PyT

A Static Analysis Tool for Detecting Security Vulnerabilities in Python Web Applications

Master's Thesis

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This report is written using LaTeX in GNU Emacs. Figures are made using dot, Tikz and PyT. For screen-shots Snipping Tool and Shutter have been used.

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Abstract:

The amount of vulnerabilities in software grows everyday. This report examines vulnerabilities in Flask web applications, which is a Python web framework. Cross site scripting, command injection, SQL injection and path traversal attacks are used as example vulnerabilities. A static analysis of Python is used to analyse the flow of information in the given program. The static analysis consists of constructing a control flow graph using polyvariant interprocedural analysis. The fixed-point theorem is used for analysing the control flow graph. Using an extended version of the reaching definitions it is possible to capture information flow through a program. A tool has been implemented and can be used on whole projects giving possible vulnerabilities as output. At last an evaluation of the tool is presented. All example vulnerabilities were detected and real world projects were successfully used as input.

Source code:
`https://github.com/SW10IoT/pyt/tree/finalfinal`

Summary

This report presents the static analysis too PyT which has been created to detect security vulnerabilities in Python web applications, in particular applications built in the framework Flask.

The tool utilizes the monotone framework for the analysis. An AST is built by the builtin AST library, and a CFG is built from the AST. The resulting CFG is then processed so Flask specific features are taken into account. A modified version of the reaching definitions algorithm is now run by the fixed-point algorithm to aid the finding of vulnerabilities. Vulnerabilties are detected based on a definition file containing 'trigger words'. A trigger word is a word that indicate where the flow of the program can be dangerous. The detected vulnerabilities are in the end reported to the developer.

PyT has been created with flexibility in mind. The analysis can be either changed or extended so the performance of PyT can be improved upon. Also the Flask specific processing can be changed so other frameworks can be analysed without major changes to PyT.

In order to test the abilities of PyT a number of vulnerable applications was manufactured and PyT was evaluated with these. All the manufactured examples was correctly identified as being vulnerable by PyT.

To test PyT in a more realistic setting it was also run on 7 open source projects. Here no vulnerabilities were found. One of the projects was so big that PyT spent very long on the analysis and was therefore terminated.

Preface

This master's thesis has been prepared by 10th semester Software Engineering students at Aalborg University, during the spring-semester of 2016. It is expected of the reader to have a background in IT/software, due to the technical content.

References and citations are done by the use of numeric notation, e.g. [1], which refers to the first item in the bibliography.

We would like to thank our supervisor René Rydhof Hansen and co-supervisor Mads Chr. Olesen for their excellent supervision throughout the project period.

Aalborg University, May 31, 2016

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Chapter 1

Introduction

Vulnerabilities are being found all the time in software. As new software and features get published, potential vulnerabilities get released. The attacker has the advantage in terms of variety of attacks. He can comfortably attempt each attack in his arsenal while the publisher frantically tries to patch up the breaches. The publisher often finds out about a vulnerability when it is too late and important data has been stolen. So the element of surprise is certainly also there. As Bruce Schneier said:

> *''Attackers are at an advantage in cyberspace – this will not always be true, but it'll certainly be true for the next bunch of years – and that makes defence difficult.''*[1]

Vulnerabilities in web applications There are constantly popping up new technologies and old ones are evolving and developing new features. These new technologies and features can be used by the attackers as well. Therefore it is important to be updated on current and new technologies when developing anything to the web.[2]

The *The OWASP Top Ten Project* [3] lists the most critical web application security flaws. The list is produced by a broad spectrum of security experts. They recommend that each application is checked for these ten critical security flaws and each organisation gets aware of how to detect and prevent these flaws.

Considering the difficulty of these problems and the size of code bases in the average software project, it would be an advantage to have a tool that could help finding security vulnerabilities. As both of us have an interest in Python development we decided to look into tools the could help developing secure Python web applications. We encountered two Python web frameworks, Django and Flask, that both do their part in helping the developer. But even though the framework

helps the developer, it is can still possible to circumvent or overlook these features. Therefore we looked into tools that could analyse and find vulnerabilities in Python code. When examining this type of tools we did not find anything that satisfied our needs (see Section 2.1) This report will thus create a tool that aids detection of security flaws in Python web applications, focusing on the Flask web application framework.

Chapter 2

Preliminaries

In order to analyse a Flask application it is necessary to have a basic understanding of both the Flask framework and the Python programming language. In addition we need to have an understanding of the security vulnerabilities that we want to detect.

This chapter will start out by describing the tools that already exists for finding security vulnerabilities in Python web applications. Afterwards it will look at related work performed in this area of research. At last it will examine what web frameworks exist in order to choose one to focus on throughout the project.

2.1 Existing Tools

In this section we will look at open source tools that find security vulnerabilities by analysing Python web applications. We have found two tools which are described in the following.

2.1.1 Python Taint Mode

The Python Taint Mode, Conti and Russo [4], is a library which contains a series of functions that are used as decorators to taint the source code. To use the library one has to annotate the source code. Dangerous methods have to be provided with the `untrusted` and `ssink` decorators, indicating where untrusted data comes from and where it can be damaging. Dangerous variables have to be marked with a function `taint`.

Some of these annotations can be provided in the beginning of the file, while others, like the tainting of variables have to be tainted directly in the code. This means that one has to go through the whole source code and taint variables and functions in order to get a proper analysis.

The tool can not handle booleans and has some built in class function it can not handle. The effectiveness of the tool is not documented.

2.1.2 Rough Auditing Tool for Security

The Rough Auditing Tool for Security(RATS)[5] is a tool for C, C++, Perl, PHP and Python. It is said to be fast and is good for integrating into a building process. For Python the tool only checks for risky builtin functions so it is rather basic. Also RATS has not been developed on since 2013 and the open source project seems dead.

2.1.3 Comparison

Having found two analysis tools which both are rather different there is not much to compare. This is because Python Taint Mode requires the developer to decorate the source code and the RATS tool is checking for builtin functions only. As we can see there are not many tools and the RATS tool is not even being supported anymore. This pushed us in the direction of considering to making an open source tool that finds security vulnerabilities in Python web applications.

2.2 Related Work

As mentioned in Section 2.1, few tools exist that do anything like what we want. The same is the case in terms of research papers. This section will present the single paper that had a similar goal as our project.

2.2.1 Balancing Cost and Precision of Approximate Type Inference in Python

This section contains and overview of the work of Fritz [6]. This master's thesis implements a data flow analysis for performing approximate type inference on Python code.

Fritz [6] builds a CFG of the source code, and uses the worklist algorithm to compute the result of an analysis using fixpoint iteration. The result is then used to perform type inference on.

The thesis contains brief explanation about the implementation in Appendix A. Unfortunately the source code is not available. If the source code would have been available, the implementation of the control flow graph and the worklist algorithm could have been used as a foundation for our project.

2.3 Python Web Frameworks

Before trying to remove security vulnerabilities in applications we needed a framework to focus on. This section contains short descriptions of two of the available Python web frameworks. The web frameworks were chosen from *Web Frameworks for Python* [7]. There are two sets of Python web frameworks, full-stack and non-full-stack frameworks, one of each was chosen. A full-stack framework is a framework that contains all you need to develop a web application. A non-full-stack framework is a framework which does not contain all packages to develop a complete web application. Choosing either of these two categories is a matter of taste, full-stack framework are ready out of the box while non full-stack needs additional packages, but non-full-stack frameworks have the advantage that the developer can choose his preferred packages for the job. First the Django web framework was chosen, which is a full-stack framework. Django was chosen because it is one of the most popular web frameworks. The second choice was the Flask micro web framework, one of the most popular non-full-stack frameworks.

2.3.1 Django

Django[8] is a web framework that contains all you need to make a complete web application. Django is using the Model-View-Controller architecture pattern(MVC)[9]. It is built in a way that forces the developer to add functionality in a specific way. This means that there is not a lot customisability in the architecture of the project.

Django operates with an abstract concept of apps. An app contains the following modules:

- Main module - where the app is starting to execute code.
- Tests module - testing of the app.
- Views module - visualisation of the app.
- Urls module - maps urls to views.
- Models module - models for instance from a database.
- Apps module - nested apps.

A Django web application consists of a combination of apps. The power of Django is the ease of reuse of an app as they are easily linked together using urls.

2.3.2 Flask

Flask[10] is a micro web framework. Flask is highly customizable as you can choose your own architecture of your web application. Also it is possible for instance to make your own form validation or use a form validation package that one wants. Flask comes with the following features:

- Development server
- Unit test support
- REST support

The power of Flask is that the developer is able to customise everything.

2.4 Why Flask

This section argues why the the Flask web framework was chosen for this project. The two key factors was its simplicity and our previous experience with the framework. These factors will be described shortly in the following.

Simplicity The simplicity of Flask enables us to focus on the important task at hand and not on how to develop a web application. This means rapid development of web applications used as examples and for testing the tool during the project.

Previous experience The project group has previous experience using Flask. This again means that we can develop examples faster, without having to spend time getting acquainted with the framework.

Chapter 3

Python

This chapter contains an overview of the Python programming language, its parameter passing and some surprising features.

3.1 Python

This section will shortly give an overview of the Python programming language version 3.5.1. The purpose is to provide a basic knowledge of the programming language making it possible to follow the Python code used throughout the report. This section is based on *Python 3.5.1 documentation* [11].

3.1.1 About Python

The Python programming language is a dynamic, interpreted programming language created by Guido van Rossum in the early 1990s. Python supports multiple programming paradigms, including object oriented and functional programming. The design philosophy of python values code readability and expressivity.

3.1.2 Parsing Python

A Python program uses newlines as delimiters between statements.[1] But if an expression is stretched over several lines for instance in parentheses it is still one line but several physical lines. A comment starts with a "`#`" symbol. Indentation is used for grouping statements for instance a body of a function. A file is a module which contains definitions and statements and ends with the suffix `.py`. A program can contain several modules.

[1] A line can be joined with the next line if it has a "\" at the end of the line.

3.1.3 Objects

All data in Python is represented as objects. An object consists of an identity, a type and a value. The identity of an object never changes and is represented as an integer. The type of an object defines how the object can be used and which operations are supported by the object. The value of an object can for some objects change. Objects whose value can be changed are called mutable, while objects whose value can not be changed are immutable.

Definition of objects happen in class definitions. Classes have methods and attributes attached to it. In Listing 3.1 a class is defined. The `__init__()` method is an initializer function which is called after a new instance is created of that class. The `self` keyword references instance variables and instance methods. This example defines the `MyClass` class which has one instance method `print_i` and one instance variable `i`. An instance of this class is created with the value five passed to the `i` variable through the initializer. The `print_i()` instance method is then called, which will print the value of `i`.

```
1 def MyClass(object):
2     def __init__(self, i):
3         self.i = i
4
5     def print_i(self):
6         print('Now i is:' +  i)
7
8 mc = MyClass(5)
9 mc.print_i()
```

Listing 3.1: Class definition

3.1.4 Collections

Python contains a number of built in collection classes used to store items in a structured way. The following will shortly describe the most common collections and their uses, based on *Data structures in Python* [12] where additional information can also be found. The mentioned operations will be exemplified in Listing 3.2.

Lists A list is a mutable sequence of items. A list can be appended and extended items, and membership testing can be performed with the `in` keyword. A list is iterable and can be indexed to retrieve individual items. Lists are created with square brackets or the `list()` function.

Tuples A tuple is similar to a list, but is an immutable sequence of a number of values. A tuple is created with round brackets or the `tuple()` function.

Sets A set is an implementation of the mathematical set. It is an unordered collection that contains no duplicates. A set is created with curly brackets or the `set()` function.

Dictionaries A dictionary is an associative map, mapping a key to an item. The key can be any immutable type which can then be extracted as when indexing a list. Dictionaries are constructed with curly brackets contained key-value pairs or with the `dict()` function.

```
1  l = [1, 2, 3, 4] # a list of 4 elements - 1, 2, 3, 4
2  l.append(9) # append to the list -> 1, 2, 3, 4, 9
3
4  s = (5, 6, 7, 8, 8, 8, 8) # a set of 4 elements - 5, 6, 7, 8
5  l.extend(s) # extend the list with the set
6              # -> 1, 2, 3, 4, 10, 5, 6, 7, 8
7
8  l.sort() # sort the list
9  l # the sorted list -> 1, 2, 3, 4, 5, 6, 7, 8, 9
10
11 t1 = (1,2) # a tuple -> (1,2)
12 t1[1] # retrieve the element at index 1 -> 2
13
14 t2 = (3,4) # another tuple -> (3,4)
15
16 d = dict([t1,t2]) # creating a dictionary from a list of tuples
17                    # -> {1 : 2, 3 : 4}
18 d[1] # retrive item at key 1 - 2
19
20 d[1] in l # membership testing. Is 2 in l? -> True
21
22 for element in l: # iterating over the list
23     print(element)
```

Listing 3.2: Usage of Python collections

3.1.5 Control Structures

The python programming language has three control structures, `if`, `while` and `for`. In the following they are presented with simple code examples and a figure showing the possible information flow through the control structure.

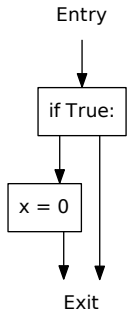
If The `if` control structure has several variants:

1. A simple `if` statement
2. An `if-else` statement

3. An `if-elif-else` statement where the `elif` statement can be repeated

Figure 3.1 shows a simple `if` control structure containing only one `if` statement. The code, Figure 3.1a, is an `if` statement with a condition, `True`. If the condition holds the body is executed and if not, the program moves on to the next piece of code. This flow is depicted on Figure 3.1b.

```
1 if True:
2     x = 0
```



(a) Code example **(b)** Possible flows

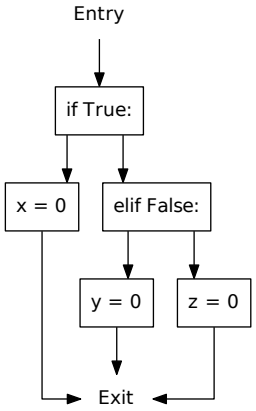
Figure 3.1: A simple `if` control structure containing one `if` statement

The two other variants of the `if` control structure utilise the `else` clause to define what should be executed if the condition is `False`. This `else` clause can be a statement body, or a nested `if` which is denoted as an `elif`. An example of this can be seen on Figure 3.2. The outmost `if` has a nested `elif` statement which then contains a body executed when the `elif` condition evaluates to `True` and an `else` executed when it evaluates to `False`.

Note that the *else* clause is not represented as a independent node, the false branch is represented in the same way as the true branch in a "if-else" structure.

```
1 if True:
2     x = 0
3 elif False:
4     y = 0
5 else:
6     z = 0
```

(a) Code example



(b) Possible flows

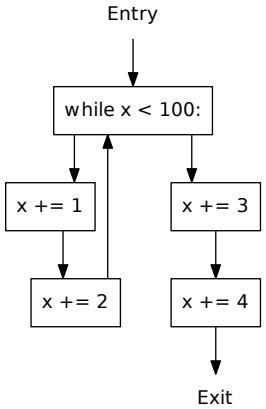
Figure 3.2: An `if` control structure containing an `if`, an `elif`, and an `else` statement

While The `while` control structure has a condition which evaluates to true or false. If the condition is true the body is executed and the condition is evaluated again, if it still holds the body is executed again. This process continues until the condition is false. A `while` control structure can also have an `else` clause. The body of the `else` clause is executed when the condition of the `while` statement is false.

An example is displayed in Figure 3.3 which contains a `while` control structure with the condition `x > 100` and an `else` clause. The possible flows can be seen on Figure 3.3b, where the `else` clause is executed when the condition resolves to `False`.

```
1 while x < 100:
2     x += 1
3     x += 2
4 else:
5     x += 3
6     x += 4
```

(a) Code example



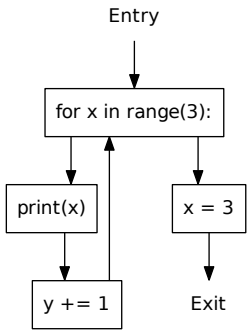
(b) Possible flows

Figure 3.3: A `while` control structure

For The `for` control structure is used for iterating over an object that is iterable. This could for instance be a list or a tuple. This control structure has an optional `else` statement, which body is executed when there is nothing to iterate or the `for` statement is done iterating. To illustrate the `for` control structure we provide two examples. The first example, on Figure 3.4, shows the most common usage of the `for` control structure. Here we iterate over a range, which is a built in function that returns a range of numbers, in this case 0, 1 and 2.

```
1 for x in range(3):
2     print(x)
3     y += 1
4 x = 3
```

(a) Code example



(b) Possible flows

Figure 3.4: A `for` control structure

3.1.6 Decorators

The following is based on Lutz [13, p. 558]. Python contains a syntax that allows one to transform a function into another function easily. This syntax is called a decorator and it is denoted with a `@method` before a function. A simple decorator is shown in Listing 3.3. The class `Decorator` implements the `__init__` method which is used to save the arguments of the decorator, and the `__call__` which is used to replace the original method with a transformation. In this example the `__call__` method prints the argument passed to the decorator and then returns the original function. The output of running this example is presented in Listing 3.4. Decorators can be used to perform modifications to functions, like preprocessing some of the arguments or logging the arguments passed to the function.

```
1 class LabelDecorator(object):
2     def __init__(self, number):
3         self.number = number
4
5     def __call__(self, func):
6         print('Function: ', self.number)
7         return func
8
9 @LabelDecorator(1)
```

```
10 def foo(a, b):
11     return a + b
12
13 print(foo(3, 4))
```

Listing 3.3: Implementation of a simple decorator

```
1 $ python decorator.py
2 Function:  1
3 7
```

Listing 3.4: Output when running the previous example

3.1.7 Import

In Python it is possible to import other modules. Import is possible with the import statement:

```
1   import module_name
```

Listing 3.5: Import statement.

When using the above import statement the whole module gets imported and creates a reference to that module in the current namespace. So it imports functions, classes and variables and they can be accessed and used by prefixing with "module_name". An example would look like this:

```
1   import module_name
2
3   x = module_name.fib(10)
```

Listing 3.6: Import from statement.

The import statement also has another variant the import-from statement:

```
1   from module_name import Class, function, variable
```

Listing 3.7: Import from statement.

The import-from statement is importing all names that are defined after the `import` keyword and adds them to the local namespace. Accessing this module is different as the names are now in the local namespace one does not need to prefix them. An example of using a function would look like this:

```
1   from module_name import fib
2
3   x = fib(10)
```

Listing 3.8: Import from statement.

3.2 Parameter Passing

This section describes how Python deals with parameter passing and is inspired by *Is Python pass-by-reference or pass-by-value?* [14], official documentation for this can be found at *Defining Functions* [15]. This section is included as it is important to factor in when parameters are assigned in functions.

The most known parameter passing techniques are pass-by-reference and pass-by-value. A short description of these two will lead up to an explanation of how Python is handling parameter passing. Python is basically using pass-by-value but objects are passed by reference, this is the same as for instance in Java and C#. To illustrate the different approaches the following two functions are used, Listing 3.9 and Listing 3.10.

```
1  def reassign(l):
2      l = [1]
```

Listing 3.9: Parameter passing: `reassign` function.

```
1  def append(l):
2      l.append(1)
```

Listing 3.10: Parameter passing: `append` function.

An abstract way of showing the internal representation will be used. An example can be seen on Figure 3.5 where the variable `l` points at a list which is an object stored in memory as `[0]`. In python a variable is just a name that points to some object in memory. A name is illustrated as a box. Assigning '1' to a variable 'k' and then reassigning it to '2' does not change the '1' in memory. It just creates the '2' object in memory and makes the 'k' point at this object.[2]

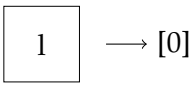


Figure 3.5: A variable `l` pointing at a list `[0]`

Pass-by-reference Pass-by-reference is a parameter passing mechanism where the argument is directly passed into the function. Consider passing `l = [0]` to the function `reassign`. After the call the object `l` is changed to: `l = [1]`, visualised on Figure 3.6.

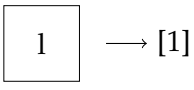


Figure 3.6: The variable `l` pointing at the list `[0]` after calling function `reassign`

[2]The garbage collector is removing the 1 if it is not used anymore.

This is because the variable is passed directly which means that the function is operating directly on the object. The `append` function behaves similarly, but because append adds to the list the result is: `l = [0, 1]`, visualised in Figure 3.7.

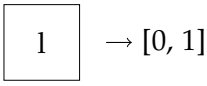
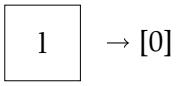
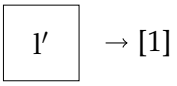


Figure 3.7: The variable `l` pointing at the list `[0, 1]` after calling function `append`

Pass-by-value The other well known parameter passign mechanism is pass-by-value, where the actual parameter is copied and passed into the function. The actual parameter is copied and stored a new place in memory and the copy is passed into the function. Given the object `l = [0]` passed as parameter to the function `reassign`, the copied object `l'` is changed to: `l' = [1]`. The original object `l` remains the same as it is not manipulated by the function.



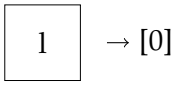
(a) The variable `l` pointing at the list `[0]` after calling the functions `reassign`



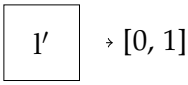
(b) The variable `l'` pointing at the list `[1]` after calling function `reassign`

Figure 3.8: When reassigning in pass-by-value, only the copied list is changed

A similar thing happens in the `append` function, where after calling the function `l = [0]` and `l' = [0, 1]`. To visualise see Figure 3.9a and Figure 3.9b, here it becomes clear that when we access `l` after the call nothing has changed.



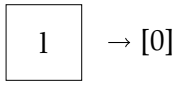
(a) The variable `l` pointing at the list `[0]` after calling the functions and `append`



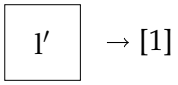
(b) The variable `l'` pointing at the list `[0, 1]` after calling function `append`

Figure 3.9: When appending in pass-by-value, only the copied list is changed

Pass-by-object-reference Pass-by-object-reference is the Python way of handling parameter passing. In this parameter passing mechanism the argument is copied into a new variable local to the function, but both refer to the same object in memory. Given the object `l = [0]` when calling the function `reassign`, a new variable `l'` is created that refers to the same `[0]` object in memory. So `reassign` sets `l' = [1]` but not `l` because `reassign` is not manipulating the object but only the name that is referring to it. Calling `reassign` manipulates the variables and is visualised in Figure 3.10a and Figure 3.10b.



(a) The variable `l` pointing at the list `[0]` after calling function `reassign`



(b) The variable `l′` pointing at the list `[1]` after calling function `reassign`

Figure 3.10: Pass-by-object-reference copies the variable, but points it at the same object as the original variable

When calling the `append` function the object is referenced and both `l` and `l′` are changed to `[0, 1]`. Calling `append` manipulates the objects referenced by the variables. This is visualised in Figure 3.11.

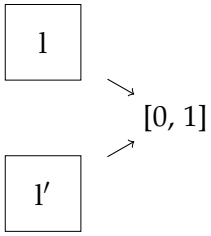


Figure 3.11: The variable `l` and `l′` stored in memory as `[0, 1]` when calling function Listing 3.10.

3.3 Surprising Features in Python

When working so close to the specification of a language some weird or surprising structures in the language arise. While we programmed the conversion from abstract syntax tree to a control flow graph, we had these experiences once in a while, and working with the structures has given us some insight, both in the workings of python and in the details of these interesting structures. This section will discuss some of these experiences.

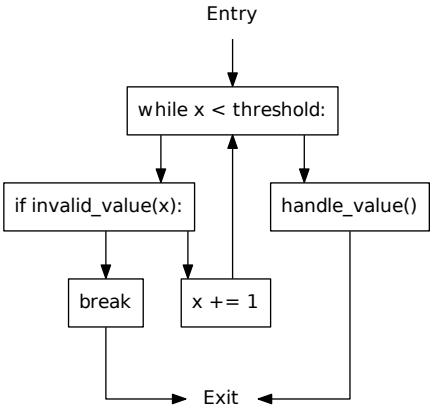
3.3.1 While - Else

Normally we know `while` as a simple control structure that has a condition and a body. The body will execute until the condition is false. This implementation is also found in Python, but Python has an extra variant of the while loop - an else clause. An example of a while loop with an else clause can be seen on Figure 3.12a.

The else clause will execute when the condition is false, but if the body is exited by a `break` statement, the else clause will not be executed. In the example in Figure 3.12a, this is being utilised to handle values that are unexpected in some way. If that is the case, we break the body and do not execute the else clause which contains some logic for the value behaved as expected.

```
1 while x < threshold:
2     if invalid_value(x):
3         break
4     x += 1
5 else:
6     handle_value()
```

(a) A while loop with an else clause



(b) Possible flows

Figure 3.12: An example of a while loop with a break statement

The `for` loop in Python also has an `else` clause which works in the same way. A example of this can be seen in Figure 3.13.

3.3.2 Generator Expression

The Python language has a goal of being simple, explicit and readable[16]. This can often be seen in some very elegant constructions contained in the language. One of those is the generator expression, which was discovered during the development of PyT.

A generator expression is a concise notation for a common pattern: iterating over a collection of items and then performing some operation on every element[17].

```
1 strings = ['King Arthur   ', '', '   Queen Elizabeth',
2            '', '   Arnold Schwarzenegger   ']
3
4 people = (line.strip() for line in strings if line != '')
```

Listing 3.11: Generator expression, stripping white-space from strings

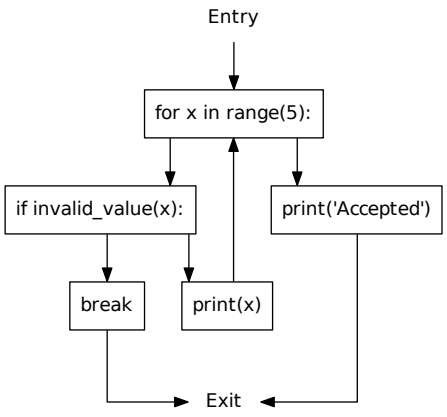
In Listing 3.11 some file has been parsed into an array. The resulting strings have some undesirable white-space, and some of the strings are even empty. The subsequent generator expression handles both of these problems.

A generator expression consists of an expression part and a for part. The for part is evaluated and the expression is executed on each element of the resulting iterable. The result is a generator that contains the results.

In Listing 3.11 the generator iterates over the strings with the `for` statement and filters out empty strings with the `if` statement. The resulting elements are the

```
1 for x in range(5):
2     if invalid_value(x):
3         break
4     print(x)
5 else:
6     print('Accepted')
```

(a) Code example



(b) Possible flows

Figure 3.13: A `for` control structure with an `else` statement

stripped of white-space by the initial expression.

The generator in Listing 3.11 can be written without using a generator expression. This can be seen in Listing 3.12. The generator expression is very clear in conveying its purpose while being shorter than the "old way".

```
1 for line in strings:
2     if not line != '':
3         yield line.strip()
```

Listing 3.12: Listing 3.11 implemented without using an generator expression

Python contains similar constructs called the comprehensions which return a list, set or dictionary of the element instead of a generator. This construct uses square or curly parenthesis instead of round parenthesis, but are not different in any other way. An example of a list comprehension can be seen in Listing 3.13.

```
1 people = [line.strip() for line in strings if line != '']
```

Listing 3.13: The generator from Listing 3.11 changed to a list comprehension

Chapter 4

Flask

4.1 Flask

Flask is a framework for developing web applications in Python[10]. Its goal is to be minimal without compromising functionality. It is extensible and flexible, so components like database and form validation can be chosen by the developer.

The minimal nature of Flask makes it possible to write a web page in a very small amount of code. The following program, see Listing 4.1, creates a web server that serves a "Hello World!" page on the root.

```
1 from flask import Flask
2 app = Flask(__name__)
3
4 @app.route('/')
5 def hello_world():
6     return 'Hello World!'
7
8 if __name__ == '__main__':
9     app.run()
```

Listing 4.1: Minimal Flask application

The Flask framework is imported and a function is defined with the `app.route` decorator which tells the framework where to serve the page. The function returns the string "Hello World!" which is shown on the web page.

The following will present the Flask functionality that will be used in this project. The descriptions will be based on the *Flask Documentation* [18].

Routing The `app.route` decorator is used to bind a function to a URL. The parameter provided binds the function to the relative path. Example paths are '/' for the root and '/hello_world' for a sub-page. The example in Listing 4.1 binds the function `hello_world()` to the url `hostname/`.

HTTP methods Another parameter for the `app.route` decorator is the methods allowed. This parameter enables other HTTP methods than the default GET. An example of enabling the POST method can be seen on Listing 4.2.

```
1 @app.route('/login', methods=['GET', 'POST'])
2 def login():
3     if request.method == 'POST':
4         do_the_login()
5     else:
6         show_the_login_form()
```

Listing 4.2: Enabling POST requests for a login form

Requests Interaction with the incoming request happens through the `request` object. This object contains all attributes of the request such as arguments from the query string, form data from POST requests and uploaded files. Listing 4.3 shows a very simple use of the query string. The query string 'name' is retrieved with the default value 'no name' and assigned to `param`, which is then returned to the user.

```
1 @app.route('/query_param')
2 def query_param():
3     param = request.args.get('name', 'no name')
4     return name
```

Listing 4.3: Simple use of the query string

Responses When returning from a function that will be rendered as a web page, Flask provides several possibilities that makes this process flexible. For example a returned string will automatically be converted to a valid HTML page. Special functions for creating responses exist, such as `send_file(path, name)` which sends a file to the client. HTML files can be rendered with `make_response()`, and more complex pages can be constructed with the template engine. The template engine will be explained in the following.

Templates Flask uses a template engine called *Jinja2*, which helps the developer keep the application secure. The template engine escapes any dangerous user inputs without the developer having to consider it.

```
1 from flask import render_template
2
3 @app.route('/hello/<name>')
4 def hello(name=None):
5     return render_template('hello.html', name=name)
```

Listing 4.4: Rendering a template that displays the name parameter

```
<!doctype html>
<title>Hello from Flask</title>

<h1>Hello {{ name }}!</h1>
```

Listing 4.5: The Jinja2 template used by the hello example

Listing 4.4 shows a simple example of a template being rendered. The `render_template` function takes the template displayed in Listing 4.5 and replaces the name variable with the name entered in the URL. The template engine handles all escaping, so a malicious user cannot compromise the page through the URL.

The Response object Sometimes a page is more complex than just rendering a template and replacing variables with the appropriate values. Web pages have response codes to indicate errors, headers that define the parameters of the request and cookies to keep track of the user. In order to work with these aspects we need to get hold of the response before sending it to the client. This is done with the `make_response()` method. The usage of the `make_response()` method is shown in Listing 4.6 where a handler for 404 errors is defined. Instead of showing the browser's default 404 error, we want to show our own error. `make_response()` takes a parameter for setting the status code, so creating the custom 404 handler just renders a template and sets the error code to 404. The `make_response()` method returns a response object, which can then be manipulated by for example add a header, or a cookie with `set_cookie(name, value)`.

```
@app.errorhandler(404)
def not_found(error):
    resp = make_response(render_template('error.html'), 404)
    resp.headers['X-Something'] = 'A value'
    return resp
```

Listing 4.6: Using make_response to create a custom 404 handler

SQLAlchemy SQL Alchemy is a toolkit for operating on SQL databases directly from Python. Its goal is to provide "efficient and high performing database access, adapted into a simple and Pythonic domain language"[19].

The code displayed on Listing 4.7 shows how the connection to a database is created. The URI of the database is provided to the config attribute of the flask application, and a database object is created. This object contains a `Model` class that can be used to declare the model. In the example, a `User` model is declared.

```
from flask import Flask
from flask_sqlalchemy import SQLAlchemy

```

```
4  app = Flask(__name__)
5  app.config['_DATABASE_URI'] = 'sqlite:////tmp/database.db'
6  db = SQLAlchemy(app)
7
8
9  class User(db.Model):
10     id = db.Column(db.Integer, primary_key=True)
11     username = db.Column(db.String(80), unique=True)
12     email = db.Column(db.String(120), unique=True)
13
14     def __init__(self, username, email):
15         self.username = username
16         self.email = email
```

Listing 4.7: A SQLAlchemy database model

Now that the database model is created we can populate it. In Listing 4.8 the usage of a SQLAlchemy database is shown. Between line 1 and line 6 Users are created and inserted into the database. Afterwards, in line 8, the database is being queried, first to show all Users, and afterwards to show only the first User named 'admin'.

```
1  admin = User('admin', 'admin@example.com')
2  guest = User('guest', 'guest@example.com')
3
4  db.session.add(admin)
5  db.session.add(guest)
6  db.session.commit()
7
8  users = User.query.all()
9  admin = User.query.filter_by(username='admin').first()
```

Listing 4.8: Populating the database and querying the content

Chapter 5

Security Vulnerabilities

To make a tool that finds security vulnerabilities in a program is a very broad and ambitious task. In order to make the task more manageable we have picked three common types of vulnerabilities from the OWASP list of top 10 vulnerabilities in web applications [3]. The chosen vulnerabilities will in the following be described and code examples will be presented showing the vulnerability in practice. These code examples will later be used for testing the application.

5.1 Injection Attacks

An injection is an uncontrolled use of user input that reaches an interpreter. This could be a SQL interpreter, the command line or the Python interpreter. If an injection vulnerability exists the user can send arbitrary commands to the server, and possibly access or alter data without authorisation. The typical workaround is to sanitise the input so only the desired characters will be accepted. [20]

The following will present two subgroups of injection attacks, SQL injections and command injections.

5.1.1 SQL Injection

This description is based on *SQL injection in CWE* [21]. SQL injections happen when an application creates a query partly or entirely from user input without sanitising this input. The user can escape the query and add an arbitrary query. Depending on the system, the user can now change the database, read the database or in severe cases even execute system commands.

Example An implementation of two possible SQL injections can be found in Appendix A.1. Here a database is setup with the library SQLAlchemy which has protection against SQL injection built in. The problem is that it also supports raw

SQL queries, and these examples utilise these. The specific problems of the examples will be examined in the following.

Naive SQL Handling The first example is a naive handling of SQL queries. In this example the user has to input the whole query and the query is executed directly on the database. The method for this is shown on Listing 5.1.

```
24 @app.route('/raw')
25 def index():
26     param = request.args.get('param', 'not set')
27     result = db.engine.execute(param)
28     print(User.query.all(), file=sys.stderr)
29     return 'Result is displayed in console.'
```

Listing 5.1: An SQL statement is taken as input and executed directly on the database

This is a very unlikely case, but if it gets served by accident, it is a very dangerous vulnerability.

SQL Filter The second example is where the user has to input the parameter for the filter method used for filtering the query. The code for the method taking the parameter as input and querying the database with the filter parameter is shown on Listing 7.9.

```
31 @app.route('/filter')
32 def filter():
33     param = request.args.get('param', 'not set')
34     Session = sessionmaker(bind=db.engine)
35     session = Session()
36     result = session.query(User).filter("username={}".format(
           param))
37     for value in result:
38         print(value.username, value.email)
39     return 'Result is displayed in console.'
```

Listing 5.2: A filter string is taken as input and used as a parameter in the filter function.

Because the input string is not sanitised, the user can input whatever he wants, and an input like

$$2 \text{ or } 1 = 1$$

will return all users in the database, which is of course not intended behaviour. The key is to insert the `or` keyword which makes another statement possible. The second statement just has to evaluate to true then all possible database entries are returned. This ultimately means that the statement sent to the SQL interpreter looks for all users instead of just a particular one.

5.1.2 Command Injection

This description is based on *Command injection in CWE* [22]. Command injections are very similar to SQL injections, but instead of injecting commands into a database system, this attack makes it possible to inject commands into server shell. The ability to perform commands on a server opens up possibilities to read password files, delete system files and various other dangerous operations.

Example An example of a command injection vulnerable application is presented in Appendix A.2. In this example a textfile is being used as store for a site where customers can suggest items for a menu. When customers enter an item into a textbox, it is stored on a new line in the file. The content of the file is then read and displayed on the screen, showing all the suggestions. The dangerous function is shown in Listing 5.3 where it can be seen how the parameter from a textbox is being passed directly to the shell call in line 18. Entering a string starting with a command separator (semicolon in bash and ampersand in windows cmd), makes it possible to interact directly with the system shell. Thus entering a string like

; ls

will print out the contents of folder containing the application. Having access to the filesystem is obviously dangerous, as a malicious user can now perform arbitrary commands on the server.

```
13 @app.route('/menu', methods=['POST'])
14 def menu():
15     param = request.form['suggestion']
16     command = 'echo ' + param + ' >> ' + 'menu.txt'
17
18     subprocess.call(command, shell=True)
19
20     with open('menu.txt','r') as f:
21         menu = f.read()
22
23     return render_template('command_injection.html', menu=menu)
```

Listing 5.3: The culprit making command injection possible. Param is not being escaped before being executed by the shell.

5.2 XSS

Cross site scripting (abbreviated XSS) occur when a site takes untrusted data and sends it to other users without sanitisation. The description i based on *Cross site scripting in CWE* [23]. One example could be a comment section where an evil

user sends in a comment containing some JavaScript. When other users see this comment, their browser runs this JavaScript, which can access cookies or redirect to a malicious site. Again, this can be prevented by sanitising user input that is stored.

Example A very simple example of a cross site scripting is presented in Appendix A.3. The main part is displayed in Listing 5.4. In line 8 some input is taken and it is inserted into the result page in line 11. A link to the vulnerable web page can be constructed and sent to a unknowing user who opens the link and gets important information stolen. In this example the input is not saved permanently, but if it was saved as for example a comment, a malicious user could inject arbitrary JavaScript, which all subsequent users would execute in their browsers.

An easy way of avoiding this vulnerability, is to use the template engine of Flask. If the template engine was used instead of manually replacing the string, the template engine would sanitise the input.

```
6  @app.route('/XSS_param', methods =['GET'])
7  def XSS1():
8      param = request.args.get('param', 'not set')
9
10     html = open('templates/XSS_param.html').read()
11     resp = make_response(html.replace('{{ param }}', param))
12     return resp
```

Listing 5.4: The main part of the XSS example from Appendix A.3

5.3 Path Traversal

Path traversal is when access to a resource gives unintended access to the file system of the server. This description is based on *Path traversal in CWE* [24]. An example could be attaching an image to the page decided by some user input. If the input is not validated an attacker will be able to traverse the file system with the parent directory element ('..').

Example An example of this vulnerability can be seen in Appendix A.4. The main part of the example is displayed in Listing 5.5. Providing the request parameter as *?image_name=../file.txt* will open and show file.txt in the browser. This could possibly result in database content or passwords to be accessed by intruders.

```
6  @app.route('/')
7  def cat_picture():
8      image_name = request.args.get('image_name')
9      if not image_name:
```

```
10          return 404
11      return send_file(os.path.join(os.getcwd(), image_name))
```

Listing 5.5: The main part of the path traversal from Appendix A.4

5.4 Detecting Vulnerabilities

Common for these three security vulnerabilities is that some user input reaches a sensitive piece of code. An SQL injection happens when user input reaches a database query Cross site scripting happens when user input reaches some HTML. Path traversal happens when user input reaches a piece of code that performs file system access.

To detect these vulnerabilities we need to create a tool that can connect information about user input and sensitive code to detect when the operations performed are dangerous.

Chapter 6

Theory

As we concluded in Section 5.4 we are interested in determining when dangerous input from a user is able to reach a place in the code where it can cause damage. A technique for determining this is static analysis where the source of a program is statically analysed for some property.

This chapter will describe the theory used for building the static analysis engine used by PyT. It will primarily be based on the lecture notes on static analysis in Schwartzbach [25].

Undecidable As mentioned above we want to track input and determine whether it is harmful or not in the way it is used throughout the application. Unfortunately, it turns out that we will not be able to provide definite answers to this question, but only qualified approximations. This is due to Rice's theorem which can be phrased as "all interesting questions about the behaviour of programs are undecidable" [25, p. 3]. These *interesting questions* constitute a rather large group of problems, and our problem is part of this group.

Static analysis Static analysis is the theoretical topic that engage in solving this type of problem. The problem is characterised by setting up a number of rules which define the problem. The program is then converted into a model which represents the flow of the program. The solution to the problem will then be gradually approached by an algorithm that applies the defined rules on the model. The algorithm stops when it can not get closer to an answer. This result is then the approximation which can be used for further analysis and be the basis of an answer to the problem.

6.1 General Example

In order to make this theory chapter more understandable an example is introduced which is used throughout this chapter. The code for this example is shown in Listing 6.1. The example corresponds to the example in Schwartzbach [25] adapted to Python code.

```
1  x = input()
2  x = int(x)
3  while x > 1:
4      y = x / 2
5      if y > 3:
6          x = x-y
7      z = x-4
8      if z > 0:
9          x = x / 2
10     z = z - 1
11 print(x)
```

Listing 6.1: The general code example used throughout the theory chapter

The program is very simple, it takes some user input which is sent through a `while` loop that changes the three variables x, y and z, depending on two `if` statements. The x variable is printed out as the last operation of the program. Although it is simple it presents some interesting statements and scopes.

6.2 Control Flow Graph

The analysis we want to perform is flow sensitive, meaning that the order of the statements in the program influence the result of the analysis. When performing a flow sensitive analysis, a Control Flow Graph (abbreviated CFG for convenience) can be used to describe the flow of the program.

A CFG is simply just another representation of the program source. It is a directed graph where a node is a specific place in the program and edges represent the possible options to which the program can execute to. A CFG always consists of one entry node and one exit node, called *entry* and *exit*. Given a node n the set of predecessor nodes are denoted *pred(n)* and the set of successors are denoted *succ(n)*.

Python control flow graphs CFGs for simple Python statements, such as an assignment, have an entry node, a node containing the assignment and an exit node. The CFG of the sequence of two statements S_1 and S_2 are constructed by deleting the exit node of S_1 and the entry node of S_2 and *gluing* the two resulting graphs together. This process is depicted on Figure 6.1.

(a) A single statement **(b)** A sequence of two statements

Figure 6.1: Construction of a control flow graph for two sequential statements

The CFGs of control flow structures in the Python programming language was presented in the figures provided in Section 3.1.5.

The CFG for a complete program is produced by systematically combining the building blocks. A CFG of the general example in Listing 6.1, is shown on Figure 6.2.

6.2.1 Interprocedural Analysis

As Python contain functions we need a strategy for dealing with these. Schwartzbach [25] presents two strategies for dealing with this. The first strategy is to analyse a function when its definition is read in the source code, while the other is to analyse the function each time it is called.

The first strategy, called monovariant interprocedural analysis, requires that we assume the worst about every function call, because we cannot know anything about the context the function is called in.

The second strategy is called polyvariant interprocedural analysis, and produces a single CFG from a program with a number of function calls. This is done by *gluing* the function bodies into the main CFG every time a function is called. From a source code perspective this would be like in-lining all functions that are called.

On Figure 6.3 is an example of two CFGs where the first one calls a function, which is represented by the second CFG. The analysis need to be able to glue these together without changing the semantics of the program.

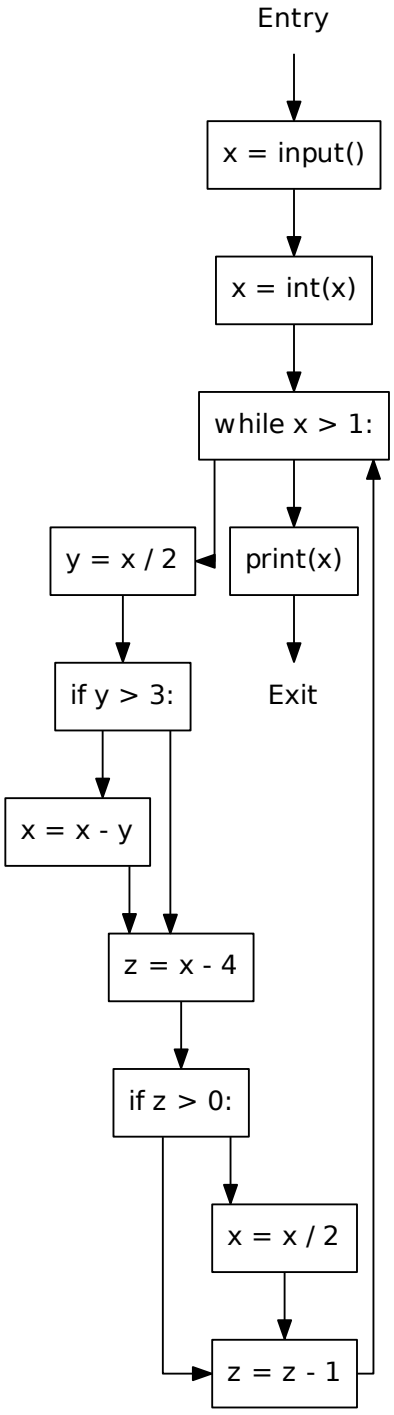


Figure 6.2: The control flow graph of the general example, Listing 6.1.

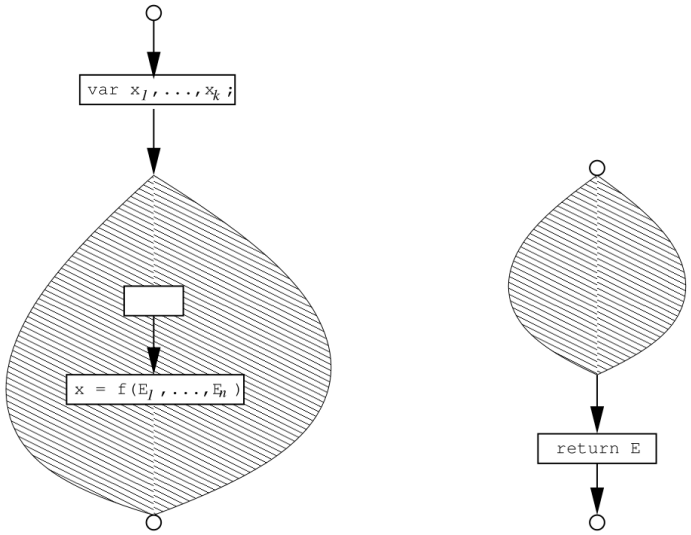


Figure 6.3: Two CFGs, one for the calling function and one for the called function. Illustration from Schwartzbach [25, p. 37]

Shadow variables In order to maintain the correct values for all variables across scopes we introduce *shadow variables*. Because parameters of functions have no relation to the scope of other functions, parameters can be the same for many different function scopes. Shadow variables ensure that the meaning of the different scopes are kept when gluing the function CFG into the main CFG. The process of gluing a function into the calling function can be split up into four steps:

- When calling a function all the variables of the current scope need to be saved, ensuring no clashes with the variables of the function body.
- Then all the formal parameters of the function definition are saved and the actual parameters are inserted into appropriate variables in order to create the function local scope.
- The body of the function can now be inserted as it was originally defined, with the exception that all returns need to be assigned to a unique variable.
- After the function body all the saved variables need to be restored.

The final result is a single CFG for the caller with the callee interwoven in. The result is depicted on Figure 6.4. Here all the saved variables are characterised with a prefix and a number i, which is a unique index for the called function.

Adjusting shadow variables to Python The previous description of shadow variables results in a CFG that simulates the call-by-value parameter passing mechanism. As described in Section 3.2, Python uses call-by-object-reference. We have

not been able to make an adjustment that captures this completely. Instead we have made an approximation that ensures that values changed inside a function will persist after the call.

The modification changes the last of the four steps. Instead of restoring all saved variables, the variables will be assigned the formal parameter that is being used inside the function body. In this way the changes made to the formal parameter will persist. This solution is inaccurate because it does not represent reassigning the parameter correctly (the `reassign` case in Section 3.2). Instead of being local to the function body, such a change will persist.

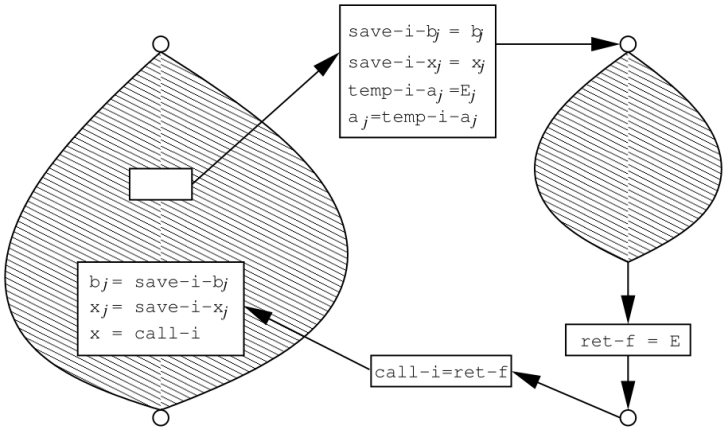
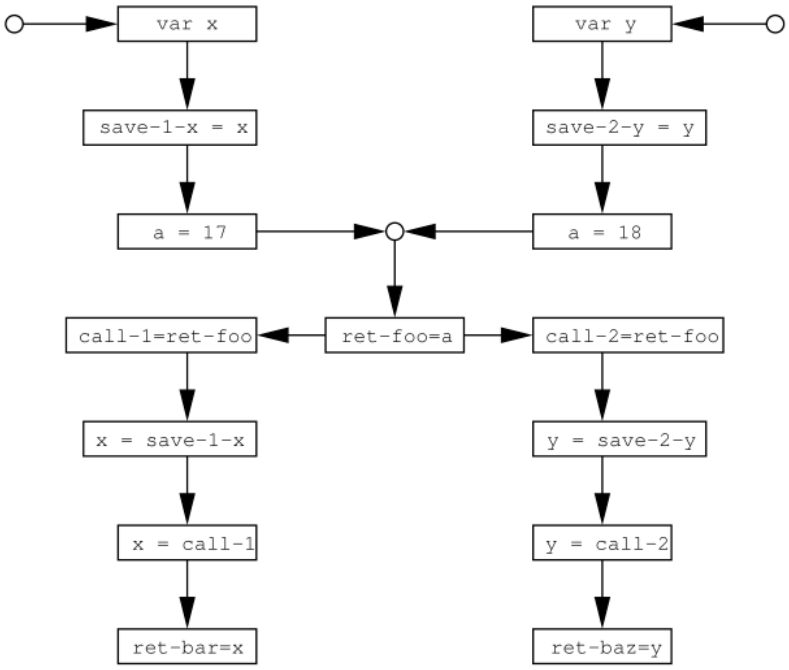


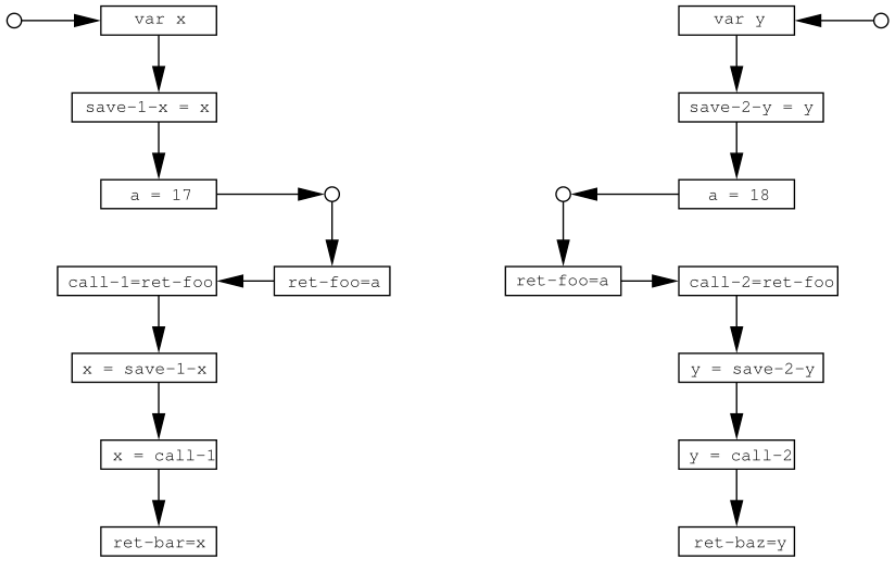
Figure 6.4: The two CFGs glued together with shadow variables. Illustration from Schwartzbach [25, p. 38]

Polyvariance If we "glue in" the function bodies of called function by referencing the respective CFG, we get a *monovariant* analysis. An example of monovariant analysis can be seen on Figure 6.5a This method puts some limitations on the analyses that are performed on the CFG. For example constant propagation analysis will be inaccurate because more than one call will be represented in the callee CFG. For our purposes we need propagation of assignments to be accurate for an arbitrary number of calls to a function.

The solution is to make the analysis *polyvariant*. This is done by making multiple copies of the function body for each call site. This solves the problem about propagation because every call site has a separate copy of the function where the analysis can perform unique calculations.



(a) Example CFG of monovariant analysis



(b) Example CFG of polyvariant analysis

Figure 6.5: The difference between monovariant and polyvariant interprocedural analysis. Illustrations from Schwartzbach [25, p. 40]

6.3 Lattice

The static analysis we want to perform utilises the mathematical theory of lattices together with a monotone function to guarantee that the analysis will terminate. The theory behind lattices will be described in the following.

Partial orders A lattice is a specialisation of a partial order which will be described in the following. A partial order is a mathematical structure $L = (S, \sqsubseteq)$ where S is a set and $\sqsubseteq$ is a binary relation where the following conditions are satisfied:

- Reflexivity: $\forall x \in S : x \sqsubseteq x$
- Transitivity: $\forall x, y, z \in S : x \sqsubseteq y \wedge y \sqsubseteq z \Rightarrow x \sqsubseteq z$
- Antisymmetry: $\forall x, y \in S : x \sqsubseteq y \wedge y \sqsubseteq x \Rightarrow x = y$

Least upper bound As the name states, a least upper bound is the least of all upper bounds. An upper bound y of a set X where $X \subseteq S$ and S is a partial order is written as $X \sqsubseteq y$. y is an upper bound of X if we have that $\forall x \in X : x \sqsubseteq y$.

We can now define the least upper bound, written as $\sqcup X$:

$$X \sqsubseteq \sqcup X \wedge \forall y \in S : X \sqsubseteq y \Rightarrow \sqcup X \sqsubseteq y$$

The greatest lower bound $\sqcap X$ can be defined by the same logic.

Lattice A lattice can now be defined as a partial order in which $\sqcup X$ and $\sqcap X$ is defined for all $X \subset S$. It should be noted that a lattice must have a unique largest element $\top$ defined as $\top = \sqcup S$ and unique smallest element $\bot$

In Figure 6.6 a lattice with four elements is depicted. These four elements are deduced from a subset of the general example program on Listing 6.1 (in order to keep the size of the lattice manageable). The subset can be seen on Listing 6.2.

```
1  x = input()
2  x = int(x)
3  while x > 1:
4      y = x / 2
5      if y > 3:
6          x = x-y
7  print(x)
```

Listing 6.2: The general code example used throughout the theory chapter

This lattice is defined by the set of four expressions $\{x > 1, x/2, y > 3, x - y\}$. In general the set A defines a lattice $(2^A, \sqsubseteq)$ where $\top = A$, $\bot = \emptyset$, $x \sqcup y = x \cup y$ and $x \sqcap y = x \cap y$.

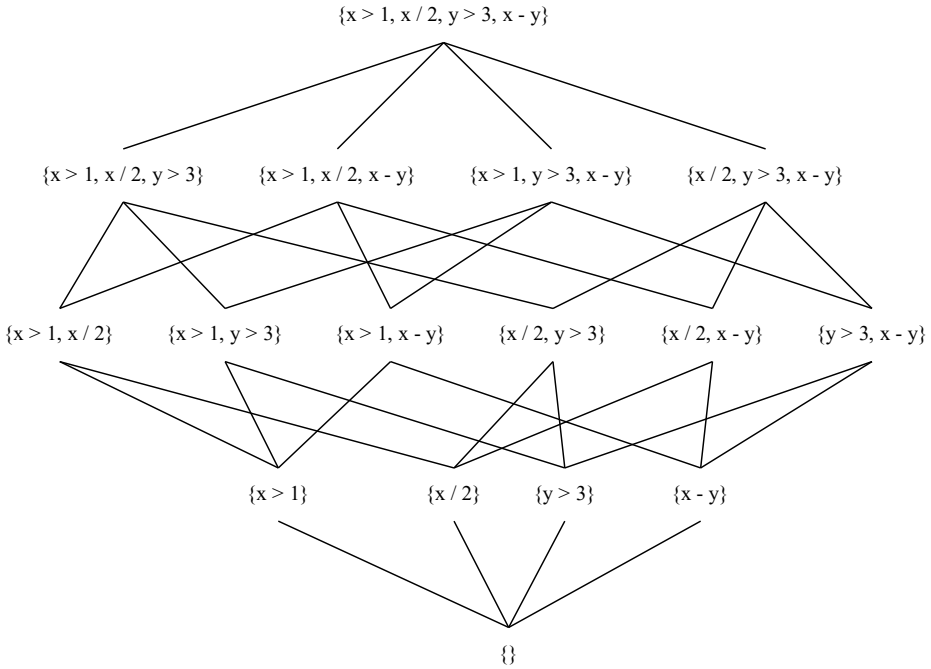


Figure 6.6: A lattice with four expressions.

Every analysis requires the lattice to contain certain elements of the program in order to work. Examples range from expressions or assignments to variables. The presented type of lattice is used in analyses that depend on information about the expressions in a program. One example of such analysis is 'available expressions' which is presented in Schwartzbach [25, p. 22]. This analysis finds expressions that are *available* at a program point. An available expression is an expression that has already been calculated earlier in the execution. Finding available expressions can be used to optimize the program by saving the calculation and thus avoid recalculating it.

6.4 Monotone Functions

A function $f : L \to L$ is monotone when $\forall x, y \in S : x \sqsubseteq y \Rightarrow f(x) \sqsubseteq f(y)$. Being monotone does not imply that the function is increasing. All constant functions are monotone.

If we look at the least upper bound and greatest lower bound as functions they are monotone in both arguments. This means that we can apply the least upper bound function on two arguments and be certain that it will never decrease. This is an important requirement for the fixed-point theorem which will be presented in the next section.

6.5 Fixed-point

For the static analysis of a program we need a theorem that can find the best approximation of some dataflow problem. Because we will generally consider problems that are undecidable, see Chapter 6, we need a framework that overestimate the answer, and thus makes an approximation.

This framework will be based on the fixed-points theorem which states the following (quoted from Schwartzbach [25, p. 13]):

> **Definition 6.1 (Fixed-point theorem)**
> In a lattice L with finite height, every monotone function f has a unique least fixed-point defined as
>
> $$fix(f) = \bigsqcup_{i \geq 0} f^i(\bot)$$
>
> for which $f(fix(f)) = fix(f)$

The proof of this theorem can be found in Schwartzbach [25, p. 13].

This theorem enables us to find an approximation to an undecidable problem by walking up the lattice until a fixed-point is reached. This computation has been

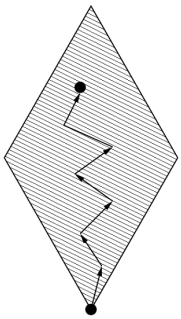


Figure 6.7: A walk through the lattice, starting a $\perp$ and ending in the fixed-point. Illustration from Schwartzbach [25, p. 13]

illustrated in Figure 6.7 where the analysis starts at $\perp$ and end in the fixed-point which is the approximation to the problem at hand.

6.6 Systems of Equations

Combining equations into a system of equations can be solved by using fixed-points. Consider an equation system of the form:

$$\begin{aligned} x_1 &= F_1(x_1, \ldots, x_n) \\ x_2 &= F_2(x_1, \ldots, x_n) \\ &\vdots \\ x_n &= F_n(x_1, \ldots, x_n) \end{aligned}$$

Here x_i are variables and $F_i : L^n \to L$ is a monotone function. A least unique solution to such a system can be found as the least fixed-point of the combined function $F : L^n \to L^n$ defined by:

$$F(x_1, \ldots, x_n) = (F_1(x_1, \ldots, x_n), \ldots, F_n(x_1, \ldots, x_n))$$

6.7 Dataflow Constraints

For analysing a CFG of a program we need to be able to describe the relationship between the individual nodes. Some analyses track variable content while others track use of certain expressions. Similarly, some analyses need information from its successors while others need information from its predecessors.

To describe these different analyses we annotate each node with a *dataflow constraint*. Dataflow constraints relate the value of a node to its neighbouring nodes and is denoted $[\![v]\!]$. A dataflow analysis consists of a number of dataflow constraints that each defines the relation of a construction in the programming lan-

guage.

An example of a dataflow constraint could be conditions (from the liveness example in Schwartzbach [25])

$$[\![v]\!] = JOIN(v) \cup vars(E)$$

where JOIN combines the constraints of the successors of v and vars(E) denote the set of variables occurring in E.

6.8 The Fixed-point Algorithm

A CFG has been defined in Section 6.2 and a lattice has been defined in Section 6.3. Given a CFG, a lattice and associated dataflow constraints, the fixed-point algorithm can compute the fixed-point. The following is from Schwartzbach [25].

Operating on a CFG that contains the nodes $\{v_1, v_2, \ldots, v_n\}$ we work with the lattice L^n. Assuming that the node v_i generates the dataflow equation $[\![v_i]\!] = F_i([\![v_1]\!], \ldots, [\![v_n]\!])$, the equations of all the nodes can be combined in a function $F : L^n \to L^n$.

$$F(x_1, \ldots, x_n) = (F_1(x_1, \ldots, x_n), \ldots, F_n(x_1, \ldots, x_n))$$

This combined function resembles the function presented in Section 6.6, and it can indeed be solved by fixed-points. A naive algorithm for solving such a function is presented in Schwartzbach [25]:

```
1 x = (⊥, ..., ⊥)
2 do
3 |   t = x
4 |   x = F(x)
5 while x ≠ t
```

Algorithm 1: The naive Fixed-Point algorithm as presented in Schwartzbach [25, p.18]

As L^n is finite and assuming that the constraints that make up $F(x)$ are monotonous, the fixed-point algorithm will always terminate according to the Fixed-point theorem, see definition 6.1.

There exist more efficient algorithms than the naive version presented, some of them are described in Schwartzbach [25, p. 18]. Because efficiency was not a high priority these have not been examined.

6.9 Dataflow Analysis

The type of dataflow analysis that we want to perform is called the *monotone framework*. The monotone framework utilises the concepts that have now been introduced.

A CFG of the program is generated to represent the flow of the program. A lattice with finite height together with a collection of dataflow constraints comprise the analysis to be performed. Running the fixed-point algorithm on the parts will result in an approximation of the answer to the analysis which can then be interpreted.

This section contains a description of the used dataflow analyses.

6.9.1 Reaching definitions

To solve our problem of detecting when unsanitised user input reaches a critical point in the code, we need an analysis of what assignments may influence the values of all variables at any point in the program. The *Reaching Definitions* as presented in Schwartzbach [25, p. 26] achieves just this.

Consider the Python code from the general example on Listing 6.1. When executing the program and providing some arbitrary input at line 1, the value will slide through the control flow of the program until it is printed in the end. At this point x has been changed by assignments a number of times, and it is not obvious where the value comes from. By performing the reaching definitions analysis we can find possible origins of the value.

Performing the analysis As stated earlier a dataflow analysis consist of many of the concepts that have been introduced until now. These concepts will in the following be instantiated on the previously introduced example as to present the complete analysis.

Control flow graph The CFG of this code was presented in Listing 6.1.

The flow of the program is linear until the while loop. The while loop diverts the flow into the loop and ultimately to the print statement. The loop has two if statements where the flow is again split up. It is easy to see from the flow graph that there are many possible routes from entry to exit, and the propagation of values is not straightforward.

Lattice The lattice used for this analysis is a power set lattice of all the assignments in the program.

$$L = (2^{\{x=\text{input()},\ x=\text{int(x)},\ y=x/2,\ x=x-y,\ z=x-4,\ x=x/2,\ z=z-1\}}, \subseteq)$$

The lattice of a simplified version of this lattice was described and depicted in Figure 6.6. Providing an illustration of the full latice would be intangible, but the structure is similar.

Dataflow Constraint System The analysis is performed backwards by joining the constraints of all predecessors of all nodes. This can be expressed as the following function:

$$JOIN(v) = \bigcup_{w \in pred(v)} [\![w]\!]$$

All nodes other that assignment just join all constraints of their predecessors:

$$[\![v]\!] = JOIN(v)$$

Assignment nodes changes the content of a variable. The former assignment to this variable will therefore be discarded and replaced with the current assignment node:

$$[\![v]\!] = JOIN(v) \downarrow id \cup \{v\}$$

Here the $\downarrow$ function removes all assignments to the variable *id* from the result of the JOIN.

Applying the previously defined dataflow constraints to the generated CFG looks as follows:

$$\begin{array}{lcl}
[\![entry]\!] & = & \{\} \\
[\![x = input()]\!] & = & [\![entry]\!] \downarrow x \cup x = input() \\
[\![x = int(x)]\!] & = & [\![x = input]\!] \downarrow x \cup x = int(x) \\
[\![\text{while } x > 1]\!] & = & [\![x = int(x)]\!] \cup [\![z = z - 1]\!] \\
[\![y = x/2]\!] & = & [\![\text{while } x > 1]\!] \downarrow y \cup y = x/2 \\
[\![\text{if } y > 3]\!] & = & [\![y = x/2]\!] \\
[\![x = x - y]\!] & = & [\![\text{if } y > 3]\!] \downarrow x \cup x = x - y \\
[\![z = x - 4]\!] & = & ([\![x = x - y]\!] \cup [\![\text{if } y > 3]\!]) \downarrow z \cup z = x - 4 \\
[\![\text{if } z > 0]\!] & = & [\![z = x - 4]\!] \\
[\![x = x/2]\!] & = & [\![\text{if } z > 0]\!] \downarrow x \cup x = x/2 \\
[\![z = z - 1]\!] & = & ([\![\text{if } z > 0]\!] \cup [\![x = x/2]\!] \downarrow z \cup z = z - 1 \\
[\![print(x)]\!] & = & [\![\text{while } x > 1]\!] \\
[\![exit]\!] & = & [\![print(x)]\!]
\end{array}$$

Figure 6.8: Dataflow constraints applied on the generated CFG

Solving the equation system Solving this system of equations with the fixed-point algorithm will provide the information we need in order work with our problem.

The first iteration of this looks as follows:

$$
\begin{array}{lcl}
[\![entry]\!] & = & \{\} \\
[\![x = input()]\!] & = & \{x = input()\} \\
[\![x = int(x)]\!] & = & \{x = int(x)\} \\
[\![\text{while } x > 1]\!] & = & \{\} \\
[\![y = x/2]\!] & = & \{y = x/2\} \\
[\![\text{if } y > 3]\!] & = & \{\} \\
[\![x = x - y]\!] & = & \{x = x - y\} \\
[\![z = x - 4]\!] & = & \{z = x - 4\} \\
[\![\text{if } z > 0]\!] & = & \{\} \\
[\![x = x/2]\!] & = & \{x = x/2\} \\
[\![z = z - 1]\!] & = & \{z = z - 1\} \\
[\![print(x)]\!] & = & \{\} \\
[\![exit]\!] & = & \{\}
\end{array}
$$

Figure 6.9: First iteration of the fixed-point algorithm

Here it is clear that only the constraints of assignments have walked up the lattice, each to the node indicating the flownode itself. After nine iterations all the assignments will propagate through the program, and the result can be seen on Figure 6.10. These constraints can now be interpreted in order to answer question that require knowledge of which assignments reach which nodes.

$$
\begin{array}{lcl}
[\![entry]\!] & = & \{\} \\
[\![x = input()]\!] & = & \{x = input()\} \\
[\![x = int(x)]\!] & = & \{x = int(x)\} \\
[\![\text{while } x > 1]\!] & = & \{x = int(x),\ y = x/2,\ x = x - y,\ x = x/2,\ z = z - 1\} \\
[\![y = x/2]\!] & = & \{x = int(x),\ y = x/2,\ x = x - y,\ x = x/2,\ z = z - 1\} \\
[\![\text{if } y > 3]\!] & = & \{x = int(x),\ y = x/2,\ x = x - y,\ x = x/2,\ z = z - 1\} \\
[\![x = x - y]\!] & = & \{y = x/2,\ x = x - y,\ z = z - 1\} \\
[\![z = x - 4]\!] & = & \{x = int(x),\ y = x/2,\ x = x - y,\ z = x - 4,\ x = x/2\} \\
[\![\text{if } z > 0]\!] & = & \{x = int(x),\ y = x/2,\ x = x - y,\ z = x - 4,\ x = x/2\} \\
[\![x = x/2]\!] & = & \{y = x/2,\ z = x - 4,\ x = x/2\} \\
[\![z = z - 1]\!] & = & \{x = int(x),\ y = x/2,\ x = x - y,\ x = x/2,\ z = z - 1\} \\
[\![print(x)]\!] & = & \{x = int(x),\ y = x/2,\ x = x - y,\ x = x/2,\ z = z - 1\} \\
[\![exit]\!] & = & \{x = int(x),\ y = x/2,\ x = x - y,\ x = x/2,\ z = z - 1\}
\end{array}
$$

Figure 6.10: Final result of the fixed-point algorithm

Interpreting the result Looking at the final equations the potential flow of values through the program can be seen. For example, looking at the print statement, the value of x could have originated from three places in the program: the $x = int(x)$, $x = x - y$ or the $x = x/2$ statement. Depending on the purpose of the analysis, this information can be used to deduce whether any dangerous flows are possible.

6.10 Taint Analysis

The following is based on Schwartz, Avgerinos, and Brumley [26, Part 3]. An expression which introduces user input in some way is called a *source*, while a dangerous destination for such input is called a *sink*. A function that can neutralise input so it is not dangerous to send to a sink is called a *sanitiser*.

Taint analysis is used for tracking the information between sources and sinks. If some data comes from an untrusted or tainted source it is regarded as being tainted. All other data is untainted. Which sources introduce taint are defined by the user of the analysis.

If a taint analysis is marking too much data as tainted, the analysis is *overtainting*, while an analysis that is marking too little data as tainted it is *undertainting*. If the analysis is neither over- or undertainting it is *precise*. Undertainting leads to missing some vulnerabilities while overtainting leads to false positives.

Because finding all vulnerabilities is critical it is common to strive to overtainting rather than undertainting. This can lead to a problem called *taintspread* which is when more and more data is tainted and that with less precision. To help with that, one can include *sanitisers* in the analysis which untaints the data.

6.11 Analysis Extension

The previously described algorithm is able to detect that a value flows from a source to a sink. Unfortunately this method is insufficient in finding all vulnerabilities. When a value from a source is assigned to a variable *s*, this variable is not necessarily the one being used when arriving at a sink. Other variables can be assigned to values that derive from *s*, or *s* can be reassigned to a modified version of *s*.

These two problems arise from using the method presented in Section 6.9.1. Two small examples of the problems can be seen in Figure 6.11a and Figure 6.11b. Here the method `source` is an arbitrary method that introduces taint while `sink` is an arbitrary sensitive sink.

```
1 s = source()
2
3 s = 'input: ' + s
4
5 sink(s)
```

(a) Reassigning a tainted variable with a modification of the tainted value

```
s = source()

user_input = 'input: ' + s

sink(user_input)
```

(b) Assigning a derived value of the tainted variable

In neither of the two examples it will be possible to detect the vulnerability with the method from Section 6.9.1, because the flow is cut off by the assignments. To fix this we have introduced two extensions to the method.

6.11.1 Propagation of Reassignments

In order to maintain the tainted variable *s* 'alive' we have modified the assignment dataflow constraint presented in Section 6.9.1. We want to let both the original assignment as well as the reassignment live in the analysis. First we check if the current assignment is a reassignment. An assignment is a reassignment if the variable assigned to also is part of the right hand side. If it is a reassignment, we omit the arrow function of the original rule, else the rule is as defined originally. The extended constraint rule is shown below:

$$
\begin{aligned}
[\![v]\!] = \text{if v is a reassignment:} \\
& JOIN(v) \cup \{v\} \\
\text{else:} \\
& JOIN(v) \downarrow id \cup \{v\}
\end{aligned}
$$

Now both the original assignment and the reassignment will propagate to the sink. This modification will still guarantee that the analysis will terminate, because the analysis will still only walk up the lattice. This is true because the added case only adds a node to the constraint, which causes the analysis to walk up in the lattice.

6.11.2 Assignment of Variable Derivations

To be able to detect derivations of variables as being vulnerabilities, we need to keep track of assignments to these derivations. This will be done when finding sources in the CFG. Each time a source is found, the subsequent nodes will be checked for assignments of derivations of this source node. Nodes that fit this description will be saved together with the source node as a 'secondary' source node. When checking for pairs of sources and sinks these assignments will also be considered as sources.

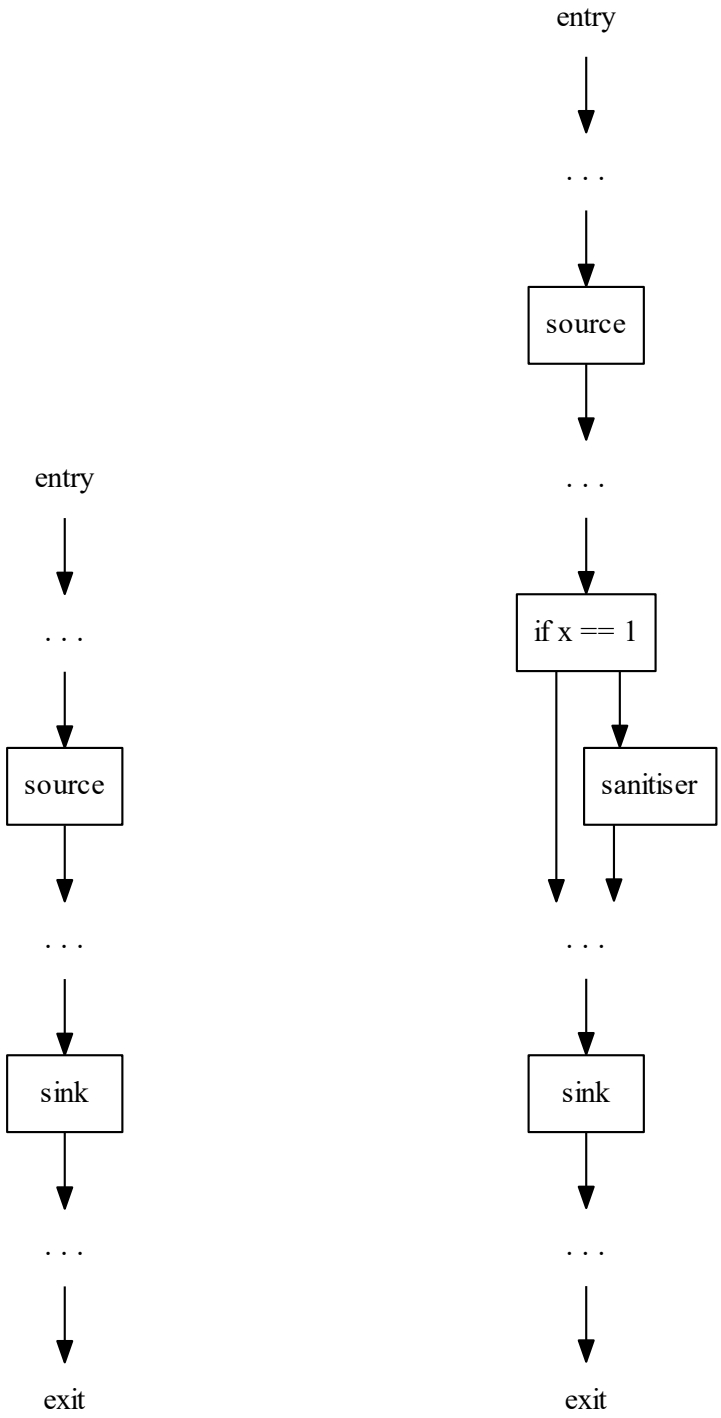
6.12 Finding Vulnerabilities

Armed with the information provided by the reaching definitions analysis we should be able to find vulnerabilities in applications. The vulnerabilities mentioned in Chapter 5 all have in common that one expression introduces user input into the program, and a later expression executes this input. The structure of such application is outlined on Figure 6.12a.

Using the reaching definitions analysis it is possible to determine if the data obtained at the source will reach the sink, by examining the constraints provided by the analysis. The secondary nodes mentioned in Section 6.11.2 will likewise be considered as a source. If the source is contained in the set of constraints of the sink and the source variable is being used as a parameter by the sink, we can regard it as a potential security vulnerability.

Such a vulnerability can potentially be harmless because of processing on the path towards the sink, by a *sanitiser*. Figure 6.12b shows the outline of an application where a sanitiser is used. The flow of such a program makes it impossible to guarantee that the application is safe, but reporting it to the developer may ease the process of securing the application.

A sanitised version of the cross site scripting example from Section 5.2 can be seen in Listing 6.3. The function `Markup.escape()` takes a string input and returns an escaped version, making it safe to insert into html. PyTwill report this as a vulnerability, but will add that it may be sanitised by the `Markup.escape()` function.



(a) A vulnerable application **(b)** A sanitiser eliminating the vulnerability

Figure 6.12: Control Flow Graphs for applications with potential vulnerabilities

```
1  from flask import Flask, request, make_response, Markup
2
3  app = Flask(__name__)
4
5  @app.route('/XSS_param', methods =['GET'])
6  def XSS1():
7      param = request.args.get('param', 'not set')
8
9      param = Markup.escape(param)
10
11     html = open('templates/XSS_param.html').read()
12     resp = make_response(html.replace('{{ param }}', param))
13     return resp
14
15 if __name__ == '__main__':
16     app.run(debug= True)
```

Listing 6.3: The cross site scripting example sanitised by the escape function

Chapter 7

Implementation

This section will give an overview of the different components and the overall flow of PyT. An illustration giving an abstract overview can be seen on Figure 7.1.

The illustration shows how PyT takes the source code as input, manipulates it and finally outputs a list of potential vulnerabilities. The process will be described in the following on a general level.

- The source code is parsed to an abstract syntax tree (denoted as AST) representation of each file in the project being analysed. The AST is generated using the standard Python library `ast`[27].
- The AST is systematically traversed and turned into a control flow graph by the CFG component.
- The resulting CFG is not prepared for the analysis by a framework adaptor, depending on the web framework used in the source code. The default adaptor is the Flask adaptor, but a similar module for Django applications could be devised.
- The fixed point algorithm is applied on the CFG and the resulting constraints are annotated on each CFG node The fixed point module is flexible which means that the analysis can be substituted or extended with other analyses. By default PyT uses the extended reaching definitions analysis presented in the previous chapter.
- At last the annotated CFG is investigated, and a log is provided to the user giving precise information about the potential vulnerabilities found by the analysis

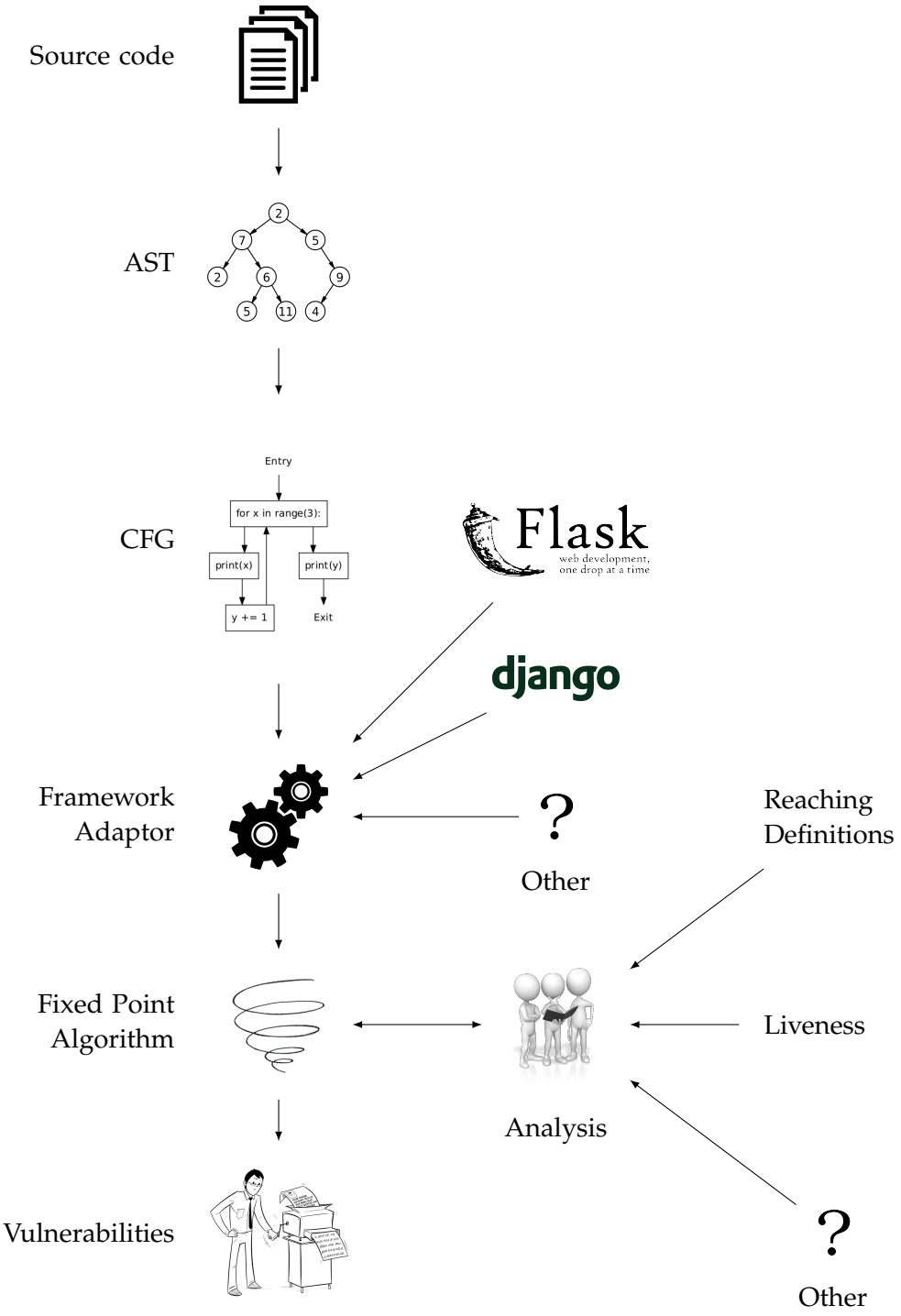


Figure 7.1: An abstract overview of the implementation of PyT, showing the main components and the flow

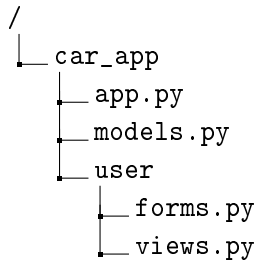
7.1 Handling Imports

This section contains a description of how imports are handled when processing a file. Handling imports is essentially just coupling called functions, class instantiations and variables to the correct definition in another file. As such it is not theoretically interesting. However, it is a requirement for being able to run PyT on real projects, which is important because we want to evaluate the security of complete web applications.

The import statements The two ways of importing in Python, import and import-from, are presented in Section 3.1.7 and these two ways need to be handled separately. When referencing a function in a module imported with the `import` statement the function needs to be prefixed with the name of the module while this is not the case for `import-from`.

The file that is given as input to PyT is used as the entry point. First, the `project_handler` module is used to get what we call local modules and project modules. A local module is a Python file that is in the same folder as the file. A project module is a Python file that is in the same project as the file. The project modules are used to resolve the location of modules placed in another directory.

To illustrate the above consider the following example project structure below.



Consider the entry point being the *app.py* file. The `project_handler` module will construct a list of project modules containing the following modules: [*car_app.app.py, car_app.models.py, car_app.user.forms.py, car_app.user.views.py*]. And a list of local modules containing the modules that are in the same folder as the entry file: [*app.py, models.py*].

The module definitions stack Using the `ast` module, described in Section 7.2, the abstract syntax tree(AST) is generated for the entry point. When visiting an import or import-from node the module and its definitions are loaded. A definition in this context is a definition of a variable, function or class. A file being loaded usually also contains imports. In order to control the different import contexts, a module definition stack is built. Each entry in the stack contains a list of loaded definitions

for one file.

To illustrate consider these two modules:

```
1  def fuel(km):
2      ...
3
4  class Car():
5      ...
6
7  class Owner():
8      ...
```

Listing 7.1: A module that defines a function and two classes called `a`

```
1  ...
2
3  import a
4
5  ...
6
7  c = a.Car()
```

Listing 7.2: A module called `b` importing the above module `a`

First the AST for the entry file is created in this case we say its module `b`. Then an entry in the stack created for `b`. So the stack contains one module definitions: stack = [module_definitions<b>].

The AST is visited and when an import statement is visited a new module is visited and a new module definitions is created and added to the stack. Visiting the import of `a` results in the following stack: stack = [module_definitions<b>, module_definitions<a>]

The definitions in the `a` list are: `foo`, `Car` and `Owner`. These are added to the list of module `a`: module_definitions<a> = [`foo`, `Car`, `Owner`]. Additionally they are added to the list of module `b` with names prepended with an `a`: module_definitions<b> = [`a.foo`, `a.Car`, `a.Owner`].

This is important so that when one of the imported definitions later is used in `b` the list of `b` contains the correct definition.

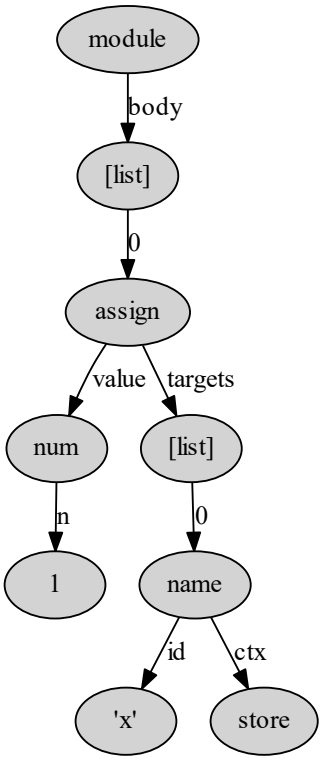
Every time there is an import a new list is added to the stack. When the import is done the stack is popped. This process handles the names for different modules and nested imports.

7.2 Abstract Syntax Tree

The `ast` module from the standard library in Python is used for building an abstract syntax tree from the source code. This module contains a `parse` method that

```
x = 1
```

(a) A small Python program



(b) The syntax tree of the code in Figure 7.2a

Figure 7.2: A piece of code and the corresponding syntax tree

constructs an AST from a string containing Python code. The abstract grammar of Python can be found in Appendix B. Selected rules, which are relevant for the following example, are displayed in Listing 7.3.

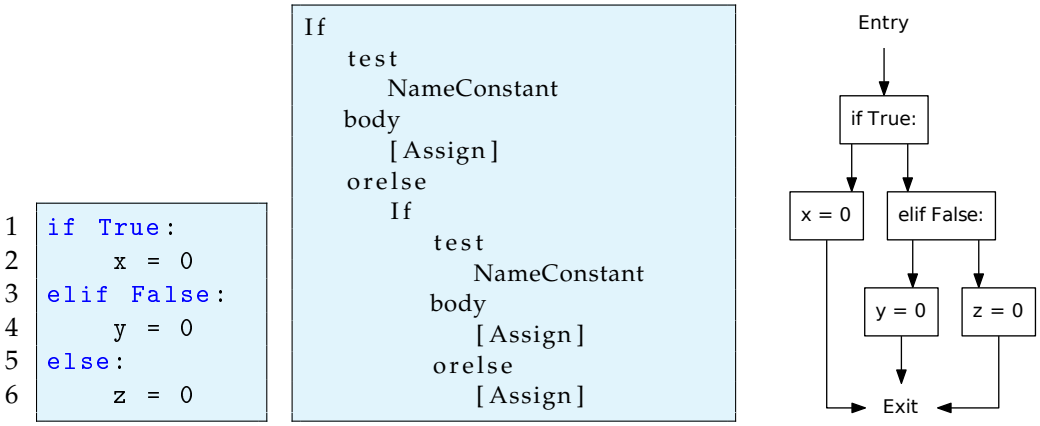
```
1 mod = Module(stmt* body)
2
3 stmt = Assign(expr* targets, expr value)
4
5 expr = Num(object n)
6      | Name(identifier id, expr_context ctx)
```

Listing 7.3: Selected rules from the Python abstract grammar

Figure 7.2 shows the abstract syntax tree for the small piece of code presented in Figure 7.2a. The root of the program is the `Module` statement which contains a list of `stmts`. In this case this `stmt` is an `Assign` which then contains a list of targets and a value. In this concrete example there is a single target which is the `Name` x, and the value is a `Num` with the number 1.

7.3 Control Flow Graph

The `cfg` module contains a class, `Visitor`, that takes an AST and builds a CFG from it. The CFG is built by traversing the generated AST using the visitor pattern.[28] The visitor pattern is implemented by the AST module, and our CFG module utilizes this implementation. The `Visitor` class constructs a list of nodes which are saved as a `CFG`.



(a) Code example **(b)** Abstract Syntax Tree **(c)** Possible flows

Figure 7.3: An AST and the expected CFG

7.3.1 From AST to CFG

Implementing the CFG requires considering all the cases mentioned in Section 3.1.5. Figure 7.3 shows an one of the cases with the intermediate AST step included (Figure 7.3b). Here the AST is visualised as a tree, where the first node is an `If` node[1] This node contains a test node, a body, represented as a list of nodes, and an orelse body, also represented as a list of nodes. In this example the conditions are `NameConstant` nodes and all statements are `Assign` nodes. The orelse body of the outer `If` node contains another `If` node which contains the `elif` which has the else in its orelse body.

The CFG of the program is generated by traversing the AST and creating a CFG node at each node. These nodes are then connected so the resulting CFG reflects the flow of the program. The implementation of the `If` visitor will be described in the following.

[1] An AST for a complete program starts with a `Module` node, but this is not shown here in order to simplify the tree

7.3.2 Visitor implementation

Listing 7.4 shows the implementation of visiting an `If` AST node. First, another visitor, the `LabelVisitor` is used to find labels of statements in the CFG. In line 2 it is used to generate the label of the condition in the `if`. Afterwards a CFG node is created for the condition and appended to the list of CFG nodes. In line 8 the body of the `if` is handled by the `stmt_star_handler` method. This method visits all nodes in the body and connects them properly. Line 11 now handles `elif` and `else` cases. Again `stmt_star_handler` handles the connection of the bodies.

Through the implementation a number of 'last nodes' are being kept track of. This is for instance seen in line 13 where the 'last nodes' of the orelse node are added to the 'last nodes' of the body. A 'last statement' is in this context any statement that needs to be connected to the subsequent statement of the `if`. Among these are `raise` statements, `return` statements and the last statements of the body, `elif` bodies and the `else` body. These are sent to the calling function by returning a `ControlFlowNode` in line 19. This calling function is `stmt_star_handler` which, as stated above, connects all the nodes properly.

```
1  def visit_If(self, node):
2      label_visitor = LabelVisitor()
3      label_visitor.visit(node.test)
4
5      test = self.append_node(Node(label_visitor.result, node,
           line_number = node.lineno))
6      self.add_if_label(test)
7
8      body_connect_stmts = self.stmt_star_handler(node.body)
9      test.connect(body_connect_stmts.first_statement)
10
11     if node.orelse:
12         orelse_last_nodes = self.handle_or_else(node.orelse,
               test)
13         body_connect_stmts.last_statements.extend(
               orelse_last_nodes)
14     else:
15         body_connect_stmts.last_statements.append(test)
16
17     last_statements = self.remove_breaks(body_connect_stmts.
           last_statements)
18
19     return ControlFlowNode(test, last_statements,
           break_statements=body_connect_stmts.break_statements)
```

Listing 7.4: Visiting an If AST node.

7.4 Framework adaptor

Our goal of our tool is to target web application frameworks. As there exist different frameworks and these are organised in different manners, we need to accommodate for these variations. The framework adaptor is purposed to accommodate for different web application frameworks. The `FrameworkAdaptor` class is an abstract class with an abstract method `run`. It contains a list of CFGs where the adaptor is expected to put the result of the adaptation. The implementation of `run` should include processing for all framework specific details that are needed in order to get a correct model of the application. This adaptor can be implemented for an arbitrary framework like Django or, in our case, Flask.

The Flask Adaptor In Flask all web pages are defined in a function with a decorator. This function is never explicitly called in the source code, so a single traversal by the CFG visitor of the file will not include all these methods in the resulting list of CFGs. The `FlaskAdaptor` was implemented for this purpose. The result of the CFG visitor contains all functions found during the traversal. The Flask adaptor goes through these and finds all functions that are defined with the `@app.route()` decorator, and adds it to the list of CFGs. This results in a list of CFGs that cover all the code needed for analysing the application.

Implementing a custom adaptor The adaptor component is in place for making it possible to adapt the analysis to any framework. This paragraph will describe how such an implementation should be devised.

In Appendix C the implementation of the Flask adaptor is shown. This implementation will be used as a basis for this description. The adaptor inherits from the class `FrameworkAdaptor` which contains an instance variable for a CFG list and the abstract function `run`. The `run` function is the entry point to an adaptor.

In the Flask implementation the CFG list, which is initially populated with the result of the CFG visitor, is iterated over and the `find_flask_route_functions` function is called on each.[2] The idea of the `find_flask_route_functions` was described in the previous paragraph. A similar consideration has to be made for the framework in question and then implemented in a similar fashion.

After implementing a custom adaptor, PyT will be able to analyse any application using this framework.

[2] In our case there is always one CFG in this list, but other implementations might have more than one.

7.5 Flexible analysis

As mentioned in the implementation overview, the fixed point analysis is implemented so that the analysis can be changed. For our purposes the modified *reaching definitions* analysis presented in Section 6.11 is sufficient – it provides the answers we need to locate the security vulnerabilities in web applications.

However, one could imagine improving PyT by utilising other analyses that could help identify the vulnerabilities. In such a case PyT has been implemented so it can be easily expanded with another analysis. The liveness analysis presented in Schwartzbach [25, p. 19] has been implemented in order to exemplify the process of implementing new analyses. This process will be explained in the following.

7.5.1 Implementing Liveness

The complete implementation is presented in Appendix D. The implementation corresponds to the definition presented in Schwartzbach [25, p. 20]. The `LivenessAnalysis` class inherits from `AnalysisBase` which contains logic for annotating the CFG with extra information. In the case of the liveness analysis we need information about the `vars(E)` of each node. The deduction of these are defined as a visitor `VarsVisitor` which visits an AST node and finds the variables as defined in Schwartzbach [25].

`LivenessAnalysis` contains the constraints of the liveness analysis defined in `fixpointmethod`, which is shown in Listing 7.5. This method is used by the fixed point analysis to apply the constraints on each node. This method uses a helper `JOIN` which corresponds to the JOIN function in Schwartzbach [25], and the variables found by `VarsVisitor`.

```
24      def fixpointmethod(self, cfg_node):
25          """Setting the constraints of the given cfg node
26          obeying the liveness analysis rules."""
27
28          # if for Condition and call case: Join(v) u vars(E).
29          if cfg_node.ast_type == Compare.__name__ or
30             cfg_node.ast_type == Call.__name__:
31              JOIN = self.join(cfg_node)
32              # set union
33              JOIN.update(self.annotated_cfg_nodes[cfg_node])
34              cfg_node.new_constraint = JOIN
35
36          # if for Assignment case: Join(v) \ {id} u vars(E).
37          elif isinstance(cfg_node, AssignmentNode):
38              JOIN = self.join(cfg_node)
39              # set difference
40              JOIN.discard(cfg_node.ast_node.targets[0].id)
41              # set union
```

```
42              JOIN.update(self.annotated_cfg_nodes[cfg_node])
43              cfg_node.new_constraint = JOIN
44
45          # if for entry and exit cases: {}.
46          elif cfg_node.ast_type == "ENTRY" or
47               cfg_node.ast_type == "EXIT":
48              pass
49          # else for other cases.
50          else:
51          cfg_node.new_constraint = self.join(cfg_node)
```

Listing 7.5: Implementation of liveness analysis - `fixpointmethod`

With this implementation the PyT fixed point algorithm implementation can perform liveness analysis on an arbitrary piece of python source code. The PyT vulnerability checker could likewise be expanded with any analysis that could aid the detection of security vulnerabilities.

7.6 Vulnerabilities

This module uses the result of the fixed-point analysis to detect vulnerabilities in the application. First it is needed to determine which flows are dangerous. Then taint analysis can be employed, and the resulting vulnerabilities will be recorded and displayed in a readable manner to the developer.

7.6.1 Taint Analysis

In order to find dangerous flows in a program we need to know what expressions introduce user input and what expressions may not receive input. We also need to be able to detect when the program actually makes such input harmless. The theoretical background for this was discussed in Section 6.10

```
1 x = input()
2 print('this is dangerous!')
3 eval(x)
```

Listing 7.6: A simple vulnerable program

The program in Listing 7.6 is vulnerable to a user executing arbitrary code. `input()` is a source and `eval()` is a sink. The result of `input()` is being handed over to `eval()` without any sanitisation. Imagine this program being served on a server which also contains confidential information. An attacker would possibly be able to retrieve this confidential information from the server.

7.6.2 Sources, Sinks and Sanitisers in Flask

Flask is a web framework, so it uses some different means of user input than the `input()` method. This section will cover a selection of these in order to have a basis for performing an analysis of a Flask application.

Sources In Section 4.1 the `request` object was introduced. This object is used to access the input provided by the user through interaction with the page.

Query parameters Query parameters submitted to the URL of the format 'domain.com?query=parameter' can be accessed with the `request.args.get(key, default)` method. This method takes the key to retrieve a value from and a default value as parameters. If this methods returns a value that is different from the default, it is potentially dangerous.

Form content Input submitted through form fields can be accessed with the `request.form[key]` attribute. This attribute is a dictionary that maps a form field to its value. Values retrieved from this dictionary are potentially dangerous.

Sinks User input can arrive at a wealth of methods which can be regarded as a sink. We explored three vulnerabilities in Chapter 5 which we would like to be able to detect. The following is the sinks that can possibly enable the chosen vulnerabilities. These are obviously only a small selection of all possible sinks.

Homemade templates When utilising the template engine of Flask many security concerns are ruled out. An eager developer that is too impatient to read the documentation for *Jinja2* may resort to a solution that works, but is subpar regarding security. One example of this could be to use `string.replace(old, new)` instead of the template engine. The developer creates his own template format, and replaces placeholders with user input. It works, but if the input does not get sanitised, the user can inject javascript into the page, see Section 5.2.

The input passed to `string.replace()` can be sanitised using the `Markup` class provided by Flask. `Markup` is used to represent HTML markup and marks them as being safe. It contains an `escape` function that escapes HTML tags and thereby sanitises the input. Manipulating a markup object with string interpolation also escapes all values. An example of escaping user input can be seen on Listing 7.7 where the `Markup.escape` method is used to sanitise the input before inserting it with the `string.replace()` method.

```
1  html = open('templates/example1.html').read()
2  unsafe = request.args.get(param)
3
```

```
4   sanitised = Markup.escape(unsafe)
5
6   resp = make_response(html.replace('{{ param }}', sanitised))
```

Listing 7.7: An example of escaping user input

Database access The recommended way to work with a database in Flask is by using a package called SQLAlchemy[29, 30]. This package gives the developer the option to setup and/or communicate with a database. In the following two examples of SQL injection, described in Section 5.1, will be presented. The complete source code of the web application can be found in Listing A.1. The examples both print out the result of the SQL queries to the console. In a real application there would be some web interface where it is presented to the user.

The first example, Listing 7.8, shows that the address "/raw" takes a parameter called `param`. This parameter is then executed directly on the database. The result is printed to the console. The problem here is that the user is able to execute every query he wants. But SQLAlchemy prevents from executing several SQL commands and from changing the database by for example deleting all of it.

```
1 @app.route('/raw')
2 def index():
3     param = request.args.get('param', 'not set')
4     result = db.engine.execute(param)
5     print(User.query.all(), file=sys.stderr)
6     return 'Result is displayed in console.'
```

Listing 7.8: An example of executing a raw sql query without sanitising.

The second example, Listing 7.9, shows how the parameter of the filter function is not sanitised. The address "/filter" takes a parameter, `param`, as input. This `param` is used directly in a filter function on the database. If the value of the `param` is "2 or 1 = 1" the filter function will return all users because the `param` always evaluates to true.

```
1 @app.route('/filter')
2 def filter():
3     param = request.args.get('param', 'not set')
4     Session = sessionmaker(bind=db.engine)
5     session = Session()
6     result = session.query(User).filter("username={}".format(
          param))
7     for value in result:
8         print(value.username, value.email)
9     return 'Result is displayed in console.'
```

Listing 7.9: An example of inserting a raw sql parameter without sanitising it.

Filesystem access Files can be sent to the client with the `send_file(filename)` method. This method takes a file from the filesystem and sends it to the user. If the filename parameter is set by user input, the user can possibly traverse the filesystem of the server, see Section 5.3. This can be sanitised by disallowing the use of '..' in the variable passed to the filename parameter.

7.6.3 Trigger Word Definition

A definition file is provided that contains sources, sinks and sanitisers which are used to find vulnerabilities in the source code. A simple text file with two keywords is used for this purpose. The keywords "sources:" and "sinks:" are used to indicate the content of the section. Each source or sink is written on a separate line. A sink can have a number of sanitisers attached written with as a comma separated list after an arrow ("->"). Sinks, sources and sanitisers are called trigger words, and the definition file is called a trigger word file, and an example can be seen in Listing 7.10. The defintion file used by PyT can be found in Appendix E.

```
1  sources:
2  source_1
3  source_2(
4
5  sinks:
6  sink_1[
7  sink_2 -> sanitiser_1
8  sink_3 -> sanitiser_1 , sanitiser_2 , sanitiser_3
```

Listing 7.10: How the trigger word file should be defined.

The words trigger a source if the trigger word is a substring of the node. This means that the words have to be chosen carefully. Because of this, "function" and "function(" can give different results Choosing the right one is therefore crucial. This can appear too simple, but it gives more flexibility to define trigger words that are either functions, indexes or have other characteristics without having an elaborate but restrictive syntax for this.

7.6.4 Finding and Logging Vulnerabilities

After parsing the file all potential vulnerabilities are found and saved in a log. The concept of finding vulnerabilities was described in Section 6.12. Vulnerabilities are found by first identifying all nodes which contain a trigger word. All sources are then checked if their constraint contain a source, and i that is the case, if a sanitiser is in between the two. These cases are then logged to the vulnerability log. A `Vulnerability` is an object which consists of a source and a sink CFG node, and which words triggered the detection of these. A source and a sink have attached

a line number to them, this line number tells where they are located in the source code. This information is used to make it as easy as possible for the developer to find and determine whether the vulnerability found is harmful. An example of a vulnerability log can be found in Listing 7.11. The output shown is after running PyT on Listing 5.4. The vulnerability is reported by showing details of both source and sink, with the relevant trigger word and the line number in the source code. This should enable the developer to either fix the vulnerability or assess it as being safe.

```
1 vulnerability found:
Vulnerability 1:
File: example/vulnerable_code/XSS.py
 > User input at line 6, trigger word "get(":
        param = request.args.get('param', 'not set')
Reassigned in:
        File: example/vulnerable_code/XSS.py
         > Line 10: ret_make_response = resp
File: example/vulnerable_code/XSS.py
 > reaches line 9, trigger word "replace(":
        resp = make_response(html.replace('{{ param }}',
           param))
```

Listing 7.11: An example of how the vulnerability log looks after it found one vulnerability.

7.7 PyT

This section contains a description of how to use PyT. PyT is a command line tool which requires one argument, the path of the file that should be analysed, and several optional arguments. These are described below.

7.7.1 Positional Arguments

PyT requires one positional argument, `filepath`, which is the path of the file which should be analysed. If the file is a part of a project the folder in which the file is in is used as root. To specify another root one can use the optional argument `-project-root` explained below in Section 7.7.2.

7.7.2 Optional Arguments

This section contains a brief description of the optional arguments of PyT.

Project Root The project root argument is used for specifying the root of the project when the filepath given is not in the root folder of the project.

Draw CFG This argument is useful to visualise a CFG. It outputs a PDF file that contains a graph like the one on Figure 6.2.

Output Filename This argument can be used to specify the output name of the file that is generated when using the `-draw-cfg` or the `-create-database` argument.

Print This outputs the CFG to the standard output in simple representation. This prints all labels of each node in the CFG.

Verbose Print The same as the print argument but more verbose. This means that all information a node contains is send to the output.

Trigger Word File This argument is used for specifying a trigger word file which is a file as defined in Section 7.6. This is optional as per default the Flask trigger word file that comes with PyT.

Log Level This argument is used for setting the log level of the logger that is used. The log level can be changed to the following levels, highest level first: CRITICAL, ERROR, WARNING, INFO, DEBUG or NOTSET. Setting the log level will result in the log containing messages from the chosen level and the levels above. The default log level is `WARNING` and the logger writes the output of the logging to a text file "logger.log".

Adaptor This argument is used for specifying a framework adaptor. Per default PyT uses the Flask adaptor which comes with it, see Section 7.4.

Create Database Creates a script that creates two database tables and inserts all CFG nodes and all vulnerabilities. This feature is not tested due to time constraints.

Help This options shows a short overview of the available arguments and their meaning. On Figure 7.4 the output of running PyT with this argument is depicted.

7.7.3 Command Line Argument Summary

Figure 7.5 shows a quick overview of the arguments of PyT and the corresponding flags to use when running the tool.

```
$ python3 pyt.py -h
usage: pyt.py [-h] [-pr PROJECT_ROOT] [-d] [-o OUTPUT_FILENAME] [-p | -vp]
              [-t TRIGGER_WORD_FILE] [-l LOG_LEVEL] [-a ADAPTOR] [-db]
              filepath

positional arguments:
  filepath              Path to the file that should be analysed.

optional arguments:
  -h, --help            show this help message and exit
  -pr PROJECT_ROOT, --project-root PROJECT_ROOT
                        Add project root, this is important when the entry
                        file is not at the root of the project.
  -d, --draw-cfg        Draw CFG and output as .pdf file.
  -o OUTPUT_FILENAME, --output-filename OUTPUT_FILENAME
                        Output filename.
  -p, --print           Prints the nodes of the CFG.
  -vp, --verbose-print  Verbose printing of -p.
  -t TRIGGER_WORD_FILE, --trigger-word-file TRIGGER_WORD_FILE
                        Input trigger word file.
  -l LOG_LEVEL, --log-level LOG_LEVEL
                        Chose logging level: CRITICAL, ERROR,
                        WARNING(Default), INFO, DEBUG, NOTSET.
  -a ADAPTOR, --adaptor ADAPTOR
                        Chose an adaptor: FLASK(Default) or DJANGO.
  -db, --create-database
                        Creates a sql file that can be used to create a
                        database.
$
```

Figure 7.4: An overview of PyT and its arguments.

Argument	Description
`filepath`	Specify path of file to analyse.
`-pr, -project-root`	Specify project root.
`-d, -draw-cfg`	Draw CFG and output as a PDF file.
`-o, -output-filename`	Name of the file that is output.
`-p, -print`	Prints a CFG with simple information about the nodes.
`-vp, -verbose-print`	Same as print but with all information about the nodes.
`-t, -trigger-word-file`	Specify a trigger word file.
`-l, -log-level`	Set a log level.
`-a, -adaptor`	Chose an adaptor.
`-db, -create-database`	Create a sql file of the CFG.

Figure 7.5: PyTs arguments.

7.8 Testing

During the development of the application we have had great success working test oriented. In particular when developing the conversion from abstract syntax tree to control flow graph, testing has been invaluable. The abstract nature of the syntax tree together with the many possibilities of python yield a huge number of cases for each construct, and the edges have to be just right in every one of them.

When developing all these fragments of the complete grammar, we need to be sure that our previous work still works as intended. To help us be sure that all our assumptions and implementations hold we have utilised unit testing a great deal. The following will mention some of the issues where testing has helped the process.

Cases An example of a construct which has many different cases is the `if` control structure, which has variants with `elif` and `else` statements. The `if` abstract syntax node contains an *orelse* reference which can either be another `if`, representing an elif clause, or a list of statements, representing the body of an `else` clause. In addition an `if` can have many different expressions in its *test* clause. These expressions are often logic expressions but can also be nameconstants, function calls, lambdas and even a list. To illustrate the three different cases three abstract directed graphs have been made.

- The graph for a single `if` statement can be seen on the left on Figure 7.6.
- The graph for an `if` and an `elif` statement can be seen on the right on Figure 7.6.
- The graph for an `if`, `elif` and else statement can be seen on Figure 7.7

Note: On Figure 7.6 and Figure 7.7, *expr* is an expression and *stmt** is a list of statements.

When the basic cases of the `if` is implemented we also need to know that `if` statements inside the body of an `if` statement works properly. When that works we need to consider how to handle `break`, `yield` and `return` statements inside the `if`.

Testing has greatly helped when exploring and developing these cases, because they explicitly run each case every time the test is run. This assures that a change fixing one case did not break another case.

Complex features The development of python is still ongoing which results in periodic changes to both the grammar and the semantics of the language. Continuously adding features from both the object oriented and the functional paradigm

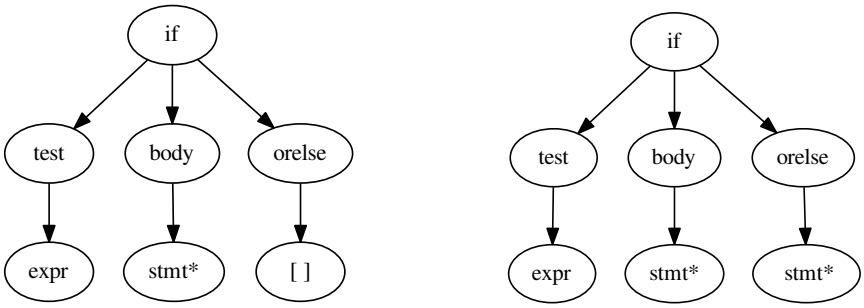


Figure 7.6: Abstract graph showing the nodes in the abstract syntax tree for a single `if` statement on the left and an `if` and `else` statement on the right

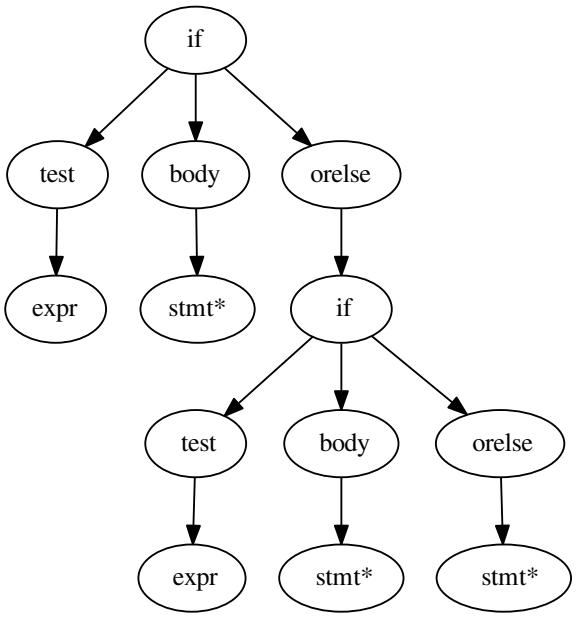


Figure 7.7: Abstract graph showing the nodes in the abstract syntax tree for an `if`,`elif` and `else` statement

results in more possibilities but also a more complex internal structure. This is evident when attempting to generate control flow graphs from the abstract syntax.

One example is that you can assign a list to a tuple, and python will *unpack* and assign the items of the list to the corresponding items of the tuple. This is possible using the `*`-operator. An example is show on Listing 7.12, where x is assigned the value 4 and the tuple y is overwritten with the list [5, 6].

```
1  x = 1
2  y = (2,3)
3  x,*y = [4,5,6]
```

Listing 7.12: Tuple unpacking

Generating the control flow graph for expressions like these have given a lot of insight into python, but it has also been a challenge to represent them properly in the control flow graph. Also here testing has provided useful for keeping track of the parts involved. The example consists of assignments, a tuple, the star operator and a list in order to show off one concept. All the concepts both need to work individually and together, and tests have helped ensuring this.

Dynamic types Python is a dynamic language which can be unforgiving to debug. A wrong type returned from a function produces an error in a function somewhere else. That can result in a big stack trace which can be hard to follow.

When developing with tests a catalogue of small tests are naturally developed. When introducing an error that breaks more than just the construct at hand, test have helped pinpointing the real cause of the error. This has sometimes lead to insight that either helped us understand why our implementation was wrong, or why what we expected was not the real outcome.

Integration test At last some integration tests were added to ensure that PyT produces the right output for each vulnerability example described in Chapter 5. This helped the process of implementing the vulnerability detection, by pointing out when the detected vulnerabilities changed.

7.9 Limitations

This section will list the limitations that the implementation of PyT has.

7.9.1 Dynamic Features

The following dynamic features are not supported meaning that the right flow of the source code is not captured and therefore is not taken into account in the analysis. PyT does not support the built in functions `eval` and `exec`. These functions

take a string as input which are executed as Python code. This means that the content of this string cannot be evaluated statically, and PyT cannot anticipate what will happen.

PyT does also not support monkey patching. Monkey patching is used to replace functions in order to manipulate modules or classes. This is powerful but also difficult to capture.

Not supporting the above dynamic features means that taint can be introduced without PyT noticing. One way to fix this is to overtaint by just tainting all nodes containing `eval` and `exec` for instance.

7.9.2 Decorators

Decorators are used to transform a function into another function. Flask uses this to register functions that should be accessible as a webpage. In practice a decorator is implemented as a class or a function that contains a transformation function that returns the transformed function. When a function definition is decorated, the transformed function will be used instead. An example was provided in Section 3.1.6.

The current implementation does not perform this decoration process. A decorated definition is not transformed, and the decorator is stored. This means that some details may be lost. Some transformations may introduce taint, which will not be caught by PyT.

A correct implementation of decorators will be very similar to that of a function call, but there will be some considerations on how to capture the transformed function correctly.

7.9.3 Libraries

The import handling does its best to find the implementation of functions called throughout the program, but it can only find the implementation of functions where the source code is available. This may be limiting the analysis, but having to traverse all library code will be a major task. Fixing this requires considerations of when it is worth doing, and when it is just increasing running time, without adding value.

7.9.4 Language Constructs

This section contains a list of language constructs that were not implemented due to time constraints and were not deemed important as most of them were not faced in the projects we ran as input. Language constructs not implemented:

- **Async** - used for asynchronous programming.[31]
- **Decorators** - used for function transformations, explained in Section 3.1.6.

- **Try** - used for catching exceptions.[32]
- **Delete** - a statement to delete a name.[33]
- **Assert** - a statement that can be used to insert debugging assertions into a program.[34]
- **Global** - a statement that declares a name global so that one can access global names from other scopes.[35]
- **Yield** - used in generator functions to “return” one item at a time.[36]
- **Starred** - used for unpacking (only partially implemented).[37]

Chapter 8

Discussion

This chapter contains an evaluation of PyT, reflections and future works.

8.1 Evaluation

This section will contain an evaluation of PyT. First the vulnerabilities described in Chapter 5 will be run and serve as proof that the tool catches these vulnerabilities. Thereafter PyT will be run on real projects and the performance of the tool will be evaluated.

8.1.1 Detecting Manufactured Vulnerabilities

In Chapter 5 we presented four implementation mistakes that would leave a web application vulnerable. In this section PyT will be run on the presented examples to see if they are being detected as hoped.

SQL injection The first example was the SQL injection which can be found in Appendix A.1. Here we expect to find the two vulnerabilities presented in Section 5.1.1, the naive execution of the query parameter and the unescaped filter.

As seen on Figure 8.1 we get a report with two vulnerabilities. The first one detected is the filtering vulnerability. PyT tells us that the trigger word 'get' was found in line 33, which then reached line 36 where the trigger word 'filter' marked it as a sink.

The second one is the naive implementation of the database query. Here the vulnerability is reported to begin at line 26 where the trigger word 'get' pointed out a sink. This sink then reaches line 27 where the trigger word 'execute' indicates a sink.

Both vulnerabilities were thus able to be found by PyT.

```
$ python3 pyt.py ../example/vulnerable_code/sql/sqli.py
2 vulnerabilities found:
Vulnerability 1:
File: ../example/vulnerable_code/sql/sqli.py
 > User input at line 33, trigger word "get":
        param = request.args.get('param', 'not set')
File: ../example/vulnerable_code/sql/sqli.py
 > reaches line 36, trigger word "filter":
        result = session.query(User).filter('username={}'.format(param))

Vulnerability 2:
File: ../example/vulnerable_code/sql/sqli.py
 > User input at line 26, trigger word "get":
        param = request.args.get('param', 'not set')
File: ../example/vulnerable_code/sql/sqli.py
 > reaches line 27, trigger word "execute":
        result = db.engine.execute(param)

$
```

Figure 8.1: Running PyT on the SQL injection example

Command injection The next example was the command injection which can be found in Appendix A.2. Here we expect to find the one vulnerability presented in Section 5.1.2 where the content of the form field reaches the subprocess call.

The execution of PyT on the example can be seen on Figure 8.2. PyT reports one vulnerability being present in the application. A source is found on line 15 with the trigger word 'form', which reaches a sink in line 18 marked because of the trigger word 'subprocess.call'. In this case the source was assigned to a new variable in line 16 to make up the complete command to be run. This is shown by PyT as to provide information to the developer of how the tainted value did flow through the code.

Cross site scripting The next vulnerability presented was the cross site scripting attack described in Section 5.2. The code can be found in Appendix A.3.

The execution of PyT on the example can be seen on Figure 8.3. Here a source is found in line 6 with the trigger word 'get', which reaches the sink in line 9 with the trigger word 'replace'. Notice that the vulnerability reports a reassignment in line 10 which is irrelevant to the vulnerability because it happens after the sink. Also notice that the reported line looks different than the source line because of the CFG representation of a return node. This can potentially be confusing for the user of PyT.

Sanitised cross site scripting example As mentioned in Section 6.12 some vulnerabilities can be sanitised by special functions, making the dangerous code

```
$ python3 pyt.py ../example/vulnerable_code/command_injection.py
1 vulnerability found:
Vulnerability 1:
File: ../example/vulnerable_code/command_injection.py
 > User input at line 15, trigger word "form":
        param = request.form'suggestion'
Reassigned in:
        File: ../example/vulnerable_code/command_injection.py
         > Line 16: command = 'echo ' + param + ' >> ' + 'menu.txt'
File: ../example/vulnerable_code/command_injection.py
 > reaches line 18, trigger word "subprocess.call":
        subprocess.call(command,shell=True)

$
```

Figure 8.2: Running PyT on the command injection example

```
$ python3 pyt.py ../example/vulnerable_code/XSS.py
1 vulnerability found:
Vulnerability 1:
File: ../example/vulnerable_code/XSS.py
 > User input at line 6, trigger word "get":
        param = request.args.get('param', 'not set')
Reassigned in:
        File: ../example/vulnerable_code/XSS.py
         > Line 10: ret_XSS1 = resp
File: ../example/vulnerable_code/XSS.py
 > reaches line 9, trigger word "replace":
        resp = make_response(html.replace('{{ param }}', param))

$
```

Figure 8.3: Running PyT on the XSS example

```
$ python3 pyt.py ../example/vulnerable_code/XSS_sanitised.py
1 vulnerability found:
Vulnerability 1:
File: ../example/vulnerable_code/XSS_sanitised.py
 > User input at line 8, trigger word "get":
        param = request.args.get('param', 'not set')
Reassigned in:
        File: ../example/vulnerable_code/XSS_sanitised.py
         > Line 10: param = Markup.escape(param)
        File: ../example/vulnerable_code/XSS_sanitised.py
         > Line 14: ret_XSS1 = resp
File: ../example/vulnerable_code/XSS_sanitised.py
 > reaches line 13, trigger word "replace":
        resp = make_response(html.replace('{{ param }}', param))
This vulnerability is potentially sanitised by: ['escape']

$
```

Figure 8.4: Running PyT on the sanitised XSS example

```
$ python3 pyt.py ../example/vulnerable_code/path_traversal.py
1 vulnerability found:
Vulnerability 1:
File: ../example/vulnerable_code/path_traversal.py
 > User input at line 8, trigger word "get":
       image_name = request.args.get('image_name')
File: ../example/vulnerable_code/path_traversal.py
 > reaches line 11, trigger word "send_file":
       ret_cat_picture = send_file(os.path.join(os.getcwd(), image_name))

$
```

Figure 8.5: Running PyT on the Path traversal example

harmless. Running PyT on the sanitised version presented in Listing 6.3 results in the output presented in Figure 8.4

Here the vulnerability is found as in the above, but it concludes the vulnerability report by adding that it is potentially sanitised by the 'escape' function.

Path traversal The final vulnerability presented was the path traversal. The code can be found in Appendix A.4. In this example we expect to find the vulnerability presented in Section 5.3.

The execution of PyT on the example is shown in Figure 8.5. Here the report shows one vulnerability, starting with a sink found in line 8 with the trigger word 'get'. This source then reaches the sink in line 11 which is detected by the trigger word 'send_file'.

Project	Vulnerabilities
brightonpy.org[38]	0
flask-pastebin[39]	0
flask_heroku[40]	0
guacamole[41]	0
flamejam[42]	0
microblog[43]	0
flaskbb[44]	undecided

Figure 8.6: Results.

8.1.2 Detecting Vulnerabilities in Real Projects

Six open source projects were tested with PyT, for evaluation its performance on realistic inputs. A table with the results can be seen on Figure 8.6.

As one can see on the table, no vulnerabilities were found and there were even one project where PyT did not terminate. This shows that PyT can be used for real projects

Flaskbb Flaskbb did not terminate in a reasonable amount of time, and the run was manually stopped. Upon further inspection it turns out to be due to the amount of nodes being created. 432855 nodes were created, just in the main control flow graph. This huge amount of nodes makes the analysis takes up much time and space.

8.2 Reflections

This chapter will reflect on PyT and the experiences we have had during the development of the tool.

8.2.1 Are Frameworks like Flask Good for Web Security?

In the beginning of the project period we had an idea of making a tool that could find security flaws in web applications. We were well aware that vulnerabilities would not be in an abundance. Even when looking at lists of well known vulnerabilities, these were hard to apply to Flask applications. Flask takes care of a lot without the user even having to think about it.

We therefore had to resort to the vulnerabilities we presented in Chapter 5. These vulnerabilities are still dangerous, but could be unlikely to be found in the wild. (Maybe with the exception of the command injection vulnerability. This may actually be valid for some cases.)

Our experience with the Flask framework is therefore an indication that frameworks like Flask definitely help security of web applications.

8.3 Future Works

This section contains a number of subjects which can be improved upon and worked on in the future.

8.3.1 Better Trigger Word Definitions

Finding sources and sinks was a feature where the literature was sparse. Plenty of papers use the terms, but no one described a clever way to find them. We therefore devised our own system.

The implemented system uses a text file with the trigger words written in a very simple syntax. The labels of CFG nodes are compared with the trigger words, and if they contain one, they are marked as being either a source, a sink or a sanitiser. Using this simple implementation we ran into problems like finding the trigger word in variable names. The quick solution was to add a '(' to the trigger word, which fixed that single problem.

In further development the whole trigger word system should be reconsidered. The definition should be more sophisticated, and the comparison should be more intelligent than just comparing in the label.

8.3.2 More Vulnerability Definitions

One of the reasons that our evaluation found no vulnerabilities in real applications (see Section 8.1), is the small number of vulnerabilities PyT looks for. The used trigger word definition file only finds those particular vulnerabilities that was found in the beginning of the project. In order to make PyT really useful, this trigger word definition should be expanded, not only with new vulnerabilities, but also with variants of the vulnerabilities already being searched for. The two SQL injection attacks presented in Section 5.1.1 is one example of a vulnerabilities where variants of the same vulnerability exists. It is imaginable that many vulnerabilities exists in a number of variants that all need to be defined by trigger words.

8.3.3 More Efficient Fixed-point Algorithm

In this project efficiency has not been a priority, and for the most part is has not been a problem. In the evaluation performed on real projects, described in Section 8.1.2, this suddenly became a hurdle. It turns out that big projects produce CFGs that are so large that PyT simply does not terminate in a realistic amount of time. It would therefore be a natural next step to attempt to improve this in-

efficiency. As mentioned in Section 6.8 this project has not spent time examining alternative implementations of the fixed-point algorithm. One suggestion would therefore be to attempt to implement the improved version of the algorithm, in order to get a faster analysis.

8.3.4 Expanding PyT with Other Analyses

As discussed in Section 7.5, PyT has been implemented in a flexible way, so that any analysis can be implemented. This means that it is possible to expand the analysis with supporting analyses. The implemented example, liveness analysis, could be used to determine if a found vulnerability is in a piece of dead code. If this is the case, the developer might not be interested in this particular vulnerability. The danger of not displaying vulnerabilities in dead code is of course that this code may become live at any time, and then the vulnerability is suddenly dangerous. There could therefore be a optional command line flag that filters out dead code, based on the liveness analysis.

Other analyses could also prove helpful in the detection of vulnerabilities.

8.3.5 Support More Frameworks

This project has only looked into the Flask web framework. In order to make PyT even more useful, more frameworks should be supported. As mentioned in Section 2.3, Django is a very popular framework. Implementing support for Django could greatly increase the number of applications that PyT is able to analyse.

Implementing another framework requires a new adaptor. The process of writing a new framework adaptor was described in Section 7.4.

Chapter 9

Conclusion

This report engaged in creating a tool for detecting security flaws in Python web applications. Firstly, the background for the project was examined, including the Python programming language and the Flask web framework. We then proceeded to manufacture some Flask applications with vulnerabilities. The resulting applications would then be used to check if the tool was able to detect them.

The theory needed to build such a tool was then described. The theory includes control flow analysis, the monotone framework and taint analysis.

The tool PyT was then implemented with the aim of being flexible. PyT is specialised to find vulnerabilities in Flask using a modified reaching definitions analysis, but it is the intention that both aspects can be expanded on. It is thereby possible to implement support for Django or use other analyses, without having to make major changes.

At last PyT was evaluated. PyT was able to find all the manufactured vulnerabilities. It was also able to run on open source Flask projects and did not find any vulnerabilities in these.

Appendix A

Vulnerability implementations

A.1 SQL injection

```
1  from flask import Flask, request
2  from flask_sqlalchemy import SQLAlchemy
3  from sqlalchemy.orm import sessionmaker
4  import sys
5
6  app = Flask(__name__)
7
8  # SQL Alchemy setup
9  app.config['SQLALCHEMY_DATABASE_URI'] = 'sqlite:////tmp/test.db
       '
10 db = SQLAlchemy(app)
11
12 class User(db.Model):
13     id = db.Column(db.Integer, primary_key=True)
14     username = db.Column(db.String(80), unique=True)
15     email = db.Column(db.String(120), unique=True)
16
17     def __init__(self, username, email):
18         self.username = username
19         self.email = email
20
21     def __repr__(self):
22         return '<User %r>' % self.username
23
24 @app.route('/raw')
25 def index():
26     param = request.args.get('param', 'not set')
27     result = db.engine.execute(param)
28     print(User.query.all(), file=sys.stderr)
```

```
29      return 'Result is displayed in console.'
30
31  @app.route('/filtering')
32  def filtering():
33      param = request.args.get('param', 'not set')
34      Session = sessionmaker(bind=db.engine)
35      session = Session()
36      result = session.query(User).filter("username={}".format(
            param))
37      for value in result:
38          print(value.username, value.email)
39      return 'Result is displayed in console.'
40
41  if __name__ == '__main__':
42      app.run(debug=True)
```

Listing A.1: SQL injection examples, using Flask and SQLAlchemy.

A.2 Command Injection

```
1   from flask import Flask, request, render_template
2   import subprocess
3
4   app = Flask(__name__)
5
6   @app.route('/')
7   def index():
8       with open('menu.txt','r') as f:
9           menu = f.read()
10
11      return render_template('command_injection.html', menu=menu)
12
13  @app.route('/menu', methods=['POST'])
14  def menu():
15      param = request.form['suggestion']
16      command = 'echo ' + param + ' >> ' + 'menu.txt'
17
18      subprocess.call(command, shell=True)
19
20      with open('menu.txt','r') as f:
21          menu = f.read()
22
23      return render_template('command_injection.html', menu=menu)
24
25  @app.route('/clean')
```

```
26 def clean():
27     subprocess.call('echo Menu: > menu.txt', shell=True)
28
29     with open('menu.txt','r') as f:
30         menu = f.read()
31
32     return render_template('command_injection.html', menu=menu)
33
34 if __name__ == '__main__':
35     app.run(debug=True)
```

Listing A.2: Command injection example, using Flask.

A.3 XSS

```
1  from flask import Flask, request, make_response
2  import random
3  import string
4  app = Flask(__name__)
5
6  @app.route('/XSS_param', methods =['GET'])
7  def XSS1():
8      param = request.args.get('param', 'not set')
9
10     html = open('templates/XSS_param.html').read()
11     resp = make_response(html.replace('{{ param }}', param))
12     return resp
13
14 if __name__ == '__main__':
15     app.run(debug= True)
```

A.4 Path Traversal

```
1  import os
2  from flask import Flask, request, send_file
3
4  app = Flask(__name__)
5
6  @app.route('/')
7  def cat_picture():
8      image_name = request.args.get('image_name')
9      if not image_name:
10         return 404
```

```
11      return send_file(os.path.join(os.getcwd(), image_name))
12
13
14  if __name__ == '__main__':
15      app.run(debug=True)
```

Appendix B

The Abstract Syntax of Python

The following shows the complete abstract syntax of the python programming language. It is taken directly from *Abstract Syntax of Python* [45].

```
1  -- ASDL's six builtin types are identifier, int, string,
       bytes, object, singleton
2
3  module Python
4  {
5      mod = Module(stmt* body)
6          | Interactive(stmt* body)
7          | Expression(expr body)
8
9          -- not really an actual node but useful in Jython's
               typesystem.
10         | Suite(stmt* body)
11
12     stmt = FunctionDef(identifier name, arguments args,
13                        stmt* body, expr* decorator_list, expr
                              ? returns)
14           | AsyncFunctionDef(identifier name, arguments args,
15                              stmt* body, expr* decorator_list
                                    , expr? returns)
16
17           | ClassDef(identifier name,
18              expr* bases,
19              keyword* keywords,
20              stmt* body,
21              expr* decorator_list)
22           | Return(expr? value)
```

```
23
24          | Delete(expr* targets)
25          | Assign(expr* targets, expr value)
26          | AugAssign(expr target, operator op, expr value)
27
28          -- use 'orelse' because else is a keyword in target
                languages
29          | For(expr target, expr iter, stmt* body, stmt*
                orelse)
30          | AsyncFor(expr target, expr iter, stmt* body, stmt
                * orelse)
31          | While(expr test, stmt* body, stmt* orelse)
32          | If(expr test, stmt* body, stmt* orelse)
33          | With(withitem* items, stmt* body)
34          | AsyncWith(withitem* items, stmt* body)
35
36          | Raise(expr? exc, expr? cause)
37          | Try(stmt* body, excepthandler* handlers, stmt*
                orelse, stmt* finalbody)
38          | Assert(expr test, expr? msg)
39
40          | Import(alias* names)
41          | ImportFrom(identifier? module, alias* names, int?
                level)
42
43          | Global(identifier* names)
44          | Nonlocal(identifier* names)
45          | Expr(expr value)
46          | Pass | Break | Continue
47
48          -- XXX Jython will be different
49          -- col_offset is the byte offset in the utf8 string
                the parser uses
50          attributes (int lineno, int col_offset)
51
52          -- BoolOp() can use left & right?
53    expr = BoolOp(boolop op, expr* values)
54         | BinOp(expr left, operator op, expr right)
55         | UnaryOp(unaryop op, expr operand)
56         | Lambda(arguments args, expr body)
57         | IfExp(expr test, expr body, expr orelse)
```

```
58          | Dict(expr* keys, expr* values)
59          | Set(expr* elts)
60          | ListComp(expr elt, comprehension* generators)
61          | SetComp(expr elt, comprehension* generators)
62          | DictComp(expr key, expr value, comprehension*
                generators)
63          | GeneratorExp(expr elt, comprehension* generators)
64          -- the grammar constrains where yield expressions
                can occur
65          | Await(expr value)
66          | Yield(expr? value)
67          | YieldFrom(expr value)
68          -- need sequences for compare to distinguish between
69          -- x < 4 < 3 and (x < 4) < 3
70          | Compare(expr left, cmpop* ops, expr* comparators)
71          | Call(expr func, expr* args, keyword* keywords)
72          | Num(object n) -- a number as a PyObject.
73          | Str(string s) -- need to specify raw, unicode, etc
                ?
74          | Bytes(bytes s)
75          | NameConstant(singleton value)
76          | Ellipsis
77
78          -- the following expression can appear in assignment
                context
79          | Attribute(expr value, identifier attr,
                expr_context ctx)
80          | Subscript(expr value, slice slice, expr_context
                ctx)
81          | Starred(expr value, expr_context ctx)
82          | Name(identifier id, expr_context ctx)
83          | List(expr* elts, expr_context ctx)
84          | Tuple(expr* elts, expr_context ctx)
85
86          -- col_offset is the byte offset in the utf8 string
                the parser uses
87          attributes (int lineno, int col_offset)
88
89      expr_context = Load | Store | Del | AugLoad | AugStore |
            Param
90
```

```
91      slice = Slice(expr? lower, expr? upper, expr? step)
92            | ExtSlice(slice* dims)
93            | Index(expr value)
94
95      boolop = And | Or
96
97      operator = Add | Sub | Mult | MatMult | Div | Mod | Pow |
            LShift
98                | RShift | BitOr | BitXor | BitAnd |
                      FloorDiv
99
100     unaryop = Invert | Not | UAdd | USub
101
102     cmpop = Eq | NotEq | Lt | LtE | Gt | GtE | Is | IsNot |
           In | NotIn
103
104     comprehension = (expr target, expr iter, expr* ifs)
105
106     excepthandler = ExceptHandler(expr? type, identifier?
           name, stmt* body)
107                   attributes (int lineno, int col_offset)
108
109     arguments = (arg* args, arg? vararg, arg* kwonlyargs,
           expr* kw_defaults,
110                  arg? kwarg, expr* defaults)
111
112     arg = (identifier arg, expr? annotation)
113           attributes (int lineno, int col_offset)
114
115     -- keyword arguments supplied to call (NULL identifier
           for **kwargs)
116     keyword = (identifier? arg, expr value)
117
118     -- import name with optional 'as' alias.
119     alias = (identifier name, identifier? asname)
120
121     withitem = (expr context_expr, expr? optional_vars)
122 }
```

Listing B.1: The abstract syntax of Python

Appendix C

Flask adaptor implementation

The following code listing presents the implementation of the adaptor that adapts Flask projects to be analysed by PyT This is also the default adaptor used by the PyT command line.

```
"""Adaptor for Flask web applications."""
import ast

from framework_adaptor import FrameworkAdaptor
from ast_helper import get_call_names, Arguments
from cfg import build_function_cfg
from module_definitions import project_definitions
from framework_adaptor import TaintedNode

class FlaskAdaptor(FrameworkAdaptor):
    """The flask adaptor class manipulates the CFG to adapt to
       flask applications."""

    def get_last(self, iterator):
        """Get last element of iterator."""
        item = None
        for item in iterator:
            pass
        return item

    def is_flask_route_function(self, ast_node):
        """Check whether function uses a decorator."""
        for decorator in ast_node.decorator_list:
            if isinstance(decorator, ast.Call):
                if self.get_last(get_call_names(decorator.func)
                   ) == 'route':
                    return True
        return False
```

```
27
28      def get_cfg(self, definition):
29          """Build a function cfg and return it."""
30          cfg = build_function_cfg(definition.node, self.
                project_modules, self.local_modules, definition.path
                , definition.module_definitions)
31
32          args = Arguments(definition.node.args)
33
34          if args:
35              definition_lineno = definition.node.lineno
36
37              cfg.nodes[0].outgoing = []
38              cfg.nodes[1].ingoing = []
39
40              for i, argument in enumerate(args, 1):
41                  taint = TaintedNode(argument, argument, None,
                        [], line_number=definition_lineno, path=
                        definition.path)
42                  previous_node = cfg.nodes[0]
43                  previous_node.connect(taint)
44                  cfg.nodes.insert(1, taint)
45
46              last_inserted = cfg.nodes[i]
47              after_last = cfg.nodes[i+1]
48              last_inserted.connect(after_last)
49
50          return cfg
51
52      def get_func_nodes(self):
53          """Get all nodes from a function."""
54          return [definition for definition in
                project_definitions.values() if isinstance(
                definition.node, ast.FunctionDef)]
55
56      def find_flask_route_functions(self, cfg):
57          """Find all flask functions with decorators."""
58          for definition in self.get_func_nodes():
59              if definition.node and self.is_flask_route_function
                    (definition.node):
60                  yield self.get_cfg(definition)
61
62      def run(self):
63          """Executed by the super class, everything that needs
                to be executed goes here."""
64          function_cfgs = list()
65          for cfg in self.cfg_list:
```

```
66              function_cfgs.extend(self.
                    find_flask_route_functions(cfg))
67          self.cfg_list.extend(function_cfgs)
```

Listing C.1: Implementation of the Flask adaptor

Appendix D

Implementation of the liveness analysis

```
"""Module implements liveness analysis."""
from cfg import AssignmentNode
from copy import deepcopy
from ast import NodeVisitor, Compare, Call

from analysis_base import AnalysisBase

class LivenessAnalysis(AnalysisBase):
    """Implement liveness analysis rules."""

    def __init__(self, cfg):
        """Initialize using parent with the given cfg."""
        super(LivenessAnalysis, self).__init__(cfg, VarsVisitor
            )

    def join(self, cfg_node):
        """Join outgoing old constraints
        and return them as a set."""
        JOIN = set()
        for outgoing in cfg_node.outgoing:
            if outgoing.old_constraint:
                JOIN |= outgoing.old_constraint
        return JOIN

       def fixpointmethod(self, cfg_node):
        """Setting the constraints of the given cfg node
        obeying the liveness analysis rules."""

        # if for Condition and call case: Join(v) u vars(E).
```

```
29          if cfg_node.ast_type == Compare.__name__ or
30             cfg_node.ast_type == Call.__name__:
31              JOIN = self.join(cfg_node)
32              # set union
33              JOIN.update(self.annotated_cfg_nodes[cfg_node])
34              cfg_node.new_constraint = JOIN
35
36          # if for Assignment case: Join(v) \ {id} u vars(E).
37          elif isinstance(cfg_node, AssignmentNode):
38              JOIN = self.join(cfg_node)
39              # set difference
40              JOIN.discard(cfg_node.ast_node.targets[0].id)
41              # set union
42              JOIN.update(self.annotated_cfg_nodes[cfg_node])
43              cfg_node.new_constraint = JOIN
44
45          # if for entry and exit cases: {}.
46          elif cfg_node.ast_type == "ENTRY" or
47               cfg_node.ast_type == "EXIT":
48              pass
49          # else for other cases.
50          else:
51          cfg_node.new_constraint = self.join(cfg_node)
52
53
54  class VarsVisitor(NodeVisitor):
55      """Class that finds all variables needed
56      for the liveness analysis."""
57
58      def __init__(self):
59          """Initialise list of results."""
60          self.result = list()
61
62      def visit_Name(self, node):
63          self.result.append(node.id)
64
65      #  Condition and call rule
66      def visit_Call(self, node):
67          for arg in node.args:
68              self.visit(arg)
69          for keyword in node.keywords:
70              self.visit(keyword)
71
72      def visit_keyword(self, node):
73          self.visit(node.value)
74
75      def visit_Compare(self, node):
```

```
76            self.generic_visit(node)
77
78        #  Assignment rule
79        def visit_Assign(self, node):
80            self.visit(node.value)
```

Listing D.1: Implementation of liveness analysis

Appendix E

Trigger word definition for flask

The following file is used as the default trigger definition file in PyT. It is tailored for flask projects.

```
1  sources:
2  get(
3  form[
4  Markup(
5
6  sinks:
7  replace( -> escape
8  send_file( -> '..', '..' in
9  execute(
10 filter(
11 subprocess.call(
```

Listing E.1: Trigger word definition for flask projects

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