BitBlaze & WebBlaze: Tools for Computer Security using SMT Solvers

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Outline

Core technique: symbolic reasoning

Binary-level bug-finding

Binary-level influence measurement

Strings and browser content sniffing

Strings and JavaScript vulnerabilities

Basic idea

- Choose some of state (e.g., program or function input) to be symbolic: introduce variables for their values
- Computations on symbolic state produce formulas rather than concrete (e.g., integer) values
- Construct queries with these formulas, solve to answer questions about possible program behavior

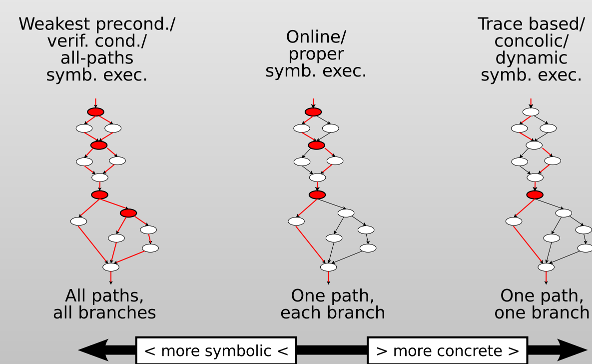
Why symbolic reasoning?

+ *Precise*: formulas can capture exact program behavior without approximation
+ *Complete solver*: (i.e. *decision procedure*) will always produce a correct solution without human help
+ *Flexibility*: Formulas independent of particular form of query

Why not symbolic reasoning?

- Precise, but often not complete: don't prove that a given behavior can never happen
- Complete solver, but solution not guaranteed within reasonable space/time
- Flexibility, but may be be less efficient than more specialized approach

Possible approaches



Applications

Vulnerability signatures [Oakland'06,CSF'07] Protocol replay [CCS'06] Deviation discovery [USENIX'07] Patch-based exploit generation [Oakland'08] Modeling content sniffing [Oakland'09] Influence measurement [PLAS'09] Loop-extended SE [ISSTA'09] Protocol-level exploration [RAID'09] Kernel API exploration Decomposing crypto functions [CCS'10] Fixing under-tainting [NDSS'11] Protocol-model assisted SE [USENIX'11] JavaScript SE [Oakland'10] Static-guided test generation [ISSTA'11] Emulator verification [submitted]

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Challenges of binary symbolic reasoning

- Instruction set complexity
  - Rewrite to simpler intermediate language
- Variable-size memory accesses
  - Lazy conversion with mixed-granularity storage
- No type distinction between integers and pointers
  - Analyze symbolic expression structure

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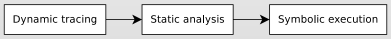
Setting: vulnerability finding

- Find exploitable bugs in software, before the bad guys do
- Many bugs found by independent researchers, without benefit of source code
- Example vulnerability type: buffer overflow
  - Incorrect or missing bounds check allows malicious input to overwrite other sensitive state
  - Despite extensive research, and some progress in practice, still a major bug category in C/C++ programs

Static analysis

- Widely used at source-code level
- Can be *sound* (report all potential problems), at cost of false positives (*imprecision*)
- Challenge 1: more difficult at binary level
  - Soundness/precision tradeoff less favorable
- Challenge 2: developers have a low tolerance for false positives
  - Won't use a tool that wastes their time

Combined static/dynamic approach



- Before static analysis, use dynamic traces to help where static binary analysis has trouble (e.g., indirect control flow)
- Design and optimize static analysis for binary-level challenges (e.g., variable identification, overlapping memory accesses)
- After static analysis, prioritize true positives by searching for test cases with symbolic execution

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Key challenge: guiding the search

- Increase the chances that the paths we explore will lead to a bug
  - Path must reach the code location of the bug
  - Program state at that location must trigger the bug
- Combination of two approaches:
  1. Data-flow slice and control-flow distance to direct paths toward a potential bug
  2. Explore patterns of loop body paths to cover cases likely to overflow

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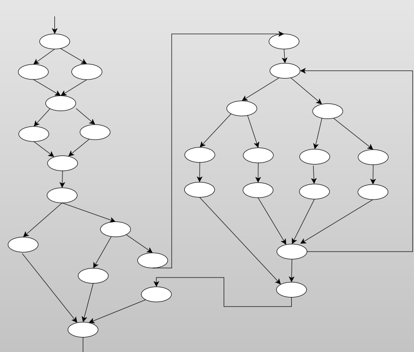
Guidance toward a bug



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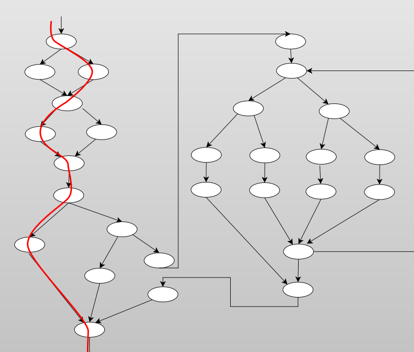

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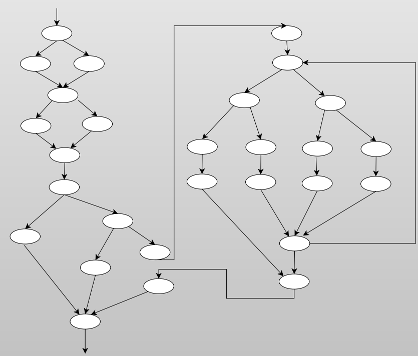

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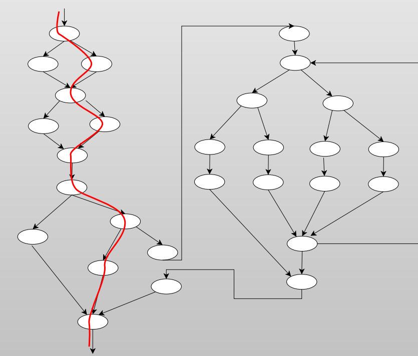

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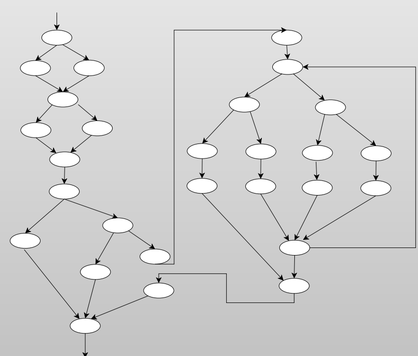

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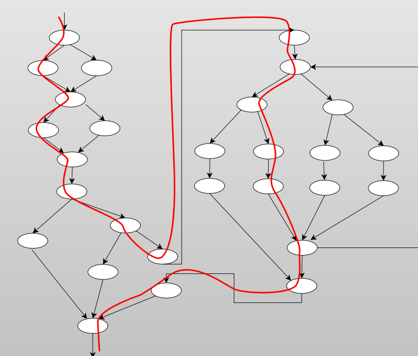

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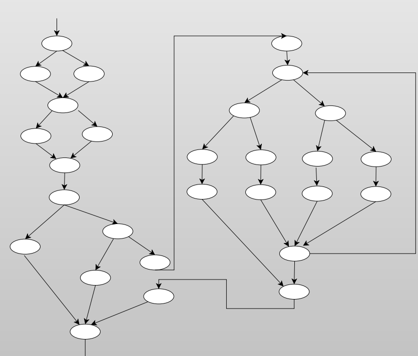

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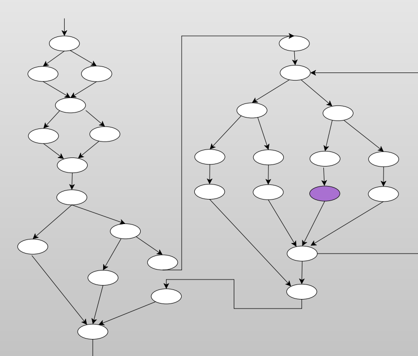

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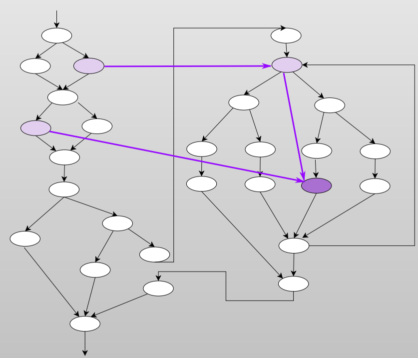

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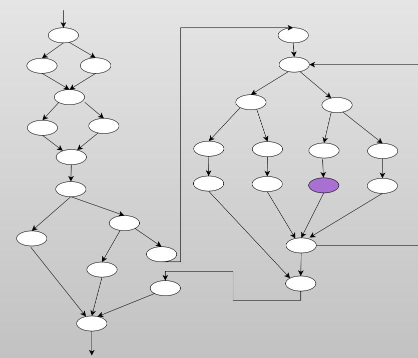

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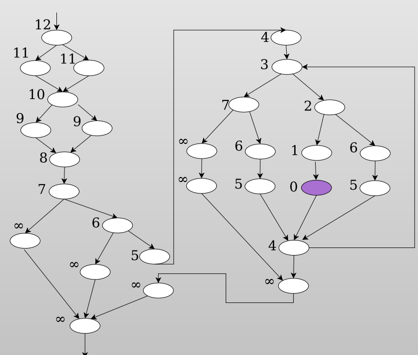

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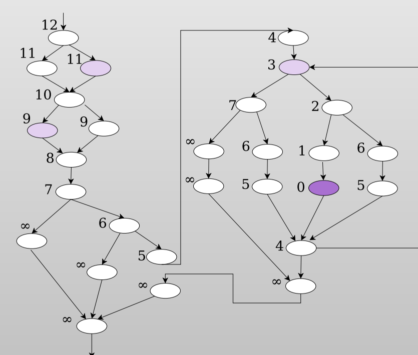

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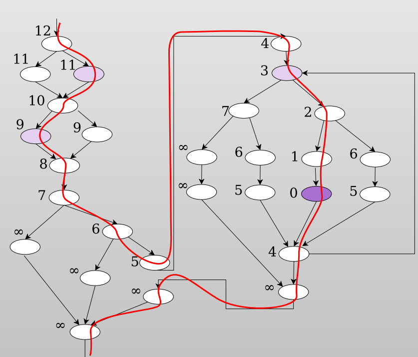

Sub-problem: control-flow distance

- An *interprocedural control-flow graph* has nodes for statements, and edges between statements and for calls and returns
- However, we can't use a regular graph distance measure (Dijkstra's algorithm), because of call and return matching
  - Exclude: `f` calls `g`, `g` returns to `h`
- Instead, new two-phase distance algorithm that first computes entry-to-exit distances bottom up, then adds unmatched returns and calls

Guidance results

Benchmark	Unguided		Guided	
	Paths	Time (s)	Paths	Time (s)
BIND/b4	1	1.9	1	1.8
Sendmail/s5	3	19.0	3	22.9
BIND/b1	54	2.8	20	3.6
BIND/b2	137	13.3	72	25.1
BIND/b3	9	1.6	4	2.6
Sendmail/s2	16	2.9	9	97.0
Sendmail/s7	56	6.9	1	1.9
WU-FTPD/f1	309	8.1	11	1.1
WU-FTPD/f2	1455	65.8	11	1.4
WU-FTPD/f3	143	60.0	18	11.4
Sendmail/s5	T/O	> 21600.0	332	200.4
Sendmail/s6	T/O	> 21600.0	86	11.3
Sendmail/s1	T/O	> 21600.0	7297	7474.4
Sendmail/s3	T/O	> 21600.0	T/O	> 21600.0

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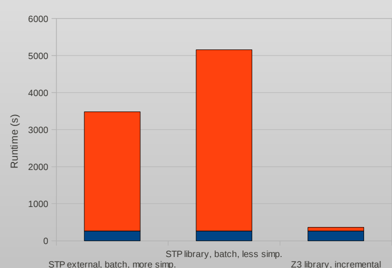
$\rightarrow$ Sendmail/s3	T/O	$>$ 21600.0	T/O	$>$ 21600.0

What do our formulas look like?

- The key theory is fixed-size bit-vectors, representing machine integers
  - Exact treatment of overflow, signs, etc. important for binaries
- Could use arrays for general memory, lookup tables, but usually don't
  - Instead, fix memory layout to be concrete (or unconstrained symbolic)
- Usually easy to solve, whether SAT or UNSAT

Solver performance

For easy formulas, mundane changes matter (sample of 84355 formulas, not a general tool comparison)



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Strings and JavaScript vulnerabilities

Due and undue influence

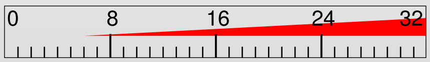
- How much influence should network inputs have on a program?
- For instance, on an indirect jump target
  - Some influence $\rightarrow$ select a legal behavior
  - Too much influence $\rightarrow$ control flow hijacking attack

High and low influence examples

```
void (*func_ptr)(void);
func_ptr = untrusted_input();
(*func_ptr)();
```

```
void (*func_ptr)(void);
switch (untrusted_input()) {
    case CMD_OPEN: func_ptr = &open_file;
    case CMD_READ: func_ptr = &read_file;
    default:       func_ptr = &error;
}
(*func_ptr)();
```

Channel capacity as influence



- For a given variable, how many values can an attacker produce?
- Influence $= \log_2(\#\text{ values})$
- Special case of channel capacity from information theory

Scalability and precision

- Want to analyze large (e.g., commercial) software
- Want results with no error
- Our goal: improved trade-off points between these ideals

Problem statement

- Given:
  - A deterministic program with designated inputs
  - An output variable
- Question: how many values of the output are possible, given different inputs?

Program to formula example

```
/* Convert low 4 bits of integer to hex */
char tohex(int i) {
    int low = i & 0xf;
    char v;
    if (low < 10)
        v = '0' + low;
    else
        v = 'a' + (low - 10);
    return v;
}
```

Dynamic: $(i \,\&\, 15) < 10 \wedge (v = 48 + (i \,\&\, 15))$

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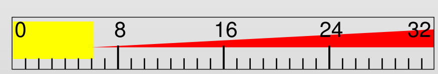
}
```

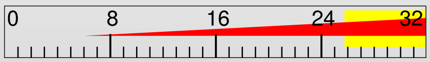
Static: $((i \,\&\, 15) < 10 \wedge (v = 48 + (i \,\&\, 15)) \vee$
$((i \,\&\, 15) \geq 10 \wedge (v = 97 + (i \,\&\, 15) - 10))$

Query techniques



- Point-by-point exhaustion
- Range exclusion
- Random output sampling
- Probabilistic model counting

Query techniques



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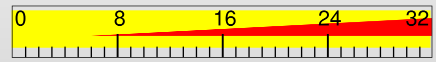

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Point-by-point exhaustion

- Is $v = f(i)$ satisfiable?
- Suppose it is, by $v_1 = f(i_1)$
- Is $v = f(i) \wedge v \neq v_1$ satisfiable?
- $\ldots$
- We repeat up to at most $2^6 = 64$ distinct outputs, so every bound up to 6 bits is exact

Range exclusion

- Is $v = f(i) \wedge (a \leq v \leq b)$ satisfiable?
- If not, a whole range is excluded
- If so, can subdivide
- We also use this with binary search to find the minimum and maximum outputs

Random output sampling

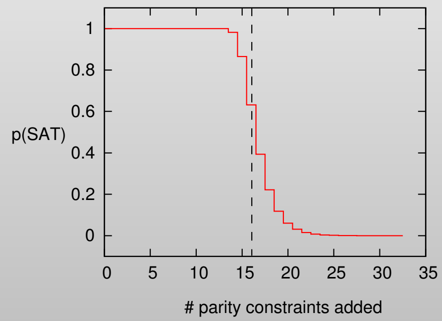
- Pick v_r at random, and check if $v_r = f(i)$ is satisfiable
- By default, our tool uses 20 samples, and computes a 95% confidence interval

Probabilistic model counting

- Use XOR streamlining [GSS06] to probabilistically reduce #SAT to SAT
- Analogy: counting audience members
- Random parity constraints over enough bits are effectively independent
- Perform repeated experiments with different numbers of constraints

Probabilistic model counting

Choose # of constraints so that $p(\text{SAT}) \approx 0.5$



Identity function

```
v = i
```

Low	High	Sample	#SAT	Actual
6.04	32.0	[31.8, 32.0]	32.0	32

Feasible Point
Infeasible Range
~100% (Probabilistic)
~50% (Probabilistic)
< 5% (Probabilistic)

`tohex`

```
sprintf(&v, "%x", i & 0xf)
```

Static:

Low	High	Sample	#SAT	Actual
4.00	4.00	N/A	N/A	4

Dynamic:

Low	High	Sample	#SAT	Actual
3.32	3.32	N/A	N/A	$\log_2 10$
2.58	2.58	N/A	N/A	$\log_2 6$

Mix and duplicate

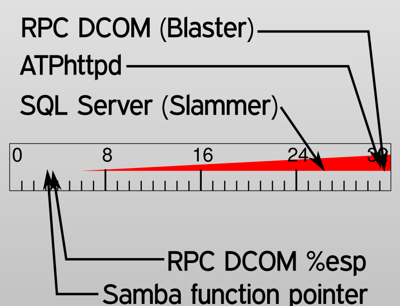
$$f(x \circ y) = (x \oplus y) \circ (x \oplus y)$$

```
f(0x00000042) = 0x00420042
f(0x02461111) = 0x13571357
f(0xcafebebe) = 0x74407440
```

Low	High	Sample	#SAT	Actual
6.04	32.0	[0.0, 28.6]	15.8	16

Results summary

Goal: distinguish attacks from false positives



Confirming attacks

- Vulnerable Windows and Linux binaries
- Real attacks all have high influence, at least 26 bits

Program	High	Sample	#SAT	Value Set
RPC DCOM	32.0	[31.8, 32.0]	30.4	
SQL Server	30.9	[26.7, 28.3]	26.6	
ATPhttpd	32.0	[31.8, 32.0]	31.0	

Reveal false positives

- Examples cause taint analysis warnings
- Measured influence exactly, less than 5 bits

Program	Low	High	Value Set
RPC %esp	3.81	3.81	
Samba func. ptr	3.32	3.32	

Directions for improving solving

- Further targeted query strategies
  - E.g., two-bit patterns [Meng & Smith, PLAS'11]
- Refined strategy for choosing number of parity constraints
- Interface with off-the-shelf #SAT solvers
  - Question: how to restrict counting to output bits?

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Web browser content sniffing

- An HTTP response contains a content type header
  - E.g., `text/html` or `image/png`
- But sometimes (~1%) the content type is missing or invalid
- Thus browsers sometimes attempt to sniff (guess) the type from the content or URL

When content sniffing goes bad

- Content type matters because it affects privilege
  - Some types of content (HTML, Flash) can contain code
- An unexpected upgrade can allow an untrusted user to inject JavaScript
  - I.e., a kind of cross-site scripting (XSS)
- Usually a mismatch between the browser and another filter

HotCRP attack example

- Conference site allows authors to upload PostScript papers
- What if the site accepts this file as PS, but the reviewer's browser considers it HTML?

```
%!PS-Adobe
%%Creator: <script>submitReview("A+");
...
```

- Your paper gets accepted :-)

Modeling content sniffing

- To understand such attacks, we want a formal model of the sniffer's behavior
- E.g., $M^H(c) =$ true if the file contents c are sniffed as HTML
- Boolean combinations correspond to possible mismatch attacks
  - $M_1^P(c) \wedge M_2^H(c)$

Model extraction

- The content-sniffing strategies of closed-source browsers are often un- or under-documented
  - We look at IE 7, Safari 3.1
- Extract from the binary using white-box exploration (symbolic execution)
- Model is a disjunction of path conditions from accepting paths

Abstracting string functions

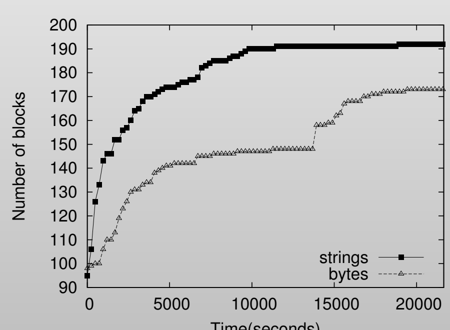
- Sniffing code makes heavy use of string routines
- Reason about their semantics, not their implementation
- \+ Summarize multiple paths
- \+ Skip implementation details
- \+ Take advantage of specialized solvers (future)

Translating string functions

1. Recognize over 100 binary-level functions (mostly documented)
2. Canonicalize to 14 semantic classes
3. Express in terms of a core constraint language
4. Reduce core constraints to STP bit vectors

Exploration advantage of strings

Block coverage for Safari:



Summary of attacks found

- Tool finds attacks to upgrade 6 content types each in IE and Safari to HTML.
  - But which pass a common server-side filter
  - Wikipedia has a more complex filter, but it can also be bypassed
- Automatically generated PS $\longrightarrow$ HTML example:

```
%!t?HPTw\n0tKoCglD<HeadswssssRsD
```

Happy ending: safe sniffing

- Our models can be used to create matching server-side filters
- We propose client-side design principles for safe sniffing
  - Avoid privilege escalation
  - Prefix-disjoint signatures
- Adopted by IE 8 (partial), Chrome, and HTML 5

Outline

Core technique: symbolic reasoning

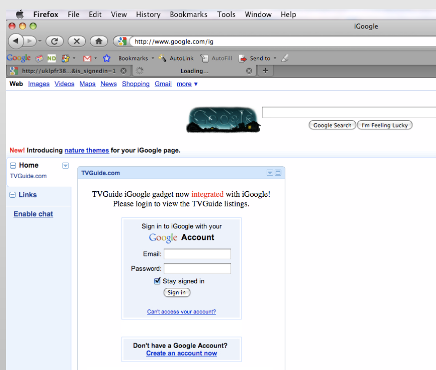
Binary-level bug-finding

Binary-level influence measurement

Strings and browser content sniffing

Strings and JavaScript vulnerabilities

Example attack: gadget overwrite



Example attack: explanation

- Cross-site scripting can exist entirely in client-side JavaScript
- Unsanitized data passed to HTML creation (`document.write`) or `eval`
- In the example, a malicious link injects code into the TVGuide gadget, turning it into a phishing vector

What's new here?

- Source/sink problem, somewhat like SQL injection or server-side XSS, but:
  - JS code takes many kinds of inputs as unstructured strings, requiring custom parsing
  - Sanitization is not standardized, and often application-specific

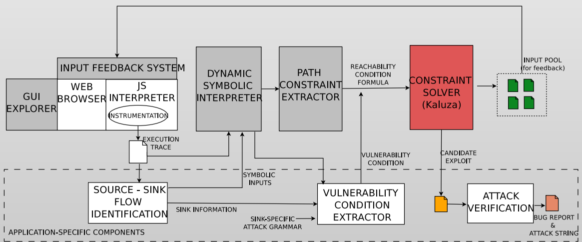
→ More difficult challenges for string reasoning

Exploration overview

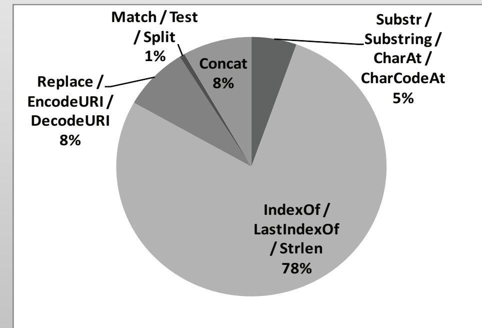
Two kinds of exploration:

- Event space: GUI actions such as clicking check-boxes or links
- Value space: contents of form, message, and URL inputs
  - Explore new program paths
  - Check whether sanitization is sufficient (compare to attack grammar)

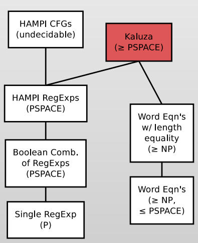
Kudzu system overview



Usage of string operations



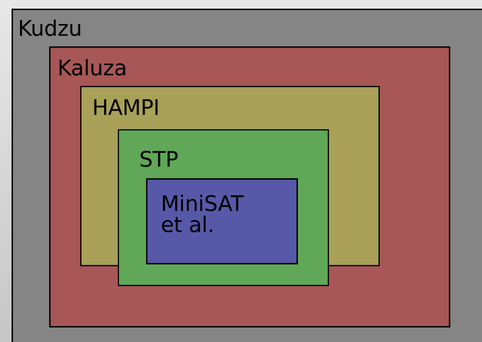
Expressiveness



(Complexities are for unbounded variants)

- Regular expression membership
- Arbitrary concatenation (word equations)
- String length function
- Can also mix in boolean and (31-bit) integer constraints

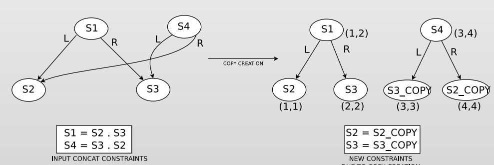
Nested architecture



Approach overview

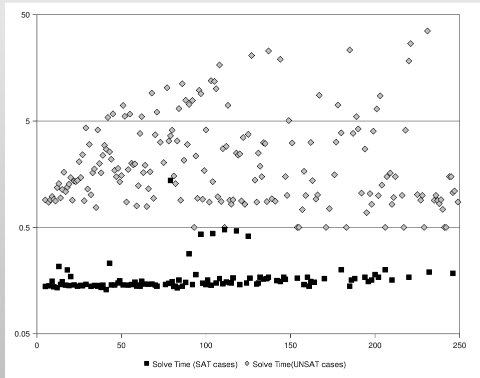
- Flatten concatenations to a linear sequence
- Abstract to length constraints
- For each length assignment:
  - Expand regexps (HAMPI code)
  - Combine in single bitvector query
  - bitvector SAT $\longrightarrow$ string SAT
- Exhausted lengths $\longrightarrow$ string UNSAT

Approach details



- Real JavaScript "regexes" are more complex that textbook ones
- Regexp lengths $\longrightarrow$ ultimately periodic set
- Translate `replace` with fixed number of occurrences

Kaluza performance results



Overall results

- Tested 5 AJAX applications and 13 iGoogle gadgets (all live)
- Event and value space exploration both contribute to coverage
  - But some code and events not yet covered
- Found vulnerabilities in 11 apps, including 2 missed by our previous taint-directed fuzzer

Summary, and for more info

- Symbolic execution and SMT solvers enable a wide variety of security applications
- Web sites have papers and TRs, plus:
- `http://bitblaze.cs.berkeley.edu/`
  - BitBlaze core: Vine and TEMU (GPL/LGPL)
- `http://webblaze.cs.berkeley.edu/`
  - Kaluza solver binary download and online demo