# Gummy Browsers: Targeted Browser Spoofing against State-of-the-Art Fingerprinting Techniques

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Abstract. We present a simple yet potentially devastating and hard-to-detect threat, called Gummy Browsers<sup>4</sup>, whereby the browser fingerprinting information can be collected and spoofed without the victim's awareness, thereby compromising the privacy and security of any application that uses browser fingerprinting. The idea is that the attacker A first makes the user U connect to his website (or to a well-known site the attacker controls) and transparently collects the information from U that is used for fingerprinting purposes (just like any fingerprinting website W collects this information). Then, A orchestrates a browser on his own machine to replicate and transmit the same fingerprinting information when connecting to W, fooling W to think that U is the one requesting the service rather than A. As a consequence, if W populates targeted ads for U based on only browser fingerprints. A can now start seeing the same or similar ads on his browser as U would see. This will allow the attacker to profile U and compromise U's privacy. We design and implement the Gummy Browsers attack using three orchestration methods based on script injection, browser settings and debugging tools, and script modification, that can successfully spoof a wide variety of fingerprinting features to mimic many different browsers (including mobile browsers and the Tor browser). We then evaluate the attack against two state-of-the-art browser fingerprinting systems, FPStalker and Panopticlick. Our results show that A can accurately match his own manipulated browser fingerprint with that of any targeted victim user U's fingerprint for a long period of time, without significantly affecting the tracking of U and when only collecting U's fingerprinting information only once. The TPR (true positive rate) for the tracking of the benign user in the presence of the attack is larger than 0.9 in most cases. The FPR (false positive rate) for the tracking of the attacker is also high, larger than 0.9 in all cases. We also argue that the attack can remain completely oblivious to the user and the website, thus making it extremely difficult to thwart in practice.

### 1 Introduction

Many websites and web services leverage browser fingerprinting techniques to track their users for various purposes, including targeted advertisements [35] based on browsing history and habits, user authentication [1,8,6], and fraud detection [32,7]. Browser

<sup>&</sup>lt;sup>4</sup> Named after "Gummy Fingers" that can impersonate a user's fingerprint biometrics.

fingerprinting aims to uniquely identify web browsers. Specifically, browser fingerprinting uses a stateless identifier for web browsers composed of a set of browser and system attributes, including browser vendor and version, plugins and extensions, canvas rendering, available fonts, performance characteristics, platform, clock skews and screen resolutions. These attributes are collected through JavaScript APIs and HTTP headers.

Based on different combinations of browser and system attributes, and their uniqueness to the browser, researchers and practitioners have proposed a myriad of browser fingerprinting techniques [19,25,48,44,43,28,31,12,46,15,23,49,11,16,47,42]. However, the uniqueness of the fingerprint alone is not sufficient for prolonged user tracking because the browser fingerprint changes over time, potentially when the browsers are updated or configured differently [53]. For a successful long-term user tracking, changes to the fingerprints need to be tracked to link the current fingerprint with previously recorded fingerprints [53,29], using what is referred to as a *tracking technique*.

The fingerprint linking algorithm *Panopticlick*, proposed by Eckersley, [29], and *FP-Stalker* developed by Vastel et al. [53], are representative instantiations of such tracking techniques. Panopticlick showed that its visitors can be uniquely identified from a fingerprint composed of only eight browser and system attributes. It follows a very simple heuristic based on the comparison of the string representation of browser characteristics. FP-Stalker consists of two variants of fingerprint linking algorithms – a *rule-based variant* and a *hybrid variant*, which leverage ruleset and machine learning algorithms. These algorithms aim to link browser fingerprint evolutions for tracking the user. The experiment conducted in the FP-Stalker paper [53] showed that its linking algorithm, especially the hybrid variant, can track a given browser instance for a long period of time, significantly better than Panopticlick.

In this paper, we closely investigate the potential privacy leakage and security vulnerability associated with state-of-the-art browser fingerprint linking algorithms, Panopticlick and FP-Stalker to be specific, motivated by their very appealing applications and practicality features. Unfortunately, we identify a significant threat vector against such linking algorithms. Specifically, we find that an attacker can capture and spoof the browser characteristics of a victim's browser, and hence can "present" its own browser as the victim's browser when connecting to a website. The browser attributes can be easily captured (one-time or frequently based on the application) by luring the victim into visiting a benign-looking website controlled by the attacker (or a malicious website). Then, all (or most of) these attributes can be spoofed (once, or continually based on the intended level of adversarial impact on the victim), for example, by injecting a web script, modifying the existing web script, or utilizing the browser's built-in settings and debugging tools. By spoofing the victim's browser would be recognized as the victim's browser when visiting a targeted website.

Exploiting this general threat, we introduce *Gummy Browsers*, an attack system that can fully compromise the security and privacy of the schemes that leverage browser fingerprinting techniques. For instance, if the browser fingerprinting is employed for personalized and targeted ads, the web server, hosting a benign website, would push the same or similar ads to the attacker's browser like the ones that would have been pushed to the victim's browser because the web server considers the attacker's browser as the

victim's browser. Based on the personalized ads (e.g., related to pregnancy products, medications and brands), the attacker can infer various sensitive information about the victim (e.g, gender, age group, health condition, interests, salary level, etc.), even build a personal behavioral profile of the victim. Leakage of such personal and private information can raise a frightful privacy threat to the user. The study of Castelluccia et al. [27] has demonstrated that the knowledge of the ads the user is provided in targeted advertising can indeed leak significant sensitive information about the user. Similarly, if browser fingerprinting is used for security purposes, such as user authentication and fraud detection (e.g., clickbot detection), our fingerprint spoofing attacker can circumvent the security functionality of such defensive schemes. The authentication system may be based on some other factors beyond browser fingerprinting. In this paper, we only show how to defeat the fingerprinting factor.

Gummy Browsers can remain hidden and invisible to the targeted user and the targeted website. Since the capturing and spoofing of the browser attributes is done fully transparently and remotely, Gummy Browsers can be launched easily and effectively without being noticed by the user or the website. In this light, given the fact that browser fingerprinting techniques are getting deployed widely in the real world, Gummy Browsers can have a devastating and lasting impact on the online privacy and security of the users. Capturing the victim's fingerprinting information just once allows the attacker to spoof the victim for a long period of time. The process can be repeated for further impact. Given the fundamental nature of the attack, it would be very difficult to defeat.

Our experiments consider that the website only uses browser fingerprinting for tracking, and does not employ cookies (or cookies are blocked by the user). Therefore our attacks and implications of our attacks are only limited to fingerprint spoofing. **Our Contributions:** We believe that our work makes the following contributions:

- A Novel Threat of Spoofing Browser Fingerprints: We introduce a novel and serious threat raised due to the use of browser fingerprinting techniques to track the user, referred to as Gummy Browsers. Specifically, this attacker with the ability to capture and spoof the browser fingerprint can learn various personal and sensitive information about the user based on personalized ads and compromise the security of browserfingerprinting based defensive applications, such as user authentication and fraud detection. The ease with which this threat can be perpetrated is a strength of our work since it can be deployed in real world by even naive attackers.
- 2. Design and Implementation of Gummy Browsers: We provide the design and implementation of Gummy Browsers that enable an attacker to glean sensitive information about the user and compromise the browser fingerprinting based defensive schemes. Gummy Browsers leverages a benign-looking fake website to capture the victim's browser characteristics (could also be a malicious, attacker-controlled website). Gummy Browsers then utilizes spoofing methods, such as script injection, script modification, or browser's built-in setting and debugging tool to orchestrate its browser to appear as the victim's browser.
- 3. *Evaluation against Notable Fingerprinting Techniques:* We employ state-of-theart browser fingerprinting algorithms, specifically *Panopticlick* [29] and *FP-Stalker* [53], and evaluate the performance of Gummy Browsers against them. Based on a dataset of 200+ users, our results show that the attacker can successfully spoof the

fingerprint of the browser instance to match with that of the targeted victim's browser instance for a long period of time without any significant impact on the tracking of the victim.

## 2 Background and Related Work

## 2.1 Browser Fingerprinting

Different combinations of the browser and system attributes can be used to generate a unique identifier for a given browser, referred to as the *browser fingerprint*. Based on different combinations of attributes, various browser fingerprinting techniques have been proposed [19,25,48,44,43,28,47,42]. These attributes can be grouped into three different categories [22] as presented in Table 1.

(C1) Browser-Provided Information: JavaScript API can be used to extract a wide range of system information, referred to as browser-provided information, that can be employed to fingerprint a device. A set of such features are listed in the first row of Table 1. The feature set in this category includes software and hardware details (e.g., browser/OS vendor and version, system language [23], platform [15], user-agent string [25], resolution, etc.), device timezone and clock drift [25] from Coordinated Universal Time (UTC), battery information [48] (e.g., battery charge level, discharge rate), and password autofill [46] (e.g., the password is user-typed or auto-filled by a browser or password manager). The information corresponding to WebGL [19], a JavaScript API for rendering graphics within web browsers, and WebRTC [24], a set of W3C standards that supports browser-to-browser applications, e.g., voice and video chat, can also be used to fingerprint a browser. WebGL information includes the WebGL vendor and version, maximum texture size, supported WebGL extensions, renderer strings, etc. WebRTC information includes connected media devices (e.g., webcam and microphones) information. The support for *local storage*, which enables the browser to store data without any expiration [20], and the status of *do not track*, which blocks (or allows) the website from tracking [16] are also often used in browser fingerprinting.

(C2) Inference based on Device Behavior: The device information can also be extracted by executing a specially crafted JavaScript code on the browser and observing the resulting effect. This category of the fingerprinting features is based on the fact that the execution of JavaScript code creates different effects based on the software and hardware configuration of the device, and hence can be used to infer various characteristics of the device. For instance, HTML5 canvas renders the text and graphics differently based on OS, available fonts, and the video driver [44]. The elapsed time to execute the JavaScript code can be used to infer the performance characteristics of the device [43]. Various aspects of a pointing device can be inferred by monitoring the scroll events generated by the mouse wheel or touchpad [28]. The browser vendor and version can be inferred by testing CSS features [42]. The presence (or absence) of different fonts can be inferred by rendering a text with a predefined list of fonts [31].

(C3) Browser Extensions and Plugins: The aforementioned approaches can be used to extract information about the browser extensions and plugins to build a browser fingerprint. Various browser plugins, e.g., Java, Flash and Silverlight, can be queried

Table 1: Three different categories of brow	ser fingerprinting features [22], and a summary of how
they can be spoofed via our attack.	
Category Feature Name	Spoofable Spoofing Approach Detectable by Targeted Websites

Category	Feature Ivanie	Spoorable	spooning Approach	Detectable by Targeteu websites
C1	1. User-agent + - * [25]		a, b, c	
	<ol><li>WebGL information - * [19]</li></ol>		b	
	3. System time + - *[25]		a, b	
	4. Battery information [48]		a, b	
	5. Cookie enabled + - * [12]		a, b, c	
	6. WebRTC [24]		b	
	<ol><li>Password autofill [46]</li></ol>	Yes	b	Hard
	8. Platform - * [15]		a, b	
	9. Language + - * [23]		a, b, c	
	10. Local storage + - * [49]		b	
	11. Resolution + - * [11]		a, b	
	12. Do Not Track - * [16]		a, b, c	
C2	1. HTML5 canvas fingerprinting - * [44]		b	
	2. System performance [43]		b	
	3. Font detection [31]	Yes	b	Hard
	4. Scroll wheel fingerprinting [47]		b	
	5. CSS feature detection [42]		b	
C3	1. Browser plugin fingerprinting + - * [30]		a, b	
	2. Browser extension fingerprinting [36]	Yes	b	Hard

I. +: Features used in Panopticlick [29]. -: Features used in Rule-based Linking Algorithm [53]. \*: Features used in Hybrid Linking Algorithm [53].

II. C1: Browser-provided information. C2: Inference based on device behavior. C3: Extensions and plugins.

III. a: Script Injection. b: Script Modification. c: Browser Setting and Debugging Tool.

through JavaScript APIs to reveal system information [30]. For instance, Flash can provide the OS kernel version. Both Java and Flash can provide an enumerated list of system fonts. Installed NoScript (that disables JavaScript) and its blacklisted website can be detected by loading a large set of websites. Similarly, AdBlocker can be detected by monitoring if fake ads are loaded on the websites [36] or not. Other extensions can also be detected by other methods.

#### 2.2 Representative Fingerprinting Techniques

As mentioned earlier, various browser fingerprinting approaches have been proposed in the literature, each utilizing a different set of device characteristics. Panopticlick [29] and FP-Stalker [53], specifically its Rule-based Linking Algorithm and Hybrid Linking Algorithm, are representative browser fingerprint linking techniques.

**Panopticlick:** Panopticlick [29] leverages eight different browser and system attributes to track the user through browser fingerprinting. It categorizes these attributes into two groups. The first group contains cookies enabled (C1-5), screen resolution (C1-11), time zone (C1-3), and partial supercookie test (e.g., local storage, session storage and IE userData) (C1-10). The second group contains user-agent (C1-1), HTTP ACCEPT headers (C1-9), system fonts (C2-3), and browser plugins information (C3-1). To learn the identity of an unknown fingerprint ' $F_u$ ', Panopticlick compares  $F_u$  with each of the pre-stored fingerprints ' $F_k$ '. If  $F_u$  has all the eight attributes the same as that of  $F_k$ , Panopticlick marks them as the same fingerprint, i.e., generated from the same browser instance. If any of the attributes in the first group and more than one attribute from the second group differs, Panopticlick marks  $F_u$  and  $F_k$  as different fingerprints. In the case where there is only one difference in the attribute set from the first group, Panopticlick estimates the similarity score of that attribute between  $F_u$  and  $F_k$ . If the similarity score

is higher than a set threshold (say 0.85),  $F_u$  is marked the same as  $F_k$ . In the rest of the scenarios,  $F_u$  is marked differently from  $F_k$ .

**Rule-based Linking Algorithm (RLA):** This approach for browser fingerprinting categorizes the fingerprinting attributes under consideration into three sets. The first attribute set consists of operating system (C1-1), platform (C1-8), browser name (C1-1), local storage (C1-10), do not track (C1-12), cookies enable (C1-5), and canvas (C2-1). The second set consists of user-agent (C1-1), GPU vendor (C1-2), renderer (C1-2), browser plugins (C3-1), system language (C1-9) and HTTP accept headers (C1-9). The third feature set consists of the resolution (C1-11), time zone (C1-3) and encoding (HTTP header). Similar to Panopticlick, RLA compares the aforementioned attributes of an unknown fingerprint  $F_u$  with each of the stored fingerprint  $F_k$ . If all the attributes of both the fingerprints are the same, RLA marks them as *exact* fingerprints. If  $F_{\mu}$  and  $F_k$  have differences in at least one of the attributes in the first set, RLA marks them as different. if  $F_{\mu}$  has an older version of the browser, the algorithm will mark them as different. Otherwise, it estimates the similarity between the remaining attributes from the second and third sets. If the similarity score is greater than the set threshold (say 0.75), the algorithm counts the number of features that are different between  $F_u$  and  $F_k$ . All the  $F_k$ s that have less than one different attribute from the first set and less than two different attributes from the first and second sets are marked as candidate fingerprints. If all the  $F_k$ -s that have been marked as *exact* fingerprints correspond to the same user,  $F_k$  is assigned to that particular user. Similarly, if all the  $F_k$ -s that have been marked as candidate fingerprints belong to the same user,  $F_u$  is assigned to that particular user. In the rest of the cases,  $F_u$  is recognized as a new user.

Hybrid Linking Algorithm (HLA): This approach enhances RLA with the machine learning technique. HLA divides the browser attributes into two sets. The first set consists of the operating system (C1-1), device platform (C1-8), browser information (C1-1), local storage (C1-10), do not track (C1-12), cookies enable (C1-5), and canvas (C2-1). The second set contains the following nine features - number of changes, system languages (C1-9), HTTP based user-agent (C1-1), canvas (C2-1), created time (C1-3), browser plugins (C3-1), fonts (C2-3), renderer (C1-2) and resolution (C1-11). HLA compares an unknown fingerprint ' $F_u$ ' with each of the known fingerprints ' $F_k$ ' to give an identity to  $F_u$ .  $F_k$  is assigned to the set "exact" if these two fingerprints have the exact same first attribute set, otherwise, to the set " $F_{k_sub}$ ". If all the fingerprints in the set *exact* have the same id, this id is assigned to  $F_u$ , otherwise, a new id is given to  $F_u$ . If there are no fingerprints in the set *exact*, HLA compares the first attribute set of  $F_u$ with that of each of the  $F_k$  in  $F_{k\_sub}$ . Each attribute comparison results in '1' if the attribute is the same in both  $F_k$  and  $F_u$ , otherwise, '0'. If there are less than five different attributes, HLA feeds the results to the machine learning model, Random Forest to be specific, resulting in a similarity score (in the range of 0 and 1). The  $F_k$  having a score higher than 0.994 is assigned to the set 'candidates'. The  $F_k$ -s in the candidate set are sorted in descending order of the score. If the first score is larger than the second one plus 0.1, the id of  $F_{\mu}$  ID becomes the top-one id. If the top-one and top-two ids have the same id, this id is assigned to  $F_u$ , otherwise, a new ID is given to  $F_u$ .

### 2.3 Applications of Browser Fingerprinting

**Targeted Advertising:** The browser fingerprinting can be employed to provide targeted and personalized ads on the user devices (e.g., general desktop PC, handheld mobile device) [35]. When a user visits a website, the web server (or the online service provider) extracts and stores the browser fingerprint along with the user's browsing behavior. When the user revisits the same website, the web server looks for his fingerprint in its repository and pushes the relevant ads based on the user's prior browsing behavior. Besides browser fingerprinting, there exist other approaches for targeted advertisements, such as account-based targeted ads [51] and cookie-based targeted ads [52]. Unlike these approaches, the browser fingerprinting neither requires the user to log into his online account, nor requires the user to enable the cookie, rather it works transparently.

**User Authentication:** Various services, such as Oracle [1], Inauth [8] and SecureAuth IdP [6] are leveraging the browser fingerprinting technique to enhance the overall security and usability of their authentication mechanisms [40]. The browser fingerprinting is usually integrated with existing authentication schemes, such as two-factor authentication (2FA) schemes [6]. On successful login, the web server captures and stores the browser fingerprint of the device that the user has used to login. Next time, when the user attempts to login to the same web service using the same device, the current browser fingerprint is matched against the stored fingerprints. If they match with a high score, the second-factor of 2FA process is dropped (i.e., no need to provide the PIN), merely typing in the password is sufficient to login. Thus, browser fingerprinting approach for authentication lowers the user-effort during the authentication process, and hence improves the system's usability.

**Fraud Detection:** Several security services, e.g., Seon [32] and IPQualityScore [7], are leveraging browser fingerprinting for the purpose of fraud detection and prevention in the online setting. The fraud detection techniques can be categorized into two groups – *supervised* and *unsupervised* methods [26]. The supervised method leverages the information from the prior fraud behavior (i.e., already marked as fraud) to build a model to infer if the current behavior is fraud or non-fraud. The unsupervised method does not rely on the prior fraudulent behavior, rather it sets a baseline for normal behavior. If the current behavior significantly deviates from the baseline behavior, the unsupervised method marked the behavior as fraudulent. The browser fingerprinting can be used to mark the user as a fraudster or a legitimate user. When any of these methods find the user's behavior fraudulent, the service provider captures and flags the browser fingerprint as fraudulent. Since the browser fingerprint against the flagged fingerprints. If the risk level is significantly high, the current user is flagged as a fraudster.

### 3 Attack Model & Spoofing Methods

### 3.1 Attack Model

Gummy Browsers consider a remote adversary who can spoof the victim's browser to a target remote web service. The main goal of Gummy Browsers is to fool the web server into believing that a legitimate user is accessing its services so that it can learn sensitive

Zengrui Liu, Prakash Shrestha, and Nitesh Saxena

8



Fig. 1: A high-level overview of the Gummy Browsers attack model.

information about the user (e.g., interests of the user based on the personalized ads), or circumvent various security schemes (e.g., authentication and fraud detection) that rely on the browser fingerprinting. A high-level overview of the attack is shown in Figure 1.

We assume that the attacker has obtained the browser fingerprint of the victim. The adversary can easily capture the victim's fingerprinting information by designing a benign-looking website and luring the victim into visiting his website. The adversary can leverage the exact mechanism as that of any fingerprinting website to acquire the browser fingerprint, i.e., via JavaScript APIs. It is also possible that a compromised web service, running a malicious script, could acquire the victim's browser fingerprint when the victim visits the attacker-owned website.

We also assume that before accessing a target web service, the attacker spoofs (or injects) previously acquired victim's browser information into his own fully controlled device to present it as the victim's device. When the attacker visits the target website, the target web server would receive the victim's fingerprint from the attacker's device. Therefore, for the target web service, it looks like the victim is accessing its services, and can not really recognize the malicious attacker.

We consider three different modes of executing the attack. An adversary can retrieve and spoof the victim's browser fingerprint only once, referred to *Acquire-Once-Spoof-Once*. *Acquire-Once-Spoof-Once* can be used to bypass the security of the user authentication scheme. Alternatively, to increase the impact of the attack, the attacker can spoof the same browser fingerprint instance multiple times over a few days gap, referred to *Acquire-Once-Spoof-Frequently*. Leveraging *Acquire-Once-Spoof-Frequently*, the attacker can track the personalized ads associated with the victim for a long period of time, and can infer various sensitive information about the user, even build a personal profile of the victim. Since the browser fingerprint changes over time, to increase the attack success rate, the attacker can also retrieve and spoof the browser fingerprint multiple times, and is referred to *Acquire-Frequently-Spoof-Frequently*. With this approach, the attacker could always obtain the latest browser fingerprint of the victim. This can enable the attacker to compromise the security of the fraud detection mechanism.

#### 3.2 Spoofing Methods

The key component of Gummy Browsers is the ability of the attacker to spoof the victim's browser fingerprint so that the attacker can present its own browser as if it is the victim's browser in front of the web service. Our spoofing methods are only focusing on the features which are listed in Table 1, and we did not spoof network level features like IP address. The attacker can leverage the following methods to spoof the fingerprint.

3.2.1 Script Injection In browser fingerprinting, when the browser loads a website, the website executes scripts consisting of various JavaScript API calls to extract the browser information. To spoof the browser fingerprint, the values extracted by the JavaScript API calls should be changed before the browser executes the scripts embedded in the website. The objects where these extracted values are stored can be overwritten by creating a new object with the same name and constructor as that of the original JavaScript APIs. To implement this method, a browser extension, a specialized and independent software module for customizing a web browser, and/or Selenium [18], a portable framework for testing web applications, can be utilized. The browser always loads and executes the website scripts in the browser extension prior to loading and executing it to the client machine. Those scripts would not change any scripts contents that are loaded from the visited websites. In the case of Selenium, pre-designed scripts are executed, which is followed by launching the browser, loading the website, and executing the embedded scripts. The feature of the browser extension and Selenium to execute the scripts prior to loading the website allows the adversary to overwrite the browser properties extracted through JavaScript API calls. An example is listed in Appendix C.

**3.2.2** Browser Setting and Debugging Tool Many of the browsers offer a mechanism in the form of the *browser setting* and the *debugging tool* that enables its users (the attacker in our case) to change various attributes of the client device and the browser. For instance, cookies, local storage and "do not track" options can be enabled or disabled simply through the browser setting in the Google Chrome browser [41] and the "about:config" page in the Firefox browser [5]. Further, about:config page in the Firefox browser allows the user to design his own APIs that can overwrite the browser's pre-defined APIs. This approach can completely change the browser's attributes.

The browser also offers a *debugging tool* intended for web application developers that allows them to debug and improve their web application functionality [4]. Using the debugging tool, various browser attributes, such as user-agent, geolocation, and caches disabled can be easily changed. The changes affect both the JavaScript API (e.g., navigator.userAgent) and the corresponding value in the HTTP header (e.g., the value of user-agent field). The debugging tool allows the changes on the browser's attributes to any custom value, whether it is a pre-defined valid string, or a random text.

**3.2.3** Script Modification The browser properties can also be changed by modifying the scripts embedded in the website. Once the embedded scripts have extracted the browser information, they can be changed before the website sends it to the web server. Utilizing the developer debugging tool (mentioned earlier), a breakpoint can be set at the beginning of each script of the website so that the scripts' execution gets paused at the set breakpoint. By inspecting the embedded scripts, the JavaScript API expression can be replaced with the spoofed values. For instance, platform = navigator.platform can be replaced with platform = "Win32" that exposes the underlying platform of the device as Win32, instead of the actual platform. However, each API expression should be changed very carefully as the use of an incorrect expression (i.e., its value and format) can alert the web service, and the changes can fail.

A more convenient method to spoof the browser information is to leverage the fact that JavaScript always uses *Ajax* (Asynchronous JavaScript And XML) to transfer the data to the remote server [33]. Since Ajax employs JSON (JavaScript Object Notation)

[13][14] format when transferring data to the web server, the browser information can be changed by checking the variable in the JSON object. Given that the debugging tool shows current variables and their values at each breakpoint, the values can be changed easily. Once the changes on the scripts are completed, the breakpoints are removed allowing the execution of the modified scripts. With this approach, the remote web service would receive the spoofed browser attributes. As the executed scripts are never sent outside the client machine, the approach remains oblivious to the remote web server.

Most websites or web services use JavaScript obfuscation on the scripts, instead of the native ones. The purpose of using obfuscation is to make the scripts difficult to understand. JavaScript Obfuscator Tool [3] is an example of such obfuscation methods. JavaScript obfuscation can indeed make script modification harder than native scripts. However, there are JavaScript deobfuscation methods that can help us to get native scripts. A previous study [39] and deobfuscation service [21] have proved that deobfuscation.

We have listed all spoofing approaches for each feature in Table 1. More details for spoofing all features are listed in Appendix A.

## 4 Attack Implementation

### 4.1 Acquiring User Browser Fingerprint

To impersonate as the victim in front of the target website, Gummy Browsers needs to acquire the device fingerprinting information from the victim's device. Gummy Browsers employ the following two methods to capture the victim's browser fingerprint.

With JavaScript: JavaScript provides a variety of APIs that can be utilized to extract the device information. The execution of these APIs does not require any permission from the users [45]. For instance, the API navigator.platform retrieves the details on the platform (e.g., MacIntel, Win32, Linux, etc.) of the device that the user is using. The cookieEnabled API tells if the browser has disabled cookies or not. These methods are exactly the same as deployed by the web service that uses browser fingerprinting. All these APIs are completely transparent to the user.

Without JavaScript: Some device fingerprinting attributes can also be extracted through methods other than JavaScript APIs. For instance, user-agent, supported languages and their order can be retrieved from the HTTP header [38], fonts can be extracted using Flash and CSS. Although JavaScript has navigator.userAgent API, the use of HTTP header is preferred to retrieve user-agent because the user can disable the JavaScript, thereby failing the retrieval of user-agent through JavaScript API. Fortunately, in such a situation, the HTTP header can still provide the user-agent attribute of the browser. For some of the attributes, such as the list of fonts in the device, JavaScript does not offer any APIs. Flash and CSS are used to list the available fonts in the device.

## 4.2 Visual Attack

We utilize the Panopticlick website [17] and the FingerprintJS demo website [9] to assess the effectiveness of various spoofing methods, referred to as the *visual attack*.

Attacking Panopticlick Site: Panopticlick provides a dashboard for displaying the browser information, which we leverage to assess our spoofing methods. Figure 7 in Appendix B presents a snapshot of the Panopticlick dashboard showing fingerprint information when a (victim) user uses a Firefox browser on a Windows machine, i.e., "Win+Firefox". By visually inspecting the information displayed on the dashboard, we validated if the spoofing methods succeed in injecting spoofed attributes. We use the browser setting and debugging tool to modify the following attributes – user-agent, HTTP accept header, cookie enabled, and local storage, used in Panopticlick. Specifically, we use the debugging tool to change the user-agent and the browser's setting option to change the language attribute found in HTTP accept header. We change the language category and its order in the Google Chrome browser to meet target languages combination. To modify the cookie enabled and local storage, we use corresponding options in the privacy setting of the Google Chrome browser. To change the remaining attributes used in Panonpticlick, either the script injection or the script modification approach is used. Due to the convenience of using script modification, we use this approach for the said purpose. Specifically, we change the attributes' value in the JSON file of the script such that the Panopticlick would receive the modified values.

Attacking FingerprintJS Site and Real-Life Fingerprint Service: We also successfully did the visual attack against FingerprintJS website and the Fingerprintjs pro service. We listed full details in Appendix B.

#### 4.3 Algorithm Attack: Attacking Prominent Fingerprinting Based Techniques

We emulate the attack against the browser fingerprinting algorithms by simply copying the entire fingerprint, referred to as the *algorithm attack*. To evaluate the performance of our algorithm attack, we employ three prominent browser fingerprinting algorithms – *Panopticlick, RLA, HLA* and launch the algorithm attack against them. We utilize the dataset from [50], referred to as the *original dataset*, to evaluate the performance of the algorithm attack. Details on the dataset are provided in Section 5.1. Each fingerprint in the dataset has following three timestamps: *created\_date, updated\_date* and *expired\_date*, which denote the timestamps when the fingerprint is created/recorded, updated, and expired, respectively. Utilizing the original dataset, various datasets are generated based on different collect frequency, referred to as the *benign dataset*.

In a real-world setting, an adversary can capture the victim's browser fingerprint at any point in time. Given this, we consider that the attacker can spoof any of the fingerprints in the original dataset. Therefore, we copy one fingerprint instance of the given user at a time, update the creation date and order, consider it as a spoofed fingerprint, and inject it back into the original dataset, forming the *attack dataset*. Such an injection of copied fingerprint simulates the scenario where an adversary acquires the victim's fingerprint, and then tries to impersonate the victim by spoofing the fingerprint. The fingerprinting algorithms are executed on the attack dataset to link together the browser fingerprints from the same user. The attack succeeds if the fingerprinting algorithm incorrectly marks the spoofed fingerprint as from the victim.

11

Since the browser fingerprint changes over time, the impact of the algorithm attack may vary based on the gap between the time when the fingerprint is acquired and the time when the attack is launched, referred to as *"time gap"*. In terms of the dataset, the time gap refers to the difference in the *created\_date* between two fingerprints from the same user. To measure the effectiveness of the time gap in our algorithm attack, we design and build nine different attacks based on nine different time gaps. The attack number and corresponding time gaps are presented in Table 2.

In the original dataset, each user has more than one fingerprint collected over a long period of time. To execute the aforementioned nine different attacks, we assume that the adversary captures the oldest of the fingerprints (the first one) of the user and spoofs after each of the 'n' days considered in nine different attacks, referred to as spoofed/copied fingerprint. Thus, we consider Acquire-Once-Spoof-Frequently setting for our nine attacks. The *created\_date* of the spoofed fingerprint is set as 'n' days after its original *created\_date*. Similarly, the *expired\_date* is set to 5 days after its value to "NULL". Although we employ Acquire-Once-Spoof-Frequently approach for all our attacks, the results are also applicable to Acquire-Once-Spoof-Once, where the fingerprint is spoofed only once. If the fingerprint is acquired frequently over a period of time, our attack would have a higher chance to succeed.

To evaluate our algorithm attack, we utilize the exact same code as that of FP-Stalker, which is made publicly available in the GitHub repository by its authors [50]. They have implemented all three algorithms, namely Panopticlick, RLA, and HLA, considered in our study, and can be found in their code repository. For each user in the dataset, we run these algorithms in two different settings -i) the benign setting without any spoofed fingerprints, and ii) the attack setting with nine different spoofed (or attack) fingerprints.

### 5 Dataset & Evaluation Methodology

#### 5.1 FP-Stalker Dataset

We use the FP-Stalker dataset [50] to evaluate the performance of Gummy Browsers against browser fingerprinting techniques. The authors of FP-Stalker designed and built two extensions, one for the Firefox browser and the other for the Chrome browser, and used the AmIUnique website to collect the browser fingerprints. Although they noted that their dataset consists of 98598 browser fingerprints from 1905 users collected over a period of two years in their paper, their public dataset contains only 15000 fingerprints collected from 1819 users. Each fingerprint in the dataset contains 40 variables. 38 of them correspond to browser fingerprinting attributes. The remaining two variables are "Counter" and "ID". The counter denotes the order of the fingerprint based on the created date of the fingerprint. ID uniquely represents an individual user, referred to as "original ID" in our analysis.

We observed that the fingerprints in the dataset have inconsistency, i.e., the fingerprints from the given user do not have consistent browser attributes, e.g., different operating systems, the newer fingerprint having older browser version/vendor than the older fingerprint. As such inconsistency in the dataset may impact the performance of the browser fingerprint algorithms as well as that of our attack, we removed all inconsistent fingerprints resulting in the dataset with the fingerprints from 275 users. Further, we remove the user having less than seven fingerprints, which is considered insufficient for the three fingerprint algorithms, dropping the user counts in the dataset from 275 to 239. This dataset is what we use to evaluate our attack.

**Collect frequency:** We sample the dataset using a configurable collect frequency similar to FP-Stalker. Collect frequency indicates how often a browser is fingerprinted. The lesser the fingerprinting frequency (or the higher collect frequency), the harder it would be to track the user. We use 11 different collect frequencies – 1, 2, 3, 4, 5, 6, 7, 8, 10, 15, and 20, in terms of days. To generate a dataset for a given collect frequency, we employ the approach as suggested in FP-Stalker. When a dataset is sampled using a collect frequency, the approach usually extends the dataset by copying (or replicating) the fingerprints at missing dates, therefore, we refer to it as the *expansion algorithm*. The expansion algorithm iterates in time with a step of collect frequency days and creates (or recovers) the browser fingerprint at each time step  $(t \pm f_c * i)$ , where t is the fingerprint creation date,  $f_c$  is collect frequency, and i is a natural number. The iteration continues until the expired date of the previous and the current fingerprint is reached. The process is repeated for each of the fingerprints collected from the given user. Thus, the expansion algorithm generates a new dataset with the fingerprints sampled at a consistent frequency of collect frequency days.

### 5.2 Evaluation Methodology

**5.2.1** Visual Attack We leverage the Panopticlick website and the FingerprintJS demo website and use various combinations of the terminal and the browser that the victim user may use to visually assess the spoofing methods. We employ a Mac laptop running macOS 10.14 Mojave, an Android phone running Android OS Pie 9.0, a Windows desktop running Windows 10 OS as the terminal, while we use Google Chrome, Mozilla Firefox, Microsoft Edge, and Tor as the browser. Using the Panopticlick website, we note all the fingerprinting features when using different terminal-browser combinations.

For the purpose of our evaluation, we consider that the attacker uses the Google Chrome browser on the Mac laptop, i.e., "Mac+Chrome" to launch the attack. We believe that this is a very standard setup, and the attacker can just use this setup to launch the spoofing attack. Since the user may use different combinations of the terminal and the browser to access the target website, we consider the browser fingerprint obtained from all the remaining combinations of the terminal and the browser as the victim's browser fingerprint. We spoof each of the victim's fingerprints on the attacker's Mac+Chrome setup using various spoofing methods detailed in Section 3.2. To validate if the spoofing methods have indeed succeeded or not, we compare the fingerprint shown on the attacker's browser after spoofing with the previously noted victim's fingerprint.

**5.2.2** Algorithm Attack Evaluation Scenarios: As mentioned earlier, to emulate our attack against the three fingerprinting algorithms, we insert nine spoofed fingerprints, each corresponding to our nine different attacks, to the original dataset. We inject the spoofed fingerprint after the latest fingerprint in the dataset that has the smaller (or same) created date as that of the spoofed fingerprint. As the counter in the dataset represents the order of the fingerprint based on its created date, when injecting the spoofed fingerprint,

the dataset is re-organized for the counter. Thus, after injecting all our nine spoofed fingerprints, the new dataset would contain 15009 fingerprints (the original dataset had 15000 fingerprints), with a different and corrected order in terms of the counter.

In our evaluation, we choose one user as a victim at a time and evaluate our attack against the three fingerprinting algorithms, i.e., nine spoofed fingerprints corresponding to the chosen user are injected into the original dataset generating the attack dataset. The attack dataset is then reverted back to the original dataset. We repeat the process for each user in the dataset, resulting in a total of 239 attacks (for 239 users).

FP-Stalker uses 40% of the total fingerprints as a training dataset and the remaining fingerprints as the testing dataset. The fingerprint dataset is extended leveraging the expansion algorithm (which is based on the collect frequency provided in FP-Stalker) resulting in a sufficiently large fingerprint dataset.

**Evaluation Metrics:** To evaluate the performance of fingerprinting algorithms in the benign setting (using benign dataset), we use true positive rate (TPR), whereas, to evaluate the performance of our attack against fingerprinting algorithms, we use false positive rate (FPR). TPR measures how often the legitimate fingerprints have been correctly identified as belonging to the correct user's device. FPR measures how often the spoofed fingerprints are incorrectly identified as belonging to the victim.

In our evaluation, since we consider the tracking of the user over a period of time, we compute TPR and FPR for each day separately. When computing TPR and FPR for a given day, we consider only the fingerprints from that particular day. We expect the TPR to be high, close to 1, which indicates the benign user is being tracked well even in the presence of the Gummy Browsers attack. We also expect FPR to be close to 1, which denotes the attack is highly successful.

### 6 Results

#### 6.1 Visual Attack Results

We have successfully spoofed all the fingerprinting information on Panopticlick and FingerprintJS website. The full details of spoofing results are listed in Appendix B.

#### 6.2 Algorithm Attack Results

**6.2.1 Benign Setting** To validate the implementation of the three algorithms (obtained from FP-Stalker repository), similar to FP-Stalker, we plot various graphs on the performance of these algorithms for tracking the users. Figure 2 shows the average tracking duration (and Appendix Figure 15 shows the average of *maximum* tracking duration) as a function of collect frequency for the three different fingerprinting algorithms. The tracking duration indicates the time duration (in terms of days) that the fingerprinting algorithm can track the user. The higher value of average tracking duration is considered good for user tracking. Figure 2 (and Appendix Figure 15) shows that the HLA outperforms Panopticlick and RLA at tracking the user, which is inline with the one reported in FP-Stalker. Further, we achieved similar results as those reported in FP-Stalker for each of the three fingerprinting algorithms.

Figure 3 shows the average ownership as a function of collect frequency. Ownership indicates how often the fingerprints were correctly associated with their actual users by



Fig. 2: Average tracking duration as a function of collect frequency for three different algorithms.



Fig. 3: Average ownership as a function of collect frequency for three fingerprinting algorithms.

the fingerprinting algorithms. The higher the ownership score, the better would be the performance of the fingerprinting algorithms. We achieved average ownership of above 0.95 for all the three fingerprinting algorithms, which is inline with that reported in FP-Stalker [50]. Appendix Figure 16 shows the number of new IDs assigned to each user as a function of collect frequency for three different fingerprinting algorithms. If the number of new IDs assigned to a user is '1', this means all his fingerprints have been identified as from the original user (the best result). If the number of new assigned IDs is larger than '1', say 'n', this means the user's fingerprints are still tracked correctly, but as 'n' separate tracking durations, which can be seen as from three different users. Although we used the exact same implementation of the three algorithms from FP-Stalker, we achieved slightly different results compared to those in FP-Stalker. We attribute this difference to the difference in the volume of our dataset (239 users) compared to that used in FP-Stalker (1905 users).

Figure 4a, 4b, and 4c show the performance of the tracking algorithms in the benign setting. Specifically, they show the TPRs as a function of tracking days (when the collect frequency was set as 1) for Panopticlick, RLA, and HLA, respectively. Like earlier, RLA and HLA perform better than Panopticlick.

**6.2.2 Attack Setting** To evaluate the performance of our attack and its impact on the tracking of legitimate users, we compute the average of TPRs and the average of FPRs over 239 attacks. Figure 5a, 5b, and 5c show the average TPRs as a function of tracking days in the attack setting for Panopticlick, RLA, and HLA, respectively, when collect frequency is set to 1. When comparing these TPRs with those in the benign setting, we see only a very minor difference in the TPR scores, potentially because of the addition of the spoofed fingerprints in the attack setting. This indicates that our attack does not have any significant impact on the performance of fingerprinting algorithms.

Similarly, Figure 6a, 6b and 6c show the average FPRs as a function of tracking days in the attack setting for Panopticlick, RLA, and HLA, respectively, when the collect frequency is set to 1. We achieved average FPRs of greater than 0.95, mostly close to 1.00, which indicates that most of the spoofed fingerprints were misrecognized as the

16 Zengrui Liu, Prakash Shrestha, and Nitesh Saxena



Fig. 4: True positive rate (TPR) as a function of tracking days in the benign setting when the collect frequency is set as 1.



Fig. 5: True positive rate (TPR) as a function of tracking days in the attack setting when the collect frequency is set as 1.



Fig. 6: False positive rate (FPR) as a function of tracking days in the attack setting when the collect frequency is set to 1.

legitimate ones. In other words, these results show that our attacks were highly successful in fooling the fingerprinting algorithms into believing the spoofed fingerprints as the legitimate fingerprints. We note that similar results were achieved in both the benign and attack settings when the collect frequency was set to values other than 1.

## 7 Implications of Our Attack

As the browser fingerprinting is processed at the backend (i.e., the remote server) of the website and no web services are claiming that they are using any browser fingerprinting approaches, we could not verify the actual impact of our attacks without inspecting the backend codes of the website. However, our results show that if they were to implement only fingerprinting techniques (without integration with any of the cookies, caches, or authentication mechanisms), our attack can have a significant impact on the user's privacy and security applications as described below.

**Compromising Ad Privacy**: A prior study [28] has shown that by simply monitoring the user's personalized ads, one can build the user's personal profile. In our attack, the attacker is successful at presenting his device to a target website as if it is the victim user's device through various spoofing methods. If the target website only uses browser fingerprinting to track the user and for personalized ads, the same or similar ads, or the ads from the same category would show up on the attacker's device. Given this, the

attacker may learn various sensitive information about the user, including his gender, age group, the potential location of the user, his habits, and many more. Further, the attacker can sell such user's information for the purpose of personal and financial gain. **Defeating User Authentication**: The purpose of browser fingerprinting in authentication is to remember the old device and enhance the security of traditional authentication methods such as passwords. For account login, since the attacker exposes his device as the victim's device in our attack, the target website will misrecognize the attacker as the victim who is using an old device, assuming that the attacker has obtained the victim's login credentials (i.e., the user's username and password). The authentication mechanisms only based on browser fingerprinting cannot block such an attack.

**Bypassing Fraud Detection**: Given the fact that many of the fraud detection techniques use browser fingerprinting information, the attacker can circumvent the detection by exposing his device as the victim's device leveraging various spoofing methods. Unless the victim user does not make any major big changes on his device (e.g., changing to a different operating system, downgrading system version, or replacing hardware) the attacker can impersonate the victim and bypass the detection. Generally, the attacker would be unaware of such big changes. However, the attacker can always pull the most recent browser fingerprint by simply fooling the user into visiting an attacker designed website. Given this, the fraud-detection algorithm cannot thwart our attack solely based on browser fingerprinting. It needs some additional metrics to detect fraud.

#### 8 Discussion

Potential Attack Detection: The web service may detect our attack if the adversary does not follow the correct data format, provides invalid data, or takes time longer than the set time limit. However, the attack can remain undetected if the adversary carefully provides the correct and valid spoofed data within the set time limit. To use the script injection approach, the attacker should use a valid value to replace the Javascript API values, e.g., in the Date() object, 'year' should be replaced with 'year' (not 'month'). When employing the script modification approach, the attacker has to use the correct data format in the return value, e.g., '2020-04-12' can be replaced with '2020-03-29', but not with '2020.04.12'. We note that the spoofed date should not be older than the current date. To detect our attack, the web service may periodically request a response from the website running in the client machine, e.g., request the current time for every 5 seconds. When modifying the script, the adversary needs to stop all the scripts on the website, and thus prevent the website from sending the response to the web service. When the web service does not receive the expected response from the client machine in a timely manner, it can detect the potential attack. However, the attacker can use a pre-designed script to overwrite the existing scripts in the targeted website. The use of such a pre-designed script automates the script modification process, thereby defeating the above detection approach.

**Limitations and Future Work**: Although the fingerprinting techniques, considered in our study, utilize many of the attributes, they exclude several attributes used in other fingerprinting algorithms, such as the ones related to network and protocols (e.g., TCP/IP stack fingerprinting [34], DNS resolver [37]), and the hardware sensors [28]

on the performance of our attack. The impact of these attributes on the performance of our attack has not been assessed in our study. Further investigation is needed to explore this direction. As noted earlier, the current dataset is insufficient to evaluate the performance of fingerprinting algorithms and that of our attacks after 130 tracking days. Further study with a larger dataset would be needed to assess the performance of our attack for a longer tracking period. Our study assumes that the attacker can fully spoof all browser information obtained from the victim's device. In some scenarios, the spoofed information may be outdated. In such a scenario, only partial browser information is correctly spoofed that may impact our attack. Future work would be needed to evaluate the impact of partial spoofing on the performance of our attack. Furthermore, an ethically-sound study of attacking personalized ads, authentication and fraud detection schemes that use fingerprinting in the real world via Gummy Browsers should be conducted in future work. Our spoofing methods (detailed in Section 4.2) can also be extended as an evasion technique that can obfuscate the true user's identity by creating and supplying a fake browser fingerprint to the visiting website. Similar to Gummy Browsers, the evasion can be oblivious to the target website. The impact of such evasion and subtle difference between Gummy Browsers and the evasion technique should be evaluated and discussed further in future work.

## 9 Conclusion

In this paper, we identified a novel and serious threat akin to the well-studied and popular notion of browser fingerprinting. Specifically, we showed that an attacker can make its own browser appear as the victim's browser by simply capturing (through an attackercontrolled or a malicious website) and mimicking the browser fingerprint (through script injection/modification or the leveraging browser's built-in settings and debugging tools). By exploiting this threat, we introduced and designed Gummy Browsers, an attack system that would enable a malicious entity to subvert any web application that uses browser fingerprinting, for example, to glean various sensitive information about the user in a targeted advertising application and to compromise the security of online defensive schemes, such as user authentication and fraud detection. We employed stateof-the-art browser fingerprinting techniques, Panopticlick and FP-Stalker, and evaluated the performance of Gummy Browsers against these algorithms. Our results showed that Gummy Browsers can successfully impersonate the victim's browser transparently almost all the time without affecting the tracking of legitimate users. Since acquiring and spoofing the browser characteristics is oblivious to both the user and the remote web-server, Gummy Browsers can be launched easily while remaining hard to detect. The impact of Gummy Browsers can be devastating and lasting on the online security and privacy of the users, especially given that browser-fingerprinting is starting to get widely adopted in the real world. In light of this attack, our work raises the question of whether browser fingerprinting is safe to deploy on a large scale.

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## Appendix

## A Examples of Applying Spoofing Methods

Below we describe how we spoof different attributes listed in Table 1.

**C1: Browser-provided Information:** To spoof user-agent (C1-1), cookie enabled (C1-5), and do not track (C1-12) attributes, we used all three spoofing approaches mentioned earlier. A separate script can also be designed to overwrite respective JavaScript APIs – navigator.userAgent, navigator.cookieEnabled and navigator.doNotTrack through script injection such that they return the spoofed value when they are invoked. We employ the following approach when using browser setting and debugging tool. In the Google Chrome browser, we set the user-agent through its debugging tool. In the Firefox browser, we set the user-agent in its about : config setting page. The cookie enable and do not track attribute can be easily spoofed by simply going through the browser setting. These three attributes can also be spoofed by changing their associated variables in the object being sent to the remote server, i.e. through script modification.

We utilize the script injection and script modification methods to spoof system time (C1-3), battery information (C1-4), Platform (C1-8), and resolution (C1-11). To spoof WebGL (C1-2) information, WebRTC characteristics (C1-6), password autofill feature (C1-7), and local storage (C1-10) attributes, we employ the script modification method. The remote server may verify the validity of WebRTC information based on the browser version and the operating system. Fortunately, these attributes can also be spoofed. For spoofing the language, we used the browser setting option.

**C2: Inference based on Device Behavior:** We used script modification approach to spoof all the attributes in this category, such as canvas information (C2-1), system performance (C2-2), font list (C2-3), scroll wheel related attributes (C2-4), and CSS feature (C2-5). Specifically, we changed the variables related to these attributes in the return object before sending it to the remote web server.

**C3: Extensions and Plugins:** For spoofing the plugins information (C3-1), we used the script injection and script modification methods. We overwrite the JavaScript navigator.plugins API to modify the plugins attributes with the spoofed values. We also changed the related variable in the server's return object for spoofing. We used script modification approach to spoof the browser extension related attributes (C3-2). The website script can inspect if an extension has been installed in the browser. If the ads field in the website is replaced or deleted, it shows that the browser may have the extension to block the ads. We used script modification to change these results.

## **B** Visual Attack and Results

#### **B.1** Visual Attack

We have introduced the visual attack against Panopticlick site. In this section, we will describe how we attack FingerprintJS site and a real-life fingerprint service.

Attacking FingerprintJS Site: Unlike the Panopticlick website, the FingerprintJS pro service website does not show all the fingerprint features, but it provides the user's

browsing history which can help to prove that our spoofing is successful. We use the browser setting and debugging tool to spoof the user-agent and languages, and use the script modification approach to spoof other features collected by the FingerprintJS website. Figure 12 in Appendix B presents a snapshot of the FingerprintJS dashboard showing fingerprint information when a user uses the Google Chrome browser on a Windows machine, i.e., "Win+Chrome". Since we were not sure if all values in the return object (e.g., 'rid', 'cv', 'url', etc) are used to construct the unique ID at the FingerprintJS remote server, we spoofed all the variables extracted from the browser.

Attacking Real-Life Fingerprinting Service: Attacking a real-world fingerprinting based service can test the strength of our spoofing attack. Although FingerprintJS pro service did not provide all the fingerprint features they used in their service on the result page, FingerprintJS pro service website has the open source code [10] which can output all the fingerprint features in browser console. We deployed this open source script on our own server without making any changes and called this website Testing Site, then used Script Injection and Script Modification to do the attack. We did not combine those two methods together. Each attack method can be seen as an independent attack. In Script Injection, we used selenium to change all the fingerprint features that are used in the FingerprintJS open source code except fonts, and then visit the *Testing Site*. We changed supported fonts in the operating system language setting. In Script Modification, we first set break point at the beginning of the Testing Site. This break point is set in the browser debugging tool, not the server. Then we spoofed all the values in the return value in the script main function, as those values are all fingerprint feature values and haslied detection values. haslied detection functions include hasLiedLanguagesKey, hasLiedResolutionKey, hasLiedOsKey and hasLiedBrowserKey. hasLiedLanguagesKey checks the consistency of values in two APIs "navigator.languages" and "navigator.language". hasLiedResolutionKey compares if value of APIs "window.screen.width" is less than "window.screen.availWidth", or "window.screen.height" is less than "window.screen.availHeight". hasLiedOsKey detects if the operating system value in APIs "navigator.userAgent", "navigator.oscpu" or "navigator.platform" are spoofed. hasLiedBrowserKey extracts value in APIs "navigator.userAgent" and "navigator.productSub" to find the spoofed browser features. This experiment demonstrates that we can effective execute the spoofing attack against any real-life service that deploys this FingerprintJS open source code.

### **B.2** Result

**Result:** Attacking Panopticlick Site: Figure 8 shows a snapshot of the *actual* device information shown by the Panopticlick website when using the *Mac+Chrome* setting. To spoof the fingerprint of the victim's device, i.e., *Win+Firefox*, (as shown in Figure 7), we employed the three methods discussed earlier in Section 3.2 such that *Mac+Chrome* (i.e., the attacker's device) appears as *Win+Firefox* (i.e., the victim's device). After spoofing using *Mac+Chrome*, the Panopticlick website shows the browser information as depicted in Figure 10, which is exactly the same as that when using *Win+Firefox* (i.e., the victim's device). This indicates that our spoofing methods were successful in replicating the victim's browser fingerprint. We were even able to spoof the Google Chrome browser on the Android phone, the *Android+Chrome* setting, and the Tor browser on

the Mac laptop, the *Mac+Tor* setting, using Mac+Chrome. Figure 9 and Figure 11 show the snapshots of spoofing *Android+Chrome* and *Mac+Tor* using *Mac+Chrome*, respectively. We achieved similar results when spoofing the device information obtained from various other terminal-browser combinations using the *Mac+Chrome* setting. This indicates that our spoofing methods succeeded to spoof all the fingerprinting information, regardless of the victim's terminal-browser combination.

**Result:** Attacking FingerprintJS Site: Figure 13 and Figure 12 present the snapshots of original device information corresponding to the attacker and the victim, respectively, when they visit the *FingerprintJS* website. Figure 14 shows the snapshot of the attacker's device information when he has spoofed the victim's device information. As can be seen from the figure, we could check the victim's browsing history after spoofing.

**Result:** Attacking Real-Life Fingeprinting Services: In attacking *Testing site* that deployed the FingerprintJS open source code, our two attack methods *Script Injection* and *Script Modification* all successfully spoofed all the 29 fingerprinting features listed in the script, and passed four *haslied* detection functions which are used to detect if the current visit used spoofed fingerprinting features or not. We picked the *Windows-Firefox* as the victim device operating system and browser setting, and used *Mac-Chrome* as the attacker device.

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Browser Characteristic	bits of identifying information	one in <i>x</i> browsers have this value	value
User Agent	3.95	15.45	Mozilla/5.0 (Windows NT 10.0; Win64; x64; rv:75.0) Gecko/20100101 Firefox/75.0
HTTP_ACCEPT Headers	1.82	3.54	text/html, */*; q=0.01 gzip, deflate, br en-US,en;q=0. 5
Browser Plugin Details	0.88	1.84	undefined
Time Zone Offset	4.63	24.83	300
Time Zone	4.87	29.18	America/Chicago
Screen Size and Color Depth	5.55	46.75	1600x900x24
System Fonts	4.31	19.87	Arial, Arial Black, Arial Narrow, Arial Rounded MT B old, Book Antiqua, Bookman Old Style, Calibri, Ca mbria, Cambria Math, Century, Century Gothic, Cen tury Schoolbook, Comic Sans MS, Consolas, Couri er, Courier New, Georgia, Helvetica, Impact, Lucida Bright, Lucida Calligraphy, Lucida Console, Lucida Fax, Lucida Handwriting, Lucida Sans, Lucida Sans Typewriter, Lucida Sans Unicode, Microsoft Sans S erif, Monotype Corsiva, MS Gothic, MS Outlook, M S PGothic, MS Reference Sans Serif, MS Sans Ser if, MS Serif, Palatino Linotype, Segoe Print, Segoe Script, Segoe UI, Segoe UI Light, Segoe UI Semibo Id, Segoe UI Symbol, Tahoma, Times, Times New R oman, Trebuchet MS, Verdana, Wingdings, Wingdin gs 2, Wingdings 3 (via javascript)
Are Cookies Enabled?	0.2	1.15	Yes
Limited supercookie test	1.12	2.18	DOM localStorage: Yes, DOM sessionStorage: Yes, IE userData: No, openDatabase: false, indexed db: true
Hash of canvas fingerprint	2.92	7.56	randomized by first party domain
Hash of WebGL fingerprint	7.15	141.72	844e8424d47a59e2c091b48df30815b0
WebGL Vendor & Renderer	5.49	44.89	Google Inc.~ANGLE (Intel(R) UHD Graphics 620 Di rect3D11 vs_5_0 ps_5_0)
DNT Header Enabled?	1.04	2.05	False
Language	0.93	1.91	en-US
Platform	1.19	2.28	Win32
Touch Support	5.05	33.18	Max touchpoints: 10; TouchEvent supported: false; onTouchStart supported: false
Ad Blocker Used	0.37	1.29	False

Fig. 7: Victim User: The original features of combination "Win+Firefox". Testing website: **Panop-ticlick** 

25

Browser Characteristic	bits of identifying information	one in x browsers have this value	value	
User Agent	10.8	1779.88	Mozilla/5.0 (Macintosh; Intel Mac OS X 10_14_6) AppleWebKit/537.36 (KH TML, like Gecko) Chrome/81.0.4044.129 Safari/537.36	
HTTP_ACCEPT Headers	2.8	6.97	text/html, */*; q=0.01 gzip, deflate, br en-US,en;q=0.9	
Browser Plugin Details	3.01	8.04	Plugin 0: Chrome PDF Plugin; Portable Document Format; internal-pdf-v wer; (Portable Document Format; application/x-google-chrome-pdf; pdf). ugin 1: Chrome PDF Vewer; "Internal-mach-plugin; (Native Client Executable; application/x-nact); (Portable Native Client Executable; appli ation/x-pnact).	
Time Zone Offset	4.63	24.82	300	
Time Zone	4.87	29.16	America/Chicago	
Screen Size and Color Depth	4.62	24.58	1440x900x24	
System Fonts	10.96	1994.13	Andale Mono, Arial, Arial Black, Arial Hebrew, Arial Narrow, Arial Rounded MT Bold, Arial Unicode MS, Bookman Old Style, Comic Sans MS, Courier Courier New, Geneva, Georgia, Helvelica, Helvelica Reue, Impact, LUCIC A GRANDE, Microsoft Sans Serif, Monaso, Palatino, Tahoma, Times, Tim s New Roman, Trebuchet MS, Verdana, Wingdings, Wingdings 2, Wingdin g S (via javascript)	
Are Cookies Enabled?	0.2	1.15	Yes	
Limited supercookie test	1.55	2.93	DOM localStorage: Yes, DOM sessionStorage: Yes, IE userData: No, oper Database: true, indexed db: true	
Hash of canvas fingerprint	11.65	3214.42	945768992f0d7bc5d40996011f15bf31	
Hash of WebGL fingerprint	8.94	492.83	66d6cd5d05008e9711a66a97c80124af	
WebGL Vendor & Renderer	7.58	190.93	Intel Inc.~Intel Iris Pro OpenGL Engine	
DNT Header Enabled?	1.04	2.05	False	
Language	0.93	1.91	en-US	
Platform	3.23	9.38	MacIntel	
Touch Support	0.64	1.56	Max touchpoints: 0; TouchEvent supported: false; onTouchStart supported false	
Ad Blocker Used	0.37	1.29	False	

Fig. 8: Attacker (before the attack): The original features of combination "Mac+Chrome". Testing website: **Panopticlick** 

Browser Characteristic	bits of identifying information	one in x browsers have this value	value
User Agent	16.19	74796.67	Mozilla/5.0 (Linux; Android 10; SM-G975U1) AppleWebKit/537.3 6 (KHTML, like Gecko) Chrome/80.0.3987.87 Mobile Safari/537. 36
HTTP_ACCEPT Headers	3.08	8.45	text/html, */*; q=0.01 gzip, deflate, br en-US,en;q=0.9
Browser Plugin Details	0.88	1.84	undefined
Time Zone	4.37	20.65	360
Screen Size and Color Depth	7.98	253.26	412x869x24
System Fonts	3.69	12.93	Arial, Courier, Courier New, Georgia, Helvetica, Monaco, Palatir o, Tahoma, Times, Times New Roman, Verdana, Wingdings 2, V ingdings 3 (via javascript)
Are Cookies Enabled?	0.21	1.16	Yes
Limited supercookie test	0.32	1.25	DOM localStorage: Yes, DOM sessionStorage: Yes, IE userData No
Hash of canvas fingerprint	8.37	330.47	b7d30324f15998955383d20d0dafae27
Hash of WebGL fingerprint	9.96	992.88	41ace8e36310ab0278ec495bdafcc173
DNT Header Enabled?	1.1	2.15	False
Language	0.93	1.91	en-US
Platform	4.16	17.92	Linux armv8l
Touch Support	2.79	6.91	Max touchpoints: 5; TouchEvent supported: true; onTouchStart : upported: true

Fig. 9: Attacker (after the attack): The spoofed features of combination "Android+Chrome". Testing website: **Panopticlick** 

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Browser Characteristic	bits of identifying information	one in x browsers have this value	value
User Agent	3.95	15.44	Mozilla/5.0 (Windows NT 10.0; Win64; x64; rv:75.0) Gecko/20100101 Fire ox/75.0
HTTP_ACCEPT Headers	2.8	6.96	text/html, */*; q=0.01 gzip, deflate, br en-US,en;q=0.9
Browser Plugin Details	0.88	1.84	undefined
Time Zone Offset	4.63	24.82	300
Time Zone	4.87	29.16	America/Chicago
Screen Size and Color Depth	5.55	46.74	1600x900x24
System Fonts	4.31	19.87	Arial, Anial Biack, Arial Narrow, Arial Rounded MT Bold, Book Antiqua, Bo- kman Old Slyke, Calibri, Cambria, Cambria Math, Century, Century Gothio Century Schoolbook, Comic Sans MS, Consolas, Courier, Cever, Gorgia, Holveiton, Impact, Lucida Bright, Lucida Calibrgraphy, Lucida Conso e, Lucida Fast, Lucida Handwriting, Lucida Sans, Lucida Sans Typewriter, Lucida Sans Unicode, Microsoft Sans Serif, Monotype Orativa, MS Gothic, MS Outlook, MS PGothic, MS Reference Sans Serif, MS Sans Serif, MS erif, Palatino Linotype, Segoe Print, Segoe Script, Segoe UJ, Segoe UJ, Segoe UJ, Segoe JD, Segoe Script, Segoe US, Segoe N, Segoe N, Segoe N, Segoe Shan, Times, Times New Rc man, Trebuchet MS, Verdana, Wingdings X, Wingdings 2, Wingdings 3 (via avacript)
Are Cookies Enabled?	0.2	1.15	Yes
Limited supercookie test	1.12	2.18	DOM localStorage: Yes, DOM sessionStorage: Yes, IE userData: No, oper Database: false, indexed db: true
Hash of canvas fingerprint	2.92	7.56	randomized by first party domain
Hash of WebGL fingerprint	7.15	141.66	844e8424d47a59e2c091b48df30815b0
WebGL Vendor & Renderer	5.49	44.86	Google Inc.~ANGLE (Intel(R) UHD Graphics 620 Direct3D11 vs_5_0 ps_5 _0)
DNT Header Enabled?	1.04	2.05	False
Language	0.93	1.91	en-US
Platform	1.19	2.28	Win32
Touch Support	5.05	33.16	Max touchpoints: 10; TouchEvent supported: false; onTouchStart supported d: false
Ad Blocker Used	0.37	1.29	False

Fig. 10: Attacker (after the attack): The spoofed features of combination "Win+Firefox". Testing website: **Panopticlick** 

Browser Characteristic	bits of identifying information	one in <i>x</i> browsers have this value	value
User Agent	2.62	6.16	Mozilla/5.0 (Windows NT 10.0; rv:68.0) Gecko/20100101 Firefox/6 8.0
HTTP_ACCEPT Headers	3.08	8.45	text/html, */*; q=0.01 gzip, deflate, br en-US,en;q=0.9
Browser Plugin Details	0.88	1.84	undefined
Time Zone	2.28	4.84	0
Screen Size and Color Depth	7.56	188.37	1000x700x24
System Fonts	7.49	179.76	Arial, Courier, Geneva, Georgia, Helvetica, Helvetica Neue, LUCID A GRANDE, Monaco, Tahoma, Times, Times New Roman, Verdan a, Wingdings 2, Wingdings 3 (via javascript)
Are Cookies Enabled?	0.21	1.16	Yes
Limited supercookie test	0.32	1.25	DOM localStorage: Yes, DOM sessionStorage: Yes, IE userData: N o
Hash of canvas fingerprint	2.83	7.09	a273d6a847f0e2a57fa0161158f12fed
Hash of WebGL fingerprint	6.56	94.62	2ef68bcd75e09a41aea04bae556f3ecc
DNT Header Enabled?	1.1	2.15	False
Language	0.93	1.91	en-US
Platform	3.19	9.14	MacIntel
Touch Support	0.74	1.67	Max touchpoints: 0; TouchEvent supported: false; onTouchStart su pported: false

Fig. 11: Attacker (after the attack): The spoofed features of combination "Mac+Tor". Testing website: **Panopticlick** 



Fig. 12: Victim User: The original features of combination "Win+Chrome". Testing website: FingerprintJS

## Your ID: t60c5CYrmolFUz7JmnoU



Fig. 13: Attacker (before the attack): The original features of combination "Mac+Chrome". Testing website: **FingerprintJS** 



Fig. 14: Attacker (after the attack): The spoofed features of combination "Win+Chrome", showed in Google Chrome of combination "Mac+Chrome". Testing website: **FingerprintJS** 

## C Example of Script Injection

An example script to overwrite the platform information acquired through navigator.platform API [2] is presented below.

In the example script above, a new object navigator.platform is defined with the value "my platform". The object is then injected at the start of all the scripts extracted from the target website. Given this, when the script calls the navigator.platform API, it receives the spoofed value, i.e., "my platform", because the original API object has been overwritten by the injected object.

Thus, when using such codes (added as a browser extension or ran in Selenium), the remote web server would always receive the spoofed values added by the injected



Fig. 15: Average of maximum tracking duration (in terms of days) as a function of collect frequency for three different browser fingerprinting techniques.



Fig. 16: Average number of IDs assigned per user as a function of collect frequency for the three different fingerprinting algorithms.

codes. In theory, any of the Javascript APIs can be self-designed and/or overwritten. However, the getOwnPropertyDescriptor API can be used to detect if any specific property exists in a web object or property. This API returns "undefined" if a property, say navigator.platform, has not been defined or overwritten. It returns an object if the property exists and has been overwritten. Fortunately, we can also overwrite the getOwnPropertyDescriptor API itself such that it always returns "undefined", indicating there has not been any manipulation on the object. Therefore, any detection mechanism solely based on JavaScript would not work on script injection and modification. Thus, our spoofing method is hard to detect as noted in Table 1. As this method pre-changed the API values, attacks using this method can be finished automatically.

## D Performance Comparison of FP-Stalker Implementation

Figure 15b and Figure 16b show the average of maximum tracking duration and the average number of IDs assigned per user as a function of collect frequency for three different browser fingerprinting techniques, respectively.