

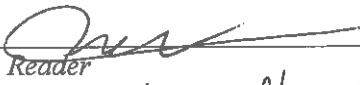



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Understanding and Mitigating the Security Risks of Content Inclusion in Web Browsers

AUTHOR: **Sajjad Arshad**

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William Robertson <i>Thesis Advisor</i>	 _____	04 / 12 / 2019 <i>Date</i>
Engin Kirda <i>Thesis Reader</i>	 _____	04 / 12 / 2019 <i>Date</i>
Guevara Noubir <i>Thesis Reader</i>	 _____	04 / 12 / 2019 <i>Date</i>
Gianluca Stringhini <i>Thesis Reader</i>	 _____	04 / 12 / 2019 <i>Date</i>
_____	_____	_____
<i>Thesis Reader</i>		<i>Date</i>

GRADUATE SCHOOL APPROVAL:

 <i>Director, Graduate School</i>	_____	4/16/19 <i>Date</i>
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Understanding and Mitigating the Security Risks of Content Inclusion in Web Browsers

A dissertation presented in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

in the field of

Information Assurance

by

Sajjad Arshad

Khoury College of Computer Sciences
Northeastern University

Ph.D. Committee

William Robertson	Advisor, Northeastern University
Engin Kirda	Advisor, Northeastern University
Guevara Noubir	Internal, Northeastern University
Gianluca Stringhini	External, Boston University

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Abstract

Thanks to the wide range of features offered by web browsers, modern websites include various types of content such as JavaScript and Cascading Style Sheets (CSS) in order to create interactive user interfaces. Browser vendors also provided extensions to enhance web browsers with additional useful capabilities that are not necessarily maintained or supported by default.

However, included content can introduce security risks to users of these websites, unbeknownst to both website operators and users. In addition, the browser's interpretation of the resource URLs may be very different from how the web server resolves the URL to determine which resource should be returned to the browser. The URL may not correspond to an actual server-side file system structure at all, or the web server may internally rewrite parts of the URL. This semantic disconnect between web browsers and web servers in interpreting relative paths (*path confusion*) could be exploited by *Relative Path Overwrite (RPO)*. On the other hand, even though extensions provide useful additional functionality for web browsers, they are also an increasingly popular vector for attacks. Due to the high degree of privilege extensions can hold, extensions have been abused to inject advertisements into web pages that divert revenue from content publishers and potentially expose users to malware.

In this thesis, I propose novel research into understanding and mitigating the security risks of content inclusion in web browsers to protect website publishers as well as their users. First, I introduce an in-browser approach called EXCISION to automatically detect and block malicious third-party content inclusions as web pages are loaded into the user's browser or during the execution of browser extensions. Then, I propose ORIGINTRACER, an in-browser approach to highlight extension-based content modification of web pages. Finally, I present the first in-depth study of style injection vulnerability using RPO and discuss potential countermeasures.

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Chapter 1

Introduction

Linking to the web content has been one of the defining features of the World Wide Web since its inception, and this feature remains strongly evident today. For instance, recent research [91] reveals that more than 93% of the most popular websites include JavaScript from external sources. Developers typically include third-party content for convenience and performance – e.g., many JavaScript libraries are hosted on fast content delivery networks (CDNs) and are likely to already be cached by users – or to integrate with advertising networks, analytics frameworks, and social media. Content inclusion has also been used by entities other than the website publishers themselves. For example, ad injection has been adopted by ISPs and browser extension authors as a prominent technique for monetization [82]. Browser extensions enhance browsers with additional useful capabilities that are not necessarily maintained or supported by the browser vendor. Instead, this code is typically written by third parties and can perform a wide range of tasks, from simple changes in the appearance of web pages to sophisticated tasks such as fine-grained filtering of content. To achieve these capabilities, browser extensions possess more privilege than other third-party code that runs in the browser. For instance, extensions can access cross-domain content, and perform network requests that are not subject to the same origin policy.

However, the inherent feature of content-sharing on the Web is also an Achilles heel when

it comes to security. Advertising networks, as one example, have emerged as an important vector for adversaries to distribute attacks to a wide audience [71, 72, 92, 114, 130]. Moreover, users are more susceptible to *malvertising* in the presence of ad injection [54, 117, 127]. In general, linking to third-party content is essentially an assertion of trust that the content is benign. This assertion can be violated in several ways, however, due to the dynamic nature of the Web. Since website operators cannot control external content, they cannot know *a priori* what links will resolve to in the future. The compromise of linked content or pure malfeasance on the part of third parties can easily violate these trust assumptions. This is only exacerbated by the transitive nature of trust on the Web, where requests for content can be forwarded beyond the first, directly observable origin to unknown parties.

Furthermore, since extensive capabilities of browser extensions allow a comparatively greater degree of control over the browser, they provide a unique opportunity to attack users and their data, the underlying system, and even the Internet at large. For this reason, newer browser extension frameworks such as Chromium’s have integrated least privilege separation via isolated worlds and a fine-grained permissions system to restrict the capabilities of third-party extensions [15]. However, extension security frameworks are not a panacea. In practice, their effectiveness is degraded by over-privilege and a lack of understanding of the threats posed by highly-privileged extensions on the part of users [34]. Indeed, despite the existence of extension security frameworks, it has recently been shown that extension-based advertisement injection has become a popular and lucrative technique for dishonest parties to monetize user web browsing. These extensions simply inject or replace ads in web pages when users visit a website, thus creating or diverting an existing revenue stream to the third party. Users often are not aware of these incidents and, even if this behavior is noticed, it can be difficult to identify the responsible party.

Web browsers also load internal resources using either absolute URLs or relative ones. Before a web browser can issue a request for such a resource to the server, it must expand the relative path into an absolute URL. Web browsers basically treat URLs as file system-like

paths. However, the browser’s interpretation of the URL may be very different from how the web server resolves the URL to determine which resource should be returned to the browser. The URL may not correspond to an actual server-side file system structure at all, or the web server may internally rewrite parts of the URL. This semantic disconnect between web browsers and web servers in interpreting relative paths (*path confusion*) could be exploited by *Relative Path Overwrite (RPO)*. When an injection vulnerability is present in a page, an attacker could manipulate the URL such that the web page references itself as the stylesheet, which turns a simple text injection vulnerability into a style sink [50]. The general threat model of RPO resembles that of Cross-Site Scripting (XSS). Typically, the attacker’s goal is to steal sensitive information from a third-party site or make unauthorized transactions on the site, such as gaining access to confidential financial information or transferring money out of a victim’s account.

1.1 Thesis Contributions

Due to the increasing reliance of users on web browsers for day to day activities, I believe it is important to characterize the extent of security risks of content inclusion on the Web. In this thesis, I investigate the feasibility and effectiveness of novel approaches to measure and reduce the security risks for website publishers as well as their users. I show that our novel techniques are complementary to the existing defenses. To support my claim, I propose the following:

First, I present a novel in-browser approach called EXCISION that automatically detects and blocks malicious third-party content before it can attack the user’s browser. The approach leverages a high-fidelity in-browser vantage point that allows it to construct a precise inclusion sequence for every third-party resource. We also describe a prototype of EXCISION for the Chromium browser that can effectively prevent inclusions of malicious content. Furthermore, we evaluate the effectiveness and performance of our prototype, and show that

it is able to automatically detect and block malicious third-party content inclusions in the wild – including malicious resources not previously identified by popular malware blacklists – without a significant impact on browser performance. Finally, we evaluate the usability of our prototype and show that most users did not notice any significant quality impact on their browsing experience.

Then, I introduce a novel in-browser approach to provenance tracking for web content at the granularity of DOM elements, and present semantics for provenance propagation due to script and extension execution. The approach leverages a high-fidelity in-browser vantage point that allows it to construct a precise provenance label set for each DOM element introduced into a web page. We also implement a prototype called `ORIGINTRACER` that uses content provenance to identify and highlight third-party content injection – e.g., unwanted advertisements – by extensions to notify users of their presence and the originating principal. Furthermore, we evaluate the effectiveness, performance, and usability of our prototype, and show that it is able to significantly assist users in identifying ad injection by extensions in the wild without degrading browser performance or the user experience.

Finally, I present the first automated and large-scale study of the prevalence and significance of RPO vulnerabilities in the wild. To date, little is known about how widespread RPO vulnerabilities are on the Web. Especially since the attack is more recent and less well-known than traditional XSS, we believe it is important to characterize the extent of the threat and quantify its enabling factors. Our measurement methodology tests how often these preconditions hold in the wild in order to quantify the vulnerability and exploitability of pages with respect to RPO attacks. We enumerate a range of factors that prevent a vulnerable page from being exploited, and discuss how these could be used to mitigate these vulnerabilities.

1.2 Thesis Structure

The remainder of this thesis is organized as follows. Chapter 2 presents the related work. The design and implementation of EXCISION for detecting malicious third-party content inclusions are introduced in Chapter 3. Chapter 4 presents the architecture and evaluation of ORIGINTRACER to identify ad injection in browser extensions. We propose our methodology for large-scale analysis of style injection by relative path overwrite in Chapter 5. Finally, Chapter 6 concludes the thesis.

Chapter 2

Related Work

In this chapter, we place our proposed approaches in the context of related work.

2.1 Content Isolation and Containment

Several recent research projects [41, 115, 121] attempted to improve the security of browsers by isolating browser components in order to minimize data sharing among software components. The main issue with these approaches is that they do not perform any isolation between JavaScript loaded from different domains and web applications, letting untrusted scripts access the main web application’s code and data. Efforts such as AdJail [77] attempt to protect privacy by isolating ads into an iframe-based sandbox. However, this approach restricts contextual targeting advertisement in which ad scripts need to have access to host page content.

Another approach is to search and restrict third-party code included in web applications [35, 42, 80]. For example, ADsafe [3] removes dangerous JavaScript features (e.g., `eval`), enforcing a whitelist of allowed JavaScript functionality considered safe. It is also possible to protect against malicious JavaScript ads by enforcing policies at runtime [98, 102]. For example, Meyerovich et al. [84] introduce a client-side framework that allows web applications to enforce fine-grained security policies for DOM elements. AdSentry [30] provides a

shadow JavaScript engine that runs untrusted ad scripts in a sandboxed environment.

2.2 Blacklisting Malicious Domains

There are multiple approaches to automatically detecting malicious web domains. Madtracer [72] has been proposed to automatically capture malvertising cases. But, this system is not as precise as our approach in identifying the causal relationships among different domains. EXPOSURE [18] employs passive DNS analysis techniques to detect malicious domains. SpiderWeb [114] is also a system that is able to detect malicious web pages by crowd-sourcing redirection chains. Segugio [101] tracks new malware-control domain names in very large ISP networks. WebWitness [90] automatically traces back malware download paths to understand attack trends. While these techniques can be used to automatically detect malicious websites and update blacklists, they are not online systems and may not be effectively used to detect malicious third-party inclusions since users expect a certain level of performance while browsing the Web.

Another effective detection approach is to produce blacklists of malicious sites by scanning the Internet that can be efficiently checked by the browser (e.g., Google Safe Browsing [40]). Blacklist construction requires extensive infrastructure to continuously scan the Internet and bypass cloaking and general malware evasion attempts in order to reliably identify malware distribution sites, phishing pages, and other Web malice. These blacklists sometimes lag the introduction of malicious sites on the Internet, or fail to find these malicious sites. However, they are nevertheless effective, and we view the approach we propose as a complementary technique to established blacklist generation and enforcement techniques.

2.3 Browser Extension Security

Browser extension security has become a hot topic. The Chromium extension framework substantially improved the ability of users to limit the amount of privilege conferred upon

potentially vulnerable extensions [15], and follow-on work has studied the success of this approach [34, 75]. Other works have broadly studied malicious extensions that attempt to exfiltrate sensitive user data [73, 78]. For instance, Arjun et al. showed that many extensions in the Chrome Web Store are over-privileged for the actual services they purport to provide [43].

A line of work has focused on the problem of ad injection via browser extensions. Thomas et al. [117] proposed a detection methodology in which, they used a priori knowledge of a legitimate DOM structure to report the deviations from that structure as potential ad injections. However, this approach is not purely client-side and requires cooperation from content publishers. Expectator [127] inspects a browser extension and determines if it injects advertisements into websites. Hulk [58] is a dynamic analysis system that automatically detects Chrome extensions that perform certain types of malicious behaviors, including ad injection. WebEval [54] is an automatic system that considers an extension’s behaviors, code, and author reputation to identify malicious extensions distributed through the Chrome Web Store. Web Tripwires [103] were also proposed to detect in-flight page changes performed in order to inject advertisements.

In contrast, our work does not attempt to automatically classify extensions that engage in content modification as malicious or not, but rather focuses on enabling users to make informed decisions as to whether extensions engage in desirable behavior or not.

2.4 Provenance Tracking

A significant amount of work has examined the use of provenance in various contexts. For instance, one line of work has studied the collection of provenance information for generic applications up to entire systems [36, 46, 99]. However, to our knowledge, no system considers the provenance of fine-grained web content comprising the DOM. Provenance tracking is also related to information flow control (IFC), for which a considerable body of work exists at the

operating system level [32, 63, 131], the language level [87, 22], as well as the web [37, 51]. In contrast to our work, IFC is focused more on enforcing principled security guarantees for new applications rather than tracking and indicating data provenance for existing ones. Numerous systems have examined the use of dynamic taint analysis, a related concept to provenance. Some prior work [17, 33] focuses on tracking information flow within the browser, Sabre [29] detects whether extensions access sensitive information within the browser, and DSI enforcement [88] defends against XSS attacks by preserving the integrity of document structure in the browser. While there is certainly an overlap between dynamic taint analysis and provenance, taint analysis is most often focused on simple reachability between sources and sinks, while provenance is concerned with precisely tracking principals that influenced data.

Finally, there is a line of work that examines provenance on the web. Some prior work [44, 45, 86] concerns coarse-grained ontologies for describing the origins of data on the web, and does not consider provenance at a fine-grained scale within the browser. ESCUDO [56] only considers the principals that can be controlled by web applications, and it does not handle plug-ins and browser extensions. LeakTracker [118] performs principal-based tracking on web pages to study privacy violations related to JavaScript libraries, but it only tracks injection of scripts into the page, and does not provide any provenance information for other types of DOM elements.

2.5 Relative Path Overwrite

The first account of RPO is attributed to a blog post by Gareth Heyes [50], introducing self-referencing a PHP script with server-side URL rewriting. Furthermore, the post notes that certain versions of Internet Explorer allow JavaScript execution from within a CSS context in the *Compatibility View* mode [85], escalating style injection to XSS [128]. Another blog post by Dalili [27] extends the technique to IIS and ASP.Net applications, and shows how

URL-encoded slashes are decoded by the server but not the browser, allowing not only self-reference but also the inclusion of different resources. Kettle [61] coins the term Path Relative StyleSheet Import (PRSSI) for a specific subset of RPO attacks, introduces a PRSSI vulnerability scanner for Burp Suite [20], and proposes countermeasures. Terada [116] provides more exploitation techniques for various browsers or certain web applications, and [129] discusses an example chaining several vulnerabilities to result in a combination of RPO and a double style injection attack. Gil shows how attackers can deceive web cache servers by using RPO [38, 39]. Some of the attacks discussed in the various blog posts are custom-tailored to specific sites or applications, whereas others are more generic and apply to certain web server configurations or frameworks.

We are not aware of any scholarly work about RPO, or any research about how prevalent RPO vulnerabilities are on the Web. To the best of our knowledge, Burp Suite [20] is the first and only tool that can detect PRSSI vulnerabilities based on RPO in web applications. However, in contrast to our work, it does not determine if the vulnerability can be exploited. Furthermore, we are the first to provide a comprehensive survey of how widespread RPO style vulnerabilities and exploitabilities are in the wild.

2.6 Client-side Attacks

Script-based attacks has been studied extensively, such as systematic analysis of XSS sanitization frameworks [124], detecting XSS vulnerabilities in Rich Internet Applications [12], large-scale detection of DOM-based XSS [68, 76], and bypassing XSS mitigations by Script Gadgets [67, 66]. An array of XSS prevention mechanisms have been proposed, such as XSS Filter [104], XSS-Guard [19], SOMA [93], BluePrint [79], Document Structure Integrity [89], XSS Auditor [16], NoScript [81], Context-Sensitive Auto-Sanitization (CSAS) [106], DOM-based XSS filtering using runtime taint tracking [111], preventing script injection through software design [59], Strict CSP [123], and DOMPurify [48]. However, the vulnerability

measurements and proposed countermeasures of these works on script injection do not apply to RPO-based style injection.

Chapter 3

Detection of Malicious Third-Party Content Inclusions

3.1 Introduction

While the Same Origin Policy (SOP) enforces a modicum of origin-based separation between code and data from different principals, developers have clamored for more flexible sharing models provided by, e.g., Content Security Policy (CSP) [10], Cross-Origin Resource Sharing (CORS) [9], and `postMessage`-based cross-frame communication. These newer standards permit greater flexibility in performing cross-origin inclusions, and each come with associated mechanisms for restricting communication to trusted origins. However, recent work has shown that these standards are difficult to apply securely in practice [109, 125], and do not necessarily address the challenges of trusting remote inclusions on the dynamic Web. In addition to the inapplicability of some approaches such as CSP, third parties can leverage their power to bypass these security mechanisms. For example, ISPs and browser extensions are able to tamper with HTTP traffic to modify or remove CSP rules in HTTP responses [54, 117].

In this chapter, we propose an in-browser approach called `EXCISION` to automatically

detect and block malicious third-party content inclusions as web pages are loaded into the user’s browser or during the execution of browser extensions. Our approach does not rely on examination of the content of the resources; rather, it relies on analyzing the sequence of inclusions that leads to the resolution and loading of a terminal remote resource. Unlike prior work [72], EXCISION resolves *inclusion sequences* through instrumentation of the browser itself, an approach that provides a high-fidelity view of the third-party inclusion process as well as the ability to interdict content loading in real-time. This precise view also renders ineffective common obfuscation techniques used by attackers to evade detection. Obfuscation causes the detection rate of these approaches to degrade significantly since obfuscated third-party inclusions cannot be traced using existing techniques [72]. Furthermore, the in-browser property of our system allows users to browse websites with a higher confidence since malicious third-party content is prevented from being included while the web page is loading.

We implemented EXCISION as a set of modifications to the Chromium browser, and evaluated its effectiveness by analyzing the Alexa Top 200K over a period of 11 months. Our evaluation demonstrates that EXCISION achieves a 93.39% detection rate, a false positive rate of 0.59%, and low performance overhead. We also performed a usability test of our research prototype, which shows that EXCISION does not detract from the user’s browsing experience while automatically protecting the user from the vast majority of malicious content on the Web. The detection results suggest that EXCISION could be used as a complementary system to other techniques such as CSP.

The rest of this chapter is organized as follows. Section 3.2 outlines the necessary background. Section 3.3 presents the architecture of EXCISION, while Section 3.4 discusses the implementation of our system. We present an evaluation of the effectiveness, usability, and performance of our prototype in Section 3.5. Finally, a discussion about our system is presented in Section 3.6, and Section 3.7 summarizes the chapter.

3.2 Background

In the following, we first discuss the threats posed by third-party content and then motivate our work.

3.2.1 Threats

While the inclusion of third-party content provides convenience for web developers and allows for integration into advertising distribution, analytics, and social media networks, it can potentially introduce a set of serious security threats for users. For instance, advertising networks and social media have been and continue to be abused as a vector for injection of malware. Website operators, or publishers, have little control over this content aside from blind trust or security through isolation. Attacks distributed through these vectors – in the absence of isolation – execute with the same privileges as all other JavaScript within the security context of the enclosing DOM. In general, malicious code could launch drive-by downloads [25], redirect visitors to phishing sites, generate fraudulent clicks on advertisements [72], or steal user information [52].

Moreover, ad injection has become a new source of income for ISPs and browser extension authors [82]. ISPs inject advertisements into web pages by tampering with their users' HTTP traffic [23], and browser extension authors have recently started to inject or replace ads in web pages to monetize their work. Ad injection negatively impacts both website publishers and users by diverting revenue from publishers and exposing users to malvertising [117, 127]. In addition to ad injection, malicious browser extensions can also pose significant risks to users due to the special privileges they have [58].

3.2.2 Motivation

Publishers can try to isolate untrusted third-party content using iframes (perhaps enhanced with HTML5 sandboxing features), language-based sandboxing, or policy enforcement [3,

35, 42, 77, 80]. However, these approaches are not commonly used in practice; some degrade the quality of ads (from the advertiser’s perspective), while others are non-trivial to deploy. Publishers could attempt to use Content Security Policy (CSP) [10] to define and enforce access control lists for remote inclusions in the browser. However, due to the dynamic nature of the web, this approach (and similar access control policy-based techniques) has problems. Recent studies [109, 125] indicate that CSP is difficult to apply in practice. A major reason for this is the unpredictability of the origins of inclusions for third-party resources, which complicates the construction of a correct, yet tight, policy.

For example, when websites integrate third-party advertisements, multiple origins can be contacted in order to deliver an ad to the user’s browser. This is often due to the practice of re-selling ad space (a process known as ad syndication) or through real-time ad auctions. Either of these approaches can result in ads being delivered through a series of JavaScript code inclusions [113]. As a consequence, a long inclusion sequence of distinct origins will be observed that – critically – does not remain constant on successive loads of the enclosing web page. Additionally, the growing number of browser extensions makes it a non-trivial task for website operators to enumerate the set of benign origins from which browser extensions might include a resource. Therefore, defining an explicit whitelist of CSP rules is a challenging task.

To illustrate, Figure 3.1 shows the unique number of domains as well as the cumulative number of unique domains included by `theverge.com` over a period of 11 months. The unique number of domains increases roughly linearly over this period; clearly, constructing an effective access control policy that tightly captures the set of allowable inclusions while avoiding false positives that would lead to either lost revenue or broken functionality is difficult.

Even if website publishers can keep pace with origin diversity over time with a comprehensive list of CSP rules, ISPs and browser extensions are able to tamper with in-transit HTTP traffic and modify CSP rules sent by the websites. In addition, in browsers such as Chrome, the web page’s CSP does not apply to extension scripts executed in the page’s

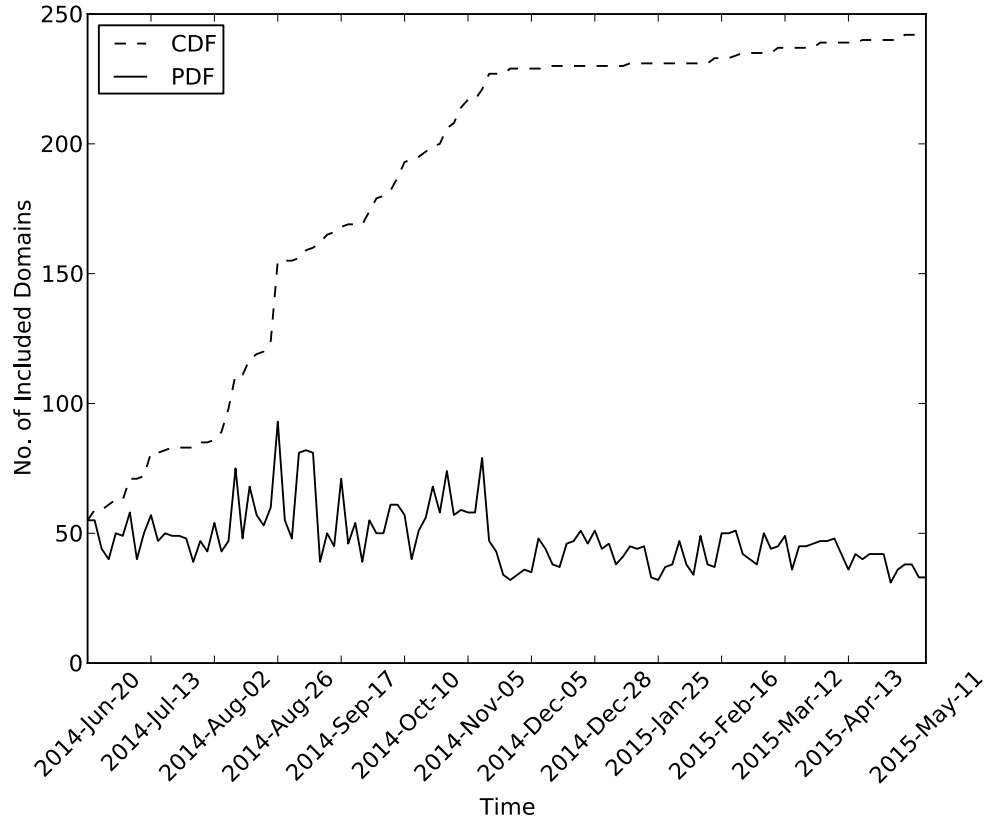


Figure 3.1: Unique number of included domains in `theverge.com` over 11 months. Measurements were collected as part of the data set described in Section 3.5; the sampling frequency was approximately once every three days

context [4]; hence, extensions are able to include arbitrary third-party resources into the web page.

Given the challenges described above, we believe that existing techniques such as CSP can be evaded and, hence, there is a need for an automatic approach to protect users from malicious third-party content. We do not necessarily advocate such an approach in isolation, however. Instead, we envision this approach as a complementary defense that can be layered with other techniques in order to improve the safety of the Web.

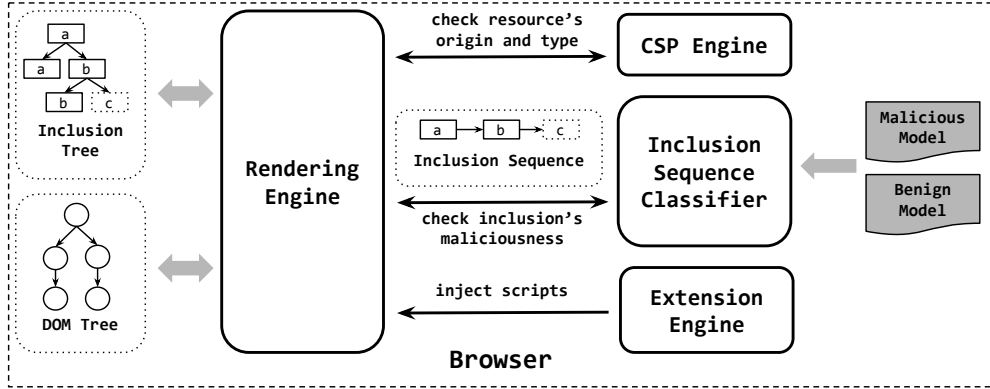


Figure 3.2: An overview of EXCISION

3.3 Design

In this section, we describe EXCISION, our approach for detecting and blocking the inclusion of malicious third-party content in real-time. An overview of our system is shown in Figure 3.2. EXCISION operates by extracting resource *inclusion trees* from within the browser. The inclusion tree precisely records the inclusion relationships between different resources in a web page. When the user requests a web page, the browser retrieves the corresponding HTML document and passes it to the rendering engine. The rendering engine incrementally constructs an inclusion tree for the DOM and begins extracting external resources such as scripts and frames as it reaches new HTML tags. For inclusion of a new resource, the rendering engine consults the CSP engine and the *inclusion sequence classifier* in order to decide whether to include the resource. If the resource’s origin and type are whitelisted in the CSP rules, the rendering engine includes the resource without consulting the inclusion sequence classifier and continues parsing the rest of the HTML document. Otherwise, it extracts the *inclusion sequence* (path through the page’s inclusion tree) for the resource and forwards this to the inclusion sequence classifier. Using pre-learned models, the classifier returns a decision about the malice of the resource to the rendering engine. Finally, the rendering engine discards the resource if it was identified as malicious. The same process occurs for resources that are included dynamically during the execution of extension content scripts

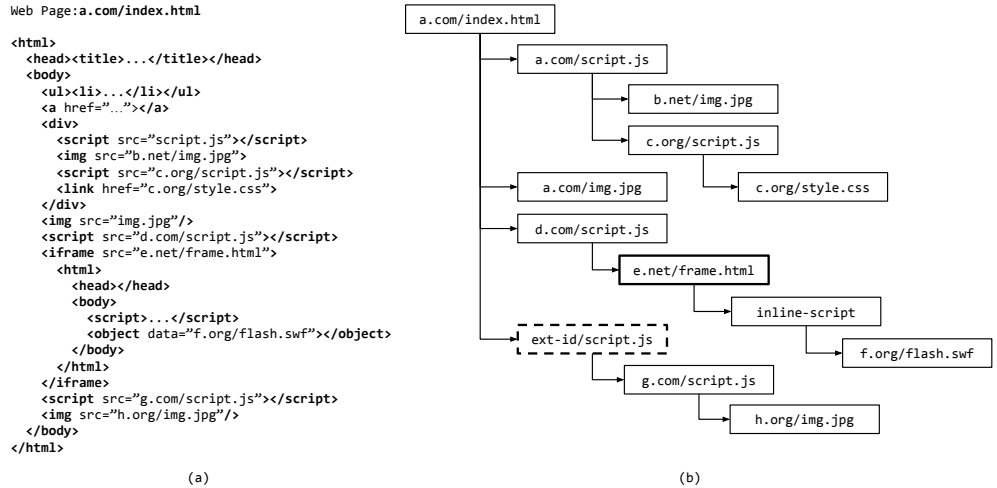


Figure 3.3: (a) DOM Tree, and (b) Inclusion Tree

after they are injected into the page.

3.3.1 Inclusion Trees and Sequences

A website can include resources in an HTML document from any origin so long as the inclusion respects the same origin policy, its standard exceptions, or any additional policies due to the use of CSP, CORS, or other access control framework. A first approximation to understanding the inclusions of third-party content for a given web page is to process its DOM tree [126] while the page loads. However, direct use of a web page’s DOM tree is unsatisfactory because the DOM does not in fact reliably record the inclusion relationships between resources referenced by a page. This follows from the ability for JavaScript to manipulate the DOM at run-time using the DOM API.

Instead, in this work we define an *inclusion tree* abstraction extracted directly from the browser’s resource loading code. Unlike a DOM tree, the inclusion tree represents how different resources are included in a web page that is invariant with respect to run-time DOM updates. It also discards irrelevant portions of the DOM tree that do not reference remote content. For each resource in the inclusion tree, there is an *inclusion sequence* that begins with the root resource (i.e., the URL of the web page) and terminates with the corresponding

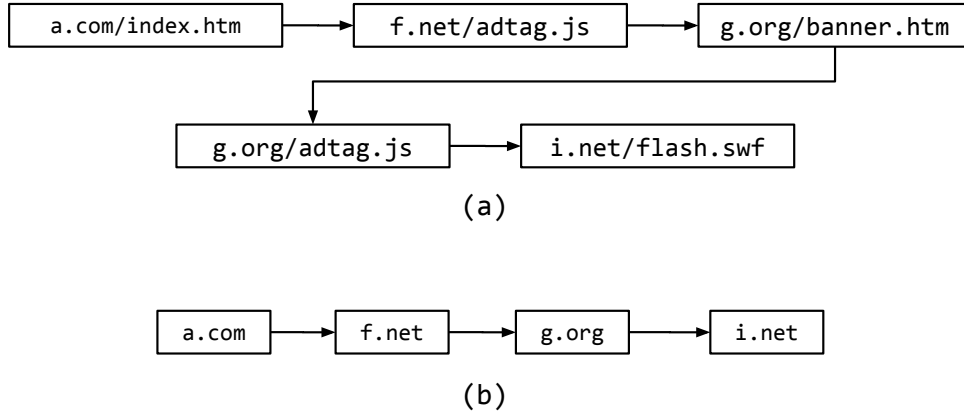


Figure 3.4: (a) URL Inclusion Sequence, and (b) Domain Inclusion Sequence

resource. Furthermore, browser extensions can also manipulate the web page by injecting and executing JavaScript code in the page’s context. Hence, the injected JavaScript is considered a direct child of the root node in the inclusion tree. An example of a DOM tree and its corresponding inclusion tree is shown in Figure 3.3. As shown in Figure 3.3b, `f.org/flash.swf` has been dynamically added by an `inline script` to the DOM tree, and its corresponding inclusion sequence has a length of 4 since we remove the inline resources from inclusion sequence. Moreover, `ext-id/script.js` is injected by an extension as the direct child of the root resource. This script then included `g.com/script.js`, which in turn included `h.org/img.jpg`.

When we consider the full URL for constructing an inclusion sequence, the resulting sequence is called a *URL Inclusion Sequence*. Figure 3.4a shows the URL inclusion sequence of the resource `i.net/flash.swf`. However, some malware campaigns change their URL patterns frequently to avoid detection. This can be done by changing the URL path and the parameter values [72]. To overcome this problem and capture the high-level relationships between different websites, we only consider a domain part of the URL to build the *Domain Inclusion Sequence*. Figure 3.4b shows the domain inclusion sequence corresponding to the aforementioned URL inclusion sequence. As depicted, if consecutive URLs in a sequence have the same domains, we merge them into one node. From now on, by inclusion sequence,

we refer to a domain inclusion sequence unless we mention URL inclusion sequence explicitly.

3.3.2 Inclusion Sequence Classification

Given an inclusion sequence, EXCISION must classify it as benign or malicious based on features extracted from the sequence. The task of the *inclusion sequence classifier* is to assign a class label from the set `{benign,malicious}` to a given sequence based on previously learned models from a labeled data set. In our definition, a malicious sequence is one that starts from the root URL of a web page and terminates in a URL that delivers malicious content. For classification, we used hidden Markov models (HMM) [100]. Models are comprised of states, each of which holds transitions to other states based on a probability distribution. Each state can probabilistically emit a symbol from an alphabet. There are other sequence classification techniques such as Naïve Bayes [69], but we used an HMM for our classifier because we also want to model the inter-dependencies between the resources that compose an inclusion sequence.

In the training phase, the system learns two HMMs from a training set of labeled sequences, one for the benign class and one for the malicious class. We estimated the HMM parameters by employing the Baum-Welch algorithm which finds the maximum likelihood estimate of these parameters based on the set of observed sequences. In our system, we empirically selected 20 for the number of states that are fully connected to each other. In the subsequent detection phase, we compute the likelihood of a new sequence given the trained models using the forward-backward algorithm and assign the sequence to the class with the highest likelihood. Training hidden Markov models is computationally expensive. However, computing the likelihood of a sequence is instead very efficient, which makes it a suitable method for real-time classification [100].

Table 3.1: TLD values

(a) Individual		(b) Relative	
Value	Example	Value	Example
none	IPs, Extensions	none	root resource
gen	*.com, *.org	{got,lost}-tld	Ext. \rightarrow *.de, *.us \rightarrow IP
gen-subdomain	*.us.com	gen-to-{cc,other}	*.org \rightarrow {*.de, *.info}
cc	*.us, *.de, *.cn	cc-to-{gen,other}	*.uk \rightarrow {*.com, *.biz}
cc-subdomain	*.co.uk, *.com.cn	other-to-{gen,cc}	*.info \rightarrow {*.net, *.uk}
cc-int	*.xn--p1ai (ru)	same-{gen,cc,other}	*.com \rightarrow *.com
other	*.biz, *.info	diff-{gen,cc,other}	*.info \rightarrow *.biz

3.3.3 Classification Features

Let $r_0 \rightarrow r_1 \rightarrow \dots \rightarrow r_n$ be an inclusion sequence as described above. Feature extraction begins by converting the inclusion sequence into sequences of feature vectors. After analyzing the inclusion trees of several thousand benign and malicious websites for a period of 11 months, we identified 12 feature types from three categories. For each feature type, we compute two different features: individual and relative features. An individual feature value is only dependent on the current resource, but a relative feature value is dependent on the current resource and its preceding (or parent) resources. Consequently, we have 24 features for each resource in an inclusion sequence. Individual features can have categorical or continuous values. All continuous feature values are normalized on $[0, 1]$ and their values are discretized. In the case of continuous individual features, the relative feature values are computed by comparing the individual value of the resource to its parent’s individual value. The result of the comparison is `less`, `equal`, or `more`. We use the value `none` for the root resource. To capture the high-level relationships between different inclusions, we only consider the domain part of the URL for feature calculation.

3.3.3.1 DNS-based Features

The first feature category that we consider is based on DNS properties of the resource domain.

Table 3.2: Type values

(a) Individual		(b) Relative	
Value	Example	Value	Example
ipv6	2607:f0d0:::4	none	root resource
ipv4-private	192.168.0.1	same-site	w.google.com → ad.google.com
ipv4-public	4.2.2.4	same-sld	1.dyndns.org → 2.dyndns.org
extension	Ext. Scripts	same-company	ad.google.com → www.google.de
dns-sld	google.com	same-eff-tld	bbc.co.uk → london.co.uk
dns-sld-sub	www.google.com	same-tld	bbc.co.uk → london.uk
dns-non-sld	abc.dyndns.org	different	google.com → facebook.net
dns-non-sld-sub	a.b.dyndns.org		

Top-Level Domain. For this feature, we measure the types of TLDs from which a resource is included and how it changes along the inclusion sequence. For every resource in an inclusion sequence, we assign one of the values in Table 3.1a as an individual feature. For the relative feature, we consider the changes that occur between the top-level domain of the preceding resource and the resource itself. Table 3.1b shows 15 different values of the relative TLD feature.

Type. This feature identifies the types of resource domains and their changes along the inclusion sequence. Possible values of individual and relative features are shown in Table 3.2a and Table 3.2b respectively.

Level. A domain name consists of a set of labels separated by dots. We say a domain name with n labels is in level $n - 1$. For example, `www.google.com` is in level 2. For IP addresses and extension scripts, we consider their level to be 1. For a given domain, we compute the individual feature by dividing the level by a maximum value of 126.

Alexa Ranking. We also consider the ranking of a resource’s domain in the Alexa Top 1M websites. To compute the normalized ranking as an individual feature, we divide the ranking of the domain by one million. For IP addresses, extensions, and domains that are not in the top 1M, we use the value `none`.

3.3.3.2 String-based Features

We observed that malicious domain names often make liberal use of digits and hyphens in combination with alphabetical characters. So, in this feature category, we characterize the string properties of resource domains. For IP addresses and extension scripts, we assign the value 1 for individual features.

Non-Alphabetic Characters. For this feature, we compute the individual feature value by dividing the number of non-alphabetical characters over the length of domain.

Unique Characters. We also measure the number of unique characters that are used in a domain. The individual feature is the number of unique characters in the domain divided by the maximum number of unique characters in the domain name, which is 38 (26 alphabets, 10 digits, hyphen, and dot).

Character Frequency. For this feature, we simply measure how often a single character is seen in a domain. To compute an individual feature value, we calculate the frequency of each character in the domain and then divide the average of these frequencies by the length of the domain to normalize the value.

Length. In this feature, we measure the length of the domain divided by the maximum length of a domain, which is 253.

Entropy. In practice, benign domains are typically intended to be memorable to users. This is often not a concern for attackers, as evidenced by the use of domain generation algorithms [18]. Consequently, we employ Shannon entropy to measure the randomness of domains in the inclusion sequence. We calculate normalized entropy as the absolute Shannon entropy divided by the maximum entropy for the domain name.

3.3.3.3 Role-based Features

We observed that identifying the role of resources in the inclusion sequences can be helpful in detecting malicious resources. For example, recent work [92] reveals that attackers misuse ad networks as well as URL shortening services for malicious intent. So far, we consider three roles for a resource: *i)* ad-network, *ii)* content delivery network (CDN), and *iii)* URL shortening service. In total, we have three features in this category, as each domain can simultaneously perform multiple roles. Both individual and relative features in this category have binary values. For the individual feature, the value is **Yes** if the domain has the role, and **No** otherwise. For the relative feature, we assign a value **Yes** if at least one of the preceding domains have the corresponding role, and **No** otherwise. For extension scripts, we assign the value **No** for all of the features. To assign the roles, we compiled a list of common domains related to these roles that contains 5,767 ad-networks, 48 CDNs, and 461 URL shortening services.

3.4 Implementation

In this section, we discuss our prototype implementation of EXCISION for detecting and blocking malicious third-party content inclusions. We implemented EXCISION as a set of modifications to the Chromium browser. In order to implement our system, we needed to modify Blink and the Chromium extension engine to enable EXCISION to detect and block inclusions of malicious content in an online and automatic fashion while the web page is loading. The entire set of modifications consists of less than 1,000 lines of C++ and several lines of JavaScript¹. While our implementation could be adopted as-is by any browser vendors that use WebKit-derived engines, the design presented here is highly likely to be portable to other browsers.

¹<https://github.com/sajjadum/Excision>

3.4.1 Enhancements to the Blink

Blink is primarily responsible for parsing HTML documents, managing script execution, and fetching resources from the network. Consequently, it is ideally suited for constructing the inclusion tree for a web page, as well as blocking the inclusion of malicious content.

3.4.1.1 Tracking Resource Inclusion

Static resource inclusions that are hard-coded by publishers inside the page's HTML are added to the inclusion tree as the direct children of the root node. For dynamic inclusions (e.g., via the `document.createElement()` and `document.write()` DOM API functions), the system must find the script resource responsible for the resource inclusion. To monitor dynamic resource inclusions, the system tracks the start and termination of script execution. Any resources that are included in this interval will be considered as the children of that script resource in the inclusion tree.

3.4.1.2 Handling Events and Timers

Events and timers are widely used by web developers to respond to user interactions (e.g., clicking on an element) or schedule execution of code after some time has elapsed. To capture the creation and firing of events and timers, the system tracks the registration of callback functions for the corresponding APIs.

3.4.2 Enhancements to the Extension Engine

The Chromium extension engine handles the loading, management, and execution of extensions. To access the page's DOM, the extension injects and executes *content scripts* in the page's context which are regular JavaScript programs.

3.4.2.1 Tracking Content Scripts Injection and Execution

Content scripts are usually injected into web pages either via the extension’s manifest file using the `content_scripts` field or at runtime via the `executeScript` API. Either way, content scripts are considered direct children of the root node in the inclusion tree. Therefore, in order to track the inclusion of resources as a result of content script execution, the extension engine was modified to track the injection and execution of content scripts.

3.4.2.2 Handling Callback Functions

Like any other JavaScript program, content scripts rely heavily on callback functions. For instance, `onMessage` and `sendMessage` are used by content scripts to exchange messages with their background pages. To track the execution of callback functions, two JavaScript files were modified in the extension engine which are responsible for invocation and management of callback functions.

3.5 Analysis

In this section, we evaluate the security benefits, performance, and usability of the EXCISION prototype. We describe the data sets we used to train and evaluate the system, and then present the results of the experiments.

3.5.1 Data Collection

To collect inclusion sequences, we performed two separate crawls for websites and extensions. The summary of crawling statistics are presented in Table 3.3.

3.5.1.1 Website Crawl

We built a crawler based on an instrumented version of PhantomJS [6], a scriptable open source browser based on WebKit, and crawled the home pages of the Alexa Top 200K.

Table 3.3: Summary of crawling statistics

Item	Website Crawl	Extension Crawl
Websites Crawled	234,529	20
Unavailable Websites	7,412	0
Unique Inclusion Trees	47,789,268	35,004
Unique Inclusion Sequences	27,261,945	61,489
Unique URLs	546,649,590	72,064
Unique Domains	1,368,021	1,144
Unique Sites	459,615	749
Unique SLDs	419,119	723
Unique Companies	384,820	719
Unique Effective TLDs	1,115	21
Unique TLDs	404	21
Unique IPs	9,755	3

We performed our data collection from June 20th, 2014 to May 11th, 2015. The crawl was parallelized by deploying 50 crawler instances on five virtual machines, each of which crawled a fixed subset of the Alexa Top 200K websites. To ensure that visited websites did not store any data on the clients, the crawler ran a fresh instance of PhantomJS for each visit. Once all crawlers finished crawling the list of websites, the process was restarted from the beginning. To thwart cloaking techniques [57] utilized by attackers, the crawlers presented a user agent for IE 6.0 on Windows and employed Tor to send HTTP requests from different source IP addresses. We also address JavaScript-based browser fingerprinting by modifying the internal implementation of the `navigator` object to return a fake value for the `appName`, `appVersion`, `platform`, `product`, `userAgent`, and `vendor` attributes.

3.5.1.2 Extension Crawl

To collect inclusion sequences related to extensions, we used 292 Chrome extensions reported in prior work [127] that injected ads into web pages. Since ad-injecting extensions mostly target shopping websites (e.g., Amazon), we chose the Alexa Top 20 shopping websites for crawling to trigger ad injection by those 292 extensions. We built a crawler by instrumenting Chromium 43 and collected data for a period of one week from June 16th to June 22nd,

Table 3.4: Data sets used in the evaluation

Dataset	No. of Inclusion Sequences		No. of Terminal Domains	
	Website Crawl	Ext. Crawl	Website Crawl	Ext. Crawl
Benign	3,706,451	7,372	35,044	250
Malicious	25,153	19	1,226	2

2015. The system loaded every extension and then visited the home pages of the Alexa Top 20 shopping websites using Selenium WebDriver [107]. This process was repeated after crawling the entire set of extensions. In addition, our crawler triggered all the events and timers registered by content scripts.

3.5.2 Building Labeled Datasets

To classify a given inclusion sequence as benign or malicious, we trained two hidden Markov models for benign and malicious inclusion sequences from our data set. We labeled collected inclusion sequences as either benign or malicious using VirusTotal [8]. VirusTotal’s URL scanning service aggregates reports of malicious URLs from most prominent URL scanners such as Google Safe Browsing [40] and the Malware Domain List. The malicious data set contains all inclusion sequences where the last included resource’s domain is reported malicious by at least three out of the 62 URL scanners in VirusTotal. On the other hand, the benign data set only contains inclusion sequences that do not contain any domain in the entire sequence that is reported as malicious by any URL scanner in VirusTotal. To build benign data set, we considered reputable domains such as well-known search engines and advertising networks as benign regardless of whether they are reported as malicious by any URL scanner in VirusTotal. Table 3.4 summarizes the data sets². The unique number of inclusion sequences and terminal domains are shown separately for the website and extension data sets. The terminal domains column is the number of unique domains that terminate inclusion sequences.

²<https://github.com/sajjadum/Excision>

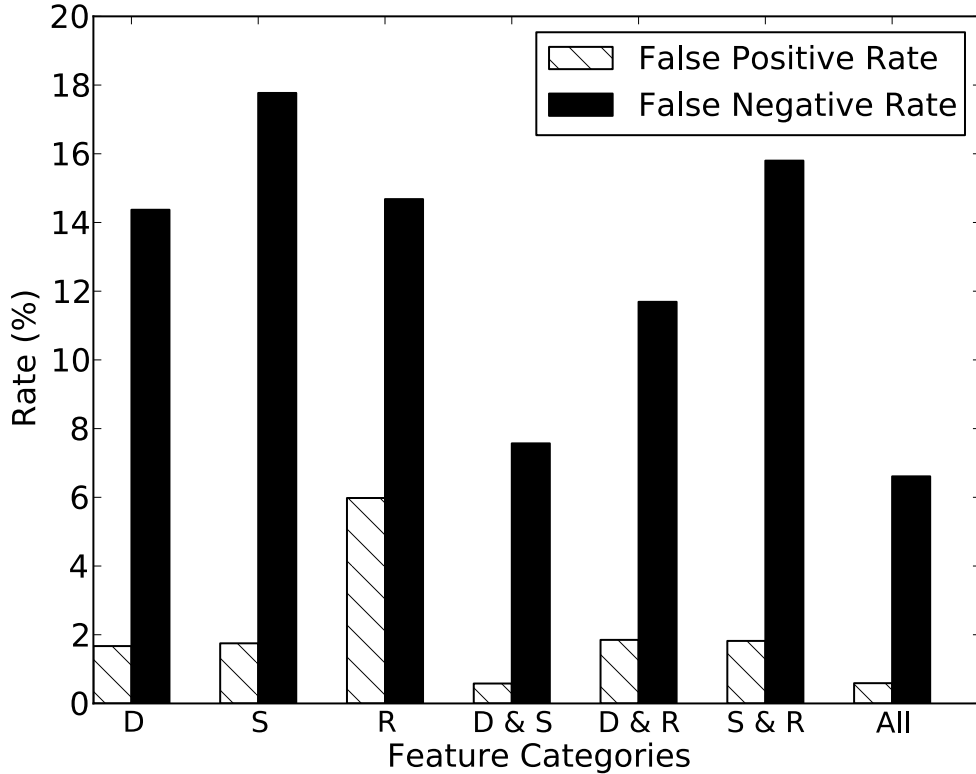


Figure 3.5: Effectiveness of features for classification (D = DNS, S = String, R = Role)

3.5.3 Detection Results

To evaluate the accuracy of our classifier, we used 10-fold cross-validation, in which we first partitioned each data set into 10 equal-sized folds, trained the models on nine folds, and then validated the resulting models with the remaining fold. The process was repeated for each fold and, at the end, we calculated the average false positive rate and false negative rate. When splitting the data set into training and testing sets, we made sure that inclusion sequences with different lengths were present in both. We also ensured that both sets contained extension-related inclusion sequences.

The results show that our classifier achieved a false positive rate of 0.59% and false negative rate of 6.61% (detection rate of 93.39%). Most of the false positives are due to inclusion sequences that do not appear too often in the training sets. Hence, users are unlikely to experience many false positives in a real browsing environment (as will be shown

in our usability analysis in Section 3.5.6).

To quantify the contribution of different feature categories to the classification, we trained classifiers using different combinations of feature categories and compared the results. Figure 3.5 shows the false positive rate and false negative rate of every combination with a 10-fold cross-validation training scheme. According to Figure 3.5, the best false positive and false negative rates were obtained using the combination of all feature categories.

3.5.4 Comparison with URL Scanners

To evaluate the ability of our system in detecting unreported suspicious domains, we ran our classifier on inclusion sequences collected from June 1st until July 14th, 2015. We compared our detection results with reports from URL scanners in VirusTotal and detected 89 new suspicious domains. We believe that these domains are in fact dedicated malicious domains that play the role of redirectors and manage malicious traffic flows as described in prior work [71]. These domains did not deliver malicious resources themselves, but they consistently included resources from other domains that were flagged as malicious by URL scanners. Out of 89 suspicious domains, nearly 44% were recently registered in 2015, and more than 23% no longer resolve to an IP address.

Furthermore, we detected 177 domains that were later reported by URL scanners after some delay. Figure 3.6 shows the early detection results of our system. A significant number of these domains were not reported until some time had passed after EXCISION initially identified them. For instance, nearly 78% of the malicious domains were not reported by any URL scanner during the first week.

3.5.5 Performance

To assess the performance of EXCISION, we used Selenium to automatically visit the Alexa Top 1K with both original and modified Chromium browsers. In order to measure our prototype performance with a realistic set of extensions, we installed five of the most popular

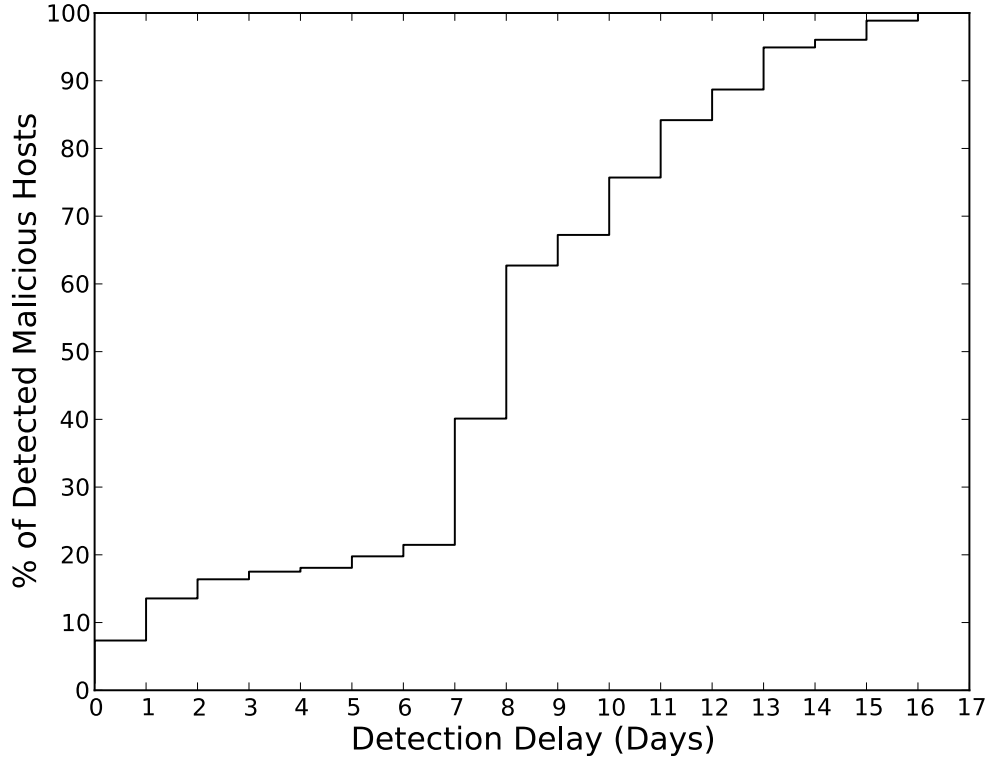


Figure 3.6: Early detection results

extensions in the Chrome Web Store: Adblock Plus, Google Translate, Google Dictionary, Evernote Web Clipper, and Tampermonkey.

For each browser, we visited the home pages of the entire list of websites and recorded the total elapsed time. Due to the dynamic nature of ads and their influence on page load time, we repeated the experiment 10 times and measured the average elapsed time. On average, the elapsed times were 3,065 and 3,438 seconds for the original and modified browsers, respectively. Therefore, EXCISION incurred a 12.2% overhead on browsing time on average, which corresponds to a noticeable overhead that is nevertheless acceptable for many users (see Section 3.5.6). To measure the overhead incurred by EXCISION on browser startup time, we launched the modified browser 10 times and measured the average browser launch time. EXCISION caused a 3.2 seconds delay on browser startup time, which is ameliorated by the fact that this is a one-time performance hit.

3.5.6 Usability

We conducted an experiment to evaluate the impact of EXCISION on the user’s browsing experience. We conducted the study on 10 students that self-reported as expert Internet users. We provided each participant with a list of 50 websites that were selected randomly from the Alexa Top 500 and then asked them to visit at least three levels down in each website. Participants were asked to report the number of visited pages and the list of domains reported as malicious by our system. In addition, participants were asked to record the number of errors they encountered while they browsed the websites. Errors were considered to occur when the browser crashed, the appearance of a web page was corrupted, or page load times were abnormally long. Furthermore, in order to ensure that benign extensions were not prevented from executing as expected in the presence of our system, the browser was configured to load the five popular extensions listed in Section 3.5.5 and participants were asked to report any problem while using the extensions.

The results of the study show that out of 5,129 web pages visited by the participants, only 83 errors were encountered and the majority of web pages loaded correctly. Most of these errors happened due to relatively high load times. In addition, none of the participants reported any broken extensions. Furthermore, 31 malicious inclusions were reported by our tool that were automatically processed (without manual examination, for privacy reasons) using VirusTotal. Based on the results, we believe that our proof-of-concept prototype is compatible with frequently used websites and extensions, and can be improved through further engineering to work completely free of errors.

Ethics. In designing the usability experiment, we made a conscious effort to avoid collecting personal or sensitive information. In particular, we restricted the kinds of information we asked users to report to incidence counts for each of the categories of information, except for malicious URLs that were reported by our tool. Malicious URLs were automatically submitted to VirusTotal to obtain a malice classification before being discarded, and were

not viewed by us or manually inspected. In addition, the participants were asked to avoid browsing websites requiring a login or involving sensitive subject matter.

3.6 Discussion

Our study shows that detecting malicious third-party inclusions is possible by analyzing resource inclusion sequences. According to the evaluation results, EXCISION can detect a large number of malicious inclusions with a low false positive rate of 0.59%. However, due to the in-browser and real-time nature of our system, we cannot easily incorporate other useful features such as domain registration information or a global view of Web inclusions into our detection system. For domain registration information, we would need to regularly fetch domain *whois* records; as these databases are rate-limited, this is not currently feasible. In this work, we crafted a feature set that is suited for an online, in-browser system to detects malicious inclusion sequences as web pages load. But, attackers might try to exploit features we adopt to avoid detection by EXCISION. For example, they might choose more meaningful names for their domains or improve their domains' Alexa rankings with SEO techniques [57]. However, these attempts are not very effective since EXCISION rely on the business relationship between the hosts inside the inclusion sequences for finding malicious resource in addition to the individual hosts characteristics. Attackers need to change the sequence of inclusions to evade our system which is not a trivial task and it increases the difficulty of the attack significantly.

Moreover, we envision that both web users and website administrators can benefit from using EXCISION. EXCISION protects users from attacks by preventing browsers from including a malicious resource into web pages. Furthermore, EXCISION allows website administrators to have more control over the content that is delivered to their visitors when they sell space to ad networks. Administrators do not need to write comprehensive CSP rules to control dynamic content that is managed by third-party content providers. In addition to

website administrators and web users, the models learned by EXCISION can be used by ad networks, URL scanners, and large organizations as well. They could passively crawl various websites to identify compromised websites and malicious origins, and this information could be used to augment blacklists and reputation-based services (e.g., Google Safebrowsing) and also update corporate firewall policies to prevent other clients from loading resources from those malicious origins.

3.7 Chapter Summary

In this chapter, we presented EXCISION, an in-browser system to automatically detect and block malicious third-party content inclusions before they can attack the user’s browser. Our system is implemented as a set of modifications to the Chromium browser and does not perform any blacklisting to detect malicious third-party inclusions. Our evaluation over an 11 month crawl of the Alexa Top 200K demonstrates that the prototype implementation of EXCISION achieved a 93.39% detection rate with a false positive rate of 0.59%. We also evaluated the performance and usability of EXCISION when browsing popular websites, and showed that the approach is capable of improving the security of users on the Web by detecting 31 malicious inclusions during a user study without significantly degrading the user experience.

Chapter 4

Identifying Ad Injection in Browser Extensions

4.1 Introduction

While ad injection cannot necessarily be categorized as an outright malicious activity on its own, it is highly likely that many users in fact *do not want or expect* browser extensions to inject advertisements or other content into Web pages. Moreover, it can have a significant impact on the security and privacy of both users as well as website publishers. For example, recent studies have shown that ad-injecting extensions not only serve ads from ad networks other than the ones with which the website publishers intended, but they also attempt to trick users into installing malware by inserting rogue elements into the web page [117, 127].

To address this problem, several automatic approaches have been proposed to detect malicious behaviors (e.g., ad injection) in browser extensions [127, 58, 54]. In addition, centralized distribution points such as Chrome Web Store and Mozilla Add-ons are using semi-automated techniques for review of extension behavior to detect misbehaving extensions. However, there is no guarantee that analyzing the extensions for a limited period of time leads to revealing the ad injection behaviors. Finally, a client-side detection methodo-

logy has been proposed in [117] that reports any deviation from a legitimate DOM structure as potential ad injections. However, this approach requires a priori knowledge of a legitimate DOM structure as well as cooperation from content publishers.

Although ad injection can therefore potentially pose significant risks, this issue is not as clear-cut as it might first seem. Some users might legitimately want the third-party content injected by the extensions they install, even including injected advertisements. This creates a fundamental dilemma for automated techniques that aim to identify clearly malicious or unwanted content injection, since such techniques cannot intuit user intent and desires in a fully automatic way.

To resolve this dilemma, we present ORIGINTRACER, an in-browser approach to highlight extension-based content modification of web pages. ORIGINTRACER monitors the execution of browser extensions to detect content modifications such as the injection of advertisements. Content modifications are visually highlighted in the context of the web page in order to *i)* notify users of the presence of modified content, and *ii)* inform users of the *source* of the modifications.

With this information, users can then make an informed decision as to whether they actually want these content modifications from specific extensions, or whether they would rather uninstall the extensions that violate their expectations.

ORIGINTRACER assists users in detecting content injection by distinguishing injected or modified DOM elements from genuine page elements. This is performed by annotating web page DOM elements with a *provenance label set* that indicates the principal(s) responsible for adding or modifying that element, both while the page is loading from the publisher as well as during normal script and extension execution. These annotations serve as trustworthy, fine-grained provenance indicators for web page content. ORIGINTRACER can be easily integrated into any browser in order to inform users of extension-based content modification. Since ORIGINTRACER identifies all types of content injections, it is able to highlight all injected advertisements regardless of their types (e.g., flash ads, banner ads, and text ads).

We implemented a prototype of `ORIGINTRACER` as a set of modifications to the Chromium browser, and evaluated its effectiveness by conducting a user study. The user study reveals that `ORIGINTRACER` produced a significantly greater awareness of third-party content modification, and did not detract from the users' browsing experience.

The rest of this chapter is organized as follows. Section 4.2 outlines the necessary background on browser extensions and ad injection. Section 4.3 presents our approach to web content provenance, while Section 4.4 discusses the implementation of our prototype system. An evaluation of the effectiveness, usability, and performance of our prototype is presented in Section 4.5 and Section 4.6 summarizes the paper.

4.2 Background

In the following, we introduce background information on browser extensions, present an overview of advertisement injection as a canonical example of questionable content modification, and motivate our approach in this context.

4.2.1 Browser Extensions

Browser extensions are programs that extend the functionality of a web browser. Today, extensions are typically implemented using a combination of HTML, CSS, and JavaScript written against a browser-specific extension API. These APIs expose the ability to modify the browser user interface in controlled ways, manipulate HTTP headers, and modify web page content through the document object model (DOM) API. An extension ecosystem is provided by almost all major browser vendors; for instance, Google and Mozilla both host centralized repositories of extensions that users can download at the Chrome Web Store and Mozilla Add-ons sites, respectively.

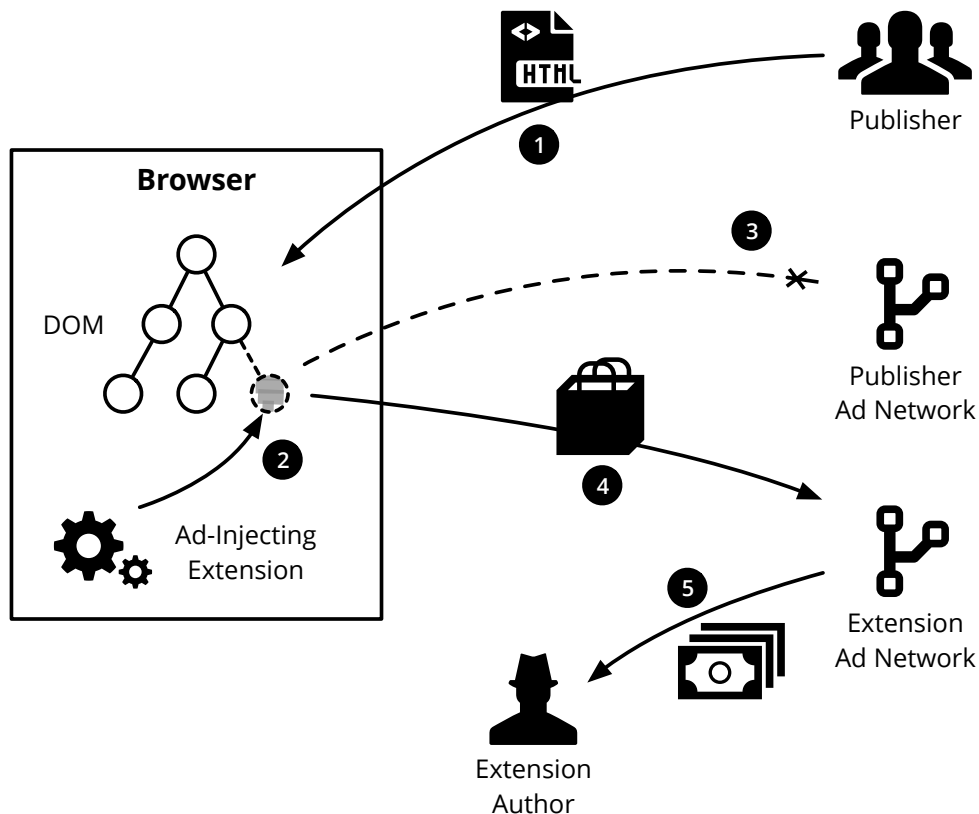


Figure 4.1: Overview of advertisement injection. (1) The user accesses the publisher’s site. (2) An ad-injecting browser extension adds DOM elements to display ads to the user, and optionally removes existing ads. (3) Ad revenue is diverted from the publisher. (4) Ad impressions, clicks, and conversions are instead directed to the extension’s ad network. (5) Ad revenue flows to the extension author.

4.2.2 Advertisement Injection

As web advertising grew in popularity, those in a position to modify web content such as ISPs and browser extension authors realized that profit could be realized by injecting or replacing ads in web pages. For instance, some ISPs began to tamper with HTTP traffic in transit, injecting DOM elements into HTML documents that added ISP’s advertisements into pages visited by their customers [24, 64]. In a similar fashion, browser extensions started modifying pages to inject DOM elements in order to show ads to users without necessarily obtaining the user’s prior consent. Ad injection has evolved to become a common form of unrequested third-party content injection on today’s web [82].

These practices have several effects on both publishers and users. On one hand, ad injection diverts revenue from the publisher to the third party responsible for the ad injection. If advertisements are the primary source of income for a publisher, this can have a significant effect on their bottom line. If the injected ads contain or reference undesired content (e.g., adult or political topics), ad injection can also harm the reputation of the publisher from the user’s perspective. If the content injection is also malicious in nature, the publisher’s reputation can be further harmed in addition to exposing users to security risks due to malware, phishing, and other threats. Prior work has shown that users exposed to ad injection are more likely to be exposed to “malvertising” and traditional malware [117, 127]. Figure 4.1 gives an overview of ad injection’s effect on the normal ad delivery process, while Figure 4.3 shows an instance of ad injection on `amazon.com` website.

4.2.3 Motivation

Recently, there have been efforts by browser vendors to remove ad-injecting extensions from their repositories [1]. Although semi-automated central approaches have been successful in identifying ad-injecting extensions, deceptive extensions can simply hide their ad injection behaviors during the short period of analysis time. In addition, finding web pages that trigger ad injection is a non-trivial task, and they can miss some ad-injecting extensions. Moreover, there are extensions that are not provided through the web stores, and users can get them from local marketplaces, which may not examine the extensions properly. Hence, we believe that there is a need for a protection tool to combat ad injection on the client side in addition to centralized examination by browser vendors.

Furthermore, automatically determining whether third-party content modification – such as that due to ad injection – should be allowed is not straightforward. Benign extensions extensively modify web pages as part of their normal functionality. To substantiate this, we examined five popular Chrome extensions as of the time of writing; these are listed in Table 4.1. Each of these extensions are available for all major browsers, and all modify

Table 4.1: Five popular Chrome extensions that modify web pages as part of their benign functionality

Extension	No. of Users	Injected Element
Adblock Plus	10,000,000+	<iframe>
Google Translate	6,000,000+	<div>
Tampermonkey	5,800,000+	
Evernote Web Clipper	4,300,000+	<iframe>
Google Dictionary	3,000,000+	<div>

web pages (e.g., inject elements) to implement their functionality. Therefore, automated approaches based on this criterion run a high risk of false positives when attempting to identify malicious or undesirable extensions.

Moreover, it is not enough to identify that advertisements, for instance, have been injected by a third party. This is because some users *might legitimately desire* the content that is being added to web pages by the extensions they install. To wit, it is primarily for this reason that a recent purge of extensions from the Chrome Web Store did not encompass the entirety of the extensions that were identified as suspicious in a previous study, as the third-party content modification could not be clearly considered as malicious [117]. Instead, we claim that *users themselves* are best positioned to make the determination as to whether third-party content modification is desired or not. An approach that proceeds from this observation would provide sufficient, easily comprehensible information to users in order to allow an informed choice as to whether content is desirable or should be blocked. It should be noted that defending against drive-by downloads and general malware is not the focus of this paper. Rather, the goal is to highlight injected ads to increase likelihood that user will make an informed choice to not click on them.

We envision that ORIGINTRACER could be used as a complementary approach to existing techniques such as central approaches used by browser vendors. Also, browser vendors can benefit from using our system in addition to end users to detect the content modifications by extensions in a more precise and reliable way. In the following sections, we present design and implementation of our system.

4.3 Design

In this section, we describe an in-browser approach for identifying third-party content modifications in web browsers. The approach adds *fine-grained provenance tracking* to the browser, at the level of individual DOM elements. Provenance information is used in two ways: *i)* to distinguish between content that originates from the web page publisher and content injected by an unassociated third party, and *ii)* to indicate *which* third party (e.g., extension) is responsible for content modifications using provenance indicators. By integrating the approach directly into the browser, we guarantee the trustworthiness of both the provenance information and the visual indicators. That is, as the browser is already part of the trusted computing base (TCB) in the web security model, we leverage this as the appropriate layer to compute precise, fine-grained provenance information. Similarly, the browser holds sufficient information to ensure that provenance indicators cannot be tampered with or occluded by malicious extensions. While we consider malicious or exploited browser plug-ins such as Flash Player outside our threat model, we note that modern browsers take great pains to isolate plug-ins in least privilege protection domains. We report separately on the implementation of the approach in Section 4.4.

In the following, we present our approach to tracking and propagating content provenance, and then discuss provenance indicators and remediation strategies.

4.3.1 Content Provenance

Web pages are composed of HTML that references resources such as stylesheets, scripts, images, plug-ins such as Flash objects, or even other web pages loaded inside frames. The document object model (DOM) is a natural structural representation of a web page that can be manipulated through a standard API, and serves as a suitable basis for provenance tracking. In particular, our system tracks the provenance of each element e contained in a DOM. Provenance for a DOM element is recorded as a set of labels $\ell \in \mathcal{P}(L)$, where the set

of all labels L corresponds to a generalization of standard web origins to include extensions. That is, instead of the classic origin 3-tuple of $\langle \text{scheme}, \text{host}, \text{port} \rangle$, we record

$$\begin{aligned} L &= \langle S, I, P, X \rangle \\ S &= \{\text{scheme}\} \cup \{\text{"extension"}\} \\ I &= \{\text{host}\} \cup \{\text{extension-identifier}\} \\ P &= \{\text{port}\} \cup \{\text{null}\} \\ X &= \{0, 1, 2, \dots\} \end{aligned}$$

In other words, a label is a 4-tuple that consists of a normal network scheme or **extension**, a network host or a unique extension identifier, a port or the special **null** value, and an index used to impose a global total order on labels as described below. While browsers use different extension identifiers, including randomly-generated identifiers, the exact representation used is unimportant so long as there is a one-to-one mapping between extensions and identifiers and their use is locally consistent within the browser. An overview of provenance tracking is depicted in Figure 4.2.

4.3.1.1 Static Publisher Provenance

Content provenance tracking begins with a web page load. As the DOM is parsed by the browser, each element is labeled with a singleton label set containing the origin of the publisher, $\{l_0\}$. Thus, static provenance tracking is straightforward and equivalent to the standard use of origins as a browser security context.

4.3.1.2 Dynamic Publisher Provenance

Content provenance becomes more interesting in the presence of dynamic code execution. As JavaScript can add, modify, and remove DOM elements in an arbitrary fashion using the

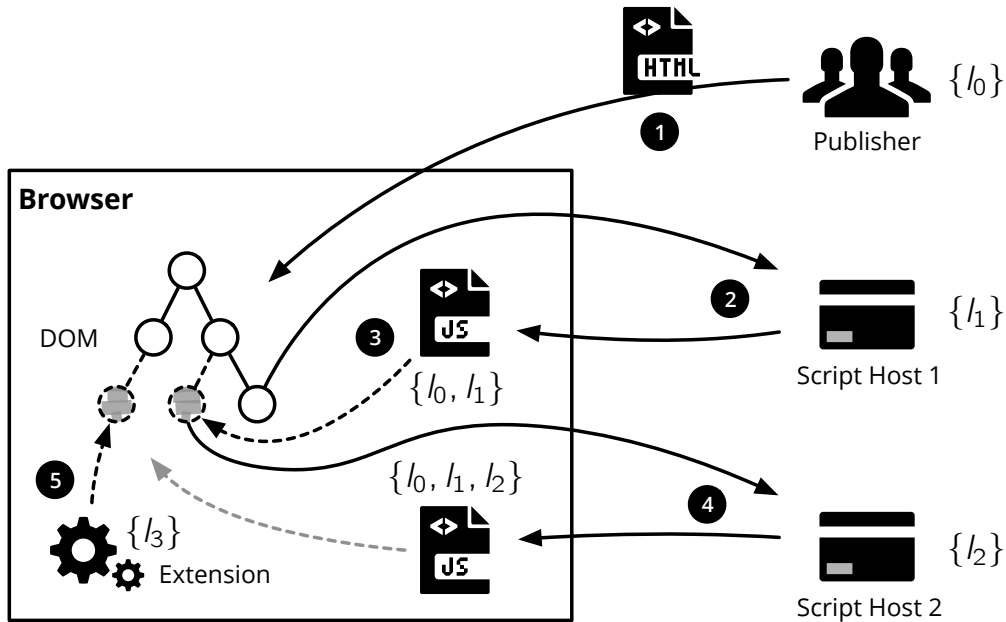


Figure 4.2: Element-granularity provenance tracking. (1) Content loaded directly from the publisher is labeled with the publisher’s origin, l_0 . (2) An external script reference to origin l_1 is performed. (3) DOM modifications from l_1 ’s script are labeled with the label set $\{l_0, l_1\}$. (4) Further external script loads and subsequent DOM modifications induce updated label sets – e.g., $\{l_0, l_1, l_2\}$. (5) A DOM modification that originates from an extension produces provenance label sets $\{l_0, l_1, l_2, l_3\}$ for the element

DOM API exposed by the browser, it is necessary to track these modifications in terms of provenance labels.

New provenance labels are created from the publisher’s label set $\{l_0\}$ as follows. Whenever an external script is referenced from the initial DOM resulting from the page load, a new label $l_i, i \in \{1, 2, \dots\}$ is generated from the origin of the script. All subsequent DOM modifications that occur as a result of an external script loaded from the initial DOM are recorded as $\{l_0, l_i\}$. Successive external script loads follow the expected inductive label generation process – i.e., three successive external script loads from unique origins will result in a label set $\{l_0, l_i, l_j, l_k\}$. Finally, label sets contain unique elements such that consecutive external script loads from a previously accessed origin are not reflected in the label for subsequent DOM modifications. For instance, if the web page publisher loads a script from the publisher’s origin, then any resulting DOM modifications will have a provenance label

set of $\{l_0\}$ instead of $\{l_0, l_0\}$. Content provenance is propagated for three generic classes of DOM operations: element insertion, modification, and deletion.

Element insertions produce an updated DOM that contains the new element labeled with the current label set, and potentially generates a new label set if the injected element is a script. Element modifications produce a DOM where the modified element's label set is merged with the current label set. Finally, element deletions simply remove the element from the DOM.

4.3.1.3 Extension Provenance

The third and final form of provenance tracking concerns content modifications due to DOM manipulations by extensions. In this case, provenance propagation follows the semantics for the above case of dynamic publisher provenance. Where these two cases differ, however, is in the provenance label initialization. While provenance label sets for content that originates, perhaps indirectly, from the web page publisher contains the publisher's origin label l_0 , content that originates from an extension is rooted in a label set initialized with the *extension's* label. In particular, content modifications that originate from an extension *are not labeled* by the publisher's origin. An exception to this occurs when the extension, either directly or indirectly, subsequently loads scripts from the publisher, or modifies an existing element that originated from the publisher.

4.3.2 Content Provenance Indicators

With the fine-grained content provenance scheme described above, identifying the principal responsible for DOM modifications is straightforward. For each element, all that is required is to inspect its label set ℓ to check whether it contains the label of any extension.

A related, but separate, question is how best to relay this information to the user. In this design, several options are possible on a continuum from simply highlighting injected content without specific provenance information to reporting the full ordered provenance

chain from the root to the most recent origin. The first option makes no use of the provenance chain, while the other end of the spectrum is likely to overwhelm most users with too much information, degrading the practical usefulness of provenance tracking. We suspect that a reasonable balance between these two extremes is a summarization of the full chain, for instance by reporting only the label of the corresponding extension.

Finally, if a user decides that the third-party content modification is unwanted, another design parameter is how to act upon this decision. Possible actions include blocking specific element modifications, removing the offending extension, or reporting its behavior to a central authority. We report on the specific design choices we made with respect to provenance indicators in the presentation of our implementation in Section 4.4.

4.4 Implementation

In this section, we present ORIGINTRACER, our prototype implementation for identifying and highlighting extension-based web page content modifications. We implemented ORIGINTRACER as a set of modifications to the Chromium browser¹. In particular, we modified both Blink and the extension engine to track the provenance of content insertion, modification, and removal according to the semantics presented in Section 4.3. These modifications also implement provenance indicators for suspicious content that does not originate from the publisher. In total, our changes consist of approximately 900 SLOC for C++ and several lines of JavaScript². In the following, we provide more detail on the integration of ORIGINTRACER into Chromium.

4.4.1 Tracking Publisher Provenance

A core component of ORIGINTRACER is responsible for introducing and propagating provenance label sets for DOM elements. In the following, we discuss the implementation of proven-

¹<https://github.com/sajjadum/OriginTracer>

²SLOC were measured using David Wheeler’s SLOCCount [7].

ance tracking for publisher content.

4.4.1.1 Tracking Static Elements

As discussed in Section 4.3, provenance label sets for static DOM elements that comprise the HTML document sent by the publisher as part of the initial page load are equivalent to the publisher’s web origin – in our notation, l_0 . Therefore, minimal modifications to the HTML parser were necessary to introduce these element annotations, which is performed in an incremental fashion as the page is parsed.

4.4.1.2 Tracking Dynamic Elements

To track dynamic content modifications, this component of `ORIGINTRACER` must also monitor JavaScript execution. When a `script` tag is encountered during parsing of a page, Blink creates a new element and attaches it to the DOM. Then, Blink obtains the JavaScript code (fetching it from network in the case of remote script reference), submits the script to the V8 JavaScript engine for execution, and pauses the parsing process until the script execution is finished. During execution of the script, some new elements might be created dynamically and inserted into the DOM. According to the provenance semantics, these new elements inherit the label set of the script. In order to create new elements in JavaScript, one can *i)* use DOM APIs to create a new element and attach it to the web page’s DOM, or *ii)* write HTML tags directly into the page. In the first method, to create a new element object, a canonical example is to provide the tag name to the `createElement` function. Then, other attributes of the newly created element are set – e.g., after creating an element object for an `a` tag, an address must be provided for its `href` attribute. Finally, the new element should be attached to the DOM tree as a child using `appendChild` or `insertBefore` functions. In the second method, HTML is inserted directly into the web page using the functions such as `write` and `writeln`, or by modifying the `innerHTML` attribute. In cases where existing elements are modified (e.g., changing an image’s `src` attribute), the element inherits the la-

bel set of the currently executing script as well. In order to have a complete mediation of all DOM modifications to Web page, several classes in Blink implementation were instrumented in order to assign provenance label sets for newly created or modified elements using the label set applied to the currently executing script.

4.4.1.3 Handling Events and Timers

An additional consideration for this ORIGINTRACER component is modifications to event handlers and timer registrations, as developers make heavy use of event and timer callbacks in modern JavaScript. For instance, such callbacks are used to handle user interface events such as clicking on elements, hovering over elements, or to schedule code after a time interval has elapsed. In practice, this requires the registration of callback handlers via `addEventListener` API for events, and `setTimeout` and `setInterval` for timers. To mediate callbacks related to the addition and firing of events and timers, we slightly modified the `EventTarget` and `DOMTimer` classes in Blink, respectively. Specifically, we record the mapping between the running scripts and their registered callback functions, and then recover the responsible scripts for DOM modification during callback execution.

4.4.2 Tracking Extension Provenance

Chromium's extension engine is responsible for loading extensions, checking their permissions against those declared in the manifest file, injecting content scripts, dispatching background scripts and content scripts to the V8 script engine for execution, and providing a channel for communication between content scripts and background page.

Chromium extensions can manipulate the web page's content by injecting *content scripts* into the web page or using the `webRequest` API. Content scripts are JavaScript programs that can manipulate the web page using the shared DOM, communicate with external servers via `XMLHttpRequest`, invoke a limited set of `chrome.*` APIs, and interact with their owning extension's background page. By using `webRequest`, extensions are also able to modify and

block HTTP requests and responses in order to change the web page’s DOM.

In this work, we only track content modifications by content scripts and leave identifying ad injection by `webRequest` for future engineering work. Prior work, however, has mentioned that only 5% of ad injection incidents occurred via `webRequest`; instead, Chrome extensions mostly rely on content scripts to inject advertisements [117]. Moreover, with modern websites becoming more complex, injecting stealthy advertisement into the page using `webRequest` is not a trivial task.

4.4.2.1 Tracking Content Script Injection and Execution

To track elements created or modified during the execution of content scripts, extension engine was modified to hook events corresponding to script injection and execution. Content scripts can be inserted into the web page using different methods. If a content script should be injected into every matched web page, it must be registered in the extension manifest file using the `content_scripts` field. By providing different options for this field, one can control when and where the content scripts be injected. Another method is programmatic injection, which is useful when content scripts should be injected in response to specific events (e.g., a user clicks the extension’s browser action). With programmatic injection, content scripts can be injected using the `tabs.executeScript` API if the `tabs` permission is set in the manifest file. Either way, content scripts have a provenance label set initialized with the extension’s label upon injection.

4.4.2.2 Handling Callback Functions

Chromium’s extension engine provides a messaging API as a communication channel between the background page and the content scripts. The background page and content scripts can receive messages from each other by providing a callback function for the `onMessage` or `onRequest` events, and can send messages by invoking `sendMessage` or `sendRequest`. To track the registration and execution of callback functions, the `send_request` and `event`

modules were slightly modified in the extension engine. Specifically, we added some code to map registered callbacks to their corresponding content scripts in order to find the extension responsible for DOM modification.

4.4.3 Content Provenance Indicators

Given DOM provenance information, `ORIGINTRACER` must first *i)* identify when suspicious content modifications – e.g., extension-based ad injection – has occurred, and additionally *ii)* communicate this information to the user in an easily comprehensible manner.

To implement the first requirement, our prototype monitors for content modifications where a subtree of elements are annotated with label sets that contains a particular extension’s label. This check can be performed efficiently by traversing the DOM and inspecting element label sets after a set of changes have been performed on the DOM.

There are several possible options to communicate content provenance as mentioned in Section 4.3. In our current prototype, provenance is indicated using a configurable border color of the root element of the suspicious DOM subtree. This border should be chosen to be visually distinct from the existing color palette of the web page. Finally, a tooltip indicating the root label is displayed when the user hovers their mouse over the DOM subtree. An example is shown in Figure 4.3. To implement these features, `ORIGINTRACER` modifies `style` and `title` attributes. In addition, since `ORIGINTRACER` highlights elements in an online fashion, it must delay the addition of highlighting until the element is attached to the page’s DOM and is displayed. Therefore, modifications were made to the `ContainerNode` class that is responsible for attaching new elements to the DOM.

While we did not exhaustively explore the design space of content provenance indicators in this work (e.g., selective blocking of extension-based DOM modifications), we report on the usability of the prototype implementation in our evaluation.

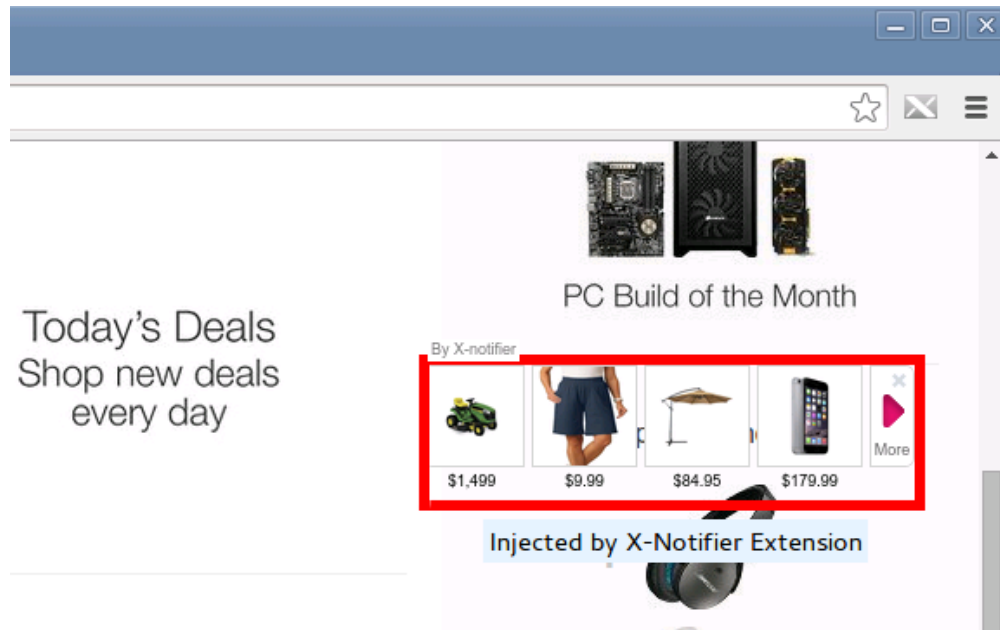


Figure 4.3: An example of indicator for an injected advertisement on `amazon.com` website

4.5 Analysis

In this section, we measure the effectiveness, usability, and performance of content provenance indicators using the `ORIGINTRACER` prototype. In particular, the questions we aim to answer with this evaluation are:

- (Q1) How susceptible are users to injected content such as third-party advertisements? (§4.5.1.1)
- (Q2) Do provenance indicators lead to a significant, measurable decrease in the likelihood of clicking on third-party content that originates from extensions? (§4.5.1.2)
- (Q3) Are users likely to use the system during their normal web browsing? (§4.5.2)
- (Q4) Does integration of the provenance tracking system significantly degrade the users' browsing experience and performance of the browser on a representative sample of websites? (§4.5.3)

Ethics. As part of the evaluation, we performed two experiments involving users unaffiliated with the project as described below. Due to the potential risk to user confidentiality and

privacy, we formulated an experimental protocol that was approved by our university’s institutional review board (IRB). This protocol included safeguards designed to prevent exposing sensitive user data such as account names, passwords, personal addresses, and financial information, as well as to protect the anonymity of the study participants with respect to data storage and reporting. While users were not initially told the purpose of some of the experiments, all users were debriefed at the end of each trial as to the true purpose of the study.

4.5.1 Effectiveness

Similar to prior work [28], we performed a user study to measure the effectiveness of content provenance in enabling users to more easily identify unwanted third-party content. However, we performed the user study with a significantly larger group of participants. The study population was composed of 80 students that represent a range of technical sophistication. We conducted an initial briefing prior to the experiments where we made it clear that we were interested in honest answers.

4.5.1.1 User Susceptibility to Ad Injection

The goal of the first phase of the experiment was to measure whether users were able to detect third-party content that was not intended for inclusion by the publishers of web pages presented to them. Users were divided into two equal sized groups of 40. In each group, users were first presented with three unmodified Chromium browsers, each of which had a separate ad-injecting extension installed: `Auto Zoom`, `Alpha Finder`, and `X-Notifier` for the first group, and `Candy Zapper`, `uTorrent`, and `Gethoneybadger` for the second group. These extensions were chosen because they exhibit a range of ad injection behaviors, from subtle injections that blend into the publisher’s web page to very obvious pop-ups that are visually distinct from the publisher’s content.

Using each browser, the participants were asked to visit three popular retail websites:

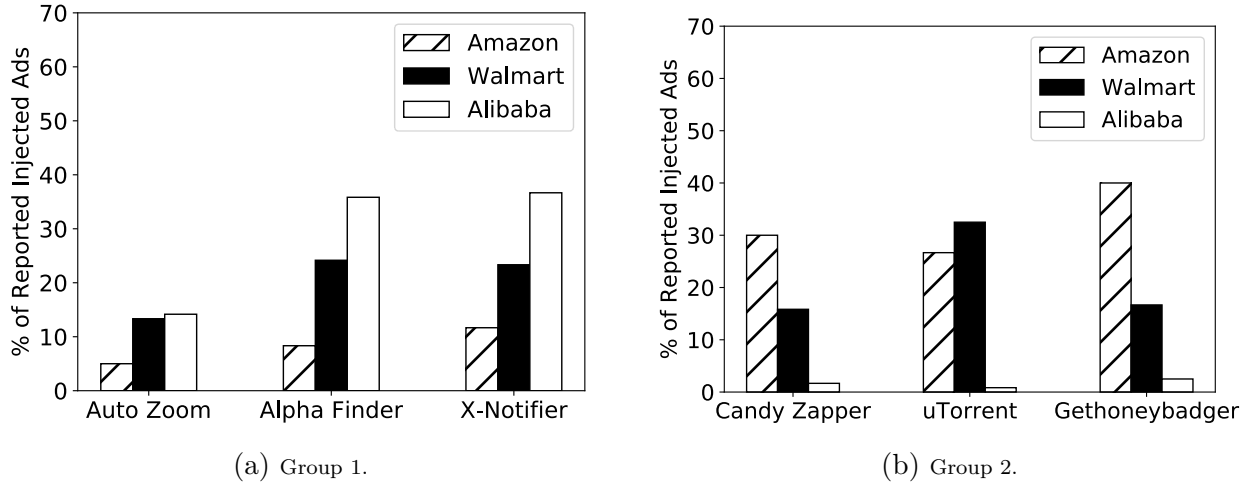


Figure 4.4: Percentage of injected ads that are reported correctly by all the participants

Amazon, Walmart, and Alibaba. Each ad-injecting extension monitors for visits to these websites, and each injects three different types of advertisements into these sites. For each website, we asked the participants to examine the page and tell us if they noticed any content in the page that did not belong to the website – in other words, whether any content did not seem to originate from the publisher. For each group, we aggregated the responses and presented the percentage of correctly reported ad injection incidents for each extension in Figure 4.4.

The results demonstrate that a significant number of Internet users often do not recognize when ad injection occurs in the wild, even when told to look for foreign content. For example, 34 participants did not recognize *any* injected ads out of the three that were added to Amazon website by Auto Zoom extension. Comparatively more users were able to identify ads injected by Alpha Finder and X-Notifier. We suspect the reason for this is because these extensions make use of pop-up advertisements that are easier to recognize as out-of-place. However, a significant number of users nevertheless failed to note these pop-up ads, and even after prompting stated that they thought these ads were part of the publisher’s content. More generally, across all websites and extensions, many participants failed to identify any injected ads whatsoever.

We then asked each participant whether they would click on ads in general to measure

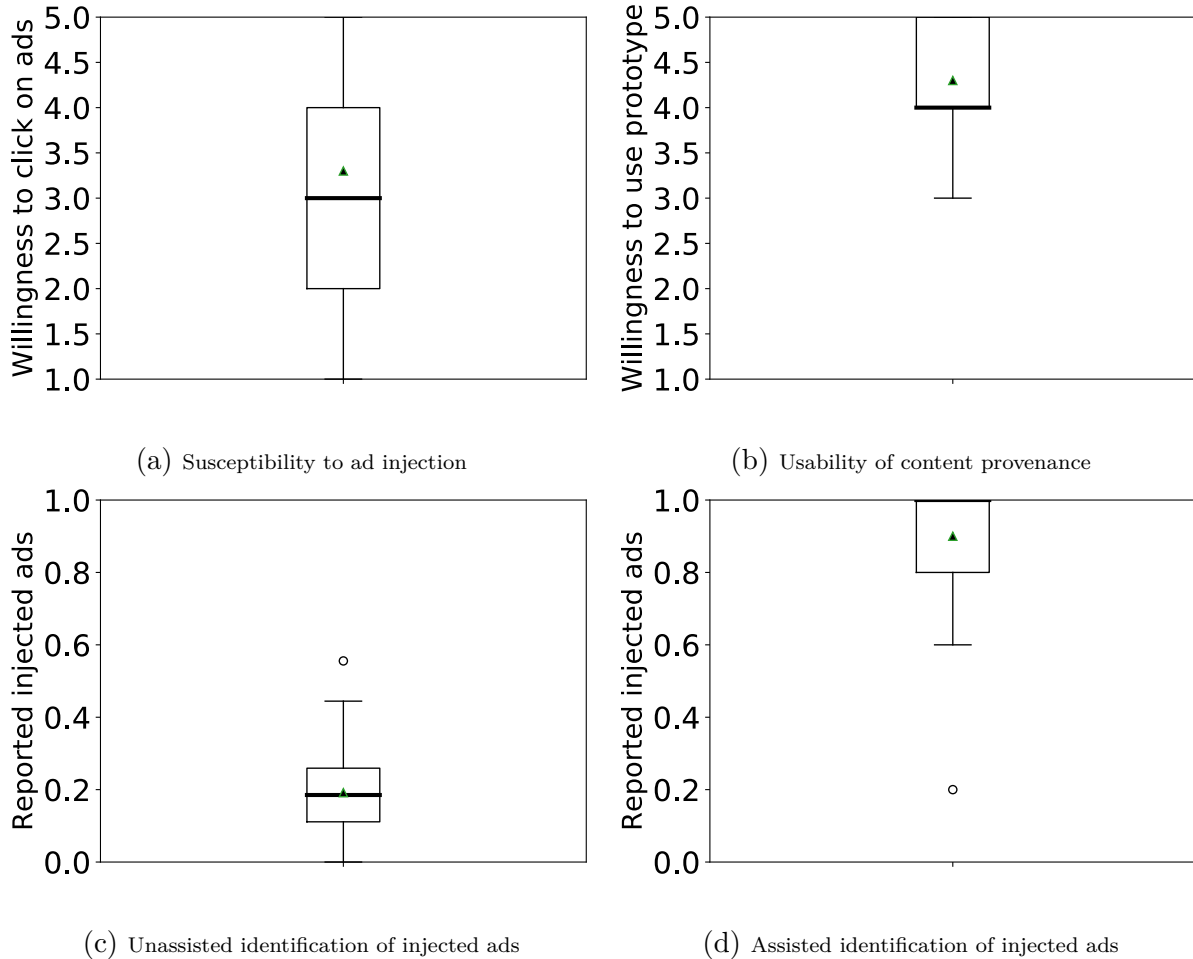


Figure 4.5: User study results. For each boxplot, the box represents the boundaries of the first and third quartiles. The band within each box is the median, while the triangle is the mean. The whiskers represent 1.5 IQR boundaries, and outliers are represented as a circle

the degree of trust that users put into the contents on the publisher’s page. Specifically, we asked participants to rate the likelihood of clicking on ads on a scale from one to five, where one means that they would never click on an ad while five means that they would definitely click on an ad. We aggregated the responses and present the results in Figure 4.5a.

These results show that a significant number of users, roughly half, *would* click on advertisements that might not originate from the publisher, but that were instead injected by an extension. This demonstrates the effectiveness of ad injection as a mechanism for diverting revenue from publishers to extension authors. It also shows the potential effectiveness of malicious extensions in using content modifications to expose users to traditional malware.

4.5.1.2 Effectiveness of Content Provenance Indicators

After the first phase of the experiment, we briefly explained the purpose of ORIGINTRACER and content provenance to the participants. Then, for each participant in each group, we picked one of the three ad-injecting extensions in which, the participant did not detect most of the injected ads and installed it on a Chromium instance equipped with ORIGINTRACER. Then, each participant was asked to visit one of the three retail websites by his choice and identify third-party content modifications – i.e., injected ads – with the help of provenance indicators. The results (normalized to $[0, 1]$) for unassisted and assisted identification of injected ads are shown in Figure 4.5c and Figure 4.5d, respectively. Unassisted identification is the aggregated number of reported ad injections without any assistance in the presence of three ad-injecting extensions across three retail websites, and assisted identification is the number of reported injected ads with the help of content provenance indicators.

These results clearly imply that users are more likely to recognize the presence of third-party content modifications using provenance indicators. To confirm statistical significance, we performed a hypothesis test where the null hypothesis is that provenance indicators do not assist in identifying third-party content modifications, while the alternative hypothesis is that provenance indicators do assist in identifying such content. Using a paired t-test, we obtain a p-value of 4.9199×10^{-7} , sufficient to reject the null hypothesis at a 1% significance level. The outliers in assisted identification are due to the fact that our ad highlighting technique was not identifiable by a small number of participants. We believe that using different visual highlighting techniques would make it easier for users to identify the injected ads.

Finally, we asked each participant how likely they would be to use the content provenance system in their daily web browsing. We asked participants to rate this likelihood on a scale from one to five, where one means they would never use the system and five means that they would always use it. The results are shown in Figure 4.5b, and indicate that most users would be willing to use a content provenance system. The reason behind the outliers is

because a few of the participants stated that they do not need our system since they would not click on any advertisements. However, we note that it can be difficult to distinguish between advertisements and other legitimate content (e.g., products in retail sites) and, consequently, users might be lured into clicking on ad content injected by extensions.

4.5.1.3 Summary

From this user study, we draw several conclusions. First, we confirm that in many cases users are unable to distinguish injected third-party content from publisher content. We also show that because users place trust in publishers, they will often click on injected ads, and thus they tend to be susceptible to ad injection. Our data shows that content provenance assists in helping users distinguish between trusted publisher content and injected third-party content that should not be trusted. Finally, we show that many users would be willing to use the system based on their experience in this study.

4.5.2 Usability

We conducted another experiment on a separate population of users to measure the usability of the ORIGINTRACER prototype. The user population was composed of 13 students with different technical background. We presented the participants with ORIGINTRACER integrated into Chromium 43, and asked them to browse the web for several hours, visiting any websites of their choice. For privacy reasons, however, we asked users to avoid browsing websites that require a login or that involve sensitive subject matter (e.g., adult or financial websites). In addition, for each user, we randomly selected 50 websites from the Alexa Top 500 that satisfy our user privacy constraints and asked the user to visit them. In particular, each participant was asked to browse at least three levels down from the home page and visit external links contained in each site. Finally, to gain some assurance that ORIGINTRACER would not break benign extensions, we configured the browser with the five high-profile extensions list in Table 4.1.

During the browsing session, the browser was modified to record the number of URLs visited. We also asked participants to record the number of pages in which they encountered one of two types of errors. Type I errors are those where the browser crashed, system error messages were displayed, pages would not load, or the website was completely unusable for some other reason. Type II errors include non-catastrophic errors that impact usability but did not preclude it – e.g., the page took an abnormally long time to load, or the appearance of the page was not as expected. We also asked users to report any broken functionality for the benign extensions described above as well.

Out of close to 2,000 URLs, two catastrophic errors and 27 non-catastrophic errors were encountered. However, we note that the majority of URLs rendered and executed correctly. In addition, none of the participants reported any broken extensions. We therefore conclude that the proposed approach is compatible with modern browsers and benign extensions, and further work would very likely allow the prototype to execute completely free of errors.

4.5.3 Performance

To measure the performance overhead of ORIGINTRACER, we configured both an unmodified Chromium browser and the prototype to automatically visit the Alexa Top 1K. The Alexa Top 1K covers many popular websites and is weighted towards being representative of the sites that people use most often. By using this test set, we ensured that each browser visited a broad spectrum of websites that include both static and dynamic content, and especially websites that make heavy use of third-party components and advertisements. Moreover, we configured both browser instances with the five benign extensions discussed in Section 4.2 that change the DOM to measure performance in the presence of extensions. A more detailed evaluation would analyze more pages on these websites to garner a more realistic representation, but that is beyond the scope of the current work.

We built a crawler based on Selenium [107] to automatically visit the entire list of websites and recorded the total elapsed time from the beginning of the browsing process until the

entire list of websites was visited. Specifically, our crawler moves to the next website in the list when the current website is fully loaded, signified by the firing of the `onload` event. In order to account for fluctuations in browsing time due to network delays and the dynamic nature of advertisements, we repeated the experiment 10 times and measured the average elapsed time. The average elapsed time for browsing the home pages of the Alexa Top 1K websites measured in this way is 3,457 seconds for the unmodified browser and 3,821 seconds for ORIGINTRACER. Therefore, ORIGINTRACER incurred a 10.5% overhead on browsing time on average. We also measured the delay imposed by ORIGINTRACER on startup time by launching the browser 10 times and measuring the average launch time. ORIGINTRACER did not cause any measurable overhead on startup time.

While this overhead is not insignificant, we note that our user study in Section 4.5.2 indicates that many users would be willing to trade off actual perceived performance overhead against the security benefits provided by the system. Moreover, this prototype is just a proof-of-concept implementation of our system and there is still room for optimizing the implementation to decrease the page load time.

4.6 Chapter Summary

In this chapter, we evaluated a prototype implementation of web content provenance tracking, a modified version of Chromium we call ORIGINTRACER, through a user study that demonstrated a statistically significant improvement in the ability of users to identify unwanted third-party content. Our performance evaluation shows a modest overhead on a large representative sample of popular websites, while our user experiments indicate that users are willing to trade off a slight decrease in performance for more insight into the sources of web content that they browse. We also performed a comprehensive study on the content modifications performed by ad-injecting extensions in the wild.

Chapter 5

Analysis of Style Injection by Relative Path Overwrite

5.1 Introduction

Cross-Site Scripting (XSS) [94] attacks are one of the most common threats on the Web. While XSS has traditionally been understood as the attacker's capability to inject script into a site and have it executed by the victim's web browser, more recent work has shown that script injection is not a necessary precondition for effective attacks. By injecting Cascading Style Sheet (CSS) directives, for instance, attackers can carry out so-called *scriptless* attacks [47] and exfiltrate secrets from a site.

The aforementioned injection attacks typically arise due to the lack of separation between code and data [31], and more specifically, insufficient sanitization of untrusted inputs in web applications. While script injection attacks are more powerful than those based on style injection, they are also more well-known as a threat, and web developers are comparatively more likely to take steps to make them more difficult. From an attacker's point of view, style injection attacks may be an option in scenarios where script injection is not possible.

There are many existing techniques of how style directives could be injected into a site [47,

53]. A relatively recent class of attacks is Relative Path Overwrite (RPO), first proposed in a blog post by Gareth Heyes [50] in 2014. These attacks exploit the semantic disconnect between web browsers and web servers in interpreting relative paths (*path confusion*). More concretely, in certain settings an attacker can manipulate a page’s URL in such a way that the web server still returns the same content as for the benign URL. However, using the manipulated URL as the base, the web browser incorrectly expands relative paths of included resources, which can lead to resources being loaded despite not being intended to be included by the developer. Depending on the implementation of the site, different variations of RPO attacks may be feasible. For example, an attacker could manipulate the URL to make the page include user-generated content hosted on the same domain [116]. When an injection vulnerability is present in a page, an attacker could manipulate the URL such that the web page references itself as the stylesheet, which turns a simple text injection vulnerability into a style sink [50]. Among these attack instantiations, the latter variant has preconditions that are comparatively frequently met by sites. Our work focuses on this variant of RPO.

In this chapter, we present the first in-depth study of style injection vulnerability using RPO. We extract pages using relative-path stylesheets from the Common Crawl dataset [26], automatically test if style directives can be injected using RPO, and determine whether they are interpreted by the browser. Out of 31 million pages from 222 thousand Alexa Top 1 M sites [13] in the Common Crawl that use relative-path stylesheets, we find that 377 k pages (12 k sites) are vulnerable; 11 k pages on 1 k sites can be exploited in Chrome, and nearly 55 k pages on over 3 k sites can be exploited in Internet Explorer.

The rest of this chapter is organized as follows. Section 5.2 outlines the necessary background on cross-site scripting, scriptless attacks, and relative path overwrite. Section 5.3 presents the design and implementation of our measurement methodology, while Section 5.4 presents our findings. Finally, we summarize the chapter in Section 5.5.

5.2 Background

The general threat model of Relative Path Overwrite (RPO) resembles that of Cross-Site Scripting (XSS). Typically, the attacker’s goal is to steal sensitive information from a third-party site or make unauthorized transactions on the site, such as gaining access to confidential financial information or transferring money out of a victim’s account.

The attacker carries out the attack against the site indirectly, by way of a victim that is an authorized user of the site. The attacker can trick the victim into following a crafted link, such as when the victim visits a domain under the attacker’s control and the page automatically opens the manipulated link, or through search engine poisoning, deceptive shortened links, or through means of social engineering.

5.2.1 Cross-Site Scripting

Many sites have vulnerabilities that let attackers inject malicious script. Dynamic sites frequently accept external inputs that can be controlled by an attacker, such as data in URLs, cookies, or forms. While the site developer’s aim would have been to render the input as text, lack of proper sanitization can result in the input being executed as script [97]. The inclusion of unsanitized inputs could occur on the server side or client side, and in a persistent *stored* or volatile *reflected* way [94]. To the victim’s web browser, the code appears as originating from the first-party site, thus it is given full access to the session data in the victim’s browser. Thereby, the attacker bypasses protections of the Same-Origin Policy.

5.2.2 Scriptless Attacks

Cross-Site Scripting is perhaps the most well-known web-based attack, against which many sites defend by filtering user input. Client-side security mechanisms such as browser-based XSS filters [16] and Content Security Policy [110, 120] also make it more challenging for attackers to exploit injection vulnerabilities for XSS. This has led attackers (and researchers)

to investigate potential alternatives, such as *scriptless* attacks. These attacks allow sniffing users' browsing histories [74, 55], exfiltrating arbitrary content [62], reading HTML attributes [49, 65], and bypassing Clickjacking defenses [49]. In the following, we highlight two types of scriptless attacks proposed in the literature. Both assume that an attacker cannot inject or execute script into a site. Instead, the attacker abuses features related to Cascading Style Sheets (CSS).

Heiderich et al. [47] consider scenarios where an attacker can inject CSS into the context of the third-party page so that the style directives are interpreted by the victim's browser when displaying the page. That is, the injection sink is either located inside a style context, or the attacker can inject markup to create a style context around the malicious CSS directives. While the CSS standard is intended for styling and layout purposes such as defining sizes, colors, or background images and as such does not contain any traditional scripting capabilities, it does provide some context-sensitive features that, in combination, can be abused to extract and exfiltrate data. If the secret to be extracted is not displayed, such as a token in a hidden form field or link URL, the attacker can use the CSS attribute accessor and content property to extract the secret and make it visible as text, so that style directives can be applied to it. Custom attacker-supplied fonts can change the size of the secret text depending on its value. Animation features can be used to cycle through a number of fonts in order to test different combinations. Media queries or the appearance of scrollbars can be used to implement conditional style, and data exfiltration by loading a different URL for each condition from the attacker's server. Taken together, Heiderich et al. demonstrate that these techniques allow an attacker to steal credit card numbers or CSRF tokens [96] without script execution.

Rather than using layout-based information leaks to exfiltrate data from a page, Huang et al. [53] show how syntactically lax parsing of CSS can be abused to make browsers interpret an HTML page as a "stylesheet." The attack assumes that the page contains two injection sinks, one before and one after the location of the secret in the source code. The attacker

injects two CSS fragments such as `{}*{background:url('//attacker.com/? and ');}`, which make the secret a part of the URL that will be loaded from the attacker's server when the directive is interpreted. It is assumed that the attacker cannot inject markup, thus the injected directive is not interpreted as style when the site is conventionally opened in a browser. However, the CSS standard mandates that browsers be very forgiving when parsing CSS, skipping over parts they do not understand [119]. In practice, this means that an attacker can set up a site that loads the vulnerable third-party site *as a stylesheet*. When the victim visits the attacker's site while logged in, the victim's browser loads the third-party site and interprets the style directive, causing the secret to be sent to the attacker. To counter this attack, modern browsers do not load documents with non-CSS content types and syntax errors as stylesheets when they originate from a different domain than the including page. Yet, attacks based on tolerant CSS parsing are still feasible when both the including and the included page are loaded from the same domain. Relative Path Overwrite attacks can abuse such a scenario [129].

5.2.3 Relative Path Overwrite

Relative Path Overwrite vulnerabilities can occur in sites that use relative paths to include resources such as scripts or stylesheets. Before a web browser can issue a request for such a resource to the server, it must expand the relative path into an absolute URL. For example, assume that a web browser has loaded an HTML document from `http://example.com/rpo/test.php` which references a remote stylesheet with the relative path `dist/styles.css`. Web browsers treat URLs as file system-like paths, that is, `test.php` would be assumed to be a file within the parent directory `rpo/`, which would be used as the starting point for relative paths, resulting in the absolute URL `http://example.com/rpo/dist/styles.css`.

However, the browser's interpretation of the URL may be very different from how the web server resolves the URL to determine which resource should be returned to the browser. The URL may not correspond to an actual server-side file system structure at all, or the web server

may internally rewrite parts of the URL. For instance, when a web server receives a request for `http://example.com/rpo/test.php/` with an added trailing slash, it may still return the same HTML document corresponding to the `test.php` resource. Yet, to the browser this URL would appear to designate a directory (without a file name component), thus the browser would request the stylesheet from `http://example.com/rpo/test.php/dist/styles.css`. Depending on the server configuration, this may either result in an error since no such file exists, or the server may interpret `dist/styles.css` as a parameter to the script `test.php` and return the HTML document. In the latter case, the HTML document includes itself as a stylesheet. Provided that the document contains a (text) injection vulnerability, attackers can carry out the scriptless attacks; since the stylesheet inclusion is same-origin, the document load is permitted.

5.2.4 Preconditions for RPO Style Attacks

For the purpose of this work, we focus on a generic type of RPO attack because its preconditions are less specific and are likely met by a larger number of sites. More formally, we define a page as *vulnerable* if:

- The page includes at least one stylesheet using a relative path.
- The server is set up to serve the same page even if the URL is manipulated by appending characters that browsers interpret as path separators.
- The page reflects style directives injected into the URL or cookie. Note that the reflection can occur in an arbitrary location within the page, and markup or script injection are not necessary.
- The page does not contain a `<base>` HTML tag before relative paths that would let the browser know how to correctly expand them.

This attack corresponds to style injection by means of a page that references itself as a stylesheet (PRSSI). Since the “stylesheet” self-reference is, in fact, an HTML document, web servers would typically return it with a `text/html` content type. Browsers in standards-compliant mode do not attempt to parse documents with a content type other than CSS even if referenced as a stylesheet, causing the attack to fail. However, web browsers also support *quirks mode* for backwards compatibility with non-standards compliant sites [108]; in this mode, browsers ignore the content type and parse the document according to the inclusion context only.

We define a vulnerable page as *exploitable* if the injected style is interpreted by the browser—that is, if an attacker can force browsers to render the page in quirks mode. This can occur in two alternative ways:

- The vulnerable HTML page specifies a *document type* that causes the browser to use quirks mode instead of standards mode. The document type indicates the HTML version and dialect used by the page; Section 5.4.3.1 provides details on how the major web browsers interpret the document types we encountered during our study.
- Even if the page specifies a document type that would usually result in standards mode being used, quirks mode parsing can often be enforced in Internet Explorer [61]. Framed documents inherit the parsing mode from the parent document, thus an attacker can create an attack page with an older document type and load the vulnerable page into a frame. This trick only works in Internet Explorer, however, and it may fail if the vulnerable page uses any anti-framing technique, or if it specifies an explicit value for the `X-UA-Compatible` HTTP header (or equivalent).

Our measurement methodology in Section 5.3 tests how often these preconditions hold in the wild in order to quantify the vulnerability and exploitability of pages with respect to RPO attacks.

5.3 Methodology

Our methodology consists of three main phases. We seed our system with pages from the Common Crawl archive to extract *candidate* pages that include at least one stylesheet using a relative path. To determine whether these candidate pages are *vulnerable*, we attempt to inject style directives by requesting variations of each page’s URL to cause *path confusion* and test whether the generated response reflects the injected style directives. Finally, we test how often vulnerable pages can be *exploited* by checking whether the reflected style directives are parsed and used for rendering in a web browser.

Ethics. One ethical concern is that the injected CSS might be stored on the server instead of being reflected in the response, and it could break sites as a result. We took several cautionary steps in order to minimize any damaging side effects on sites we probed. First, we did not try to login to the site, and we only tested RPO on the publicly available version of the page. In addition, we only requested pages by tainting different parts of the URL, and did not submit any forms. Moreover, we did not click on any button or link in the page in order to avoid triggering JavaScript events. These steps significantly decrease the chances that injected CSS will be stored on the server. In order to minimize the damaging side effects in case our injected CSS was stored, the injected CSS is not a valid style directive, and even if it is stored on the server, it will not have any observable effect on the page. In addition, experiment resulted in the discovery of vulnerable content management systems (CMSes) used world-wide, and we contacted them so they can fix the issue. We believe the real-world experiments that we conducted were necessary in order to measure the risk posed by these vulnerabilities and inform site owners of potential risks to their users.

5.3.1 Candidate Identification

For finding the initial seed set of candidate pages with relative-path stylesheets, we leverage the Common Crawl from August 2016, which contains more than 1.6 billion pages. By

Table 5.1: Sample URL grouping.

Group By	URL
Query Parameter	http://example.com/?lang= en http://example.com/?lang= fr
Path Parameter	http://example.com/ 028 http://example.com/ 142

using an existing dataset, we can quickly identify candidate pages without creating any web crawl traffic. We use a Java HTML parser to filter any pages containing only inline CSS or stylesheets referenced by absolute URLs, leaving us with over 203 million pages on nearly 6 million sites. For scalability purposes, we further reduce the set of candidate pages in two steps:

1. We retain only pages from sites listed in the Alexa Top 1 million ranking, which reduces the number of candidate pages to 141 million pages on 223 thousand sites. In doing so, we bias our result toward popular sites—that is, sites where attacks could have a larger impact because of the higher number of visitors.
2. We observed that many sites use templates customized through query strings or path parameters. We expect these templates to cause similar vulnerability and exploitability behavior for their instantiations, thus we can speed up our detection by grouping URLs using the same template, and testing only one random representative of each group.

In order to group pages, we replace all the values of query parameters with constants, and we also replace any number identifier in the path with a constant. We group pages that have the same abstract URL as well as the same document type in the Common Crawl dataset. Table 5.1 illustrates this process.

Since our methodology contains a step during which we actively test whether a vulnerability can be exploited, we remove from the candidate set all pages hosted on sites in `.gov`, `.mil`, `.army`, `.navy`, and `.airforce`. The final candidate set consists of 137 million pages (31 million page groups) on 222 thousand sites.

5.3.2 Vulnerability Detection

To determine whether a candidate page is vulnerable, we implemented a lightweight crawler based on the Python Requests API. At a high level, the crawler simulates how a browser expands relative paths and tests whether style directives can be injected into the resources loaded as stylesheets using path confusion.

For each page group from the candidate set, the crawler randomly selects one representative URL and mutates it according to a number of techniques explained below. Each of these techniques aims to cause path confusion and taints page inputs with a style directive containing a long unique, random string. The crawler requests the mutated URL from the server and parses the response document, ignoring resources loaded in frames. If the response contains a `<base>` tag, the crawler considers the page not vulnerable since the `<base>` tag, if used correctly, can avoid path confusion. Otherwise, the crawler extracts all relative stylesheet paths from the response and expands them using the mutated URL of the main page as the base, emulating how browsers treat relative paths (see Section 5.2.3). The crawler then requests each unique stylesheet URL until one has been found to reflect the injected style in the response.

The style directive we inject to test for reflection vulnerabilities is shown in the legend of Figure 5.1. The payload begins with an encoded newline character, as we observed that the presence of a newline character increases the probability of a successful injection. We initially use `%0A` as the newline character, but also test `%0C` and `%0D` in case of unsuccessful injection. The remainder of the payload emulates the syntax of a simple CSS directive and mainly consists of a randomly generated string used to locate the payload in the body of the server response. If the crawler finds a string match of the injected unique string, it considers the page vulnerable.

In the following, we describe the various URL mutation techniques we use to inject style directives. All techniques also use RPO so that instead of the original stylesheet files, browsers load different resources that are more likely to contain an injection vulnerability.

Conceptually, the RPO approaches we use assume some form of server-side URL rewriting as described in Section 5.2.3. That is, the server internally resolves a crafted URL to the same script as the “clean” URL. Under that assumption, the path confusion caused by RPO would result in the page referencing itself as the stylesheet when loaded in a web browser. However, this assumption is only conceptual and not necessary for the attack to succeed. For servers that do not internally rewrite URLs, our mutated URLs likely cause error responses since the URLs do not correspond to actual files located on these servers. Error responses are typically HTML documents and may contain injection sinks, such as when they display the URL of the file that could not be found. As such, server-generated error responses can be used for the attack in the same way as regular pages.

Our URL mutation techniques differ in how they attempt to cause path confusion and inject style directives by covering different URL conventions used by a range of web application platforms.

5.3.2.1 Path Parameter

A number of web frameworks such as PHP, ASP, or JSP can be configured to use URL schemes that encode script input parameters as a directory-like string following the name of the script in the URL. Figure 5.1a shows a generic example where there is no parameter in the URL. Since the crawler does not know the name of valid parameters, it simply appends the payload as a subdirectory to the end of the URL. In this case, content injection can occur if the page reflects the page URL or referrer into the response. Note that in the example, we appended two slashes so that the browser does not remove the payload from the URL when expanding the stylesheet reference to the parent directory (`../style.css`). In the actual crawl, we always appended twenty slashes to avoid having to account for different numbers of parent directories. We did not observe relative paths using large numbers of `../` to reference stylesheets, thus we are confident that twenty slashes suffice for our purposes.

Different web frameworks handle path parameters slightly differently, which is why we

```
http://domain/dir/page.asp
http://domain/dir/page.asp/PAYLOAD//
http://domain/dir/page.asp/PAYLOAD/style.css
```

(a) Path Parameter (Simple)

```
http://domain/page.php/param
http://domain/page.php/PAYLOADparam//
http://domain/page.php/PAYLOADparam/style.css
```

(b) Path Parameter (PHP or ASP)

```
http://domain/dir/page.jsp;param
http://domain/dir/page.jsp;PAYLOADparam//
http://domain/dir/page.jsp;PAYLOADparam/style.css
```

(c) Path Parameter (JSP)

```
http://domain/dir/page.aspx
http://domain/PAYLOAD/..%2Fdir/PAYLOAD/..%2Fpage.aspx//
http://domain/PAYLOAD/..%2Fdir/PAYLOAD/..%2Fpage.aspx/style.css
```

(d) Encoded Path

```
http://domain/dir/page.html?key=value
http://domain/dir/page.html%3Fkey=PAYLOADvalue//
http://domain/dir/page.html%3Fkey=PAYLOADvalue/style.css
```

(e) Encoded Query

```
http://domain/dir/page.php?key=value
http://domain/dir/page.php//?key=value
http://domain/dir/page.php/style.css
```

```
Original Cookie: name=val
Crafted Cookie: name=PAYLOADval
```

(f) Cookie

Figure 5.1: Various techniques of **path confusion** and **style injection**. In each example, the first URL corresponds to the regular page, and the second one to the page URL crafted by the attacker. Each HTML page is assumed to reference a stylesheet at `./style.css`, resulting in the browser expanding the stylesheet path as shown in the third URL. **PAYLOAD** corresponds to `%0A{}body{background:NONCE}` (simplified), where NONCE is a randomly generated string.

distinguish a few additional cases. If parameters are present in the URL, we can distinguish these cases based on a number of regular expressions that we generated. For example, parameters can be separated by slashes (Figure 5.1b, PHP or ASP) or semicolons (Figure 5.1c, JSP). When the crawler detects one of these known schemes, it injects the payload into each parameter. Consequently, in addition to URL and referrer reflection, injection can also be successful when any of the parameters is reflected in the page.

5.3.2.2 Encoded Path

This technique targets web servers such as IIS that decode encoded slashes in the URL for directory traversal, whereas web browsers do not. Specifically, we use %2F, an encoded version of '/', to inject our payload into the URL in such a way that the canonicalized URL is equal to the original page URL (see Figure 5.1d). Injection using this technique succeeds if the page reflects the page URL or referrer into its output.

5.3.2.3 Encoded Query

Similar to the technique above, we replace the URL query delimiter '?' with its encoded version %3F so that web browsers do not interpret it as such. In addition, we inject the payload into every value of the query string, as can be seen in Figure 5.1e. CSS injection happens if the page reflects either the URL, referrer, or any of the query values in the HTML response.

5.3.2.4 Cookie

Since stylesheets referenced by a relative path are located in the same origin as the referencing page, its cookies are sent when requesting the stylesheet. CSS injection may be possible if an attacker can create new cookies or tamper with existing ones (a strong assumption compared to the other techniques), and if the page reflects cookie values in the response. As shown in Figure 5.1f, the URL is only modified by adding slashes to cause path confusion. The

payload is injected into each cookie value and sent by the crawler as an HTTP header.

5.3.3 Exploitability Detection

Once a page has been found to be vulnerable to style injection using RPO, the final step is to verify whether the reflected CSS in the response is evaluated by a real browser. To do so, we built a crawler based on Google Chrome, and used the Remote Debugging Protocol [11] to drive the browser and record HTTP requests and responses. In addition, we developed a Chrome extension to populate the cookie header in CSS stylesheet requests with our payload.

In order to detect exploitable pages, we crawled all the pages from the previous section that had at least one reflection. Specifically, for each page we checked which of the techniques in Figure 5.1 led to reflection, and crafted the main URL with a CSS payload. The CSS payload used to verify exploitability is different from the simple payload used to test reflection. Specifically, the style directive is prefixed with a long sequence of } and] characters to close any preceding open curly braces or brackets that may be located in the source code of the page, since they might prevent the injected style directive from being parsed correctly. The style directive uses a randomly-generated URL to load a background image for the HTML body. We determine whether the injected style is evaluated by checking the browser's network traffic for an outgoing HTTP request for the image.

5.3.3.1 Overriding Document Types

Reflected CSS is not always interpreted by the browser. One possible explanation is the use of a modern document type in the page, which does not cause the browser to render the page in quirks mode. Under certain circumstances, Internet Explorer allows a parent page to force the parsing mode of a framed page into quirks mode [61]. To test how often this approach succeeds in practice, we also crawled vulnerable pages with Internet Explorer 11 by framing them while setting `X-UA-Compatible` to `IE=EmulateIE7` via a meta tag in the attacker's page.

Table 5.2: Narrowing down the Common Crawl to the candidate set used in our analysis (from left to right)

	Relative CSS	Alexa Top 1M	Candidate Set
All Pages	203,609,675	141,384,967	136,793,450
Tested Pages	53,725,270	31,448,446	30,991,702
Sites	5,960,505	223,212	222,443
Doc. Types	9,833	2,965	2,898

5.3.4 Limitations

RPO is a class of attacks and our methodology covers only a subset of them. We target RPO for the purpose of style injection using an HTML page referencing itself (or, accidentally, an error page) as the stylesheet. In terms of style injection, our crawler only looks for reflection, not stored injection of style directives. Furthermore, manual analysis of a site might reveal more opportunities for style injection that our crawler fails to detect automatically.

For efficiency reasons, we seed our analysis with an existing Common Crawl dataset. We do not analyze the vulnerability of pages not contained in the Common Crawl seed, which means that we do not cover all sites, and we do not fully cover all pages within a site. Consequently, the results presented in this paper should be seen as a lower bound. If desired, our methodology can be applied to individual sites in order to analyze more pages.

5.4 Analysis

For the purposes of our analysis, we gradually narrow down the seed data from the Common Crawl to pages using relative style paths in the Alexa Top 1M, reflecting injected style directives under RPO, and being exploitable due to quirks mode rendering.

Table 5.2 shows a summary of our dataset. *Tested Pages* refers to the set of randomly selected pages from the page groups as discussed in Section 5.3.1. For brevity, we are referring to *Tested Pages* wherever we mention pages in the remainder of the paper.

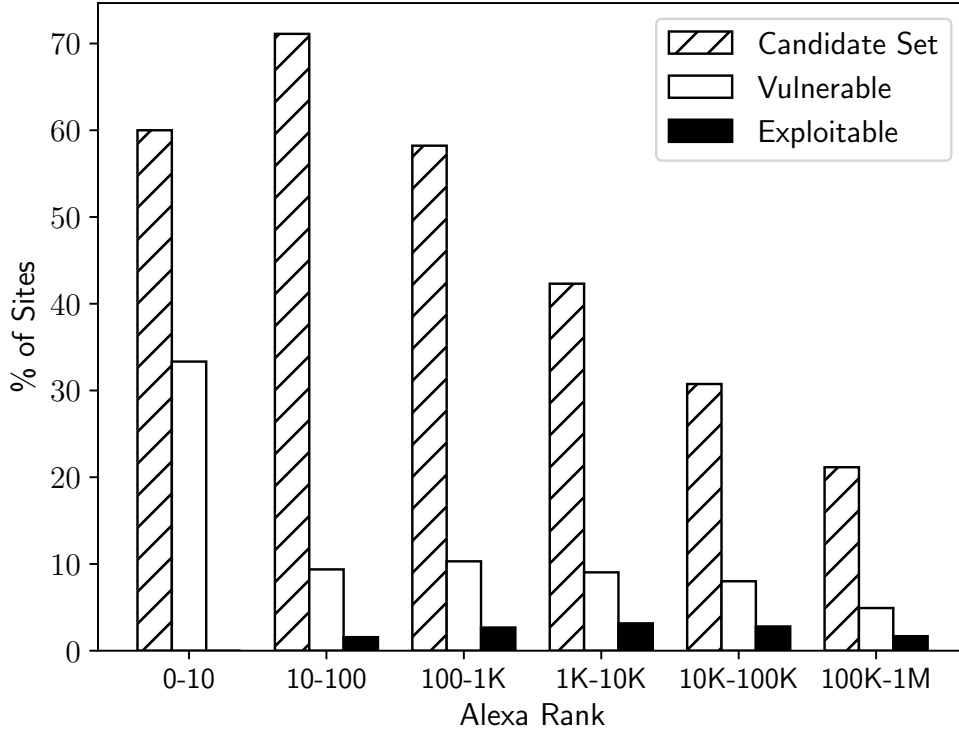


Figure 5.2: Percentage of the Alexa site ranking in our candidate set (exponentially increasing bucket size).

5.4.1 Relative Stylesheet Paths

To assess the extent to which our Common Crawl-seeded candidate set covers sites of different popularity, consider the hatched bars in Figure 5.2. Six out of the ten largest sites according to Alexa are represented in our candidate set. That is, they are contained in the Common Crawl, and have relative style paths. The figure shows that our candidate set contains a higher fraction of the largest sites and a lower fraction of the smaller sites. Consequently, our results better represent the most popular sites, which receive most visitors, and most potential victims of RPO attacks.

While all the pages in the candidate set contain at least one relative stylesheet path, Figure 5.3 shows that 63.1% of them contain multiple relative paths, which increases the chances of finding a successful RPO and style injection point.

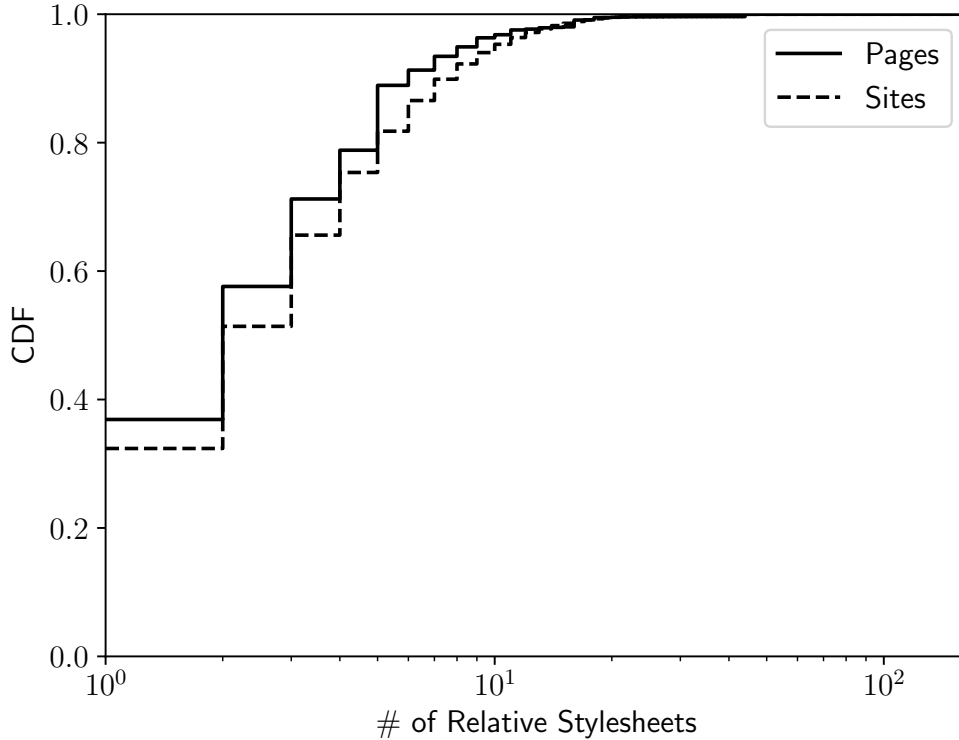


Figure 5.3: CDF of total and maximum number of relative stylesheets per web page and site, respectively.

5.4.2 Vulnerable Pages

We consider a candidate page vulnerable if one of the style injection techniques of Section 5.3.2 succeeds. In other words, the server’s response should reflect the injected payload. Furthermore, we conservatively require that the response not contain a `base` tag since a correctly configured base tag can prevent path confusion.

Table 5.3 shows that 1.2% of pages are vulnerable to at least one of the injection techniques, and 5.4% of sites contain at least one vulnerable page. The path parameter technique is most effective against pages, followed by the encoded query and the encoded path techniques. Sites that are ranked higher according to Alexa are more likely to be vulnerable, as shown in Figure 5.2, where vulnerable and exploitable sites are relative to the candidate set in each bucket. While one third of the candidate set in the Top 10 (two out of six sites) is vulnerable, the percentage oscillates between 8 and 10% among the Top 100k. The candid-

Table 5.3: Vulnerable pages and sites in the candidate set

Technique	Pages	Sites
Path Parameter	309,079 (1.0%)	9,136 (4.1%)
Encoded Path	53,502 (0.2%)	1,802 (0.8%)
Encoded Query	89,757 (0.3%)	1,303 (0.6%)
Cookie	15,656 (<0.1%)	1,030 (0.5%)
Total	377,043 (1.2%)	11,986 (5.4%)

ate set is dominated by the smaller sites in the ranks between 100k and 1M, which have a vulnerability rate of 4.9% and push down the average over the entire ranking.

A **base** tag in the server response can prevent path confusion because it indicates how the browser should expand relative paths. We observed a number of inconsistencies with respect to its use. At first, 603 pages on 60 sites contained a **base** tag in their response; however, the server response after injecting our payload did not contain the tag anymore, rendering these pages potentially exploitable. Furthermore, Internet Explorer’s implementation of the **base** tag appears to be broken. When such a tag is present, Internet Explorer fetches two URLs for stylesheets—one expanded according to the base URL specified in the tag, and one expanded in the regular, potentially “confused” way of using the page URL as the base. In our experiments, Internet Explorer always applied the “confused” stylesheet, even when the one based on the **base** tag URL loaded faster. Consequently, **base** tags do not appear to be an effective defense against RPO in Internet Explorer (They seem to work as expected in other browsers, including Edge).

5.4.3 Exploitable Pages

To test whether a vulnerable page was exploitable, we opened it in Chrome, injected a style payload with an image reference (randomly generated URL), and checked if the image was indeed loaded. This test succeeded for 2.9% of vulnerable pages; 0.5% of sites in the candidate set had at least one exploitable page (Table 5.4).

In the following, we explore various factors that may impact whether a vulnerable page

Table 5.4: Exploitable pages and sites in the candidate set (IE using framing)

Technique	Chrome		Internet Explorer	
	Pages	Sites	Pages	Sites
Path Parameter	6,048 (<0.1%)	1,025 (0.5%)	52,344 (0.2%)	3,433 (1.5%)
Encoded Path	3 (<0.1%)	2 (<0.1%)	24 (<0.1%)	5 (<0.1%)
Encoded Query	23 (<0.1%)	20 (<0.1%)	137 (<0.1%)	43 (<0.1%)
Cookie	4,722 (<0.1%)	81 (<0.1%)	2,447 (<0.1%)	238 (0.1%)
Total	10,781 (<0.1%)	1,106 (0.5%)	54,853 (0.2%)	3,645 (1.6%)

Table 5.5: Quirks mode document types by browser

Browser	Version	OS	Doc. Types
Chrome	55	Ubuntu 16.04	1,378 (31.9 %)
Opera	42	Ubuntu 16.04	1,378 (31.9 %)
Safari	10	macOS Sierra	1,378 (31.9 %)
Firefox	50	Ubuntu 16.04	1,326 (30.7 %)
Edge	38	Windows 10	1,319 (30.5 %)
IE	11	Windows 7	1,319 (30.5 %)

can be exploited, and we show how some of these partial defenses can be bypassed.

5.4.3.1 Document Types

HTML document types play a significant role in RPO-based style injection attacks because browsers typically parse resources with a non-CSS content type in a CSS context only when the page specifies an ancient or non-standard HTML document type (or none at all). The pages in our candidate set contain a total of 4,318 distinct document types. However, the majority of these unique document types are not standardized and differ from the standardized ones only by small variations, such as forgotten spaces or misspellings.

To determine how browsers interpret these document types (i.e., whether they cause them to render a page in standards or quirks mode), we designed a controlled experiment. For each unique document type, we set up a local page with a relative stylesheet path and carried out an RPO attack to inject CSS using a payload similar to what we described in Section 5.3.3. We automatically opened the local page in Chrome, Firefox, Edge, Internet Explorer, Safari, and Opera, and we kept track of which document type caused the injected

Table 5.6: Most frequent document types causing all browsers to render in quirks mode, as well as the sites that use at least one such document type

Doc. Type (shortened)	Pages	Sites
(none)	1,818,595 (5.9%)	56,985 (25.6%)
"-//W3C//DTD HTML 4.01 Transitional//EN"	721,884 (2.3%)	18,648 (8.4%)
"-//W3C//DTD HTML 4.0 Transitional//EN"	385,656 (1.2%)	11,566 (5.2%)
"-//W3C//DTD HTML 3.2 Final//EN"	22,019 (<0.1%)	1,175 (0.5%)
"-//W3C//DTD HTML 3.2//EN"	10,839 (<0.1%)	927 (0.4%)
All	3,046,449 (9.6%)	71,597 (32.2%)

CSS to be parsed and the injected background image to be downloaded.

Table 5.5 contains the results of this experiment. Even though the exact numbers vary among browsers, roughly a third of the unique document types we encountered result in quirks mode rendering. Not surprisingly, both Microsoft products Edge and Internet Explorer exhibit identical results, whereas the common Webkit ancestry of Chrome, Opera, and Safari also show identical results. Overall, 1,271 (29.4%) of the unique document types force all the browsers into quirks mode, whereas 1,378 (31.9%) of them cause at least one browser to use quirks mode rendering. Table 5.6 shows the most frequently used document types that force all the browsers into quirks mode, which includes the absence of a document type declaration in the page.

To test how often Internet Explorer allows a page’s document type to be overridden when loading it in an `iframe`, we created another controlled experiment using a local attack page framing the victim page, as outlined in Section 5.3.3. Using Internet Explorer 11, we loaded our local attack page for each unique document type inside the frame, and tested if the injected CSS was parsed. While Internet Explorer parsed the injected CSS for 1,319 (30.5%) of the document types in the default setting, the frame override trick caused CSS parsing for 4,248 (98.4%) of the unique document types.

While over one thousand document types result in quirks mode, and around three thousand document types cause standards mode parsing, the number of document types that have been standardized is several orders of magnitude smaller. In fact, only a few (standard-

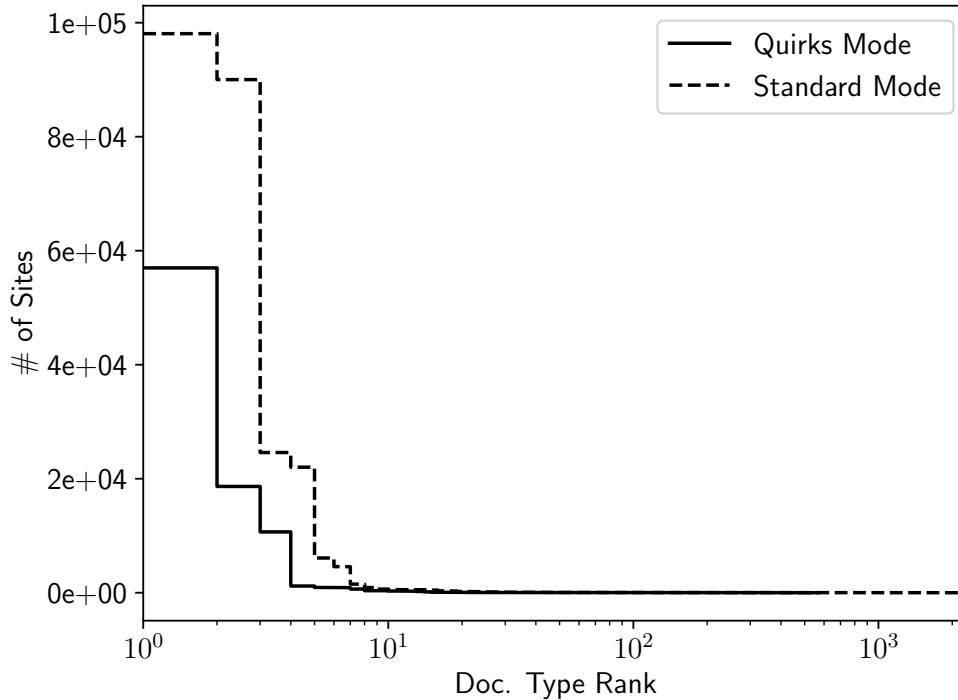


Figure 5.4: Number of sites containing at least one page with a certain document type (ordered by doctype rank).

Table 5.7: Summary of document type usage in sites

Doc. Type	At Least One Page	All Pages
None	56,985 (25.6%)	19,968 (9.0%)
Quirks	27,794 (12.5%)	7,720 (3.5%)
None or Quirks	71,597 (32.2%)	30,040 (13.5%)
Standards	192,403 (86.5%)	150,846 (67.8%)

ized) document types are used frequently in pages, whereas the majority of unique document types are used very rarely. Figure 5.4 shows that only about ten standards and quirks mode document types are widely used in sites. Furthermore, only about 9.6% of pages in the candidate set use a quirks mode document type; on the remaining pages, potential RPO style injection vulnerabilities cannot be exploited because the CSS would not be parsed (unless Internet Explorer is used). However, when grouping pages in the candidate set by site, 32.2% of sites contain at least one page rendered in quirks mode (Table 5.7), which is one of the preconditions for successful RPO.

5.4.3.2 Internet Explorer Framing

We showed above that by loading a page in a frame, Internet Explorer can be forced to disregard a standards mode document type that would prevent interpretation of injected style. To find out how often this technique can be applied for successful RPO attacks, we replicated our Chrome experiment in Internet Explorer, this time loading each vulnerable page inside a frame. Around 14.5% of vulnerable pages were exploitable in Internet Explorer, five times more than in Chrome (1.6% of the sites in the candidate set as shown in Table 5.4).

Figure 5.2 shows the combined exploitability results for Chrome and Internet Explorer according to the rank of the site. While our methodology did not find any exploitable vulnerability on the six highest-ranked sites in the candidate set, between 1.6% and 3.2% of candidate sites in each remaining bucket were found to be exploitable. The highest exploitability rate occurred in the ranks 1 k through 10 k.

Broken down by injection technique, the framing trick in Internet Explorer results in more exploitable pages for each technique except for cookie injection (Table 5.4). One possible explanation for this difference is that the Internet Explorer crawl was conducted one month after the Chrome crawl, and sites may have changed in the meantime. Furthermore, we observed two additional impediments to successful exploitation in Internet Explorer that do not apply to Chrome. The framing technique is susceptible to frame-busting methods employed by the framed pages, and Internet Explorer implements an anti-MIME-sniffing header that Chrome appears to ignore. We analyze these issues below.

5.4.3.3 Anti-Framing Techniques

Some sites use a range of techniques to prevent other pages from loading them in a frame [105]. One of these techniques is the `X-Frame-Options` header. It accepts three different values: `DENY`, `SAMEORIGIN`, and `ALLOW-FROM` followed by a whitelist of URLs.

In the vulnerable dataset, 4,999 pages across 391 sites use this header correctly and as a result prevent the attack. However, 1,900 pages across 34 sites provide incorrect values for

this header, and we successfully attack 552 pages on 2 sites with Internet Explorer.

A related technique is the `frame-ancestors` directive provided by Content Security Policy. It defines a (potentially empty) whitelist of URLs allowed to load the current page in a frame, similar to `ALLOW-FROM`. However, it is not supported by Internet Explorer, thus it cannot be used to prevent the attack.

Furthermore, developers may use JavaScript code to prevent framing of a page. Yet, techniques exist to bypass this protection [95]. In addition, the attacker can use the HTML 5 `sandbox` attribute in the `iframe` tag and omit the `allow-top-navigation` directive to render JavaScript frame-busting code ineffective. However, we did not implement any of these techniques to allow framing, which means that more vulnerable pages could likely be exploited in practice.

5.4.3.4 MIME Sniffing

A consequence of self-reference in the type of RPO studied in this paper is that the HTTP content type of the fake “stylesheet” is `text/html` rather than the expected `text/css`. Because many sites contain misconfigured content types, many browsers attempt to infer the type based on the request context or file extension (*MIME sniffing*), especially in quirks mode. In order to ask the browser to disable content sniffing and refuse interpreting data with an unexpected or wrong type, sites can set the header `X-Content-Type-Options: nosniff` [14, 60, 83].

To determine whether the injected CSS is still being parsed and executed in presence of this header while the browser renders in quirks mode, we ran an experiment similar to Section 5.4.3.1. For each browser in Table 5.5, we extracted the document types in which the browser renders in quirks mode, and for each of them, we set up a local page with a relative stylesheet path. We then opened the page in the browser, launched an RPO attack, and monitored if the injected CSS was executed.

Only Firefox, Internet Explorer, and Edge respected this header and did not interpret

injected CSS in any of the quirks mode document types. The remaining browsers did not block the stylesheet even though the content type was not `text/css`. With an additional experiment, we confirmed that Internet Explorer blocked our injected CSS payload when `nosniff` was set, even in the case of the framing technique.

Out of all the vulnerable pages, 96,618 pages across 232 sites had a `nosniff` response header; 23 pages across 10 sites were confirmed exploitable in Chrome but not in Internet Explorer, since the latter browser respects the header while the former does not.

5.4.4 Content Management Systems

While analyzing the exploitable pages in our dataset, we noticed that many appeared to belong to well-known CMSes. Since these web applications are typically installed on thousands of sites, fixing RPO weaknesses in these applications could have a large impact.

To identify CMSes, we visited all exploitable pages using Wappalyzer [122]. Additionally, we detected two CMSes that were not supported by Wappalyzer. Overall, we identified 23 CMSes on 41,288 pages across 1,589 sites. Afterwards, we manually investigated whether the RPO weakness stemmed from the CMS by installing the latest version of each CMS (or using the online demo), and testing whether exploitable paths found in our dataset were also exploitable in the CMS. After careful analysis, we confirmed four CMSes to be exploitable in their most recent version that are being used by 40,255 pages across 1,197 sites.

Out of the four exploitable CMSes, one declares no document type and one uses a quirks mode document type. These two CMSes can be exploited in Chrome, whereas the remaining two can be exploited with the framing trick in Internet Explorer. Beyond the view of our Common Crawl candidate set, Wappalyzer detected nearly 32 k installations of these CMSes across the Internet, which suggests that many more sites could be attacked with RPO. We reported the RPO weaknesses to the vendors of these CMSes using recommended notification techniques [70, 112, 21]. Thus far, we heard back from one of the vendors, who acknowledged the vulnerability and are going to take the necessary steps to fix the issue. However, we have

not received any response from the other vendors.

5.4.5 Mitigation Techniques

Relative path overwrites rely on the web server and the web browser interpreting URLs differently. HTML pages can use only absolute (or root-relative) URLs, which removes the need for the web browser to expand relative paths. Alternatively, when the HTML page contains a `<base>` tag, browsers are expected to use the URL provided therein to expand relative paths instead of interpreting the current document's URL. Both methods can remove ambiguities and render RPO impossible if applied correctly. Specifically, base URLs must be set according to the server's content routing logic. If developers choose to calculate base URLs dynamically on the server side rather than setting them manually to constant values, there is a risk that routing-agnostic algorithms could be confused by manipulated URLs and re-introduce attack opportunities by instructing browsers to use an attacker-controlled base URL. Furthermore, Internet Explorer does not appear to implement this tag correctly.

Web developers can reduce the attack surface of their sites by eliminating any injection sinks for strings that could be interpreted as a style directive. However, doing so is challenging because in the attack presented in this paper, style injection does not require a specific sink type and does not need the ability of injecting markup. Injection can be accomplished with relatively commonly used characters, that is, alphanumeric characters and `(){}"/`. Experience has shown that despite years of efforts, even context-sensitive and more special character-intensive XSS injection is still possible in many sites, which leads us to believe that style injection will be similarly difficult to eradicate. Even when all special characters in user input are replaced by their corresponding HTML entities and direct style injection is not possible, more targeted RPO attack variants referencing existing files may still be feasible. For instance, it has been shown that user uploads of seemingly benign profile pictures can be used as "scripts" (or stylesheets) [116].

Instead of preventing RPO and style injection vulnerabilities, the most promising ap-

proach could be to avoid exploitation. In fact, declaring a modern document type that causes the HTML document to be rendered in standards mode makes the attack fail in all browsers except for Internet Explorer. Web developers can harden their pages against the frame-override technique in Internet Explorer by using commonly recommended HTTP headers: `X-Content-Type-Options` to disable “content type sniffing” and always use the MIME type sent by the server (which must be configured correctly), `X-Frame-Options` to disallow loading the page in a frame, and `X-UA-Compatible` to turn off Internet Explorer’s compatibility view.

5.5 Chapter Summary

In this chapter, we showed that over 5% of sites in the intersection of the Common Crawl and the Alexa Top 1M are vulnerable to at least one injection technique. While the number of exploitable sites depends on the browser and is much smaller in relative terms, it is still consequential in absolute terms with thousands of affected sites. RPO is a class of attacks, and our automated crawler tested for only a subset of conceivable attacks. Therefore, the results of our study should be seen as a lower bound; the true number of exploitable sites is likely higher.

Chapter 6

Conclusion

In this thesis, I developed three systems to measure and reduce the security risks of content inclusions for website publishers as well as their users. More importantly, our novel techniques are complementary to the existing defenses and users can browse websites with a higher confidence.

In chapter 3, we presented EXCISION as a complementary system to other defensive approaches such as CSP and Google Safe Browsing. EXCISION incrementally constructs an *inclusion tree* for a given web page and automatically prevents loading malicious resources by classifying their *inclusion sequences* using a set of pre-built models. EXCISION detected a significant number of malicious third-party content in the wild and was also able to detect previously unknown malicious inclusions while not impacting users' browsing experience negatively.

In chapter 4, we introduced fine-grained *web content provenance* tracking and demonstrated its use for identifying unwanted third-party content (e.g., *injected advertisements*) through ORIGINTRACER, our prototype implementation. Due to the highly interconnected structure of the web and the oftentimes obscure nature of its trust relationships, we believe that surfacing this information in the form of provenance is a generally useful capability, and can be applied in other novel ways in order to lead to safer and more informed web browsing.

Our evaluation suggests that ORIGINTRACER can be used as a complementary system to ad blocking systems such as AdblockPlus [2] and Ghostery [5].

In chapter 5, we presented a systematic study of *style injection by relative path overwrite (RPO)* in the wild. We discussed a range of factors that prevent a vulnerability from being exploited, and found that simple countermeasures exist to mitigate RPO. We also linked many exploitable pages to installations of Content Management Systems (CMSes), and notified the vendors. Compared to XSS, it is much more challenging to avoid injection of style directives. Yet, developers have at their disposal a range of simple mitigation techniques that can prevent their sites from being exploited in web browsers.

6.1 Publications

This thesis is written based on the following three published papers:

- **Chapter 3:** Sajjad Arshad, Amin Kharraz, William Robertson, Include Me Out: In-Browser Detection of Malicious Third-Party Content Inclusions, *Financial Cryptography and Data Security (FC)*, 2016¹
- **Chapter 4:** Sajjad Arshad, Amin Kharraz, William Robertson, Identifying Extension-based Ad Injection via Fine-grained Web Content Provenance, *Research in Attacks, Intrusions and Defenses (RAID)*, 2016²
- **Chapter 5:** Sajjad Arshad, Seyed Ali Mirheidari, Tobias Lauinger, Bruno Crispo, Engin Kirda, William Robertson, Large-Scale Analysis of Style Injection by Relative Path Overwrite, *The Web Conference (WWW)*, 2018

Our *inclusion tree* crawler has also been evolving, called `DeepCrawling`³, and was utilized in topics such as tracking and privacy, and web security:

¹<https://github.com/sajjadium/Excision>

²<https://github.com/sajjadium/OriginTracer>

³<https://github.com/sajjadium/DeepCrawling>

- Muhammad Ahmad Bashir, Sajjad Arshad, William Robertson, Christo Wilson, Tracing Information Flows Between Ad Exchanges Using Retargeted Ads, *USENIX Security Symposium, 2016*⁴
- Muhammad Ahmad Bashir, Sajjad Arshad, Christo Wilson, Recommended For You: A First Look at Content Recommendation Networks, *ACM Internet Measurement Conference (IMC), 2016*⁵
- Tobias Lauinger, Abdelberi Chaabane, Sajjad Arshad, William Robertson, Christo Wilson, Engin Kirda, Thou Shalt Not Depend on Me: Analysing the Use of Outdated JavaScript Libraries on the Web, *Network and Distributed System Security Symposium (NDSS), 2017*⁶
- Muhammad Ahmad Bashir, Sajjad Arshad, Engin Kirda, William Robertson, Christo Wilson, How Tracking Companies Circumvented Ad Blockers Using WebSockets, *ACM Internet Measurement Conference (IMC), 2018*

The author has also been involved with topics other than web security including malware detection and binary analysis:

- Amin Kharraz, Sajjad Arshad, Collin Muliner, William Robertson, Engin Kirda, UNVEIL: A Large-Scale, Automated Approach to Detecting Ransomware, *USENIX Security Symposium, 2016*
- Reza Mirzazade farkhani, Saman Jafari, Sajjad Arshad, William Robertson, Engin Kirda, Hamed Okhravi, On the Effectiveness of Type-based Control Flow Integrity, *Annual Computer Security Applications Conference (ACSAC), 2018*⁷

⁴<http://personalization.ccs.neu.edu/Projects/Retargeting/>

⁵<http://personalization.ccs.neu.edu/Projects/Recommended/>

⁶<https://seclab.ccs.neu.edu/static/projects/javascript-libraries/>

⁷<https://github.com/sajjadium/typed-cfi>

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