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Using Static Code Analysis Tools for Detection of Security Vulnerabilities

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Information assurance and IV&V

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- NASA develops, runs, and maintains many systems for which one or more security attributes (i.e. confidentiality, integrity, availability, authentication, authorization, and non-repudiation) are of vital importance

- Information assurance and cyber security have to be integrated in the traditional verification and validation process

Static code analysis

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- Static analysis of source code provides a scalable method for code review
- Tools matured rapidly in the last decade
  - from simple lexical analysis to more complex and accurate techniques
- In general, static analysis problems are undecidable (i.e. it is impossible to construct an algorithm which always leads to a correct answer)
  - False negatives
  - False positives

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To examine the ability of static code analysis tools to detect security vulnerabilities

Approach

- Surveyed the literature and vendor provided information on the state-of-the-art and practice of static code analysis tools
  - 15 commercial products
  - 8 tools licensed under some kind of open source license
- Selected three tools for detailed evaluation
  - To fully use the provided functionality all three tools require a build to be created or at least the software under test to be compiled
- Performance was evaluated using
  - Micro-benchmarking test suites for C/C++ and Java
  - Three open source programs with known vulnerabilities

EVALUATION BASED ON THE JULIET TEST SUITE

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Juliet test suite

- Micro-benchmarking suite which covers large number of CWEs
  - Each CWE (Common Weakness Enumeration) represents a single vulnerability type
- Created by NSA and made publicly available at the NIST Web site
- C/C++ suite (version 1.1)
  - 119 CWEs
  - 57,099 test cases
- Java suite (version 1.1.1)
  - 113 CWEs
  - 23,957 test cases

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Juliet test suite

- This presentation is focused on the CWEs covered by all three tools
  - 22 common C/C++ CWEs among the three tools (~21,000 test cases)
  - 19 common Java CWEs among the three tools (~7,500 test cases)
- Two of the tools covered significantly more CWEs
  - 90 C/C++ CWEs (~34,000 test cases)
  - 107 Java CWEs (~16,000 test cases)
  - Results were similar to the ones presented here

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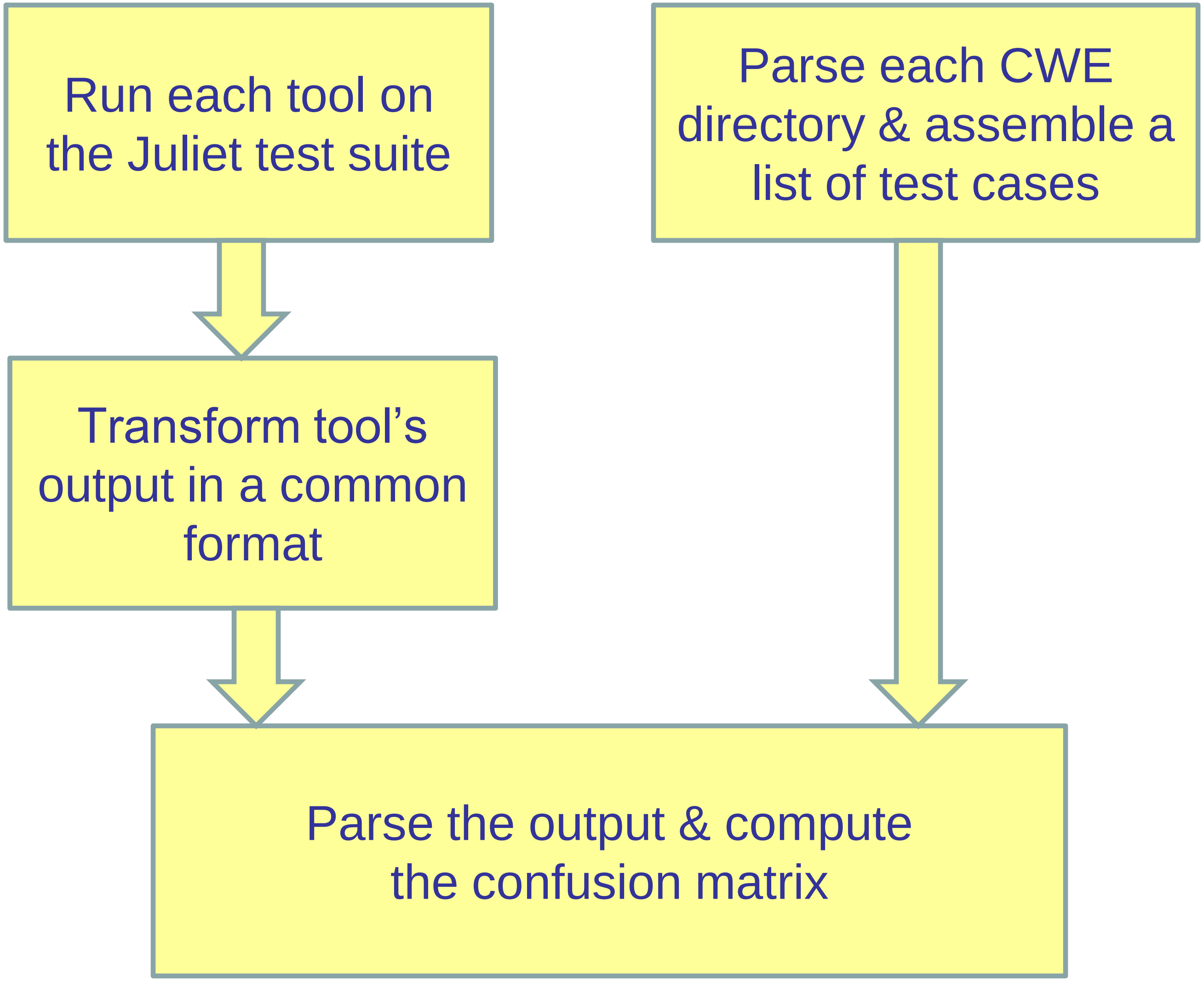
Automatic assessment



Confusion matrix & metrics

	Reported vulnerability	**No warning/error reported**
Actual vulnerability	True Positives (**TP**)	False Negatives (**FN**)
No vulnerability (good function/method)	False Positives (**FP**)	True Negatives (**TN**)

% of functions that are classified correctly $Accuracy = \frac{TN + TP}{TN + FN + FP + TP}$

Probability of detecting a vulnerability (recall) $PD = \frac{TP}{TP + FN}$

Probability of misclassifying a good function as a bad function (false alarm) $PF = \frac{FP}{TN + FP}$

How close is the result to the ideal point (pf, pd)=(0,1) $Balance = 1 - \frac{\sqrt{(0 - PF)^2 + (1 - PD)^2}}{\sqrt{2}}$

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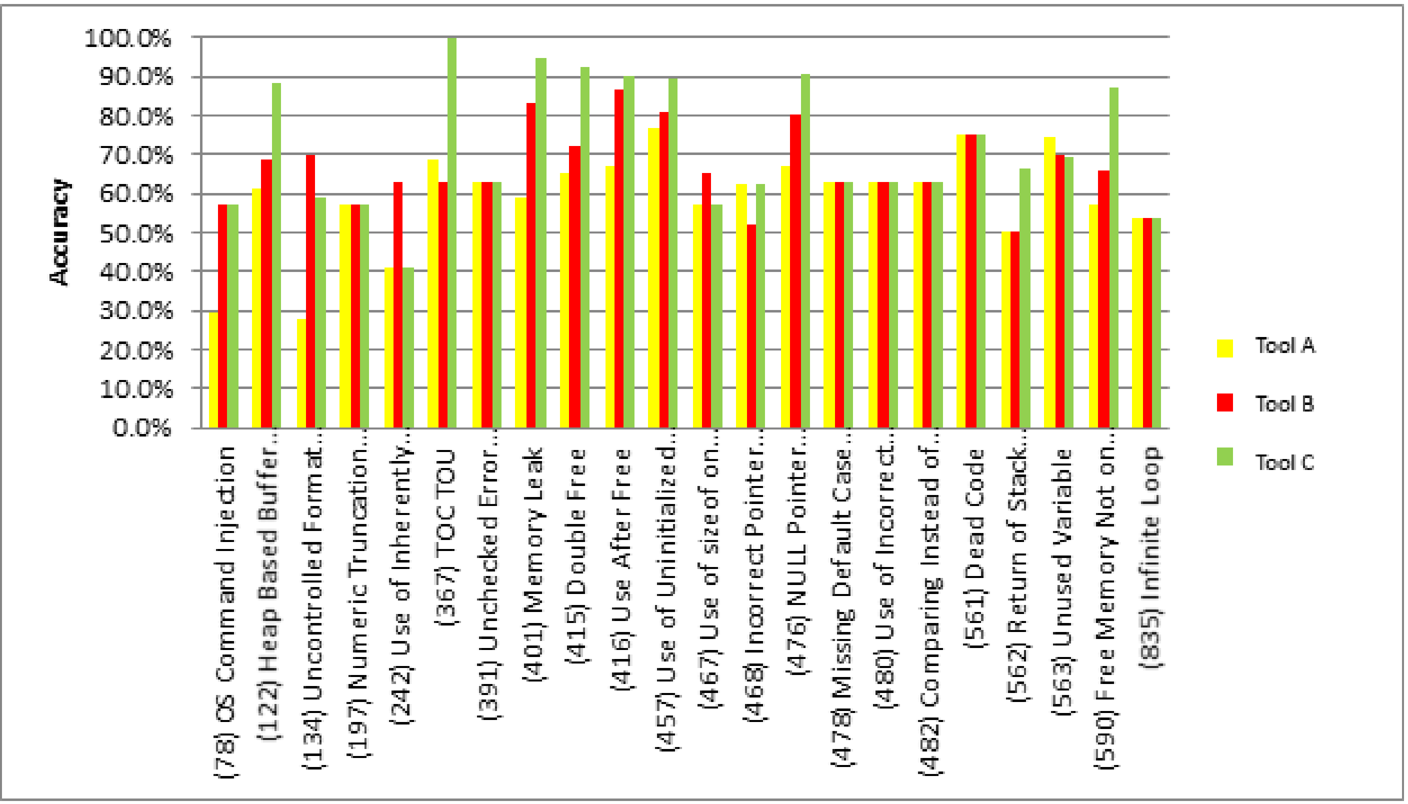
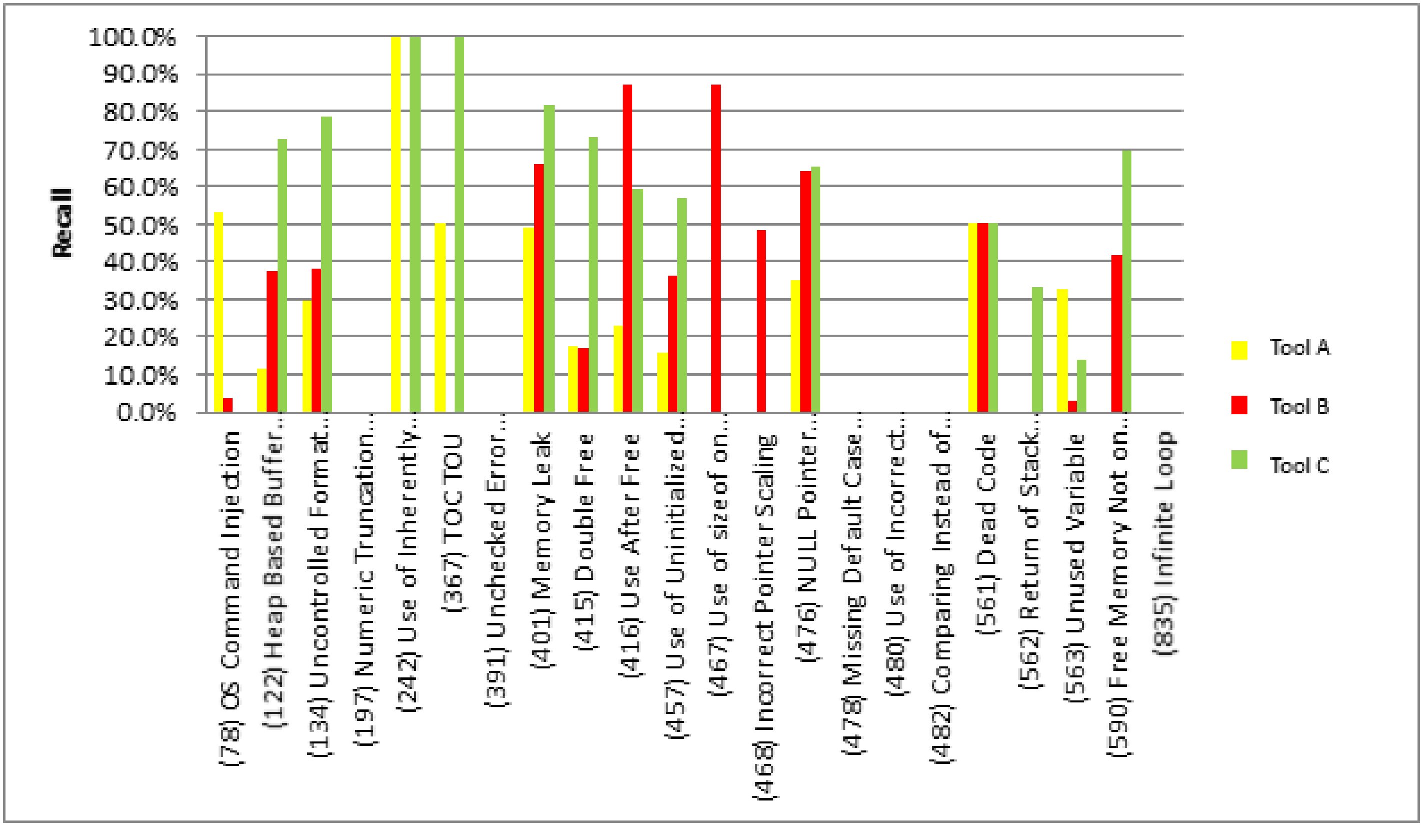
Accuracy: C/C++ CWEs



The three tools have similar performance with Tool C performing slightly better

Tool A: Range [0.27,0.77], Average = 0.59, Median = 0.63
Tool B: Range [0.50, 0.87], Average = 0.67, Median = 0.64
Tool C: Range [0.41,1], Average = 0.72, Median = 0.64

Recall: C/C++ CWEs



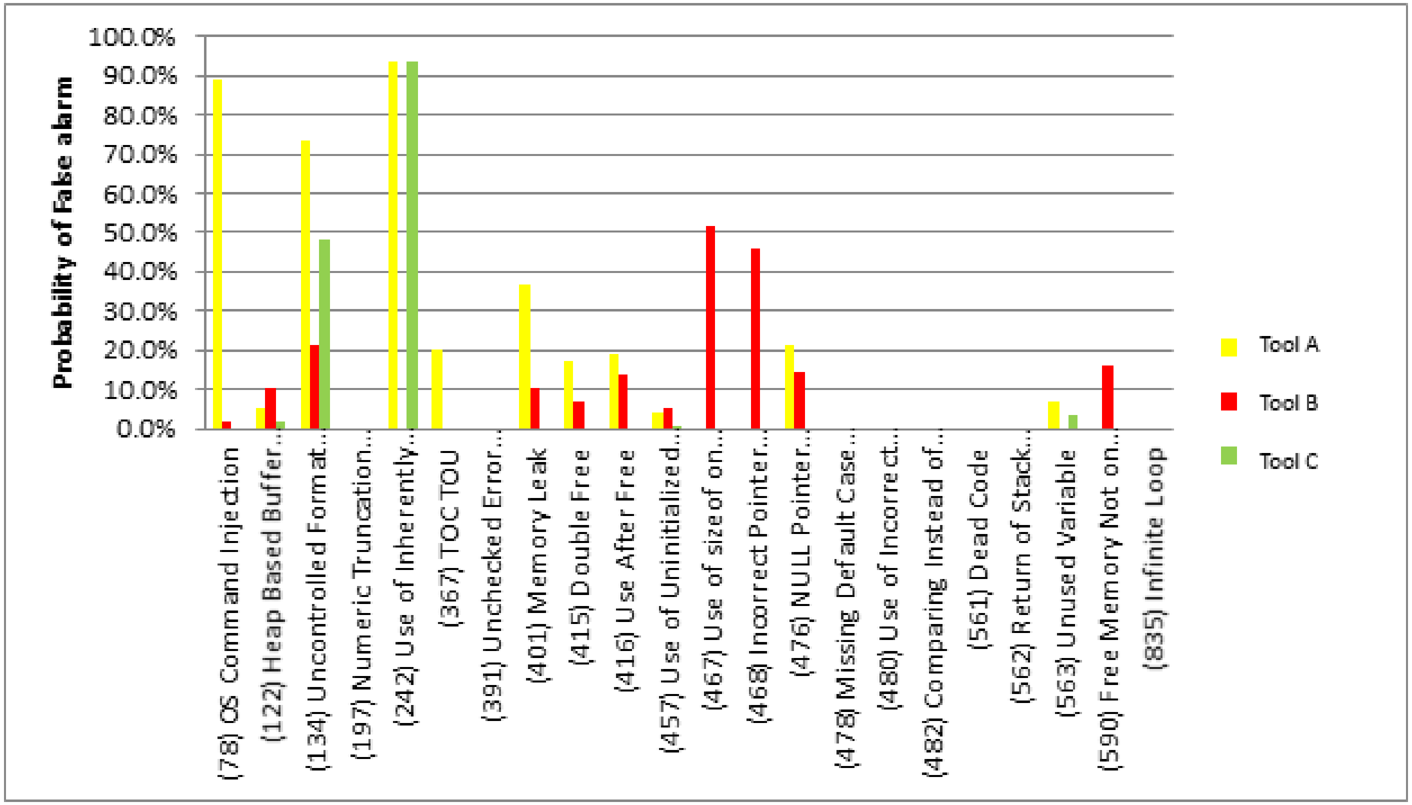
Each tool has 0% recall for some CWEs

For some CWEs (i.e.,197, 391, 478, 480, 482, 835) all three tools have 0% recall

Accuracy on its own is not a good metric for tools' performance

Tool A: Range [0, 1], Average = 0.21 , Median = 0.14
Tool B: Range [0, 0.87], Average = 0.26, Median = 0.10
Tool C: Range [0,1], Average = 0.39, Median = 0.42

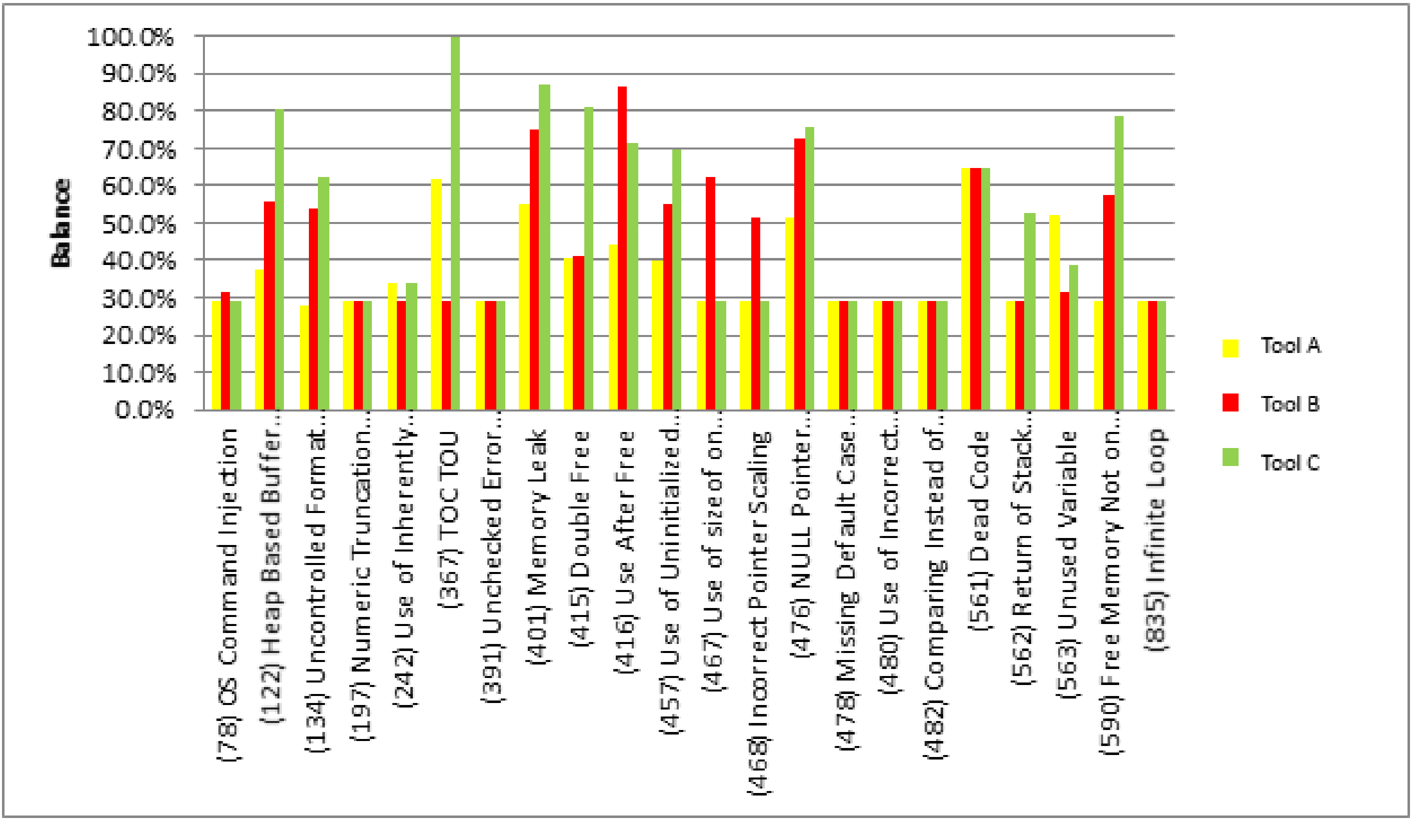
Probability of false alarm: C/C++ CWEs



Tool C has noticeably lower false positive rate than Tools A and B

Tool A: Range [0, 0.94], Average = 0.18, Median = 0.02
Tool B: Range [0, 0.52], Average = 0.09, Median = 0.01
Tool C: Range [0,0.94], Average = 0.07, Median = 0

Balance: C/C++ CWEs



Balance values for many CWEs were around 30%, which indicates poor overall performance

Tool C performed slightly better than the other two tools

Tool A: Range [0.28, 0.65], Average = 0.39, Median = 0.29
Tool B: Range [0.29, 0.87], Average = 0.46, Median = 0.36
Tool C: Range [0.29,1], Average = 0.53, Median = 0.46

ROC squares for C/C++ CWEs

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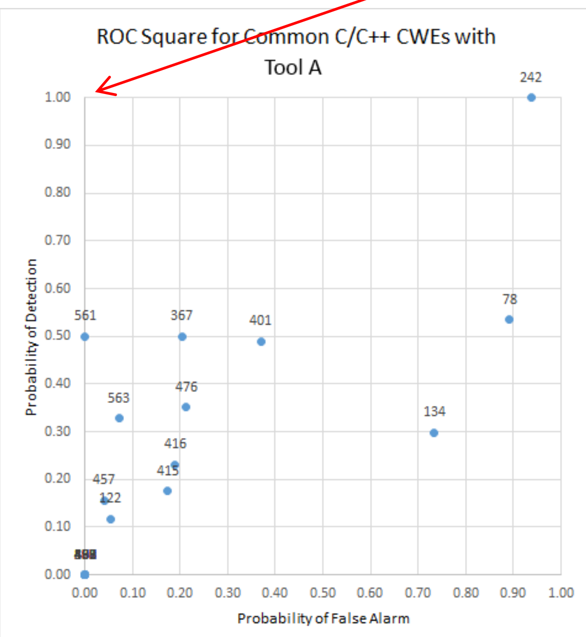
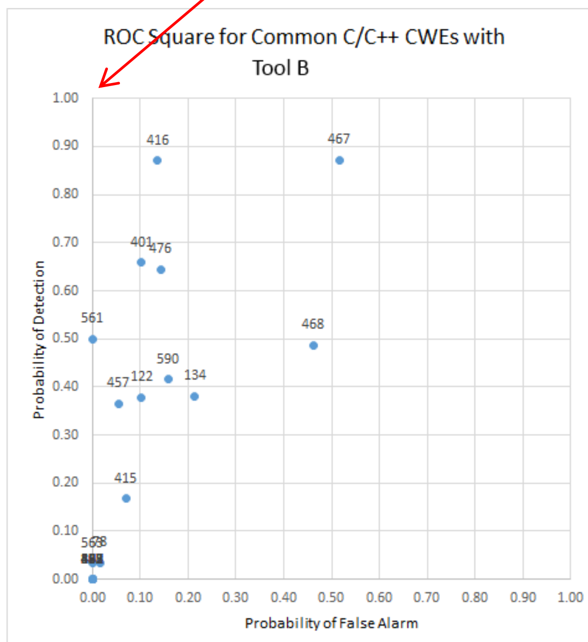
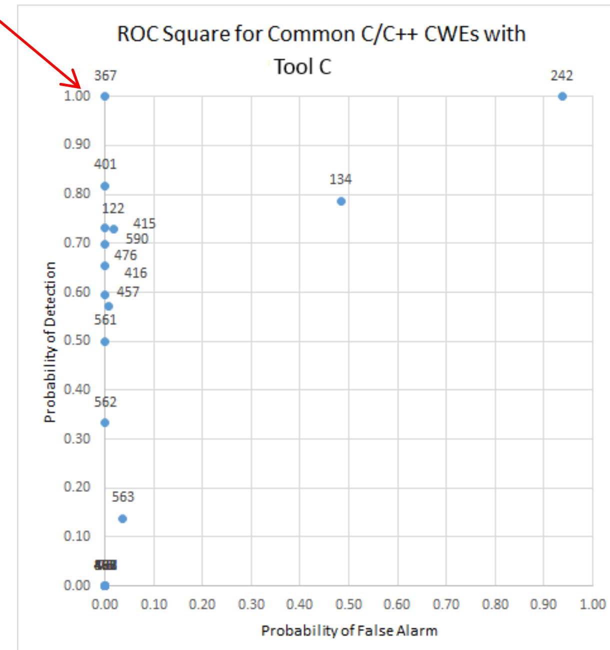
Ideal result
(pf, pd) = (0, 1)







Not many points are close to the ideal (0,1) point
Tool C has noticeably lower false alarm rate
For each tool there are multiple CWEs at the (0,0) point

Accuracy: Java CWEs

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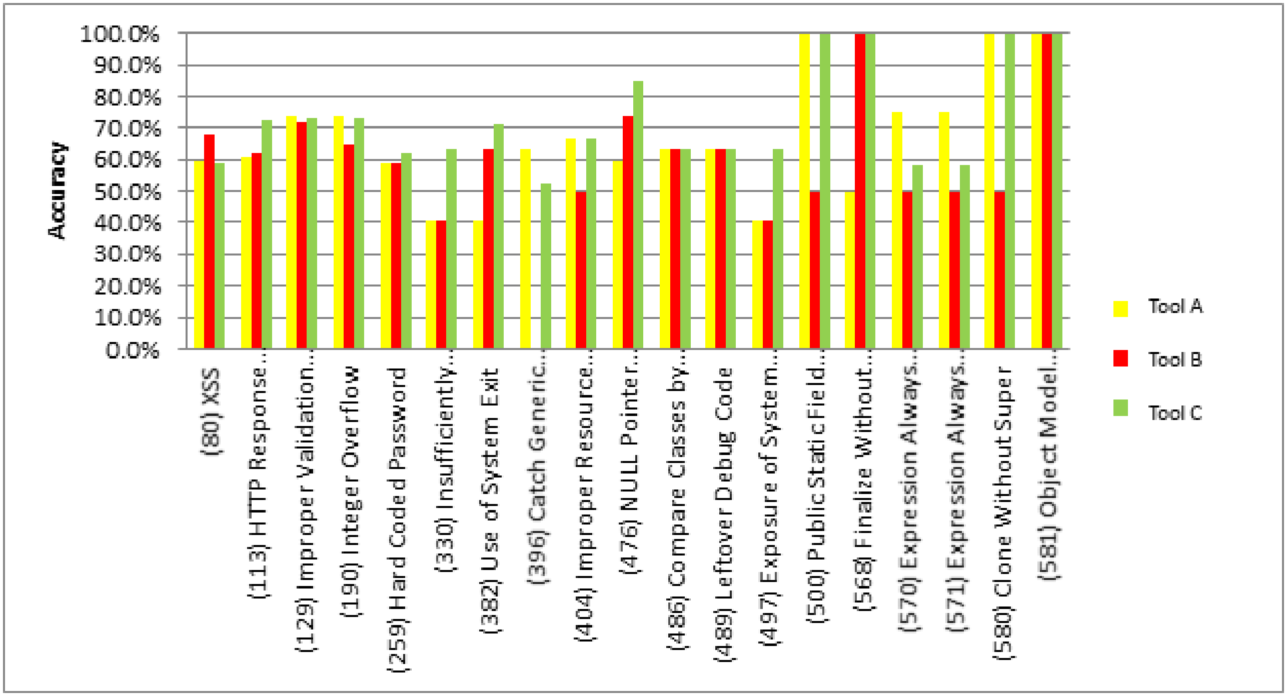


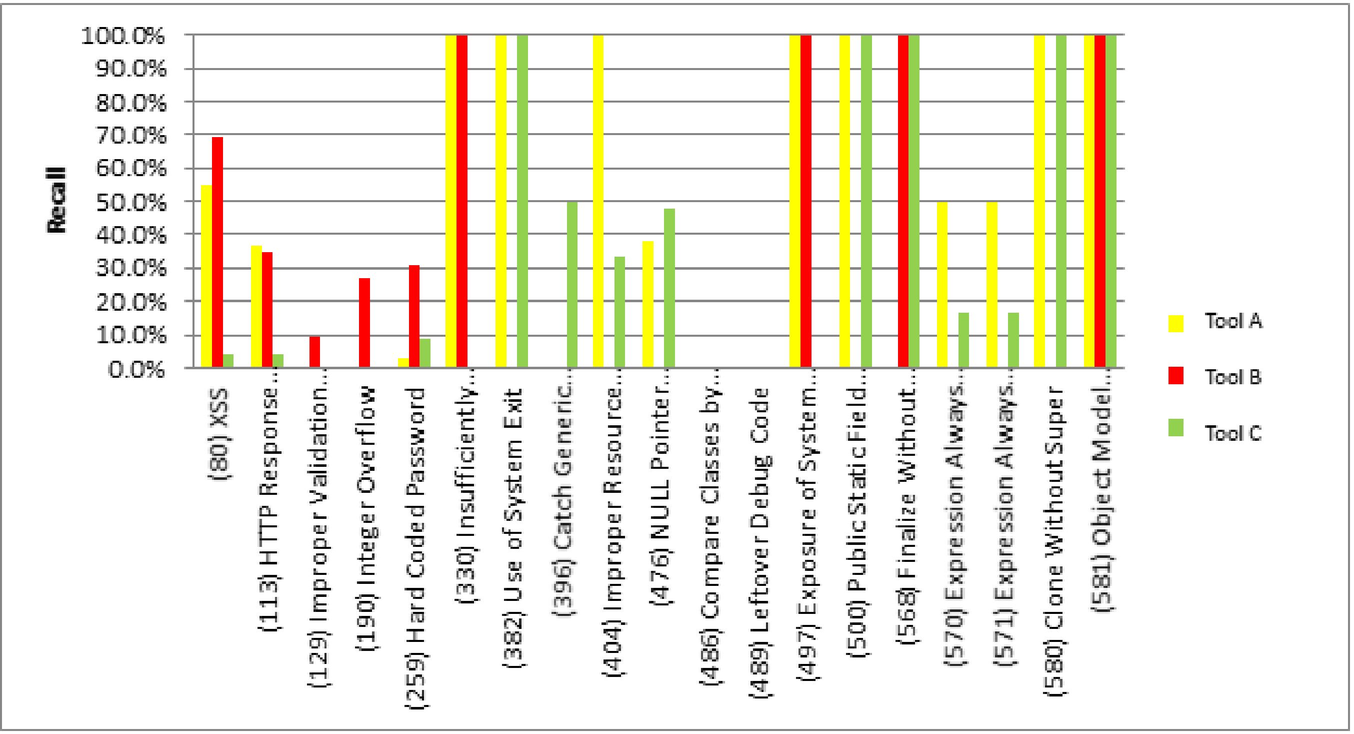
Accuracy values for Java CWEs vary somewhat more than those for C/C++ CWEs

All three tools attain a maximum accuracy value for several CWEs

Tool C seems to be performing slightly better than the other two tools

Tool A: Range [0.41,1], Average = 0.67, Median = 0.63
Tool B: Range [0,1], Average = 0.60, Median = 0.63
Tool C: Range [0.52,1], Average = 0.73, Median = 0.67

Recall: Java CWEs



Again, there were CWEs (i.e., 486 and 489) for which none of the tools correctly flagged any flawed constructs

However, not as many as in case of C/C++ test suite

Tool A performed slightly better than the other two tools

Tool A: Range [0,1], Average = 0.49, Median = 0.50
Tool B: Range [0,1], Average = 0.35, Median = 0.18
Tool C: Range [0,1], Average = 0.36, Median = 0.17

Probability of false alarm: Java CWEs

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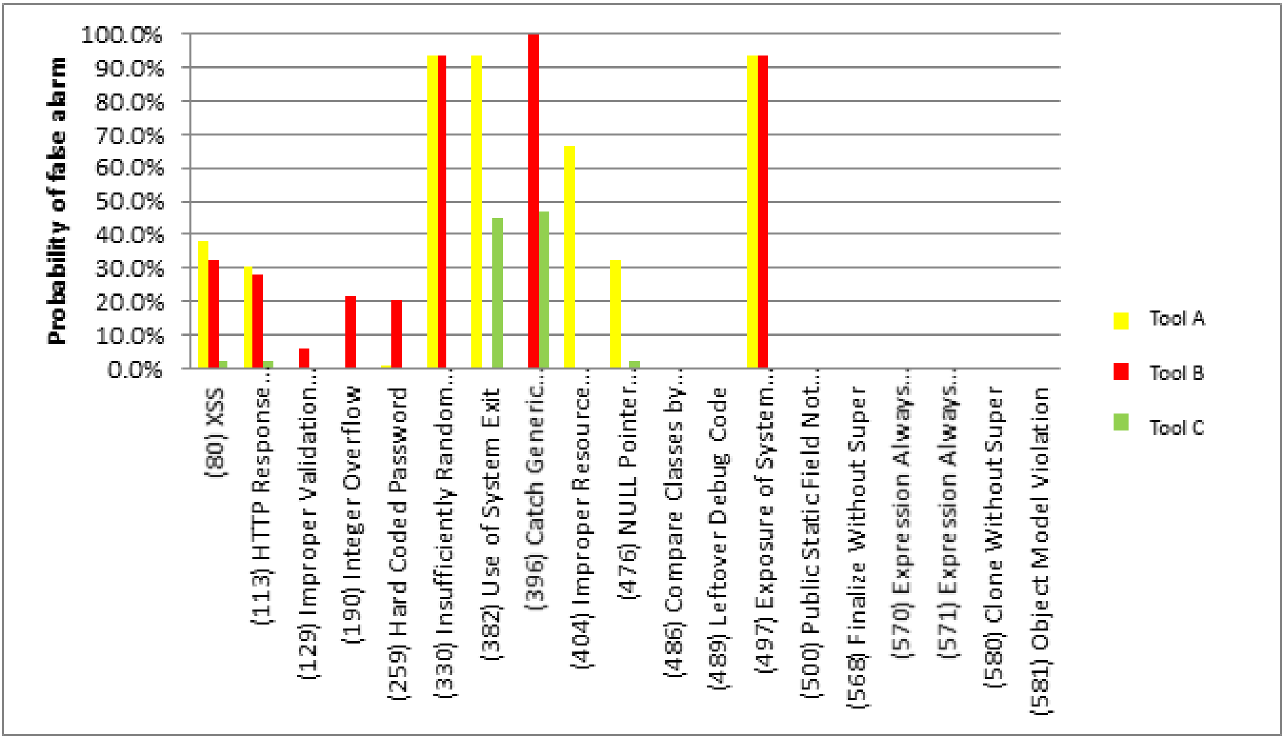

Similar trend as in case of the C/C++ false alarm values

Tool C performed better than the other two tools; Tool A performed slightly better than Tool B.

Tool A: Range [0,0.94], Average = 0.24, Median = 0
Tool B: Range [0,1], Average = 0.25, Median = 0.03
Tool C: Range [0,0.47], Average = 0.05, Median = 0

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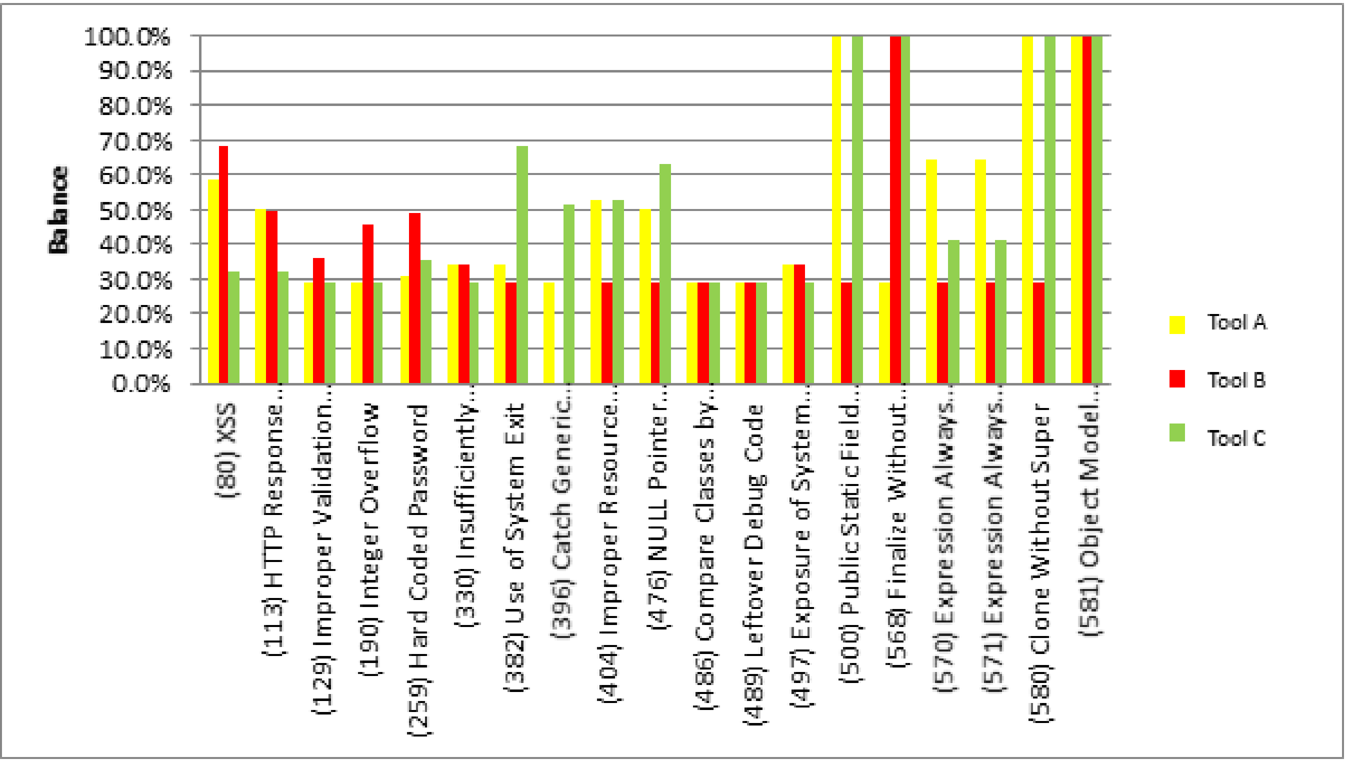
Balance: Java CWEs



Similar trend as in case of C/C++ balance values

For many CWEs balance values were around 30%, which is an indicator of overall poor performance

Tools A and C appear to perform slightly better than Tool B

Tool A: Range [0.29,1], Average = 0.50, Median = 0.34
Tool B: Range [0,1], Average = 0.43, Median = 0.34
Tool C: Range [0.29,1], Average = 0.52, Median = 0.41

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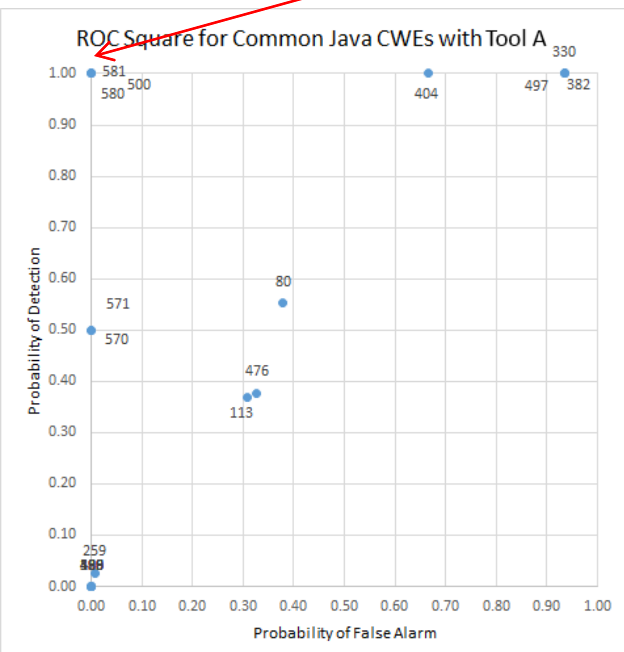
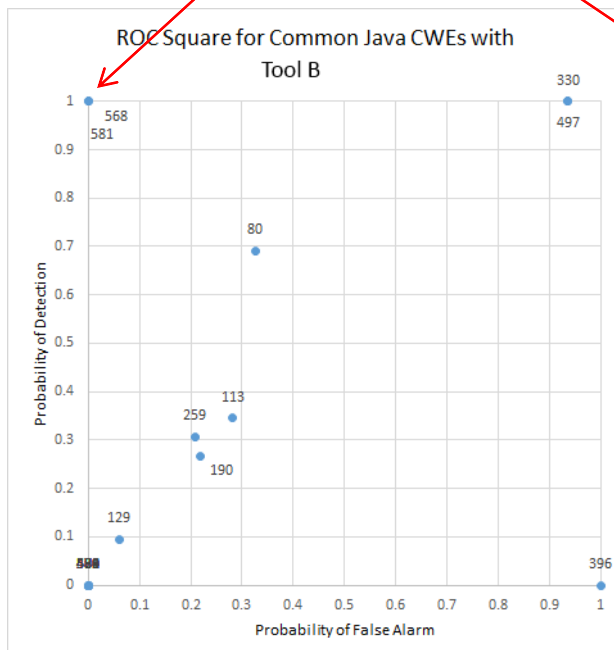
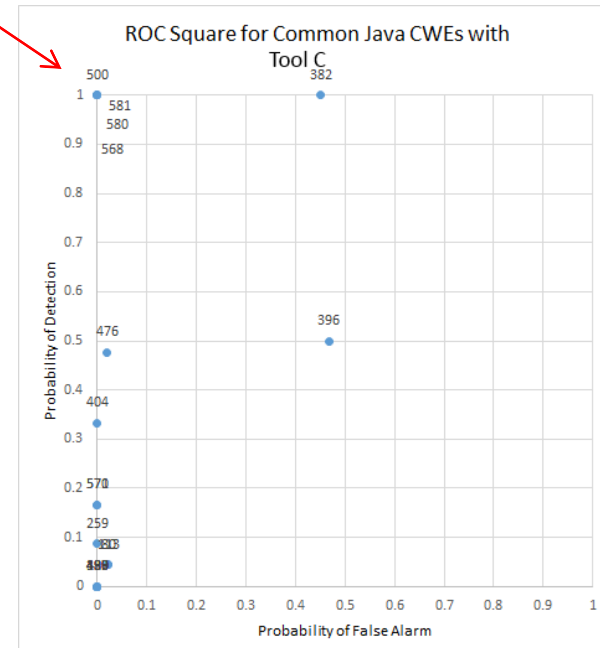
ROC squares for Java CWEs

Ideal result
(pf, pd) = (0, 1)







Not many points are close to the ideal (0,1) point
Tool C has noticeably lower false alarm rate
For each tool there are multiple CWEs at the (0,0) point

CWE/SANS top 25 most dangerous software errors

C/C++

- CWE 78 OS Command Injection
  - Tool A had the highest recall (54%), but also very high probability of false alarm (89%)
  - Tools B and C performed poorly, with recall values around 4% and 0% respectively
- CWE 134 Uncontrolled Format String
  - Tool C was the most successful (with recall close to 79%), but with high probability of false alarm (i.e., 48%)
  - Tools A and B had lower recall values (i.e., around 30% and 38%, respectively)

CWE/SANS top 25 most dangerous software errors

Java

- CWE 190 Integer Overflow
  - Tool B had recall of around 27%, with relatively high false alarm rate of almost 22%
  - Neither Tool A nor Tool B detected CWE 190 (i.e. they had 0% recall)

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EVALUATION BASED ON REAL PROGRAMS

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Evaluation based on real software

- Three open-source software applications
  - Gzip
  - Dovecot
  - Apache Tomcat
- Older version with known vulnerabilities
- More recent version with the same vulnerabilities being fixed was used as an oracle
- A total of 44 known vulnerabilities in the three applications, mapped to 8 different CWEs

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Gzip: Basic facts

- Popular open source archiving tool
- Written in C
- ~8,500 LOC
- Vulnerable version: 1.3.5 with 4 known vulnerabilities
- Version with fixed vulnerabilities: 1.3.6

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Gzip: Results

Gzip-1.3.5 version with known vulnerabilities

Tool	Warnings	Number of detected vulnerabilities
Tool A	112	1 out of 4
Tool B	36	0 out of 4
Tool C	119	1 out of 4

True positive

Gzip-1.3.6 version with fixed vulnerabilities

Tool	Warnings	Number of reported vulnerabilities
Tool A	206	1 out of 4
Tool B	125	0 out of 4
Tool C	374	1 out of 4

False positive

Dovecot: Basic facts

- IMAP/POP3 server for Unix-like operating systems
- Written in C
- ~280,000 LOC
- Vulnerable version: 1.2.0 with 8 known vulnerabilities
- Version with fixed vulnerabilities: 1.2.17

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Dovecot: Results

Dovecot-1.2.0 version with known vulnerabilities

Tool	Warnings	Number of detected vulnerabilities
Tool A	8,263	0 out of 8
Tool B	538	0 out of 8
Tool C	1,356	0 out of 8

Dovecot-1.2.17 version with fixed vulnerabilities

Tool	Warnings	Number of reported vulnerabilities
Tool A	8,655	0 out of 8
Tool B	539	0 out of 8
Tool C	1,293	0 out of 8

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Tomcat: Basic facts

- Open source Java Servlet and JavaServer Pages implementation
- Written in Java
- ~4,800,000 LOC
- Vulnerable version: 5.5.13 with 32 known vulnerabilities
- Version with fixed vulnerabilities: 5.5.33

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Tomcat: Basic facts

- Due to its much greater complexity, the majority of Tomcat's vulnerabilities span several files and/or locations within each file
  - 4 out of 32 vulnerabilities occur at one location within one file
  - 9 out of 32 vulnerabilities occur at multiple locations within one file
  - 19 out of 32 vulnerabilities occur in multiple files
- We consider a true positive found if at least one of the file(s)/location(s) are matched by a tool

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Tomcat: Results

Tomcat-5.5.13 version with known vulnerabilities

Tool	Warnings	Number of detected vulnerabilities
Tool A	12,399	7 out of 32
Tool B	12,904	3 out of 32
Tool C	20,608	5 out of 32

True positives

Tomcat-5.5.33 version with fixed vulnerabilities

Tool	Warnings	Number of reported vulnerabilities
Tool A	167,837	2 out of 32
Tool B	13,129	0 out of 32
Tool C	21,128	1 out of 32

False positives

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CONCLUDING REMARKS

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Conclusions

- None of the three tools produced very good results (i.e., high probability of detection (i.e., recall) and low probability of false alarm)
- Tool C had the smallest false alarm rate among the three tools (mean value of 7% for the common C/C++ CWEs and 5% for the common Java CWEs)
- Some CWEs were detected by all three tools, others by a combination of two tools or a single tool, while some CWEs were missed by all three tools

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Conclusions

- The results of the evaluation with real open source programs were consistent with the evaluation based on the Juliet test suite
  - All three tools had high false negative rates (i.e. were not able to identify majority of the known vulnerabilities)
  - Tool A outperformed the other two tools on the application implemented in Java
- Static code analysis cannot be used as an assurance that the software is secure. Rather, it should be one of the techniques used, in addition to other complementary techniques