PriVaricator: Deceiving Fingerprinters with Little White Lies

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ABSTRACT

Researchers have shown that, in recent years, unwanted web tracking is on the rise, with browser-based fingerprinting being adopted by more and more websites as a viable alternative to third-party cookies.

In this paper we propose PriVaricator, a solution to the problem of browser-based fingerprinting. A key insight is that when it comes to web tracking, the real problem with fingerprinting is not *uniqueness* of a fingerprint, it is *linkability*, i.e., the ability to connect the same fingerprint across multiple visits. Thus, making fingerprints non-deterministic also makes them hard to link across browsing sessions. In PriVaricator we use the power of randomization to "break" linkability by exploring a space of parameterized randomization policies. We evaluate our techniques in terms of being able to prevent fingerprinting and not breaking existing (benign) sites. The best of our randomization policies renders *all* the fingerprinters we tested ineffective, while causing minimal damage on a set of 1,000 Alexa sites on which we tested, with no noticeable performance overhead.

Categories and Subject Descriptors

K.6.5 [**Security and Protection (D.4.6, K.4.2)**]: Invasive software

Keywords

tracking; fingerprinting; randomization

1. INTRODUCTION

Browser-based fingerprinting, proposed as a theoretical threat to online privacy several years ago, has emerged as a full-fledged alternative to traditional cookie-based tracking. Recent work has demonstrated the growing proliferation of JavaScript-based fingerprinting on the web [2, 20]. Today, companies such as BlueCava [7], ThreatMetrix [23] and iovation [15] routinely fingerprint millions of web users. However, despite several attempts, mostly involving privacy-enhancing browser extensions, there has been a dearth of comprehensive privacy-enhancing technologies addressing in-browser fingerprinting. In this paper, we propose a comprehensive approach to prevent reliable fingerprinting in the browser, called PriVaricator.

Key insight: Much has been made of the fact that it is possible to derive a unique fingerprint of a user, primarily via JavaScript as shown by the Panopticlick project [12]. The main insight behind PriVaricator is the realization that the culprit behind fingerprinting is not the fact that a user's fingerprint is *unique*, but that it is *linkable*, *i.e.*, it can be reliably associated with the same user over multiple visits. While popular prevention techniques have attempted to make the fingerprints of large groups of users look *the same* [24], the key insight our paper explores involves doing the *opposite*. PriVaricator modifies the browser to make every visit appear different to a fingerprinting site, resulting in a *different* fingerprint that cannot be easily linked to a fingerprint from another visit, thus frustrating tracking attempts.

Randomization policies: In this paper we explore a space of *randomization policies* designed to produce unique fingerprints. The basis of our approach is to change the way the browser represents certain important properties, such as `offsetHeight` (used to measure the presence of fonts) and plugins, to the JavaScript environment. We observe that creatively misrepresenting — or lying — about these values introduces an element of non-determinism, which generally makes fingerprints unlinkable over visits.

Note that the randomization is not as easy as it might sound: as discussed by Nikiforakis et al. [20], producing practically impossible combinations of, say, browser headers and the `navigator` object, can actually *reduce* user privacy. Intuitively, blatant lying is *not* such a good idea, since it can significantly degrade the user experience by, for instance, presenting Firefox-optimized sites to users of IE, leading to visual discrepancies or calls into missing APIs. However, *subtly* misrepresenting key properties of the browser environment goes a long way towards combating fingerprinters. In summary, a randomization policy should 1) produce unlinkable fingerprints and 2) not break existing sites.

Practical focus: In this paper we concentrate our attention on randomizing plugins and fonts, as these dominate in the current generation of fingerprinters (Table 1). We, however, consider the approach presented here to be fully extendable to other fingerprinting vectors if that becomes necessary. Since today's browsers update themselves as frequently as once a week, the list of randomization policies can

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be expanded over time if needed. The issue of extensibility over time is discussed in Section 6.

Deployment: We have implemented PriVaricator on top of the Chromium web browser. We position PriVaricator as an enhancement to the private browsing mode already present in the majority of browsers. Existing private modes help prevent stateful tracking via cookies; PriVaricator focuses on preventing stateless tracking. We believe that it is better to integrate PriVaricator into the browser itself as opposed to providing it via an extension. One of the reasons for this, is the fact that most privacy extensions so far have only enjoyed a small deployment base, which in fact often makes it *easier* for the fingerprinter to identify the user [20].

Evaluation: We discovered that a number of our policies are able to render the fingerprinters we tested ineffective, while creating minimal damage to benign sites. In particular, the best of our policies renders *all* the fingerprinters we tested on ineffective, while only altering the visual appearance of, on average, 0.7% of the content offered by the top 1,000 Alexa sites. Using three JavaScript benchmark suites, we show that the modifications needed to implement PriVaricator on top of the Chromium browser cause a negligible performance overhead.

The reader may improve their intuition by watching two short "before/after" demo videos that show how PriVaricator helps against BlueCava, one of the most widely used fingerprinting services. In the first video BlueCava fingerprints a "vanilla" browser (`https://vimeo.com/95340734`). In the second video, BlueCava is failing to fingerprint against PriVaricator (`https://vimeo.com/95366100`).

2. BACKGROUND

Recent studies have discovered that fingerprinting is emerging as a real alternative to traditional cookie-based tracking [1, 2, 20]. A device *fingerprint* is a set of system attributes that are usually combined in the form of a string. This combination of attributes is generally designed to be unique with a high likelihood and, as such, can function as a device identifier. Attributes that range over a broader set of values (*e.g.*, the list of fonts and plugins) are more identifying than values shared by many devices (*e.g.*, version of the operating system). Stability is a desirable property in a fingerprinting strategy; choosing attributes with values that are more stable over time (*i.e.*, that change only infrequently or very gradually) facilitate reliable identification, compared to those that change frequently and unpredictably.

Web-based device fingerprinting is the process of collecting sufficient information through the browser to perform stateless device identification. The collected information is generally obtained via JavaScript and includes the device's screen size, the versions of installed browser plugins, and the list of installed fonts. Figure 1 shows how modern fingerprinters can use the differences in the sizes of strings rendered with different fonts to collect a user's list of fonts, bypassing the need of explicit font-providing APIs. Due to space limitations, we refer the interested reader to some of our previous work [20] for a more thorough explanation of the font-detecting capabilities of modern fingerprinters.

2.1 Why Fingerprint?

When it comes to the motivation behind web-based device fingerprinting, two reasons have emerged as most common.

```
function getFonts(){
    /* Long list of fonts */
    var fonts = ["cursive","monospace","serif","sans-
         serif","fantasy","Arial","Arial Black","Arial
          Narrow",...]

    /* Measuring ground truth */
    var ground_truth = getFontMeasurement("sans");
    var discovered_fonts = []

    /* Testing for each font family */
    for(var i=0; i < fonts.length; i++){
        c_measurement = getFontMeasurement(fonts[i]);
        if (c_measurement[0] != ground_truth[0] ||
            c_measurement[1] != ground_truth[1]){
            discovered_fonts.push(fonts[i]);
        }
    }
    return discovered_fonts;
}
```

Figure 1: Font detection through JavaScript

Third-party tracking: Probably the most common use of fingerprinting involves tracking the user across multiple, possibly unrelated, web sites to construct an interest profile for the user; this profile can then be employed to deliver targeted ads. As has been argued before, fingerprinting is an effective and stealthy alternative to stateful cookie-based user tracking. In a sense, the better fingerprinting works, the more information is learned about the user with a higher degree of reliability, leading to better ad targeting and thus to higher conversion rates for the advertisers. This creates a direct incentive for ad delivery networks to invest in better fingerprinting strategies, especially given that fingerprinters might not necessarily obey browser-provided Do-Not-Track (DNT) headers [2].

Fraud prevention: Third-party tracking, an activity that has provoked much outrage on the part of both privacy advocates and some users, is not the only motivation behind fingerprinting. It is sometimes argued that fingerprints can be used for fraud prevention. We refer the interested reader to some of the literature from the fingerprinting companies themselves [15, 22, 23] for further details. We should note that it is not obvious that collected fingerprints cannot be also sold to third parties or abused for tracking purposes by the companies that collect them.

In connection to fraud prevention, advocates of fingerprinting claim that a device fingerprint is a powerful tool for finding related transactions either as an identifier in itself or as a means of finding transactions with related characteristics. Fingerprints also can be used to find out when accounts are being illegally shared by more than one persons. The gathered fingerprints can be augmented with device reputation information and be used to blacklist fraudulent users and their activities.

Opt-out: While some of the aforementioned fingerprinting companies offer opt-out pages for the user, it is highly non-obvious what a successful opt-out really means. Ironically, to know that a user has opted-out of tracking, the fingerprinters still first need to compute the fingerprint (assuming cookies are disabled) and then, if they are honest, proceed to disregard information from that session.

Compared to stopping stateful tracking that can be achieved at the client-side, via disabling or clearing cookies, and the help of many extensions, this server-side approach to opt-

Fingerprinting provider	Script name	Plugin enumeration	Screen properties	Uses canvas	Access to offsetWidth	Access to offsetHeight
BlueCava	`BCAC5.js`	✓	✓	✗	63	63
Perferencement	`tagv22.pkmin.js`	✓	✓	✗	155	155
CoinBase	`application-9a3a[...].js`	✓	✓	✗	592	197
MaxMind	`device.js`	✓	✓	✗	261	27
Inside graphs	`ig.js`	✓	✓	✗	1,050	48

Table 1: Techniques used by various fingerprinters in the wild.

ing out is not satisfying because, ultimately, the user needs to trust the fingerprinting server. With PriVaricator, *reliable* fingerprinting is rendered impossible in the first place.

3. OVERVIEW

At the heart of PriVaricator is a strategy for misrepresenting the way parts of the browser environment are presented to the JavaScript language runtime. Previous studies of fingerprinters in the wild [2] have identified certain parts of the browser environment reflected into JavaScript as key to producing a reliable fingerprint. These properties range from common ones such as `navigator.userAgent` to ones that are significantly more obscure such as `getBoundingClientRect` which may be used to test for the presence of particular fonts on a user's machine, instead of the `offsetHeight` and `offsetWidth` attributes of DOM elements. Of course, our wish is to misrepresent environment properties of features that would be most damaging to fingerprinters without breaking existing code. As such, lying about `navigator.userAgent` is generally not a good idea: this may very well cause the server to send HTML code designed for a different browser. However, subtly changing the results of offset measurements turns out to be a better option.

Table 1 lists some of the representative fingerprinters found in the wild, showing which fingerprinting features they use [2]. While none of these fingerprinting companies employ canvas-based fingerprinting, as described in [18], concurrent work by Acar et al. [1] showed that other tracking companies have started making use of it. Even though our current prototype of PriVaricator does not address canvas-based fingerprinting, it is straightforward to add support for it, as further elaborated in Section 6.

Based on this information, combined with statistics about which features provide the highest number of bits of identifying information, in this paper, we primarily focus on randomizing 1) plugins and 2) fonts. Each of these provide more than 21 bits of identifying information, according to Panopticlick [12].

3.1 Randomization Policies

Our strategy in PriVaricator is to intercept each of the accesses to DOM properties of interest and augment the values returned to the JavaScript environment using a set of *randomization policies*. A wide range of randomization policies may apply in principle; for example, for integer values of properties such as `offsetWidth`, a slight change to the returned value is enough. For a property that is more structural and complex, such as the `toDataURL` function used in canvas-based fingerprinting that returns the current state of the canvas as an image [18], a different randomization policy may be used; an example policy for images may add slight visual *noise* to the returned image.

Policies for offset measurements: For the values of `offsetHeight`, `offsetWidth`, and `getBoundingClientRect` in PriVaricator, we propose the following randomization policies: a) Zero; b) Random(0..100); and c) ± 5% Noise. When these policies are active, instead of returning the original offset value, they return zero, a random number between 0 and 100, and the original number ±5% noise, respectively. What these policies have in common is that they perform arithmetic operations on numbers with deterministic and non-deterministic results. While one can probably envision many more randomization policies, we focused on those that generate plausible offset values (e.g. no generation of negative numbers) as well as those that will create enough noise to confuse fingerprinting efforts. For instance, for the third policy, if the percentage of noise added to an offset is too little, then, for small offset values, it may be rounded off to the same original integer value and become ineffective.

These policies are controlled by a *lying threshold* (denoted as θ) and a *lying probability* (denoted as $P(lie)$). θ controls how fast PriVaricator starts lying, *i.e.*, after how many accesses to `offsetWidth` or `offsetHeight` values, will the policy kick in. $P(lie)$ specifies the probability of lying, *after* the θ threshold has been surpassed.

Policies for plugins: For the randomization of plugins, we define a probability $P(plug\_hide)$ as the probability of hiding each individual entry in the plugin list of a browser, whenever the `navigator.plugins` list is populated.

Example: As an example, a configuration of

$$\begin{aligned} \mathsf{Rand\_Policy} &= \mathsf{Zero}, \\ \theta &= 50, \\ P(lie) &= 20\%, \\ P(plug\_hide) &= 30\% \end{aligned}$$

instructs PriVaricator to start lying after 50 offset accesses, to only lie in 20% of the cases, to respond with the value 0 when lying, and to hide approximately 30% of the browser's plugins. In Section 5 we investigate which combinations of values provide the best tradeoff between the production of unlinkable fingerprints and the breakage of benign websites.

3.2 Breakage Concerns

Building an effective fingerprinting prevention tool involves balancing the effectiveness of preventing fingerprinters and breaking real sites. To better understand the latter, we crawled the top 10,000 Alexa sites to determine which ones use properties that are of interest to fingerprinters.

Access to property `offsetHeight` tends to be pretty telling. Overall, 82.3% of scripts have 0 accesses to `offsetHeight`. However, 1.87% of scripts have more than 50 accesses when visited at runtime. We summarize the results of our crawl in Table 2, sorted by the number of runtime accesses to `offsetHeight`. Fortunately, the majority of sites seem to be ranked not very high. However, some of the sites listed,

Alexa Rank	Domain	*Screen* colorDepth	height	pixelDepth	width	*Navigator* mimeType	platform	language	userAgent	appName	vendor	appCodeName	appVersion	plugins	*HTML element* getBounding-ClientRect	offsetWidth	offsetHeight
6,444	`bunte.de`	0	1	0	1	0	0	2	8	0	0	0	0	1	2	205,115	202,909
8,039	`nzz.ch`	3	34	1	34	4	4	4	176	5	0	0	5	4	248	187,881	187,349
191	`spiegel.de`	2	4	0	4	0	0	0	15	3	0	0	1	4	7	154,265	149,293
4,037	`wistia.com`	1	2	0	2	0	0	3	81	0	0	0	0	0	0	109,347	109,299
1,369	`zeit.de`	0	4	1	4	0	0	2	8	3	2	0	0	5	1,318	70,025	72,268
8,894	`menards.com`	0	0	0	0	0	0	0	3,783	0	0	0	0	0	37	43,847	38,715
4,754	`groupon.fr`	0	0	0	0	0	0	0	1	0	0	0	0	0	15	150,717	36,627
7,488	`xinmin.cn`	0	0	0	1	0	0	0	70,380	0	0	0	3	0	4,426	34,229	31,996
2,320	`celebuzz.com`	2	55	0	55	4	2	0	23	0	0	0	0	4	326	27,831	27,779
1,370	`wetter.com`	4	30	0	30	6	1	8	18	5	0	0	1	7	212	22,578	21,764

Table 2: How widely are various fingerprintable browser properties used in the wild.

such as `spiegel.de`, are clearly important and we should take care not to break them in PriVaricator.

4. IMPLEMENTATION

In Section 3 we discussed the possible randomization policies that can be applied on the browser interfaces that are commonly abused for fingerprinting purposes. Since web-based device fingerprinting happens on the client side, the aforementioned policies could, in theory, be applied via an HTTP proxy, a browser extension, or built into the browser itself. We ultimately chose to instrument the browser itself, although we first examined the other approaches.

Strawman approach: JavaScript-level interception: During preliminary experimentation, we attempted to detect accesses to fingerprintable properties by using getters, as defined in ECMAScript5, on the objects and attributes of choice, *e.g.*, `navigator.plugins`. At first glance, given the amount of obfuscation routinely found in JavaScript code, this seems a better strategy than attempting to instrument JavaScript code at the source level (e.g. via an HTTP proxy). The JavaScript code that defined these getters was injected in a page using a browser extension.

During that time, however, we encountered many browser-specific issues that eventually steered us towards modifying the browser itself. For instance, in order to be able to lie about the `offsetWidth` and `offsetHeight` of any given element, we need to intercept the requests of these attributes on all elements on a page, since we cannot *a priori* know which element(s) are going to be used for font detection. Unlike the `navigator` and `screen` objects which are created by the browser and thus always available, HTML elements are created initially when parsing a page's HTML code, as well as on-demand, whenever a programmer wishes to do so through JavaScript. As such, we need to intercept the creation of all HTML elements and define getters upon their creation.

The natural way to do this, is to "poison" the correct object prototype, so that all future JavaScript objects that inherit from that prototype will also inherit the getters. We discovered that although our prototype poisoning was working in Mozilla Firefox, it failed to work as expected in Google Chrome. By investigating the issue, we discovered that in Chrome, the `offsetWidth` and `offsetHeight` properties are not part of the `HTMLElement` prototype, but rather they are defined and initialized upon the creation of new elements. Interestingly, this is not the case for the the `getBoundingClientRect` method which also returns an element's `offsetWidth` and `offsetHeight`, and yet is defined in the expected prototype.

Browser	JSBench		SunSpider		Kraken	
Chromium	72.31	±0.40	139.20	±1.00	1,146	±20.48
PriVaricator	72.10	±0.31	138.70	±0.49	1,142	±20.09

Table 3: Performance comparison of "vanilla" Chromium and Chromium equipped with PriVaricator. All measurements are in *ms*.

In addition to this browser-specific behavior, the use of getters also suffers from transparency issues. That is, a (malicious) script can check for the existence of getters using, among others, the `Object.getOwnPropertyDescriptor` method. Achieving transparency at the language level is fundamentally difficult [14].

Our implementation: For the reasons of better compatibility and transparency, we ultimately chose to implement our randomization policies within the browser, by changing the appropriate C++ code in the classes responsible for creating the `navigator` object, and the ones measuring the dimensions of elements. These changes are, by nature, very local; our full prototype involves modifications to a total of seven files in the WebKit implementation of the Chromium browser, version 34.0.1768.0 (242762).

5. EVALUATION

The goal of PriVaricator's evaluation is three-fold. In addition to ensuring that the overhead of PriVaricator is minimal (Section 5.1), we want to maximize the effectiveness of fingerprinting prevention (Section 5.2), while minimizing the overall damage to the way users perceive the web (Section 5.3). When it comes to privacy-enhancing technologies, this tradeoff is not entirely new. For example, Mozilla Firefox decided to misreport (to JavaScript programs) the computed styles for links in order to prevent history leaks [5], after they had been demonstrated on a large scale.

5.1 Performance Overhead

In order to assess the performance overhead of PriVaricator, we used three independently-developed JavaScript benchmark suites: SunSpider version 1.0.2, Kraken version 1.1, and JSBench version 2013.1. Even though these benchmark suites already take repeated measurements, we also executed each suite five times, clearing the browser's cache in between runs. The experiments were run on a desktop machine, running a recent Ubuntu Linux distribution, with an Intel Core i5-3570 CPU @ 3.40 GHz processor, and 8 GB of RAM.

Table 3 shows the average benchmark execution times (in ms) and standard deviations for an unmodified version of the Chromium browser, and for the same Chromium browser with our modifications present and enabled. To calculate the upper bound of PriVaricator's overhead, we used the lying policy with the most computations ($\pm$ 5% Noise) configured with the worst (from a performance point of view) parameter settings, i.e., θ equal to zero and $P(lie)$ equal to 100%. All three benchmarks reported that our runs with PriVaricator executed, on average, slightly *faster* than the ones of the unmodified browser. Given the standard deviation of our measurements, our instrumentation is not, in reality, speeding up the browser; instead, these measurements show that the added overhead of PriVaricator is so negligible that it does not exceed the inherent noise in the reported execution time of browser benchmarks.

5.2 Preventing Fingerprinting

While one can fully analyze the client-side JavaScript code of fingerprinters, the way in which a user's fingerprintable attributes are combined and mapped to a fingerprint (also known as a *device identifier*) is not necessarily a client-side operation. In order to assess how our randomization policies affect a fingerprinter's ability of identifying us, we chose four services that can be used as black-box oracles. Some of these revealed the device identifier as part of the opt-out process, while with others more investigation was required. Unfortunately, finding fingerprinters that are willing to disclose information about their internal workings is a major challenge and it took us some time to understand how to test these four fingerprinters. For this evaluation, we measured how PriVaricator stands against BlueCava, Coinbase, PetPortal, and fingerprintjs, as explained below.

BlueCava: Similar to other third-party trackers, BlueCava provides an opt-out page (`http://bluecava.com/opt-out`) for users who wish to opt-out of tracking by BlueCava. On this page, users are fingerprinted and their fingerprintable attributes are sent to BlueCava's server. The server then responds with a device identifier, *e.g.*, `18B1-EBFC-A3F0-6D81-6DE8-D8DA-CA56-A22B`, and whether this device identifier has already opted-out in the past. The details of how a user's fingerprintable attributes are combined into a device identifier are proprietary and are unknown to us.

PetPortal: Boda *et al.* have created a cross-browser fingerprinting suite as part of their research in browser fingerprinting [9], available at `http://fingerprint.pet-portal.eu/`. As in the case of BlueCava, the user's fingerprintable attributes are delivered to the server, which then sends back a device identifier and whether the device identifier belongs to a new, or returning, user.

Coinbase: Even though Coinbase does not provide an opt-out page, the algorithm for deriving a device identifier from a user's fingerprintable attributes is part of their client-side JavaScript code. More specifically, when a site includes remote JavaScript code for obtaining Coinbase's "Pay with Bitcoin" button, the remote code creates an `iframe`, in which the fingerprinting code runs [10]. Once the fingerprint is computed, it is MD5-ed and then set as a cookie on the user's machine. When the user clicks on the payment button, her fingerprint will be automatically submitted to the Coinbase server via the user's cookies.

fingerprintjs: Finally, fingerprintjs is an open-source fingerprinting library which, like Coinbase, runs fully on the client-side. fingerprintjs is inspired by Panopticlick [12] and contains most of its features. Interestingly, fingerprintjs is also the only library, that we encountered, that fingerprints a user's machine using the HTML5 canvas as proposed by Mowery *et al.* [18]. It should be noted that it is not yet entirely clear how effective canvas-based fingerprinting is, in practice [4]. Lastly, note that fingerprintjs does not support JavaScript-based font detection.

5.2.1 Experimental Setup

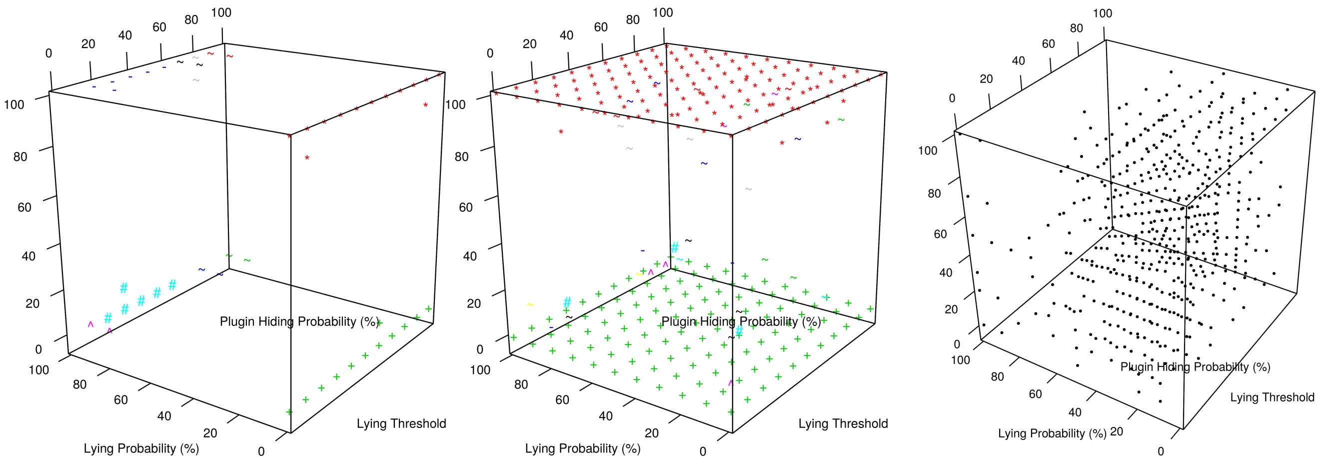
In all four cases, the individual fingerprinting providers gave us a way of assessing the efficacy of PriVaricator, simply by visiting each provider multiple times using different randomization settings, and recording the fingerprint provided by each oracle. To explore the space of possible policies in detail, we performed an automated experiment where we visited each fingerprinting provider 1,331 times, to account for 11^3 parameter combinations, where each parameter of our randomized policy (lying threshold, lying probability, and plugin-hiding probability) ranged from 0 to 100 in increments of 10.

Before we present the results of this experiment we would like to elaborate on two of our decisions.

Panopticlick: We chose against the use of Panopticlick [11] since the feedback that it provides to users is of a semi-qualitative nature, *e.g.*, "You are unique among 4 million users". This type of statement does not allow us to compare the fingerprints received from multiple visits, and thus does not allow us to reason about the effect that our parameterized randomization policies have against it. In addition, since all the sets of attributes collected by the studied fingerprinters are supersets of Panopticlick, we have no reason to expect that our results would have been dramatically different, had we been able to include Panopticlick in our study.

Focusing on the $\pm$ 5% Noise policy: Even though we propose multiple lying policies about offsets, in this section, we only show the effect of PriVaricator's $\pm$ 5% Noise policy, on the four aforementioned fingerprinters. This decision is made in favor of more compact presentation of our results, and in light of the fact that, as described in detail in Section 5.3, the $\pm$ 5% Noise policy incurs the least amount of breakage on legitimate websites thus is the policy that strikes the desired balance between thwarting fingerprinting and maintaining the usability of benign web pages. Do note, however, that all policies have similar results due to the effect of randomization on the way fingerprinters detect the installed fonts.

This is because, as shown in the font-detecting JavaScript snippet (Figure 1), fingerprinting providers first establish ground truth using a font-family that they expect to be present on all devices (*e.g.* sans), and then compare the `offsetWidth` and `offsetHeight` of text using other font-families against that ground truth. PriVaricator will cause deviations from that ground truth and may even poison the fingerprinters' ground truth itself, if the ground truth is acquired *after* the lying threshold (θ) of our policies is



(a) BlueCava **(b)** fingerprintjs **(c)** PetPortal

Figure 2: Distribution of device identifiers across three different fingerprinters. For graphs (a) and (b), we show the points where the fingerprinters recognized us as the same user, i.e., PriVaricator failed. For graph (c) we show the points where PetPortal did *not* recognize us as the same user, i.e., PriVaricator succeeded.

surpassed. As such, all of our lying policies will cause the fingerprinter to believe that our machine has fonts that it actually does not have (false positives).

5.2.2 Results

The results of this set of experiments are shown in Figure 2. In all three scatter-plots, the x-axis represents the probability of lying, the y-axis represents the lying threshold, while the z-axis represents the probability of hiding each individual plugin in our browser's list of plugins. For the first two graphs, colors and symbols represent *clusters* of fingerprints, *e.g.*, all green plus signs denote the same fingerprint, within a given service.

BlueCava: For BlueCava, in Figure 2a one can see that their fingerprinting algorithm can only track us mostly along the edges of the graph. For example, when our plugin-hiding probability is 0, *i.e.*, we always show all plugins, and the lying probability is also 0, i.e., we never lie, we get the same fingerprints (green plus-signs at the "bottom" of the graph).

What is also interesting is how fingerprints change when the lying threshold is less than 60, or greater than 60. One reasonable explanation for this effect is that when our threshold is lower than 60, we then poison the ground truth of the JavaScript-based font detection algorithm, which leads to having an increased number of fonts marked as "present." This change of fingerprint is visible both when the plugin probability is 0% (bottom-left of the graph), as well as when the plugin-hiding probability is 100% (top-left of the graph).

At the same time, it is also evident that most of the cube is empty, that is, in all points other than the ones present, every fingerprint was *unique*, yielding 96.32% of all fingerprints being unique. This shows how fragile BlueCava's identification is against our randomization policies.

fingerprintjs and Coinbase: For fingerprintjs, Figure 2b, the arrangement of points is visibly different from BlueCava's. Since this library does not support for JavaScript-based font detection, our choices of lying probability and lying threshold have no effect. What has the most influence is the value of the plugin-hiding probability. It is evident that fingerprintjs can only track us either when we have no plugins showing, *i.e.*, hiding probability equals 100%, or all plugins showing, *i.e.*, hiding probability is 0%.

In nearly all intermediate points (78.36% of the total set of collected fingerprints), randomness works in our favor by returning different sets of plugins, which, in turn, result in different fingerprints. These results show how important it is to *combine* randomization approaches in order to deter fingerprinters who do not utilize all fingerprintable attributes of a user's browsing environment. In Section 6 we briefly discuss why, given the current state of the art in fingerprinting, a fingerprinter *cannot* avoid extracting both fonts and plugins, while maintaining meaningful results. Coinbase's results were very similar to fingerprintjs's; we briefly discuss them in the Appendix.

PetPortal: Lastly, Figure 2c, shows the results of our experiment against PetPortal. Note that for this figure, because of the large number of clusters, to make the results more readable, we show all the configurations that resulted in *unique fingerprints*, instead of showing clusters of same fingerprints. It is evident that PetPortal succeeds more in tracking us than BlueCava, Coinbase, and fingerprintjs.

In contrast with the other three services, we were able to get unique fingerprints in "only" 37.83% of the 1,331 parameter combinations. One can notice from this graph that we defeat tracking when the lying probability is in the range of 10% to 60%. When the lying probability exceeds 60% we begin lying too often, which likely results in having most fonts marked as "present." There, we also see a lack of effect from the plugin-hiding probability which cannot recover us from being accurately fingerprinted. This likely means that PetPortal places more weight on the discovered fonts, and less on the claimed plugins.

Summary: Overall, our experiments showed that, while the specific choices of each fingerprinter affect the uniqueness of our fingerprints, PriVaricator was able to deceive all of them for a large fraction of the tested combination settings. Moreover, the presence of clusters of identical fingerprints demonstrates that most fingerprinting providers derive a fingerprint by following a more complicated approach than just hashing all fingerprintable attributes together. Comparatively speaking, PetPortal was most resistant to PriVaricator.

5.3 Assessing the Breakage

In the previous section, we demonstrated that PriVaricator was able to withstand fingerprinting by measuring the number of unique fingerprints received, for a total of 1,331 settings combinations. By computing the intersection of the points resulting in unique fingerprints across all four fingerprinting providers, (essentially identical to PetPortal's results), we obtain a range of settings, all of which provide prevention from reliable fingerprinting. In this section, we assess the level of breakage of benign sites for each of those parameter combinations.

Experimental setup: An element's offset properties (accessible through `offsetWidth` and `offsetHeight`) provide information to a JavaScript program about the size of that element, as is currently rendered on a user's screen. When PriVaricator lies about these values, it creates a potential for visual breakage. For example, by reporting that an element is smaller than it actually is, PriVaricator could cause the page to place it in a smaller container, hiding part of its content from the user. Numerically, we define *breakage* as the fraction of pixels that are different when a site is loaded with a vanilla browser (PriVaricator turned off) and with PriVaricator.

To assess the breakage, we instrumented Chromium to visit the main pages of the top 1,000 Alexa sites, for 48 different combinations of lying probability and lying threshold; these were the parameter combinations that resulted in unique fingerprints, as described in the previous section. To contain the dimensionality of this experiment, we statically assigned the plugin-hide probability to zero (showing all plugins) since we reasoned that the main pages of the most popular sites of the web likely behave the same for users with different plugins. At every site visit, the browser waited for 25 seconds and then captured a screenshot (1,050x850 pixels) of the rendered content.

In order to separate between visual differences caused by PriVaricator, and visual differences caused by the inherent variation of a site, *e.g.*, ads, image carousels, and newly posted content, we collected a new vanilla-browser screenshot every ten visits of a page, resulting in a total of five extra screenshots. Since any visual variation detected on these five screenshots can be attributed to a website's dynamic content, we computed a visual mask of differences appearing on them, and used it when comparing a screenshot captured using a specific policy parameter combination, to the vanilla one. This mask can be applied to all PriVaricator screenshots to exclude the naturally varying parts of a page from subsequent breakage comparisons. For illustration, Figure 3 shows three different vanilla-browser screenshots of `tumblr.com` and the computed mask.

Finally, while in the previous section the choice of randomization policy was not as important, in this section, different policies are likely to produce different visual results, *e.g.*, receiving a value that is 5% off the expected one, versus receiving a value that is completely random. Thus, the entire experiment had to be repeated for every randomization policy: (a) Random(0..100); b) Zero; and c) ± 5% Noise). Overall, we collected a total of approximately 159,000 images, occupying 54 GB of disk space, which we compared in order to quantify the breakage caused by PriVaricator.

Results: The results of our breakage experiments are first detailed in Figure 4 and then summarized in Table 4. Table 4a presents the minimum, average, and maximum breakage for all three policies when considering the fractions of different pixels across all sites. Since we noticed that, in some cases, the computed masks were too *large*, we also calculated the breakage of sites when ignoring sites that had masks with size larger than 30% of the total image; this is shown in Table 4b. This way, we ignore sites that would give PriVaricator an unfair advantage by hiding real breakage under a site's natural variation. While the latter set of numbers is slightly larger than the former, it is evident, not only that the ± 5% Noise policy incurs the least breakage but that the breakage itself is, on average, less than 1%.

Policy	Min	Mean	Max %
Random(0..100)	0.8%	1.4%	2.1%
Zero	0.4%	0.8%	1.3%
± 5% Noise	**0.4%**	0.6%	0.9%

(a) Summary of breakage results.

Policy	Min	Mean	Max %
Random(0..100)	0.8%	1.5%	2.3%
Zero	0.4%	0.9%	1.4%
± 5% Noise	**0.4%**	0.7%	1.0%

(b) Breakage when ignoring pages with masked content greater than 30% (approx. 84% of pages remaining).

Table 4: Breakage summary with and without including sites with large masks.

Every point in Figure 4 is the average breakage of all 1,000 Alexa sites visited with PriVaricator using a specific $\langle P(lie), \theta \rangle$ configuration, and one of our three lying policies. For instance, in Figure 4b, the average breakage of sites when visited by PriVaricator configured with a lying probability equal to 10% and a lying threshold of 30 accesses is 0.004, under the Zero policy. That is, the sites visited by PriVaricator with that specific combination of settings had, on average, 0.4% different pixels when compared to the vanilla screenshots.

For the breakage caused by the Random(0..100) policy (Figure 4a) and Zero policy (Figure 4b), one can discern a positive relationship between the lying probability and the resulting breakage. This relationship makes intuitive sense. The more often PriVaricator lies using these policies, the more often a website receives an unexpected value of 0, or a random number between 0 and 100. On the other hand, this relationship is significantly weaker in ± 5% Noise policy results (Figure 4c). We argue that this is because the modified offset value is relatively close to the value that a script would otherwise expect, thus minimizing the number of sites breaking because of such small modifications.

Inspecting breakage: To understand how a user would experience potential breakage, we manually reviewed the 100 screenshots (under the ± 5% Noise policy) with the largest reported breakage. In this analysis, we discovered that in only 8 cases, the differences could be attributed to PriVaricator. The rest of the screenshots (92/100) were very different from the vanilla screenshots due to a site's inherent variations and errors, not captured in any of the five vanilla screenshots. In many cases, the sites would show an "in-page" pop-up asking the user to participate in a survey. Usually, this pop-up would add a semi-transparent gray overlay over the page,

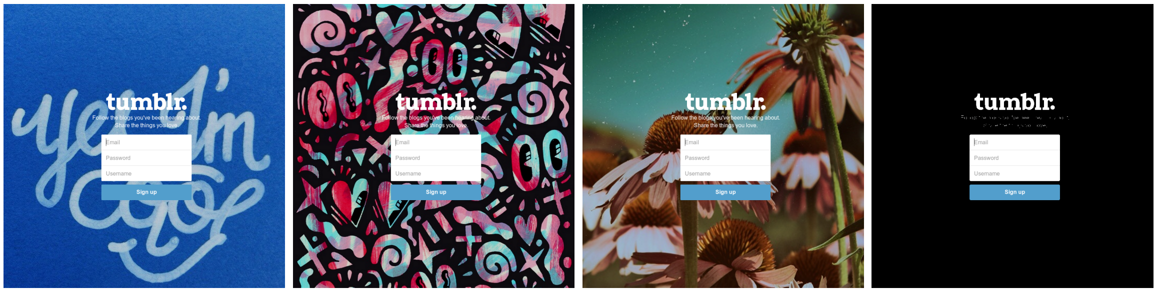
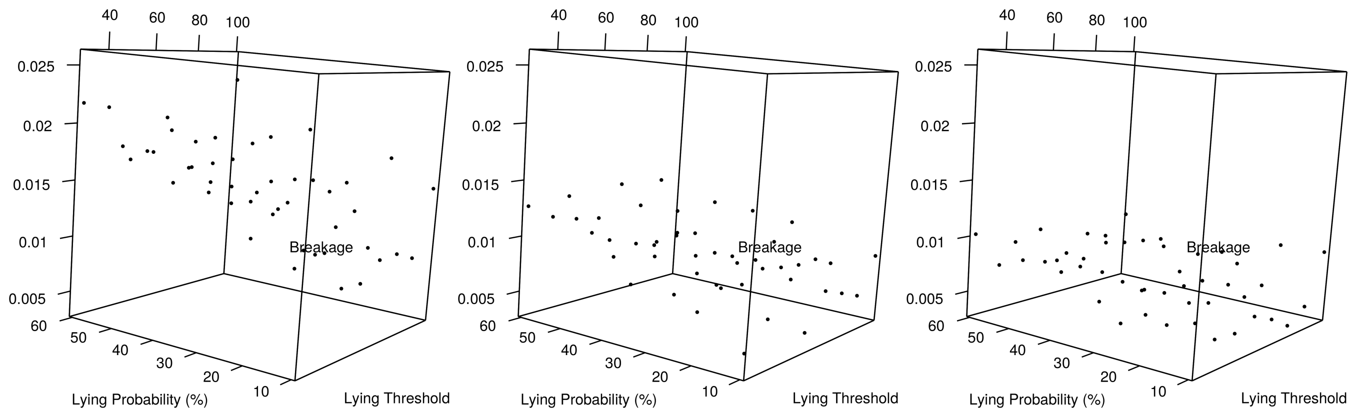


Figure 3: The first three screenshots show `tumblr.com` and its ever-changing backgrounds. The last image is an automatically-generated mask for assessing the true breakage caused by PriVaricator. Black areas denote masked-out content.



(a) Random(0..100) policy **(b)** Zero policy **(c)** $\pm$ 5% Noise policy

Figure 4: Breakage caused by PriVaricator, given a series of possible configurations and a randomization policy

causing our automatic comparison algorithms to report a very large visual difference.

Next to surveys, the reported breakage was due to missing or not-fully loaded ads, error-pages and image carousels. In one case, PriVaricator had caused a slight stretch of a site's background image. While this led to a large computed breakage, users would not notice the change if they could not compare the page with the original non-stretched version. Finally, we manually inspected the sites making the most use of offset accesses (listed in Table 2) by visiting them with PriVaricator and clicking on a few links on each site. All sites were operational and usable, with the only difference being the location and movement of some objects, e.g., moving ads, whose motion and placement was slightly affected by the randomization policies of PriVaricator.

Summary: Overall, the results of our breakage experiments show that the negative effect that PriVaricator has on a user's browsing experience is negligible. Moreover, our manual analysis revealed that we have likely overestimated the breakage since most of the pages with the highest reported breakage turned out to be false positives.

Our low breakage results also allow us to avoid the temptation of cherry-picking configurations for the $\pm$ 5% Noise policy, something which could lead to issues related to overfitting. Instead, any of the many parameter configurations could be picked for deployment, e.g., picking one at random when a user starts a private mode session. We opine that an average breakage of 0.7% (likely an upper bound with the actual damage as much as $10x$ less) provides an acceptable trade-off for the extra privacy that the user gains in return.

6. DISCUSSION

Explicit fingerprinting: Note that we do not claim to solve the *entire* problem of web-based device fingerprinting with PriVaricator. The focus of our work is on explicit attempts to fingerprint users via capturing the details of the browser environment. We do *not* attempt to provide protection against sophisticated side-channels such as browser performance [17] which may be used as part of fingerprinting. Our focus is on *explicit fingerprinting*, *i.e.*, JavaScript-based fingerprinting which operates by computing a function of environment variables exposed within the browser, as these are exclusively used in by the popular fingerprinters.

6.1 Comparing to Existing Approaches

Most existing attempts to combat fingerprinting rely on making multiple users look identical. In terms of sophistication, browser extensions that spoof a browser's user agent, such as UserAgent Switcher and UserAgent RG, can be viewed as the most straightforward fingerprinting countermeasure. These extensions attempt to hide the true nature of a browser and show another, possibly more mainstream and less identifying, version. Unfortunately, however, these extensions are trivially bypassable as explained by Nikiforakis *et al.* [20], since an attacker can deduce the original version of the browser by searching for vendor- and version-specific functionality.

On the other side of the spectrum, the Tor browser makes cross-cutting changes to present the same browser attributes for all Tor users so that a probing website may not be able to differentiate between different users of the Tor network.

While Tor happily sacrifices usability for anonymity by disabling all plugins, reporting false screen dimensions, and limiting the number of fonts that any given page can use, we reason that this may not be the goal for most online users. We argue that PriVaricator is the middle-of-the-road option that will allow benign web pages to be rendered with minimum breakage (*e.g.*, no limits in font loading, no unnecessary changes in screen dimensions), while defeating the fingerprinting efforts, as demonstrated in Section 5.2.

6.2 Deployment challenges

The key advantages of PriVaricator are its negligible overhead and the relative ease of porting. It is easy to underestimate the importance of low overhead, but given the current emphasis on browser performance, it is unlikely that a privacy solution that suffers a large performance hit will be deployed. Our design of PriVaricator has emphasized minimal modifications to existing technology, which leads to small overhead and negligible porting costs; overall, the automatically generated patch of our modifications to Chromium (including comments) is only 947 lines long.

Transparency: As with any defense strategy there is a question of *transparency*. We do not claim to preserve transparency in PriVaricator; indeed, this is a tough property to maintain for just about any runtime protection mechanism.

Specifically, since PriVaricator is using randomness to report different values for popular fingerprintable attributes, a motivated fingerprinter could test for the presence of unexpected randomness, *e.g.*, by inquiring about the dimensions of an element 100 times, and then checking for differences in responses. Similarly, a statistical attack may collect multiple readings and average them over a large number of samples, in an effort to approximate the real measurement.

Lie cache: One possible solution that alleviates this transparency issue and thwart some of the statistical attacks is setting up a "lie cache", a mechanism where the browser would report the *same* false value for multiple inquires about the same, unmodified element. To break linkability, the lie cache should be reset at the beginning of every new private mode session, *i.e.*, when a user is opening a private mode tab or window of her browser. This would enhance the transparency at the cost of linkability within the same private mode session. We leave the exploration of this solution and its tradeoffs for future work.

6.3 Making PriVaricator Extensible and Future-Proof

Withstanding small changes: In Section 5.2 we showed that PriVaricator's randomization policies can thwart all modern commercial and open-source fingerprinting projects we have access to. In this paper, we primarily cover two fingerprinting vectors: plugins and fonts. Given that these two vectors contain the highest discriminating power, it is to the advantage of the fingerprinter to use *both*.

One, however, could argue that fingerprinters will adapt to PriVaricator and change their strategy. If, for instance, a fingerprinting library were to stop using plugin information and would only rely on fonts, PriVaricator still offers a large set of combinations for the Lying Probability and Lying threshold parameters resulting in different fonts detected, and thus different fingerprints for the same user.

In a similar fashion, PriVaricator can adapt to a fingerprinter that does not use font information, as was demonstrated in Figure 2b, since the fingerprintjs library does not use fonts. It is also important to stress that every time that a fingerprinter consciously forsakes a fingerprinting vector, he is increasing the probability of collisions of fingerprints of different people. For example, two users may have the same browser plugins but may have installed applications that included different fonts and thus will have different fonts detected by the fingerprinting scripts.

Lastly, if a fingerprinter decides to use neither fonts nor plugins, he will be abandoning the two most powerful identifying attributes of modern browsers. Thus, in this case, while the fingerprint that PriVaricator will provide may be stable, it will have little discriminating power, rendering such an approach useless as a tracking mechanism.

Future fingerprinting vectors: Just like with most defense mechanisms, more sophisticated attacks often are developed in response to them. Security literature is full of such examples, with major attacks, such as buffer overflows and cross-site scripting, evolving significantly over the years, with attacks and defenses adapting to each other. We, unfortunately, cannot foresee new fingerprintable vectors that might appear in the coming years — in the same way that Eckersley could not foresee the use of timing attacks against JavaScript engines [17]. Note, however, that as long as either plugins or fonts are included as part of a user's fingerprint and relied upon to provide meaningful information to the fingerprinting party, the current version of PriVaricator is likely to provide adequate randomization.

Extensibility of PriVaricator: Next to protecting against the current generation of fingerprinting attacks, one of the goals of PriVaricator is to provide a platform for supporting evolving defenses as new fingerprinting vectors emerge. For example, canvas-based fingerprinting, can be thwarted by adding small amounts of noise to the image returned via `getImageData`. Based on our experience in implementing the existing randomization policies, we believe that adding canvas support to PriVaricator will not differ in any substantial way, in terms of the extent of the changes (topical changes in a small number of canvas-specific functions to probabilistically modify pixel values) and performance overhead. Moreover, the effect of adding, say, 5% random noise to a handful of pixels in the canvas, will break the linkability of canvas-fingerprints while being imperceptible to users. Thus we consider it unlikely that the implementation of canvas-support in PriVaricator would significantly change our current performance and usability results.

Fluid browser updates enable changing PriVaricator policies: Given that today's browsers have migrated to an almost weekly update cadence (at least in the case of Firefox and Chrome), shipping updated randomization policies is an easy task. Note that similar updates are shipped to other browser-hosted security mechanisms such as XSS filters, malware filters, and tracking protection lists (TPLs). Extensions such as ad blockers [3] also update their blacklists on a regular basis. As such, we feel that PriVaricator provides an extensible platform for stateless fingerprinting defenses. All of the above examples constitute much more sizable changes compared to small PriVaricator policy updates.

7. RELATED WORK

In this section, we provide an overview of literature focusing on browser fingerprinting.

History of fingerprinting: The work of Mayer [16] and Eckersley [12] presents large-scale studies that show the possibility of effective stateless web tracking via only the attributes of a user's browsing environment. These studies prompted some follow-up efforts [13, 25] to build better fingerprinting libraries. Yen *et al.* [27] performed a fingerprinting study by analyzing month-long logs of Bing and Hotmail and showed that the combination of the User-agent HTTP header with a client's IP address were enough to track approximately 80% of the hosts in their dataset.

While the majority of fingerprinting efforts have focused on fonts and plugins, Mowery and Shacham proposed fingerprinting through the rendering of text and WebGL scenes to a `<canvas>` element [18]. Different browsers will display text and graphics in a different way which, however small, can be used to differentiate and track users. The downsides to this method are that these technologies are only available in the latest versions of modern browsers and that the canvas-generated entropy is not sufficient for it to be used as the only fingerprinted attribute. This is, in practice, exemplified by the statement of AddThis, the company responsible for 95% of the canvas-based fingerprinting that Acar et al. [1] discovered in a recent study. In a follow-up interview, AddThis claimed about canvas-based fingerprinting that "It's not uniquely identifying enough." [4]

Extensions: As analyzed by Nikiforakis *et al.* [20] and discussed in Section 6, browser extensions that spoof a browser's User Agent, may actually be counter-productive, since they considerably narrow down the population of possible users to fingerprint, in addition to frequently reporting impossible combinations of environment variables. PriVaricator goes deeper than these extensions, focusing on portions of the environment that can be spoofed to break fingerprinters, while not significantly affecting other sites.

FireGloves, proposed by Boda *et al.* [8, 9] but no longer supported, was a browser extension that attempted to frustrate fingerprinting attempts by faking the screen resolution and timezone, presenting an empty `navigator.plugins` list, limiting the number of font families allowed to load per tab, and randomizing the return value of `offsetWidth` and `offsetHeight` of elements. As we showed in Section 5.2, presenting an empty list of plugins is as bad as presenting a full list of plugins, since the majority of browsers support at least one plugin. In contrast, PriVaricator chooses to randomize the existing list of plugins which results in a large number of different plugin combinations. The randomized offset value of FireGloves is a random value between 0 and 1,000. As shown in our evaluation of site breakage, Section 5.3, this randomization approach produces the most breakage. Moreover, our randomized values were constrained to a range of 0 to 100, meaning that if one assumes a positive correlation between the size of the set of possible offset values and breakage, FireGloves has the potential to cause considerably more breakage. Contrastingly, in PriVaricator, we sought to find the best balance between defeating fingerprinters and minimizing breakage, by systematically testing our randomization policies against both, and arriving at a range of suitable parameters. Lastly, since FireGloves performs its operations through getters and setters, it suffers from the transparency and compatibility problems we mentioned in Section 4.

In recent work, Besson et al. [6] modeled the problem of privacy protection against fingerprinting and provided upper bounds for the identifiability of each user under different randomization algorithms and usability constraints.

Side channels: Researchers have proposed a variety of side channels for browser fingerprinting which have not yet been discovered to be used in practice. Mowery *et al.* [17] proposed the use of benchmark execution time as a way of fingerprinting JavaScript implementations, under the assumption that specific versions of JavaScript engines will perform in a consistent way. Closely related is the work of Mulazzani *et al.* who used the errors produced by JavaScript engines when executing standard test suites to differentiate between browsers [19]. Olejnik *et al.* [21] show that web history can also be used as a way of fingerprinting for tracking purposes. The authors make this observation by analyzing a corpus of data from when the CSS-visited history bug was still present in browsers. Today, however, all browsers have corrected this issue, so extraction of user history is not as straightforward, especially without user interaction [26]. We are not aware of wide-scale fingerprinting on the web using any of these side channels. This is part of the reason why chose to focus on explicit fingerprint in PriVaricator.

8. CONCLUSION

This paper proposes PriVaricator, an addition to privacy modes present in modern browsers. The goal of PriVaricator is to combat stateless tracking, which is being done primarily using device-fingerprinting JavaScript code. We use careful randomization as a way to make subsequent visits to the same fingerprinter difficult to link together. We evaluate several families of *randomization functions* to find those that result in the best balance between fingerprinting prevention and breaking existing sites. While our implementation has focused on randomizing font- and plugin-related properties, we demonstrate how our approach can be made general with pluggable randomization policies.

Our best randomization policies reliably prevent *all* fingerprinting when tested with several well-known device fingerprinting providers, while incurring minimal damage on the content of the Alexa top 1,000 sites. Furthermore, we found the runtime overhead of PriVaricator to be negligible and discussed how PriVaricator can be used as a platform where randomization-based countermeasures can be straightforwardly incorporated as new fingerprinting vectors emerge.

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9. REFERENCES

[1] G. Acar, C. Eubank, S. Englehardt, M. Juarez, A. Narayanan, and C. Diaz. In *Proceedings of the 21st ACM Conference on Computer and Communications Security (CCS)*, 2014.

[2] G. Acar, M. Juarez, N. Nikiforakis, C. Diaz, S. Gürses, F. Piessens, and B. Preneel. FPDetective: Dusting the Web for fingerprinters. In *Proceedings of the ACM Conference on Computer and Communications Security (CCS)*, 2013.

[3] Adblock plus - for annoyance-free web surfing. `http://adblockplus.org`.

[4] J. Angwin. Meet the Online Tracking Device That is Virtually Impossible to Block. `http://www.propublica.org/article/meet-the-online-tracking-device-that-is-virtually-impossible-to-block`.

[5] D. Baron. Preventing attacks on a user's history through CSS:visited selectors. `http://dbaron.org/mozilla/visited-privacy`, 2010.

[6] F. Besson, N. Bielova, and T. Jensen. Browser Randomisation against Fingerprinting: A Quantitative Information Flow Approach. In *Proceedings of the 19th Nordic Conference on Secure IT Systems (NordSec)*, pages 181–196, 2014.

[7] BlueCava. Measuring Mobile Advertising ROI Using BlueCava Device Identification. 2011.

[8] K. Boda. Firegloves. `http://fingerprint.pet-portal.eu/?menu=6`.

[9] K. Boda, A. M. Földes, G. G. Gulyás, and S. Imre. User tracking on the web via cross-browser fingerprinting. In *Proceedings of the Nordic Conference on Information Security Technology for Applications (NordSec)*, 2012.

[10] Bitcoin Payment Buttons - Bitcoin Merchant Tools. `https://coinbase.com/docs/merchant_tools/payment_buttons`.

[11] P. Eckersley. The Panopticlick project. `https://panopticlick.eff.org/`.

[12] P. Eckersley. How Unique Is Your Browser? In *Proceedings of the Privacy Enhancing Technologies Symposium (PETS)*, pages 1–17, 2010.

[13] E. Flood and J. Karlsson. Browser fingerprinting, 2012.

[14] C. Fournet, N. Swamy, J. Chen, P.-E. Dagand, P.-Y. Strub, and B. Livshits. Fully abstract compilation to javascript. In *Proceedings of the Symposium on Principles of Programming Languages (POPL)*, 2013.

[15] iovation. Solving online credit fraud using device identification and reputation. 2007.

[16] J. R. Mayer. Any person... a pamphleteer. Senior Thesis, Stanford University, 2009.

[17] K. Mowery, D. Bogenreif, S. Yilek, and H. Shacham. Fingerprinting information in JavaScript implementations. In H. Wang, editor, *Proceedings of W2SP 2011*. IEEE Computer Society, May 2011.

[18] K. Mowery and H. Shacham. Pixel perfect: Fingerprinting canvas in HTML5. In *Proceedings of the Workshop on Web 2.0 Security and Privacy (W2SP)*. IEEE Computer Society, May 2012.

[19] M. Mulazzani, P. Reschl, M. Huber, M. Leithner, S. Schrittwieser, and E. Weippl. Fast and reliable browser identification with javascript engine fingerprinting. In *Web 2.0 Workshop on Security and Privacy (W2SP)*, May 2013.

[20] N. Nikiforakis, A. Kapravelos, W. Joosen, C. Kruegel, F. Piessens, and G. Vigna. Cookieless monster: Exploring the ecosystem of web-based device fingerprinting. In *Proceedings of the IEEE Symposium on Security and Privacy*, pages 541–555, 2013.

[21] Ł. Olejnik, C. Castelluccia, and A. Janc. Why Johnny Can't Browse in Peace: On the Uniqueness of Web Browsing History Patterns. In *Proceedings of the Workshop on Hot Topics in Privacy Enhancing Technologies (HOTPETS)*.

[22] K. Sivaramakrishnan. The Drawbridge Cross Device Matching Technology.

[23] ThreatMetrix. Device Fingerprinting and Fraud Protection Whitepaper.

[24] Tor: Cross-Origin Fingerprinting Unlinkability. `https://www.torproject.org/projects/torbrowser/design/#fingerprinting-linkability`.

[25] V. Vasilyev. fingerprintjs library. `https://github.com/Valve/fingerprintjs`, 2013.

[26] Z. Weinberg, E. Y. Chen, P. R. Jayaraman, and C. Jackson. I still know what you visited last summer: Leaking browsing history via user interaction and side channel attacks. In *Proceedings of the IEEE Symposium on Security and Privacy*, 2011.

[27] T.-F. Yen, Y. Xie, F. Yu, R. P. Yu, and M. Abadi. Host fingerprinting and tracking on the Web: Privacy and security implications. In *Proceddings of the Network and Distributed System Security Symposium (NDSS)*, 2012.

APPENDIX

Coinbase

Figure 5 shows the distribution of non-unique device identifiers when testing PriVaricator (with the ± 5% Noise policy active) against Coinbase. Colors and symbols represent clusters of identical values, e.g., all green plus-signs denote the same device identifier as generated and reported by Coinbase. As was the case with fingerprintjs (discussed in Section 5.2), PriVaricator deceives Coinbase in the majority of cases (78.81% of the extracted device identifiers were unique).

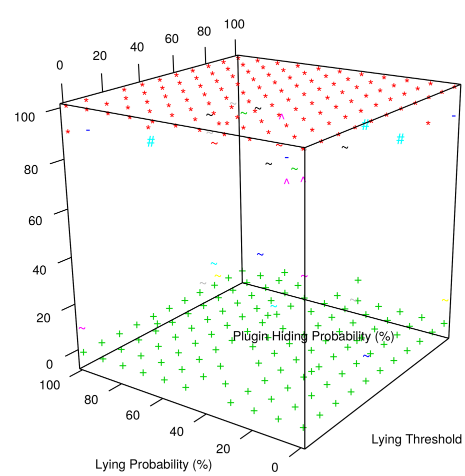

Figure 5: Distribution of non-unique device identifiers of PriVaricator against the Coinbase service.