Static Detection of Web Application Vulnerabilities

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Reading Assignment

- Jovanovic et al. “Pixy: A Static Analysis Tool for Detecting Web Application Vulnerabilities.”
- Wassermann and Su. “Sound and Precise Analysis of Web Applications for Injection Vulnerabilities” (PLDI 2007).

Pixy

[Jovanovic, Kruegel, Kirda]

- Uses static analysis to detect cross-site scripting and SQL injection vulnerabilities in PHP apps
  - Same ideas apply to other languages
- Basic idea: identify whether “tainted” values can reach “sensitive” points in the program
  - Tainted values: inputs that come from the user (should always be treated as potentially malicious)
  - Sensitive “sink”: any point in the program where a value is displayed as part of HTML page (XSS) or passed to the database back-end (SQL injection)

Example of Injection Vulnerabilities

```
1: function postcomment($id, $title) {
2:     ...
3:     $title = urldecode($title);
4:     ...
5:     echo $title;
6:     ...
7: }
```

tainted

sensitive sink

```
 1: if (...) {
 2:     $entry = $_GET['entry'];
 3:     ...
 4:     $temp_file_name = $entry;
 5:     ...
 6: } else {
 7:     ...
 8:     $temp_file_name =
            stripslashes($_POST['file_name']);
 9:     ...
10: }
11: ...
12: echo($temp_file_name);
```

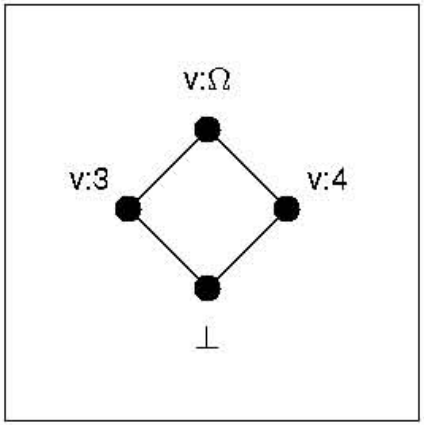
Main Static Analysis Issues

- Taint analysis
  - Determine, at each program point, whether a given variable holds unsanitized user input
- Data flow analysis
  - Trace propagation of values through the program
- Alias analysis
  - Determine when two variables refer to the same memory location (why is this important?)
- Pixy: flow-sensitive, context-sensitive, interprocedural analysis (what does this mean?)

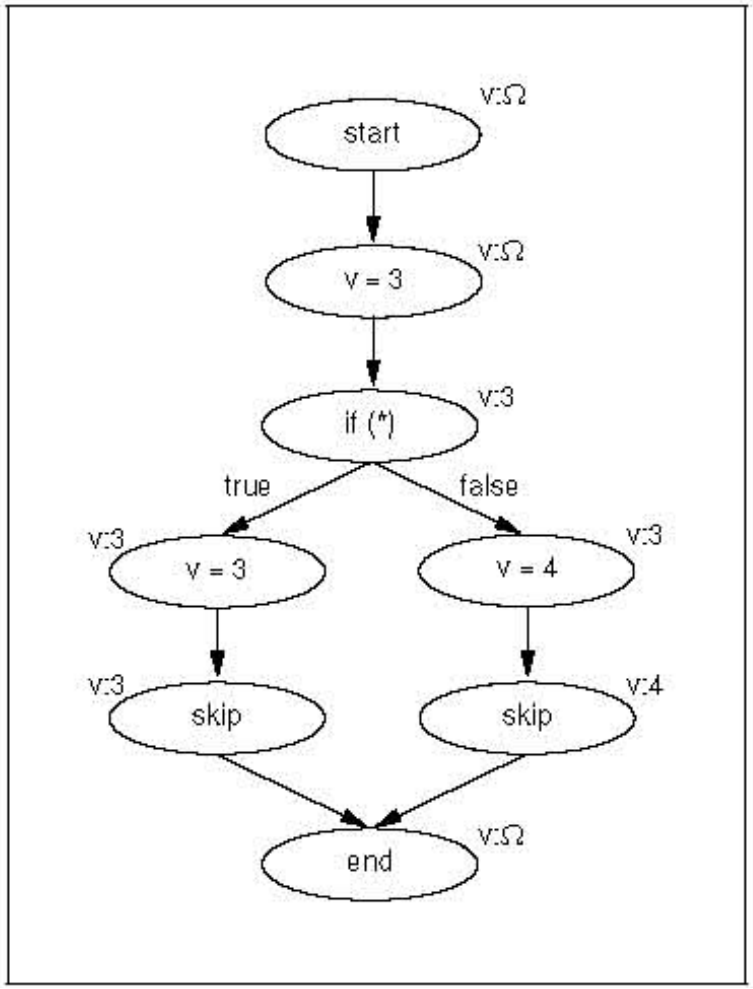
Handling Imprecision

- Static data flow analysis is necessarily imprecise (why?)
- Maintain a lattice of possible values
  - Most precise at the bottom, least precise (Ω) at the top
- Example from the paper

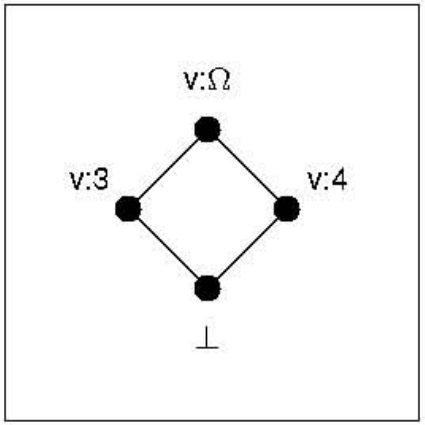
```
v = 3;
if (some condition on user input)
                v = 3;
else            v = 4;
```



Annotated Control-Flow Graph



Carrier lattice



Data Flow Analysis in PHP

- PHP is untyped; this makes things difficult
- How do we tell that a variable holds an array?
  - Natural: when it is indexed somewhere in program
  - What about this code?

```
$a[1] = 7;  $b = $a;  $c = $b;  echo $c[1];
```

- Assignments to arrays and array elements
  - `$a = $b;  // ... where $a is an array`
  - `$a[1][2][3] = ...`
  - `$a[1][$b[$i]] = ...`

Other Difficulties

- Aliases (different names for same memory loc)

  $a = 1; $b = 2; $b =& $a; $a=3; // $b==3, too!

- Interprocedural analysis
  - How to distinguish variables with the same name in different instances of a recursive function?

```
 1: function f1() {
 2:   // when entering this function, the local variables $a and $b
 3:   // do NOT point to the same memory location
 4:   $a; $b;
 5:
 6:   // after the following statement, $a and $b DO point to the same memory location,
 7:   // but this must not affect $a and $b in other incarnations of this function
 8:   $a =& $b;
 9:
10:   if (..) f1();
11: }
```

What is the depth of this recursion?

Modeling Function Calls

- Call preparation
  - Formal parameter ← actual argument
    - Similar to assignment
  - Local variables ← default values
- Call return
  - Reset local variables
  - For pass-by-reference parameters,
    actual argument ← formal parameter
    - What if the formal parameter has an alias inside function?
  - What about built-in PHP functions?
    - Model them as returning Ω, set by-reference params to Ω

Taint Analysis

- Literal – always untainted
- Variable holding user input – tainted
  - Use data flow analysis to track propagation of tainted values to other variables
- A tainted variable can become untainted
  - $a = <user input>; $a = array();
  - Certain built-in PHP functions
    - htmlentities(), htmlspecialchars() – what do they do?

False Positives in Pixy

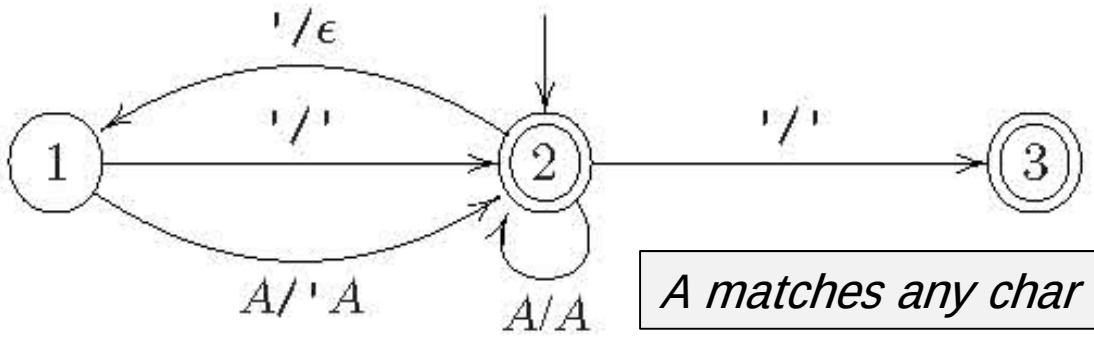
- Dynamically initialized global variables
  - When does this situation arise?
  - Pixy conservatively treats them as tainted
- Reading from files
  - Pixy conservatively treats all files as tainted
- Global arrays sanitized inside functions
  - Pixy doesn't track aliasing for arrays and array elements
- Custom sanitization
  - PhpNuke: remove double quotes from user-originated inputs, output them as attributes of HTML tags – is this safe? why?

Wassermann-Su Approach

- Focuses on SQL injection vulnerabilities
- Soundness
  - Tool is guaranteed to find all vulnerabilities
  - Is Pixy sound?
- Precision
  - Models semantics of sanitization functions
  - Models the structure of the SQL query into which untrusted user inputs are fed
  - How is this different from tools like Pixy?

“Essence” of SQL Injection

- Web app provides a template for the SQL query
- Attack = any query in which user input changes the intended structure of SQL query
- Model strings as context-free grammars (CFG)
  - Track non-terminals representing tainted input
- Model string operations as language transducers
  - Example: str_replace(“ ’ ’ “, “ ’ “, $input)



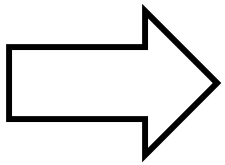
A matches any char except “ ’ “

Phase One: Grammar Production

- Generate annotated CFG representing set of all query strings that program can generate

```
...
01 isset ($_GET['userid']) ?
02     $userid = $_GET['userid'] : $userid = '';
03 if ($USER['groupid'] != 1)
04 {
05     // permission denied
06     unp_msg($gp_permserror);
07         exit;
08 }
09 if ($userid == '')
10 {
11     unp_msg($gp_invalidrequest);
12     exit;
13 }
14 if (!eregi('[0-9]+', $userid))
15 {
16     unp_msg('You entered an invalid user ID.');
17     exit;
18 }
19 $getuser = $DB->query("SELECT * FROM `unp_user`"
20                       ."WHERE userid='$userid'");
21 if (!$DB->is_single_row($getuser))
22 {
23     unp_msg('You entered an invalid user ID.');
24     exit;
25 }
...
```

Example code with an SQLCIV.



query → *query1*'
query1 → *query2 userid*
query2 → *query3* WHERE userid='
query3 → SELECT * FROM `unp_user`
userid → *GETuid*
GETuid → Σ* [0–9] Σ*

direct = {*GETuid*} indirect = {}

Grammar productions of possible query strings

Direct:
data directly from users
(e.g., GET parameters)

Indirect:
second-order tainted
data (means what?)

String Analysis + Taint Analysis

- Convert program into static single assignment form, then into CFG
  - Reflects data dependencies
- Model PHP filters as string transducers
  - Some filters are more complex:
    preg_replace("/a([0-9]*)b/", "x\\1\\1y", "a01ba3b") produces "x0101yx33y"
- Propagate taint annotations

(a)
```
$X = $UNTRUSTED;
if ($A) {
   $X = $X."s";
} else {
   $X = $X."s";
}
$Z = $X;
```

(b)
```
$X1 = $UNTRUSTED;
if ($A) {
   $X2 = $X1."s";
} else {
   $X3 = $X1."s";
}
$X4 = φ($X2, $X3);
$Z = $X4;
```

(c)

$$
\begin{array}{ll}
UNTRUSTED & \rightarrow \Sigma^* \\
X_1 & \rightarrow UNTRUSTED \\
X_2 & \rightarrow X_1\mathbf{s} \\
X_3 & \rightarrow X_1\mathbf{s} \\
X_4 & \rightarrow X_2 \mid X_3 \\
Z & \rightarrow X_4
\end{array}
$$

Phase Two: Checking Safety

- Check whether the language represented by CFG contains unsafe queries
  - Is it syntactically contained in the language defined by the application's query template?

query → *query1* '
query1 → *query2 userid*
query2 → *query3* `WHERE userid='`
query3 → `SELECT * FROM `unp_user``
userid → *GETuid*
GETuid → $\Sigma*$ [0–9] $\Sigma*$

direct = {*GETuid*} indirect = {}

Grammar productions of possible query strings

This non-terminal represents tainted input

For all sentences of the form σ_1 GETUID σ_2 derivable from query, GETUID is between quotes in the position of an SQL string literal (means what?)

Safety check:
Does the language rooted in GETUID contain unescaped quotes?

Tainted Substrings as SQL Literals

- Tainted substrings that cannot be syntactically confined in any SQL query
  - Any string with an odd # of unescaped quotes (why?)
- Nonterminals that occur only in the syntactic position of SQL string literals
  - Can an unconfined string be derived from it?
- Nonterminals that derive numeric literals only
- Remaining nonterminals in literal position can produce a non-numeric string outside quotes
  - Probably an SQL injection vulnerability
  - Test if it can derive DROP WHERE, --, etc.

Taints in Non-Literal Positions

- Remaining tainted nonterminals appear as non-literals in SQL query generated by the application
  - This is rare (why?)
- All derivable strings should be proper SQL statements
  - Context-free language inclusion is undecidable
  - Approximate by checking whether each derivable string is also derivable from a nonterminal in the SQL grammar
    - Variation on a standard algorithm

Evaluation

- Testing on five real-world PHP applications
- Discovered previously unknown vulnerabilities, including non-trivial ones
  - Vulnerability in e107 content management system:

    a field is read from a user-modifiable cookie, used in a query in a different file
- 21% false positive rate
  - What are the sources of false positives?

Example of a False Positive

```
isset($_GET['newsid']) ?
    $getnewsid = $_GET['newsid'] :
    $getnewsid = false;
if ((($getnewsid != false) &&
    (!preg_match('/^[\d]+$/', $getnewsid)))
{
    unp_msg('You entered an invalid news ID.');
    exit;
}
...
if (!$showall && $getnewsid)
{
   $getnews = $DB->query("SELECT * FROM `unp_news`"
                        ."WHERE `newsid`='$getnewsid'"
                        ."ORDER BY `date`DESC LIMIT 1");
}
```