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Vulnerability Test Suite Generator (VTSG) Version 3

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Vulnerability Test Suite Generator (VTSG) Version 3

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Abstract

The Vulnerability Test Suite Generator (VTSG) can create vast numbers of synthetic programs with and without specific flaws or vulnerabilities. It was designed by the Software Assurance Metrics and Tool Evaluation (SAMATE) team and originally implemented by students from TELECOM Nancy. The latest version is structured to be able to generate vulnerable and nonvulnerable synthetic programs expressing specific flaws in *any* programming language. It has libraries to generate PHP, C#, and Python programs. This document may help if you are trying to generate test cases written in PHP, C#, or Python, adding new complexities or types of vulnerability, or modifying VTSG Version 3 to generate test cases in other programming languages.

Key words

Software assurance; static analyzer; test case generator; software vulnerabilities.

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We would appreciate acknowledgment if this document is used.

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1. Introduction

The Vulnerability Test Suite Generator (VTSG) generates collections of vulnerable and non-vulnerable synthetic programs expressing specific flaws. The programs can be used as test cases to evaluate static analyzers. Each test case targets one flaw. There are two types of test cases: cases with flawed code (unsafe), leading to a vulnerability, and cases that have similar behavior, but have the flaw corrected, that is, no vulnerability (safe). Exactly corresponding vulnerable and non-vulnerable cases could, in theory, be generated in pairs. However, since each test case is generated separately, there is no exact correspondence between cases.

NIST's Software Assurance Reference Dataset (SARD) has suites of paired test cases in the Juliet test suites for C/C++ and Java, which are available as SARD test suites 108 and 109. These and many other test suites are available at <https://samate.nist.gov/SARD/testsuite.php>.

The generator is written in Python 3. The VTSG git repository is at <https://github.com/usnistgov/VTSG>. The list of files and the README.md file are given in App. D.

1.1 History

VTSG version 1 only generated C# programs. VTSG version 2 generated PHP programs [1] in addition. Version 2 is more customizable to generate other programming languages. VTSG version 3 (V3) systematically maintains indentation, so also generates Python programs. VTSG V3 produces manifest files in the Static Analysis Results Interchange Format (SARIF) Version 2.1.0 [2] format.

Readers can download the PHP and C# test cases generated by earlier versions as SARD test suites 103 and 105 from <https://samate.nist.gov/SARD/testsuite.php>.

1.2 Install Supporting Packages

The following instructions are provided for users who may not have these packages already installed on their Linux machines. Users who already have these packages may skip this section.

To download files from Github, first install the *Git* package. Here is the command to install it:

```
sudo apt-get install git
```

VTSG is written in Python 3, so Python 3 must be installed, too. Here is the command to install it:

```
sudo apt-get install python3
```

To download Python source code packages, install the *pip* Python package manager. Here is the command to install it:

```
sudo apt-get install python-pip
```

One may also have to install the *pip Python 3* package manager. Here is the command to install it:

```
sudo apt-get install python3-pip
```

Another way to install *pip* is:

```
sudo python3 -m pip install --upgrade pip
```

To validate C# test cases, install *mono* and *mcs* to run them. The Mono project created *mono* as an open source platform, which implements the .NET Framework. Class libraries and C# compilation are enabled by *mcs* (<http://github.com/mono/mono>).

Here is the command to install it:

```
sudo apt-get install mono-complete
```

Here is the command to install it:

```
sudo apt-get install mcs
```

1.3 Install VTSG

To copy the generic VTSG from GitHub to a local Linux machine, change to a directory under which you want to install VTSG.

Looking at the GitHub website, one will see a green box labeled “Code”. See Fig. 1. Click on it, then click on the “copy” icon to copy the web URL.

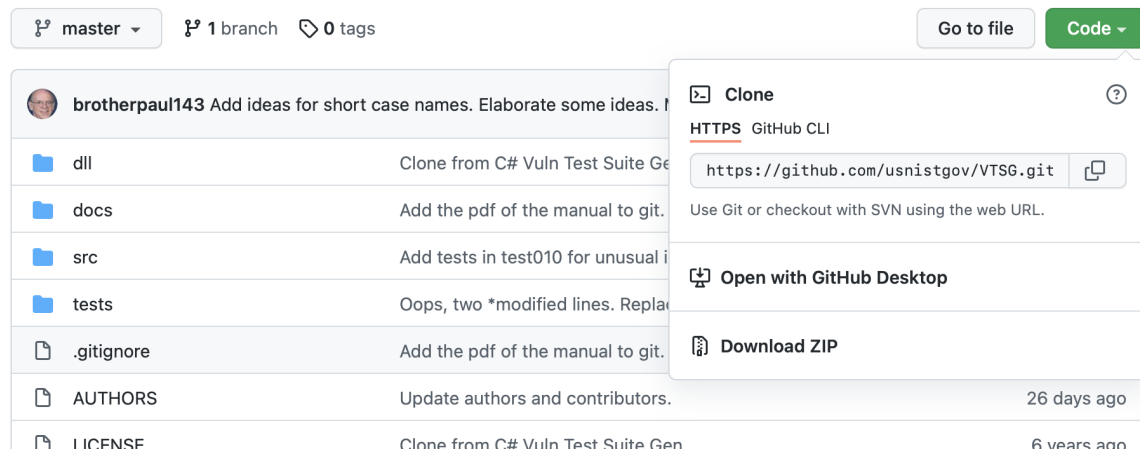


Fig. 1. usnistgov/VTSG: button to clone repository.

Here is the command to copy the source code and other material to the local directory:


```
git clone https://github.com/usnistgov/VTSG.git
```

If one types the `ls` command, one will see that the **VTSG** directory was created. Go into that directory, using this command:

```
cd VTSG
```

To install the dependencies, use this command:

```
pip3 install --user -r requirements.txt
```

1.4 Users

There are two groups who will typically use VTSG. The first group comprises people requiring test cases written in PHP, C#, or Python to evaluate a static analyzer. These users must know how to invoke VTSG with the command line interface and retrieve the appropriate sample from the generated and categorized folders.

The second targeted audience of the VTSG is comprised of people wishing to generate test cases using a programming language other than the languages currently supported. The second group of users must create new templates for the program using the XML tags, execute VTSG with the command line interface, and retrieve the samples from the generated and categorized file folders.

1.5 Vulnerabilities Currently Encoded in VTSG Files

Vulnerabilities are encoded in the language files, see Sec. 4. Some of the OWASP Top 10 [3] and Common Weakness Enumerations (CWEs) [4] are encoded. See App. A and B for details.

2. Command Line Interface

For users who wish to generate PHP, C#, or Python test suites, a command line interface can generate all test cases or a specific group of test cases based on several options. For example, the user can generate vulnerable or non-vulnerable test cases based on selected OWASP categories or weakness types. The user must specify the programming language. The invocation command looks like this:

```
$ python3 vtsg.py -l {php,cs,py} <options>
```

Where `<options>` can be selected from Table 1.

-h --help	Show help and quit
--version	Show version number and quit
-l LANGUAGE --language=LANGUAGE	Language of generated cases. Currently one of php, for PHP cases, cs, for C# cases, or py, for Python cases. See Sec. 3.2.
-f FLAW_GROUP[,FLAW_GROUP]* --flaw-group=FLAW_GROUP[,FLAW_GROUP]*	Only generate cases with vulnerabilities from the specified group(s). See Sec. 4.6
-c Flaw[,Flaw]* --cwe=Flaw[,Flaw]*	Only generate cases with vulnerabilities from the specified flaw(s). See Sec. 4.6
-s --safe	Only generate non-vulnerable cases
-u --unsafe	Only generate vulnerable cases
-r DEPTH --depth=DEPTH	Maximum nested depth of complexities (Default: 1) See Sec. 3.3
-g NUMBER --number-generated=NUMBER	Maximum number of sink, filter, input (and exec query) combinations to generate. (Default: -1, meaning all) See below for explanation.
-d --debug	for programmer use

Table 1. Options for Command Line Invocation

2.1 Explanation of Options

The default is to generate both the unsafe (buggy or vulnerable) test cases and the safe (not buggy) test cases. You can select either only safe (-s) or only unsafe (-u) cases. The options are mutually exclusive.

The -g (number-generated) option has limited utility. When the specified number of sink, filter, input (and exec query, if needed) combinations are generated, VTSG terminates. The default, -1, means generate all combinations.

Each combination of sink, filter, input, and exec query is elaborated with DEPTH nested complexities. Suppose there are 5 complexities and VTSG is invoked with -r 2. Each combination will yield 1 (no complexities) + 5 (each complexity, not nested) + 25 (each complexities nested within every complexity) = 31 test cases. Hence VTSG will generate *far* more test cases than the number given with the -g option.

2.2 Example Invocations

Show the help message:

```
$ python3 vtsg.py --help
```

Generate all PHP test cases:

```
$ python3 vtsg.py -l php
```

This takes about 25 minutes. (Generating all the C# cases takes about four minutes.)

Generate a C# (-l cs) test suite made of vulnerable (unsafe) test cases (-u) with SQL injection vulnerabilities (--cwe=CWE_89) and up to 3 nested levels of complexity (-r 3).

```
$ python3 vtsg.py -l cs -r 3 --cwe=CWE_89 -u
```

3. Overview of VTSG

Please note that this document describes two different program structures: the structure of VTSG itself and the structure of test cases that it generates.

3.1 Overview of Test Case Generation

VTSG V3 generates test cases from information in Template, Input, Filter, Sink, Complexity and ExecQuery files (see Fig. 2):

- Template is the overall structure of each program.
- Input is the source of untrusted data in the program, e.g., command line, variable, files, or form methods.
- Filtering filters the input with functions or methods such as sanitization functions, casting, or deprecated functions.
- Sink is where a sensitive operation, such as a database query, is executed with potentially untrusted input and where the vulnerability is triggered.
- ExecQuery is an additional piece of code that is mandatory to trigger the vulnerability.
- Complexity are additional data flow or control flow complications that are worked into the structure of the program to exercise tools' abilities.

The content of these files is detailed in Sec. 4. Details of the generation process are explained in Sec. 3.3.

When invoked to generate test cases, VTSG creates a directory with all the results. The directory is named for the date and time created, for example, TestSuite_03-08-2022_16h46m35. The language directory, PHP, Csharp, or Python is created in this directory. This language name comes from the name in the file_template.xml file. See Sec. 4.2.

Under the language directory, VTSG creates one directory for each flaw group, for instance, OWASP_a1 or OWASP_a4. These come from the flaw_group in the sink.xml file;

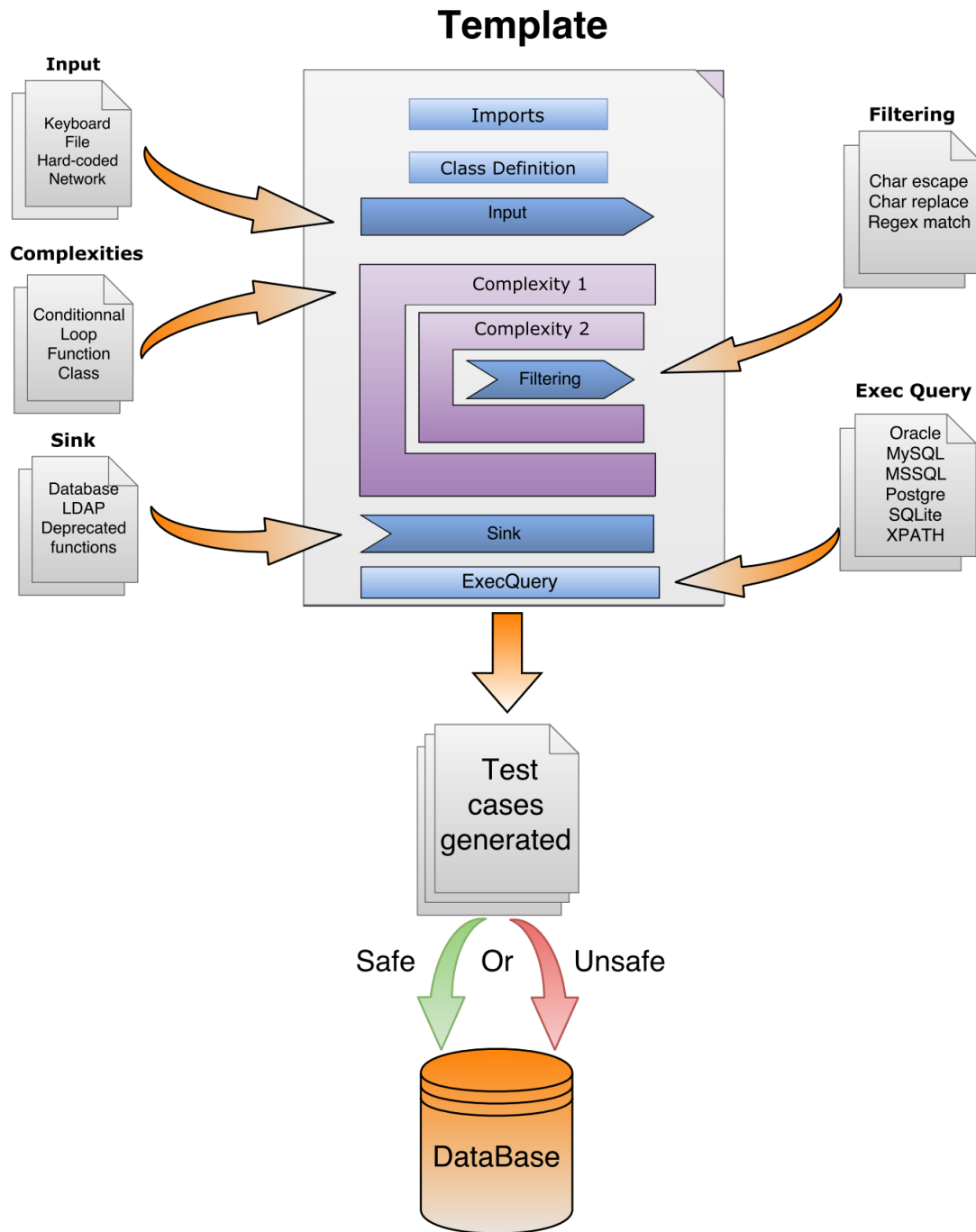


Fig. 2. Overview of VTSG test case generation process. The Template specifies how pieces are assembled. The Input, Filter, Complexities, Sink, and ExecQuery modules provide alternative code. An example of a generated test case is in Figs. 10 and 11.

see Sec. 4.6. Under each flaw group directory is a subdirectory for each specific flaw type, for instance, `CWE_78` or `CWE_89`. These come from the `flaw_type` entries, which are also in the `sink.xml` file. VTSG also creates a manifest file of all the test cases generated for each flaw group, named `manifest.xml`.

Under the flaw type directory are directories for safe or unsafe (vulnerable) test cases, depending on which are generated.

3.2 VTSG Directory Structure

All the information files are in a `templates` subdirectory. Under this is one subdirectory for each language. VTSG chooses the directory based on the language indicated in the `-l` command line option. Each language subdirectory has six files for that language. The files are `file_template.xml`, `input.xml`, `complexities.xml`, `filtering.xml`, `sink.xml`, and `exec_queries.xml`. The files are described in Sec. 4. To add another language, simply create a subdirectory for that language with the six description files.

The `templates` directory also has `file_rights.txt`, which is copied into each generated test case to declare license rights and authorship, see Sec. 4.2, and a `dtd` subdirectory, which has document type definitions (DTDs) for all of the XML files.

3.3 Details of Test Case Generation

Each test case is constructed based on the file template, as shown in Fig. 2. Test cases are programs in a specific program language. Each test case is generated by assembling the modules according to the Template. The template may direct construction of a simple test case with just an Input and a Sink. The Filtering code may be embedded in data and control flow Complexity code.

VTSG generates test cases with two broad steps. First, VTSG selects Input, Filter, Complexities, Sink, and ExecQuery modules that are compatible with each other and consistent with any flaw group or type constraints the user gives on the command line. Second, VTSG composes test case source code from the selected modules, synthesizing variable and functions names, and writes the file(s).

The code structure is roughly

```
for each specified sink
  for each filter
    for each input
      for each exec query
        for up to DEPTH combinations of each complexity
          compose a test case with these modules
```

The code is more complicated because only compatible modules are selected. In addition, some sinks do not need any input or filtering at all, see Sec. 4.6. The code is structured as a series of function calls to allow types of modules to be skipped. Here is a slightly more detailed overview of those steps, which are in `generator.py`:

```

for each sink:
    if this sink is the type specified:
        use this sink
        if input is needed:
            select_filtering()
        else:
            select_exec_queries()

def select_filtering():
    for each filter:
        if filter is compatible with sink:
            use this filter
            select_input()

def select_input()
    for each input:
        if input is compatible with filter and sink:
            use this input
            select_exec_queries()

def select_exec_queries()
    if sink needs exec_query:
        for each exec_query:
            if exec_query is compatible with sink:
                use this exec_query
                recursion_or_compose()
    else:
        recursion_or_compose()

def recursion_or_compose():
    if input_type is not none:
        recursive_select_complexity()
    else:
        compose()

... and so forth

```

The *vtsg.py* script creates a new object of the *Generator* class. The program iterates through all sink modules, selecting those specified by the user, see Sec. 2, or all of them if the user does not specify. It subsequently selects a compatible filter. It then goes through all inputs. The `<input_type>` and `<output_type>` must be consistent with the “Filtering” and “Sink” XML tags. Then an exec query and complexities are selected that are compatible with the currently selected sink module.

When VTSG has selected a set of modules, it begins composing their code to generate the source code for a test case. The process of composing modules to generate source code is based on XML metadata tags. After the imports and class definition declaration for the specific program language, the “Input” metadata <code> portion is added to the test case. The “Filtering” metadata <code> portion, plus its <flaw type> and safety indicator, are added to the test case. Next, the “Sink” metadata <code> portion is added to the test case. Finally, the “ExecQuery” type is noted and the <code> portion of the “ExecQuery” is added to the test case. The test case is written to a file. The location of the file is described in Sec. 3.1. Section 5 describes how VTSG names the file.

VTSG generates many different test cases, both with and without flaws, with various control flow complexities. After VTSG finishes generating each vulnerability category, it displays how many safe (non-vulnerable) and unsafe (vulnerable) test cases it produced. VTSG generates hundreds of test cases in minutes.

VTSG is built to generate test cases with all consistent combinations of modules for the flaw groups and types specified in the invocation. If VTSG is invoked with flaw groups (-f) or types (-c), only sinks satisfying those specified are used. If no flaw groups are specified, all flaw groups are used. If no flaw types are specified, all types are used.

The depth command line option, -r or --depth, specifies the most nested flow control complexities produced. VTSG generates test cases with all complexities up to the depth indicated. For example, the default depth, 1, leads VTSG to generate all test cases with no flow complexities and all test cases with one complexity. The option -r 2 leads VTSG to generate all cases with no complexities, all cases with one complexity, and all cases with two nested complexities. See Sec. 3.4 for an example of three nested control flow complexities.

3.4 Code Complexities

In theory, a static analysis tool only needs to process a few lines of code that embody the vulnerability. In practice, a tool must analyze most of the program, noting its control and data flows, to accurately track data and determine the conditions when the code with weaknesses may be executed. Code complexities are constructs that may confuse static analysis tools. Each code complexity element can have many different attributes associated with it. They are combined and nested to create more realistic source code. For example, the value of an expression may come from a constant, a single variable, some arithmetic combination, or the return value of a function call. Flow of control may be influenced by loops, conditionals, and functions calls. Also, there could be many layers or depths of such nesting structures.

The complexities currently defined for PHP and C# are listed in the appendixes for their languages.

Here is an example code complexity from cwe_89__I_shell_commands__F_no_filtering__S_select_from-concatenation_simple_quote__EQ_mysql__3-2.5-9-21a.cs:

```

if((Math.Pow(4, 2)<=42)){
    switch(6){
        case(6):
            Class_489618 var_489618 = new Class_489618(tainted_5);
            tainted_6 = var_489618.get_var_489618();
            tainted_7 = tainted_6;
            break;
        default:
            break;
    }
}
}
}

```

The above has complexity depth 3, note __3 near the end of the file name. They correspond to:

Level 1 is the conditional id = 2 with condition 5

Level 2 is the switch statement id = 9

Level 3 is the call of a method from a Class defined in a different file, id = 21.

4. Template, Input, Filter, Sink, Exec_Query, and Complexity Files

These XML files are required for each language. There are a few XML-specific caveats that must be paid attention to when creating these files. Table 2 lists the symbols that may cause errors during the process and the XML equivalent replacement necessary to complete the task without error.

Character	Replacement
<	<
>	>
"	"
'	'
&	&

Table 2. Replacement sequences for characters that are treated in a special way in XML files.

VTSG uses Jinja to compose code. In addition to the above, Jinja recognizes double-curly-brackets ({{ and }}) as introducing Jinja-specific variables and controls. Do not use pairs of curly brackets in your files, except for VTSG-related variables.

Characteristics of modules and their information are stored in XML files. This section of the document describes the structure of each type of module and the meaning of each

element and its tags.

Most of the file types have an example followed by an explanation of what it does and what it generates.

Each language directory has one file of each name. That is, one `file_template.xml` file, one `input.xml` file, one `filtering.xml` file, one `complexities.xml` file, one `sink.xml` file, and one `exec_queries.xml` file.

All the files, except `file_template.xml`, may have many modules, that is alternate chunks of code, in them. For example, `input.xml`, Sec. 4.4, typically has many input modules. Each module in `input.xml` provides a method to get input from a different source, such as command line options or hard-coded values.

4.1 Using INDENT ... ENDINDENT to Maintain Indentation

INDENT ... ENDINDENT sections may appear in any of the above files. However, they most often occur in `file_template.xml` and `complexities.xml` files.

VTSG using Jinja does a haphazard job of producing proper indentation. Indentation is not critical for many languages. It is critical for Python, however. To maintain correct indentation, use INDENT and ENDINDENT lines in code chunks to indicate that any code between those lines should be indented consistently. For example,

```
def main():
INDENT
    {{local_var}}
    {{input_content}}
    {{filtering_content}}
    {{sink_content}}
    {{exec_queries_content}}
ENDINDENT
```

All code produced from the statements between the INDENT/ENDINDENT lines will be consistently indented with the string defined in `<indent> </indent>`, which appears in `file_template.xml`, see Sec. 4.2. That string is typically four spaces.

INDENT sections may be nested. For example, here is a sink module with code that needs additional indentation.

```
print(f'file "{ {{in_var_name}} }" ', end='')
{{flaw}}
if os.path.exists({{in_var_name}}):
INDENT
    print('exists')
ENDINDENT
else:
INDENT
    print('does not exist')
```

ENDINDENT

If the INDENT lines were not included, VTSG produces the following code.

```
def main():
    tainted_0 = None
    tainted_1 = None

    tainted_0 = input()
    tainted_1 = tainted_0

    # No filtering (sanitization)
    tainted_1 = tainted_0

    print(f'file "{ tainted_1 }" ', end='')
    #flaw
    if os.path.exists(tainted_1):
        print('exists')
else:
    print('does not exist')
```

Notice that the indentation is not consistent. This is not valid Python code. With INDENT lines, VTSG produces the following, which is valid Python.

```
def main():
    tainted_0 = None
    tainted_1 = None

    tainted_0 = input()
    tainted_1 = tainted_0

    # No filtering (sanitization)
    tainted_1 = tainted_0

    print(f'file "{ tainted_1 }" ', end='')
    #flaw
    if os.path.exists(tainted_1):
        print('exists')
    else:
        print('does not exist')
```

Here are details of using INDENT and ENDINDENT.

VTSG processes code within INDENT sections line by line. No semantic parsing or analysis is done.

A section to be fixed is indicated by a line beginning with INDENT, possibly with leading whitespace. The end of the section is indicated by a line beginning with ENDINDENT, again possibly with leading whitespace. Any text after INDENT or ENDINDENT to the end of the line is ignored.

Indent sections may be nested.

INDENT and ENDINDENT lines are removed. For lines within an INDENT ... ENDINDENT section,

- first, any leading whitespace is removed, and
- second, indent is added for each nested INDENT ... ENDINDENT section this is in if the line is not empty.

Here is a convoluted example to illustrate the fine points. Suppose this is the code generated by the modules.

```
        if Condition:
INDENT            text after INDENT is ignored
                    line 1
                        while not True:
INDENT
                    line 3 - INDENT not at the beginning is ignored
ENDINDENT

                    line above is empty
ENDINDENT
line 5
```

If the indent string is specified as <indent>..,</indent>, the following is the result. (Note: typically, the indent is four spaces. The preceding string with periods and a comma is only for example clarity.)

```
        if Condition:
..,line 1
..,while not True:
..,..,line 3 - INDENT not at the beginning is ignored

..,line above is empty
    line 5
```

Note: because *all* leading whitespace is removed from lines in indent sections, using INDENT ... ENDINDENT anywhere means that every indentation must be indicated with INDENT ... ENDINDENT lines.

4.2 File Template

```
<template type="" name="">
  <file_extension></file_extension>
  <comment>
    <open></open>
    <close></close>
    <inline></inline>
  </comment>
  <syntax>
    <statement_terminator></statement_terminator>
    <indent></indent>
  </syntax>
  <namespace></namespace>
  <variables prefix="" import_code="using {{import_file}};">
    <variable type="" code="" init=""/>
  </variables>
  <imports>
    <import></import>
  </imports>
  <code></code>
</template>
```

- name: Programming language name, e.g., PHP, Csharp, or Python. This appears in the manifest. It is also the name of the subdirectory under the TestSuite directory where all the generated test cases are placed.
- file_extension: Extension of the generated files.
- comment: Strings indicating comments.
 - open: string to begin a comment, which may span many lines
 - close: string to end a comment, which may span many lines
 - inline: string to begin a one-line comment
- syntax: Other language-specific syntax.
 - statement_terminator: string to show the end of a statement. This is semicolon <statement_terminator>;</statement_terminator> in PHP, C, Java, and C#. Python does not have a terminator, so this is the empty string: <statement_terminator></statement_terminator>.
 - indent: string used to indent code, see Sec. 4.1. This is typically four spaces, but can be any string.

- namespace: Namespace name, if applicable
- variables: Information about variable names and types and how to include libraries.
 - prefix: Any prefix required for variable names. \$ for PHP. Leave it empty if not required.
 - import_code: Code to include a library. The code should have the placeholder `{{import_file}}`. For example, `#include <{{import_name}}>`.
 - variable: Defines each variable type and how it will be used.
 - * type: Names the type. This string does not appear in the test case code. It tells VTSG the type of variable that is being used. The `input_type` and `output_type` in Input, Filter, and Sink modules use this string.
 - * code: A piece of code declaring the type of the variable. For some languages, such as PHP and Python, this field can be blank. This value takes the variable type when being declared (for example, `string myString;`). In this case, “string” is the value put in this attribute.
 - * init: Value assigned when this type of variable is initialized. VTSG uses this value when declaring all variables.
- code: the template code. It should contain the following placeholders:
 - comments: This is replaced by the comments from Input, Filtering, Sink, and ExecQuery modules. This is intended to describe the variants, options, and use of this test case.
 - license: This is replaced by the contents of the `file_rights.txt` file. This is intended to hold authors’ names, usage and copyrights, contact information, etc.
 - `stdlib_imports`: This tag is a placeholder for *all* imports for the generated program
 - `namespace_name`: Used if the language requires it
 - `main_name`: Name of the main class
 - `local_var`: Location for local variables (required)
 - `input_content`: Location for the Input (required)
 - `filtering_content`: Location for complexities, if any, along with the Filter
 - `sink_content`: Location for the Sink
 - `exec_queries_content`: Location for the ExecQuery
 - `static_methods`: Location for the static functions.

4.3 Attributes Shared By Modules

Many kinds of modules use the same attributes. Instead of repeating explanation of these attributes, they are here.

4.3.1 Module Description in Path and Dir Tags

Within the `<path>` keywords, modules may have one or more `<dir>` tags. These tags provide the descriptions of the module that is used in the file name, see Sec. 5. For example, when the key word in a selected input module is “none”, the file name will contain `..._I_none_...`, where “I” indicates the input module selected.

If a module has more than one `<dir>` tag, the strings are joined with dashes. For example, if a sink have

```
<path>
  <dir>select_from</dir>
  <dir>concatenation_simple_quote</dir>
</path>
```

then cases using that module will have file names containing `_S_select_from-concatenation_simple_quote_`.

Note: we cannot think of any reason why it is better to give multiple description strings instead of just one string. But the functionality is provided in VTSG, and some modules use it.

4.3.2 Marking Modules as Safe and Unsafe

Using some modules in a program for certain flaws may make them safe or may make them unsafe. For instance, prepared SQL statements are always safe from SQL injection vulnerabilities. In contrast using a broken cryptographic algorithm is always unsafe, regardless of how much any user input is filtered. Similarly certain hard-coded inputs may always make a program safe from certain flaws, and some filters may make a program safe from certain flaws for any user input.

Input, filter, and sink modules can be marked as always safe or always unsafe using `safe="1"` or `unsafe="1"`. Modules may be always safe or always unsafe (or neither) for some types of flaws and have different safety attributes for other flaw types.

Exec query modules may be marked as always safe. (No exec query module can make the program unsafe.)

A generated program is not safe if any of the selected input, filter, or sink modules are always unsafe, that is `unsafe="1"`. A program is safe if the selected input, filter, sink, or exec query is always safe, `safe="1"`, and none are unsafe. The filter module must be executed to be considered. In other words, if a complexity never executes the filter, then the filter’s safe or unsafe marking is ignored. Table 3 expresses this as a table.

	Any module has safe="1"	No module is always safe
Any module has unsafe="1"	not safe	not safe
No module is always unsafe	safe	not safe

Table 3. Decision table for whether a selection of modules is considered safe or unsafe.

4.4 Input Modules

The `input.xml` file has one or more “sample” input modules. Each module provides one way for the generated program to get input.

```
<sample>
  <path>
    <dir></dir>
  </path>
  <comment></comment>
  <flaws>
    <flaw flaw_type="" [safe=""] [unsafe=""]/>
  </flaws>
  <imports>
    <import></import>
  </imports>
  <code></code>
  <input_type></input_type>
  <output_type></output_type>
</sample>
```

- `path`: used as the description of the input module in the file name. See Sec. 4.3.1 for details.
- `flaw`: vulnerability categories where the sample can be used, that is, the flaws that the input is compatible with. Also whether it is always safe or always unsafe for that vulnerability type. See Sec. 4.3.2 for more details. If this input is generic and compatible with all types of vulnerabilities, put “default” as the `flaw_type`.
- `input_type`: this string is placed in the manifest. It has no other function in VTSG.
- `output_type`: the type of output. The variable generated with the placeholder `{{out_var_name}}` in the code will be that type.

```

<sample>
  <path>
    <dir>args</dir>
  </path>
  <comment>Command line args</comment>
  <flaws>
    <flaw flaw_type="default" safe="0" unsafe="0"/>
  </flaws>
  <imports>
  </imports>
  <code>
    {{out_var_name}} = args[1];
  </code>
  <input_type>input : Command line args</input_type>
  <output_type>string</output_type>
</sample>

```

Fig. 3. Example Input module. Instantiated at line 14 of Fig. 10.

- **code:** The source code of an input. It should contain the placeholder `{{out_var_name}}`. That placeholder will be replaced by the variable name used in the Filtering and Sink. Do not declare this variable.

The case generated from the example Input in Fig. 3 takes an argument from the command line as Input. The input string can be either safe or unsafe, depending on user input.

4.5 Filter Modules

All filter modules are in the `filtering.xml` file.

```

<sample>
  <path>
    <dir></dir>
  </path>
  <comment></comment>
  <flaws>
    <flaw flaw_type="" [safe=""] [unsafe=""]/>
  </flaws>
  <imports></imports>

```



```

<code></code>
<input_type></input_type>
<output_type></output_type>
</sample>

```

- **path**: the description of the filter module in the file name. See Sec. 4.3.1 for details.
- **input_type**: the input type of the filter. The variable generated with the placeholder `{{in_var_name}}` will be that type. Declarations of `variable` in the File Template give available types, see Sec. 4.2.
- **output_type**: the output type of the filter. The variable generated with the placeholder `{{out_var_name}}` will be that type.
Tip: To generate a test without Filtering, assign `in_var_name` to `out_var_name` and make the `input_type` and `output_type` `nofilter`. This passes the variable from the Input directly to the Sink.
- **flaw**: vulnerability categories where the filter can be used, that is, the flaws that the filter is compatible with. Also whether it is always safe or always unsafe for that vulnerability type. See Sec. 4.3.2 for more details. If this filter is generic and compatible with all types of vulnerabilities, put “default” as the `flaw_type`.
- **code**: The source code of an filter. It should contain the placeholders `{{in_var_name}}` and `{{out_var_name}}`. Those placeholders will be replaced by the variable names used in the Input and Sink. Do not declare these variables.

The example Filter file in Fig. 4 makes sure the Input contains only a number. The flag `safe` is 1, because you cannot cause an SQL Injection (CWE 89) with only numbers.

4.6 Sink Modules

All sink modules are in the language’s `sink.xml` file.

```

<sample>
  <path>
    <dir></dir>
  </path>
  <flaw_type flaw_group=""></flaw_type>
  <safety safe="" unsafe=""/>
  <comment></comment>
  <imports>
    <import></import>
  </imports>

```

```

<sample>
  <path>
    <dir>func_preg_match</dir>
    <dir>only_numbers</dir>
  </path>
  <comment>filtering : check if there is only numbers</comment>
  <flaws>
    <flaw flaw_type="CWE_89" safe="1" unsafe="0"/>
    <flaw flaw_type="CWE_78" safe="0" unsafe="0"/>
    <flaw flaw_type="CWE_91" safe="0" unsafe="0"/>
    <flaw flaw_type="CWE_90" safe="0" unsafe="0"/>
  </flaws>
  <imports>
    <import>System.Text.RegularExpressions</import>
  </imports>
  <code>
    string pattern = @"^[0-9]*$/";
    Regex r = new Regex(pattern);
    Match m = r.Match({{in_var_name}});
    if(!m.Success){
      {{out_var_name}} = "";
    }else{
      {{out_var_name}} = {{in_var_name}};
    }
  </code>
  <input_type>string</input_type>
  <output_type>string</output_type>
</sample>

```

Fig. 4. Example Filter module. Instantiated in lines 19–27 of Fig. 11.

```

<code></code>
<input_type></input_type>
<exec_type></exec_type>
</sample>

```

- **path:** the description of the sink module in the file name. See Sec. 4.3.1 for details.
- **flaw_type:** the `flaw_group` is a general category of vulnerability. Generated test cases are placed under the flaw group subdirectory, then in the flaw type subdirectory under that. The user can limit cases generated to certain flaw groups with the `-f` command line option or certain flaw types with the `-c` option.
- **input_type:** the input type of the sink. The variable generated with the placeholder `{{in_var_name}}` will be that type. If the sink does not require an input, this type should be `none`. The code should not contain the placeholder `{{in_var_name}}`. Declarations of variable in the File Template give available types, see Sec. 4.2.
- **exec_type:** link a sink to the exec queries. It must have the type of an `ExecQuery`. If it does not require an `ExecQuery`, `exec_type` should be `none`.
- **safety:** whether the sink is always safe or always unsafe. For instance, a deprecated function may be marked (always) unsafe. See Sec. 4.3.2 for more details.
- **code:** The source code of a sink. It should contain the placeholder `{{in_var_name}}`. The placeholder will be replaced by the variable name used in the Filter. Do not declare this variable.

The placeholder `{{flaw}}` indicates that the next line is the location of the flaw. In other words, if this case is unsafe, the manifest reports a flaw at the number of the line following this. In generated unsafe cases, `{{flaw}}` is replaced with the one-line comment string, see Sec. 4.2, and “flaw”. It does not appear in generated safe cases.

The Sink example in Fig. 5 concatenates the filtered string with an SQL query. This block of code can only be used for SQL Injection. Whether or not it is vulnerable depends on the input string.

4.7 Exec_Query Modules

All query execution modules are in the language’s `exec_query.xml` file.

```

<exec_query type="" safe="">
  <path>
    <dir></dir>
  </path>

```

```

<sample>
  <path>
    <dir>select_from</dir>
    <dir>concatenation_simple_quote</dir>
  </path>
  <flaw_type flaw_group="A1">CWE_89</flaw_type>
  <comment>construction : concatenation with simple quote</comment>
  <imports></imports>
  <code>
    {{flaw}}
    string query = "SELECT * FROM '" + {{in_var_name}} + "'";
  </code>
  <safety safe="0" unsafe="0"/>
  <input_type>string</input_type>
  <exec_type>SQL</exec_type>
</sample>

```

Fig. 5. Example Sink module. Instantiated at line 23 of Fig. 10.

```

<comment></comment>
<imports>
  <import></import>
</imports>
<code></code>
</exec_query>

```

- path: the description of the exec query module in the file name. See Sec. 4.3.1 for details.
- type: the type of the ExecQuery. This is used in the exec_type tag of the Sink to link them together during generation process. The type should only contain letters, numerals, and underscore (“_”).
Languages currently available for VTSG V3 support many database management systems, including ORACLE, MySQL, MSSQL, PostgreSQL, SQLite, and XPATH. The syntax of each ExecQuery must be compatible with its associated database system language.
- safe: whether the ExecQuery always makes the case safe. See Sec. 4.3.2 for more details.
- code: The source code of a query. It does not contain placeholders. It should be

linked to the corresponding variable from the Sink. The linking is done through the "exec_type" attributes within the XML files.

```
<exec_query type="SQL" safe="0">
  <path>
    <dir>sql_server</dir>
  </path>
  <comment></comment>
  <imports>
    <import>System.Data.SqlClient</import>
  </imports>
  <code>
    string connectionString = @"server=localhost;uid=sql_user;password=sql_password;database=dbname";
    SqlConnection dbConnection = null;
    try {
      dbConnection = new SqlConnection(connectionString);
      dbConnection.Open();
      SqlCommand cmd = dbConnection.CreateCommand();
      cmd.CommandText = query;
      SqlDataReader reader = cmd.ExecuteReader();
      while (reader.Read()){
        Console.WriteLine(reader.ToString());
      }
      dbConnection.Close();
    } catch (Exception e) {
      Console.WriteLine(e.ToString());
    }
  </code>
</exec_query>
```

Fig. 6. Example Exec_Query module. Instantiated in lines 25–39 of Fig. 10.

The block of code in the Exec_Query example, Fig. 6, executes the SQL query, used for database management systems, including MySQL, Oracle, PostgreSQL, and SQLite. This example is vulnerable. If a non-vulnerable execution of an SQL query is required, use an SQL prepared statement.

4.8 Test Condition and Code Complexity Modules

All test condition and code complexity modules are in the language's complexities.xml file. This file has a <root> with one <conditions> and one <complexities>. All condition modules are inside <conditions>. All complexity modules are inside <complexities>.

```
<root>
  <conditions>
    <condition ...>
      ...
    </condition>
```

```

    ....
</conditions>
<complexities>
  <complexity ...>
    ...
  </complexity>
  ....
</complexities>

```

4.8.1 Test Condition Modules

```

<condition id="">
  <code></code>
  <value></value>
</condition>

```

- id: string indicating this condition. Appears in the test case file name. Typically this is a number.
- code: the source code of the conditional test.
- value: either <value>True</value> or <value>False</value> depending on whether the code evaluates to true or false.

```

<condition id="7">
  <code>(Math.Sqrt(42)&lt;=42)</code>
  <value>True</value>
</condition>

```

Fig. 7. Example test condition module. Instantiated in Fig. 10, line 16.

4.8.2 Code Complexity Modules

```

<complexity id="" type="" group="" executed="" in_out_var="i"
                                     indirection="" need_id="">
  <code></code>
  <body></body>
</complexity>

```

- id: string indicating this complexity. Appears in the test case file name. Typically this is a number.
- type: Supported types are: if, switch, goto, for, foreach, while, function, and class.

- **group:** Supported groups are: conditionals, jumps, loops, functions, and classes.
- **executed:** whether the placeholder will be executed or not. Four values are allowed:
 - 0: Never executed
 - 1: Always executed
 - condition: Executed if the condition is true
 - not condition: Executed if the condition is false
- **in_out_var:** whether the variable (from the Input) will be used or transformed in the Complexity before being used in the Filter. If the variable is neither used nor transformed, do not use this attribute. Three values are allowed:
 - in: the variable is used before the placeholder
 - out: the variable is used after the placeholder
 - traversal: the variable is used in the placeholder

If this attribute is used, the code should contain the following placeholders: `{{in_var_name}}`, `{{out_var_name}}`, and `{{var_type}}`.

- **indirection:** “1” if the code is split into two chunks (call and declaration) or calls a function. The body tag should be present when calling a function.
- **need_id:** “1” if the code has a placeholder, `{{id}}`, to generate a unique ID for the Complexity. This ID to generate a label, a parameter, or a function name in a nested context.
- **code:** the source code of the Complexity. Code or body should contain `{{placeholder}}` where the Filter is inserted. It may also contain `{{condition}}` where the Condition is inserted.
- **body:** Contains the source code not in the main execution flow, e.g., functions or classes. (optional)

VTSG can use several complexities in one test case. The example in Sec. 6 has two types of Complexity: a control flow complexity and a data flow complexity. The control flow complexity specification is in Fig. 8. It is instantiated in lines 16–21 of Fig. 10. Line 16 is the instantiation of the control flow condition specified in Fig. 7.

The data flow complexity is a method call within the `while` loop. The specification is in Fig. 9. The `<code>` part is instantiated in lines 18 and 19 of Fig. 10. The `<body>` part is instantiated in Fig. 11.

```

<complexity id="11" type="while" group="loops" executed="condition">
  <code>
    while({{ condition }}){
      {{ placeholder }}
      break;
    }
  </code>
</complexity>

```

Fig. 8. Example Complexity module with a while loop. Instantiated in Fig. 10, lines 16–21.

```

<complexity id="20" type="class" group="classes" executed="1" in_out_var="traversal" need_id="1" indirection="1">
  <code>
    {{call_name}} var_{{id}} = new {{call_name}}({{in_var_name}});
    {{out_var_name}} = var_{{id}}.get_var_{{id}}();
  </code>
  <body>
    /*
    {{comments}}
    */
    /*
    {{license}}
    */
    {{ imports }}
    namespace default_namespace{
      class {{call_name}}{

        {{in_var_type}} var_{{id}};

        public {{call_name}}({{in_var_type}} {{in_var_name}}_{{id}}){
          var_{{id}} = {{in_var_name}}_{{id}};
        }

        public {{out_var_type}} get_var_{{id}}(){
          {{local_var}}
          {{in_var_name}} = var_{{id}};
          {{ placeholder }}
          return {{out_var_name}};
        }

        {{static_methods}}
      }
    }
  </body>
</complexity>

```

Fig. 9. Example Complexity module with a method invocation. The `<code>` part is instantiated in Fig. 10, lines 18 and 19. The `<body>` part is instantiated in Fig. 11.

5. Generated Test Case File Names

This section describes what the names of test case files mean.

VTSG creates directories and subdirectories for the test cases that it generates. The structure is described in Sec. 3.1.

VTSG names test case files as `FLAW__I_INPUT__F_FILTER__S_SINK__EQ_EXEC_QUERY__NBCPLX-CPLX1-CPLX2.CONDx.EXT`

- **FLAW:** Flaw type, e.g. CWE_89, BF, or STR30-PL
- **INPUT:** Input description (optional)
- **FILTER:** Filter description (optional)
- **SINK:** Description of the critical function
- **EXEC_QUERY:** ExecQuery description (optional)
- **NBCPLX:** The number of complexities. Each complexity has the tags
 - **CPLX1, CPLX2, ...:** ID given in code complexity modules, see Sec. 4.8.2. Tables 4 and 6 in the language appendixes list complexity IDs used in C# and PHP. (optional)
 - **COND:** ID given in test condition modules, see Sec. 4.8.1. Tables 5 and 7 list condition IDs used in C# and PHP. (optional)
- **x:** Sequence of the file within the test. If the test consists of just one file, there is no sequence letter. If the test consists of more than one file, the main file is “a”, and other files, such as classes, are “b”, “c”, “d”, etc.
- **EXT:** file extension, given in the `file_template.xml` file, see Sec. 4.2.

See the next section, 6, for an example of the file name of a generated test case and the various pieces.

File names reflect the entire case, not just the code in a particular file. If a case consists of more than one file, as in the example in Sec. 6, all files have identical names, except for the final sequence letter.

6. Example Test Case

This section has an example test case. The case consists of two files. Fig. 10 is the main file of the example. Fig. 11 is an auxiliary class file. The code in the main file invokes the class at line 18.

The name of the main file is `CWE_89__I_shell_commands__F_func_preg_match-only_numbers__S_select_from-concatenation_simple_quote__`

```

1  using System.Text.RegularExpressions;
2  using System;
3  using System.IO;
4  using MySql.Data.MySqlClient
5  using System.Diagnostics;
6
7  namespace default_namespace{
8      class MainClass476688{
9          public static void Main(string[] args){
10
11              string tainted_7 = null;
12              string tainted_2 = null;
13
14              tainted_2 = args[1];
15
16              while((Math.Sqrt(42)<=42)){
17
18                  Class_476686 var_476686 = new Class_476686(tainted_2);
19                  tainted_7 = var_476686.get_var_476686();
20                  break;
21              }
22
23              string query = "SELECT * FROM '" + tainted_7 + "'";
24
25              string connectionString = @"server=localhost;uid=mysql_user;
26              password=mysql_password;database=dbname";
27              MySqlConnection dbConnection = null;
28              try {
29                  dbConnection = new MySqlConnection(connectionString);
30                  dbConnection.Open();
31                  MySqlCommand cmd = dbConnection.CreateCommand();
32                  cmd.CommandText = query;
33                  MySqlDataReader reader = cmd.ExecuteReader();
34                  while (reader.Read()){
35                      Console.WriteLine(reader.ToString());
36                  }
37                  dbConnection.Close();
38              } catch (Exception e) {
39                  Console.WriteLine(e.ToString());
40              }
41          }
42      }

```

Fig. 10. Main file of example. Line 14 instantiates input code from Fig. 3. Lines 16–19 instantiates complexity code from Fig. 8. Line 16 instantiates condition code from Fig. 7. Lines 18 and 19 instantiate code from the `<code>` part of Fig. 9. Line 23 instantiates critical preparation code from Fig. 5. Lines 25–39 instantiate query execution code from Fig. 6.

```

1  using System.Text.RegularExpressions;
2
3  namespace default_namespace{
4      class Class_476686{
5
6          string var_476686;
7
8          public Class_476686(string tainted_4_476686){
9              var_476686 = tainted_4_476686;
10         }
11
12
13         public string get_var_476686(){
14             string tainted_4 = null;
15             string tainted_5 = null;
16
17             tainted_4 = var_476686;
18
19             string pattern = @"/^[0-9]*$/";
20             Regex r = new Regex(pattern);
21             Match m = r.Match(tainted_4);
22
23             if(!m.Success){
24                 tainted_5 = "";
25             }else{
26                 tainted_5 = tainted_4;
27             }
28
29             return tainted_5;
30         }
31     }
32 }

```

Fig. 11. Auxiliary file of example. It instantiates code from the $\langle \text{body} \rangle$ part of Fig. 9. Lines 19–27 instantiate filter code from Fig. 4.

sql_server__2-11.7-20a.cs. The name of the class file, Fig. 11, is identical, except for the file letter, “b”.

Using Sec. 5 and the extension, cs, which shows that it is a C# file, the file name is read as follows:

CWE 89: Improper Neutralization of Special Elements used in an SQL Command (‘SQL Injection’) [5]

The input comes from shell_commands, see specification in Fig. 3.

The filter is func_preg_match-only_numbers, Fig. 4.

The sink is select_from-concatenation_simple_quote_sql_server, Fig. 5.

The next part, 2-11.7-20, means this has two complexities. Tables 4 and 5 help us decode them. The first, outer complexity is 11 with condition 7. 11 is while, Fig. 8, with condition 7 means $\text{Math.Sqrt}(42) \leq 42$, which always evaluates to true, Fig. 7. The second, inner complexity is 20 means the sink code is executed in the class body, Fig. 9.

“a” means this is the main file.

7. Acknowledgments

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A. C# language

This appendix documents the flaws, flaw groups, conditions, and complexities currently in the C# language files.

The following flaws are currently defined for this language:

- SQL Injection (CWE-89)
- XPath Injection (CWE-91)
- LDAP Injection (CWE-90)
- OS Command Injection (CWE-78)
- Path traversal (CWE-22)
- Information Leak Through Error Message (CWE-209)
- Storing Password in Plain Text (CWE-256)
- Use of Insecure Cryptographic Algorithm (CWE-327)
- NULL Pointer Dereference (CWE-476)

The flaws are in the following groups:

- OWASP_a1 has CWE_78, CWE_89, CWE_89, CWE_89, CWE_90, CWE_91, CWE_91, and CWE_91.
- OWASP_a2 has CWE_256.
- OWASP_a4 has CWE_22.
- OWASP_a5 has CWE_209.
- OWASP_a6 has CWE_327
- OWASP_a9 has CWE_476.

Here are the complexities currently available in C#. We explain the concept of code complexities in Sec. 3.4 and the format of complexity modules in Sec. 4.8.2. This very brief description is to remind the reader of the complexity. See the `complexity.xml` file for the specific code.

ID	Complexity
1	if condition code
2	if condition code else
3	if condition else code
4	if condition code else if not condition
5	if condition else if not condition code
6	if condition code else if not condition else
7	if condition else if not condition code else
8	if condition else if not condition else code
9	switch code executed
10	switch code not executed
11	while code
12	do code while
13	for code
14	foreach code
15	goto code not executed
16	goto code executed
17	function body executes code
18	input passed via function then code
19	code then output passed via function
20	class body executes code
21	input passed via class then code
22	code then output passed via class

Table 4. IDs and Code Description of Complexities Defined for C#

Here are the conditions currently available to be used in code complexities. We explain condition modules in Sec. 4.8.1. Table 5 shows the ID, the code, and whether it always evaluates to true or false.

ID	Code	Value
1	1==1	True
2	1==0	False
3	4+2<=42	True
4	4+2>=42	False
5	Math.Pow(4, 2)<=42	True
6	Math.Pow(4, 2)>=42	False
7	Math.Sqrt(42)<=42	True
8	Math.Sqrt(42)>=42	False

Table 5. IDs, Code, and Value to Which it Evaluates of Conditions Defined for C#

B. PHP language

This documents the flaw, flaw group, conditions, and complexities currently in the PHP language files.

The following flaw is currently defined for this language:

- SQL Injection (CWE-89)

The flaw is in the following group:

- OWASP_injection has CWE_89.

Here are the complexities currently available in PHP. We explain the concept of code complexities in Sec. 3.4 and the format of complexity modules in Sec. 4.8.2. This very brief description is to remind the reader of the complexity. See the complexity.xml file for the specific code.

ID	Complexity
1	if condition code
2	if condition code else
3	if condition else code
4	if condition code else if not condition
5	if condition else if not condition code
6	if condition code else if not condition else
7	if condition else if not condition code else
8	if condition else if not condition else code
9	switch code executed
10	switch code not executed
11	while code
12	do code while
13	for code
14	foreach code
15	goto code not executed
16	goto code executed
17	function body executes code
18	input passed via function then code
19	code then output passed via function
20	class body executes code
21	input passed via class then code
22	code then output passed via class

Table 6. IDs and Code Description of Complexities Defined for PHP

Here are the conditions currently available to be used in code complexities. We explain condition modules in Sec. 4.8.1. Table 7 shows the ID, the code, and whether it always evaluates to true or false.

ID	Code	Value
1	1==1	True
2	1==0	False

Table 7. IDs, Code, and Value to Which it Evaluates of Conditions Defined for PHP

C. Python language

This documents the flaws, flaw groups, conditions, and complexities currently in the Python language files.

FILL IN

D. Contents of git Repository

The screenshot shows the GitHub interface for the repository `usnistgov / VTSG`, which is public. The repository has 1 branch (master) and 0 tags. The file list is as follows:

File/Folder	Description	Commit Date
<code>dll</code>	Clone from C# Vuln Test Suite Gen	6 years ago
<code>docs</code>	Add the pdf of the manual to git.	20 days ago
<code>src</code>	Add tests in test010 for unusual indentation.	13 days ago
<code>tests</code>	Oops, two *modified lines. Replace the first one with the correct *cr...	12 days ago
<code>.gitignore</code>	Add the pdf of the manual to git.	20 days ago
<code>AUTHORS</code>	Update authors and contributors.	26 days ago
<code>LICENSE</code>	Clone from C# Vuln Test Suite Gen	6 years ago
<code>Makefile</code>	Wait 1 second after short tests so they never go in the same TestSuit...	14 days ago
<code>README.md</code>	Rename the toplevel script to be vtsg.py. Also add Python and other ...	21 days ago
<code>TODO</code>	Add ideas for short case names. Elaborate some ideas. Move some f...	6 days ago
<code>compilationTester.sh</code>	Clone from C# Vuln Test Suite Gen	6 years ago
<code>requirements.txt</code>	Upgrade required packages to latest version (VTSG runs unchanged).	last month
<code>setup.py</code>	Rename the toplevel script to be vtsg.py. Also add Python and other ...	21 days ago
<code>vtsg.py</code>	Rename the toplevel script to be vtsg.py. Also add Python and other ...	21 days ago

Fig. 12. Snapshot of files in the VTSG git repository, which is at <https://github.com/usnistgov/VTSG>, as of 8 March 2022.

Vulnerability Test Suite Generator

Program to generate vulnerable and fixed synthetic test cases expressing specific flaws.

Written in Python 3

Dependencies

- Jinja2 (depends on MarkupSafe)
- Docopt
- Setuptools (for setup.py)
- Sphinx (for generating the doc)

You have three ways to install these dependencies

Using PIP

We encourage you to use pip ([installation instructions](#)) to install these dependencies (choose one):

```
- [sudo] pip3 install -r requirements.txt (as root, system-wide)
- pip3 install --user -r requirements.txt (only for your user)
```

Using a Package Manager

You can also install this dependency with your package manager (if such a package exists in your distribution) :

```
- [sudo] aptitude install python3-jinja2 (for GNU/Linux Debian for example)
- [sudo] aptitude install python3-docopt
- [sudo] aptitude install python3-setuptools
- [sudo] aptitude install python3-sphinx
```

Manually Installation

Jinja2 installation instructions [here](#)

Docopt installation instructions [here](#)

[Setuptools site](#)

Execute it

```
$ python3 vtsg.py -l cs
```

Need help ?

```
$ python3 vtsg.py --help
```

Fig. 13. README.md file, which is at <https://github.com/usnistgov/VTSG/blob/master/README.md>, as of 8 March 2022.