An Efficient Black-box Technique for Defeating Web Application Attacks

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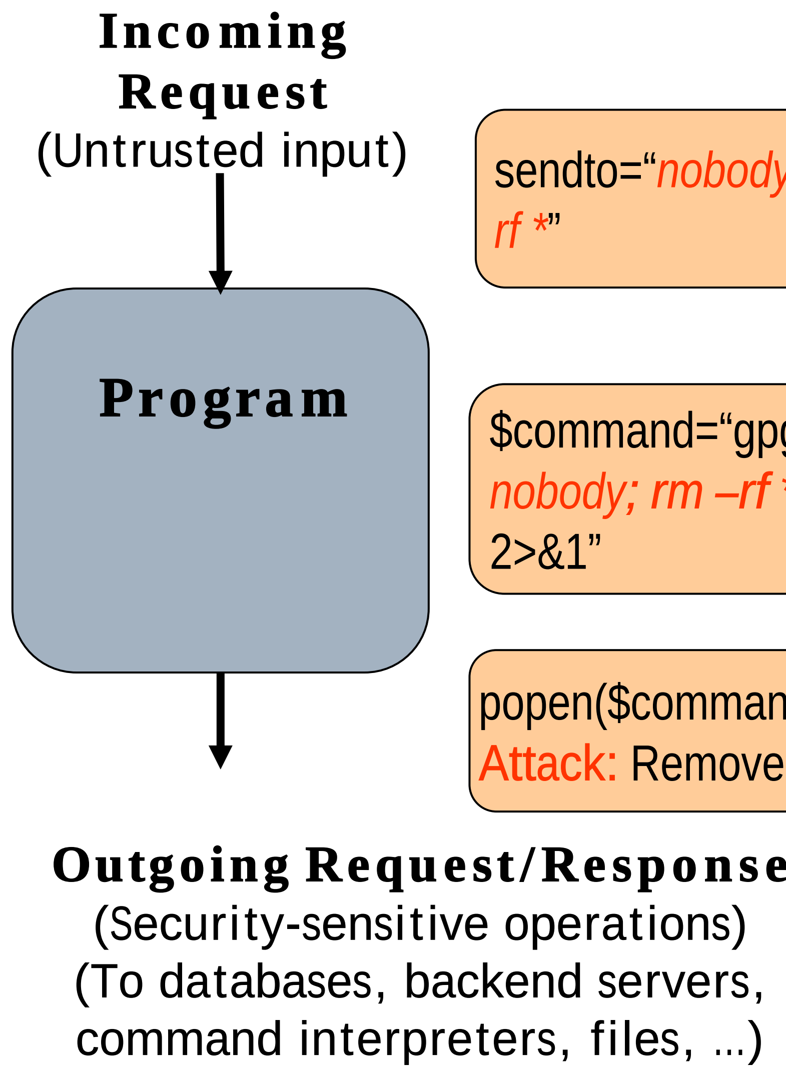
Example: SquirrelMail Command Injection

- Attack: use maliciously crafted input to exert unintended con... output operatio...
- Detect "exertion of control"
  - Based on "tain... which output d... input
- Detect if contro... intended:
  - Requires policies
    - Application-independent policies are preferable



$send_to_list = $_GET['sendto']

sendto="*nobody; rm –rf **"

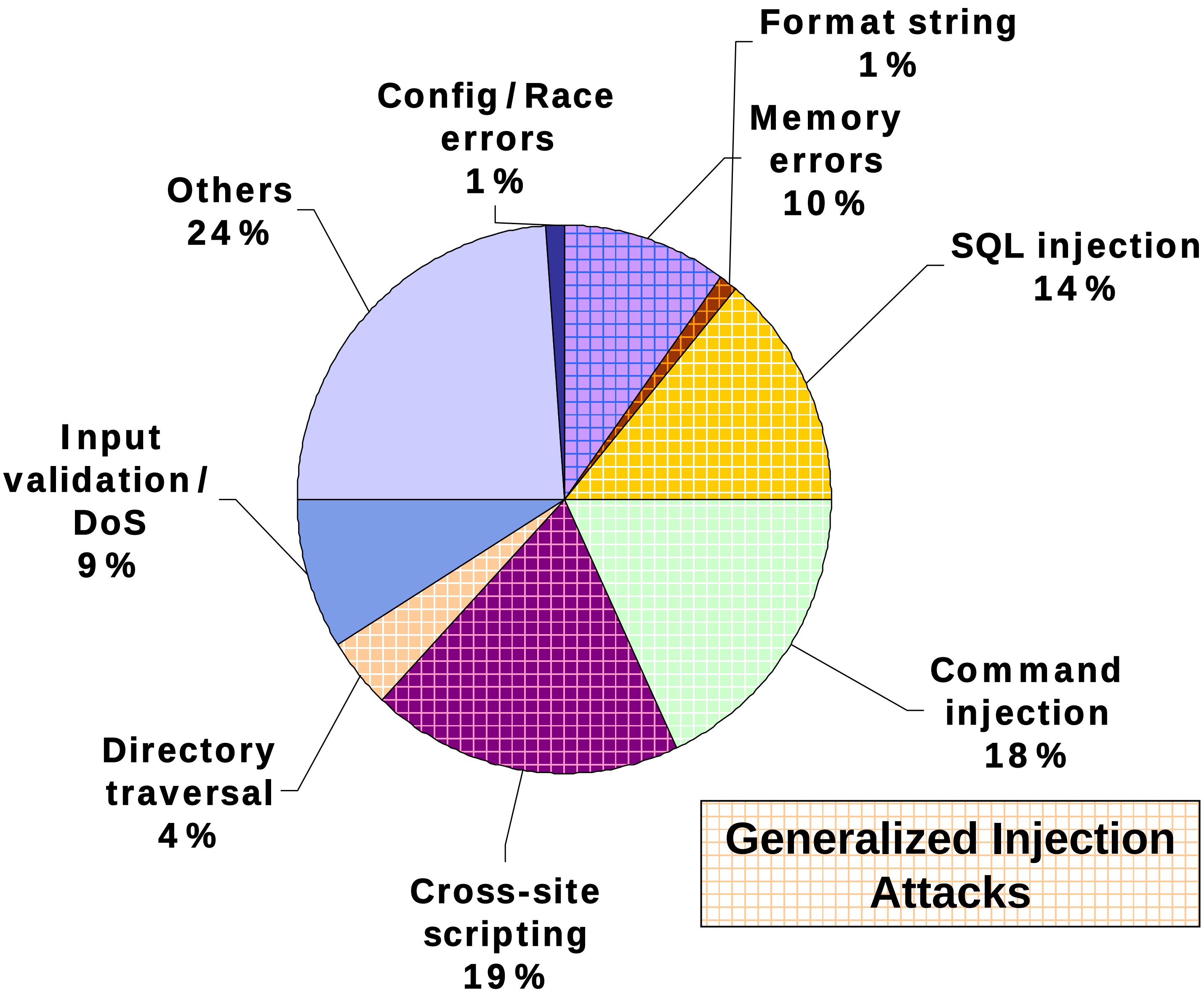
$command = "gpg -r $send_to_list 2>&1"

$command="gpg –r *nobody; rm –rf ** 2>&1"

popen($command)

popen($command)
Attack: Removes files

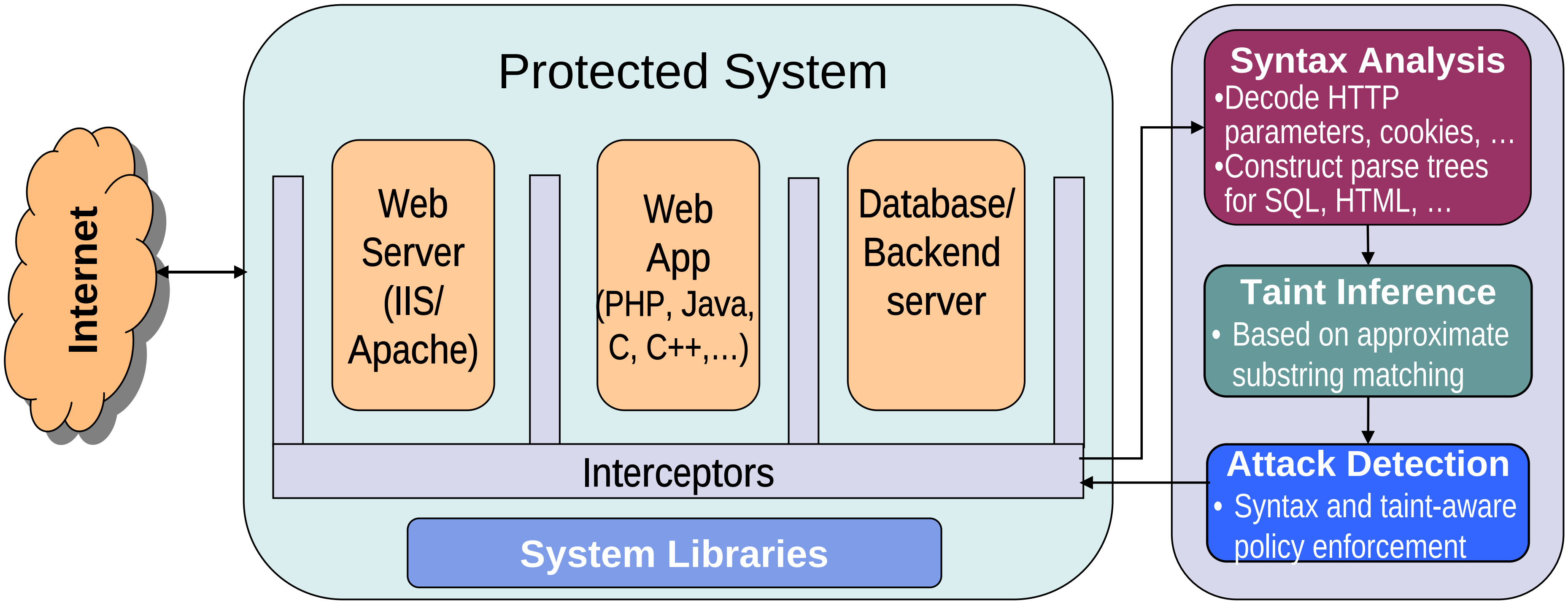
Attack Space of Interest (CVE 2006-07)



Drawbacks of Taint-Tracking and Motivation for Our Approach

- *Intrusive instrumentation*
  - Transform every statement in target application
  - Can potentially impact stability and robustness
- *High performance overheads*
  - Often slow down programs by 2x or more
- *Language dependence*
  - E.g., they apply either to Java or C/C++

Approach Overview



- Efficient, language-neutral, and non-intrusive
- Consists of
  - *Taint-inference:* Black-box technique to infer taint by observing inputs and outputs of protected apps
  - *Syntax- and Taint-aware policies* for detecting unintended use of tainted data

Syntax Analysis: Input Parsing

- Inputs:
  - Parse into components
    - Request type, URL, form parameters, cookies, ...
    - Exposes more of protocol semantics to other phases
    - All information mapped to (name, value) pairs
  - Normalize formats to avoid effect of various encoding schemes
    - To cope with evasion techniques
    - To ensure accuracy of taint-inference
  - Our implementation uses ModSecurity code

Syntax Tree Construction

- Outputs:
  - Pluggable architecture to parse different output languages
    - HTML, SQL, Shell scripts, ...
  - Use “rough” parsing, since accurate parsers are:
    - time-consuming to write
    - may not gracefully handle:
      - errors (especially common in HTML), or
      - language extensions and variations (different shells, different flavors of SQL)
  - Map to a language-neutral representation
  - Implemented using standard tools (Flex/Bison)

Taint Inference

- Infer taint by observing inputs and outputs
- Allow for simple transformations that are common in web applications
  - Space removal (or replacement with "_")
  - Upper-to-lower case transformation, quoting or unescaping, ...
  - Other application-specific changes
    - SquirrelMail, when given the "to" field value "**`alice, bob; touch /tmp/a`**" produces an output "**`-r alice@ -r bob; touch /tmp/a`**"
- Solution: use *approximate substring matching*

Taint Inference Algorithm

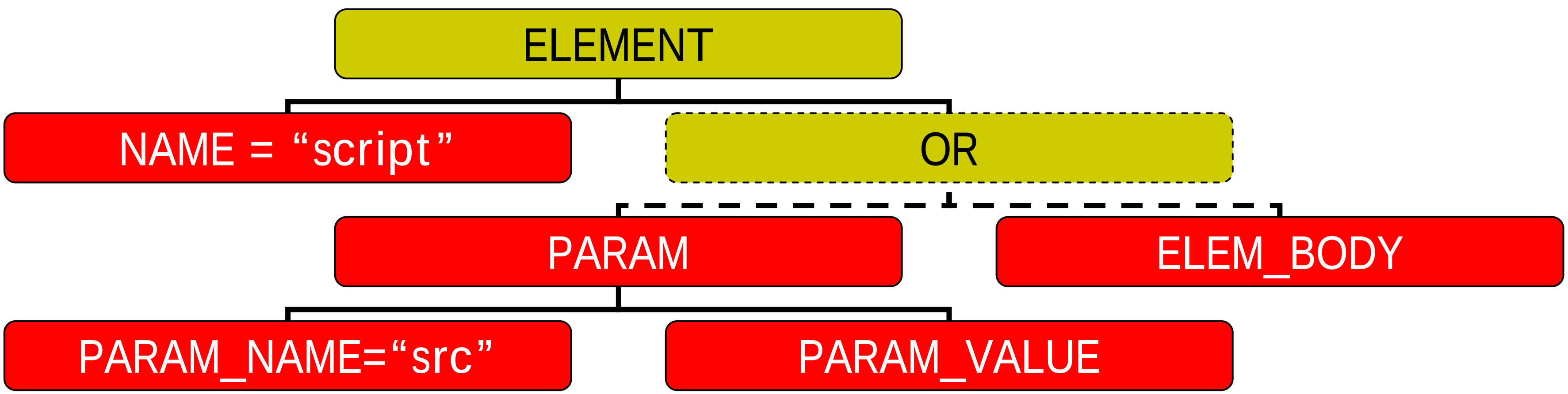
- Standard approximate substring matching algorithms have quadratic time and space complexity
  - Too high, since inputs and outputs can be quite large
- Our contribution
  - A linear-time "coarse-filtering" algorithm
    - More expensive edit-distance algorithm invoked on substrings selected by coarse-filtering algorithm
    - The combination is effectively linear-time
  - Ensures taint identification if distance between two strings is below a user-specified threshold *d*
    - Contrast with biological computing tools that provide speed up heuristics, but no such guarantee

Coarse-filtering to speed up Taint Inference

- Definition of taint:
  - A substring *u* of *t* is tainted if $ED(s, u) < d$
    - Here, ED denotes the edit-distance
- Key idea for coarse-filtering:
  - Approximate ED by $ED^{\#}$, defined on length $|s|$ substrings of *t*
  - Let *U* (and *V*) denote a multiset of characters in *u* (resp., *v*)
  - $ED^{\#}(u, v) = \min(|U-V|, |V-U|)$
    - Slide a window of size $|s|$ over *t*, compute $ED^{\#}$ incrementally
  - Prove: $ED(s, r) < d \Rightarrow ED^{\#}(s, r) < d$ for all substrings *r* of *t*
- Result:
  - $O(|s|^2)$ space in worst-case
  - performs like a linear-time algorithm in practice

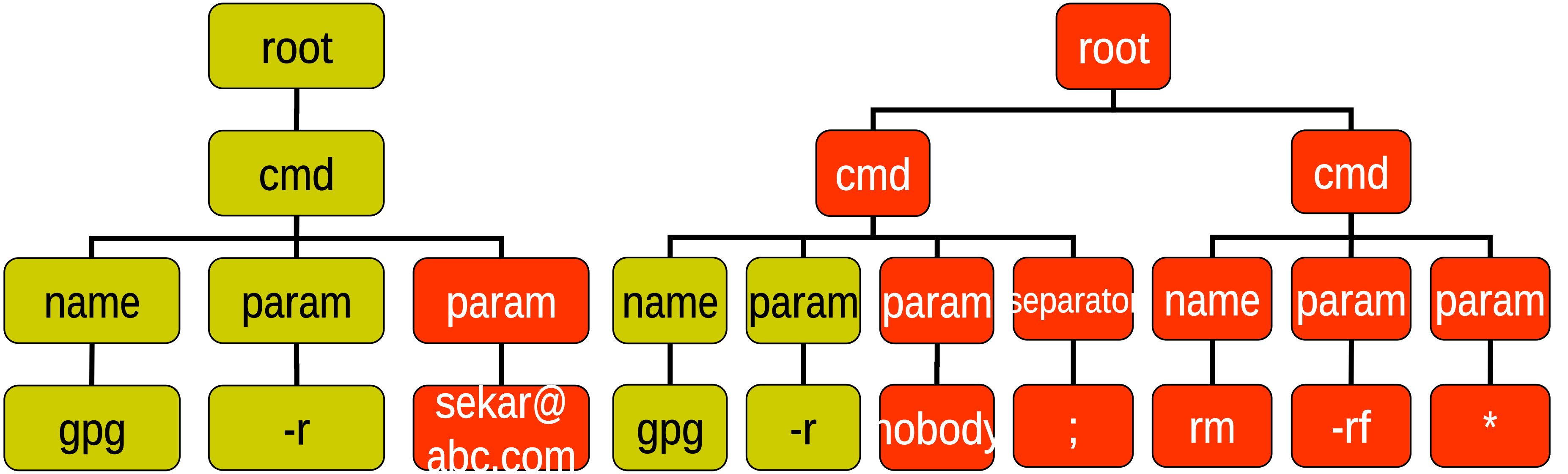
Overview of Syntax+Taint-aware Policies

- Leverage structure+taint to simplify/generalize policy
  - Policy structure mirrors that of syntax trees
    - And-Or "trees" (possibly with cycles)
  - Can specify constraints on values (using regular expressions) and taint associated with a parse tree node



1. Policy for detecting XSS

Injection attacks and Syntax-aware policies



- (2) SpanNodes policy: captures "lexical confinement"
  - tainted data to be contained within a single tree node
- (3) StraddleTrees policy: captures "overflows"
- Both are "default deny" policies
  - Tainted data begins in the middle of one syntactic structure (subtree), then flows into next subtree

Further Optimization: Pruning Policies

- Most inputs are benign, and cannot lead to violation of policies
  - Policies constrain tainted content, which comes from input
  - Thus, policies implicitly constrain inputs
- Approach:
  - Define “pruning policies” that make these implicit constraints explicit
  - Pruning policies identify subset of inputs that can possibly lead to policy violation
  - For other inputs, we can skip taint inference as well as policy checking algorithms

Evaluation: Applications and Policies

Application	Language	LOC (Size)	Environment	Attacks	Notes
phpBB	PHP/C	34K	Apache or IIS w/MySQL	SQL inj	Popular real-world apps. Exploits from the wild.
SquirrelMail	PHP/C	35K/42K	Apache or IIS	Shell command inj, XSS	
XMLRPC (library)	PHP/C	2K	Apache or IIS	PHP command inj	
Apps from gotocode.com	Java/C	30K	Apache+Tomcat w/ MySQL	SQL inj (21K attacks. 4K legitimate)	Attacks by [Halfond et al]
WebGoat	Java/C		Tomcat	command inj, HTTP response splitting	
DARPA RedTeam App	PHP	2K	Apache	SQL inj	App developed by Red Team

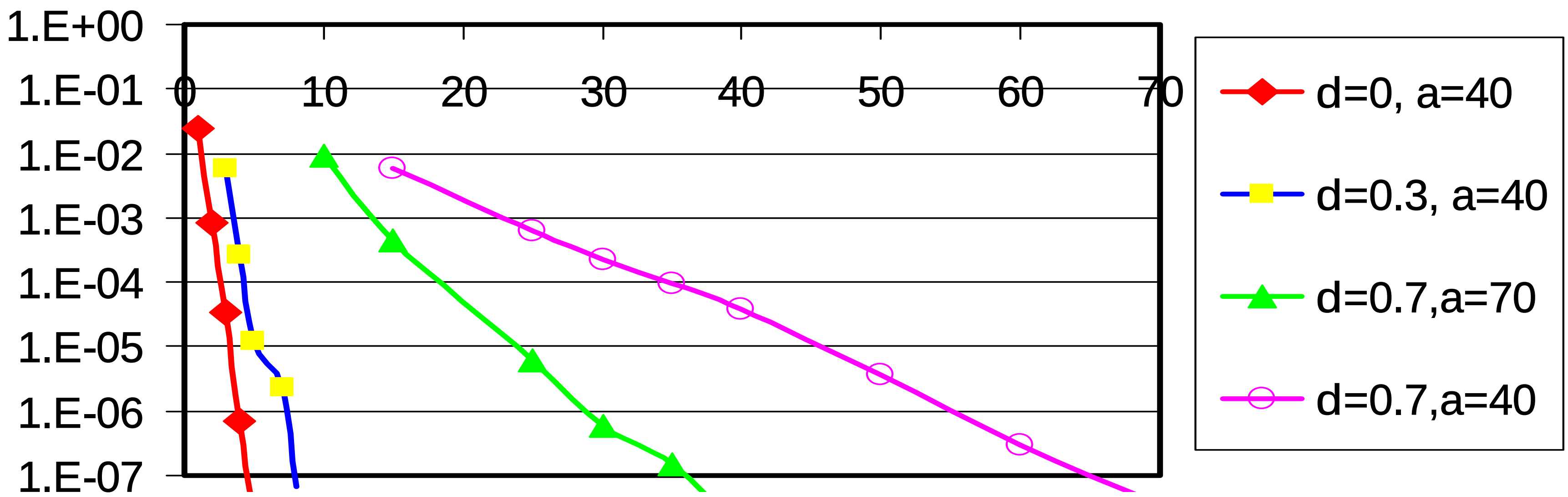
- We used the 3 policies described earlier in the talk

False Negatives (and Detection Results)

- Occur due to
  - Complex application-specific data transformations
    - Protocol/language-specific transformations handled
  - Second-order attacks (data written into persistent store, read back subsequently, and used in security-sensitive operations)
    - A limitation common to taint-based approaches
- Experimental results:
  - Detected *all* attacks in experiments with the exception of a single second-order injection attack in Red Team evaluation
    - Shell and PHP command injections and XSS on
    - ~21K SQL injection attacks on 5 moderate-size JSP applications (AMNESIA [Halfond et al] dataset)
    - HTTP response splitting on WebGoat

False Positives

- Result of coincidental matches (in taint-inference)
  - Can be controlled by setting the distance threshold *d* based on the desired false positive probability
  - Likelihood small even for short strings
  - No false positives reported in experiments
- Implication
  - Can use large distances for moderate-size strings (len > 10), thus tolerating significant input transformations



Taint inference overhead

- Coarse filtering optimization
  - 10x to 20x improvement in speed in experiments
  - 50x to 1000x reduction in space
  - time spent in coarse filtering (linear-time algorithm) exceeds time spent inside edit-distance algorithm
  - performance decreases with large values of distance
    - When coincidental probability increases beyond 10^{-6}

Overhead of different phases

- 60% spent in taint inference
  - After coarse-filtering optimization
- 20% in parsing
- 20% in policy checking
- Overhead of interposition not measured
  - but assumed to be relatively small because of reliance on library interposition

End-to-end Performance Overhead

- Measured using AMNESIA [Halfond et al] dataset on utility applications from gotocode.com
- Performance measured with pruning filters deployed
  - ~5x performance improvement due to pruning

Application	Size (LOC)	# of Requests	Response time (sec)	Overhead
Bookstore	9552	605	20.7	1.7%
Empldir	3028	660	17.3	3.4%
Portal	8775	1080	31.7	5.1%
Classifieds	5726	576	18.0	4.3%
Events	3805	900	23.0	3.1%
Total	30886	3821	110.7	**3.5%**

Related Work

- Su and Wasserman [2006]
  - Focus on formal characterization of SQL injection
  - Our contributions
    - A robust, application-independent technique to infer taint propagation
    - Policies decoupled from grammar
      - Applicable to many languages
- Dataflow anomaly detection [Bhatkar et al 2006]
  - Flow inference algorithms tuned for simpler data (file names, file descriptors, ...)
- Program transformations for taint-tracking
  - And related approaches (AMNESIA, CANDID, ...)
  - Require deep analysis/instrumentation of applications

Summary

- A black-box alternative for taint-tracking on web applications
- A simple, language-neutral policy framework
- Ability to detect a wide range of exploits across different languages (Java, C, PHP, ...) and platforms (Apache, Tomcat, IIS, ...)
  with just a few general policies
- Low performance overheads (below 5%)