be corrupted in either the receive or send operations:



To avoid this, you can implement a semaphore lock on the Operating System. Then all child processes will check with the Lock before reading or writing to the same pipe.

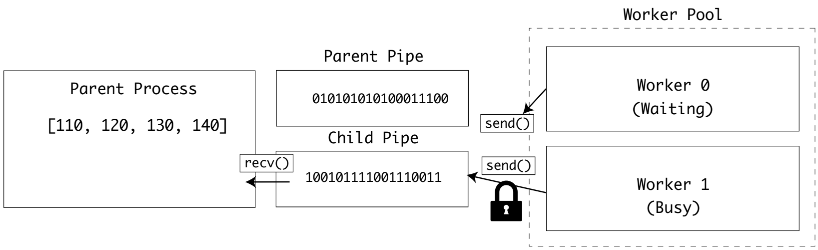
There are two locks required, one on the receiving end of the parent pipe, and another on the sending end of the child pipe:

cpython-book-samples ▸ 33 ▸ pool_pipe_locks_celcius.py

```
import multiprocessing as mp

def to_celcius(child_pipe: mp.Pipe, parent_pipe: mp.Pipe,
               child_write_lock: mp.Lock, parent_read_lock: mp.Lock):
    parent_read_lock.acquire()
    try:
        f = parent_pipe.recv()
    finally:
        parent_read_lock.release()
    # time-consuming task ...
    c = (f - 32) * (5/9)

    child_write_lock.acquire()
    try:
        child_pipe.send(c)
```

```
    finally:
        child_write_lock.release()


if __name__ == '__main__':
    mp.set_start_method('spawn')
    pool_manager = mp.Manager()
    with mp.Pool(2) as pool:
        parent_pipe, child_pipe = mp.Pipe()
        parent_read_lock = mp.Lock()
        child_write_lock = mp.Lock()
        results = []
        for i in range(110, 150, 10):
            parent_pipe.send(i)
            pool.apply_async(to_celcius, args=(child_pipe, parent_pipe,
                                               child_write_lock,
                                               parent_read_lock))
            print(child_pipe.recv())
        parent_pipe.close()
        child_pipe.close()
```

Now the worker processes will wait to acquire a lock before receiving data, and wait again to acquire another lock to send data:



This example would suit situations where the data going over the pipe is large because the chance of a collision is higher.

Shared State Between Processes

So far, you have seen how data can be shared between the child and the parent process.

There may be scenarios where you want to share data between child processes. In this situation, the `multiprocessing` package provides two solutions:

1. A performant Shared Memory API using shared memory maps and shared C types
2. A flexible Server Process API supporting complex types via the `Manager` class

Example Application

As a demonstration application, throughout this chapter, you will be refactoring a TCP port scanner for different concurrency and parallelism techniques.

Over a network, a host can be contacted on ports, which are a number from 1-65535. Common services have standard ports. For example, HTTP operates on port 80 and HTTPS on 443. TCP port scanners are used as a common network testing tool to check that packets can be sent over a network.

This code example uses the `Queue` interface, a thread-safe queue implementation similar to the one you use in the multiprocessing examples. The code also uses the `socket` package to try connecting to a remote port with a short timeout of 1 second.

The `check_port()` function will see if the `host` responds on the given `port`, and if it does respond, it adds the port number to the `results` queue.

When the script is executed, the `check_port()` function is called in sequence for port numbers 80-100.

After this has completed, the results queue is emptied out, and the results are printed on the command line.

So you can compare the difference, it will print the execution time at the end:

cpython-book-samples ▸ 33 ▸ portscanner.py

```python
from queue import Queue
import socket
import time
timeout = 1.0

def check_port(host: str, port: int, results: Queue):
    sock = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
    sock.settimeout(timeout)
    result = sock.connect_ex((host, port))
    if result == 0:
        results.put(port)
    sock.close()

if __name__ == '__main__':
    start = time.time()
    host = "localhost"  # replace with a host you own
    results = Queue()
    for port in range(80, 100):
        check_port(host, port, results)
    while not results.empty():
        print("Port {0} is open".format(results.get()))
    print("Completed scan in {0} seconds".format(time.time() - start))
```

The execution will print out the open ports and the time taken:

```
 $ python portscanner.py
Port 80 is open
Completed scan in 19.623435020446777 seconds
```

This example can be refactored to use multiprocessing. The `Queue` interface is swapped for `multiprocessing.Queue` and the ports are scanned together using a pool executor:

cpython-book-samples ▸ 33 ▸ portscanner_mp_queue.py

```python
import multiprocessing as mp
import time
import socket

timeout = 1

def check_port(host: str, port: int, results: mp.Queue):
    sock = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
    sock.settimeout(timeout)
    result = sock.connect_ex((host, port))
    if result == 0:
        results.put(port)
    sock.close()

if __name__ == '__main__':
    start = time.time()
    processes = []
    scan_range = range(80, 100)
    host = "localhost"  # replace with a host you own
    mp.set_start_method('spawn')
    pool_manager = mp.Manager()
    with mp.Pool(len(scan_range)) as pool:
        outputs = pool_manager.Queue()
        for port in scan_range:
            processes.append(pool.apply_async(check_port,
                                              (host, port, outputs)))
        for process in processes:
            process.get()
        while not outputs.empty():
            print("Port {0} is open".format(outputs.get()))
        print("Completed scan in {0} seconds".format(time.time() - start))
```

As you might expect, this application is much faster because it is testing each port in parallel:

```
$ python portscanner_mp_queue.py
Port 80 is open
Completed scan in 1.556523084640503 seconds
```

Conclusion

Multiprocessing offers a scalable, parallel execution API for Python. Data can be shared between processes, and CPU-intensive work can be broken into parallel tasks to take advantage of multiple core or CPU computers.

Multiprocessing is not a suitable solution when the task to be completed is not CPU intensive, but instead IO-bound. For example, if you spawned 4 worker processes to read and write to the same files, one would do all the work, and the other 3 would wait for the lock to be released.

Multiprocessing is also not suitable for short-lived tasks, because of the time and processing overhead of starting a new Python interpreter.

In both of those scenarios, you main find one of the next approaches is more suited.

Multithreading

CPython provides a high-level and a low-level API for creating, spawning, and controlling threads from Python.

To understand Python threads, you should first understand how Operating System threads work. There are two implementations of threading in CPython.

1. `pthreads` - POSIX threads for Linux and macOS
2. `nt threads` - NT threads for Windows

In the section on The Structure of a Process, you saw how a process has:

- A **Stack** of subroutines
- A **Heap** of memory

- Access to **Files**, **Locks**, and **Sockets** on the Operating System

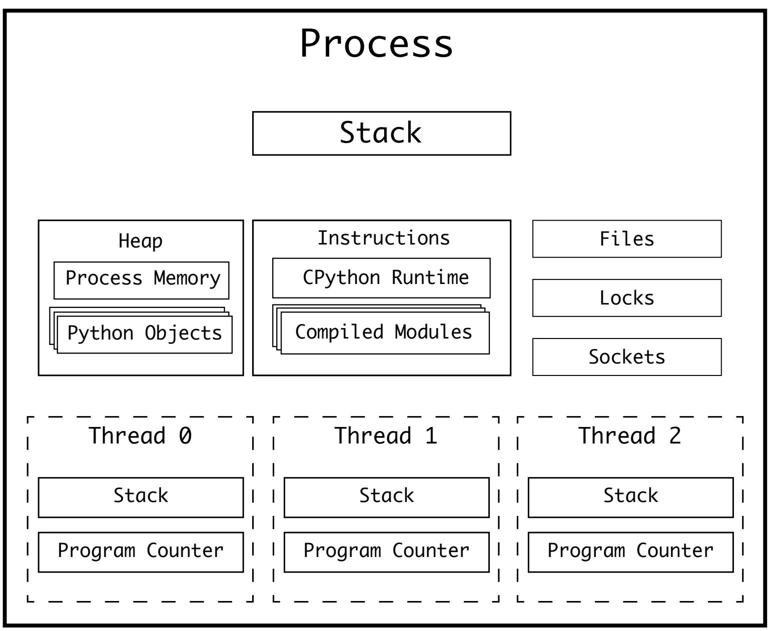
The biggest limitation to scaling a single process is that the Operating System will have a single **Program Counter** for that executable.

To get around this, modern Operating Systems allow processes to signal the Operating System to branch their execution into multiple threads.

Each thread will have its own Program Counter, but use the same resources as the host process. Each thread also has it's own call stack, so it can be executing a different function.

Because multiple threads can read and write to the same memory space, collisions could occur. The solution to this is **thread safety** and involves making sure that memory space is locked by a single thread before it is accessed.

A single process with 3 threads would have a structure:



See Also

For a great introductory tutorial on the Python threading API, check out Jim Anderson's "Intro to Python Threading."

The GIL

If you're familiar with NT threads or POSIX threads from C, or you've used another high-level language, you may expect multithreading to be parallel.

In CPython, the threads are based on the C APIs, but the threads are Python threads. This means that every Python thread needs to execute Python bytecode through the evaluation loop.

The Python evaluation loop is not thread-safe. There are many parts of the interpreter state, such as the Garbage Collector, which are shared, and global.

To get around this, the CPython developers implemented a mega-lock, called the **Global Interpreter Lock (GIL)**. Before any opcode is executed in the frame-evaluation loop, the GIL is acquired by the thread, then once the opcode has been executed, it is released.

Aside from providing a global thread-safety to every operation in Python, this approach has a major drawback. Any operations which take a long time to execute will leave other threads waiting for the GIL to be released before they can execute.

This means that only 1 thread can be executing a Python bytecode operation at any one time.

To acquire the GIL, a call is made to `take_gil()` and then again to `drop_gil()` to release it. The GIL acquisition is made within the core frame evaluation loop, `_PyEval_EvalFrameDefault()`.

To stop a single frame execution from permanently holding the GIL, the evaluation loop state stores a flag, `gil_drop_request`. After every bytecode operation has completed in a frame, this flag is checked, and the GIL is temporarily released and then reacquired:

```
    if (_Py_atomic_load_relaxed(&ceval->gil_drop_request)) {
        /* Give another thread a chance */
        if (_PyThreadState_Swap(&runtime->gilstate, NULL) != tstate) {
            Py_FatalError("ceval: tstate mix-up");
        }
        drop_gil(ceval, tstate);

        /* Other threads may run now */

        take_gil(ceval, tstate);

        /* Check if we should make a quick exit. */
        exit_thread_if_finalizing(tstate);

        if (_PyThreadState_Swap(&runtime->gilstate, tstate) != NULL) {
            Py_FatalError("ceval: orphan tstate");
        }
    }
...
```

Despite the limitations that the GIL enforces on parallel execution, it means that multithreading in Python is very safe and ideal for running IO-bound tasks concurrently.

Related Source Files

Source files related to threading are:

File	Purpose
`Include▸pythread.h`	PyThread API and definition
`Lib▸threading.py`	High Level threading API and Standard Library module
`Modules▸_threadmodule.c` |	Low Level thread API and Standard Library module
`Python▸thread.c`	C extension for the `thread` module
`Python▸thread_nt.h` |	Windows Threading API
`Python▸thread_pthread.h` |	POSIX Threading API

File	Purpose
Python▸ceval_gil.h		GIL lock implementation

Starting Threads in Python

To demonstrate the performance gains of having multithreaded code (in spite of the GIL), you can implement a simple network port scanner in Python.

Now clone the previous script but change the logic to spawn a thread for each port using `threading.Thread()`. This is similar to the `multiprocessing` API, where it takes a callable, `target`, and a tuple, `args`. Start the threads inside the loop, but don't wait for them to complete. Instead, append the thread instance to a list, `threads`:

```
    for port in range(80, 100):
        t = Thread(target=check_port, args=(host, port, results))
        t.start()
        threads.append(t)
```

Once all threads have been created, iterate through the thread list and call `.join()` to wait for them to complete:

```
    for t in threads:
        t.join()
```

Next, exhaust all the items in the `results` queue and print them to the screen:

```
    while not results.empty():
        print("Port {0} is open".format(results.get()))
```

The whole script is:

cpython-book-samples▸33▸portscanner_threads.py

```
from threading import Thread
from queue import Queue
```

```
import socket
import time

timeout = 1.0

def check_port(host: str, port: int, results: Queue):
    sock = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
    sock.settimeout(timeout)
    result = sock.connect_ex((host, port))
    if result == 0:
        results.put(port)
    sock.close()

def main():
    start = time.time()
    host = "localhost"  # replace with a host you own
    threads = []
    results = Queue()
    for port in range(80, 100):
        t = Thread(target=check_port, args=(host, port, results))
        t.start()
        threads.append(t)
    for t in threads:
        t.join()
    while not results.empty():
        print("Port {0} is open".format(results.get()))
    print("Completed scan in {0} seconds".format(time.time() - start))

if __name__ == '__main__':
    main()
```

When you call this threaded script at the command-line, it will execute 10+ times faster than the single-threaded example:

```
 $ python portscanner_threads.py
Port 80 is open
Completed scan in 1.0101029872894287 seconds
```

This also runs 50-60% faster than the multiprocessing example. Remember that multiprocessing has an overhead for starting the new processes, threading does have an overhead, but it is much smaller.

You may be wondering- if the GIL means that only a single operation can execute at once, why is this faster?

The statement that takes 1-1000ms is:

```
    result = sock.connect_ex((host, port))
```

In the C extension module, `Modules`▸`socketmodule.c`, the function that implements the connection is:

`Modules`▸`socketmodule.c` line 3245

```
static int
internal_connect(PySocketSockObject *s, struct sockaddr *addr, int addrlen,
                 int raise)
{
    int res, err, wait_connect;

    Py_BEGIN_ALLOW_THREADS
    res = connect(s->sock_fd, addr, addrlen);
    Py_END_ALLOW_THREADS
```

Surrounding the system `connect()` call are the `Py_BEGIN_ALLOW_THREADS` and `Py_END_ALLOW_THREADS` macros.

These macros are defined in `Include`▸`ceval.h` as:

```
#define Py_BEGIN_ALLOW_THREADS {
                        PyThreadState *_save;
                        _save = PyEval_SaveThread();
#define Py_BLOCK_THREADS        PyEval_RestoreThread(_save);
#define Py_UNBLOCK_THREADS      _save = PyEval_SaveThread();
#define Py_END_ALLOW_THREADS    PyEval_RestoreThread(_save);
                 }
```

So, when `Py_BEGIN_ALLOW_THREADS` is called, it calls `PyEval_SaveThread()`. This function changes the thread state to `NULL` and **drops** the GIL:

Python ▸ `ceval.c` line 444

```
PyThreadState *
PyEval_SaveThread(void)
{
    PyThreadState *tstate = PyThreadState_Swap(NULL);
    if (tstate == NULL)
        Py_FatalError("PyEval_SaveThread: NULL tstate");
    assert(gil_created());
    drop_gil(tstate);
    return tstate;
}
```

Because the GIL is dropped, it means any other executing thread can continue. This thread will sit and wait for the system call without blocking the evaluation loop.

Once the `connect()` function has succeeded or timed out, the `Py_END_ALLOW_THREADS` runs the `PyEval_RestoreThread()` function with the original thread state.
The thread state is recovered and the GIL is retaken. The call to `take_gil()` is a blocking call, waiting on a semaphore:

Python ▸ `ceval.c` line 458

```
void
PyEval_RestoreThread(PyThreadState *tstate)
{
    if (tstate == NULL)
        Py_FatalError("PyEval_RestoreThread: NULL tstate");
    assert(gil_created());

    int err = errno;
    take_gil(tstate);
    /* _Py_Finalizing is protected by the GIL */
    if (_Py_IsFinalizing() && !_Py_CURRENTLY_FINALIZING(tstate)) {
        drop_gil(tstate);
        PyThread_exit_thread();
```

```
        Py_UNREACHABLE();
    }
    errno = err;

    PyThreadState_Swap(tstate);
}
```

This is not the only system call wrapped by the non-GIL-blocking pair `Py_BEGIN_ALLOW_THREADS` and `Py_END_ALLOW_THREADS`. There are over 300 uses of it in the Standard Library. Including:

- Making HTTP requests
- Interacting with local hardware
- Encryption
- Reading and writing files

Thread State

CPython provides its own implementation of thread management. Because threads need to execute Python bytecode in the evaluation loop, running a thread in CPython isn't as simple as spawning an OS thread. Python threads are called `PyThread`, and you covered them briefly on the CPython Evaluation Loop chapter.

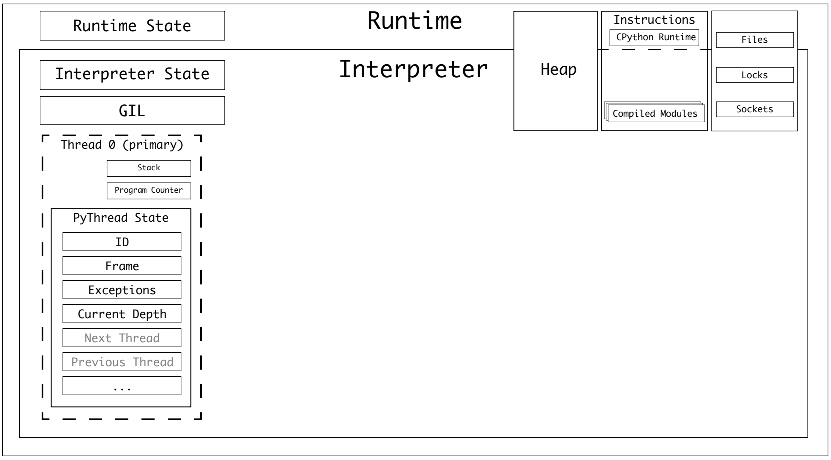
Python threads execute code objects and are spawned by the interpreter.

To recap:

- CPython has a single runtime, which has its own **runtime state**
- CPython can have one or many interpreters
- An interpreter has a state, called the **interpreter state**
- An interpreter will take a **code object** and convert it into a series of **frame objects**
- An interpreter has at least one **thread**, each thread has a **thread state**

- Frame Objects are executed in a stack, called the **frame stack**
- CPython references variables in a **value stack**
- The **interpreter state** includes a linked-list of its threads

A single-threaded, single-interpreter runtime would have the states:



The thread state type, `PyThreadState` has over 30 properties, including:

- A unique identifier
- A linked-list to the other thread states
- The interpreter state it was spawned by
- The currently executing frame
- The current recursion depth
- Optional tracing functions
- The exception currently being handled
- Any async exception currently being handled
- A stack of exceptions raised
- A GIL counter

- Async generator counters

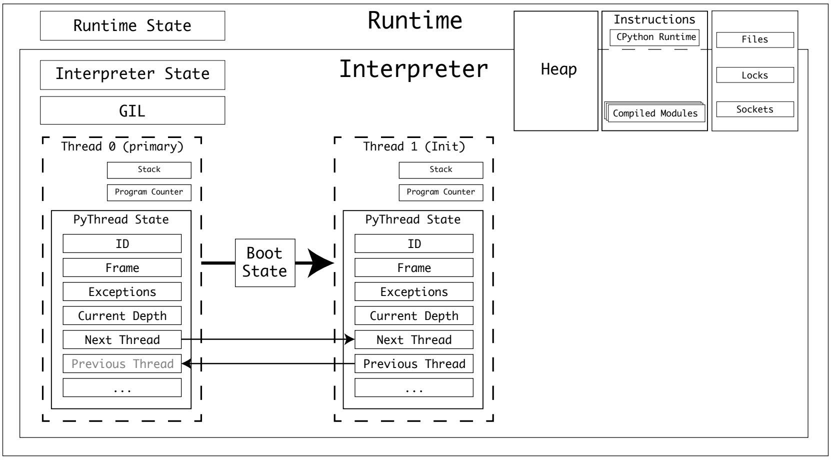
Similar to the multiprocessing **preparation data**, threads have a boot state. However, threads share the same memory space, so there is no need to serialize data and send it over a file stream.

Threads are instantiated with the `threading.Thread` type. This is a high-level module that abstracts the `PyThread` type. `PyThread` instances are managed by the C extension module `_thread`.

The `_thread` module has the entry point for executing a new thread, `thread_PyThread_start_new_thread()`. `start_new_thread()` is a method on an instance of the type `Thread`.

New threads are instantiated in this sequence:

1. The `bootstate` is created, linking to the `target`, with arguments `args` and `kwargs`
2. The `bootstate` is linked to the interpreter state
3. A new `PyThreadState` is created, linking to the current interpreter
4. The GIL is enabled, if not already with a call to `PyEval_InitThreads()`
5. The new thread is started on the Operating System-specific implementation of `PyThread_start_new_thread`



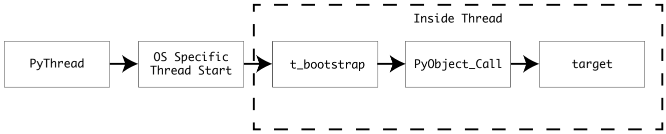
Thread `bootstate` has the properties:

Field	Type	Purpose
`interp`	`PyInterpreterState*`	Link to the interpreter managing this thread
`func`	`PyObject *` (`callable`)	Link to the `callable` to execute upon running the thread
`args`	`PyObject *` (`tuple`)	Arguments to call `func` with
`keyw`	`PyObject *` (`dict`)	Keyword arguments to call `func` with
`tstate`	`PyThreadState *`	Thread state for the new thread

With the thread bootstate, there are two implementations `PyThread` - POSIX threads for Linux and macOS, and NT threads for Windows.

Both of these implementations create the Operating System thread, set it's attribute and then execute the callback `t_bootstrap()` from within the new thread. This function is called with the single argument `boot_raw`, assigned to the bootstate constructed in `thread_PyThread_start_new_thread()`.

The `t_bootstrap()` function is the interface between a low-level thread and the Python runtime. The bootstrap will initiatilize the thread, then execute the `target` callable using `PyObject_Call()`. Once the callable target has been executed, the thread will exit:



POSIX Threads

POSIX threads, named `pthreads`, have an implementation in `Python` ▸ `thread_pthread.h`. This implementation abstracts the `<pthread.h>` C API with some additional safeguards and optimizations.

Threads can have a configured stack size. Python has it's own stack frame construct, as you explored in the chapter on the Evaluation Loop. If there is an issue causing a recursive loop, and the frame execution hits the depth limit, Python will raise a `RecursionError` which can be handled from a `try..except` block in Python code. Because pthreads have their own stack size, the max depth of Python and the stack size of the pthread might conflict.

If the thread stack size is smaller than the max frame depth in Python, the entire Python process will crash before a `RecursionError` is raised. Also, the max depth in Python can be configured at runtime using `sys.setrecursionlimit()`.

To avoid these crashes, the CPython pthread implementation sets the stack size to the `pythread_stacksize` value of the Interpreter State.

Most modern POSIX-compliant Operating Systems support system scheduling of pthreads. If `PTHREAD_SYSTEM_SCHED_SUPPORTED` is defined in `pyconfig.h`, the pthread is set to `PTHREAD_SCOPE_SYSTEM`, meaning that the priority of the thread on the Operating System scheduler is decided against the other threads on the system, not just the ones within the Python process.

Once the thread properties have been configured, the thread is created using the `pthread_create()` API. This runs the bootstrap function from inside the new thread.

Lastly, the thread handle, `pthread_t` is cast into an `unsigned long` and returned to become the thread ID.

Windows Threads

Windows threads implemented in `Python`▸`thread_nt.h` follow a similar, but simpler pattern.

The stack size of the new thread is configured to the interpreter `pythread_stacksize` value (if set).

The thread is created using the `_beginthreadex()` Windows API using the bootstrap function as the callback.

Lastly, the thread ID is returned.

Conclusion

This was not an exhaustive tutorial on Python threads. Python's thread implementation is extensive and offers many mechanisms for sharing data between threads, locking objects, and resources.

Threads are a great, efficient way of improving the runtime of your Python applications when they are IO-bound. In this section, you have seen what the GIL is, why it exists and which parts of the standard library may be exempt from its constraints.

Asynchronous Programming

Python offers many ways of accomplishing concurrent programming without using threads or multiprocessing. These features have been added, expanded, and often replaced with better alternatives.

For the target version of this book, 3.9.0b5, the following asynchronous systems are deprecated:

- The `@coroutine` decorator

The following systems are still available:

- Creating futures from `async` keywords
- Coroutines using the `yield from` keywords

Generators

Python Generators are functions that return a `yield` statement and can be called continually to generate further values.

Generators are often used as a more memory efficient way of looping through values in a large block of data, like a file, a database, or over a network. Generator objects are returned in place of a **value** when `yield` is used instead of `return`. The generator object is created from the `yield` statement and returned to the caller.

This simple generator function will yield the letters a-z:

cpython-book-samples ▸ 33 ▸ letter_generator.py

```
def letters():
    i = 97  # letter 'a' in ASCII
    end = 97 + 26  # letter 'z' in ASCII
    while i < end:
        yield chr(i)
        i += 1
```

If you call `letters()`, it won't return a value, but instead it returns a generator object:

```
>>> from letter_generator import letters
>>> letters()
<generator object letters at 0x1004d39b0>
```

Built into the syntax of the `for` statement is the ability to iterate through a generator object until it stops yielding values:

```
>>> for letter in letters():
...     print(letter)
a
b
c
d
...
```

This implementation uses the iterator protocol. Objects that have a `__next__()` method can be looped over by `for` and `while` loops, or using the `next()` builtin.

All container types (like lists, sets, tuples) in Python implement the iterator protocol. Generators are unique because the implementation of the `__next__()` method recalls the generator function from its last state. Generators are not executing in the background, they are paused. When you request another value, they resume execution.

Within the generator object structure is the frame object as it was at the last `yield` statement.

Generator Structure

Generator objects are created by a template macro, `_PyGenObject_HEAD(prefix)`.

This macro is used by the following types and prefixes:

1. `PyGenObject` - `gi_` (Generator objects)
2. `PyCoroObject` - `cr_` (Coroutine objects)
3. `PyAsyncGenObject` - `ag_` (Async generator objects)

You will cover coroutine and async generator objects later in this chapter.

The `PyGenObject` type has the base properties:

Field	Type	Purpose

Field	Type	Purpose
[x]_frame	PyFrameObject*	Current frame object for the generator
[x]_running	char	Set to 0 or 1 if the generator is currently running
[x]_code	PyObject * (PyCodeObject*)	Compiled function that yielded the generator
[x]_-weakreflist	PyObject * (list)	List of weak references to objects inside the generator function
[x]_name	PyObject * (str)	Name of the generator
[x]_qualname	PyObject * (str)	Qualified name of the generator
[x]_exc_-state	_PyErr_StackItem	Exception data if the generator call raises an exception

On top of the base properties, the `PyCoroObject` type has:

Field	Type	Purpose
cr_origin	PyObject * (tuple)	Tuple containing the originating frame and caller

On top of the base properties, the `PyAsyncGenObject` type has:

Field	Type	Purpose
ag_finalizer	PyObject *	Link to the finalizer method
ag_hooks_inited	int	Flag to mark that the hooks have been initialized
ag_closed	int	Flag to mark that the generator is closed
ag_running_async	int	Flag to mark that the generator is running

Related Source Files

Source files related to generators are:

File	Purpose
Include ▸ genobject.h	Generator API and `PyGenObject` definition

File	Purpose
`Objects▸genobject.c`	Generator Object implementation

Creating Generators

When a function containing a `yield` statement is compiled, the resulting code object has an additional flag, `CO_GENERATOR`.

In the chapter on the Execution Loop: Constructing Frames, you explored how a compiled code object is converted into a frame object when it is executed.
In the process, there is a special case for generators, coroutines, and async generators. The `_PyEval_EvalCode()` function checks the code object for the `CO_GENERATOR`, `CO_COROUTINE`, and `CO_ASYNC_GENERATOR` flags.

Instead of evaluation a code object inline, the frame is created and turned into a Generator, Coroutine or Async Generator Object. A coroutine is created using `PyCoro_New()`, an async generator is created with `PyAsyncGen_New()`, and a generator with `PyGen_NewWithQualName()`:

```
PyObject *
_PyEval_EvalCode(PyObject *_co, PyObject *globals, PyObject *locals, ...
...
    /* Handle generator/coroutine/asynchronous generator */
    if (co->co_flags & (CO_GENERATOR | CO_COROUTINE | CO_ASYNC_GENERATOR)) {
        PyObject *gen;
        PyObject *coro_wrapper = tstate->coroutine_wrapper;
        int is_coro = co->co_flags & CO_COROUTINE;
        ...
        /* Create a new generator that owns the ready to run frame
         * and return that as the value. */
        if (is_coro) {
>>>         gen = PyCoro_New(f, name, qualname);
        } else if (co->co_flags & CO_ASYNC_GENERATOR) {
>>>         gen = PyAsyncGen_New(f, name, qualname);
        } else {
>>>         gen = PyGen_NewWithQualName(f, name, qualname);
```

```
        }
        ...
        return gen;
    }
...
```

The generator factory, `PyGen_NewWithQualName()`, takes the frame and completes some steps to populate the generator object fields:

1. Sets the `gi_code` property to the compiled code object
2. Sets the generator to not running (`gi_running = 0`)
3. Sets the exception and weakref lists to `NULL`

You can also see that `gi_code` is the compiled code object for the generator function by importing the `dis` module and disassembling the bytecode inside:

```
>>> from letter_generator import letters
>>> gen = letters()
>>> import dis
>>> dis.disco(gen.gi_code)
  2           0 LOAD_CONST               1 (97)
              2 STORE_FAST               0 (i)
...
```

In the chapter on the Evaluation Loop, you explored the Frame Object Type. Frame objects contain locals and globals, the last executed instructions, and the code to be executed.

The builtin behavior and state of the frame object are how generators can *pause* and be *resumed* on demand.

Executing Generators

Whenever `__next__()` is called on a generator object, `gen_iternext()` is called with the generator instance, which immediately calls `gen_send_ex()` inside `Objects▸genobject.c`.

`gen_send_ex()` is the function that converts a generator object into the next yielded result. You'll see many similarities with the way frames are constructed from a code object as these functions have similar tasks.

The `gen_send_ex()` function is shared with generators, coroutines, and async generators and has the following steps:

1. The current thread state is fetched
2. The frame object from the generator object is fetched
3. If the generator is running when `__next__()` was called, raise a `ValueError`
4. If the frame inside the generator is at the top of the stack:
   - In the case of a coroutine, if the coroutine is not already marked as closing, a `RuntimeError` is raised
   - If this is an async generator, raise a `StopAsyncIteration`
   - For a standard generator, a `StopIteration` is raised.
5. If the last instruction in the frame (`f->f_lasti`) is still -1 because it has just been started, and this is a coroutine or async generator, then a non-None value can't be passed as an argument, so an exception is raised
6. Else, this is the first time it's being called, and arguments are allowed. The value of the argument is pushed to the frame's value stack
7. The `f_back` field of the frame is the caller to which return values are sent, so this is set to the current frame in the thread. This means that the return value is sent to the caller, not the creator of the generator
8. The generator is marked as running
9. The last exception in the generator's exception info is copied from the last exception in the thread state
10. The thread state exception info is set to the address of the generator's exception info. This means that if the caller enters a break-

point around the execution of a generator, the stack trace goes through the generator and the offending code is clear

11. The frame inside the generator is executed within the `Python` ▸ `ceval.c` main execution loop, and the value returned
12. The thread state last exception is reset to the value before the frame was called
13. The generator is marked as not running
14. The following cases then match the return value and any exceptions thrown by the call to the generator. Remember that generators should raise a `StopIteration` when they are exhausted, either manually, or by not yielding a value. Coroutines and async generators should not:
    - If no result was returned from the frame, raise a `StopIteration` for generators and `StopAsyncIteration` for async generators
    - If a `StopIteration` was explicitly raised, but this is a coroutine or an async generator, raise a `RuntimeError` as this is not allowed
    - If a `StopAsyncIteration` was explicitly raised and this is an async generator, raise a `RuntimeError`, as this is not allowed
15. Lastly, the result is returned back to the caller of `__next__()`

Bringing this all together, you can see how the generator expression is a powerful syntax where a single keyword, `yield` triggers a whole flow to create a unique object, copy a compiled code object as a property, set a frame, and store a list of variables in the local scope.

Coroutines

Generators have a big limitation. They can only yield values to their immediate caller.

An additional syntax was added to Python to overcome this- the `yield from` statement. Using this syntax, you can refactor generators into utility functions and then `yield from` them.

For example, the letter generator can be refactored into a utility function where the starting letter is an argument. Using `yield from`, you can choose which generator object to return:

cpython-book-samples ▸ 33 ▸ letter_coroutines.py

```python
def gen_letters(start, x):
    i = start
    end = start + x
    while i < end:
        yield chr(i)
        i += 1

def letters(upper):
    if upper:
        yield from gen_letters(65, 26)  # A-Z
    else:
        yield from gen_letters(97, 26)  # a-z

for letter in letters(False):
    # Lower case a-z
    print(letter)

for letter in letters(True):
    # Upper case A-Z
    print(letter)
```

Generators are also great for lazy sequences, where they can be called multiple times.

Building on the behaviors of generators, such as being able to pause and resume execution, the concept of a coroutine was iterated in Python over multiple APIs. Generators are a limited form of coroutine because you can send data to them using the `.send()` method.

It is possible to send messages bi-directionally between the caller and the target. Coroutines also store the caller in the `cr_origin` attribute.

Coroutines were initially available via a decorator, but this has since been deprecated in favor of "native" coroutines using the keywords `async` and `await`.

To mark that a function returns a coroutine, it must be preceded with the `async` keyword.

The `async` keyword makes it explicit (unlike generators) that this function returns a coroutine and not a value.

To create a coroutine, define a function with the keyword `async def`. In this example, add a timer using the `asyncio.sleep()` function and return a wake-up string:

```
>>> import asyncio
>>> async def sleepy_alarm(time):
...     await asyncio.sleep(time)
...     return "wake up!"
>>> alarm = sleepy_alarm(10)
>>> alarm
<coroutine object sleepy_alarm at 0x1041de340>
```

When you call the function, it returns a coroutine object. There are many ways to execute a coroutine. The easiest is using `asyncio.run(coro)`.

Run `asyncio.run()` with your coroutine object, then after 10 seconds it will sound the alarm:

```
>>> asyncio.run(alarm)
'wake up'
```

So far, there is a small benefit over a regular function. The benefit of coroutines is that you can run them concurrently. Because the coroutine object is a variable that you can pass to a function, these objects can be linked together and chained, or created in a sequence.

For example, if you wanted to have 10 alarms with different intervals and start them all at the same time, these coroutine objects can be converted into tasks.

The task API is used to schedule and execute multiple coroutines concurrently.

Before tasks are scheduled, an event loop must be running. The job of the event loop is to schedule concurrent tasks and connect events such as completion, cancellation, and exceptions with callbacks.

When you called `asyncio.run()`, the run function (in `Lib ▸ asyncio ▸ runners.py`) did these tasks for you:

1. Started a new event loop
2. Wrapped the coroutine object in a task
3. Set a callback on the completion of the task
4. Looped over the task until it completed
5. Returned the result

Related Source Files

Source files related to coroutines are:

File	Purpose
`Lib ▸ asyncio`	Python standard library implementation for asyncio

Event Loops

Event loops are the glue that holds async code together. Written in pure Python, event loops are an object containing tasks.

When started, a loop can either run once or run forever. Any of the tasks in the loop can have callbacks. The loop will run the callbacks if a task completes or fails.

```
loop = asyncio.new_event_loop()
```

Inside a loop is a sequence of tasks, represented by the type `asyncio.Task`, tasks are scheduled onto a loop, then once the loop is running, it loops over all the tasks until they complete.

You can convert the single timer into a task loop:

cpython-book-samples ▸ 33 ▸ sleepy_alarm.py

```
import asyncio

async def sleepy_alarm(person, time):
   await asyncio.sleep(time)
   print(f"{person} -- wake up!")

async def wake_up_gang():
    tasks = [
        asyncio.create_task(sleepy_alarm("Bob", 3), name="wake up Bob"),
        asyncio.create_task(sleepy_alarm("Sanjeet", 4), name="wake up Sanjeet"),
        asyncio.create_task(sleepy_alarm("Doris", 2), name="wake up Doris"),
        asyncio.create_task(sleepy_alarm("Kim", 5), name="wake up Kim")
    ]
    await asyncio.gather(*tasks)

asyncio.run(wake_up_gang())
```

This will print:

```
Doris -- wake up!
Bob -- wake up!
Sanjeet -- wake up!
Kim -- wake up!
```

In the event loop, it will run over each of the coroutines to see if they are completed. Similar to how the `yield` keyword can return multiple values from the same frame, the `await` keyword can return multiple states. The event loop will execute the `sleepy_alarm()` coroutine objects again and again until the `await asyncio.sleep()` yields a completed result, and the `print()` function is able to execute.

For this to work, `asyncio.sleep()` must be used instead of the blocking (and not async-aware) `time.sleep()`.

Example

You can convert the multithreaded port scanner example to asyncio with these steps:

- Change the `check_port()` function to use a socket connection from `asyncio.open_connection()`, which creates a future instead of an immediate connection
- Use the socket connection future in a timer event, with `asyncio.wait_for()`
- Append the port to the results list if succeeded
- Add a new function, `scan()` to create the `check_port()` coroutines for each port and add them to a list, `tasks`
- Merge all the tasks into a new coroutine using `asyncio.gather()`
- Run the scan using `asyncio.run()`

cpython-book-samples ▸ 33 ▸ portscanner_async.py

```
import time
import asyncio

timeout = 1.0

async def check_port(host: str, port: int, results: list):
    try:
        future = asyncio.open_connection(host=host, port=port)
        r, w = await asyncio.wait_for(future, timeout=timeout)
        results.append(port)
        w.close()
    except asyncio.TimeoutError:
        pass  # port is closed, skip-and-continue
```

```
async def scan(start, end, host):
    tasks = []
    results = []
    for port in range(start, end):
        tasks.append(check_port(host, port, results))
    await asyncio.gather(*tasks)
    return results

if __name__ == '__main__':
    start = time.time()
    host = "localhost"  # pick a host you own
    results = asyncio.run(scan(80, 100, host))
    for result in results:
        print("Port {0} is open".format(result))
    print("Completed scan in {0} seconds".format(time.time() - start))
```

Finally, this scan completes in just over 1 second:

```
 $ python portscanner_async.py
Port 80 is open
Completed scan in 1.0058400630950928 seconds
```

Asynchronous Generators

The concepts you have learned so far, generators and coroutines can be combined into a type - **asynchronous generators**.

If a function is declared with both the `async` keyword and it contains a `yield` statement, it is converted into an async generator object when called.

Like generators, async generators must be executed by something that understands the protocol. In place of `__next__()`, async generators have a method `__anext__()`.

A regular `for` loop would not understand an async generator, so instead, the `async for` statement is used.

You can refactor the `check_port()` function into an async generator that yields the next open port until it hits the last port, or it has found a specified number of open ports:

```
async def check_ports(host: str, start: int, end: int, max=10):
    found = 0
    for port in range(start, end):
        try:
            future = asyncio.open_connection(host=host, port=port)
            r, w = await asyncio.wait_for(future, timeout=timeout)
            yield port
            found += 1
            w.close()
            if found >= max:
                return
        except asyncio.TimeoutError:
            pass # closed
```

To execute this, use the `async for` statement:

```
async def scan(start, end, host):
    results = []
    async for port in check_ports(host, start, end, max=1):
        results.append(port)
    return results
```

See `cpython-book-samples` ▸ `33` ▸ `portscanner_async_generators.py` for the full example.

Subinterpreters

So far, you have covered:

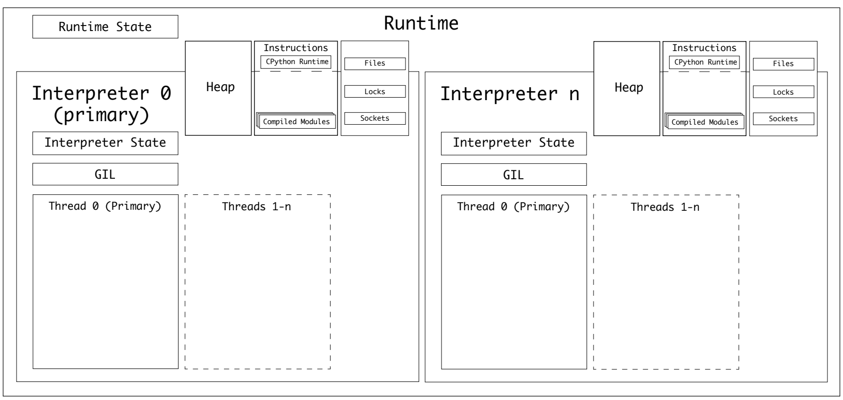
- Parallel execution with multiprocessing
- Concurrent execution with threads and async

The downside of multiprocessing is that the inter-process communication using pipes and queues is slower than shared memory. Also the overhead to start a new process is significant.

Threading and async have small overhead but don't offer truly parallel execution because of the thread-safety guarantees in the GIL.

The fourth option is `subinterpreters`, which have a smaller overhead than `multiprocessing`, and allow a GIL per subinterpreter. After all, it is the Global **Interpreter** Lock.

Within the CPython runtime, there is always 1 interpreter. The interpreter holds the interpreter state, and within an interpreter, you can have 1 or many Python threads. The interpreter is the container for the evaluation loop. the interpreter also manages its own memory, reference counter, and garbage collection. CPython has low-level C APIs for creating interpreters, like the `Py_NewInterpreter()`.



Note

The subinterpreters module is still experimental in 3.9.0b5, so the API is subject to change and the implementation is still buggy.

Because Interpreter state contains the memory allocation arena, a collection of all pointers to Python objects (local and global), subinterpreters cannot access the global variables of other interpreters. Similar to multiprocessing, to share objects between interpreters you must serialize them, or use ctypes, and use a form of IPC (network, disk or shared memory).

Related Source Files

Source files related to subinterpreters are:

File	Purpose
`Lib▸_xxsubinterpreters.c` |	C implementation of the `subinterpreters` module
`Python▸pylifecycle.c`	C implementation of the interpreter management API

Example

In the final example application, the actual connection code has to be captured in a string. In 3.9.0b5, subinterpreters can only be executed with a string of code.

To start each of the subinterpreters, a list of threads is started, with a callback to a function, `run()`.

This function will:

- Create a communication channel
- Start a new subinterpreter
- Send it the code to execute
- Receive data over the communication channel
- If the port connection succeeded, add it to the thread-safe queue

`cpython-book-samples▸33▸portscanner_subinterpreters.py`

```
import time
import _xxsubinterpreters as subinterpreters
from threading import Thread
```

```
import textwrap as tw
from queue import Queue

timeout = 1  # in seconds..

def run(host: str, port: int, results: Queue):
    # Create a communication channel
    channel_id = subinterpreters.channel_create()
    interpid = subinterpreters.create()
    subinterpreters.run_string(
        interpid,
        tw.dedent(
    """
    import socket; import _xxsubinterpreters as subinterpreters
    sock = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
    sock.settimeout(timeout)
    result = sock.connect_ex((host, port))
    subinterpreters.channel_send(channel_id, result)
    sock.close()
    """),
        shared=dict(
            channel_id=channel_id,
            host=host,
            port=port,
            timeout=timeout
        ))
    output = subinterpreters.channel_recv(channel_id)
    subinterpreters.channel_release(channel_id)
    if output == 0:
        results.put(port)

if __name__ == '__main__':
    start = time.time()
    host = "127.0.0.1"   # pick a host you own
    threads = []
    results = Queue()
    for port in range(80, 100):
        t = Thread(target=run, args=(host, port, results))
```

```
        t.start()
        threads.append(t)
    for t in threads:
        t.join()
    while not results.empty():
        print("Port {0} is open".format(results.get()))
    print("Completed scan in {0} seconds".format(time.time() - start))
```

Because of the reduced overheads compared with multiprocessing, this example should execute 30-40% faster and with fewer memory resources:

```
 $ python portscanner_subinterpreters.py
Port 80 is open
Completed scan in 1.3474230766296387 seconds
```

Conclusion

Congratulations on getting through the biggest chapter in the book! You've covered a lot of ground. Let us recap some of the concepts and their applications.

For truly **parallel execution**, you need multiple CPUs or cores. You also need to use either **multiprocessing** or **subinterpreters** packages so that the Python interpreter can be executed in parallel. Remember that startup time is significant, and each interpreter has a big memory overhead. If the tasks that you want to execute are short-lived, use a pool of workers and a queue of tasks.

If you have multiple IO-bound tasks and want them to run **concurrently**, you should use multithreading, or use coroutines with the **asyncio** package.

All four of these approaches require an understanding of how to safely and efficiently transfer data between processes or threads. The best way to reinforce what you've learned is to look at an application you've written and seen how it can be refactored to leverage these techniques.

Leave feedback on this section »

Objects and Types

CPython comes with a collection of basic types like strings, lists, tuples, dictionaries, and objects.

All of these types are built-in. You don't need to import any libraries, even from the standard library.

For example, to create a new list, you can call:

```
lst = list()
```

Or, you can use square brackets:

```
lst = []
```

Strings can be instantiated from a string-literal by using either double or single quotes. You explored the grammar definitions in the chapter "The Python Language and Grammar" that cause the compiler to interpret double quotes as a string literal.

All types in Python inherit from `object`, a built-in base type. Even strings, tuples, and lists inherit from `object`.

In `Objects` ▸ `object.c`, the base implementation of `object` type is written as pure C code. There are some concrete implementations of basic logic, like shallow comparisons.

A simple way to think of a Python object is consisting of 2 things:

1. The core data model, with pointers to compiled functions

2. A dictionary with any custom attributes and methods

Much of the base object API is declared in `Objects ▸ object.c`, like the implementation of the built-in `repr()` function, `PyObject_Repr`. You will also find `PyObject_Hash()` and other APIs.

All of these functions can be overridden in a custom object by implementing "dunder" methods on a Python object. For example:

```
class MyObject(object):
    def __init__(self, id, name):
        self.id = id
        self.name = name

    def __repr__(self):
        return "<{0} id={1}>".format(self.name, self.id)
```

All of these built-in functions are called the Python Data Model. Not all methods in a Python object are part of the Data Model, so that a Python object can contain attributes (either class or instance attributes) and methods.

See Also

One of the great resources for the Python Data Model is "Fluent Python" by Luciano Ramalho.

Examples in This Chapter

Throughout this chapter, each type explanation will come with an example. In the example, you will implement the *almost-equal* operator, that was specified in earlier chapters.

If you haven't yet implemented the changes in the Grammar and Compiler chapters, they will be required to implement the examples.

Builtin Types

The core data model is defined in the `PyTypeObject`, and the functions are defined in:

Each of the source file will have a corresponding header in `Include`. For example, `Objects/rangeobject.c` has a header file `Include▸rangeobject.h`.

Source File	Type
`Objects▸object.c`	Built in methods and base object
`Objects▸boolobject.c`	`bool` type
`Objects▸bytearrayobject.c`	`byte[]` type
`Objects▸bytesobjects.c`	`bytes` type
`Objects▸cellobject.c`	`cell` type
`Objects▸classobject.c`	Abstract `class` type, used in meta-programming
`Objects▸codeobject.c`	Built-in `code` object type
`Objects▸complexobject.c`	Complex numeric type
`Objects▸iterobject.c`	An iterator
`Objects▸listobject.c`	`list` type
`Objects▸longobject.c`	`long` numeric type
`Objects▸memoryobject.c`	Base memory type
`Objects▸methodobject.c`	Class method type
`Objects▸moduleobject.c`	Module type
`Objects▸namespaceobject.c`	Namespace type
`Objects▸odictobject.c`	Ordered dictionary type
`Objects▸rangeobject.c`	Range generator
`Objects▸setobject.c`	`set` type
`Objects▸sliceobject.c`	Slice reference type
`Objects▸structseq.c`	`struct.Struct` type
`Objects▸tupleobject.c`	`tuple` type
`Objects▸typeobject.c`	`type` type
`Objects▸unicodeobject.c`	`str` type
`Objects▸weakrefobject.c`	`weakref` type

You will explore some of those types in this chapter.

Object and Variable Object Types

Because C is not object-oriented like Python, objects in C don't inherit from one another. `PyObject` is the initial data segment for every Python object and `PyObject *` represents a pointer to it.

When defining Python types, the `typedef` uses one of two macros:

- `PyObject_HEAD` (`PyObject`) for a simple type
- `PyObject_VAR_HEAD` (`PyVarObject`) for a container type

The simple type `PyObject` has the fields:

Field	Type	Purpose
`ob_refcnt`	`Py_ssize_t`	Instance reference counter
`ob_type`	`_typeobject*`	The object type

For example, the `cellobject` declares 1 additional field, `ob_ref`, and the base fields:

```
typedef struct {
    PyObject_HEAD
    PyObject *ob_ref;       /* Content of the cell or NULL when empty */
} PyCellObject;
```

The variable type, `PyVarObject` extends the `PyObject` type and also has the fields:

Field	Type	Purpose
`ob_base`	`PyObject`	The base type
`ob_size`	`Py_ssize_t`	Number of items it contains

For example, the `int` type, `PyLongObject`, has the declaration:

```
struct _longobject {
    PyObject_VAR_HEAD
```

```
    digit ob_digit[1];
}; /* PyLongObject */
```

The `type` Type

In Python, objects have a property `ob_type`, you can get the value of this property using the builtin function `type()`:

```
>>> t = type("hello")
>>> t
<class 'str'>
```

The result from `type()` is an instance of a `PyTypeObject`:

```
>>> type(t)
<class 'type'>
```

Type objects are used to define the implementation of abstract base classes.

For example, objects alway have the `__repr__()` method implemented:

```
>>> class example:
...     x = 1
>>> i = example()
>>> repr(i)
'<__main__.example object at 0x10b418100>'
```

The implementation of the `__repr__()` method is always at the same address in the type definition of any object. This position is known as a **type slot**.

Type Slots

All of the type slots are defined in `Include`▸`cpython`▸`object.h`.

Each type slot has a property name and a function signature. The `__repr__()` function for example is called `tp_repr` and has a signature `reprfunc`:

```
struct PyTypeObject
---
typedef struct _typeobject {
    ...
    reprfunc tp_repr;
    ...
} PyTypeObject;
```

The signature reprfunc is defined in Include ▸ cpython ▸ object.h as having a single argument of PyObject* (self):

```
typedef PyObject *(*reprfunc)(PyObject *);
```

As an example, the cell object implements the tp_repr slot with the function cell_repr:

```
PyTypeObject PyCell_Type = {
    PyVarObject_HEAD_INIT(&PyType_Type, 0)
    "cell",
    sizeof(PyCellObject),
    0,
    (destructor)cell_dealloc,                /* tp_dealloc */
    0,                                       /* tp_vectorcall_offset */
    0,                                       /* tp_getattr */
    0,                                       /* tp_setattr */
    0,                                       /* tp_as_async */
    (reprfunc)cell_repr,                     /* tp_repr */
    ...
};
```

Beyond the basic PyTypeObject type slots, denoted with the tp_ prefix, there are other type slot definitions:

- PyNumberMethods denoted with the prefix nb_
- PySequenceMethods denoted with the prefix sq_
- PyMappingMethods denoted with the prefix mp_
- PyAsyncMethods denoted with the prefix am_
- PyBufferProcs denoted with the prefi bf_

All type slots are given a unique number, defined in `Include ▸ typeslots.h`.

When referring to, or fetching a type slot on an object, use these constants.

For example, `tp_repr` has a constant position of `66`, and the constant `Py_tp_repr` always matches the type slot position. These constants are useful when checking if an object implements a particular type slot function.

Working with Types in C

Within C extension modules and the core CPython code, you will be frequently working with the `PyObject*` type.

As an example, if you run `x[n]` on a subscriptable object like a list, or string, it will call `PyObject_GetItem()` which looks at the object `x` to determine how to subscript it:

`Objects ▸ abstract.c` line 146

```
PyObject *
PyObject_GetItem(PyObject *o, PyObject *key)
{
    PyMappingMethods *m;
    PySequenceMethods *ms;
...
```

The `PyObject_GetItem()` function serves both mapping types (like dictionaries) as well as sequence types (like lists and tuples).

If the instance, `o` has sequence methods, then `o->ob_type->tp_as_sequence` will evaluate to true, also if the instance, `o`, has a `sq_item` slot function defined, it is assumed that it has corrected implemented the sequence protocol.

The value of `key` is evaluated to check that it is an integer, and the item is requested from the sequence object using the `PySequence_GetItem()`

function:

```
ms = o->ob_type->tp_as_sequence;
if (ms && ms->sq_item) {
 if (PyIndex_Check(key)) {
        Py_ssize_t key_value;
        key_value = PyNumber_AsSsize_t(key, PyExc_IndexError);
        if (key_value == -1 && PyErr_Occurred())
            return NULL;
        return PySequence_GetItem(o, key_value);
    }
    else {
        return type_error("sequence index must "
                          "be integer, not '%.200s'", key);
    }
}
```

Type Property Dictionaries

Python supports defining new types with the `class` keyword. User defined types are created by `type_new()` in the type object module.

User defined types will have a property dictionary, accessed by `__dict__()`. Whenever a property is accessed on a custom class, the default `__getattr__` implementation
looks in this property dictionary. Class methods, instance methods, class properties and instance properties are located in this dictionary.

The `PyObject_GenericGetDict()` function implements the logic to fetch the dictionary instance for a given object. The `PyObject_GetAttr()` function implements the default `__getattr__()` implementation and `PyObject_SetAttr()` implements `__setattr__()`.

See Also

There are many layers to custom types, that have been extensively documented in many Python books.
I could fill an entire book on metaclasses, but have decided to stick to the implementation. If you want to learn more, check out John Sturtz' article on metaprogramming.

Bool and Long Integer Type

The `bool` type is the most straightforward implementation of the built-in types. It inherits from `long` and has the predefined constants, `Py_True` and `Py_False`. These constants are **immutable** instances, created on the instantiation of the Python interpreter.

Inside `Objects▸boolobject.c`, you can see the helper function to create a `bool` instance from a number:

`Objects▸boolobject.c` line 28

```
PyObject *PyBool_FromLong(long ok)
{
    PyObject *result;

    if (ok)
        result = Py_True;
    else
        result = Py_False;
    Py_INCREF(result);
    return result;
}
```

This function uses the C evaluation of a numeric type to assign `Py_True` or `Py_False` to a result and increment the reference counters.

The numeric functions for `and`, `xor`, and `or` are implemented, but addition, subtraction, and division are dereferenced from the base long type since it would make no sense to divide two boolean values.

The implementation of `and` for a `bool` value first checks if `a` and `b` are booleans. If they arent, they are cast as numbers, and the `and` operation is run on the two numbers:

`Objects`▸`boolobject.c` line 61

```
static PyObject *
bool_and(PyObject *a, PyObject *b)
{
    if (!PyBool_Check(a) || !PyBool_Check(b))
        return PyLong_Type.tp_as_number->nb_and(a, b);
    return PyBool_FromLong((a == Py_True) & (b == Py_True));
}
```

Long Type

The `long` type is a bit more complex than `bool`. In the transition from Python 2 to 3, CPython dropped support for the `int` type and instead used the `long` type as the primary integer type. Python's `long` type is quite special in that it can store a variable-length number. The maximum length is set in the compiled binary.

The data structure of a Python `long` consists of the `PyObject` variable header and a list of digits. The list of digits, `ob_digit` is initially set to have one digit, but it later expanded to a longer length when initialized:

`Include`▸`longintrepr.h` line 85

```
struct _longobject {
    PyObject_VAR_HEAD
    digit ob_digit[1];
};
```

For example, the number 1 would have the `ob_digits [1]`, and 24601 would have the `ob_digits [2, 4, 6, 0, 1]`.

Memory is allocated to a new `long` through `_PyLong_New()`. This function takes a fixed length and makes sure it is smaller than `MAX_LONG_DIGITS`.

Then it reallocates the memory for `ob_digit` to match the length.

To convert a C `long` type to a Python `long` type, the C `long` is converted to a list of digits, the memory for the Python `long` is assigned, and then each of the digits is set. The `long` object is initialized with `ob_digit` already being at a length of 1 if the number is less than 10 (1 digit). Then, the value is set without the memory being allocated:

`Objects`▸`longobject.c` line 297

```
PyObject *
PyLong_FromLong(long ival)
{
    PyLongObject *v;
    unsigned long abs_ival;
    unsigned long t;  /* unsigned so >> doesn't propagate sign bit */
    int ndigits = 0;
    int sign;

    CHECK_SMALL_INT(ival);
...
    /* Fast path for single-digit ints */
    if (!(abs_ival >> PyLong_SHIFT)) {
        v = _PyLong_New(1);
        if (v) {
            Py_SIZE(v) = sign;
            v->ob_digit[0] = Py_SAFE_DOWNCAST(
                abs_ival, unsigned long, digit);
        }
        return (PyObject*)v;
    }
...
    /* Larger numbers: loop to determine number of digits */
    t = abs_ival;
    while (t) {
        ++ndigits;
        t >>= PyLong_SHIFT;
    }
```

```
    v = _PyLong_New(ndigits);
    if (v != NULL) {
        digit *p = v->ob_digit;
        Py_SIZE(v) = ndigits*sign;
        t = abs_ival;
        while (t) {
            *p++ = Py_SAFE_DOWNCAST(
                t & PyLong_MASK, unsigned long, digit);
            t >>= PyLong_SHIFT;
        }
    }
    return (PyObject *)v;
}
```

To convert a double-point floating point to a Python `long`, `PyLong_FromDouble()` does the math for you.

The remainder of the implementation functions in `Objects` ▸ `longobject.c` have utilities, such as converting a Unicode string into a number with `PyLong_FromUnicodeObject()`.

Example

The rich-comparison type slot for `long` is set to the `long_richcompare`. This function wraps `long_compare`:

`Objects` ▸ `longobject.c` line 3031

```
static PyObject *
long_richcompare(PyObject *self, PyObject *other, int op)
{
    Py_ssize_t result;
    CHECK_BINOP(self, other);
    if (self == other)
        result = 0;
    else
        result = long_compare((PyLongObject*)self, (PyLongObject*)other);
    Py_RETURN_RICHCOMPARE(result, 0, op);
}
```

The `long_compare` function will first check whether the length (number of digits) of the two variables `a` and `b`. If the lengths are the same, it then loops through each digit to see if they are equal to each other.

`long_compare()` returns:

- A negative number when `a < b`
- 0 when `a == b`
- A positive number when `a > b`

For example, when you execute `1 == 5`, the `result` is `-4`. `5 == 1`, the result is `4`.

You can implement the following code block before the `Py_RETURN_-RICHCOMPARE` macro to return `True` when the absolute value of result is `<=1` using the macro `Py_ABS()`, which returns the absolute value of a signed integer:

```
    if (op == Py_AlE) {
        if (Py_ABS(result) <= 1)
            Py_RETURN_TRUE;
        else
            Py_RETURN_FALSE;
    }
    Py_RETURN_RICHCOMPARE(result, 0, op);
}
```

After recompiling Python, you should see the effect of the change:

```
>>> 2 == 1
False
>>> 2 ~= 1
True
>>> 2 ~= 10
False
```

Unicode String Type

Python Unicode strings are complicated. Cross-platform Unicode types in any platform are complicated.

The cause of this complexity is the number of encodings that are on offer, and the different default configurations on the platforms that Python supports.

The Python 2 string type was stored in C using the `char` type. The 1-byte `char` type sufficiently stores any of the ASCII (American Standard Code for Information Interchange) characters and has been used in computer programming since the 1970s.

ASCII does not support the 1000's of languages and character sets that are in use across the world. Also, there are extended glyph character sets like emojis, which it cannot support.

A standard system of coding and a database of characters was created, known as the Unicode Standard. The modern Unicode Standard includes characters for all written languages, as well as extended glyphs and characters. The **Unicode Character Database** (UCD) contains 137,929 at version 12.1 (compared with the 128 in ASCII).

The Unicode standard defines these characters in a character table called the **Universal Character Set (UCS)**. Each character has a unique identifier known as a **code point**.

There are then many **encodings** that use the Unicode Standard and convert the code-point into a binary value.

Python Unicode strings support three lengths of encodings:

- 1-byte (8-bit)
- 2-byte (16-bit)
- 4-byte (32-bit)

These variable-length encodings are referred to within the implementation as:

- 1-byte `Py_UCS1`, stored as 8-bit unsigned int type, `uint8_t`
- 2-byte `Py_UCS2`, stored as 16-bit unsigned int type, `uint16_t`
- 4-byte `Py_UCS4`, stored as 32-bit unsigned int type, `uint32_t`

Related Source Files

Source files related to strings are:

File	Purpose
`Include▸unicodeobject.h`	Unicode String Object definition
`Include▸cpython▸unicodeobject.h`	Unicode String Object definition
`Objects▸unicodeobject.c`	Unicode String Object implementation
`Lib▸encodings`	Encodings package containing all the possible encodings
`Lib▸codecs.py`	Codecs module
`Modules▸_codecsmodule.c` |	Codecs module C extensions, implements OS-specific encodings
`Modules▸_codecs` |	Codec implementations for a range of alternative encodings

Processing Unicode Code Points

CPython does not contain a copy of the UCD, nor does it have to update whenever scripts and characters are added to the Unicode standard. Unicode Strings in CPython only have to care about the encodings, the Operating System has the task of representing the code points in the correct scripts.

The Unicode standard includes the UCD and is updated regularly with new scripts, new Emojis, and new characters.

Operating Systems take on these updates to Unicode and update their software via a patch. These patches include the new UCD code-points and support the various Unicode encodings. The UCD is split into sections called **code blocks**.

The Unicode Code charts are published on the Unicode Website.

Another point of support for Unicode is the Web Browser. Web Browsers decode HTML binary data in the encoding marked HTTP encoding headers. If you are working with CPython as a web server, then your Unicode encodings must match the HTTP headers being sent to your users.

UTF8 vs UTF16

Some common encodings are:

- **UTF8**, an 8-bit character encoding that supports all possible characters in the UCD with either a 1-4 byte code point
- **UTF16**, a 16-bit character encoding, similar to UTF8, but not compatible with 7 or 8-bit encodings like ASCII

UTF8 is the most commonly used Unicode encoding.

In all Unicode encodings, the code points can be represented using a hexadecimal shorthand:

- `U+00F7` for the division character `'÷'`
- `U+0107` for the Latin Small Letter C with acute `'ć'`

In Python, Unicode code points can be encoded directly into the code using the `u` escape symbol and the hexadecimal value of the code point:

```
>>> print("u0107")
ć
```

CPython does not attempt to pad this data, so if you tried `u107`, it would give the following exception:

```
 print("u107")
  File "<stdin>", line 1
SyntaxError: (unicode error) 'unicodeescape' codec can't decode
    bytes in position 0-4: truncated uXXXX escape
```

Both XML and HTML support unicode code points with a special escape character `&#val;`, where `val` is the decimal value of the code point. If you need to encode Unicode code points into XML or HTML, you can use the `xmlcharrefreplace` error-handler in the `.encode()` method:

```
>>> "u0107".encode('ascii', 'xmlcharrefreplace')
b'&#263;'
```

The output will contain HTML/XML-escaped code-points. All modern browsers will decode this escape sequence into the correct character.

ASCII Compatibility

If you are working with ASCII-encoded text, it is important to understand the difference between UTF7/8 and UTF16. UTF8 has a major benefit of being compatible with ASCII encoded text. ASCII encoding is a 7-bit encoding.

The first 128 code points on the Unicode Standard represent the existing 128 characters of the ASCII standard. For example, the Latin letter `'a'` is the 97th character in ASCII and the 97th character in Unicode. Decimal 97 is equivalent to 61 in hexadecimal, so the Unicode code point is `U+0061`.

On the REPL, if you create the binary code for the letter `'a'`:

```
>>> letter_a = b'a'
>>> letter_a.decode('utf8')
'a'
```

This can correctly be decoded into UTF8.

UTF16 works with 2-4 byte code points. The 1-byte representation of the letter `'a'` will not decode:

```
>>> letter_a.decode('utf16')
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
```

```
UnicodeDecodeError: 'utf-16-le' codec can't decode
    byte 0x61 in position 0: truncated data
```

This is important to note when you are selecting an encoding mechanism. UTF8 is a safer option if you need to import ASCII encoded data.

Wide Character Type

When handling Unicode string input in an unknown encoding within the CPython source code, the `wchar_t` C type will be used. `wchar_t` is the C standard for a wide-character string and is sufficient to store Unicode strings in memory. After PEP 393, the `wchar_t` type was selected as the Unicode storage format.

The Unicode string object provides a utility function, `PyUnicode_FromWideChar()`, that will convert a `wchar_t` constant to a string object. For example, the `pymain_run_command()`, used by `python -c` converts the `-c` argument into a Unicode string:

`Modules▸main.c` line 226

```
static int
pymain_run_command(wchar_t *command, PyCompilerFlags *cf)
{
    PyObject *unicode, *bytes;
    int ret;

    unicode = PyUnicode_FromWideChar(command, -1);
```

Byte Order Markers

When decoding an input, like a file, CPython can detect the byte-order from a byte-order-marker (BOM). BOMs are a special character that appears at the beginning of a Unicode byte stream. They tell the receiver which byte-order the data is stored in. Different computer systems can encode with different byte-orders. If the wrong byte-order is used, even with the right encoding, the data will be garbled.

A **big-endian** ordering places the most significant byte first. A **little-endian** ordering places the least significant byte first.

The UTF8 specification does support a BOM, but it has no effect. The UTF8 BOM can appear at the beginning of a UTF8-encoded data sequence, represented as `b'\xef\xbb\xbf'`, and will indicate to CPython that the data stream is most-likely UTF8. UTF16 and UTF32 support little and big-endian BOMs.

The default byte-order in CPython is set by the `sys.byteorder` global value:

```
>>> import sys; print(sys.byteorder)
little
```

The Encodings Package

The encodings package in `Lib ▸ encodings` comes with over 100 builtin supported encodings for CPython.

Whenever the `.encode()` or `.decode()` method is called on a string or byte string, the encoding is looked up from this package.

Each encoding is defined as a separate module, e.g., `ISO2022_JP`, a widely used encoding for Japanese email systems, is declared in `Lib ▸ encodings ▸ iso2022_jp.py`.

Every encoding module will define a function `getregentry()` and register:

- Its unique name
- Its encode and decode functions from a codec module
- Its incremental encoder and decoder classes
- Its stream reader and stream writer classes

Many of the encoding modules share the same codecs either from the `codecs` module, or the `_mulitbytecodec` module. Some encoding modules use a separate codec module in C, from `Modules ▸ _codecs`.

For example, the `ISO2022_JP` encoding module imports a C extension module, `_codecs_iso2022`, from `Modules` ▸ `_codecs` ▸ `_codecs_iso2022.c`:

```
import _codecs_iso2022, codecs
import _multibytecodec as mbc

codec = _codecs_iso2022.getcodec('iso2022_jp')

class Codec(codecs.Codec):
    encode = codec.encode
    decode = codec.decode

class IncrementalEncoder(mbc.MultibyteIncrementalEncoder,
                         codecs.IncrementalEncoder):
    codec = codec

class IncrementalDecoder(mbc.MultibyteIncrementalDecoder,
                         codecs.IncrementalDecoder):
    codec = codec
```

The encodings package also has a module, `Lib` ▸ `encodings` ▸ `aliases.py`, containing a dictionary, `aliases`. This dictionary is used to map encodings in the registry by alternative names. For example, `utf8`, `utf-8` and `u8` are all aliases of the `utf_8` encoding.

The Codecs Module

The `codecs` module handles the translation of data with a specific encoding.

The encode or decode function of a particular encoding can be fetched using the `getencoder()` and `getdecoder()` functions respectively:

```
>>> iso2022_jp_encoder = codecs.getencoder('iso2022_jp')
>>> iso2022_jp_encoder('u3072u3068')  # hi-to
(b'x1b$B$R$Hx1b(B', 2)
```

The encode function will return the binary result and the number of bytes in the output as a tuple.

The `codecs` module also implements the builtin function `open()` for opening file handles from the operating system.

Codec Implementations

In the Unicode Object (`Objects` ▸ `unicodeobject.c`) implementation are the encoding and decoding methods for:

Codec	Encoder / Decoder
`ascii`	`PyUnicode_EncodeASCII()` / `PyUnicode_DecodeASCII()`
`latin1`	`PyUnicode_EncodeLatin1()` / `PyUnicode_DecodeLatin1()`
`UTF7`	`PyUnicode_EncodeUTF7()` / `PyUnicode_DecodeUTF7()`
`UTF8`	`PyUnicode_EncodeUTF8()` / `PyUnicode_DecodeUTF8()`
`UTF16`	`PyUnicode_EncodeUTF16()` / `PyUnicode_DecodeUTF16()`
`UTF32`	`PyUnicode_EncodeUTF32()` / `PyUnicode_DecodeUTF32()`
`unicode_escape`	`PyUnicode_EncodeUnicodeEscape()` / `PyUnicode_DecodeUnicodeEscape()`
`raw_unicode_escape`	`PyUnicode_EncodeRawUnicodeEscape()` / `PyUnicode_DecodeRawUnicodeEscape()`

The implementation of the other encodings is within `Modules` ▸ `_codecs` to avoid cluttering the main unicode string object implementation.

The `unicode_escape` and `raw_unicode_escape` codecs are internal to CPython.

Internal Codecs

CPython comes with a number of internal encodings. These are unique to CPython and useful for some of the standard library functions, and when working with producing source code.

These text encodings can be used with any text input and output:

Codec	Purpose
`idna`	Implements RFC 3490
`mbcs`	(Windows only): Encode according to the ANSI codepage
`raw_unicode_escape`	Convert to a string for raw literal in Python source code

Codec	Purpose
`string_escape`	Convert to a string literal for Python source code
`undefined`	Try default system encoding
`unicode_escape`	Convert to Unicode literal for Python source code
`unicode_internal`	Return the internal CPython representation

These binary-only encodings need to be used with `codecs.encode()`/ `codecs.decode()` with byte string inputs, e.g., :

```
>>> codecs.encode(b'hello world', 'base64')
b'aGVsbG8gd29ybGQ=n'
```

Codec	Aliases	Purpose
`base64_codec`	`base64`, `base-64`	Convert to MIME base64
`bz2_codec`	`bz2`	Compress the string using bz2
`hex_codec`	`hex`	Convert to hexadecimal representation, with two digits per byte
`quopri_codec`	`quoted-printable`	Convert operand to MIME quoted printable
`rot_13`	`rot13`	Returns the Caesar-cypher encryption (position 13)
`uu_codec`	`uu`	Convert using uuencode
`zlib_codec`	`zip`, `zlib`	Compress using gzip

Example

The `tp_richcompare` type slot is allocated to the `PyUnicode_RichCompare()` function in the `PyUnicode_Type`. This function does the comparison of strings and can be adapted to the `~=` operator.

The behaviour you will implement is a case-insensitive comparison of the two strings.

First, add an additional case statement to check when the left and right strings have binary equivalence.

`Objects` ▸ `unicodeobject.c` line 11361

```
PyObject *
PyUnicode_RichCompare(PyObject *left, PyObject *right, int op)
{
    ...
    if (left == right) {
        switch (op) {
        case Py_EQ:
        case Py_LE:
>>>     case Py_AlE:
        case Py_GE:
            /* a string is equal to itself */
            Py_RETURN_TRUE;
```

Then add a new `else if` block to handle the `Py_AlE` operator. This will:

1. Convert the left string to a new upper-case string
2. Convert the right string to a new upper-case string
3. Compare the two
4. Dereference both of the temporary strings so they get deallocated
5. Return the result

Your code should look like this:

```
    else if (op == Py_EQ || op == Py_NE) {
        ...
    }
    /* Add these lines */
    else if (op == Py_AlE){
        PyObject* upper_left = case_operation(left, do_upper);
        PyObject* upper_right = case_operation(right, do_upper);
        result = unicode_compare_eq(upper_left, upper_right);
        Py_DECREF(upper_left);
        Py_DECREF(upper_right);
        return PyBool_FromLong(result);
    }
```

After recompiling, your case-insensitive string matching should give the following results on the REPL:

```
>>> "hello" ~= "HEllO"
True
>>> "hello?" ~= "hello"
False
```

Dictionary Type

Dictionaries are a fast and flexible mapping type. They are used by developers to store and map data, as well as by Python objects to store properties and methods.

Python dictionaries are also used for local and global variables, for keyword arguments and many other use cases.

Python dictionaries are **compact**, meaning the hash table only stores mapped values.

The hashing algorithm that is part of all immutable builtin types is fast, and what gives Python dictionaries their speed.

Hashing

All immutable builtin types provide a hashing function. This is defined in the `tp_hash` type slot, or using the `__hash__()` magic-method for custom types. Hash values are the same size as a pointer (64-bit for 64-bit systems, 32 for 32-bit systems), but do not represent the memory address of their values.

The resulting hash for any Python Object should not change during it's lifecycle. Hashes for two immutable instances with identical values should be equal:

```
>>> "hello".__hash__() == ("hel" + "lo").__hash__()
True
```

There should be no hash collissions, two objects with different values should not produce the same hash.

Some hashes are simple, like Python longs:

```
>>> (401).__hash__()
401
```

Long hashes get more complex for a longer value:

```
>>> (401123124389798989898).__hash__()
2212283795829936375
```

Many of the builtin types use the `Python` ▸ `pyhash.c` module, which provides a hashing helper function for:

- Bytes `_Py_HashBytes(const void*, Py_ssize_t)`
- Double `_Py_HashDouble(double)`
- Pointers `_Py_HashPointer(void*)`

Unicode strings for example, use `_Py_HashBytes()` to hash the byte data of the string:

```
>>> ("hello").__hash__()
4894421526362833592
```

Custom classes can define a hashing function by implementing `__hash__()`. Instead of implementing a custom hash, custom classes should use a **unique** property. Make sure it is immutable by making it a read-only property, then use hash it using the builtin `hash()` function:

```
class User:
    def __init__(self, id: int, name: str, address: str):
        self._id = id

    def __hash__(self):
        return hash(self._id)

    @property
    def id(self):
        return self._id
```

Instances of this class can now be hashed:

```
>>> bob = User(123884, "Bob Smith", "Townsville, QLD")
>>> hash(bob)
123884
```

This instance can now be used as a dictionary key:

```
>>> sally = User(123823, "Sally Smith", "Cairns, QLD")
>>> near_reef = {bob: False, sally: True}
>>> near_reef[bob]
False
```

Sets will reduce duplicate hashes of this instance:

```
>>> {bob, bob}
{<__main__.User object at 0x10df244b0>}
```

Related Source Files

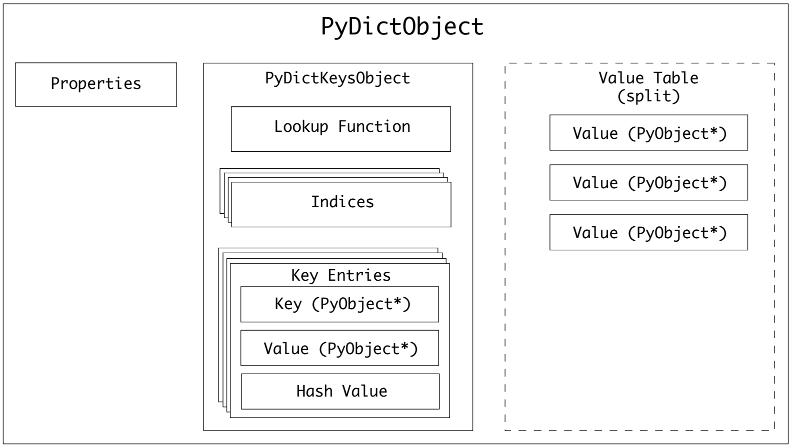
Source files related to dictionaries are:

File	Purpose
`Include▸dictobject.h`	Dictionary Object API definition
`Include▸cpython▸dictobject.h`	Dictionary Object types definition
`Objects▸dictobject.c`	Dictionary Object implementation
`Objects▸dict-common.h`	Definition of key entry, and key objects
`Python▸pyhash.c`	Internal hashing algorithm

Dictionary Structure

Dictionary objects, `PyDictObject` are comprised of:

1. The Dictionary Object, `PyDictObject`, containing the size, a version tag, the keys and values
2. A Dictionary Keys Object, containing the keys and hash values of all entries



The `PyDictObject` has the properties:

Field	Type	Purpose
`ma_used`	`Py_ssize_t`	Number of items in the dictionary
`ma_-version_tag`	`uint64_t`	Version number of the dictionary
`ma_keys`	`PyDictKeysObject *`	Dictionary Key Table Object
`ma_values`	`PyObject **`	Optional value array (see note)

Note

Dictionaries can have two states- split or combined. When dictionaries are combined, the pointers to the dictionary values are stored in the keys object.

When the dictionary is split, the values are stored in an extra property, `ma_values`, as a value table of `PyObject*`.

The dictionary key table, `PyDictKeysObject`, contains:

Field	Type	Purpose
`dk_refcnt`	`Py_ssize_t`	Reference counter

Field	Type	Purpose
dk_size	Py_ssize_t	The size of the hash table
dk_lookup	dict_lookup_-func	The lookup function (See next section)
dk_usable	Py_ssize_t	The number of usable entries in the entry table, when 0, dictionary is resized
dk_-nentries	Py_ssize_t	The number of used entries in the entry table
dk_-indices	char[]	Hash table and mapping to `dk_entries`
dk_-entries	PyDictKeyEntry[]	Allocated array of dictionary key entries

A dictionary key entry, `PyDictKeyEntry` contains:

Field	Type	Purpose
me_hash	Py_ssize_t	Cached hash code of `me_key`
me_key	PyObject*	Pointer to the key object
me_value	PyObject*	Pointer to the value object (if combined)

Lookups

For a given key object, there is a generic lookup function `lookdict()`.

Dictionary lookups need to cater for three scenarios:

1. The memory address of the key exists in the key table
2. The hash value of the object exists in the key table
3. The key does not exist in the dictionary

See Also

The lookup function is based on Donald Knuth's famous book, "The Art of Computer Programming", chapter 6, section 4 on hashing (ISBN 978-0201896855)

The sequence of the lookup function is:

1. Get the hash value of `ob`
2. Lookup the hash value of `ob` in the dictionary keys and get the index, `ix`
3. If `ix` is empty, return `DKIX_EMPTY` (not found)
4. Get the key entry, `ep` for the given index
5. If the key values match because the object, `ob` is the same pointer at the key value, return the result
6. If the key hashes match because the object, `ob` resolves to the same hash value as `ep->me_mash`, return the result

Note

The `lookupdict()` function is one of few "hot functions" in the CPython source code.

"The hot attribute is used to inform the compiler that a function is a hot spot of the compiled program. The function is optimized more aggressively and on many target it is placed into special subsection of the text section so all hot functions appears close together improving locality."

This is specific to GNUC compilers, but when compiled with PGO, this function is likely to be optimized by the compiler automatically.

Conclusion

Now that you have seen the implementation of some built-in types, you can explore others.

When exploring Python classes, it is important to remember there are built-in types, written in C and classes inheriting from those types, written in Python or C.

Some libraries have types written in C instead of inheriting from the built-in types. One example is `numpy`, a library for numeric arrays. The `nparray` type is written in C, is highly efficient and performant.

In the next chapter, you will explore the classes and functions defined in the standard library.

Leave feedback on this section »

The Standard Library

Python has always come "batteries included." This statement means that with a standard CPython distribution, there are libraries for working with files, threads, networks, web sites, music, keyboards, screens, text, and a whole manner of utilities.

Some of the batteries that come with CPython are more like AA batteries. They're useful for everything, like the `collections` module and the `sys` module. Some of them are a bit more obscure, like a small watch battery that you never know when it might come in useful.

There are two types of modules in the CPython standard library:

1. Those written in pure Python that provide a utility
2. Those written in C with Python wrappers

You will explore both types in this chapter.

Python Modules

The modules written in pure Python are all located in the `Lib` directory in the source code. Some of the larger modules have submodules in subfolders, like the `email` module.

An easy module to look at would be the `colorsys` module. It's only a few hundred lines of Python code. You may not have come across it before. The `colorsys` module has some utility functions for converting color scales.

When you install a Python distribution from source, standard library modules are copied from the `Lib` folder into the distribution folder. This folder is always part of your path when you start Python, so you can `import` the modules without having to worry about where they're located.

For example:

```
>>> import colorsys
>>> colorsys
<module 'colorsys' from '/usr/shared/lib/python3.7/colorsys.py'>

>>> colorsys.rgb_to_hls(255,0,0)
(0.0, 127.5, -1.007905138339921)
```

We can see the source code of `rgb_to_hls()` inside `Lib` ▸ `colorsys.py`:

```
# HLS: Hue, Luminance, Saturation
# H: position in the spectrum
# L: color lightness
# S: color saturation

def rgb_to_hls(r, g, b):
    maxc = max(r, g, b)
    minc = min(r, g, b)
    # XXX Can optimize (maxc+minc) and (maxc-minc)
    l = (minc+maxc)/2.0
    if minc == maxc:
        return 0.0, l, 0.0
    if l <= 0.5:
        s = (maxc-minc) / (maxc+minc)
    else:
        s = (maxc-minc) / (2.0-maxc-minc)
    rc = (maxc-r) / (maxc-minc)
    gc = (maxc-g) / (maxc-minc)
    bc = (maxc-b) / (maxc-minc)
    if r == maxc:
        h = bc-gc
```

```
    elif g == maxc:
        h = 2.0+rc-bc
    else:
        h = 4.0+gc-rc
    h = (h/6.0) % 1.0
    return h, l, s
```

There's nothing special about this function, it's just standard Python. You'll find similar things with all of the pure Python standard library modules. They're just written in plain Python, well laid out and easy to understand. You may even spot improvements or bugs, so you can make changes to them and contribute it to the Python distribution. You'll cover that toward the end of this book.

Python and C Modules

The remainder of modules are written in C, or a combination or Python and C. The source code for these is in `Lib` for the Python component, and `Modules` for the C component. There are two exceptions to this rule, the `sys` module, found in `Python` ▸ `sysmodule.c` and the `__builtins__` module, found in `Python` ▸ `bltinmodule.c`.

Python will `import * from __builtins__` when an interpreter is instantiated, so all of the functions like `print()`, `chr()`, `format()`, etc. are found within `Python` ▸ `bltinmodule.c`.

Because the `sys` module is so specific to the interpreter and the internals of CPython, that is found inside the `Python` directory. It is also marked as an "implementation detail" of CPython and not found in other distributions.

The built-in `print()` function was probably the first thing you learned to do in Python. So what happens when you type `print("hello world!")`?

1. The argument `"hello world"` was converted from a string constant to a `PyUnicodeObject` by the compiler

2. `builtin_print()` was executed with 1 argument, and NULL `kwnames`
3. The `file` variable is set to `PyId_stdout`, the system's `stdout` handle
4. Each argument is sent to `file`
5. A line break, `\n` is sent to `file`

`Python` ▸ `bltinmodule.c` line 1828

```
static PyObject *
builtin_print(PyObject *self, PyObject *const *args,
    Py_ssize_t nargs, PyObject *kwnames)
{
    ...
    if (file == NULL || file == Py_None) {
        file = _PySys_GetObjectId(&PyId_stdout);
        ...
    }
    ...
    for (i = 0; i < nargs; i++) {
        if (i > 0) {
            if (sep == NULL)
                err = PyFile_WriteString(" ", file);
            else
                err = PyFile_WriteObject(sep, file,
                                         Py_PRINT_RAW);
            if (err)
                return NULL;
        }
        err = PyFile_WriteObject(args[i], file, Py_PRINT_RAW);
        if (err)
            return NULL;
    }

    if (end == NULL)
        err = PyFile_WriteString("\n", file);
    else
        err = PyFile_WriteObject(end, file, Py_PRINT_RAW);
    ...
```

```
    Py_RETURN_NONE;
}
```

The contents of some modules written in C expose operating system functions. Because the CPython source code needs to compile to macOS, Windows, Linux, and other *nix-based operating systems, there are some special cases.

The `time` module is a good example. The way that Windows keeps and stores time in the Operating System is fundamentally different than Linux and macOS. This is one of the reasons why the accuracy of the clock functions differs between Operating Systems.

In `Modules` ▸ `timemodule.c`, the Operating System time functions for Unix-based systems are imported from `<sys/times.h>`:

```
#ifdef HAVE_SYS_TIMES_H
#include <sys/times.h>
#endif
...
#ifdef MS_WINDOWS
#define WIN32_LEAN_AND_MEAN
#include <windows.h>
#include "pythread.h"
#endif /* MS_WINDOWS */
...
```

Later in the file, `time_process_time_ns()` is defined as a wrapper for `_PyTime_GetProcessTimeWithInfo()`:

```
static PyObject *
time_process_time_ns(PyObject *self, PyObject *unused)
{
    _PyTime_t t;
    if (_PyTime_GetProcessTimeWithInfo(&t, NULL) < 0) {
        return NULL;
    }
    return _PyTime_AsNanosecondsObject(t);
}
```

`_PyTime_GetProcessTimeWithInfo()` is implemented multiple different ways in the source code, but only certain parts are compiled into the binary for the module depending on the operating system. Windows systems will call `GetProcessTimes()` and Unix systems will call `clock_gettime()`.

Other modules that have multiple implementations for the same API are the threading module, the file system module, and the networking modules. Because the Operating Systems behave differently, the CPython source code implements the same behavior as best as it can and exposes it using a consistent, abstracted API.

Leave feedback on this section »

The Test Suite

CPython has a robust and extensive test suite covering the core interpreter, the standard library, the tooling, and distribution for Windows, Linux, and macOS.

The test suite is located in `Lib ▸ test` and written almost entirely in Python.

The full test suite is a Python package, so it can be run using the Python interpreter that you've compiled.

Running the Test Suite on Windows

On Windows use the `rt.bat` script inside the `PCBuild` folder.

For example, to run the "quick" mode against the Debug configuration on an x64 architecture:

```
> cd PCbuild
> rt.bat -q -d -x64

== CPython 3.9.0b5
== Windows-10-10.0.17134-SP0 little-endian
== cwd: C:\repos\cpython\build\test_python_2784
== CPU count: 2
== encodings: locale=cp1252, FS=utf-8
Run tests sequentially
0:00:00 [  1/420] test_grammar
```

```
0:00:00 [  2/420] test_opcodes
0:00:00 [  3/420] test_dict
0:00:00 [  4/420] test_builtin
...
```

To run the regression test suite against the Release configuration, remove the `-d` flag from the command-line

Running the Test Suite on Linux/macOS

On Linux or macOS run the `test` make target to compile and run the tests:

```
$ make test
== CPython 3.9.0b5
== macOS-10.14.3-x86_64-i386-64bit little-endian
== cwd: /Users/anthonyshaw/cpython/build/test_python_23399
== CPU count: 4
== encodings: locale=UTF-8, FS=utf-8
0:00:00 load avg: 2.14 [  1/420] test_opcodes passed
0:00:00 load avg: 2.14 [  2/420] test_grammar passed
...
```

Alternatively, use the `python.exe` compiled binary path with the `test` package:

```
$ ./python.exe -m test
== CPython 3.9.0b5
== macOS-10.14.3-x86_64-i386-64bit little-endian
== cwd: /Users/anthonyshaw/cpython/build/test_python_23399
== CPU count: 4
== encodings: locale=UTF-8, FS=utf-8
0:00:00 load avg: 2.14 [  1/420] test_opcodes passed
0:00:00 load avg: 2.14 [  2/420] test_grammar passed
...
```

There are additional make targets for testing:

Target	Purpose
`test`	Run a basic set of regression tests
`testall`	Run the full test suite twice - once without .pyc files, and once with
`quicktest`	Run a faster set of regression tests, excluding the tests that take a long time
`testuniversal`	Run the test suite for both architectures in a Universal build on OSX
`coverage`	Compile and run tests with gcov
`coverage-lcov`	Create coverage HTML reports

Test Flags

Some tests require certain flags; otherwise they are skipped. For example, many of the IDLE tests require a GUI.

To see a list of test suites in the configuration, use the `--list-tests` flag:

```
$ ./python -m test --list-tests


test_grammar
test_opcodes
test_dict
test_builtin
test_exceptions
...
```

Running Specific Tests

You can run specific tests by providing the test suite as the first argument:

On Linux or macOS:

```
$ ./python -m test test_webbrowser


Run tests sequentially
```

```
0:00:00 load avg: 2.74 [1/1] test_webbrowser

== Tests result: SUCCESS ==

1 test OK.

Total duration: 117 ms
Tests result: SUCCESS
```

On Windows:

```
> rt.bat -q -d -x64 test_webbrowser
```

You can also see a detailed list of tests that were executed with the result using the -v argument:

```
$ ./python -m test test_webbrowser -v

== CPython 3.9.0b5
== macOS-10.14.3-x86_64-i386-64bit little-endian
== cwd: /Users/anthonyshaw/cpython/build/test_python_24562
== CPU count: 4
== encodings: locale=UTF-8, FS=utf-8
Run tests sequentially
0:00:00 load avg: 2.36 [1/1] test_webbrowser
test_open (test.test_webbrowser.BackgroundBrowserCommandTest) ... ok
test_register (test.test_webbrowser.BrowserRegistrationTest) ... ok
test_register_default (test.test_webbrowser.BrowserRegistrationTest) ... ok
test_register_preferred (test.test_webbrowser.BrowserRegistrationTest) ... ok
test_open (test.test_webbrowser.ChromeCommandTest) ... ok
test_open_new (test.test_webbrowser.ChromeCommandTest) ... ok
...
test_open_with_autoraise_false (test.test_webbrowser.OperaCommandTest) ... ok

----------------------------------------------------------------------

Ran 34 tests in 0.056s

OK (skipped=2)
```

```
== Tests result: SUCCESS ==

1 test OK.

Total duration: 134 ms
Tests result: SUCCESS
```

Understanding how to use the test suite and checking the state of the version you have compiled is very important if you wish to make changes to CPython. Before you start making changes, you should run the whole test suite and make sure everything is passing.

Testing Modules

To test C extension or Python modules, they are imported and tested using the `unittest` module. Tests are assembled by module or package.

For example, the Python Unicode string type has tests in `Lib` ▸ `test` ▸ `test_unicode.py`. The `asyncio` package has a test package in `Lib` ▸ `test` ▸ `test_asyncio`.

See Also

If you're new to the `unittest` module or testing in Python, check out my Getting Started With Testing in Python article on realpython.com

```python
class UnicodeTest(string_tests.CommonTest,
        string_tests.MixinStrUnicodeUserStringTest,
        string_tests.MixinStrUnicodeTest,
        unittest.TestCase):
...
    def test_casefold(self):
        self.assertEqual('hello'.casefold(), 'hello')
        self.assertEqual('hELlo'.casefold(), 'hello')
        self.assertEqual('ß'.casefold(), 'ss')
        self.assertEqual('ﬁ'.casefold(), 'fi')
```

You can extend the almost-equal operator that you implemented for Python Unicode strings in earlier chapters by adding a new test method inside the `UnicodeTest` class:

```
    def test_almost_equals(self):
        self.assertTrue('hello' ~= 'hello')
        self.assertTrue('hELlo' ~= 'hello')
        self.assertFalse('hELlo!' ~= 'hello')
```

You can run this particular test module on Windows:

```
> rt.bat -q -d -x64 test_unicode
```

Or macOS/Linux:

```
$ ./python -m test test_unicode -v
```

Test Utilities

By importing the `test.support.script_helper` module, you can access some helper functions for testing the Python runtime:

- `assert_python_ok(*args, **env_vars)` executes a Python process with the specified arguments and returns a (return code, `stdout`, `stderr`) tuple
- `assert_python_failure(*args, **env_vars)` similar to `assert_python_ok()`, but asserts that is fails to execute
- `make_script(script_dir, script_basename, source)` makes a script in `script_dir` with the `script_basename` and the `source, then returns the script path. Useful to combine with`assert_python_ok()`or`assert_python_failure()‘

If you want to create a test that is skipped if the module wasn't built, you can use the `test.support.import_module()` utility function. It will raise a `SkipTest` and signal the test runner to skip this test package, for example:

```python
import test.support

_multiprocessing = test.support.import_module('_multiprocessing')

# Your tests...
```

Conclusion

The Python regression test suite is full of two decades of tests for strange edge cases, bug fixes, and new features. Outside of this, there is still a large part of the CPython standard library that has little or no testing. If you want to get involved in the CPython project, writing or extending unit tests is a great place to start.

If you're going to modify any part of CPython or add additional functionality, you will need to have written, or extended tests as part of your patch.

Leave feedback on this section »

Debugging

CPython comes with a builtin debugger for debugging Python applications, `pdb`. The pdb debugger is excellent for debugging crashes inside a Python application, for writing tests and inspecting local variables.

When it comes to CPython, you need a second debugger, one that understands C.

In this chapter, you will learn how to:

- Attach a debugger to the CPython interpreter
- Use the debugger to see inside a running CPython process

There are two types of debugger, console and visual. Console debuggers (like pdb) give you a command prompt and custom commands to explore variables and the stack. Visual debuggers are GUI applications that present the data for you in grids.

The following debuggers are covered in this chapter:

Debugger	Type	Platform
lldb	Console	macOS
gdb	Console	Linux
Visual Studio Debugger	Visual	Windows
CLion Debugger	Visual	Windows, macOS, Linux
VS Code Debugger	Visual	Windows, macOS, Linux

Using the Crash Handler

In C, if an application tries to read or write to an area of memory that it shouldn't be, a segmentation fault is raised. This fault halts the running process immediately to stop it from doing any damage to other applications.

Segmentation faults can also happen when you try to read from memory that contains no data, or an invalid pointer.

If CPython causes a segmentation fault, you get very little information about what happened:

```
[1]    63476 segmentation fault  ./python portscanner.py
```

CPython comes with a builtin fault handler. If you start CPython with `-X faulthandler`, or `-X dev`, instead of printing the system segmentation fault message, the fault handler will print the running threads and the Python stack trace to where the fault occurred:

```
Fatal Python error: Segmentation fault
Thread 0x0000000119021dc0 (most recent call first):
  File "/cpython/Lib/threading.py", line 1039 in _wait_for_tstate_lock
  File "/cpython/Lib/threading.py", line 1023 in join
  File "/cpython/portscanner.py", line 26 in main
  File "/cpython/portscanner.py", line 32 in <module>
[1]    63540 segmentation fault  ./python -X dev portscanner.py
```

This feature is also helpful when developing and testing C extensions for CPython.

Compiling Debug Support

To get meaningful information from the debugger, the debug symbols must be compiled into CPython. Without these symbols, the stack traces within a debug session won't contain the correct function names, the variable names, or file names.

Windows

Following the same steps as you did in the chapter on Compiling CPython (Windows), ensure that you have compiled in the `Debug` configuration to get the debug symbols:

```
> build.bat -p x64 -c Debug
```

Remember, the Debug configuration produces the executable `python_d.exe`, so make sure you use this executable for debugging.

macOS/Linux

The steps in the chapter on Compiling CPython, specify to run the `./configure` script with the `--with-pydebug` flag. If you did not include this flag, go back now and run `./configure` again with your original options and the `--with-pydebug` flag. This will produce the correct executable and symbols for debugging.

Using Lldb for macOS

The `lldb` debugger comes with the Xcode developer tools, so by now you will have it installed.

Start lldb and load the CPython compiled binary as the target:

```
$ lldb ./python.exe
(lldb) target create "./python.exe"
Current executable set to './python.exe' (x86_64).
```

You will now have a prompt where you can enter some commands for debugging.

Creating Breakpoints

To create a breakpoint, use the `break set` command, with the file (relative to the root) and the line number:

```
(lldb) break set --file Objects/floatobject.c --line 532
Breakpoint 1: where = python.exe`float_richcompare + 2276 at
    floatobject.c:532:26, address = 0x000000010006a974
```

> **Note**
>
> There is also a short-hand version of setting breakpoints, e.g. `(lldb) b Objects/floatobject.c:532`

You can add multiple breakpoints using the `break set` command. To list the current breakpoints, use the `break list` command:

```
(lldb) break list
Current breakpoints:
1: file = 'Objects/floatobject.c', line = 532, exact_match = 0, locations = 1
  1.1: where = python.exe`float_richcompare + 2276 at floatobject.c:532:26,
            address = python.exe[...], unresolved, hit count = 0
```

Starting CPython

To start CPython, use the `process launch --` command with the command-line options you would normally use for Python, e.g.:

To start python with a string, e.g. `python -c "print(1)"`, use:

```
(lldb) process launch -- -c "print(1)"
```

To start python with a script, use:

```
(lldb) process launch -- my_script.py
```

Attaching to a Running CPython Interpreter

If you have a CPython interpreter running already, you can attach to it.

From inside the lldb session, run `process attach --pid` with the process id:

```
(lldb) process attach --pid 123
```

You can get the process ID from the Activity Monitor, or using `os.getpid()` in Python.

Any breakpoints setup before this point or afterward will halt the process.

An Example of Handling a Breakpoint

To see how breakpoints are handled, set a breakpoint on the `Objects` ▸ `floatobject.c` `float_richcompare()` function. Next run the process and compare 2 float values using the almost-equal operator that you developed during this book:

```
(lldb) process launch -- -c "1.0~=1.1"
Process 64421 launched: '/cpython/python.exe' (x86_64)
Process 64421 stopped
* thread #1, queue = '...', stop reason = breakpoint 1.1
    frame #0: 0x000000010006a974 python.exe`float_richcompare(v=1.0,
        w=1.1, op=6) at floatobject.c:532:26
   529          break;
   530      case Py_AlE: {
   531              double diff = fabs(i - j);
-> 532              const double rel_tol = 1e-9;
   533              const double abs_tol = 0.1;
   534              r = (((diff <= fabs(rel_tol * j)) ||
Target 0: (python.exe) stopped.
```

lldb will give you a prompt again. You can see the local variables by using the command `v`:

```
(lldb) v
(PyObject *) v = 0x000000010111b370 1.0
(PyObject *) w = 0x000000010111b340 1.1
(int) op = 6
(double) i = 1
(double) j = 1.1000000000000001
```

```
(int) r = 0
(double) diff = 0.10000000000000009
(const double) rel_tol = 2.1256294105914498E-314
(const double) abs_tol = 0
```

You can evaluate a C expression using the `expr` command with any valid C command. The variables in scope can be used. For example, to call `fabs(rel_tol)` and cast to a `double`, run:

```
(lldb) expr (double)fabs(rel_tol)
(double) $1 = 2.1256294105914498E-314
```

This prints the resulting variable and assigns it an identifier (`$1`). You can reuse this identifier as a temporary variable.

You may also want to explore `PyObject` instances, e.g.:

```
(lldb) expr v->ob_type->tp_name
(const char *) $6 = 0x000000010034fc26 "float"
```

To get a traceback from the breakpoint, use the command `bt`:

```
(lldb) bt
* thread #1, queue = '...', stop reason = breakpoint 1.1
  * frame #0: ...
        python.exe`float_richcompare(...) at floatobject.c:532:26
    frame #1: ...
        python.exe`do_richcompare(...) at object.c:796:15
    frame #2: ...
        python.exe`PyObject_RichCompare(...) at object.c:846:21
    frame #3: ...
        python.exe`cmp_outcome(...) at ceval.c:4998:16
```

To step-in, use the command `step`, or `s`.

To continue to the next statement (step-over), use the command `next`, or `n`.

To continue execution, use the command `continue`, or `c`.

To exit the session, use the command `quit`, or `q`.

See Also

The LLVM Documentation Tutorial contains a more exhaustive list of commands.

Using the Python-Lldb Extension

lldb supports extensions, written in Python. There is an open-source extension which prints additional information in the lldb session for native CPython objects.

To install it, run these commands:

```
$ mkdir -p ~/.lldb
$ cd ~/.lldb && git clone https://github.com/malor/cpython-lldb
$ echo "command script import ~/.lldb/cpython-lldb/cpython_lldb.py"
    >> ~/.lldbinit
$ chmod +x ~/.lldbinit
```

Now, whenever you see variables in lldb, there will be some additional information to the right, such as the numeric value for ints and floats, or the text for Unicode strings. Within a lldb console, there is now an additional command, `py-bt`, that prints the stack trace for Python frames.

Using Gdb

Gdb is a commonly-used debugger for C/C++ applications written on Linux platforms. It is also very popular with the CPython core development team.

When CPython is compiled, it generates a script, `python-gdb.py`. Don't execute this script directly. Instead, gdb will discover it and run it automatically once configured. To configure this stage, edit the `.gdbinit` file inside your home path and add the line:

```
add-auto-load-safe-path /path/to/checkout
```

Where `/path/to/checkout` is the path to the `cpython` git checkout.

To start gdb, run it with the argument pointing to your compiled CPython binary.

```
$ gdb ./python
```

Gdb will load the symbols for the compiled binary and give you a command prompt. Gdb has a set of built-in commands, and the CPython extensions bundle some additional commands.

Creating Breakpoints

To set a breakpoint, use the `b <file>:<line>` command, relative to the path of the executable:

```
(gdb) b Objects/floatobject.c:532
Breakpoint 1 at 0x10006a974: file Objects/floatobject.c, line 532.
```

You can set as many breakpoints as you wish.

Starting CPython

To start the process, use the `run` command followed by arguments to start the Python interpreter.

For example, to start with a string:

```
(gdb) run -c "print(1)"
```

To start python with a script, use:

```
(gdb) run my_script.py
```

Attaching to a Running CPython Interpreter

If you have a CPython interpreter running already, you can attach to it.

From inside the gdb session, run `attach` with the process id:

```
(gdb) attach 123
```

You can get the process ID from the Activity Monitor, or using `os.getpid()` in Python.

Any breakpoints setup before this point or afterward will halt the process.

Handling a Breakpoint

When a breakpoint is hit, you can use the `print`, or `p` command to print a variable:

```
(gdb) p *(PyLongObject*)v
$1 = {ob_base = {ob_base = {ob_refcnt = 8, ob_type = ...}, ob_size = 1},
ob_digit = {42}}
```

To step into the next statement, use the command `step`, or `s`. To step over the next statement, use the command `next`, or `n`.

Using the Python-Gdb Extension

The python-gdb extension will load an additional command set into the gdb console:

Command	Purpose
`py-print`	Looks up a Python variable and prints it
`py-bt`	Prints a Python stack trace
`py-locals`	Prints the result of `locals()`
`py-up`	Go down one Python frame

Command	Purpose
`py-down`	Go up one Python frame
`py-list`	Print the Python source code for the current frame

Using Visual Studio Debugger

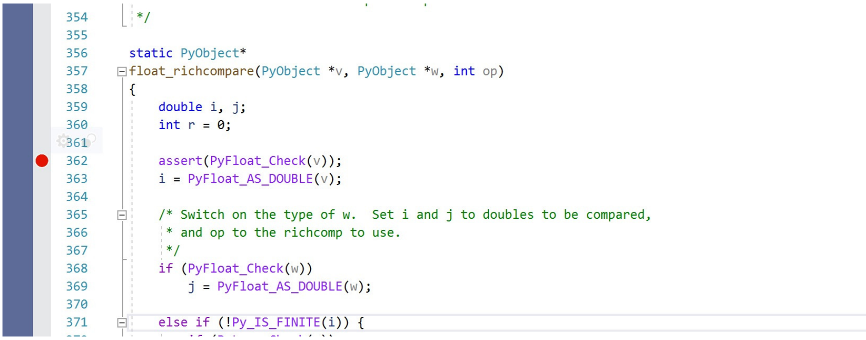
Microsoft Visual Studio comes bundled with a visual debugger. This debugger is powerful, supports a frame stack visualizer, a watch list, and the ability to evaluate expressions.

Open Visual Studio and the `PCBuild`▸`pcbuild.sln` solution file.

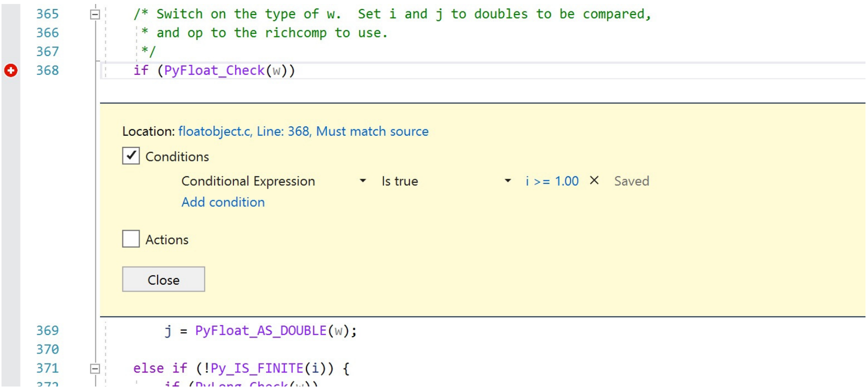
Adding Breakpoints

To add a new breakpoint, navigate to the file you want in the solution window, then click in the gutter to the left of the line number.

This adds a red circle to indicate a breakpoint has been set on this line:



When you hover over the red circle, a cog appears. Click on this cog to configure conditional breakpoints. Add one or more conditional expressions which must evaluate before this breakpoint hits:



Starting the Debugger

From the top menu, select Debug › Start Debugger, or press F5.

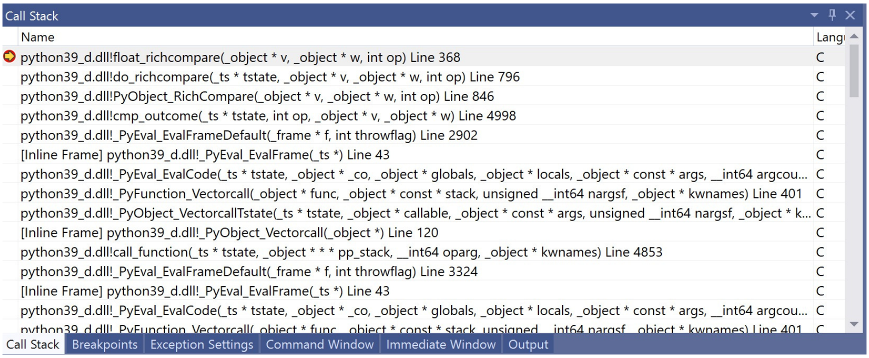
Visual Studio will start a new Python runtime and REPL.

Handling a Breakpoint

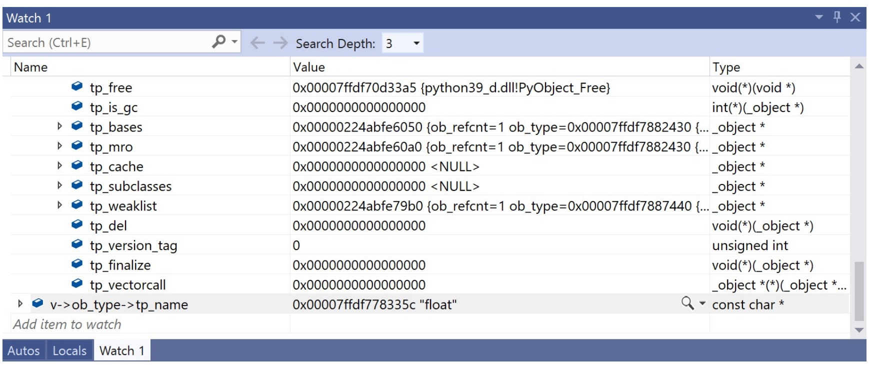
When your breakpoint is hit, you can step forward and into statements using the navigation buttons, or the shortcuts:

- Step Into F11
- Step Over F10
- Step Out Shift + F11

At the bottom, a call stack will be shown. You can select frames in the stack to change the navigation and inspect variables in other frames:



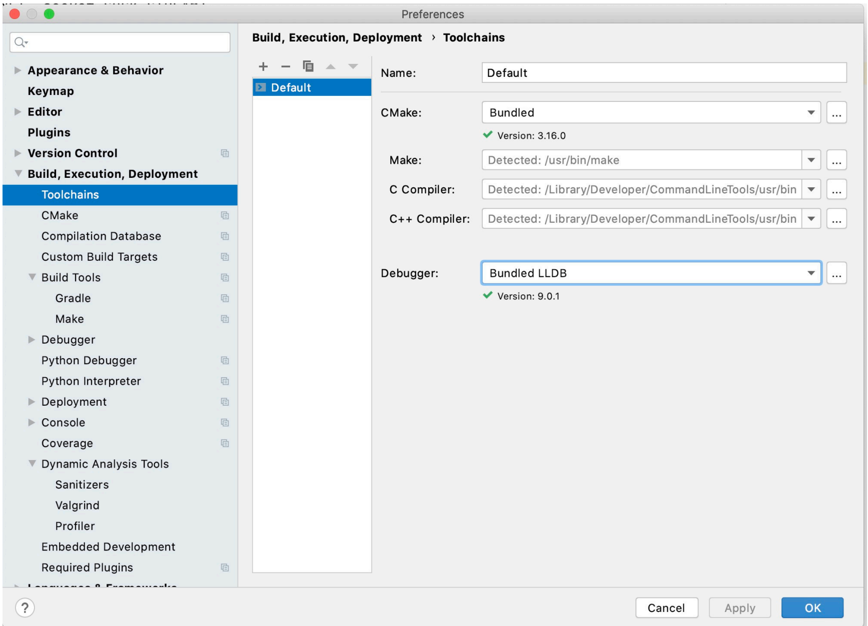
In the code editor, you can highlight any variable or expression to see its value. You can also right-click and choose “Add Watch.” This adds the variable to a list called the Watchlist, where you can quickly see the values of variables you need to help you debug:



Using CLion Debugger

The CLion IDE comes with a powerful visual debugger bundled. It works with lldb on macOS, and gdb on macOS, Windows, and Linux.

To configure the debugger, go to Preferences and select Build, Execution, Deployment > Toolchains:



There is a selection box for the target debugger. Select one of the options:

- For macOS use the "Bundled LLDB"
- For Windows or Linux, use the "Bundled GDB"

Important

Both the LLDB and GDB support benefit from the `cpython-lldb` and `python-gdb` extensions, respectively. Read the LLDB and GDB sections in this chapter for information on how to install and enable these extensions.

Debugging a Make Application

From CLion 2020.2, you can compile and debug any Makefile-based project, including CPython.

To start debugging, complete the steps in the Setting up JetBrains

CLion section in the Setting up Your Development Environment chapter. After completing these steps, you will have a `Make Application` target, select Run » Debug from the top menu to start the process and start debugging.

Alternatively, you can attach the debugger to a running CPython process.

Attaching the Debugger

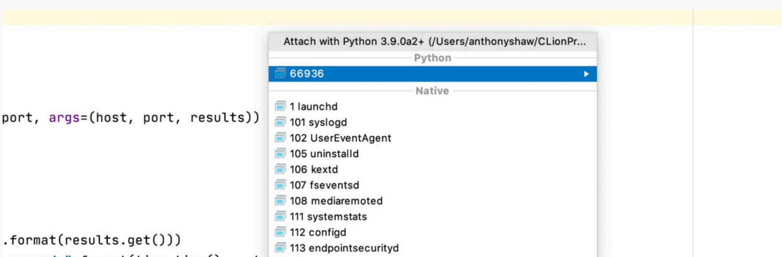
To attach the CLion debugger to a running CPython process, select Run » Attach to Process.

A list of running processes will pop-up. Find the `python` process you want to attach to and select Attach. The debugging session will begin.

Important

If you have the Python plugin installed, it will show the `python` process at the top. Don't select this one!

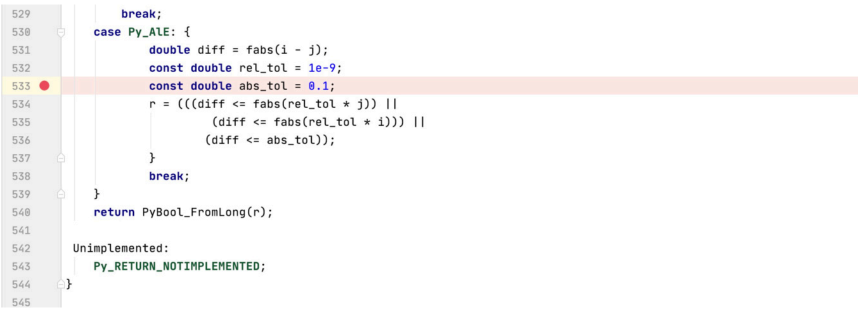
This uses the Python debugger, not the C debugger.



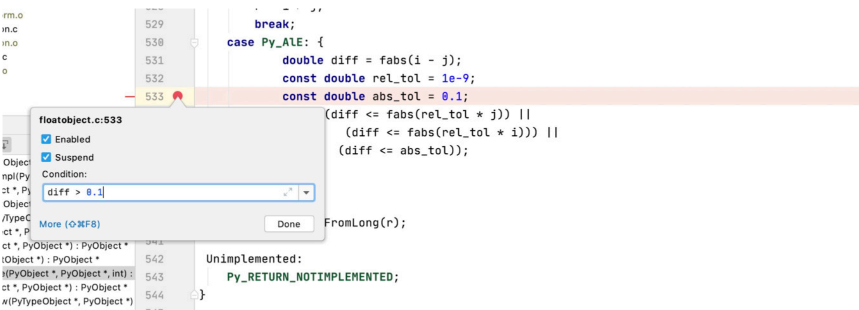
Instead, scroll further down into the "Native" list and find the correct `python` process.

Creating Breakpoints

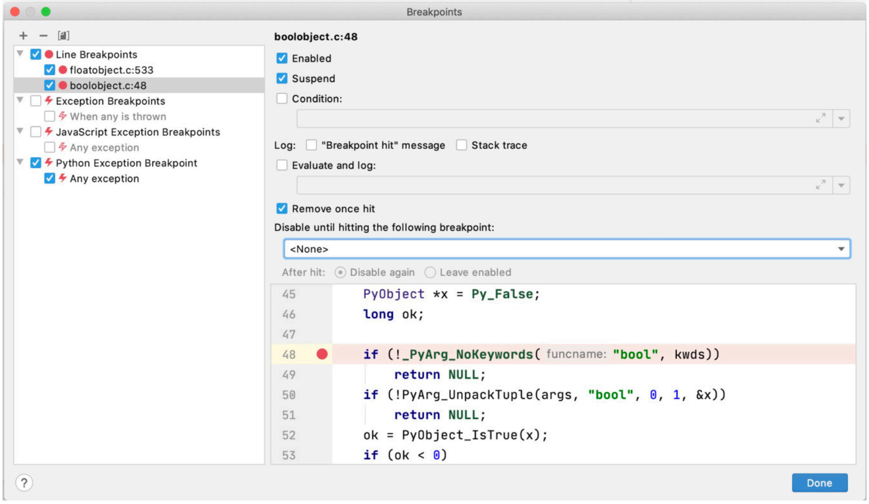
To create a breakpoint, navigate to the file and line you want, then click in the gutter between the line number and the code. A red circle will appear to indicate the breakpoint is set:



Right-click on the breakpoint to attach a condition:



To see and manage all current breakpoints, navigate from the top menu to Run › View Breakpoints:

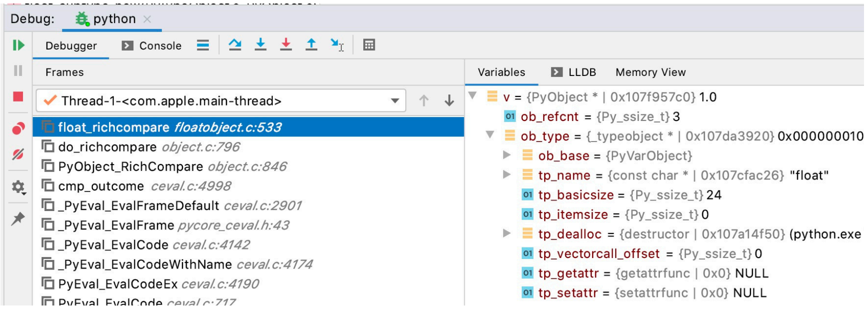


You can enable and disable breakpoints, as well as disable them once another breakpoint has been hit.

Handling Breakpoints

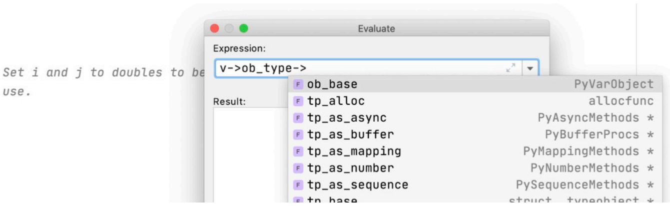
Once a breakpoint has been hit, CLion will set up the Debug panel. Inside the Debug panel is a call stack, showing where the breakpoint hit. You can select other frames in the call stack to switch between them.

Next to the call stack are the local variables. The properties of pointers and type structures can be expanded, and the value of simple types is shown:

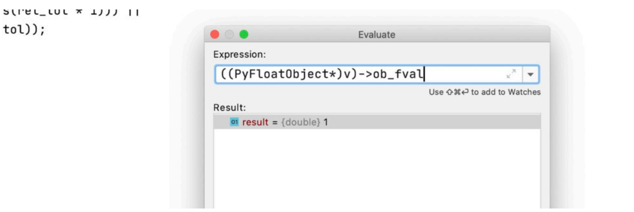


Within a break, you can evaluate expressions to get more information about the local variables. The Evaluation Window can be located in Run › Debugging Actions › Evaluate Expression, or in a shortcut icon in the Debug Window.

Inside the Evaluate window, you can type expressions and CLion will type-ahead with the property names and types:



You can also cast expressions, which is useful for casting `PyObject*` into the actual type, for example into a `PyFloatObject*`:



Conclusion

In this chapter, you've seen how to set up a debugger on all the major Operating Systems. While the initial setup is time-consuming, the reward is great. Being able to set breakpoints, explore variables, and memory for a running CPython process will give you superpowers. You can use this skill to extend CPython, optimize existing parts of the codebase, or track down nasty bugs.

Leave feedback on this section »

Benchmarking, Profiling, and Tracing

When making changes to CPython, you need to verify that your changes do not have a significant detrimental impact on performance.

You may want to make changes to CPython that improve performance.

There are solutions for profiling that you will cover in this chapter:

1. Using the `timeit` module to check a simple Python statement thousands of times for the median execution speed
2. Running the Python Benchmark suite to compare multiple versions of Python
3. Using `cProfile` to analyze execution times of frames
4. Profiling the CPython execution with probes

The choice of solution depends on the type of task:

- A **benchmark** will produce an average/median runtime of a fixed code snippet so that you can compare multiple versions of Python runtime
- A **profiler** will produce a call graph, with execution times so that you can understand which function is the slowest

Profilers are available at a C or Python level. If you are profiling a function, module, or script written in Python, you want to use a Python profiler. If you are profiling a C extension module or a modification to the C code in CPython, you need to use a C profiler (or a combination).

Here is a summary of some of the tools available:

Tool	Category	Level	OS Support
timeit	Benchmarking	Python	All
pyperformance	Benchmarking	Python	All
cProfile	Profiling	Python	All
dtrace	Tracing/Profiling	C	Linux/ macOS

Important

Before you run any benchmarks, it is best to close down all applications on your computer so the CPU is dedicated to the benchmark.

Using Timeit for Micro-Benchmarks

The Python Benchmark suite is a thorough test of CPython's runtime with multiple iterations. If you want to run a quick, simple comparison of a specific snippet, use the `timeit` module.

To run timeit for a short script, run the compiled CPython with the `-m timeit` module and a script in quotes:

```
$ ./python -m timeit -c "x=1; x+=1; x**x"
1000000 loops, best of 5: 258 nsec per loop
```

To run a smaller number of loops, use the `-n` flag:

```
$ ./python -m timeit -n 1000 "x=1; x+=1; x**x"
1000 loops, best of 5: 227 nsec per loop
```

Example

In this book, you have introduced changes to the `float` type by supporting the almost-equal operator.

Try this test to see the current performance of comparing two float values:

```
$ ./python -m timeit -n 1000 "x=1.0001; y=1.0000; x~=y"
1000 loops, best of 5: 177 nsec per loop
```

The implementation of this comparison is in `float_richcompare()`, inside `Objects▸floatobject.c`:

`Objects▸floatobject.c` line 358

```
static PyObject*
float_richcompare(PyObject *v, PyObject *w, int op)
{
    ...
    case Py_AlE: {
            double diff = fabs(i - j);
            double rel_tol = 1e-9;
            double abs_tol = 0.1;
            r = (((diff <= fabs(rel_tol * j)) ||
                     (diff <= fabs(rel_tol * i))) ||
                    (diff <= abs_tol));
            }
            break;
    }
```

Notice that the `rel_tol` and `abs_tol` values are constant, but haven't been marked as constant. Change them to:

```
const double rel_tol = 1e-9;
const double abs_tol = 0.1;
```

Now, compile CPython again and re-run the test:

```
$ ./python -m timeit -n 1000 "x=1.0001; y=1.0000; x~=y"
1000 loops, best of 5: 172 nsec per loop
```

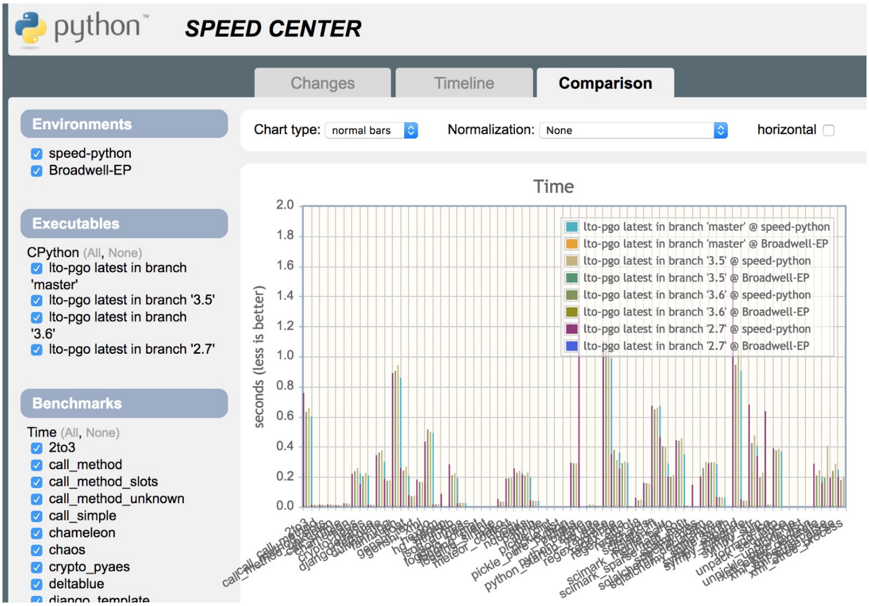
You might notice a minor (1-5%) improvement in performance.

Experiment with different implementations of the comparison to see if you can improve it further.

Using the Python Benchmark Suite for Runtime Benchmarks

The benchmark suite is the tool to use when comparing the complete performance of Python. The Python Benchmark suite is a collection of Python applications designed to test multiple aspects of the Python runtime under load. The Benchmark suite tests are pure-Python, so they can be used to test multiple runtimes, like PyPy and Jython. They are also compatible with Python 2.7 through to the latest version.

Any commits to the master branch on github.com/python/cpython will be tested using the benchmark tool, and the results uploaded to the Python Speed Center at speed.python.org:



You can compare commits, branches, and tags side by side on the speed center. The benchmarks use both the Profile Guided Optimization and regular builds with a fixed hardware configuration to produce stable comparisons.

To install the Python benchmark suite, install it from PyPi using a Python runtime (not the one you are testing) in a virtual environment:

```
(venv) $ pip install performance
```

Next, you need to create a configuration file and an output directory for the test profile. It is recommended to create this directory outside of your Git working directory. This also allows you to checkout multiple versions.

In the configuration file, e.g., `~/benchmarks/benchmark.cfg`, put the following contents:

`cpython-book-samples▸62▸benchmark.cfg`

```
[config]
# Path to output json files
json_dir = ~/benchmarks/json

# If True, compile CPython is debug mode (LTO and PGO disabled),
# run benchmarks with --debug-single-sample, and disable upload.
#
# Use this option used to quickly test a configuration.
debug = False

[scm]
# Directory of CPython source code (Git repository)
repo_dir = ~/cpython

# Update the Git repository (git fetch)?
update = False

# Name of the Git remote, used to create revision of
# the Git branch.
git_remote = remotes/origin

[compile]
# Create files into bench_dir:
bench_dir = ~/benchmarks/tmp

# Link Time Optimization (LTO)?
lto = True

# Profiled Guided Optimization (PGO)?
pgo = True

# The space-separated list of libraries that are package-only
pkg_only =

# Install Python? If false, run Python from the build directory
install = True

[run_benchmark]
```

```
# Run "sudo python3 -m pyperf system tune" before running benchmarks?
system_tune = True

# --benchmarks option for 'pyperformance run'
benchmarks =

# --affinity option for 'pyperf system tune' and 'pyperformance run'
affinity =

# Upload generated JSON file?
upload = False

# Configuration to upload results to a Codespeed website
[upload]
url =
environment =
executable =
project =

[compile_all]
# List of CPython Git branches
branches = default 3.6 3.5 2.7

# List of revisions to benchmark by compile_all
[compile_all_revisions]
# list of 'sha1=' (default branch: 'master') or 'sha1=branch'
# used by the "pyperformance compile_all" command
```

Executing the Benchmark

To run the benchmark, then run:

```
$ pyperformance compile -U ~/benchmarks/benchmark.cfg HEAD
```

This will compile CPython in the directory you specified and create the JSON output with the benchmark data in the directory specified in the config file.

Comparing Benchmarks

If you want to compare JSON results, the Python Benchmark suite doesn't come with a graphing solution. Instead, you can use this script from within a virtual environment.

To install the dependencies, run:

```
$ pip install seaborn pandas performance
```

Then create a script `profile.py`:

cpython-book-samples ▸ 62 ▸ profile.py

```python
import argparse
from pathlib import Path
from perf._bench import BenchmarkSuite

import seaborn as sns
import pandas as pd

sns.set(style="whitegrid")

parser = argparse.ArgumentParser()
parser.add_argument('files', metavar='N', type=str, nargs='+',
                    help='files to compare')
args = parser.parse_args()

benchmark_names = []
records = []
first = True
for f in args.files:
    benchmark_suite = BenchmarkSuite.load(f)
    if first:
        # Initialise the dictionary keys to the benchmark names
        benchmark_names = benchmark_suite.get_benchmark_names()
        first = False
    bench_name = Path(benchmark_suite.filename).name
    for name in benchmark_names:
```

```
        try:
            benchmark = benchmark_suite.get_benchmark(name)
            if benchmark is not None:
                records.append({
                    'test': name,
                    'runtime': bench_name.replace('.json', ''),
                    'stdev': benchmark.stdev(),
                    'mean': benchmark.mean(),
                    'median': benchmark.median()
                })
        except KeyError:
            # Bonus benchmark! ignore.
            pass

df = pd.DataFrame(records)

for test in benchmark_names:
    g = sns.factorplot(
        x="runtime",
        y="mean",
        data=df[df['test'] == test],
        palette="YlGnBu_d",
        size=12,
        aspect=1,
        kind="bar")
    g.despine(left=True)
    g.savefig("png/{}-result.png".format(test))
```

Then, to create a graph, run the script from the interpreter with the JSON files you have created:

```
$ python profile.py ~/benchmarks/json/HEAD.json ...
```

This will produce a series of graphs for each executed benchmark, in the subdirectory `png/`.

Profiling Python Code with cProfile

The standard library comes with two profilers for profiling Python code. The first is `profile`, a pure-Python profiler, and the second, `cProfile`, a faster profiler written in C. In most cases, `cProfile` is the best module to use.

The cProfile profiler is used for analyzing a running application and collecting deterministic profiles on the frames evaluated. The output from cProfile can be summarized on the command-line, or saved into a `.pstat` file for analysis in an external tool.

In the Parallelism and Concurrency chapter, you wrote a port scanner application in Python. Try profiling that application in cProfile.

Run `python` at the command-line with the `-m cProfile` argument to run the cProfile module. The second argument is the script to execute:

```
 $ python -m cProfile portscanner_multithreaded.py
Port 80 is open
Completed scan in 19.8901150226593 seconds
         6833 function calls (6787 primitive calls) in 19.971 seconds

   Ordered by: standard name

   ncalls  tottime  percall  cumtime  percall filename:lineno(function)
        2    0.000    0.000    0.000    0.000 ...
```

The output will print a table with the columns:

Column	Purpose
`ncalls`	Number of calls
`tottime`	Total time spent in the function (minus subfunctions
`percall`	Quotient of `tottime` divided by `ncalls`
`cumtime`	Total time spent in this (and subfunctions)
`percall`	Quotient of cumtime divided by primitive calls
`filename:lineno(function)`	Data of each function

You can add the `-s` argument and the column name to sort the output. E.g.:

```
$ python -m cProfile -s tottime portscanner_multithreaded.py
```

Will sort by the total time spent in each function.

Exporting Profiles

You can run the cProfile module again with the `-o` argument specifying an output file path:

```
$ python -m cProfile -o out.pstat portscanner_multithreaded.py
```

This will create a file, `out.pstat`, that you can load and analyze with the Stats class or with an external tool.

Visualizing with Snakeviz

Snakeviz is a free Python package for visualizing the profile data inside a web browser.

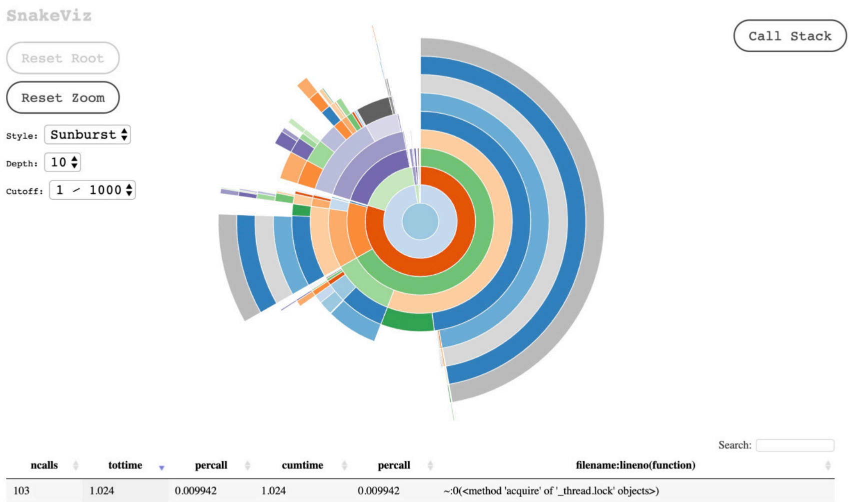
To install snakeviz, use pip:

```
$ python -m pip install snakeviz
```

Then execute snakeviz on the command line with the path to the stats file you created:

```
$ python -m snakeviz out.pstat
```

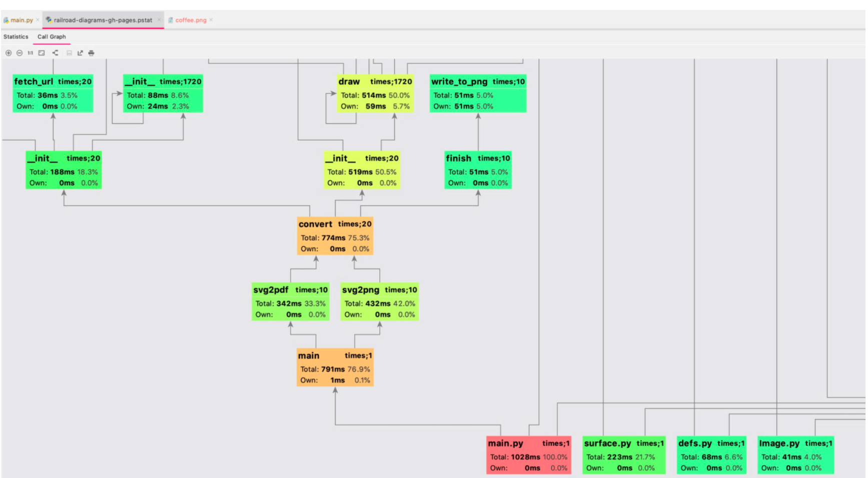
This will open up your browser and allow you to explore and analyze the data:



Visualizing with PyCharm

PyCharm has a builtin tool for running cProfile and visualizing the results. To execute this, you need to have a Python target configured.

To run the profiler, select your run target, then on the top menu select Run › Profile (target). This will execute the run target with cProfile and open a visualization window with the tabular data and a call graph:



Profiling C Code with Dtrace

The CPython source code has several markers for a tracing tool called dtrace. dtrace executes a compiled C/C++ binary, then catches and handles events within it using **probes**.

For dtrace to provide any meaningful data, the compiled application must have custom **markers** compiled into the application. These are events raised during the runtime. The markers can attach arbitrary data to help with tracing.

For example, inside the frame evaluation function, in `Python` ▸ `ceval.c`, there is a call to `dtrace_function_entry()`:

```
if (PyDTrace_FUNCTION_ENTRY_ENABLED())
    dtrace_function_entry(f);
```

This raises a marker called `function__entry` in dtrace every time a function is entered.

CPython has builtin markers for:

- Line execution
- Function entry and return (frame execution)
- Garbage collection start and completion
- Module import start and completion
- Audit hook events from `sys.audit()`

Each of these markers has arguments with more information. The `function__entry` marker has arguments for:

- File name
- Fuction name
- Line number

The static marker arguments are defined in the Official Documentation dtrace can execute a script file, written in D to execute custom code when probes are triggered. You can also filter out probes based on their attributes.

Related Source Files

Source files related to dtrace are:

File	Purpose
`Include ▸ pydtrace.h`	API definition for dtrace markers
`Include ▸ pydtrace.d`	Metadata the python provider that dtrace uses
`Include ▸ pydtrace_probes.h`	Auto-generated headers for handling probes

Installing Dtrace

dtrace comes pre-installed on macOS, and can be installed in Linux using one of the packaging tools:

For `yum` based systems:

```
$ yum install systemtap-sdt-devel
```

Or, for `apt` based systems:

```
$ apt-get install systemtap-sdt-dev
```

Compiling Dtrace Support

dtrace support must be compiled into CPython. This is done by the `./configuration` script.

Run `./configure` again with the same arguments you used in Compiling CPython and add the flag `--with-dtrace`. Once this is complete, you need to run `make clean && make` to rebuild the binary.

Check that the probe header was created by the configuration tool:

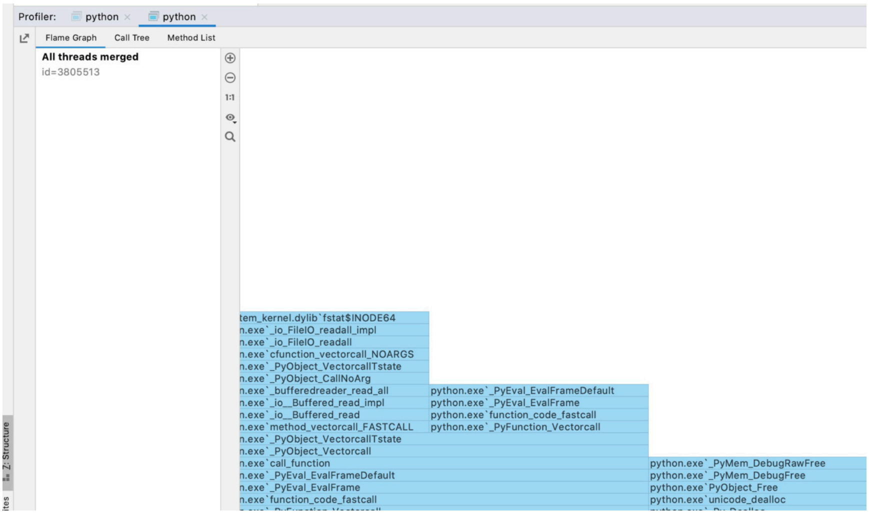
```
$ ls Include/pydtrace_probes.h
Include/pydtrace_probes.h
```

> **Important**
>
> Newer versions of macOS have kernel-level protection that interferes with dtrace called System Integrity Protection.
>
> The examples in this chapter use the CPython probes. If you want to include libc or syscall probes to get extra information, you will need to disable SIP.

Using Dtrace From CLion

The CLion IDE comes bundled with dtrace support. To start tracing, select Run > Attach Profiler to Process.. and select the running Python process.

The profiler window will prompt you to start and then stop the tracing session. Once tracing is complete, it provides you with a flame graph showing execution stacks and call times, a Call Tree and a Method List:



Example

In this example, you will test the multithreaded port scanner created in the chapter on Parallelism and Concurrency.

Create a profile script in D, `profile_compare.d`. This profiler will start when `portscanner_multithreaded.py:main()` is entered, to reduce the noise from the interpreter startup.

cpython-book-samples ▸ 62 ▸ profile_compare.d

```
#pragma D option quiet
self int indent;

python$target:::function-entry
/basename(copyinstr(arg0)) == "portscanner_multithreaded.py"
 && copyinstr(arg1) == "main"/
{
    self->trace = 1;
    self->last = timestamp;
}

python$target:::function-entry
/self->trace/
{
    this->delta = (timestamp - self->last) / 1000;
    printf("%dt%*s:", this->delta, 15, probename);
    printf("%*s", self->indent, "");
    printf("%s:%s:%dn", basename(copyinstr(arg0)), copyinstr(arg1), arg2);
    self->indent++;
    self->last = timestamp;
}

python$target:::function-return
/self->trace/
{
    this->delta = (timestamp - self->last) / 1000;
    self->indent--;
    printf("%dt%*s:", this->delta, 15, probename);
```

```
    printf("%*s", self->indent, "");
    printf("%s:%s:%dn", basename(copyinstr(arg0)), copyinstr(arg1), arg2);
    self->last = timestamp;
}

python$target:::function-return
/basename(copyinstr(arg0)) == "portscanner_multithreaded.py"
 && copyinstr(arg1) == "main"/
{
    self->trace = 0;
}
```

This script will print a line every time a function is executed and time the delta between the function starting and exiting.

You need to execute with the script argument, `-s profile_compare` and the command argument, `-c './python portscanner_multithreaded.py`:

```
$ sudo dtrace -s profile_compare.d -c './python portscanner_multithreaded.py'
0     function-entry:portscanner_multithreaded.py:main:16
28    function-entry: queue.py:__init__:33
18    function-entry:   queue.py:_init:205
29   function-return:   queue.py:_init:206
46    function-entry:   threading.py:__init__:223
33   function-return:   threading.py:__init__:245
27    function-entry:   threading.py:__init__:223
26   function-return:   threading.py:__init__:245
26    function-entry:   threading.py:__init__:223
25   function-return:   threading.py:__init__:245
```

In the output, the first column is the time-delta in microseconds since the last event, then the event name, the filename and line number. When function calls are nested, the filename will be increasingly indented to the right.

Conclusion

In this chapter, you have explored benchmarking, profiling, and tracing using a number of tools designed for CPython.

With the right tooling, you can find bottlenecks, compare performance of multiple builds and identify improvements.

Leave feedback on this section »

Conclusion

Congratulations! You've made it to all the way to the end of this book. There are three main uses of the knowledge you've learned:

1. Writing C extensions
2. Improving your Python applications
3. Contributing to the CPython Project

As a conclusion and summary of the topics, lets explore those.

Writing C Extensions for CPython

There are several ways in which you can extend the functionality of Python. One of these is to write your Python module in C or C++. This process can lead to improved performance and better access to C library functions and system calls.

If you want to write a C extension module, there are some essential things you'll need to know that this book has prepared you for:

- How to set up a C compiler and compile C modules. See the chapter on Compiling CPython.
- How to set up your development environment for C. See the Setting up Your Development Environment chapter.
- How to increment and decrement references to generated objects. See Reference Counting in the Memory Management chapter.

- What `PyObject*` is and its interfaces. See the Object and Variable Object Types section in the Objects and Types chapter.
- What type slots are and how to access Python type APIs from C. See the Type Slots section in the Objects and Types chapter.
- How to add breakpoints to C source files for your extension module and debug them. See the Debugging chapter.

See Also

Over at realpython.com, Danish Prakash has written a great tutorial on Building a C Extension Module. This tutorial includes a concrete example of building, compiling and testing an extension module.

Using This Knowledge to Improve Your Python Applications

There are several important topics covered in this book that can help you improve your applications. Here are some examples:

- Using Parallelism and Concurrency techniques to reduce the execution time of your applications. See the Parallelism and Concurrency chapter.
- Customizing the Garbage Collector algorithm to collect at the end of a task in your application to better handle memory. See the Garbage Collection section in the Memory Management chapter.
- Using the debuggers to debug C extensions and triage issues. See the Debugging chapter.
- Using profilers to profile the execution time of your code. See the Profiling Python Code with cProfile section of the Benchmarking, Profiling, and Tracing chapter.
- Analyzing frame execution to inspect and debug complex issues. See the Frame Execution Tracing section in The Evaluation Loop chapter.

Using This Knowledge to Contribute to the CPython Project

While writing this book, CPython had 12 new minor releases, 100's of changes, bug reports, and 1000's of commits to the source code.

CPython is one of the biggest, most vibrant, and open software projects out there. So what sets apart the developers who work on CPython and you, the reader?

Nothing.

That's right; the only thing stopping you from submitting a change, improvement, or fix to CPython is knowing where to start. The CPython community is eager for more contributors. Here are some places you could start:

1. Triaging issues raised by developers on bugs.python.org
2. Fixing small, easy issues

Let's explore each of those in a bit more detail.

Triaging Issues

All bug reports and change requests are first submitted to bugs.python.org. This website is the bug tracker for the CPython Project. Even if you want to submit a pull request on GitHub, you first need a "BPO Number," which is the issue number created by BPO (bugs.python.org).

To get started, register yourself as a user by going to User > Register on the left menu.

The default view is not particularly productive and shows both issues raised by users and those raised by core developers (which likely already have a fix).

Instead, after logging in, go to Your Queries > Edit on the left menu.

This page will give you a list of queries for the bug index that you can bookmark:

Figure 0.7: bpo-screenshot

Change the value to "leave in" to include these queries in the `Your Queries` menu.

Some of the queries I find useful are:

- **Easy Documentation Issues** - showing some documentation improvements that haven't been made
- **Easy Tasks** - showing some tasks that have been identified as good for beginners
- **Recently Created** - recently created issues
- **Reports without replies** - bug reports that never got a reply
- **Unread** - bug reports that never got read
- **50 latest issues** - the 50 most recently updated issues

With these views, you can follow the Triaging an Issue guide for the latest process on commenting on issues.

Raising a Pull Request to Fix an Issue

With an issue to fix, you can get started on creating a fix and submitting that fix to the CPython project.

1. Make sure you have a BPO number.
2. Create a branch on your fork of CPython. See the Getting the Source Code chapter for steps on downloading the source code.
3. Create a test to reproduce the issue. See the Testing Modules section of The Test Suite chapter for steps.
4. Make your change following the PEP7 and PEP8 style guides.
5. Run the Regression Test suite to check all the tests are passing. The regression test suite will automatically run on GitHub when you submit the Pull-Request, but it is better to check it locally first. See The Test Suite chapter for steps.
6. Commit and push your changes to GitHub.
7. Go to github.com/python/cpython and create a pull request for your branch

After submitting your pull request it will be triaged by one of the triage teams and assigned to a Core Developer or team for review.

As mentioned earlier, the CPython project needs more contributors. The time between submitting your change can be an hour, a week, or many months. Don't be dismayed if you don't get an immediate response. All of the Core Developers are volunteers and tend to review and merge pull requests in batches.

Important

It is important only to fix one thing in one pull request. If you see a separate (unrelated) issue in some code while writing your patch, make a note and submit it as a second pull request.

To help get your change merged quickly, a good explanation of the problem, the solution, and the fix go a long way.

Other Contributions

Other than bug fixes, there are some different types of improvements you can make to the CPython project:

- Many of the standard library functions and modules are missing unit tests. You can write some tests and submit them to the project.
- Many of the standard library functions don't have up-to-date documentation. You can update the documentation and submit a change.

Leave feedback on this section »

Keep Learning

Part of what makes Python so great is the community. Know someone learning Python? Help them out! The only way to know you've really mastered a concept is to explain it to someone else.

Come visit us on the web and continue your Python journey on the realpython.com website and the @realpython Twitter account.

Weekly Tips for Python Developers

Are you looking for a weekly dose of Python development tips to improve your productivity and streamline your workflows? Good news: we're running a free email newsletter for Python developers just like you.

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Appendix 1 : Introduction to C for Python Programmers

This introduction is intended to get an experienced Python programmer up to speed with the basics of the C language and how it's used in the CPython source code. It assumes you've already got an intermediate understanding of Python syntax.

That said, C is a fairly limited language and most of it's usage in CPython falls into a small set of syntax. Getting to the point where you understand the code is a much smaller step than being able to write C effectively. This tutorial is aimed at the first goal but not the second.

One of the first things that stand out as a big difference between Python and C is the C preprocessor. Let's look at that first.

C Preprocessor

The preprocessor, as the name suggests, is run on your source files before the compiler runs. It has very limited abilities, but these can be used to great advantage in building C programs. The preprocessor produces a new file which is what the compiler will actually process. All of the commands to the preprocess start at the beginning of a line with a `#` symbol as the first non-whitespace character.

The main purpose of the preprocessor is to do text substitution in the source file, but it will also do some basic conditional code for `#if` or similar statements.

Let's start with the most frequent preprocessor directive, `#include`.

#include

`#include` is used to pull the contents of one file into the current source file. There is nothing sophisticated about include. It reads that file from the file system, runs the preprocessor on that file and puts the results of that into the output file. This is done recursively for each `#include` directive found.

For example, if you look at the `Modules/_multiprocessing/semaphore.c` file, near the top you'll see:

```
#include "multiprocessing.h"
```

This tells the preprocessor to pull in the entire contents of `multiprocessing.h` and put it into the output file at this position.

You will notice two different forms for the include statement. One of them uses quotes to specify the name of the include file, the other uses angle brackets (<>). The difference comes from which paths are searched when looking for the file on the file system. If you use <> for the filename, the preprocessor will only look on "system" include files. Using quotes around the filename instead will force the preprocessor to look in the local directory first and then fall back to the system directories.

#define

`#define` allows you to do simple text substitution and also plays into the `#if` directives we'll see below.

At it's most basic, `#define` let's you define a new symbol that gets replaced with a text string in the preprocessor output.

Continuing in `semphore.c` you'll find this line:

```
#define SEM_FAILED NULL
```

This tells the preprocessor to replace every instance of `SEM_FAILED` below this point with the literal string `NULL` before the code is sent to the compiler.

`#define` items can also take parameters as in this Windows-specific version of `SEM_CREATE`:

```
#define SEM_CREATE(name, val, max) CreateSemaphore(NULL, val, max, NULL)
```

In this case and preprocessor will expect `SEM_CREATE()` to look like a function call and have three parameters. This is generally referred to as a **macro**. It will directly replace the text of the three parameters into the output code, for example, on line 459, the `SEM_CREATE` macro is used like this:

```
    handle = SEM_CREATE(name, value, max);
```

When compiling for Windows, this macro will be expanded so that line is:

```
    handle = CreateSemaphore(NULL, value, max, NULL);
```

We'll see below how this macro is defined differently on Windows and other operating systems.

#undef

This directive erases any previous preprocessor definition from `#define`. This makes it possible to have a `#define` in effect for only part of a file.

#if

The preprocessor also allows conditional statements, allowing you to either include or exclude sections of text based on certain conditions. Conditional statements are closed with the `#endif` directive and also can make use of `#elif` and `#else` for fine-tuned adjustments.

There are three basic forms of `#if` that you'll see in the CPython source:

- **`#ifdef <macro>` :** includes the following block of text if the specified macro is defined
- **`#if defined(<macro>)`:** same as `#ifdef`
- **`#ifndef <macro>`:** includes the following block of text if the specified macro is not defined
- **`#if <macro>`:** includes the following text if the macro is defined **and** it evaluates to True

Note the use of "text" instead of "code" to describe what is included or excluded from the file. The preprocessor knows nothing of C syntax and does not care what the specified text is.

`#pragma`

Pragmas are instructions or hints to the compiler. In general you can ignore these while reading the code as they usually deal with how the code is compiled, not how the code runs.

`#error`

Finally, `#error` displays a message and causes the preprocessor to stop executing. Again, you can safely ignore these for reading the CPython source code.

Basic C Syntax

This section will not cover ALL aspects of C nor, again, is it intended to teach you how to write C. It will focus on things that are different or confusing for Python developers the first time they see them.

General

Unlike in Python, whitespace is not important to the C compiler. It does not care if you split statements across lines or jam your entire program onto a single, very long line. This is because it uses delimiters for all statements and blocks.

There are, of course, very specific rules for the parser, but in general you'll understand the CPython source just knowing that each statement ends with a semicolon (`;`) and all blocks of code are surrounded by curly braces (`{}`).

The exception to this rule is that if a block has only a single statement, the curly braces can be omitted.

All variables in C must be **declared** meaning there needs to be a single statement giving the **type** of that variable. Note that, unlike Python, the data type that a single variable can hold cannot change.

Let's look at some examples:

```
/* comments are included between slash-asterisk and asterisk-slash */
/* This style of comment can span several lines -
   so this part is still a comment. */

// OR comments can be after two slashes
// This type of comments only go until the end of the line, so new
// lines must have //s again.

int x = 0; // declares x to be of type 'int' and initializes it to 0

if (x == 0) {
    // this is a block of code
    int y = 1;  // y is only a valid variable name until the closing }
    // more statements here
    printf("x is %d y is %d\n", x, y);
}

// single line blocks do not require curly brackets
```

```c
if (x == 13)
    printf("x is 13!\n");
printf("past the if block\n");
```

In general you'll see that the CPython code is very cleanly formatted and generally sticks to a single style within a given module.

`if` Statements

In C, `if` works generally like it does in Python. If the condition is true then the following block is executing. The `else` and `else if` syntax should be familiar enough to Python programmers to understand. Note that C `if` statements do not need an `endif` because blocks are delimited by `{}`.

There is a shorthand in C for short if/else statements call the **ternary operator**:

```
condition ? true_result : false_result
```

You can find it in `semaphore.c` where, for Windows, it defines a macro for `SEM_CLOSE()`:

```c
#define SEM_CLOSE(sem) (CloseHandle(sem) ? 0 : -1)
```

The return value of this macro will be `0` if the function `CloseHandle()` returns `true` and `-1` otherwise.

Just a note about `true` in C. Boolean variable types are supported and used in parts of the CPython source, but they were not a part of the original language. C interprets binary conditions using a simple rule: `0` or `NULL` is false, everything else is true.

`switch` Statements

Unlike Python, C also supports `switch`. Using `switch` can be viewed as a shortcut for extended `if/elseif` chains. This example is from `semaphore.c`:

```
switch (WaitForSingleObjectEx(handle, 0, FALSE)) {
case WAIT_OBJECT_0:
    if (!ReleaseSemaphore(handle, 1, &previous))
        return MP_STANDARD_ERROR;
    *value = previous + 1;
    return 0;
case WAIT_TIMEOUT:
    *value = 0;
    return 0;
default:
    return MP_STANDARD_ERROR;
}
```

This performs a switch on the return value from `WaitForSingleObjectEx()`. If the value is `WAIT_OBJECT_0`, the first block is executed. The `WAIT_TIMEOUT` value results in the second block, and anything else matches the `default` block.

Note that the value being tested, in this case the return value from `WaitForSingleObjectEx()`, must be an integral value or an enumerated type and that each `case` must be a constant value.

Loops

There are three looping structures in C:

- `for` loops
- `while` loops
- `do..while` loops

Let's look at each of these in turn.

`for` loops have syntax that is quite different than Python:

```
for ( <initialization>; <condition>; <increment>) {
    <code to be looped over>
}
```

In addition to the code to be executed in the loop, there are three blocks of code which control the `for` loop.

The `<initialization>` section is run exactly one time when the loop is started. It traditionally is used to set a loop counter to an initial value (and possibly declare the loop counter). The `<increment>` code is run immediately after each pass through the main block of the loop. Traditionally this will increment the loop counter. Finally, the `<condition>` is run after the `<increment>`. The return value of this code will be evaluated and the loop breaks when this condition returns false.

Here's an example from `Modules/sha512module.c`:

```
for (i = 0; i < 8; ++i) {
    S[i] = sha_info->digest[i];
}
```

This loop will run 8 times, with `i` going from 0 to 7, terminating when the condition is check and `i` is 8.

`while` loops are virtually identical to their Python counterparts. The `do..while()` syntax is a little different, however. The condition on a `do...while()` loop is not checked until after the first time the body of the loop is executed.

There are many instances of `for` loops and `while` loops in the CPython code base, but `do..while()` is unused.

Functions

The syntax for functions in C is similar to that in Python, with the addition that the return type and parameter types must be specified. The C syntax looks like this:

```
<return_type> function_name(<parameters>) {
    <function_body>
}
```

The return type can be any valid type in C, including both built-in types like `int` and `double` as well as custom types like `PyObject` like in this example from `semaphore.c`:

```
static PyObject *
semlock_release(SemLockObject *self, PyObject *args)
{
 <statements of function body here>
}
```

Here you see a couple of C-specific things in play. First off, remember that whitespace does not matter. Much of the CPython source code puts the return type of a function on the line above the rest of that function declaration. That's the `PyObject *` part. We'll talk about the `*` aspect of this a little later, but here we should point out that there are several modifiers you can place on functions and variables.

`static` is one of these modifiers. Unfortunately these modifiers have some complex rules governing how they operate. For instance, the `static` modifier here means something very different than placing it in front of a variable declarations.

Fortunately, these modifiers can generally be ignored while trying to read and understand the CPython source code.

The parameter list for functions is a comma-separated list of variables, similar to Python. Again, C requires specific types for each parameter, so the `SemLockObject *self` says that the first parameter (all parameters in C are positional) is a pointer to a `SemLockObject` and is called `self`.

Let's look at what the pointer part of that statement means.

To give some context, the parameters that are passed to C functions are all passed by value, meaning the function operates on a copy of the value and not the original in the calling function. To work around this, functions will frequently pass in the address of some data that the function can modify. These addresses are called **pointers** and have types, so `int *` is a pointer to an int value and is of a different type than `double *` which is a pointer to a double.

Pointers

As mentioned above, pointers are variables that hold the address of a value. These are used frequently in C as seen in the example above:

```
static PyObject *
semlock_release(SemLockObject *self, PyObject *args)
{
 <statements of function body here>
}
```

Here the `self` parameter will hold the address of (usually called "a pointer to") a `SemLockObject` value. Also note that the function will return a pointer to a `PyObject` value.

There is a special value in C to indicate that a pointer does not point to anything, called **`NULL`**. You'll see pointers assigned to `NULL` and checked against `NULL` throughout the CPython source. This is important as there are very few limitations as to what values a pointer can have and access a memory location that is not officially part of your program can cause very strange behavior.

If you try to access the memory at `NULL`, on the other hand, your program will exit immediately. This may not seem better, but it's generally easier to figure out a memory bug if `NULL` is accessed than if a random memory address is modified.

Strings

In C there is not a string type. There is a convention around which many standard library functions are written, but there is not an actual type. Rather, strings in C are stored as arrays of `char` or `wchar` values, each of which holds a single character. Strings are marked with a **null-terminator** which has a value `0` and is usually shown in code as `\0`.

Basic string operations like `strlen()` rely on this null-terminator to mark the end of the string.

Because strings are just arrays of values, they cannot be directly copied or compared. The standard library has the `strcpy()` and `strcmp()` functions (and their `wchar` cousins) for doing these operations and more.

Structs

Your final stop on this mini-tour of C is how you can create new types in C: **structs**. The `struct` keyword allows you to group a set of different data types together into a new, custom data type:

```
struct <struct_name> {
    <type> <member_name>;
    <type> <member_name>;
    ...
};
```

This partial example from `Modules/arraymodule.c` shows a struct declaration:

```
struct arraydescr {
    char typecode;
    int itemsize;
    ...
};
```

This creates a new data type called `struct arraydescr` which has many members, the first two of which are a `char typecode` and an `int itemsize`.

Frequently structs will be used as part of a `typedef` which provides a simple alias for the name. In the example above, all variables of the new type must be declared with the full name `struct arraydescr x;`.

You'll frequently see syntax like this:

```
typedef struct {
    PyObject_HEAD
    SEM_HANDLE handle;
```

```
    unsigned long last_tid;
    int count;
    int maxvalue;
    int kind;
    char *name;
} SemLockObject;
```

This creates a new, custom struct type and gives it a name `SemLockObject`. To declare a variable of this type, you can simply use the alias `SemLockObject x;`.

Conclusion

This wraps up the quick walk through C syntax. There were many corners that were cut in this description, but it should be sufficient to read the CPython source code.

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This is an Early Access version of "CPython Internals: Your Guide to the Python 3 Interpreter"

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— Anthony Shaw