Static Detection of Security Vulnerabilities in Scripting Languages

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Background

There are some key concepts used before diving into this static analysis approach

PHP

- Scripting languages are different
  - $_GET and $_POST user input
  - Stateless execution
- Dynamic native functionality and constructs
  - Dynamic includes
    - Mimics cut and paste of code into a script
    - Inherits runtime state of program at time of include
  - Dynamic variable types
  - Dynamic hash tables
  - Extract function
  - Eval function for implicit execution

PHP Code Examples

- Some strings are dynamic, some are not
  - $var = “$other_var”; $var = ‘$other_var’;
- This function creates different variables based on run-time user input
  - extract($_GET);
- This block loads an include file based on run-time user input
  - $operation = $_GET[‘operation’];
    include(“/includes/$operation.include”);
  - Operation include could contain trusted functionality
- Hash table using string variable keys
  - $field = ‘first_name’;
    $field_value = $_GET[$first_name];
- Possibly unmediated eval call
  - $string = $_GET[‘string’];
    eval(“echo $string;”);
  - Could contain a value like: ‘NULL; mysql_query(“delete from users”)

SQL Injection

- Unintended user input in database queries
- PHP has native functionality for databases
  - Makes it easier to produce vulnerabilities
  - No native prepared statement and object type integration like Java
- Strings are used in queries
  - String segments can be composed of one or more strings
  - One string may have influence of many variables, including user input

SQL Injection Examples

- Code
  - $whatever = $_GET[‘condition’];
  - mysql_query(“select * from users where name=‘$whatever’”)
- Retrieving information
  - Requests to page.php?condition=nothing’ or 1=1
  - Exposes all user information
- Altering information
  - Requests to page.php?condition=nothing’; delete from users;
  - Truncates data in users table

Basic Blocks

- One entry point and one exit point
  - Block comprised of one or more lines of code in between
- Basic blocks must terminate on “jumps”
  - IF statements, exit command, return command, exceptions
  - Calls and returns with functions
- A maximal basic block cannot be extended to include adjacent blocks without violating a basic block
  - The smallest basic block can be one line of code
  - Maximal basic blocks create blocks for as many lines of code as possible until it violates the rules of a basic block

Control Flow Graph: CFG

Definitions

Basic Block $\equiv$ a sequence of statements (or instructions) $S_1 \ldots S_n$ such that execution control must reach S_1 before S_2, and, if S_1 is executed, then $S_2 \ldots S_n$ are all executed in that order (unless one of the statements causes the program to halt)

Leader $\equiv$ the first statement of a basic block

Maximal Basic Block $\equiv$ a *maximal-length* basic block

CFG $\equiv$ a directed graph (usually for a single procedure) in which:

- Each node is a single basic block
- There is an edge $b_1 \rightarrow b_2$ if block b_2 *may* be executed after block b_1 in *some* execution

NOTE: A CFG is a conservative approximation of the control flow! Why?

Homework: Read Section 9.4 of *Aho, Sethi & Ullman*: algorithm to partition a procedure into basic blocks.

Symbolic Execution

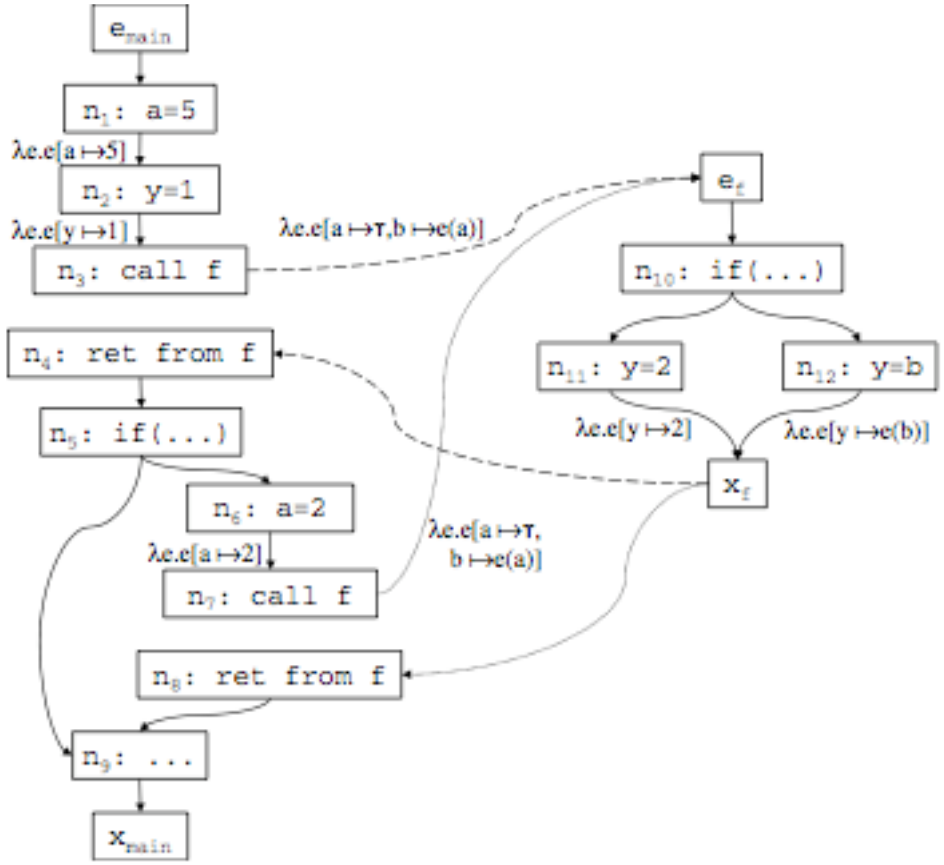
- Applying a symbol to all variables and maintain state throughout all program paths
- Useful for determining how variables change throughout a program
- It is a means of simulating the execution of a block of code

Static Analysis Concept Review

- Abstract domains
  - How the behavior of the program is modeled
- Control flow graphs (ICFG or CFG)
  - Program statements and conditions modeled as nodes
  - ICFG is a collection of CFGs accounting for procedures
- Context sensitivity
  - *Join over all paths* versus *join over all valid paths*
  - Accounting for differences of calls to the same procedure instead of summarizing behavior across all the calls
- Flow sensitivity
  - Differentiating between control-flow paths
- Lattice and transition functions
  - Specific transitions of the CFG that alter lattice within a path
- Concretization function
  - Mapping actual values to the abstract model
- Sinks and sink sources
  - Identifying areas of the code that are meaningful to the analysis
- Summary functions (may/must, Sharir/Pnueli)
  - A means of generalizing behavior of reused code, especially useful in interprocedural data flow

CFG Example from Book

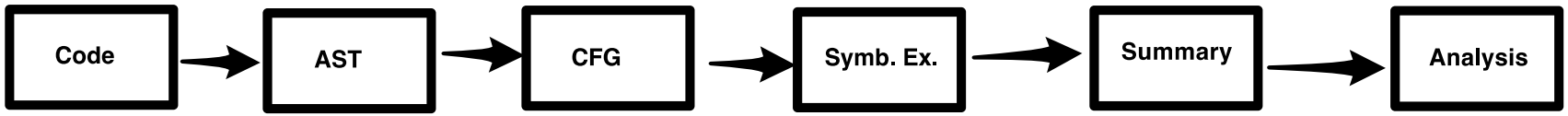
```
int y;

void main() {
  n1: int a = 5;
  n2: y = 1;
  n3,n4: f(a);
  n5: if(...) {
    n6: a = 2;
    n7,n8: f(a);
  }
  n9: ...;
}

void f(int b) {
  n10: if(...)
    n11: y = 2;
  else
    n12: y = b;
}
```



Xie's Analysis Tool (XAT)

This presents a summarization approach that utilizes some of the traditional static analysis concepts we have looked at in class.

Fundamental Workflow



Code to AST

- XAT authors wrote or found a tool to convert the PHP source code into an abstract syntax tree
- Specific to PHP 5.0.5
- AST is then used to produce a control flow graph (CFG)

CFG in XAT

- The CFG in the previous example used basic blocks as nodes
  - These were not maximal basic blocks but still sensitive to jumps
  - More nodes allow for a more precise analysis of the graph by reasoning about the impact of every line
- XAT uses *maximal basic blocks* for nodes of a CFG
  - Each node can represent multiple lines of code
  - The code within the block is summarized by symbolic execution
  - Edges still mimic control flow within graph
  - Seems to be motivated by Harvard's SUIF CFG Library
    - http://www.eecs.harvard.edu/hube/software/v130/cfg.html
- There are multiple CFGs prepared as functions are found
  - Parsing main will uncover function calls
  - Each function is parsed into an AST and gets its own CFG
  - The CFG is then used in the creation of a summary, described later

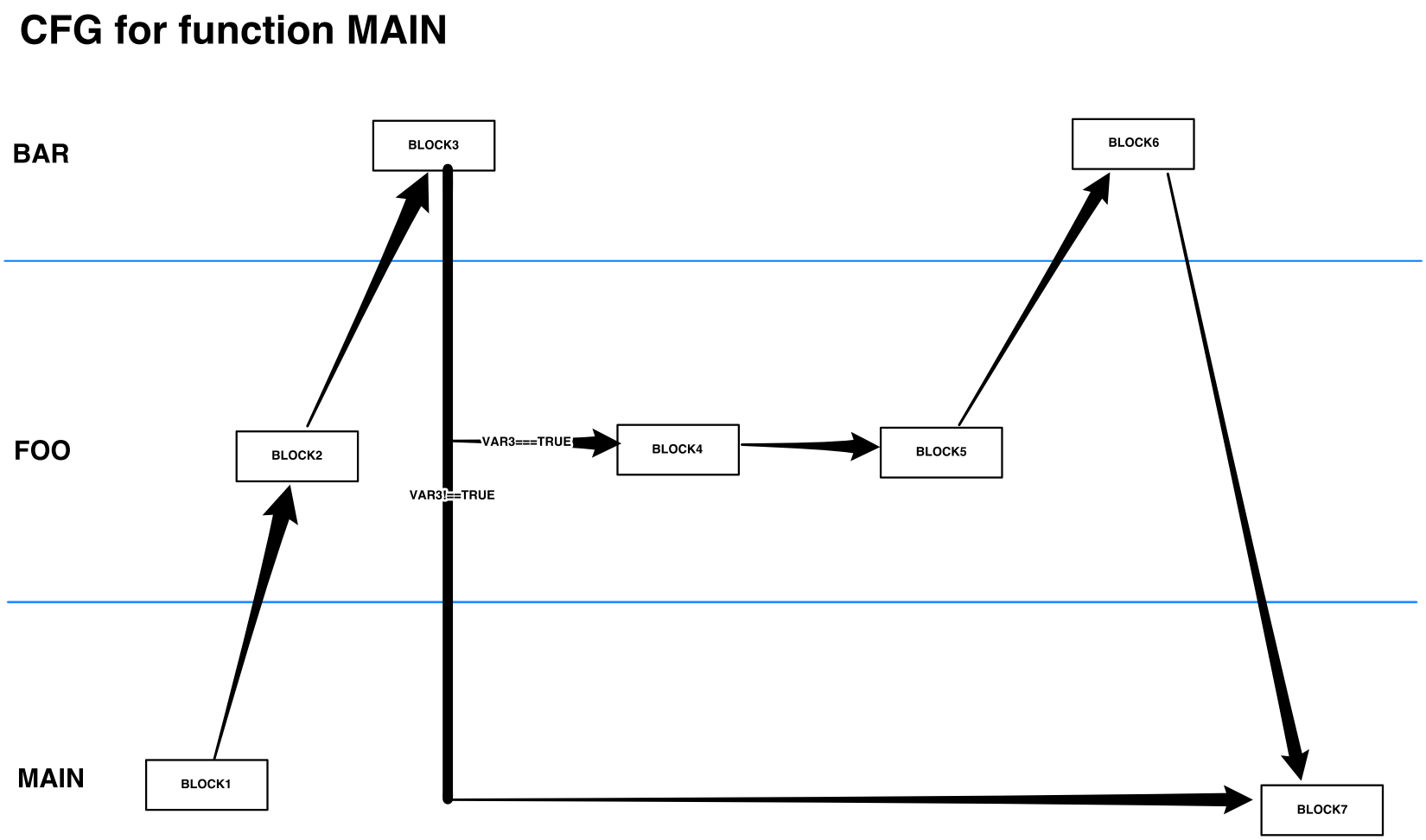
How are the CFGs prepared?

- Start with the primary script, labeled main
  - Parse main into an AST
    - Document user-defined functions found
  - CFG for main is produced by extracting the maximal basic blocks from the AST
    - Edges are the control flow between blocks (jumps)
    - Conditional edges are labeled with the branch predicate
    - Functions are represented by a single node within a calling CFG
      - This references the intraprocedural summary described later
  - Unique CFGs are created for each user-defined function
    - Parsed into an AST and converted into a CFG
    - Also leverages maximal basic blocks
    - Recursive – if functions are found, they too are added in the queue and processed in a similar fashion

Example Code of a “main” script

```
Function foo($x){ … }

Function bar($x, $y){ …. }

$var1 = ‘string value’;
$var2 = ‘string value’; //block 1
$var3 = foo($var1); //block 2
$var4 = bar($var, $var2); //block 3
if($var3 === TRUE){  //branch 1
        $var5 = foo($var4); //block 4
        $var6 = foo($var2); //block 5
        $var7 = bar($var5, $var6); //block 6
                                }
$var8 = ‘string value’;
…
Exit(); //block 7
```

Example of CFG



Symbolic Analysis in XAT

- Processes each maximal basic block found in the CFG
  - Sequential execution that starts at first block of main
  - Stops on end of block, return, exit, or call to a user-defined function that exits
- As the analysis progresses, each *location* is tracked using a *simulation state*
  - A location is a variable or entry in a hash table and has a value

$$\text{State } (\Gamma) : \text{Loc} \rightarrow \text{Value}$$

  - Example: Location X maps to an initial value X_0
  - Each hash table entry is tracked uniquely based on key
- Analysis updates each location's simulation state until the end of the block
  - The end state of the block is captured within the block summary described later

Language Constructs

$$
\begin{array}{rcl}
\text{Type } (\tau) & ::= & \text{str} \mid \text{bool} \mid \text{int} \mid \bot \\
\text{Const } (c) & ::= & \text{string} \mid k \mid \text{true} \mid \text{false} \mid \text{null} \\
\text{L-val } (lv) & ::= & x \mid \texttt{Arg\#i} \mid l[e] \\
\text{Expr } (e) & ::= & c \mid lv \mid e \text{ binop } e \mid \text{unop } e \mid (\tau)e \\
\text{Stmt } (S) & ::= & lv \leftarrow e \mid lv \leftarrow f(e_1, \ldots, e_n) \\
 & \mid & \text{return } e \mid \text{exit} \mid \text{include } e
\end{array}
$$

$$
\begin{array}{rcl}
\text{binop} & \in & \{+, -, \text{concat}, ==, !=, <, >, \ldots\} \\
\text{unop} & \in & \{-, \neg\}
\end{array}
$$

Figure 3: Language Definition

Reasoning about data types

- The symbolic execution accounts for differences in data types within the analysis
- String, boolean, integer, and unknown
  - Input parameters often start out as unknown types
- Strings are the most fundamental data type
  - User input is assumed to be a string when used within a query
  - String concatenation operation consists of other string segments
    - Each segment potentially composed of multiple variable values
  - Particularly useful in analysis of SQL injection to determine what variables influence a query

Boolean and Integer Types

- Boolean variables are useful for sanitization functions
  - Conditionally, a bool can influence sanitizing one or more other variables
  - Untaint(F-set, T-set) maps to each bool variable
    - F-set defines the list of sanitized variables when the boolean is false
    - T-set defines the list of sanitized variables when boolean is true
- Integers are tracked but “less emphasized”
  - Really only useful for when casting as a string or boolean
  - Of note: True = 1, False = 0

Data Type Value Representation

RECALL:

$$\text{State } (\Gamma) : \text{Loc} \rightarrow \text{Value}$$

LIST OF POSSIBLE VALUES:

$$\begin{aligned}
\text{Loc } (l) &::= x \mid l[\text{string}] \mid l[\bot] \\
\text{Init-Values } (o) &::= l_0 \\
\text{Segment } (\beta) &::= \text{string} \mid \text{contains}(\sigma) \\
\text{String } (s) &::= [\beta_1, \ldots, \beta_n] \\
\text{Boolean } (b) &::= \text{true} \mid \text{false} \mid \text{untaint}(\sigma_0, \sigma_1) \\
\text{Loc-set}(\sigma) &::= \{l_1, \ldots, l_n\} \\
\text{Integer } (i) &::= k \\
\text{Value } (v) &::= s \mid b \mid i \mid o \mid \bot
\end{aligned}$$

Hash Tables Case Study

PROGRAM:

```
1  $hash = $_POST;
2  $key = 'userid';
3  $userid = $hash[$key];
```

INITIALIZE:

$$\Gamma = \{\text{hash} \Rightarrow \text{hash}_0, \text{key} \Rightarrow \text{key}_0, \text{\_POST} \Rightarrow \text{\_POST}_0, \\ \text{\_POST}[\text{userid}] \Rightarrow \text{\_POST}[\text{userid}]_0\}$$

SYMBOLIC EXECUTION (Black Magic):

- hash -> $\_POST_0$
- key -> 'userid'
- Hash[key] -> $\_POST[userid]_0$
- userid -> $\_POST[userid]_0$

Include Files

- This is a special case, specific to scripting languages
- Dynamically inserting code into a program
  - Inherits variable scope at the point of include statement
  - Like a “cut and paste” of code into current location
- An include file is processed by… (Draw on board)
  - Parse as an AST and convert into a CFG
  - Extract new user defined functions and process them with their own AST and CFG
  - Remove include statement from the original code and split block into two at point of include (splice operation)
  - Create an edge from the first original calling block to the first block of the include CFG
  - Create an edge for all return blocks of the include CFG to the original second calling block
  - Remove all return statements from blocks produced from include

Summarization Concept

- Should now have an idea of the running program represented as CFGs
- Can now run the analysis using the simulation state tracking of locations and values
  - Analysis tracks information about data throughout each block
- Input to analysis: Source code, query functions, sanitization functions
  - User defined input is assumed to be not sanitized
- Goal is to track sanitization of variables
  - Analyze simulation state throughout entire execution of the program and across procedure calls

Summarization Approach

- XAT summarizes the relevant information for SQL Injection
  - Starts at the first block of the main CFG and traverses through using symbolic execution
  - Updates the simulation state as the analysis progresses
  - Function calls trigger the interprocedural analysis
    - Main calls foo, foo calls bar, etc…
- Interprocedural Analysis
  - The current simulation state of main passed to an instance of the particular intraprocedural summary
  - If no intraprocedural summary exists, it is created and then analysis continues
- Intraprocedural Summary
  - A summary of all block summaries that belong to a function
  - If no block summaries exist, they are created and then analysis continues
- Block Summary
  - Summary of a maximal basic block (node in a CFG)

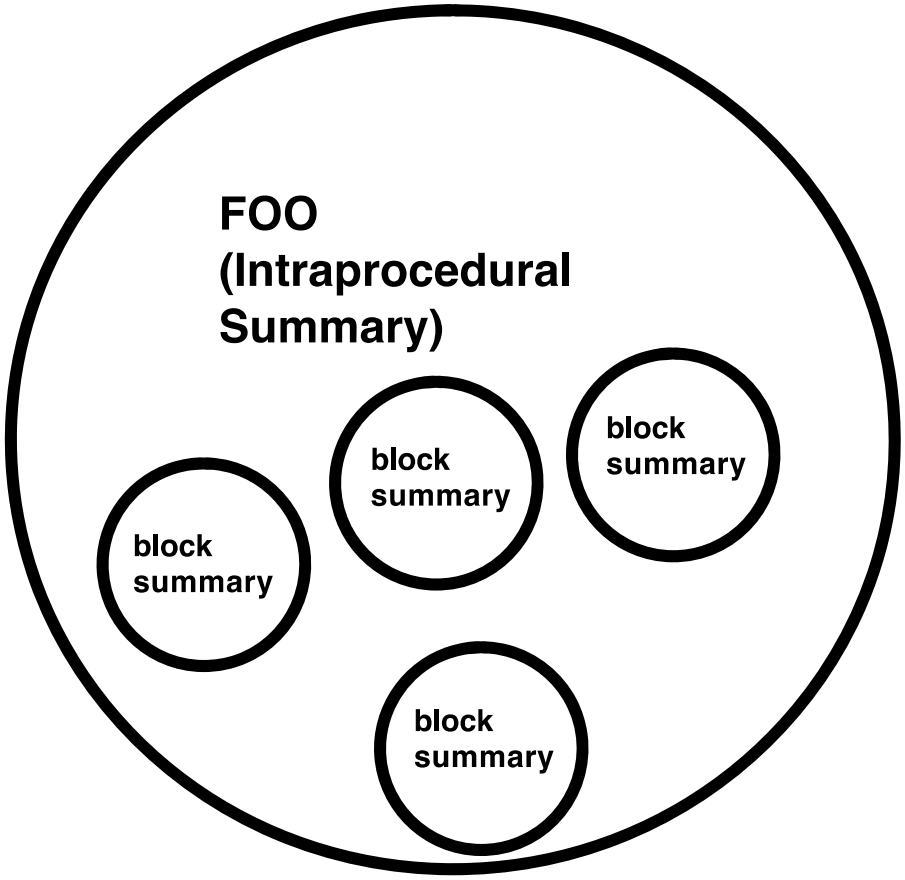
Block Summary

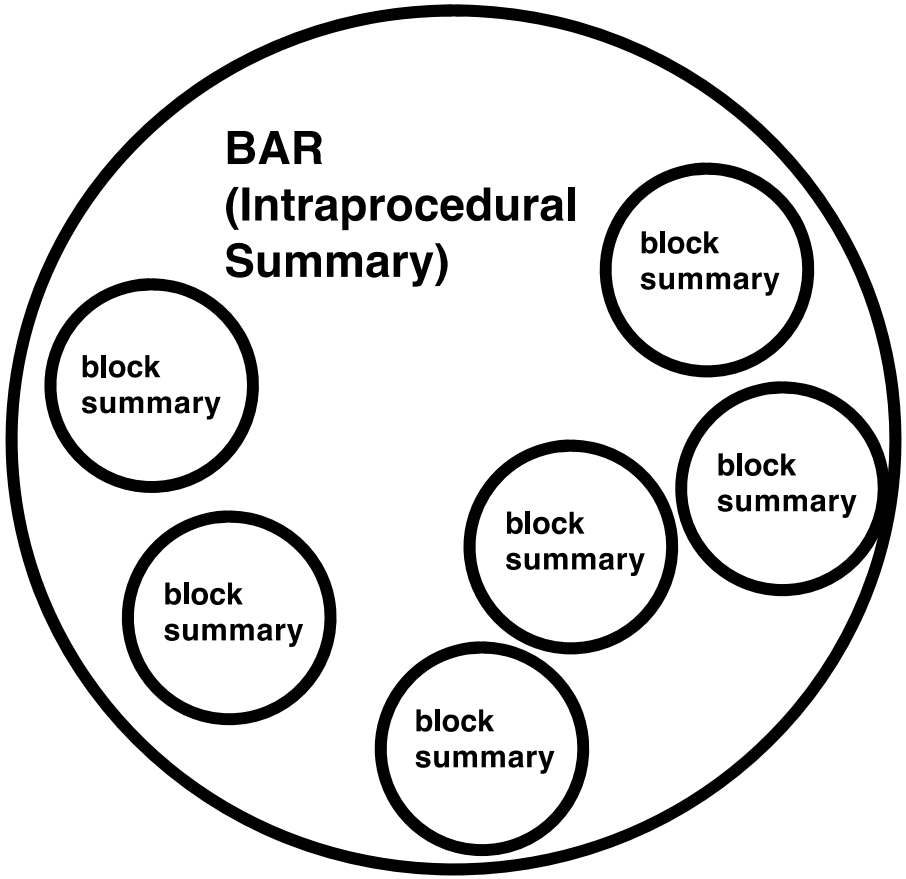
- Characterizes a CFG node
- Six Tuple: <E, D, F, T, R, U>
  - E (Error Set): Locations that flow into a query and need to be sanitized before entering the block
  - D (Definitions): Locations defined in current block
  - F (Value flow): Substring concept, pair of memory locations $<L_1, L_2>$ where L_1 is a substring of L_2 on exit of the block
  - T (Termination): A true/false value if the block exits or if the block contains a call to a function that exits
  - R (Return value): The return value or undefined
  - U (Untaint set): Analyze each successor of a block. Define the set of sanitized values for each successor

Intraprocedural Summary

- Summarize each of the block summaries within a procedure
- Four Tuple: <E, R, S, X>
  - E (Error set): Locations that flow into a query and need to be sanitized before calling the function
    - Backward reachability analysis, start with each return block and traverse to the first block of the procedure
    - Leverage E, D, F, U of block summary to calculate a global E across all blocks in procedure
    - Main must not include any user input
  - R (Return set): Set of locations that correspond to the segments of the string returned
    - Only returns a set if it is a string
  - S (Sanitization set): Set of parameters or global variables sanitized within the function
    - Forward reachability analysis, start with first block and traverse to each return block
    - Intersection of each path corresponds to the sanitization set (flow sentivity)
  - X (Program exit): True/false value if this terminates across all paths

Intraprocedural Summary





Interprocedural Analysis

- Instances of function calls map the current simulation state to the parameters used in intraprocedural summaries
- Function f has a summary tuple <E,S,R,X> which maps to an actual call $f(e_1, e_2,\ldots,e_n)$ in a block
- This is the concretization function, which substitutes simulation state values to the summaries (abstract domain)
- Simulation state reflects the current state at the location the function is called

More Interprocedural Details

- Pre-conditions: Map simulation state to elements in E based on the parameters of the specific function call
  - All members of E must be sanitized before calling function, **errors** thrown if any global variable or parameter is not sanitized before call
  - **Warnings** thrown on unknown types due to inability to sanitize
- Exit condition: Block marked as an exit block, outgoing edges removed
- Post-condition: Identify and mark sanitized parameters or global variables after execution
  - If there is conditional sanitization, the intersection of the untaint set is used
  - This is useful for the analysis of the next block
- Return value: This is based on the data type of returned variable
  - Boolean: return untaint true and false sets based on actual parameters or global values
  - String: return the actual parameters or global values that correlate to the segments of the string returned
  - Transfers sanitized data back to the block that called and its simulation state is updated accordingly

Recap of XAT

- Parse source files into ASTs for main and functions
- Convert ASTs into CFGs for functions and main
  - Maximal basic block for nodes
  - "Cut and paste" splice for include files
- Run analysis on the CFGs
  - Maintain simulation state through symbolic analysis
  - Trigger interprocedural summaries
  - Trigger intraprocedural summaries for each procedure called
  - Trigger block summaries for all blocks in a procedure called
- Analysis should report errors for all non-sanitized data
  - Warnings returned for unknown data type variables used in queries

Results

	Err Msgs	Bugs	(FP)	Warn
e107	16	16	(0)	23
News Pro	8	8	(0)	8
myBloggie	16	16	(0)	23
DCP Portal	39	39	(0)	55
PHP Webthings	20	20	(0)	6
Total	99	99	(0)	115

Table 1: Summary of experiments. Err Msgs: number of reported errors. Bugs: number of confirmed bugs from error reports. FP: number of false positives. Warn: number of unique warning messages for variables of unresolved origin (uninspected).

PHP Fusion

- Use of extract function created a lot of undefined data type variables in the analysis
  - This generated a lot of warnings
- Regular expressions created a difficulty in modeling

Correlating Static Analysis Concepts

- Sinks and sink sources
  - Database query functions and user-defined input, respectively
  - User-defined input is assumed to be tainted
- Sanitization functions
- Lattice: sanitized or not sanitized
- Abstract domains: summarization tuples and mapping to simulation state
- Soundness: It is sound since it returns errors for known issues (known data types) and warnings for issues it could not reason about (unable to model data type or dynamic functionality)
  - Sanitization set intersection of intraprocedural analysis could cause false positives though
- Completeness: Not complete; Authors admitted to struggles modeling all dynamic functionality (regular expressions, unknown data types)
  - Regular expression difficulties

More Static Analysis Concepts

- Context-sensitivity
  - It is fundamentally not context-sensitive since it does not process each function call uniquely – it uses summaries
  - This analysis does account for differences between different calls to functions due to the mapping of the simulation state and the ability to return different sanitization sets
  - Does the summarization remove data critical to context-sensitivity? Yes, according to the post-condition of the interprocedural analysis
  - JOP versus JOVP
- Flow sensitivity
  - It is not flow sensitive since the intraprocedural summary generalizes all of the control-flow paths of the blocks
  - This is seen in the intersection of the untaint set of boolean returns in intraprocedural summaries

My Thoughts

- Ease of coding and dynamic functionality make PHP very difficult to model
  - A lot of dynamic functionality
  - Heavy reliance on run-time data
  - I believe that XAT was fairly effective at trying to reason about this
- Neglected evaluated code
  - This is a logical extension of the sanitized/unsanitized string processing done in paper
  - Eval("$r = mysql_query(\"delete from $table\")");
  - This is not an explicit function call
- Left out native PHP functions
  - How are they modeled?
- Left out PHP constants and DEFINE statements
  - Mimics variables but uses non-traditional syntax
  - Can be used within strings

More Thoughts

- PHP 5.x has object orientation
  - PHP 5.3 includes namespaces
  - No mention of any of this
- No mention of association of data type to specific sanitization function
  - Does not make any sense to run *is_numeric* on a string
  - Add_slashes for a number, not validated
- This approach would work well across database platforms, since different functions can be passed for sanitization and for database queries

Questions?