Pynguin: Automated Unit Test Generation for Python

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ABSTRACT
Automated unit test generation is a well-known methodology aiming to reduce the developers’ effort of writing tests manually. Prior research focused mainly on statically typed programming languages like Java. In practice, however, dynamically typed languages have received a huge gain in popularity over the last decade. This introduces the need for tools and research on test generation for these languages, too. We introduce Pynguin, an extendable test-generation framework for Python, which generates regression tests with high code coverage. Pynguin is designed to be easily usable by practitioners; it is also extensible to allow researchers to adapt it for their needs and to enable future research. We provide a demo of Pynguin at https://youtu.be/UiGrG25Vt60; further information, documentation, the tool, and its source code are available at https://www.pynguin.eu.

CCS CONCEPTS
- Software and its engineering → Search-based software engineering; Software testing and debugging; Software maintenance tools.

KEYWORDS
Python, Automated Test Generation

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1 INTRODUCTION
Automated software test generation has a long history both in research and industrial settings. Over the years, researchers have presented many approaches for generating test input data, such as random [4] and search-based [14] techniques. Many of these approaches have been implemented in tools, most notably Random [15] and EvoSuite [5] for the Java programming language.

The focus on the Java programming language, however, represents a limitation of prior research, as dynamically typed programming languages such as JavaScript and Python have gained huge popularity over the last decade. Python, in particular, is popular in many domains such as data science and machine learning, and it nowadays ranks as one of the most used programming languages (see, for example, the IEEE Spectrum ranking'). This increasing popularity of the language requires more and better tools to support the developers and improve the general code quality they produce. Testing is one of the most important techniques to improve the quality of software, but automated tool support for test generation is currently lacking in the Python tool box. Unfortunately, automated test generation is challenging in the context of a dynamically typed language.

A crucial problem impeding the development of test generation techniques is the fact that programs written in a dynamically typed language usually do not provide any information about variable types. Statically deriving this information is hard [8], as these languages often allow to change the type of a variable’s value throughout the program, dynamically modify objects at runtime, or provide type coercions that might not match the intent of the programmer [19]. As a consequence, test generation research has so far only tackled specific aspects or restricted scenarios. For example, TSTL [9], CrossHair5, Klara3, or Auger4, require manual effort by the developer before they can produce test cases. Although Hypothesis [13] can also generate tests automatically, its aim is to find minimal property-violating input values. We therefore introduce Pynguin [10], which aims to use search-based test-generation techniques to automatically generate regression tests [22] with high code coverage, without requiring user input.

Pynguin is an open-source framework written in and for the Python programming language. It uses search-based test generation to generate tests that maximise code coverage. Pynguin by default incorporates type information into the test-generation process. However, it is also able to generate covering test cases for programs that do not explicitly provide type information. Designed as an extendable framework, Pynguin allows both researchers and practitioners to explore established and new ideas for test generation in the context of a dynamically typed programming language, such as further coverage criteria or new test-generation algorithms.

Initial empirical evaluation [10] of Pynguin shows that the automated generation of regression tests is feasible also for a dynamically typed programming language: on average, Pynguin achieved a branch coverage of up to 68.0% on 118 Python modules from 17 open-source libraries. Our initial evaluation furthermore indicates that type information is crucial also for the test-generation process: Incorporating type information leads to significantly higher coverage levels; our previous experiments show a median improvement

1https://spectrum.ieee.org/top-programming-languages/, last accessed 2022–02–10.
2https://crosshair.readthedocs.io, last accessed 2022–02–10.
3https://klara-py.readthedocs.io, last accessed 2022–02–10.
4https://github.com/laffra/auger, last accessed 2022–02–10.
5https://github.com/laffra/crosshair, last accessed 2022–02–10.
of up to 2.7 percentage points over all used projects, depending on
the test-generation algorithm [11]. This paper describes the inner
workings of Pynguin and how one can use and extend it.

2 TEST GENERATION WITH PYNGUIN

Pynguin is written in Python and requires at least Python 3.8 to
run. It can, however, generate unit tests also for Python projects
that are built for older versions of Python. Pynguin can be run
as a standalone command-line application or — which is recom-
mented — inside a Docker container. It is released under the GNU
LGPL open-source licence.

2.1 Pynguin’s Components

Figure 1 shows the components of Pynguin and their interactions
throughout the test-generation process.

Pynguin takes as input a Python module (denoted by (1) in
Fig. 1). It then analyses the module to extract information (2).
The extracted information consists, among others, of the declared
classes, functions, and methods. From this information Pynguin
builds the so-called test cluster [21] (3). The test cluster contains all
information about the module under test, most importantly, which
classes, functions, and methods are declared, and what their para-
eters are. Furthermore, Pynguin inspects the modules that are
transitively included by the module under test (shown as the context
in Fig. 1, (4)). From the context, Pynguin extracts the types they
define by searching for those class definitions that are available in
the namespace of the module under test. These types are then used
as input-type candidates during the test-generation phase. Pynguin
selects classes, methods, and functions from the test cluster during
the generation to build the test cases.

When constructing a test case, Pynguin selects a function or
method from the module under test. Consider the example code
snipped in Listing 1: there is only one function in the module,
triangle, which Pynguin selects as its target function. It therefore
adds a statement representing a method call to triangle to its internal
test-case representation. Afterwards, Pynguin aims to fulfill the
requirements of the function’s parameters in a backwards fashion.
In the example, Pynguin knows from the type annotations that int
statements are required. It therefore generates one to three variable
assignment statements of the form \texttt{var = \textless int\textgreater} and adds them to
the test case before the function-call statement. The number of int

5Usually, a module in Python is equivalent to a source file. We currently restrict the
support to modules written in Python because of the necessary code instrumentation.

statements as well as the generated values are chosen randomly by
Pynguin, because variable values can be used for more than one
parameter. Listing 2 shows two test cases that have been created by
this way. In case a more complex object is required as a parameter,
Pynguin will attempt to generate it by recursively fulfilling the
parameters of the involved methods; the necessary statements are
also prepended to the list of statements of the test case. We provide
a detailed example of this process in our previous work [11].

For test input generation (5) the user can select between various
well-established algorithms: DynaMOSA [17], MIO [1], MOSA [16],
random [15], Whole Suite [6], and Whole Suite with archive [20].
Depending on the selected algorithm, Pynguin generates one or
many test cases. It then executes the newly generated test cases
against the module under test to measure the achieved coverage (6).
Currently, Pynguin can consider line or branch coverage as an opti-
misation goal for its search algorithms. To support other variants
of coverage one needs to provide further fitness functions; further
coverage criteria are planned for future work. It is possible to select
one sort of coverage for the optimisation or a combination of many.
To measure coverage we instrument Python’s byte code on-the-fly
to trace which parts of the module under test have been executed by
a generated test. After evaluating fitness, Pynguin continues with
the next iteration of the test-generation algorithm. This process
stops once a configurable stopping condition is satisfied, such as a
time limit or a predefined amount of algorithm iterations. It is also
possible to stop the generation after all coverage goals have been
met, which means the generated tests achieve 100 % coverage.

After the test-input generation Pynguin optionally attempts to
generate regression assertions [22] to not only execute the code
under test but also check its results (7). The approach implemented
in Pynguin is based on mutation testing [7]. Pynguin utilises a
customised version of MutPy [3] to generate mutated versions
from the original module under test (8). MutPy executes the tests
generated by the previous stage of Pynguin against these mutants
as well as the original module. By tracing the values of object at-
ntributes and function returns, Pynguin determines which values
change on the mutated version, compared to the original module.
For these values Pynguin generates assertions that interpret the
returned values on the original module as the ground truth. As a
consequence, the generated assertions are able to kill the aforemen-
tioned mutants if they show different behaviour compared to the
original module. An advantage of generating regression tests this
way is that it implicitly minimises the number of assertions present
in the resulting test cases.

Figure 1: The execution steps of Pynguin.
Finally, Pynguin generates Python source code from its internal representation of the test cases and exports the source code in the style of the popular PyTest framework into a Python module. Further styles, for example, unit test from Python’s standard API, can also be integrated easily.

Each of the stages of Pynguin is built as modular and as independent of the others as possible. Pynguin itself is furthermore built with extendability in mind. This allows to replace stages and components easily.

2.2 Using Pynguin

Pynguin is written in Python. It can thus be either executed after checking out its source code or—more conveniently—be installed from the Python Package Index (PyPI) via the pip utility tool.

The primary usage of Pynguin is as a command-line application. It also provides a rudimentary API that allows controlling the framework from inside another application without the need to launch an external process. As future work we plan to enhance Pynguin’s public API such that it can also be used as a library for test generation within other projects without the necessity to execute it as a standalone application. Our presentation here, however, will only discuss the command-line interface. We refer the interested reader to Pynguin’s documentation, which describes the API. One can get an overview of all command-line arguments using the --help option after installing Pynguin:

```
$ pynguin --help
```

Please note that Pynguin requires the user to set the environment variable PYNGUIN_DANGER_AWARE; Pynguin executes the code under test with arbitrary random inputs. Depending on the code under test this can cause side effects and harm to the user’s system. By setting the environment variable to an arbitrary value the user confirms to Pynguin that they are aware of this risk.

The main arguments of Pynguin are --project-path to specify the path of the project Pynguin should generate tests for, --module-name to specify the name of the module to generate tests for, and the --output-path, where Pynguin stores the generated test cases. Pynguin requires the user to set at least those three parameters; all further arguments come with documented default values yielded by the --help parameter.

Consider the example in Listing 1, saved to a module triangle.py in the current work directory. One can now run Pynguin with minimal configuration options:

```
$ pynguin
   --project-path ./
   --module-name triangle
   --output-path /tmp/pynguin-tests
```

This results in Pynguin generating test cases using DynaMOSA (the current default algorithm). It stores them in files to the folder /tmp/pynguin-tests. Now suppose that the user wants to generate tests for the same module but with the MIO algorithm instead of DynaMOSA. All they need to do is to add --algorithm MIO to their command line:

```
$ pynguin
   --project-path ./
   --module-name triangle
   --algorithm MIO
```

Similarly, one can set further configuration options. Listing 2 shows an excerpt of the generated result. The two shown test cases in the result execute the triangle function with different parameter values to execute different branches of the function’s implementation; the test cases also provide assertions that check on the returned value of the triangle function. Please note that re-executing Pynguin will overwrite the resulting files.

In the aforementioned settings, Pynguin will not print any output to the terminal. A more verbose output can be achieved by adding the --v or --vv parameter.

2.3 Dynamic Typing

As Python is a dynamically typed language, it does not require the user to specify any type information, although recent versions of the language support annotations for such information. Pynguin aims to parse type annotations from the source code if they are available (configurable as a parameter to Pynguin). Any parsed information about parameter types of functions and methods as well about their return types is incorporated into the test cluster. The type information stored in the test cluster allows Pynguin to select specific objects to satisfy the requirements of the parameters when generating test cases for a specific function or method.

Besides extracting type information from annotations in the source code, Pynguin can also be extended to query external type-inference tools. If no type annotations are available for the code under test Pynguin considers all available types from the test cluster as

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9https://pytest.org, last access 2022–02–10.
10https://pyppi.org/project/pynguin, last accessed 2022–02–10.
11https://pynguin.readthedocs.io, last accessed 2022–02–10.

Listing 1: A simple function checking for triangle properties.

```
def triangle(x: int, y: int, z: int) -> str:
    if x == y == z:
        return "Equilateral triangle"
    elif x == y or y == z or x == z:
        return "Isosceles triangle"
    else:
        return "Scalene triangle"
```  

Listing 2: An excerpt of the test cases generated by Pynguin.

```
import example as module0

def test_case_0():
    int_0 = 4271
    int_1 = -3706
    str_0 = module0.triangle(int_0, int_0, int_1)
    assert str_0 == "Isosceles triangle"

def test_case_1():
    int_0 = -163
    int_1 = 484
    int_2 = 77
    str_0 = module0.triangle(int_0, int_1, int_2)
    assert str_0 == "Scalene triangle"
```
candidates during input generation. In this case, Pynguin currently selects one of the available types from the test cluster randomly.

Let us again consider the triangle-classification function from Listing 1. Suppose there were no type annotation present: As a consequence, Pynguin could only guess the types of the parameters and might come up with objects of arbitrary types available from the test cluster. Since our example does neither define new types nor import any modules, only the so-called ‘builtins’ are available: basic types such as float or str. Choosing parameter values of type float instead of int would be a reasonable choice for this triangle function. However, the following test case would also be valid for the Python language if there is no type information available:

```python
import example as module0

def test_case_2():
    list_0 = ["foo", "bar"]
    str_0 = module0.triangle(list_0, list_0, list_0)
    assert str_0 == "Equilateral triangle"
```

Checking the triangle type for a list of strings is not a reasonable thing, although the language would permit it. Note that the above test case is valid because it executes the program without crashes and covers parts of the code of the triangle function; it therefore contributes towards the optimisation goal of high coverage. However, the test case also shows that coverage may not be a good metric for the effects of types. Using an unexpected type as an input may often also simply lead to crashes of the program under test, for example, if the code attempts to access non-existing attributes. Furthermore, the lack of type information can also prevent Pynguin from being able to instantiate the correct objects. This simple example shows that type information is crucial for test generation to generate not only covering but also valid and useful tests. While we strongly advocate the usage of type annotations to improve Pynguin’s resulting test cases, the use of alternative means such as type inference is an open research problem. Enabling future research to address this problem is a core motivation for building Pynguin.

### 2.4 Extending Pynguin

Pynguin is a framework that allows easy extension at various points. Many extensions can be built by implementing only few classes. For example, adding a new test-generation algorithm can be achieved by extending the abstract class TestGenerationStrategy and implementing its generate_tests method. It is also necessary to register the new algorithm in the configuration and the algorithm instantiation. The algorithm instantiation provides predefined operators to the new algorithm such as a factory for new chromosomes or fitness functions for the search objectives. We designed these components with evolutionary algorithms in mind; one can of course also define purely random-based algorithms as we have done with our Random algorithm, based on the RANDOOP algorithm [15].

To demonstrate how simple this can be, Listing 3 implements an algorithm that is based on random test-case sampling: it generates a random test case by adding a method call and its dependencies — the object to call the method on as well as objects to fill the parameter values (see Sec. 2 of our previous work [11] for a detailed illustration of this process). Our example algorithm utilises the archive that is also used for the MOSA [16] algorithm to store generated test cases that cover certain coverage goals in order to keep track of them. Now the algorithm loops until the stopping condition is fulfilled or the test cases stored in the archive cover all coverage goals. In each loop iteration, the algorithm randomly samples another test case. It stores the new test case in the archive as well. The given implementation also calls some helper methods that keep track of the test-generation process; for example, they track the achieved coverage value over the generation time. In the end, the example algorithm creates a test suite, that is, a collection of the generated test cases, and returns them back to the framework. We already implemented this algorithm in Pynguin; one can select it by setting --algorithm RANDOM_TEST_CASE_SEARCH.

Similarly, other parts of Pynguin can be extended. Examples are test-case export in different styles by implementing an AST visitor or the incorporation of type-inference techniques by querying external type-inference tools.

### 3 EVALUATION

We evaluated Pynguin by conducting a small experiment for this paper, using the aforementioned algorithms for test generation. We used 118 modules from our previous work [11] for our evaluation and ran Pynguin in version 0.17.0 [12] 30 times on each module and in each configuration to minimise the influence of randomness. For the experiment, we set the timeout for test generation to 600 s. In this work we only give few insights; for a more extensive evaluation we refer the reader to our previous work [10, 11], which not only studies the differences between various algorithms in greater detail but also investigates on the influence of type information.

To gain insights on the performance of the different algorithms, we measured branch coverage. Figure 2 shows the development of the mean coverage per configuration over the generation time of
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