Scanstud
Evaluating Static Analysis Tools

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Mission statement
- Investigating the state of the art in static analysis

Project overview
- Practical evaluation of commercial static analysis tools for security
- Focus on C and Java
- 09/07 – 02/08
- Joint work of University of Hamburg and Siemens CERT
1. Introduction
2. Test methodology
3. Test code
4. Experiences and lessons learned
Agenda

1. Introduction
2. Test methodology
3. Test code
4. Experiences and lessons learned
What we WON’T tell you:
- The actual outcome of the evaluation
- Even if we wanted, we were not allowed (NDAs and such)

But:
- We do not consider the precise results to be too interesting
  - An evaluation as ours only documents a snapshot
  - and is outdated almost immediately

However:
- We hopefully will give you a general feel in respect to the current capabilities of static analysis
So, what will we tell you

This talk is mainly about our evaluation methodology

- How we did it
- Why we did it this specific way
- General infos on the outcome
- Things we stumbled over
What makes a static analysis tool good?

- Knowledge of different types of code based security problems
  - E.g., XSS, SQLi, Buffer Overflow, Format String problems...
- Language/Framework coverage
  - E.g., J2EE servlet semantics, <string.h>,...
- Understanding of flows
  - Control flow analysis (Loops invariants, integer ranges)
  - Data flow analysis (pathes from source to sink)
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General approaches towards benchmarking

Approaches

1. Use real world vulnerable software
2. Use existing or selfmade vulnerable application
   ◆ Hacme, Web Goat, etc...
3. Create specific benchmarking suite

Our goal and how to reach it

◆ We want to learn a tool’s specific capabilities
  ◆ E.g., does it understand Arrays? Does it calculate loop invariants? Does it understand inheritance, scoping,...?

◆ Approaches 1. + 2. are not suitable
  ◆ Potential side effects
    ◆ more than one non-trivial operation in every execution path
  ◆ Writing custom testcode gives us the control that we need

However the other approaches are valuable too (SAMTE)
Mission Statement

Objectives

- Easy, reliable, correct, and iterative testcase creation
  - The actual test code should be
    - short
    - manual tested
    - as human readable as possible

- Defined scope of testcases
  - A single testcase should test only for one specific characteristic

- Automatic test-execution and -evaluation
  - Allows repeated testing and iterative testcase development
  - “neutral” evaluation

[Let’s start at the bottom]
Automatic test-execution

Approach
- Test-execution via batch-processing

Problem
- All tools behave differently

Solution
- Wrapper applications
  - Unified call interface
  - Unified XML-result format
Automatic test-evaluation

Required
- Reliable mapping between alert and testcode

Approach
- One single vulnerability (or FP) per testcase
- Every testcase is hosted in an application of its own
- The rest of the application should otherwise be clean

Benefits
- Clear relation between alerts and testcases
  - Alert => the case was found / the FP triggered
  - No alert => the case was missed
Real world problem

Noise

- Even completely clean code can trigger warnings
  - The host-program may cause additional alerts
- How do we deterministically correlate scan-results to test-cases?
  - Line numbers are not always applicable.

Solution

- Result-Diff
  - Given two scan results it extracts the additional alerts
- Scan the host-program only (== the noise)
- Scan the host-program with injected testcase (== signal + noise)
- Diff the results (== signal)
Testcase creation

Approach

- Separation between
  - general support code and
  - test-specific code (the actual vulnerabilities)

Benefit

- Support code is static for all testcases
- The actual testcase-code is reduced to the core of the tested property
  - Minimizes the code, reduces error-rate, increases confidentiality
  - Allows rapid testcase creation
  - Enables clear readability

Implementation

- Code generation
  - Host-program with defined insertion points
  - Testcode is inserted in the host-program
Insertion points in the host program
- Library includes, Global structures/data, function-call to the test function

The test-case is divided in several portions
- Each portion corresponds to one of the insertion points

A script merges the two files into one testcase

```c
#include <stdio.h>
#include <string.h>

int main(int argc, char **argv)
{
    init_network();
    start_listening();
    while (p = get_packet()) {
        /* Put test case code here... */
    }
    return 0;
}
```
Example testcase(s): Buffer overflow

DESCRIPTION: Simple strcpy() overflow
ANNOTATION: Buffer Overflow [controlflow] []

EXTERNAL_HEADER:
#include <string.h>

VULNERABLE_CALL: %NAME(v)% (p);

VULNERABLE_EXTERNAL_CODE:
/* %DESCRIPTION(v)% */
void %NAME(v)% (char *p) {
    char buf[1024];
    strcpy(buf, p);    /* %ANNOTATION(v)% */
}

SAFE_CALL: %NAME(s)% (p);

SAFE_EXTERNAL_CODE:
/* %DESCRIPTION(s)% */
void %NAME(s)% (char *p) {
    char buf[1024];
    if (strlen(p) >= sizeof(buf))
        return;
    strcpy(buf, p);    /* %ANNOTATION(s)% */
}
Final testing infrastructure

Components
- Tool wrappers
- Host-program
- Test-cases
- Assembly script
- Result differ
- Evaluator

Putting it all together
- Creates test-code with the assembly-script
- Causes the wrapped tool to access the test-case
- Passes the test-result to result differ
- Diffed-result and meta-data are finally provided to the Evaluator
Conclusion: Test-code generation

Summary

- Applicable for all potential languages
- Applicable for all tools that provide a command-line interface
- Flexible
- Allows deterministic mapping code <--> findings

Fallback: Combined suite

- For cases where the tool cannot be wrapped
- All testcases are joined in one big application
1. Introduction

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Testcases versus Tests

A testcase is the smallest unit in our approach
- Contains code which should probe for exactly one result
- Either “true vulnerability” or “false positive”

A test usually consists of two testcases
- a true vulnerability and
- a false positive
- Both testing the same characteristic

A test passed only if BOTH associated testcases have been identified correctly
Testcase design

Language features and control/data flow
- Two variables ("good", "bad") → The sources
  - Both are filled with user provided data
  - The "good" variable is properly sanitized
- One sink variable ("result")
  - This variable is used to execute a security sensitive action
- Both variables are piped through a crafted control flow
- One of them is assigned to the result variable

Memory corruption
- Similar approach
- Instead of variables different sized memory regions are used
C test cases

Host program
- All C test cases are hosted in a simple TCP server
- Listens on a port and waits for new clients
- Reads data from socket and passes pointer to test case
- Less than 100 LOC

The suite
- Emphasis on vulnerability types
- Around 116 single C test cases in total

Tests for, e.g.,
- Buffer overflows, unlimited/Off-by-one pointer loop overflows, integer overflows/underflows, signedness bugs, NULL pointer dereferences
The Java suite

Host program
- J2EE application with only one servlet
  - Provides: DB connection, framing HTML content, sanitizing,...

Vulnerability classes
- XSS, SQLi, Code Injection, Path Traversal, Response Splitting
  - Emphasis on testing dataflow capabilities
- ~ 85 Java testcases in total
  - Ben Livshit’s Stanford SecuriBench Micro was very helpful

Language features
- Library, inheritance, scoping, reflection, session storage

Tests
- Global buffers, array semantics, boolean logic, second order code injection, ...
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Tool selection

Market research: 12 potential candidates

- Selection criteria:
  - Maturity
  - Is security a core-competence of the tool?
  - Language support

⇒ Selection of 10 tools

⇒ After pre-tests 6 tools were chosen for further investigation

- (no, we can’t tell you which)
Scoring

We have ~ 200 unique testcases
  - How should the results be counted?

Observation
  - If it aids the detection reliability, false positives are tolerable

Resulting quantification of the results
  - Test passed: 3 Points
  - False positive: 1 Point
  - False negative: 0 Points
## Result overview

### C Suite

<table>
<thead>
<tr>
<th>Rank</th>
<th>Tool</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Tool a.</td>
<td>72 / 168</td>
</tr>
<tr>
<td>2.</td>
<td>Tool b.</td>
<td>58 / 168</td>
</tr>
<tr>
<td>3.</td>
<td>Tool c.</td>
<td>56 / 168</td>
</tr>
<tr>
<td>4.</td>
<td>Tool d.</td>
<td>53 / 168</td>
</tr>
<tr>
<td>5.</td>
<td>Tool e.</td>
<td>50 / 168</td>
</tr>
</tbody>
</table>

### Java Suite

<table>
<thead>
<tr>
<th>Rank</th>
<th>Tool</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Tool x.</td>
<td>89 / 147</td>
</tr>
<tr>
<td>2.</td>
<td>Tool y.</td>
<td>66 / 147</td>
</tr>
<tr>
<td>3.</td>
<td>Tool z.</td>
<td>58 / 147</td>
</tr>
<tr>
<td>4.</td>
<td>Tool v.</td>
<td>53 / 147</td>
</tr>
</tbody>
</table>
Static analysis: C capabilities

Categories covered by almost all tools:
- NULL pointer dereferences
- Double free’s

Problem areas of most tools:
- Integer related bugs
  - Integer underflows / overflows leading to buffer overflows
  - Sign extension bugs
- Race conditions
  - Signals
    - `setjmp()` / `longjmp()`
- Non-implementation bugs
  - Authentication, Crypto, Privilege management, Truncation, …
Static analysis: Java Capabilities

Strengths

- Within a function all tools possess good capabilities to track dataflows
- Besides that, the behaviour/capabilities are rather heterogeneous

Problem areas of most tools

- Global buffers
  - Especially if they are contained within a custom class
- Dataflow in and out of custom objects
  - E.g., our own linked list was too difficult for all tools

```java
class Node {
    public String value;
    public Node next;
}
```

- Second order code injection
Buffer overflows 101:

- Most basic buffer overflow case?
  ```c
  strcpy()
  ```

- To our surprise, 3 out of 5 tools didn’t report this!
  - Too obvious to report?
- One vendor was provided with this sample:
  ```c
  int main(int argc, char **argv) {
    char buf[16];
    strcpy(buf, argv[1])
  }
  ```

- Vendor response:
  “argc/argv are not modeled to contain anything sensible. We will eventually change that in the future.”
Buffer overflows 101:

- Another easy one:
  ```c
  gets(buf);
  ```

- Every tool must be finding that one!
  - Actually one tool didn’t

- Vendor response:
  “Ooops, this is a bug in our tool.”
More bugs:

- One tool didn’t find anything in our “combined test case”:

```c
#include "testcase1.c"
#include "testcase2.c"
#include "testcase3.c"

int main(int argc, char **argv) {
    call_testcase1();
    call_testcase2();
    call_testcase3();
    return 0;
}
```

- Vendor response:
  “#include’ed files are not analyzed completely.
   Will be fixed in a future version.”
Fun stuff

Let’s sanitize some integers

- All tools allow the specification of sanitation functions
- So did Tool Y
- However the parameter for this function could only be
  - Int, float, ...
  - But not STRING!

Don’t trust the servlet engine

- The J2EE host program writes some static HTML to the servlet response

```java
PrintWriter writer = resp.getWriter();
writer.println("<h3>ScanStud</h3>");
```

- Tool X warned “Validation needed”
  - (are you really sure you want your data there?)
More fun and bugs

One of the tools did not find a single XSS problem

- This surprised us, as the tool otherwise showed decent results
- Reason: We used the following code
  
  ```java
  PrintWriter writer = resp.getWriter();
  ```

- But the tool did not know “getWriter()”
- After replacing it with “getOutputStream()” XSS was found

Somewhat overeager

- Our SQLi tests exclusively used SELECT statements
- While detecting the vulnerability, the tool Z also warned “stored XSS vulnerability”
A special price: The noisiest tool

We had a tool in round one that did not understood neither C nor Java

- Therefore we started a C# benchmarking suite
- After three written testcases we did a first check
  - 2 XSS (vulnerable/safe), 1 SQLi (vulnerable)

484 Vulnerabilities!

- The tool was not included in the second evaluation round
Questions?

The testing-framework and -code will be published on the SANS website

- Drop me a line, if you want to be notified
  (johns@informatik.uni-hamburg.de)
Appendix
Potential pitfall

Pitfall

- Unbalanced creation/selection of testcases can introduce unsound results

Example

- Tool X is great but does not understand language feature Y
- Therefore all tests involving Y fail
- If there is an unbalanced amount of tests involving Y tool X has an unfair disadvantage

Solution: Categories and tags

- Categories: “controlflow”, “dataflow”, “language”,...
- Tags: All significant techniques within the testcase
  - Example: [cookies,conditional,loops]
- The it would be possible to see, that X allways fails with Y
Vendor X:

- When there is a single path which includes an Array into a vulnerable data-flow, then the whole Array is tainted (even the safe values)
  - Underlying assumption: All elements of a linear data structure are on the same semantic level
  - This approach obviously breaks our test, to examine whether a tool understands Array semantics
C suite

Host program
- All C test cases are hosted in a simple TCP server
- Listens on a port and waits for new clients
- Accepts client connections
- Reads data from socket and passes pointer to test case
- Less than 100 LOC

Test cases
- Around 116 single C test cases in total
- 10 tests to determine the general performance of each tool
  - Arrays, loop constructs, structures, pointers, …
- Rest of the test cases represent real vulnerabilities, which could be found in the wild
C suite (2)

- Buffer overflows using simple unbounded string functions
  - `strcpy`, `strcat`, `gets`, `fgets`, `sprintf`, `strvis`, `sscanf`
- Buffer overflows using bounded string functions
  - `snprintf`, `strncpy`, `strncat`, `memcpy`
- Unlimited/Off-by-one pointer loop overflows
- Integer related bugs
  - Integer overflows / underflows
  - Sign extension
- Race conditions
  - Signals
  - `setjmp()`
  - `TOCTTOU`
C suite (3)

- C operator misuse
  - `sizeof()`, assignment operator, octal numbers

- Format string issues

- NULL pointer derefs

- Memory management
  - Memory leaks
  - Double free’s

- Privilege management

- Command injection
  - `popen()`, `system()`
The SATEC file format

- Each test is kept in a separate file
- The test is described using the following keywords
  - NAME (automatically generated from filename)
  - DESCRIPTION
  - ANNOTATION
- Two code blocks
  - VULNERABLE_EXTERNAL_CODE
  - SAFE_EXTERNAL_CODE
- Two calls, into the code blocks
  - VULNERABLE_CALL
  - SAFE_CALL
- Keyword expansion is possible
Example: T_001_C_XSS.java

DESCRIPTION: Very basic XSS
ANNOTATION: XSS [basic] []

VULNERABLE_CALL:
    new %NAME(v)%().doTest(req, resp); // inserted by satec

SAFE_CALL:
    new %NAME(s)%().doTest(req, resp); // inserted by satec

VULNERABLE_EXTERNAL_CODE:
class %NAME(v)% extends scanstudTestcase {
    public void doTest(HttpServletRequest req, HttpServletResponse resp){
        PrintWriter writer = resp.getWriter();
        String value = req.getParameter("testpar");
        writer.println("<h3>" + value + "</h3>"); // %ANNOTATION(v)%
    }
}

SAFE_EXTERNAL_CODE:
class %NAME(s)% extends scanstudTestcase {
    public void doTest(HttpServletRequest req, HttpServletResponse resp){
        PrintWriter writer = resp.getWriter();
        String value = HTMLEncode(req.getParameter("testpar"));
        writer.println("<h3>" + value + "</h3>"); // %ANNOTATION(s)%
    }
}