

Andromeda: Accurate and Scalable Security Analysis of Web Applications



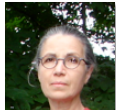
Omer Tripp
Tel Aviv University & IBM
omert@il.ibm.com



Marco Pistoia
IBM T. J. Watson Research Center
pistoia@us.ibm.com



Patrick Cousot
New York University
pcousot@cs.nyu.edu



Radhia Cousot
École Normale Supérieure
radhia.cousot@ens.fr



Salvatore Guarnieri
University of Washington & IBM
sguarni@us.ibm.com



XSS

<SCRIPT>...</SCRIPT>



3

OWASP* Top Ten Security Vulnerabilities



1. Cross-site scripting (XSS) ←
2. Injection flaws ←
3. Malicious file executions ←
4. Insecure direct object reference ←
5. Cross site request forgery (CSRF) ←
6. Information leakage and improper error handling ←
7. Broken authentication and improper session management
8. Unsecure cryptographic storage
9. Unsecure communications
10. Failure to restrict URL accesses

* Open Web Application Security Project (OWASP): <http://www.owasp.org>

2

SQL Injection



```
String query = "SELECT * FROM users WHERE name=' " +
    userName + "' AND pwd=' " + pwd + "'";
```

Username:

Password:

```
SELECT * FROM users WHERE name='jsmith' AND pwd='Demo1234'
```

Username:

Password:



Ouch!

```
SELECT * FROM users WHERE name='foo';drop table custid;--' AND pwd=''
```

4

Malicious File Executions



- Web application manage files in the file system
- The name or contents of such files are often obtained from user input
- Maliciously crafted user inputs could cause the execution or deletion of security-sensitive files

5

Existing Static-Analysis Solutions



- Type systems:
 - Complex, conservative, require code annotations
- Classic slicing:
 - Has not been shown to scale to large applications while maintaining sufficient accuracy

7

Information Leakage and Improper Error Handling



```
org.apache.jasper.JasperException: /rest.jsp(1,1) #06036: include action: Mandatory attribute page missing
org.apache.jasper.compiler.DefaultErrorHandler.jspError(DefaultErrorHandler.java:49)
org.apache.jasper.compiler.DefaultErrorHandler.dispatch(ErrorDispatcher.java:148)
org.apache.jasper.compiler.ErrorDispatcher.dispatch(ErrorDispatcher.java:150)
org.apache.jasper.compiler.TagFileCheckAction.visit(Validator.java:294)
org.apache.jasper.compiler.Validator.Validator.visit(Validator.java:149)
org.apache.jasper.compiler.NodeInclusionAction.accept(Node.java:1022)
org.apache.jasper.compiler.Node.visit(Node.java:224)
org.apache.jasper.compiler.NodeInclusion.visitBody(Node.java:234)
org.apache.jasper.compiler.Validator.visit(Node.java:230)
org.apache.jasper.compiler.NodeInclusion.visit(Node.java:460)
org.apache.jasper.compiler.Validator.visit(Node.java:224)
org.apache.jasper.compiler.Validator.visit(Node.java:175)
org.apache.jasper.compiler.Compiler.generateJava(Compiler.java:168)
org.apache.jasper.compiler.Compiler.compile(Compiler.java:147)
org.apache.jasper.compiler.Compiler.compileFromContext(Compiler.java:595)
org.apache.jasper.servlet.JspServletWrapper.service(JspServletWrapper.java:144)
org.apache.jasper.servlet.JspServlet.service(JspServlet.java:457)
org.apache.jasper.servlet.JspServletWrapper.service(JspServlet.java:151)
java.servlet.http.HttpServlet.service(HttpServlet.java:917)
com.sun.webserver.connector.napi.NAPIProcessor.service(NAPIProcessor.java:160)
```

6

Motivation

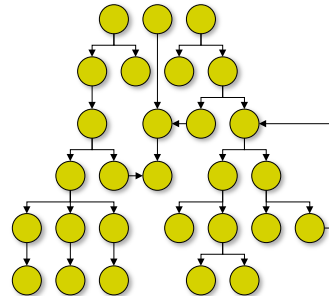


- Web applications are large and complex
- Sound analyses
 - If too precise, do not scale well
 - If too imprecise, have too many false positives
- Unsound analyses
 - Have false negatives
 - Are often unstable (extra-sensitivity to program changes)

Intuition behind Andromeda



- Taint analysis can be treated as a demand-driven problem
- This enables lazy computation of vulnerable information flows, instead of eagerly computing a complete data-flow solution



Motivating Example



```
public class Aliasing5 extends HttpServlet {
    protected void doGet(HttpServletRequest req, HttpServletResponse resp)
        throws ServletException, IOException {
        StringBuffer buf = new StringBuffer("abc");
        foo(buf, buf, resp, req);
    }

    void foo(StringBuffer buf, StringBuffer buf2, ServletResponse resp,
        ServletRequest req) throws IOException {
        String name = req.getParameter("name");
        buf.append(name);
        PrintWriter writer = resp.getWriter();
        writer.println(buf2.toString()); /* BAD */
    }
}
```

Publications on Andromeda



- FASE 2013 – Andromeda algorithm
 - Omer Tripp, Marco Pistoia, Patrick Cousot, Radhia Cousot, Salvatore Guarnieri, “Andromeda: Accurate and Scalable Security Analysis of Web Applications”
- OOPSLA 2011 – Integration with Framework for Frameworks (F4F)
 - Manu Sridharan, Shay Artzi, Marco Pistoia, Salvatore Guarnieri, Omer Tripp, Ryan Berg, “F4F: Taint Analysis of Framework-based Web Applications”
- ISSTA 2011 (1) – Andromeda for JavaScript
 - Salvatore Guarnieri, Marco Pistoia, Omer Tripp, Julian Dolby, Stephen Teilhet, Ryan Berg, “Saving the World Wide Web from Vulnerable JavaScript”
- ISSTA 2011 (2) – Andromeda as the basis for String Analysis (ACM SIGSOFT Distinguished Paper Award)
 - Takaaki Tateishi, Marco Pistoia, Omer Tripp, “Path- and Index-sensitive String Analysis based on Monadic Second-order Logic”
- IBM Journal on Research and Development 2013 – Permission analysis for Android applications
 - Dragoş Sbirlea, Michael G. Burke, Salvatore Guarnieri, Marco Pistoia, Vivek Sarkar, “Automatic Detection of Inter-application Permission Leaks in Android Applications”

Contributions of Andromeda



- Scalable and sound demand-driven taint analysis
- Modular analysis
- Incremental analysis
- Framework and library support
- Multiple language support (Java, .NET, JavaScript)
- Inclusion in an IBM product: IBM Security AppScan Source



High-level Algorithm

- Input: Web application plus supporting rules
 - $\{(Sources, Sinks, Sanitizers)\}$
- Build class hierarchy
- Construct CHA-based call graph with intra-procedural type-inference optimization
- Perform data-flow analysis (explained next)
- Report any flow from a source to a sink not intercepted by a sanitizer in the same rule



Modularity of the Analysis

- Runs on data flow (def-to-use)
- Produces and uses pre-compiled models
 - Format:


```
<method, entry> → <method, exit>
```
 - Example:


```
<m, v2.f.g> → <m, v1.h>
```



Abstract Domain

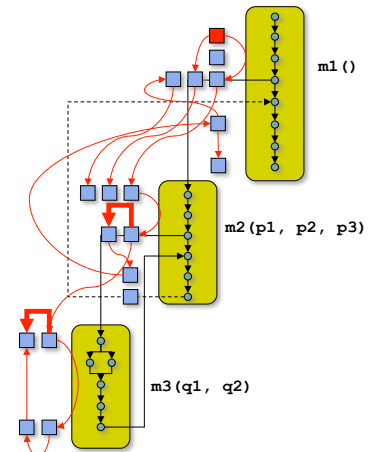
- Consists of triplets:
 - Method where Static Single Assignment (SSA) variable is defined
 - SSA variable ID
 - Access path
- Inputs form a lattice according to subsumption relation defined on access paths, e.g.:

$$o.* \geq o.f.* \geq o.f.g$$
 - The * symbol represents any feasible sub-path
 - Array load/store semantics is applied to arrays, maps, session objects, etc.



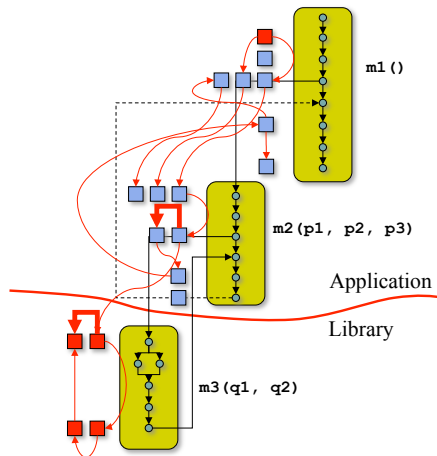
A Novel Approach to Taint Analysis

- Start from taint sources
- Propagate taint intra-procedurally through def-to-use
- Inter-procedurally propagate taint forward and record constraints in callees
- Record constraints on call sites, recursively (allows for polymorphism)
- Resolve aliasing by going back to allocation sites
- In the final *constraint-propagation graph*, detect paths between sources and sinks not intercepted by sanitizers



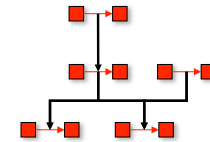
Modular Analysis

- Persist constraint edges at library entrypoints
- Constraint edges are mapped to contexts
- During analysis time, the constraint edges specific to a particular context are used
- Summaries are source-, sink- and sanitizer-specific



Incremental Analysis

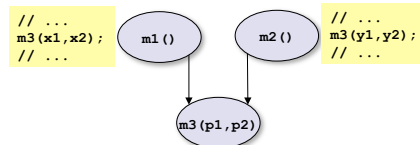
- A *taint constraint* is an edge in the constraint-propagation graph $\blacksquare \rightarrow \blacksquare$
- The *support graph* records how constraints were learned (i.e., based on which other constraints)
- Facts learned in a scope that underwent change are transitively invalidated
- Preconditions recomputed
- Fixed-point analysis recommenced



Backward Propagation

- Pushes constraints back to callers
 - Infinite context sensitivity
 - Polymorphism with respect to taint
- The constraint $p1.f.g \rightarrow p2.h$ in $m3$ is propagated to $m1$ and $m2$ (and, recursively, to their callers)

- $x1.f.g \rightarrow x2.h$
- $y1.f.g \rightarrow y2.h$



Integration with F4F

- F4F (OOPSLA 2011) analyzes code and metadata of frameworks and represents them in artifacts written in an XML-like language
- Andromeda translates those artifacts into legal Java code that – from a data-flow perspective – is equivalent to the original framework code
- New code is human-readable and reusable by other analyzers
- New code is compiled and added to the analysis scope



Experimental Results*



	ANDROMEDA	TAJ
Average TPs	82%	68%
Average FPs	12%	30%
Average Unknowns	6%	2%

Change Type	Response Time (s)			
	AltoroJ		Webgoat	
	Deletion	Addition	Deletion	Addition
Taint-propagator statement	2	2.2	1.9	2.2
Security sink	0.5	2	1.9	2.5
Security source	2.1	2.1	1.8	3.2
Irrelevant statement	1.9	2	2.5	2.8
Relevant method	2.2	1.9	1.8	2.7
Irrelevant method	2.2	1.7	1.7	1.7

* More details in paper

Thank You!

pistoia@us.ibm.com



Conclusion



- The notorious scalability barrier finally lifted without compromising soundness
- Incremental analysis is a great promise for developers
- Production summaries already generated