Generalization and Characterization Techniques for the Anomaly-based Detection of Web Attacks

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Why are web applications important?

- Web has become a ubiquitous application delivery medium
- Easy to develop, deploy, and access web applications
- Unfortunately, also easy to introduce critical security vulnerabilities
  - Lack of awareness of security issues
  - Feature-driven development
  - Time-to-market constraints

Result

Web application vulnerabilities are increasing in number and severity

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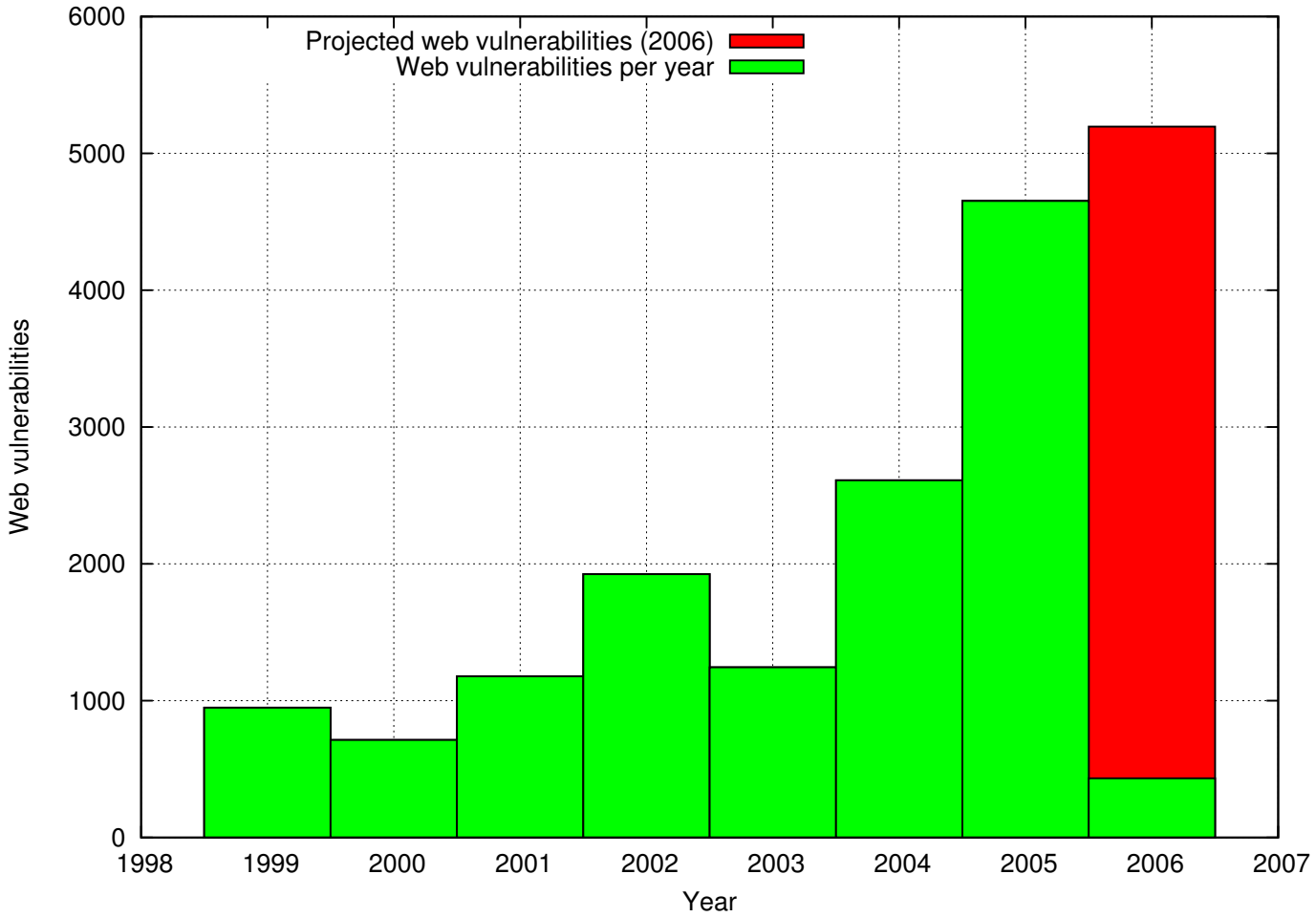
Reported web-related vulnerabilities [CVE Database]



Why anomaly detection?

- Misuse detection performs well in detecting known attacks directed at widely-deployed targets
- Many web applications, however, are custom-developed and possibly deployed at a handful of sites
- Consequently, custom misuse signatures required
  - Signature development costly, error-prone, and almost never done
- Anomaly detection is able (*in theory*) to detect novel attacks against custom code
  - Learns (or provided) a profile of normal behavior, and then detects deviations from established profile

Limitations of existing anomaly detectors

- Anomaly detectors prone to producing false positives
- Anomaly detectors give no indication as to the *nature* of a detected attack

Objective

We propose *generalization* and *characterization* techniques to mitigate these two shortcomings

Generalization and characterization example

```
ALERT 10.0.0.3 -> 10.0.0.1 [/cgi-bin/show.cgi?file attribute length exceeded (len=256)]
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Generalization and characterization example

Cross-site scripting

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Buffer overflow

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Outline

Architectural overview

Previous work

Anomaly detector Learns profiles of normal application behavior and detect deviations [Kruegel03]

Contributions

Anomaly signature generator Generates *anomaly signatures* to group "similar" alerts

Anomaly aggregator Groups anomalies according to model-specific *similarity operators*

Attack classifier Characterizes types of attacks anomalies may represent

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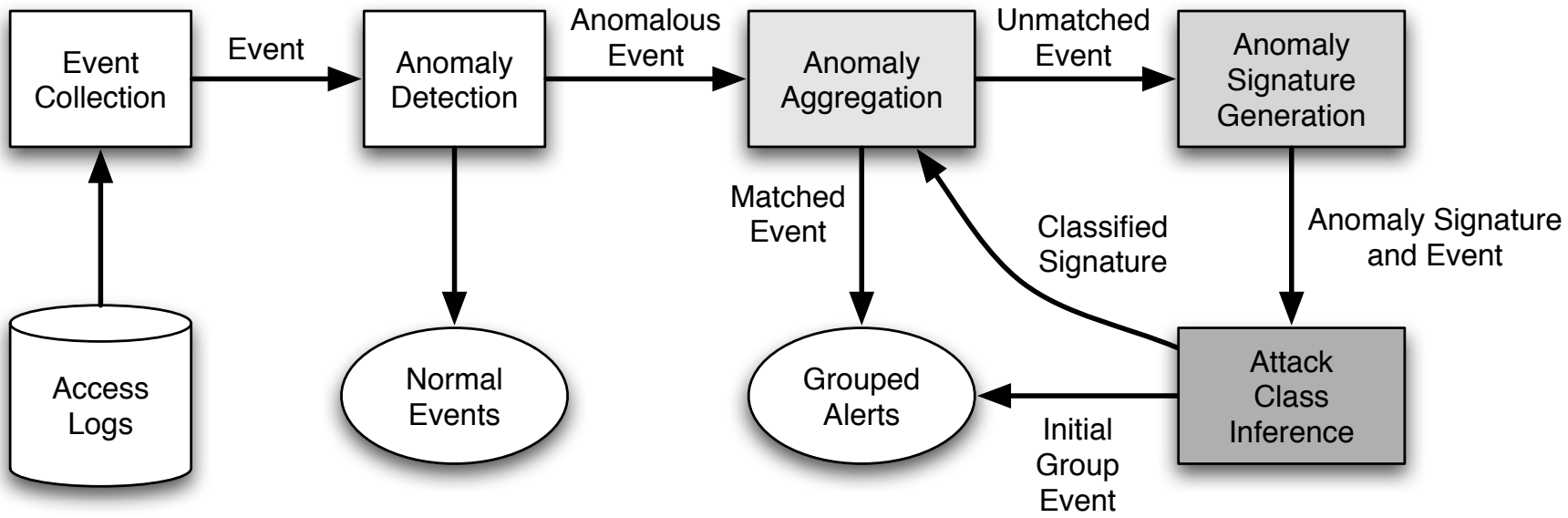

Anomaly detection component

- Examines web requests sent from clients to server
  - Application to be executed
  - Application parameters (attribute names and values)

Example

```
GET /cgi-bin/show.cgi?sID=12345&file=images/foo.png
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- Applies statistical models to each attribute of each application in two phases

Learning Builds profiles of normal behavior for each application parameter

Detection Detects deviations from learned profile

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Attribute length model

Chebyshev inequality

$$p\left(|x-\mu| > |l-\mu|\right) > p\left(l\right) = \frac{\sigma^2}{\left(l-\mu\right)^2}$$

Observation

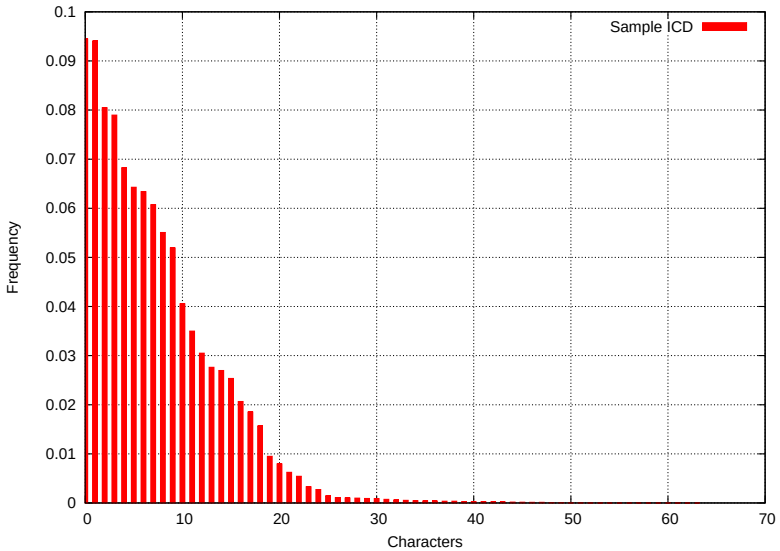
Many attribute values are either fixed in size or vary over a small range

- Model attempts to approximate actual (unknown) distribution of attribute lengths
- Weak bound results in significant tolerance to variations

Character distribution model

Observation

Many attributes take values that have similar character distributions

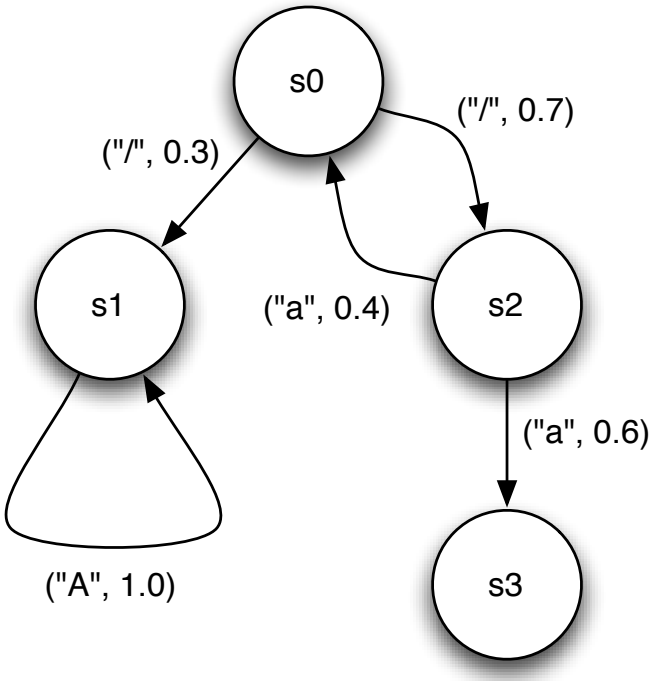


- Model creates *idealized character distribution* (ICD) for attribute
- Anomaly score calculated using variant of Pearson χ^2 test

Structural inference model

Observation

Many attribute values can be modeled as strings generated by a regular grammar

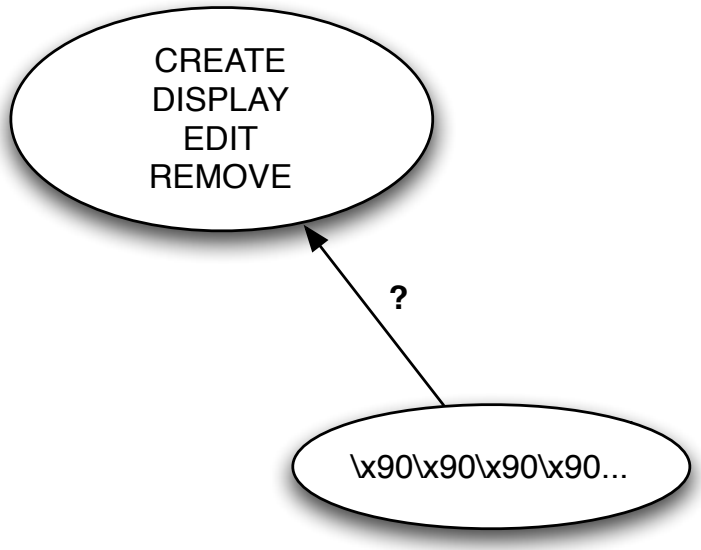


- Model constructs *probabilistic grammar* from learning set
- Anomaly score calculated as product of transition probabilities along path through NFA for a given value

Token finder model

Observation

Many attributes take values that are drawn from a small set of constants



- Model is applied to an attribute if set of unique values observed during learning phase does not grow proportionally to number of requests
- Detection performed by membership test of observed value in learned set of values

Anomaly generalization component

Anomaly generalization

Construction of an abstract model that matches initial anomaly and similar anomalies

- Parameters for each alerting model for a given anomaly are "relaxed" in a model-specific fashion
- Resulting set of relaxed models are composed to create an *anomaly signature*
- Model-specific *similarity operator* used to determine if subsequent anomalies are similar to the initial anomaly

Attribute length generalization

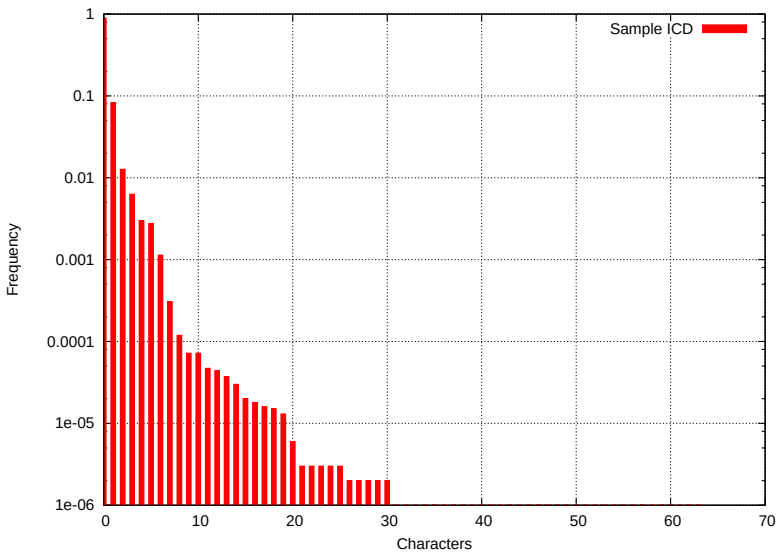
Similarity operator

$$\psi_{attrlen} \equiv \left| \frac{\sigma^2}{(l_{obsv} - \mu)^2} - \frac{\sigma^2}{(l_{orig} - \mu)^2} \right| < d_{attrlen}$$

- Parameters to attribute length model (sample mean μ and variance σ^2) are extracted
- Similarity operator $\psi_{attrlen}$ used to determine if subsequent attribute lengths l_{obsv} are within distance $d_{attrlen}$ from the original anomalous length l_{orig}

Character distribution generalization [dominators]

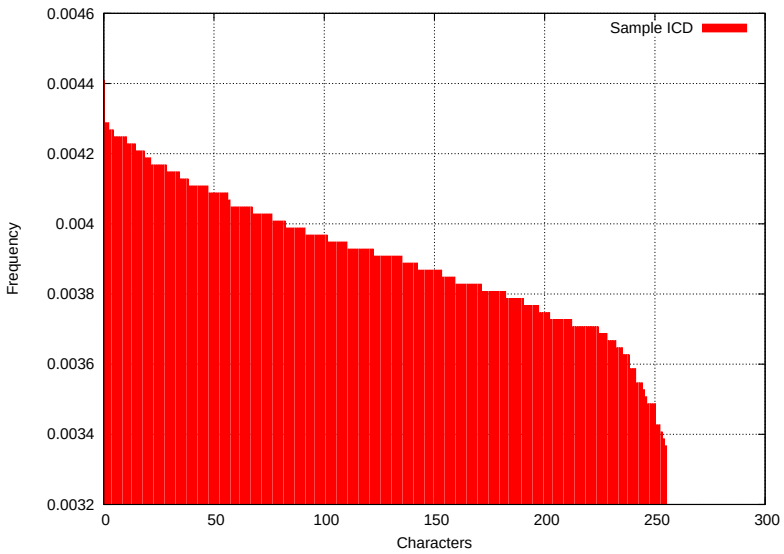
- Anomalous character distribution may exhibit a sharp drop-off, indicating a small set of dominating characters



- Set of dominating character and relative frequency pairs is extracted
- Similarity operator ψ_{cdist} tests whether character distributions share at least one dominating character with relative frequencies at most d_{cdist} apart

Character distribution generalization [uniform]

- Anomalous character distribution may be loosely approximated by the uniform distribution



- Set of character and relative frequency pairs is extracted from anomalous ICD
- Similarity operator ψ_{cdist} determines whether the maximum distance between any pair of frequency values from initial and observed character distributions is at most d_{cdist}

Structural inference generalization

Similarity Operator

$$\psi_{structure} \equiv lex\left(s_{orig}, s_{obsv}\right) < d_{structure}$$

- Prefix of anomalous value, including the first occurrence of an anomalous character, is extracted and normalized according to character class
- Subsequent anomalous values are normalized in the same manner to s_{obsv} and then compared with s_{orig}
- Lexicographical similarity function may be string equality or a string similarity metric (e.g., Hamming, Levenshtein distance)

Token finder generalization

Similarity Operator

$$\psi_{token} \equiv lex\left(l_{orig}, l_{obsv}\right) < d_{token}$$

- Anomalous value that failed membership test is extracted
- Lexicographical similarity function (as in case of structural inference) tests whether subsequent anomalous values are similar to initial anomaly

Attack class inference

- Intended to address concern that traditional anomaly detectors can detect attacks, but cannot easily explain "why"
- Observed that well-known classes of attacks deviate from learned profiles in consistent manner
- Component employs *ad hoc heuristics* to infer the type of attack represented by a detected anomaly
- Heuristics search for general features of a type of attack, not specific attacks
  - directory traversal
  - cross-site scripting
  - SQL injection
  - buffer overflows

Directory traversal

Example

```
GET /cgi-bin/show.cgi?sID=12345&file=../../../maillog
```

- Attacker attempts to access unauthorized files by traversing directory tree
- Heuristic activated if ICD dominated by "." or "/" or if structural inference model determines underivable character to be "." or "/"
- Heuristic scans for directory traversal characters

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Cross-site scripting

Example

```
GET /cgi-bin/show.cgi?sID=12345&file=<script>...</script>
```

- Attacker attempts to embed scripts in pages served by vulnerable server to be executed by other clients
- Heuristic activated if any of structural inference, character distribution, or token finder models generates an alert
- Heuristic scans for common syntactic elements of JavaScript or HTML

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SQL injection

Example

```
GET /cgi-bin/show.cgi?sID=' or 1=1;--&file=access.log
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- Attacker attempts to execute arbitrary SQL queries by exploiting lack of input sanitization
- Heuristic activated if structural inference model generates an alert
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Buffer overflows

Example

```
GET /cgi-bin/show.cgi?sID=12345&file=%90%90%90%90...
```

- Attacker attempts to influence control flow of application or corrupt data by overflowing a buffer
- Heuristic activated if character distribution, structural inference, or attribute length models generate an alert
- Variety of techniques may be used to detect executable code (e.g., non-ASCII characters, abstract payload execution, speculative disassembly, etc.)

Buffer overflows

Example

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Outline

Experimental setup

- Offline processing of web server logs collected from TU Vienna and UCSB
- Known attacks stripped from data sets, and attack variations injected using Sploit framework
- Detection performed on Pentium IV 1.8 GHz machine with 1GB of RAM
- System evaluated in terms of false positive rate, ability to group and characterize alerts, and performance

False positive rate

Data set	Queries	FP	FPR	FP/day	Groups	Grouped FPR
TUV	737,626	14	1.90×10^{-5}	0.26	2	3.00×10^{-6}
UCSB	35,261	513	1.45×10^{-2}	1.89	3	8.50×10^{-5}

- Low initial false positive rate
- Initial false positive rate further reduced through anomaly aggregation

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Attack characterization

Attack	Mutants	Groups	Alerting models	Characterization
csSearch	10	1	Length, CDist	XSS
htmlscript	10	1	Length, Structure	Directory traversal
imp	10	1	Length, CDist	XSS
phorum	10	1	Length, CDist, Token	Buffer overflow
phpnuke	10	1	Length, Structure	SQL injection
webwho	10	1	Length	None

- All attack mutations detected
- Most attacks accurately characterized

Performance [time]

Data set	Requests	Request rate	Elapsed time	Analysis rate
TUV	737,626	0.107095 req/sec	934 sec	788.06 req/sec
UCSB	35,261	0.001360 req/sec	64 sec	550.95 req/sec

- Deployable in standalone mode for low to medium traffic sites
- Cluster configuration possible for higher traffic sites

Related work

Learning-based anomaly detection

- Building profiles of user login times and actions [Denning87]
- Clustering techniques applied to unlabeled network traces [Portnoy01]

Application-level intrusion detection

- Syscall sequences [Forrest96]
- Learning of network application behavior [Mahoney02]
- Service-specific network application anomaly detection [Kruegel02]

Related work

Detection of attacks against web servers

- Misuse-based analysis of web server logs [Almgren00]
- Web server-integrated misuse-based attack detection [Almgren01]
- Misuse-based analysis of multiple event streams [Vigna03]
- Serial combination of misuse and anomaly-based detectors [Tombini04]

Conclusions

- Major limitations of anomaly detectors can be mitigated through use of *generalization* and *characterization* techniques
  - Constructing an abstract description of an anomaly allows system to group similar anomalies, reducing effective false positive rate
  - Inferring the nature of an anomaly assists administrators and developers in analyzing and patching novel vulnerabilities
- Anomaly aggregation component successfully grouped both false positives and mutated attacks in real-world data sets
- Attack inference component successfully characterized most attacks

Future work

- Apply generalization, characterization techniques to additional models
- Investigate alternative techniques for generalizing anomalies
- Improve attack inference technique
  - More sophisticated heuristics
  - Apply Bayesian techniques to infer attacks based on model outputs as evidence nodes
- Extend system to other domains (e.g., syscall arguments)