Structural Learning of Attack Vectors for Generating Mutated XSS Attacks

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Web applications suffer from cross-site scripting (XSS) attacks that resulting from incomplete or incorrect input sanitization. Learning the structure of attack vectors could enrich the variety of manifestations in generated XSS attacks. In this study, we focus on generating more threatening XSS attacks for the state-of-the-art detection approaches that can find potential XSS vulnerabilities in Web applications, and propose a mechanism for structural learning of attack vectors with the aim of generating mutated XSS attacks in a fully automatic way. Mutated XSS attack generation depends on the analysis of attack vectors and the structural learning mechanism. For the kernel of the learning mechanism, we use a Hidden Markov model (HMM) as the structure of the attack vector model to capture the implicit manner of the attack vector, and this manner is benefited from the syntax meanings that are labeled by the proposed tokenizing mechanism. Bayes theorem is used to determine the number of hidden states in the model for generalizing the structure model. The paper has the contributions are as following: (1) automatically learn the structure of attack vectors from practical data analysis to modeling a structure model of attack vectors, (2) mimic the manners and the elements of attack vectors to extend the ability of testing tool for identifying XSS vulnerabilities, (3) be helpful to verify the flaws of blacklist sanitization procedures of Web applications. We evaluated the proposed mechanism by Burp Intruder with a dataset collected from public XSS archives. The results shows that mutated XSS attack generation can identify potential vulnerabilities.

1 Introduction

According to the Open Web Application Security Project (OWASP) [15], cross-site scripting (XSS) is already the one of top two vulnerabilities in Web applications. The XSS vulnerabilities are due to using mistrusted data from the out of Web application as the partial contents of HTML page’s output and this attack may result in information disclosure [6]. Furthermore, the implementation of HTML interpreters embedded in browsers incompletely comply with specifications or provide extra functionalities (e.g., browser-specific HTML tags, attributes, and events). In the above situations, Web application programmers difficultly sanitize the input message for preventing the XSS vulnerabilities by uniform XSS patterns or detection rules.

In general, an XSS attack can be separated into the attack vector and the attack body [5]. An attack body is the main code for executing the intention (e.g., it can invoke JavaScript interpreter) after exploiting a vulnerability successfully, and it is often applied by obfuscation techniques beyond the detections. An attack vector [22, 7] is the medium for introducing the attack body. If imagining a XSS exploit as a missile, the attack vector is like the guided device of the missile, and the attack body is like the warhead.
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Figure 1: A motivation example. There is a XSS vulnerability at line 27 of this page. Someone can input a string prefixed double quote by variable “keyword” to trigger the vulnerability. When the form is submitted, the input string is assessed whether assigning a value at line 5. If true, the input string will be assigned to variable “query”. Finally, the variable “query” becomes the value of attribute “value” in the input element, and it is included between double quotes.

01: <html>
02: <head><title>Search.php</title></head>
03: <body>
04: <?
05: if(isset($_GET['keyword'])) {
06: $query = $_GET['keyword'];
07: /* obtaining data from database */
12: echo "The results are listed as below<p>";
13: /* show results */
20: }
21: else {
22: $query = "";
23: }
24: ?>
25: <form method="GET">
26: Search:
27: <input type="text" name="keyword" value="?&gt;&lt;script&gt;alert(123)&lt;/script&gt;" />
28: <input type="submit" value="submit"></form>
29: </body>
30: </html>

of the missile. Hence, an attacker can promote the attack body to be interpreted for malicious intention by using the right or efficient attack vectors.

In Figure 1 we depict the relationship between the attack vector and the attack body in the example code. It is noticeable that there is a XSS vulnerability at line 27 of this page. The vulnerability is the result of the input being used as the value of attribute “value” in the input element. Someone can input a string prefixed double quote like, “" &lt;script&gt;alert(123)&lt;/script&gt; “”, through variable “keyword” to trigger the vulnerability. However, the following attack may not work, “&lt;script&gt;alert(123)&lt;/script&gt; “”. It is clear that double quote is the critical character to introduce the attack body (i.e., “&lt;script&gt;alert(123)&lt;/script&gt; “”), and the attack vector is double quote in here. The string “"&lt;script&gt;alert(123)&lt;/script&gt;&lt;a name="" is even better, as it is seamlessly embedded in the page.

Although a lot of previous studies focus on creating attack vectors to identify XSS vulnerabilities, the involved attack vectors are either generated based on path constraints or equipped a set of attack payloads. However, when reviewing XSS cheat sheet [21] and public XSS exploits [4], it is quite obvious that attackers often use special symbols and HTML elements for crafting XSS attacks in some manners. Thus, we attempt to propose a structural learning mechanism of the attack vector for generating mutated XSS attacks.

The proposed mechanism presents an automated technique for generating mutated XSS attacks to test XSS vulnerabilities in Web applications. First, the system automatically crawls public XSS attacks existed in URLs, and extracts the elements of XSS attacks. Next, the structural learning module builds a structure model based on a hidden Markov model (HMM) while generalizing the structure of the model by Bayes’ Theorem. Finally, according to the structure model, the system generates mutated XSS attacks based on Viterbi algorithm to enlarge the detection capability of the testing tool.

The challenge in generating mutated XSS attacks is how to compose the right element in the right position of the structure to exploit the specified vulnerabilities. If the attack vector can not pass through the internal procedures (e.g., sanitization function, string manipulation function) of the Web application, the XSS attack maybe fail. There are many possible ways to invoke the JavaScript interpreter according to W3C and browser specifications. In such situations, it is impractical for an expert to spend much time
identifying a vulnerability. Hence, learning the manners and elements from the known XSS attacks is helpful for mutated attacks generation.

The goal of the proposed technique, different from previous works of Web applications testing, is aimed at learning the elements and the implicit structure which are presented within the XSS attacks. Thereby, learning from public XSS exploits can benefit from the common weaknesses of Web applications that cannot be handled well, and increasing the probability of identifying XSS vulnerabilities in black or white-box testing. In the other hand, learning the structure of attack vectors could enrich the manifestations of XSS attacks. In summary, the contributions of our proposed approach are as following:

1. can automatically learn the structure of attack vectors from practical data analysis to modeling a structure model of attack vectors.
2. can mimic the manners and the elements of attack vectors to extend the ability of testing tool for identifying XSS vulnerabilities.
3. can be helpful to verify the flaws of blacklist sanitization procedures of Web applications.

The rest of this paper is organized as follows: First, the proposed approach for generating mutated XSS attacks in Section 2. The experiment design and the evaluation are given in Section 3. After that, the related work will be introduced in Section 4. Finally, the conclusion will be briefed in Section 5.

2 Generation of Mutated XSS Attacks

The goal of our proposed approach is to learn the structure of attack vectors and generate mutated XSS attacks. The proposed mechanism consists of three components, the attack vector tokenizer, attack vector inducer, mutated attack generator, and one attack vector profile.

Mutation involves two phases, a structure learning phase and an attack generating phase. In the structure learning phase, the attack vector tokenizer attempts to extract the elements of attack vectors from known XSS URLs. Next, the attack vector inducer profiles the sequential relations among the attack elements and the attack vector profile records these sequential relations for mutating XSS attacks. In the attack generation phase, the mutation mechanism based on the XSS attacks, and transforms them into a sequence of tokens by passing it through the attack vector tokenizer. Subsequently, the mutated attack generator based on the structure of referred XSS attacks and the attack vector profile to generate mutated XSS attacks from raw corpus. Thus, the proposed approach is an automatic way from learning the structure of attack vectors to generating mutated XSS attacks. An overview of the structural learning mechanism is depicted in Figure 2.

2.1 Attack Vector Tokenizer

The attack vector tokenizer could be regarded as preprocessing module with three functionalities, including decoding, identification and tokenization. The task of the attack vector tokenizer is automatic collecting the announced XSS URLs and disassembling them from public Web sites (e.g., [4]) or information security organizations. The attack vector tokenizer has a XSS attack locator and a token extractor for handling XSS URLs. First, the XSS attack locator crawls the XSS URLs and seeks the parameters in which the XSS attack existed. Next, the token extractor abstracts the XSS attacks and outputs the tokens for subsequent procedures. Thus, the attack vector tokenizer is able to identify an XSS attack from a XSS URL and extract the elements of attack vectors. These components of the attack vector tokenizer are described in greater detail in the following subsections.
2.1.1 XSS Attack Locator and Token Extractor

The XSS attack locator is responsible for identifying an XSS attack from a XSS URL. Malicious users are familiar with obfuscating their crafted XSS attacks to evade the detection mechanism. HTML entity codes, URL encoding, Base64 and double encoding are frequently observed obfuscation techniques. Consequently, if the XSS attack locator directly processes these obfuscated XSS URLs, not only it easily fails to identify the XSS attack, but the token extractor will also lose a lot of structural information about the attack vector. To obtain the original structure of the attack vector, the XSS attack locator handles the decoding of HTML symbol entities and URL encoding, besides system control characters.

After decoding, the XSS attack locator examines the entire XSS URL to identify where the XSS attack is. According to URI syntax [25], essentially three delimiters are considered in splitting the entire URL to recognize the position from the values. The term "value" in here is the value of a parameter in a URN. The XSS attack locator complies with the delimiters to obtain one or more values in a XSS URL, and estimates the most possible value where the XSS attack existed by six weighted features.

The token extractor is responsible for transforming a XSS attack into a sequence of tokens. The types of token are as follows: start_tag, attribute, the value of an attribute, plain text, end_tag, and comment. When the token extractor receives the XSS attack, it disassembles the XSS attack into a sequence of tokens and saves the original substrings to the raw corpus. The raw corpus records the mapping information between the type of token and the original substring.

2.2 Structural Learning of Attack Vectors

In the real XSS attacks, they are often mutated with a few attack vectors for discovering increasingly the XSS vulnerabilities. In order to mimic the manners and elements from attack vectors, we propose a Structural Learning of Attack Vectors (SLAV) mechanism that can profile attack vectors in an automatic way. From learning, the SLAV attempts to learn the sequential relations among the elements of attack
vectors and these relations can be regarded as a type of implicit regular grammar that defines all possible combination of elements.

In the SLAV, we apply probabilistic models for discovering the implicit meaning behind observed elements, and the model is regarded as the structure model of attack vectors. Briefly, the structural learning procedure is comprised of three steps as follows.

1. Incorporate each token sequence into the current structure model.
2. Adjust the state topology of the model to match all of the data.
3. Output a profile of the structure model when finishing to incorporating all data.

These steps are described in full detail in the following subsections.

2.2.1 Attack Vector Structure Learning

To infer the general forms of attack vectors from token sequences, the attack vector structure learning (or saying AVSL) intends to model stochastic sequences within an finite states based on HMM. Also, this structure model of attack vectors is adjusted until it is general enough to describe all XSS attacks by Bayes’ Theorem. Thus, the entire structure model can be viewed as a probabilistic automaton \[3\]. In a probabilistic automaton, each production rule is assigned a probability, and it implies that some attack vectors are more likely to be generated than others. In a HMM, each state represents a non-terminal symbol, each observation represents a terminal symbol in grammar, and all paths that are possible routes from the starting state to the final state denote all possible production rules with non-zero probability (i.e., the product of initial probability, transition probability and emission probability). The HMM benefits the model capturing the sequential relations of tokens and obtaining the implicit grammatical manners for generating mutated XSS attacks.

For generalization, the Bayes’ Theorem can be expressed by the following equation.

\[
P(M|X) = \frac{P(M)P(X|M)}{P(X)}
\]

Here, \(M\) is the structure model, and \(X\) is a set of training token sequences. Both \(X\) and \(P(X)\) are constant and can be ignored in the computation. In order to maximize the a posteriori probability \(P(M|X)\), the product of \(P(M)\) and \(P(X|M)\) requires to be maximized. \(P(M)\) is the prior probability of the model and is assigned by the Dirichlet distribution. \(P(X|M)\) is the probability of a set of training token sequence given the model and can be calculated for a model topology (i.e., state transition and emission probabilities) with a various probabilities and performances for a fixed training tokens. Thus, Bayes’ Theorem is used to find the balance between \(P(M)\) and \(P(X|M)\) and to decide the appropriately general model for representing the form of XSS attacks without bias.

The goal of the AVSL is building a structure model with the highest generalization for describing the relations of all elements. Model-building starts with an empty structure model with no any tokens. In step 1, when a token sequence coming, it is initially modeled as a HMM \[19\] and incorporate into the current structure model. Then, in the current structure model, all of the possible pairs of states are merged and examined by Bayes’ Theorem for obtaining a merged model with the maximum posteriori probability in step 2. In step 3, if the a posteriori probability of the merged model is less than that of the current model, then the current structure model is replaced with the merged model. After repeating above steps to each token sequence, a profile of the current structure model is published. For details of the complete process, the readers are referred to \[23\] and \[24\].
2.2.2 Attack Vector Profile

Once the structure model has been built, an attack vector profile is published. An attack vector profile that describes all parameters of the structure model. These parameters contain a set of hidden states, a set of tokens, the initial probability of each state, the transition probabilities that record the likelihood of transitioning from one state to next, and the emission probabilities that record the probability distribution over the possible tokens in each state. The existing of the attack vector profile provides the information of the structure model, that is followed to generate mutated XSS attacks.

2.3 Mutated Attack Generator

The mutated attack generator attempts to simulate the structure of referred XSS attack by evaluating the possible state sequence in the structure model, and applying the original elements from raw corpus. In the attack generation phase, the procedure starts with tokenizing the referred XSS attack as a sequence of tokens. Subsequently, the mutated attack generator estimates the token sequence and seeks the maximum-likelihood state sequence by the Viterbi algorithm [26] according to the attack vector profile.

The Viterbi algorithm finds the maximum-likelihood sequence of hidden states–also called the Viterbi path–for a given sequence of tokens and profile of HMM. For purposes of generation, the Viterbi path can be interpreted as the context in which a given XSS attack takes place. Therefore, the mutated attack generator is able to acquire the structure of attack vectors for generating a variety of XSS attacks. In addition, functions embedded in the mutated attack generator include mutating attacks with obfuscation techniques, such as URL encoding and HTML entity codes.

3 Experiment and Results

In this section, we evaluated the proposed approach by the experiment that is designed for generating mutated attacks to penetrate the vulnerabilities of PHP Web applications. The used dataset and the experiment design concept are mentioned in Subsection 3.1. The evaluation metrics are described for evaluating the performance of proposed approach in the aspect of vulnerability discovering are given in Subsection 3.2. The experiment results and case studies are given in Subsection 3.3. Finally, we discuss the proposed approach in Subsection 3.4.

3.1 Experiment Design and Dataset

The goal of experiment intended to measure the effectiveness of mutated XSS attacks in identifying XSS vulnerabilities in PHP Web applications. It is noticeable that we neither claim to completely cover the space of possible variations of an attack, nor states that we guarantee that all the possible mutated attack are successful. Nevertheless, we aim at providing an effective mechanism for the structural learning of attack vectors to test the Web application. The experiment was designed to answer following research questions:

- How is the effectiveness of the mutated XSS attack generation to find out the existed vulnerabilities?
- What the manifestation of XSS attack vectors trigger potential vulnerabilities?

The configuration procedures for each target program are listed as following. First, we set up an environment for the requirements of each target program (e.g., essential configurations, database tables...
Table 1: The characteristics of Web applications (The **Vulnerabilities** column lists the number of XSS vulnerabilities mentioned in [11]. The **Downloads** column lists downloads counted by Sourceforge [8] at June 6th 2010.)

| Program (Version) | Vulnerabilities | Downloads |
|-------------------|-----------------|-----------|
| webchess (0.9.0)  | 13              | 41257     |
| schoolmate (1.5.4)| 18              | 6900      |

and so on). Second, we built the structural model of attack vectors from the public dataset and used the model to generate XSS attacks based on the attack information (i.e., the relative parameters and the attack body). Third, the Burp Intruder [16], a famous tool for automating attacks against Web applications and allowing for importing customized attack payloads, run the XSS attacks generated by proposed approach against the target Web applications. Finally, we investigated manually to check the results of XSS attacks that were reported as successful attacks whether really trigger attack bodies.

For the evaluation, the dataset (denoted as XSSed10) was collected from XSSed project[1] and the duration of the collection was between 2009/05/16 and 2010/03/13. Totally, the XSSed10 had 3019 XSS attacks for this work and several obvious characteristics were in XSSed10. For example, one or more special symbols were outside of tags (e.g., ">"\><script>) and encoding techniques were in favor.

In the structure model, we obtained totally 11 states, 1031 tokens and 192 unique token sequences from the XSSed10.

The testing target were the two PHP open-source Web applications listed in Table 1. The “schoolmate” [13] is a Web solution for assisting the elementary, junior and senior high school to provide the administration of school affairs. Another testing target naming “Webchess” [20] is an online chess game. There have been several identified vulnerabilities in these two open-source PHP Web applications, and hence, they were suitable to be used for evaluating the effectiveness of mutated XSS attacks whether they could trigger the practical vulnerabilities or not.

The referred information of XSS attacks were from [11], and they were base XSS attacks for mutation. There were many XSS vulnerabilities identified by these XSS attacks in schoolmate and webchess. Before the system generated mutated XSS attacks, the base XSS attack was tokenized as a token sequence. Then the system obtained a sequence of hidden state according to the token sequence by Viterbi algorithm. Finally, mutated XSS attacks were generated by composing the elements of raw corpus. Especially, each mutated XSS attack contained attack body, `<script>alert(123)</script>` for test oracle.

### 3.2 Evaluation Metrics

Because the target programs have been examined by previous researches, we regarded to the effectiveness of our system for assisting vulnerability scanner in attack string generation by two metrics, that is, the false positive rate (or saying FP rate) and the recall rate (or saying Recall). In here, the true positive means the attack can invoke the JavaScript interpreter. The false positive means the reported successful attack, but it cannot invoke the JavaScript interpreter. The summary of true positives and false positives are the total generated attacks. Hence, the FP rate denotes the ratio of the number of failed testing attacks in to the number of successful testing attacks in report, shown as Equation 2. This indication shows the level of threat of the mutated XSS attacks, and the more lower FP rate denotes that the set of mutated

\[FP\text{ Rate} = \frac{\text{Failed Testing Attacks}}{\text{Successful Testing Attacks}}\]
Table 2: The Recall of our approach (The higher Recall rate denotes that the set of mutated XSS attacks really contain the manners to identify XSS vulnerabilities.)

| Target Application | Identified Vulnerabilities | Missed Vulnerabilities | Total Vulnerabilities | Recall Rate |
|--------------------|---------------------------|------------------------|-----------------------|-------------|
| webchess           | 13                        | 0                      | 13                    | 100%        |
| schoolmate         | 14                        | 4                      | 18                    | 78%         |

XSS attacks are more threatening to a target Web application.

\[ FP = \frac{\text{# of real failed attacks in successful attacks}}{\text{# of whole reported successful attacks}} \]  (2)

Recall rate is used to measure the ability of mutated XSS attacks about identifying vulnerability in Web applications. In here, the numbers of total vulnerabilities were collected from [11] with 18 and 13 vulnerabilities respectively. So, the Recall rate is shown as Equation (3). The higher Recall rate means that the set of mutated XSS attacks are with much more capability to identify XSS vulnerabilities.

\[ \text{Recall} = \frac{\text{# of found vulnerabilities}}{\text{# of whole vulnerabilities in target Web application}} \]  (3)

3.3 Numerical Results and Case Studies

In Table 2, the proposed mechanism achieved 100% and 78% Recall rate for the target Web applications. In identifying vulnerabilities, our mutated XSS attacks found 27 vulnerabilities and missed 4 vulnerabilities. After the manual investigation, the two of four missed vulnerabilities could be ignored. Since input was sanitized by the PHP function, the “html specialchars” before it was saved into the database. This “htmlspecialchars” function is used to convert “&” (ampersand), “<”, and “>” into HTML markup, (i.e., “&” as “&”, “<” as “<” and “>” as “>”). When the converted input was retrieved from the database, it was already harmless. However, some un-converted part of input were still displayed on the page title, it might be the reason of being falsely determined as vulnerabilities. If adopting more strict test oracle, the false positives would not be occurred. The remained two vulnerabilities were the stored XSS vulnerabilities, and the attack, which was input from administrative page, would be triggered when the clients browsed the login page. The two vulnerabilities did not be sanitized by any filter functions, so our mutated XSS attacks succeeded in being saved into the database.

In reality, the system was able to generate more than 1,500,000 XSS attacks, since the referred XSS attack was with longer structure and had more plain-text type of tokens. We limited the system generated 928 and 300 mutated XSS attacks respectively in evaluation of testing target Web application. The FP rate regarded to “Webchess” and “schoolmate” were 53.1% and 78.7% respectively, as shown in Table 3. The performance is worth to mention that our proposed approach actually did not consider any prior knowledge about target applications, our mutated XSS attacks were still effective for testing the vulnerabilities.

In the aspect of manifestation of generated mutated XSS attacks, we found several interesting attack vectors as shown in Table 4. The first attack—the attack vector was “&gt;” and the attack body was `<iframe src=http://xssed.com>—was preferred to place between the double quotes as the value of an attribute. According to W3C specification, the tag “iframe” and the attribute “src” need to be separated by a space, but the attack body adopted the slash instead of the space and this format was recognized by
Table 3: The performance of our mutated XSS attacks (The lower FP rate denotes that the set of mutated XSS attacks were with more threats to the target Web applications.)

| Target Application | True Positive Attacks | False Positive Attacks | Reported Successful Attacks | False Positive Rate |
|--------------------|-----------------------|------------------------|-----------------------------|---------------------|
| webchess           | 435                   | 493                    | 928                         | 53.1%               |
| schoolmate         | 64                    | 236                    | 300                         | 78.7%               |

Table 4: The samples of mutated XSS attack (The attack vectors are separated by commas, and the attack bodies are denoted as italic.)

| Mutated XSS Attack Samples |
|---------------------------|
| 1. ”>, alert(123)<iframe src=http://xssed.com>alert(123)</script>alert(123) |
| 2. ”>, '></div>alert(123)<input><script>alert(123)</script></marquee>alert(123)”> |
| 3. ”>”, </p>alert(123)<marquee>alert(123)</script></title>alert(123) |
| 4. ”>/", </ScrIPT>alert(123)<title><script>alert(123)</script></SCRIPT>alert(123) |
| 5. ”>”>, </form>alert(123)<b><script>alert(123)</script></input>alert(123)“ type="hidden" /> |

Internet Explorer 8. An attacker assigns most likely the malicious Web site as the value of the attribute “src” to trigger drive-by download attack without any knowledge of client if both of the size of width and the height of iframe tag equal to zero. The drive-by download attack \[18, 17\] is a serious security threat in recent years, because this type of attacks could be downloaded the spywares, computer viruses, like Trojan horses and bot programs, by exploiting Web browser vulnerabilities. In the case of the second attack, the attack vector was the same as the first one, but the attack body showed the common attack behavior that invokes JavaScript interpreter. It was worthwhile to notice the single input tag in second attack that showed an input field in the page which was rendered by the browsers of Microsoft Internet Explorer 8 or Google Chrome. We thought that input field could be utilized to entice clients into input personal confidential data through social engineering, like phishing attacks.

The attack vector of the third attack was ”>”> that could be seamlessly integrated with the HTML page because the first > was as the value of an attribute, and in the meantime the second > was as the indicator of ending a tag. The combination of digital value (or characteristics), value delimiter, and end-tag-indicator (e.g., 1’) is the popular style to make subsequent tags or attack bodies be correctly rendered by Web browsers. For example, in the third attack, the marquee tag and attack body (i.e., <script>alert(123)</script>) have effectiveness to scroll the following texts (e.g., the reader images the ”XSS is here” instead of ”alert(123)”) and popup a dialogue window respectively. The fourth attack string was different with the third attack vector, and the difference was no prefixed characteristic or value because the / was as end-tag-indicator. The fifth attack string ”>”> was as well as the third attack vector, but former was suffixed with </form>, that was often used in input field, while inputs were output in a form block. In such situation, attackers could close the original form block for creating another form block to convince clients enter their own data and redirect the input data.

These results reveal that mutated XSS attacks can manipulate the face of response pages by HTML tags and trigger the JavaScript interpreter by inducing additional script-inducing constructs. This is
helpful to Web application programmers to know what combination of HTML tags and special symbols they must handle carefully.

### 3.4 Discussion

Our mutated XSS attacks can be used to test XSS blacklists in the Web application. This type of sanitization functions define a set of restricted XSS patterns for filtering the input. For example, phyMyAdmin, a popular administration of MySQL database in Web applications, had a blacklist bypass vulnerability in version 2.8.0 to 2.9.2. The cause resulted from ignoring the end tag, `<SCRIPT>`, and only checking the end tag, `</script>`. This vulnerability can break the section of JavaScript to interrupt original processing. Hence, an attacker can send an attack, like `</SCRIPT><script>alert(123)</script>` and invoke the JavaScript interpreter for popping a warning window on the client’s browser. The attack can be generated by our proposed approach, and exists in XSS cheat sheet. It is clear that the structural learning of attack vectors is efficient and benefited from the real XSS exploits. On the other hand, we ever tested the public XSS detection rule against the mutated XSS attacks, but the result showed that all mutated XSS attacks were detected. Because the detection rules filter all characters that range between a to z, between A to Z and % between `<` and `>`, this may detect all XSS attacks, but the false positives were still high. We believe that the testing ability of mutated XSS attacks generated by the proposed approach is as well as the XSS cheat sheet made by experts.

### 4 Related Work

Generally, three techniques are used to identify the XSS vulnerabilities in different locations and phases. These three techniques include static analysis [9, 27], black-box testing [2, 14] and hybrid testing [1, 11]. Different techniques are appropriate at different usages with their own characteristics ( strength and weakness).

Static analysis could take the whole possible values of a variable into consideration based on the source code of the Web application without executing the application. However, some fundamental problems result in more higher false positives and fail to prove the feasibility of vulnerabilities.

Black-box approach detects vulnerabilities by sending inputs to an application without priori knowledge about the target applications. Generally, the testing tools are equipped with a lot of attack payloads for triggering specified vulnerability. This type of testing not only mimics real-world attacks from malicious users, but also provides cost-effective testing for identifying a range of serious vulnerabilities.

SecuBat [10] utilized attack patterns (e.g., SQL and XSS vulnerabilities) and injected them into entry points. Then the responses from the server were analyzed to identify the vulnerabilities of the web application. However, SecuBat used fixed attack patterns for identifying SQL injection or XSS vulnerabilities and ignored knowledge about the filter functions of applications. On the other hand, our approach learns evasion techniques from real-world attacks and they are able to extend the ability of black-box testing. McAllister et al. [12] performed in-depth testing of web applications against XSS attacks by leveraging usage-based information, modifying them with attack test cases, and replaying them back. Similar to our approach, we collects attacks that are practical and malicious, and generates attacks with malicious intension.

Hybrid testing combines static and dynamic analysis to verify whether identified flaws are real vulnerabilities by executing test data. In order to enlarge the scope of testing and speed up the testing period, an automated attack-testing mechanism is required.
The above works need to maintain a corpus of XSS attacks collected from public sources or suggested by experts. These XSS attacks are examined for their attack specifications or patterns to identify XSS vulnerability. However, attacks generated in such way did not benefit from the sources, for example, the structures or elements of XSS attacks. To implement an attack, it must be crafted specifically for a certain weakness of a web application.

5 Conclusion

We have proposed a technique to automatically generate cross-site scripting (XSS) attacks for identifying XSS vulnerabilities in Web applications. For simulating the manner of crafting attacks used by attackers, this technique takes the archives of XSS attack as input, and is based on hidden Markov model (HMM) as well as Bayes’ Theorem for learning the general structure of the attack vectors. Thus, generation mechanism takes the advantage of structure model to produce mutated XSS attacks like the behavior of the attackers. In our experiments, the technique effectively produces the XSS attacks that trigger XSS vulnerabilities in target applications, and gives a help to provide a set of various mutated XSS attacks, which are essentially taken into consideration by web programmers.

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References

[1] Davide Balzarotti, Marco Cova, Vika Felmetsger, Nenad Jovanovic, Engin Kirda, Christopher Kruegel & Giovanni Vigna (2008): Saner: Composing Static and Dynamic Analysis to Validate Sanitization in Web Applications. In: Proceedings of the 2008 IEEE Symposium on Security and Privacy, Oakland, California, USA, pp. 387–401.
[2] Jason Bau, Elie Bursztein, Divij Gupta & John Mitchell (2010): State of the Art: Automated Black-Box Web Application Vulnerability Testing. In: Proceedings of the 2010 IEEE Symposium on Security and Privacy, Oakland, California, USA, pp. 332–345.
[3] Pierre Dupont, Francois Denis & Yann Esposito (2005): Links Between Probabilistic Automata and Hidden Markov Models: Probability Distributions, Learning Models and Induction Algorithms. Pattern Recognition 38(9), pp. 1349–1371.
[4] Kevin Fernandez & Dimitris Pagkalos (2007). XSSed Project. Available at http://xssed.com
[5] Prahlad Fogla, Monirul Sharif, Roberto Perdisci, Oleg Kolesnikov & Wenke Lee (2006): Polymorphic Blending Attacks. In: Proceedings of the 15th USENIX Security Symposium, pp. 241–256.
[6] Fourthdimension (2009). Stealing Cookie With XSS. Available at http://www.go4expert.com/forums/showthread.php?t=17066
[7] Simon Hansman & Ray Hunt (2005): A Taxonomy of Network and Computer Attacks. Computers and Security 24(1), pp. 31–43.
[8] Geeknet Inc. (2010). Sourceforge.net. Available at http://sourceforge.net
9] Nenad Jovanovic, Christopher Kruegel & Engin Kirda (2006): Pixy: A Static Analysis Tool for Detecting Web Application Vulnerabilities (Short Paper). In: Proceedings of the 2006 IEEE Symposium on Security and Privacy, Berkeley/Oakland, California, USA, pp. 258–263.

[10] Stefan Kals, Engin Kirda, Christopher Kruegel & Nenad Jovanovic (2006): SecuBat: A Web Vulnerability Scanner. In: Proceedings of the 15th International Conference on World Wide Web, Edinburgh, Scotland, UK, pp. 247–256.

[11] Adam Kieyzun, Philip J. Guo, Karthick Jayaraman & Michael D. Ernst (2009): Automatic Creation of SQL Injection and Cross-Site Scripting Attacks. In: Proceedings of the 31st International Conference on Software Engineering, Vancouver, Canada, pp. 199–209.

[12] Sean McAllister, Engin Kirda & Christopher Kruegel (2008): Leveraging User Interactions for In-Depth Testing of Web Applications. In: Proceedings of the 11th International Symposium on Recent Advances in Intrusion Detection, Massachusetts, USA, pp. 191–210.

[13] Mrmunkey22 (2004). SchoolMate 1.5.4. Available at http://sourceforge.net/projects/schoolmate/.

[14] Jeff Offutt, Ye Wu, Xiaochen Du & Hong Huang (2004): Bypass Testing of Web Applications. In: Proceedings of the 15th International Symposium on Software Reliability Engineering, St-Malo, France, pp. 187–197.

[15] OWASP (2010). OWASP Top 10 Project. Available at http://www.owasp.org/index.php/Category:OWASP$_$Top$_$Ten$_$Project.

[16] PortSwigger (2010). Burp Intruder 1.3.03. Available at http://portswigger.net/intruder/.

[17] Niels Provos, Panayiotis Mavrommatis, Moheeb Abu Rajab & Fabian Monrose (2008): All Your Iframes Point to Us. In: Proceedings of the 17th conference on USENIX Security Symposium, San Jose, CA, pp. 1–15.

[18] Niels Provos, Dean McNamee, Panayiotis Mavrommatis, Ke Wang & Nagendra Modadugu (2007): The Ghost in The Browser Analysis of Web-Based Malware. In: Proceedings of the first conference on First Workshop on Hot Topics in Understanding Botnets, Cambridge, MA, p. 4.

[19] Lawrence R. Rabiner & Biing-Hwang Juang (1986): An Introduction to Hidden Markov Models. ASSP Magazine, IEEE 3(1), pp. 4–16.

[20] Roflo1 & Sandking (2004). WebChess 0.9.0. Available at http://sourceforge.net/projects/webchess/.

[21] RSnake (2009). XSS (Cross Site Scripting) Cheat Sheet. Available at http://ha.ckers.org/xss.html

[22] SearchSecurity.com (2007). Security Definition-Attack Vector. Available at http://searchsecurity.techtarget.com/dictionary/definition/1005812/attack-vector.html.

[23] Andreas Stolcke & Stephen Omohundro (1993): Hidden Markov Model Induction by Bayesian Model Merging. In: Advances in Neural Information Processing Systems, 5, San Mateo, CA, pp. 11–18.

[24] Andreas Stolcke & Stephen M. Omohundro (1994): Best-first Model Merging for Hidden Markov Model Induction. Technical Report, International Computer Science Institute, Berkeley, Ca.

[25] Roy T. Fielding Tim Berners-Lee & Larry Masinter (2005). RFC3986-Uniform Resource Identifiers (URI): Generic Syntax. Available at http://tools.ietf.org/html/rfc3986.

[26] Andrew James Viterbi (1967): Error Bounds for Convolutional Codes and An Asymptotically Optimum Decoding Algorithm. IEEE Transactions on Information Theory 13(2), pp. 260–269.

[27] Gary Wassermann & Zhendong Su (2008): Static Detection of Cross-Site Scripting Vulnerabilities. In: Proceedings of the 30th International Conference on Software Engineering, Leipzig, Germany, pp. 171–180.