ExploTest, a Python Unit Test Carving Tool

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Abstract

The abstract is a concise and accurate summary of the research contained in the thesis. It states the problem, the methods of investigation, and the general conclusions, and should not contain tables, graphs or illustrations. It must not exceed 350 words, and should contain relevant keywords that will make your thesis more likely to be found in an electronic search. Do not put a separate list of keywords. There must be a single abstract for the entire thesis.

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Chapter 1

Introduction

ExploTest is a tool that solves software engineering problems!?

1.1 Problem Statement

Unit tests are the gold standard to test programs to catch analysis or programming errors. An ideal unit test only assesses one behaviour of the program, is repeatable and requires no software engineer intervention. They often aid in the debugging process, allowing software engineers to identify bugs faster, and earlier in the product life cycle. However, the creation of unit tests is often falsely perceived to not contribute to the product's development. Creating these tests also requires effort to gather the inputs to the test, and requires the software engineer to create test oracles (assertions in JUnit style testing frameworks) to model correct behaviour. As programs evolve, these oracles may shift, and inputs to the test may also change.

1.2 Scope of Research

We intend to evaluate 4 research questions enumerated below:

RQ1: To what extent does the unit test carving tool we created generate viable unit tests when applied to popular, open-source Python repositories?

RQ2: What software families and attributes are associated with the differing viabilities of unit tests created by the tool?

RQ3: What is the amount of speedup offered by the unit tests created by the tool compared to their system test runs?

RQ4: What modes of failure occur when the tool fails to create any kind of unit test?

RQ5: What is the procedure to use ExploTest to catch defects in software?

Chapter 2

Background

2.1 Unit Test Carving

Unit test carving, originally called unit test factoring, was introduced by Saff et al. Test carving is described to be "a technique for automatically creating fast, focused unit tests from slow system-wide tests; each new unit test exercises only a subset of the functionality exercised by the system tests" [15, 16]. Test carving techniques typically involve record-and-replay (also called carve-and-replay [4, 5]), recording function executions, serializing the inputs and outputs of the function, then invoking the function again with said captured inputs.

Elbaum et al. [4] coined the term unit test carving, and they abstractly break down unit test carving for a given method m during program execution. Both the program state before the first instruction of m, called s_{pre} and the state after the final instruction of m, called s_{post} are captured. A pair of states before and after the execution of m: (s_{pre}, s_{post}) constitute a unit test for m. As the codebase of a program evolves, m may change over time.

The execution of a carved unit test must first restore s_{pre}, execute m, then compare the state after the execution (s_m) to s_{post}. In common software engineering parlance, the execution of a carved unit test is as follows:

- Restoring $s_{pre} \rightarrow$ test setup; typically found in the fixtures or the `@BeforeEach` part of a unit test.
- Executing $m \rightarrow$ running the function-under-test
- Comparing s_m to $s_{post} \rightarrow$ the test oracle; typically assertions like `assertEquals`.

There are two approaches in capturing s_{pre}, explains Elbaum et al.: state-based and action-based.

State-based capture involves saving s_{pre}, typically serializing s_{pre} to disk, then de-serializing it to restore s_{pre}. ExploTest implements this in its pickle-mode. This comes with certain challenges which we will describe later in this thesis. The majority (TODO: CHECK IF THIS IS ACTUALLY TRUE!) of unit testing tools use state-based capture.

Action-based capture involves saving the instructions before s_{pre}, and later replaying those instructions to re-create s_{pre}. This resolves many of the challenges of state-based capture, but is harder to do in practice. ExploTest has a limited version of action-based capture in its argument reconstruction mode.

2.1.1 Challenges in State-based Capture

Evolution and Serialization

Serialization involves storing the state of the program to disk [2]. In turn, when we want to restore the state of the program, we have to load that state from disk. This state is entirely unaware of changes to the source code, which means any changes to the structure of the object in the source code at a later time is not reflected in the serialized format. In turn, this makes the unit tests more brittle to breaking from code evolution.

Serialization Opaqueness

Unlike the code to create objects in source code, reading objects from disk does not at all explain the process that got the object to that serialized state. This makes it much more confusing for maintainers of source code that utilizes serialized state in unit tests to change the unit tests as code evolves, worsening the evolution issue. MicroTestCarver by Deljouyi and Zaidman [3] tries to remedy this issue in their work by serializing to XML, a human-editable file format using the XStream library, however, there is no similar library that produces any kind of human readable serialization output in Python.

Non-serializable Objects

There are objects that cannot be serialized, which typically have ill-defined representations after de-serialization. Currently, the most robust Python serialization library which we elected to use, dill [12] do not support generator, traceback, and code frame objects. Code frame objects cannot be captured by state-based capture, as the creation of a code frame object entails the creation of native code objects which cannot be done without some action-based capture. Similarly, network sockets and active network connections do not have a meaningful value when de-serialized, as the server they connect has likely since closed the connection. Finally, objects which explicitly reject serialization by disabling `__reduce__` cannot be serialized. This family of objects necessitates the use of action-based capture.

2.1.2 Challenges in Action-based Capture

The Object Creation Problem

The Object Creation Problem, defined by Bach et al. [1], is the problem of finding the correct sequences of method calls to construct an object. In Python, creating is objects is not always as simple as calling the `__init__` constructor, instead, objects rely on hierarchies and overridden `__new__`, or other classes like in the factory design pattern.

Arbitrary Object Modification

Explained by Politz et al. [14], the semantics of Python allow for arbitrary modification to object attributes at any time in the programs. The shape of an object, which we define to be the number and names of fields of an object can change at any point in a Python program.

While this is a problem in unmanaged languages like C++, and the authors of [1] discuss this issue, they consider it out of scope of the object creation problem, as it is unidiomatic in C++, and often leads to undefined behaviour. Unfortunately, this technique of arbitrary modification of objects at any point is often used by Python programmers.

This presents challenges to action-based capture, as existing action-based capture unit test carving tools like ARTISAN [6] assume that the shape of an object does not change, and can assume the object

2.2 Prior Work in Test Carving for Python

2.2.1 Pythoscope

Pythoscope, by Kwiatkowski and Clements-Tiberio [9, 10, 13] is an open source Python 2 unit test generation tool, created around 2008.

2.2.2 Auger

[11]

2.2.3 Fuzzing Book Carver

[19]

2.2.4 Genthat

2.3 How ExploTest Performs Unit Test Carving of Python Programs

Originally created by Zihao Huang under the supervision of Dr. Caroline Lemieux, ExploTest is a unit test carving tool used to created unit tests from exploratory test runs. As defined by Kaner [7], exploratory testing is an unscripted technique where the software designer verifies the program's correctness using their own intuition and domain knowledge to uncover defects and create test oracles. Exploratory testing exercise the whole program, and we aim to capture unit tests for specific methods.

Chapter 3

Evaluation

3.1 Evaluation Dataset

3.1.1 Criteria

Since unit tests are used to catch defects in software, it's natural to use software defects to evaluate ExploTest. Therefore, we collected 22 bugs across 12 repositories.

In selecting bugs, we had a few criteria inspired by Pythoscope's [8] creator:

1. Since Python is a popular and general purpose programming language, we want bugs from various types of Python software.
2. Due to design limitations associated with ExploTest, the program with the bug must support Python 3.13.7.
3. Each bug must be easy to reproduce with an associated system test.
4. Each bug must have an associated function that causes the bug — i.e., the bug must be detectable by unit testing a function.
5. The root cause of the bug must be from the source code itself, not due to platform issues (e.g., a bug in the interpreter or operating system).
6. The bug cannot be so severe that the program does not execute or cause other processes to crash.

3.1.2 Dataset

We evaluate ExploTest on 22 individual bugs across 12 repositories:

Table 3.1: Repositories used in the evaluation dataset

Project name	Category	Description
`gunicorn`	Web framework	HTTP server.
`click`	UI library	Library for creating command-line interfaces.
`seaborn`	Data visualization	Data visualization library.
`Pygments`	Source code analysis	Tool for syntax highlighting source code.
`pylint`	Source code analysis	Linter for Python code.
`IPython`	Meta tooling	Enhanced interactive Python REPL.
`httpie`	Command-line utility	Command-line HTTP client and API testing tool.
`Tornado`	Web framework	Web framework.
`black`	Source code analysis	Python source code formatter.
`sanic`	Web framework	Web framework.
`PySnooper`	Meta tooling	Debugging tool that traces function inputs, outputs, and state.
`youtube-dl`	Command-line utility	Command-line tool for downloading videos from online streaming services (e.g., YouTube).

Bugs were selected from the popular BugsInPy bug repository [17] and from selected repositories in QuAC [18], a Python type inference tool.

Each bug consists of three things: the buggy commit, the fixed commit, and a bug report containing a system-test procedure on how to reproduce the bug.

3.2 Environment

The evaluation takes place on an x86_64 computer running Ubuntu 24.04.3. All code is run using Python 3.13.7 in a virtual environment for each bug.

3.3 Answering the RQs

3.3.1 ExploTest Outcomes

The unit tests that ExploTest produces can be of different qualities, or it may not produce a unit test at all due to technical limitations. As discussed in the introduction, unit tests have to exercise the function-under-test (FUT) and then assess its return value with an oracle, which in Python is an assertion. The table below outlines how we will categorize these different outcomes. In answering RQ2, we can group tests that

3.3.2 Flakiness

A unit test is considered flaky when it exhibits both passing and failing results on the same version of the source code without any changes to the code itself. We run the test twice as a rudimentary test for flakiness.

Table 3.2: Per-bug evaluation results

Repo	ID	# of tests	Function called	Output correct	Oracle created	Passes on good code	Fails on bad code
black	12	490	Yes	Yes	No	N/A	N/A
black	13	3	Yes	Yes	Yes	Yes	No
black	15	1	Yes	Yes	Yes	Yes	No
httpie	3	1	Yes	Yes	Yes	Yes	Yes
PySnooper	2	4	Yes	Yes	Yes	Yes	No
PySnooper	3	1	Yes	Yes	Yes	Yes	No
sanic	1	6	Yes	Yes	Yes	Yes	No
sanic	2	0	N/A	N/A	N/A	N/A	N/A
sanic	3	3	Yes	Yes	Yes	Yes	Yes
tornado	10	0	N/A	N/A	N/A	N/A	N/A
tornado	14	2	Yes	Yes	No	N/A	N/A
tornado	15	1	Yes	Yes	Yes	Yes	No
tornado	4	2	Yes	Yes	Yes	Yes	No
youtube-dl	12	0	N/A	N/A	N/A	N/A	N/A
click	3071	4 P / 4 ARR	Yes	Yes	No	Yes	No
gunicorn	3144	0	N/A	N/A	N/A	N/A	N/A
ipython	14930	0	N/A	N/A	N/A	N/A	N/A
pylint	10373	1	Yes	Yes	Yes	Yes	No
pylint	10402	2	Yes	Yes	Yes	Yes	No
seaborn	3542	1	Yes	Yes	No	Yes	No
seaborn	3553	0	N/A	N/A	N/A	N/A	N/A
pygments	2382	1	Yes	Yes	Yes	Yes	No

Table columns

- **Repo**: The repository the bug originates from.
- **ID**: For bugs from BugsInPy, the BugsInPy ID that the bug is associated with. For bugs from QuAC, this is the GitHub issue number that the bug is associated with.
- **# of tests**: The number of unit tests generated by the tool. The tool can generate > 1 test when the FUT is exercised more than once by the system test, or if recursive calls occur. 0 tests are generated when the tool fails to generate any test at all.
- **Function called**: Does the tool correctly setup the required
- **Output correct**: Whether the output of the function-under-test exercised by the unit test is equivalent to the system test.
- **Oracle created**: Whether assertions were created to determine the software functions correctly.
- **Passes good code**: Whether the assertions pass when running on the correct code (i.e., the code the test was generated on).
- **Fails on bad code**: Whether the assertions fail when running on the buggy code (i.e., they detect the bug).

3.3.3 Preliminary Evaluation

Preparation

For each bug, we will create a new Python virtual environment using the `venv` module.

We then install the package and its dependencies as instructed by the documentation of the package, along with ExploTest. For seaborn, since the bugs appear as plots, we install `jupyter` and `notebook` to work with plots interactively.

Finding carve target

ExploTest uses an `@explore` decorator to mark functions to carve in the source code. By placing the decorator, the function is transformed to first perform a static analysis of the function's source code (e.g., to get the function name and parameter/package information).

To evaluate RQ1, we can split the dataset into two by bug origin: bugs from BugsInPy and bugs from QuAC. Bugs from BugsInPy come with buggy functions already known, while the causes of bugs from QuAC are indeterminate. While the bugs from QuAC may contain fixes in pull requests that identify the functions that introduce the bug, we refrain from looking at them to help answer RQ5 with a cleaner slate.

Locating carve targets for bugs from BugsInPy

The data provided by BugsInPy already identify the individual lines that cause the bug to occur.

For us, the first thing to do is to place the `@explore` at the nearest function to the lines that cause the bug to occur. However, these functions might not be good candidates for carving for two reasons: (1) parameters might not be serializable, as discussed in chapter 2, or (2), the return value of the function will not allow us to generate an oracle that detects the bug.

Oftentimes, human inspection of the source code allows us to determine the presence of non-serializable objects. We can infer these properties from variable names, for example, variables named `frame` suggest the presence of frame objects which contain pointers to native code that cannot be serialized.

A similar manual source code analysis works to identify return values not conducive to good test oracles. We can inspect the source code for free-standing `return`s that indicate a function that is used for its side effects only.

When we identify a method that is a bad candidate for test carving, we walk up the call graph of the function (i.e., look at the caller and the usage of our target function), and place an `@explore` once we determined that the objects are serializable, or keep looking up.

There are cases where we cannot find any suitable candidates, in which case we consider the unit test to not be carvable with our tool.

Locating carve targets for bugs from QuAC

TBD, pending actual results.

Answering RQ1

1. Run the non-buggy version of the code and function and observe its output.
2. Use the procedure outlined above to place the `@explore` to mark the function-under-test for carving.
3. Generate the test on the non-buggy version of the code using the system test case:

   Did the tool crash? Were exceptions or errors emitted and what kind?
4. If a non-empty file was produced, inspect the file and run the test using a debugger to determine whether the FUT was reached. Observe the output of the function from the generated the unit test against the output of the system test. If they are the same, we can consider the FUT to be exercised.
5. When running the test, we can observe whether the test passes on the non-buggy code. If it passes, we move and apply the buggy commits. If the test fails on the source it was generated on, we note it down and skip the next step.
6. We then run the test, generated on the non-buggy code on the buggy version of the codebase. The test should not pass, and if it does, we consider the oracle defective.

This procedure should allow us to bucket each created test by the table, and facilitate discussion of failure cases.

Answering RQ2

Using the buckets we have in section 3.1.2, we can summarize functioning unit tests (what do we consider functioning?) by the program family they belong to. We will discuss characteristics that make programs conducive to unit test carving.

Answering RQ3

We time the time it takes to execute the system test with GNU `time` version 1.9 on our environment mentioned in section 3.2. We calculate and discuss three metrics:

- The bug detection speedup, $\frac{T^B_{\text{sys}}}{T^B_{\text{unit}}}$, which is the speedup multiplier offered by the unit test to catch buggy code.

  It is the ratio of the time it takes for a system test on buggy code to run (T^B_{sys}) and the time it takes for a unit test on buggy code (T^B_{unit}).

- The regression verification speedup, $\frac{T^P_{\text{sys}}}{T^P_{\text{unit}}}$, which is the speedup multiplier offered by the unit tests to validate code changes on a correct codebase.

  It is the ratio of the time it takes for a system test on correct code to run (T^P_{sys}) and the time it takes for a unit test on correct code (T^P_{unit}).

- Carving time, which is the difference between the system test running with ExploTest and without ExploTest.

  It is the ratio of the time to run the program while carving and without carving.

Answering RQ4

When carving tests, the most common cause of failure are non-serializable objects. We'll discuss the root cause of these objects and their frequencies. Another failure mode is a defective oracle that either fails on correct code, or oracles that pass on incorrect code.

Answering RQ5

For the assessment of this RQ to remain valid, we purposely discard the bugs found from BugsInPy, since the author was already exposed to the root causes of these bugs. Instead, the author will try to debug and root cause analyze the bugs from QuAC, using ExploTest, and determine if there is a procedure to using ExploTest to find, and potentially patch bugs.

Chapter 4

Challenges in Test Carving

4.1 Common Failure Modalities in Existing Unit Test Carving Tools

? Look at literature?

4.2 Common Failure Modalities of ExploTest

Two (big) failure modes:

- Non-serializable object
  - Existence of code objects, things like: `co_name`
  - Generators, async or non-async
- Unable to create oracle
  - Benign: FUTs don't return values, they modify class state

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Appendix A

Case studies of bugs used in evaluation