ABSTRACT

The web is used daily by billions. Even so, users are not protected from many threats by default. This paper builds on previous web privacy and security research and introduces JShelter, a webextension that fights to return the browser to users. Moreover, we introduce a library helping with common webextension development tasks and fixing loopholes misused by previous research. JShelter focuses on fingerprinting prevention, limitations of rich web APIs, prevention of attacks connected to timing, and learning information about the device, the browser, the user, and the surrounding physical environment and location. During the research of sensor APIs, we discovered a loophole in the sensor timestamps that lets any page observe the device boot time if sensor APIs are enabled in Chromium-based browsers. JShelter provides a fingerprinting report and other feedback that can be used by future web privacy research. Thousands of users around the world use the webextension every day.

KEYWORDS

Browser fingerprinting, web privacy, web security, webextension APIs, JavaScript

1 INTRODUCTION

Most people interact with web pages daily. Nowadays, many activities are often carried out exclusively in a web browser, including shopping, searching for travel information, and performing leisure activities such as gaming, business, and office work. For several years, browser vendors have been adding new JavaScript APIs to solicit the development of rich web applications [56].

Web visitors are subject to hostile tracking [10, 12, 23, 34, 44], fingerprinting [25, 31], and malware [5, 42]. Some of the recently added APIs influence the privacy of the users. For example, the Geolocation API [11] is beneficial for navigation in the real world. However, some users are only willing to share the location with some visited sites. In the case of Geolocation API, browsers ask users for permission, but not all APIs need user permission. Users cannot limit the precision of the Geolocation API. However, occasionally they want to share a more precise location (e.g. during navigation). Other times they want to share the location with limited precision (e.g. they are exploring a location unrelated to their current position).

This paper presents JShelter, a web browser extension (webextension) that allows users to tweak the browser APIs. Additionally, JShelter detects and prevents fingerprinting. Moreover, JShelter blocks attempts to misuse the browser as a proxy to access the local network. JShelter educates users by explaining fingerprinting APIs in a report. JShelter integrates several previous research projects like Chrome Zero [37] and little-lies-based fingerprinting prevention [40, 46]. As current webextension APIs lack a reliable way to modify JavaScript APIs in different contexts like iframes and web workers, we needed to solve the reliable injection. This paper introduces NoScript Commons Library (NSCL) [2] that other privacy- and security-related webextensions can reuse to solve common tasks like the reliable injection of JavaScript code into the page JavaScript context before the page scripts can access the context. We implemented JShelter for Firefox and Chromium-based browsers like Chrome, Opera, and Edge. So we gathered experience from user feedback that can be valuable to other research projects. This paper extends our SECRYPT paper [49].

The evaluation shows that JShelter prevents many attacks, including learning (1) browser and device fingerprints, (2) user biometrics, (3) computer clock-skew, and (4) running applications. Sensors available for all pages on Android make users vulnerable to several attacks [4, 22, 62]. JShelter prevents the danger by pretending to be a stationary device. JShelter mitigates leaking boot time of the device through sensor timestamps in Chromium-based browsers.

This paper is organised as follows. Section 2 presents the threats that users face while web browsing. Section 3 compares JShelter to other security- and privacy-related webextensions. Section 4 provides the design decisions that we faced during the development of JShelter. Section 5 evaluates the JShelter features and discusses user feedback. Section 6 concludes this paper.

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1https://developer.mozilla.org/en-US/docs/Web/API/Geolocation

2https://noscript.net/commons-library

3If you intend to cite our work, please, prefer citing the original paper [49].
2 THREATS

Web Technology Surveys\(^4\) report that 97.8% of pages contain JavaScript, and the percentage is rising over time. As the code is unknown to the user, it might work against user expectations [10, 23]. This section presents threats that JShelter tries to mitigate.

2.1 T1: User tracking

In theory, laws like GDPR and ePrivacy Regulation give each person control over their personal data and devices. However, there is a significant lack of control over personal data on the web [7, 23, 34, 35, 50] in practice. The advertisement technologies are under considerable scrutiny in Europe [1, 10], but tracking scripts are omnipresent on the web. Users risk complete disclosure of their browsing history.

Historically, trackers stored user identifiers in third party cookies. However, browser vendors limit third party cookies. Hence trackers move to alternative ways of identifying users. Browser and device fingerprinting is a stateless tracking method that tries to find features that make (almost) every browser uniquely identifiable [8, 11, 31, 32]. For example, the content of HTTP headers, including user agent string, screen size, language, time zone, and system fonts, together with hardware-dependent characteristics such as canvas image rendering [8, 38], audio processing [13], installed fonts [16], installed browser extensions [21, 51, 52, 58], the sites that the user is currently logged in [21], clock skew [29, 47] and other techniques [31]. The goal of the fingerprinter is to create a stable identifier of a user so that the user is identifiable on different sites. Device fingerprint is the same in every browser on the same device, while browser fingerprint differs for different browsers running on the same device. Recent studies have shown that user tracking is becoming more prevalent and complex [33]. Note that the leaking information may uncover vulnerabilities of the fingerprinted systems, and a fingerprinting database can be a valuable source of information for an adversary wanting to misuse the data.

Fingerprinting is considered passive when it contains information from HTTP headers or network traffic that is exchanged regardless of whether the fingerprinting is in place. On the other hand, active fingerprinting runs JavaScript code to retrieve data from browser APIs. Figure 1 depicts publicly available data by IAB Europe Transparency and Consent Framework (TCF)\(^5\). TCF allows companies to self-report active and passive fingerprinting. More than 400 companies passively fingerprint users and more than 100 companies actively use JavaScript APIs to create a unique fingerprint. One of the goals of JShelter is to prevent active fingerprinting.

Several studies monitored the deployed fingerprinting techniques on the Internet [2, 3, 13, 17, 25, 41]. Trackers exploit evercookies, shared cookies, font enumeration, canvas, web audio, WebRTC, and many other APIs to identify browsers and their users. However, current countermeasures are insufficient for a dedicated fingerprinter willing to reveal inconsistencies in API readings [51, 63].

\(^4\)https://w3techs.com/technologies/history_overview/client_side_language/all/y
\(^5\)See https://vendor-list.consensu.org/v2/archives/vendor-list-vNUM.json where NUM is the number of the week since the start of the framework. See https://www.fit.vutbr.cz/~polcak/tcf/tcf2.html for more data from the framework.

Figure 1: TCF participants reporting fingerprinting activities and precise geolocation processing.

Current research distinguishes targeted and non-targeted fingerprinting [31]. Non-targeted fingerprinting focuses on observing visiting browsers or device fingerprints and trying to link their identity to a previous visitor. Targeted fingerprinting tries to detect a tailored fingerprint of an individual, for example, for law enforcement investigations [51].

Browser fingerprinting can also be used for benign use cases like multifactor authentication — if a website detects that a user connects from the same device as previously seen, it is not necessary to perform additional authentication steps. A website can recommend installing critical security updates based on system properties, like the browser version. Some websites collect browser fingerprints to distinguish between human users and bots to prevent fraud.

Another branch of previous literature focused on processing behavioural biometric features derived from input user interaction (keyboard, mouse, and touch events). For example, it is possible to identify users uniquely [27, 64], derive handedness [43], or age and gender [44].

2.2 T2: Very rich browser APIs

Modern websites offer the capabilities of native applications. Browsers support video calls, audio and video editing, maps and navigation, augmented and virtual reality. One can control games with gamepads or check the battery status. The web page may change its appearance according to the ambient light. Nevertheless, most web pages do not need these advanced APIs [57]. Service Worker API allows Man-in-the-Middle adversaries inject long-lasting trackers [48]. Some APIs like Geolocation or microphone and camera access need explicit approval by users. Others like gamepads, virtual reality, battery, or sensors are available for all visited pages\(^6\).

\(^6\)Sensor APIs are currently implemented, or partially implemented, in Chromium-based browsers like Chrome, Edge, and Opera. For Android devices, the support exists in Chrome for Android, Opera for Android, and various Chromium-based browsers like Samsung Mobile or Kiwi Browser. The concrete support for individual classes depends on the browser type and version. Some features are considered experimental and only work when browser flags like #enable-experimental-web-platform-features or #enable-generic-sensor-extra-classes are enabled. Sensor APIs are enabled by default in Chrome on Android.

\(\)Iqbal et al. [25] detected misusing the APIs by many fingerprinting scripts. Both Generic Sensor W3C Candidate Recommendation
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Draft\(^7\) and literature mention several risks stemming from sensor reading like location tracking [22], eavesdropping, keystroke monitoring, device fingerprinting [62], and user identification [4]. Fig. 1 reports TCF data on companies using precise geolocation data (precision better than 500 meters).

2.3 T3: Local network scanning

Devices browsing the web are typically connected behind NAT, which does not allow external hosts to open connections to devices in the local network (e.g. printers). Although the same-origin policy does not allow a web page to access arbitrary resources, there are side channels that might provide enough information about an existence of a resource, including resources in the local network [5]. A web page can try to exploit the web browser as a proxy between the remote website and resources in the local network. Bergbom [5] demonstrated that it is possible to execute arbitrary commands on a local machine under certain circumstances (in this case, it was an insecure Jenkins configuration).

2.4 T4: Microarchitectural attacks

Previous research also focused on side-channel attacks that can reveal what the user has recently done with the device. For example, content-based page deduplication performed by an operating system or a virtual machine hypervisor can reveal if specific images or websites are currently opened [18] on the same device (hardware), possibly on another virtual machine. The reply time for a specific request depends on the cached content, so the reply time reveals if the content was recently visited [14]. Moreover, even uncached content leaks information on the server state [6]. Bortz and Boneh [6] studied server reply times influenced by different code paths taken by the server and were able to reveal private information. The `requestAnimationFrame` API can be used to time browser rendering operations and reveal information on browser history and read pixels from cross-origin iframes [59].

Operating systems isolate processes from each other and the kernel. However, deficiencies in hardware can provide possibilities to circumvent the isolation. Gruss et al. [20] exploited JavaScript to modify memory cells belonging to different processes (the attack is called Rowhammer). Hence, they gained unrestricted access to systems of website visitors. They exploited operating systems optimisations and high-precision timings [20]. Later, Gruss et al. [19] showed that industry countermeasures against Rowhammer attacks are ineffective. Spectre attacks can be executed from JavaScript and leak data in the memory of other processes running on the same system [28].

Some websites provide different content based on age, gender and location. Van Goethem et al. [61] employed timing attacks to reveal data about users by measuring the size of the reply for resources with different contents for different users.

Smith et al. [55] exploited visited link pseudoclass and timed link redrawing based on the target URL to determine browser history.

3 COUNTERMEASURES

Many popular security and privacy-enhancing approaches already exist. Let us focus on existing tools addressing the threats raised in Sect. 2.

3.1 Browser extensions

Adblockers and other tracker blockers employ lists of URLs or parts of URLs that are considered harmful to user privacy or security. The advantage of the user is that many tools focus on blocking (for example, uBlock Origin, EFF Privacy Badger, Ghostery) and also blocklists that are usually compatible with several blockers. Browsers like Firefox [30] and Brave include tracking prevention by default. The downside is that it is easy to evade blockers [36]. The malicious web server needs to change the URL of the script. Hence, blocklists are very useful as a first-line defence and improve web performance [30]. JShelter users should install a tracker blocker. However, blockers are not enough as the niche cases evade the blockers [36].

Webextensions like NoScript Security Suite\(^8\) and uMatrix Origin\(^9\) allow users to block JavaScript or other content either completely or per domain. Hence, they can address all threats raised in Sect. 2. However, many pages depend on JavaScript. Users must select what content to trust. HTTP Archive reports that an average page includes 22 external requests (21 requests for mobile devices)\(^10\) So a user trying to determine what code to run requires excellent knowledge about the external sites. Moreover, a malicious code may be only a part of a resource; the rest of the resource can be necessary for correct page functionality. So we believe that webextensions like NoScript Security Suite and uMatrix Origin are good but do not protect the user from accidentally allowing malicious code.

JavaScript Zero [37] (also known as Chrome Zero\(^11\)) expects that a user lets the browser run the vulnerable code and focuses on mitigating T4. Even most skilful users can run malicious code if the script URL evades blocklists and other parts of the code are needed for the page to display correctly. However, the practical implementation supports only Chromium-based browsers, is not maintained since 2017, and Shusterman et al. [54] have shown that the web page can obtain access to the original API calls.

Web API Manager [57] classifies JavaScript APIs into 81 standards\(^12\). A Web API Manager webextension user can disable all functionality defined by any of the standards. The authors prepared three configurations with standards blocked depending on their benefits and costs [57]. Web API Manager is most effective against T2 and not targeted T1, but it can help mitigate other threats. Unfortunately, Web API Manager does not allow a user to disable only a part of the standard, e.g. it is not possible to enable Canvas API for drawing but disable reading. Note that canvas fingerprinting is based on the reading [38]. Additionally, the webextension

\(^7\)https://www.w3.org/TR/2021/CRD-generic-sensor-20210729/#main-privacy-security-threats
\(^8\)https://noscript.net/
\(^9\)https://github.com/gorhill/uMatrix
\(^10\)https://httparchive.org/reports/page-weight?start=earliest&end=latest&view=list&reqhs
\(^11\)https://github.com/IAIK/ChromeZero
\(^12\)https://github.com/snyderp/web-api-manager/tree/master/sources/standards
is no longer maintained\textsuperscript{13}, it is not compatible with Firefox Multi-Account Containers\textsuperscript{14}, and it suffers from the Firefox bug related to Content Security Policy (CSP)\textsuperscript{39}. A Web API Manager user with a tailored configuration can potentially be uniquely identified with the JavaScript enumerating code developed by Schwarz et al.\textsuperscript{51}. As discussed below, we also studied two fingerprinting detection extensions, namely A Fingerprinting Monitor For Chrome (FP-MON)\textsuperscript{15} and Don’t FingerPrint Me (DFPM)\textsuperscript{15}. Both extensions are not maintained anymore and are not available in webextension stores.

3.2 Privacy-focused browsers

Tor is a network of onion routers that allow relaying TCP connections so that the server does not learn the IP address of a client but an IP address of their Tor exit node. Tor Browser is a Firefox fork that tries to make every instance as uniform as possible. For example, every user should browse with the same window size. However, a fingerprinter can still learn some information like the underlying operating system\textsuperscript{31}. Tor Browser also disables several APIs like WebGL. Consequently, Tor Browser is a very good solution to tackle threats T1, T2, T3, and T4.

Nevertheless, Tor Browser users should not resize the window and install additional webextensions. These requirements downgrade comfort, and users might be unwilling to abandon favourite webextensions or be tempted to resize the window for more comfort. As the communication is relayed multiple times by relays spread worldwide, latency increases, and throughput is limited. Moreover, malicious actors often misuse Tor. The list of Tor exit node IP addresses is public. Some services block Tor traffic, either to prevent frequent attacks or as a temporary measure to block an attack.

Brave browser is a Chromium fork that focuses on privacy. For example, it has a built-in blocker and anti-fingerprinting solution. Using Brave is a good option to tackle T1, T3, and T4. A disadvantage is the long build time. Often, it is not available in GNU/Linux distribution repositories.

Mozilla is working on integrating fingerprint resisting techniques from Tor Browser\textsuperscript{16} to Firefox (Firefox Fingerprinting Protection, also known as resist fingerprinting). However, the work is not done, and it is a possible related research question if the hiding in the herd strategy makes sense before it is adopted for all users. Moreover, inconsistencies arise. For example, Tor Browser does not implement WebGL. As Firefox adopts fingerprinting protections from Tor Browser, Firefox modifies readings from a 2D canvas and does not modify a WebGL canvas. That creates a false sense of protection.

3.3 Current browser fingerprinting countermeasures

Modifying the content of fingerprints is a valid choice to resist a fingerprinting attempt. However, each modification may create an inconsistency that may improve the fingerprintability of the browser\textsuperscript{31}. Currently, three anti-fingerprinting approaches exist.

(1) Create homogeneous fingerprints. If the commonly used fingerprinting APIs returned the same values in every browser, a fingerprinter would not be able to construct a fingerprint and tell the users behind the browsers apart. The leading representative of this approach is Tor Browser. Unfortunately, homogeneous fingerprints have an inherent downside of following specific rules to be effective. Most importantly, the effectiveness of the approach depends on the broad coverage of the blocked APIs and the size of the population employing the countermeasures. All browsers with the same fingerprint form an anonymity set\textsuperscript{45}. An observer cannot distinguish between browsers in the anonymity set. With every missed fingerprintable attribute, the anonymity set breaks into smaller sets. For example, Tor Browser strongly recommends using a specific window size. Suppose a user changes the window size to a value different from all other Tor Browser users. In that case, a fingerprinter can identify the user solely by this attribute. Moreover, Tor Browser hides the IP address of the user. A webextension cannot hide or mask the IP address.

(2) Change the fingerprints on different domains to disable cross-domain linkage. Brave browser modifies the results of APIs commonly used for fingerprinting. Its goal is to create a unique fingerprint for each domain and session. As the output of APIs commonly used for fingerprinting changes for every visited domain, it cannot be used for cross-domain linking of the same browser.

(3) Detect and block fingerprint attempts. A protection tool can monitor access to properties commonly misused for fingerprinting and block access to additional properties or limit the page ability to upload the fingerprint. To reliably prevent sharing the fingerprints with trackers, any network traffic to the tracking server has to be blocked, and the web page cannot have an opportunity to store the fingerprint for retrieval after page reload. Such measures can be effective against fingerprinting. Nevertheless, they also impose severe restrictions on web applications, limit overall usability, and break page behaviour. Fingerprinting detection can also be imprecise. In practice, it takes time to detect that a fingerprint is indeed being computed. As a page can immediately send the values being read for fingerprinting to the server, the server can learn a partial fingerprint before the fingerprinting is detected and blocked.

4 JSHelter Design Decisions

As the current state-of-the-art covered in Sect. 3 suggests, there is no perfect and straightforward solution for the threats raised in Sect. 2. This section covers the design decisions of JShelter and the countermeasures we decided to implement.

JShelter goals are as follows:

(1) Create a webextension because webextensions work across multiple browsers and consequently can be easily installed into any browser that supports webextensions, including Firefox and all browsers based on Chromium.

(2) Do not create a perfect solution, instead focus on what other webextensions lack: a consistent approach to the threat T1 and protection from T2, T3, and T4.

(3) Let people with different knowledge depths use the extension.

Chrome Zero\textsuperscript{37} and Web API Manager\textsuperscript{57} were the inspiration for JShelter. Chrome Zero applies protection based on closures
and Proxy objects and focuses on microarchitectural attacks. Web API Manager provides a way to disable browser APIs selectively. Both Chrome Zero and Web API Managers are no longer maintained.

Currently, JShelter offers three types of protections. (1) JavaScript Shield (JSS) modifies or disables JavaScript APIs. It aims at threats T1, T2 and time-measurement-related protection for T4. (2) Fingerprint Detector (FPD) provides heuristic analysis of fingerprinting behaviour and tackles T1. (3) Network Boundary Shield (NBS) monitors the source and destination of each web request and detects attempts to misuse the browser as a proxy to the local network (T3).

4.1 Fingerprint Detector
Fingerprint Detector (FPD) monitors APIs that are commonly used by fingerprinters and applies a heuristic approach to detect fingerprinting behaviour in real-time (see threat T1). When a fingerprinting attempt is detected, FPD notifies the user. The user can configure JShelter to reactively block subsequent asynchronous HTTP requests initiated by the fingerprinting page and clear the storage facilities where the page could have stored a (partial) fingerprint. However, this behaviour may break the page. The goal of the aggressive mode is to prevent the page from uploading the full fingerprint to a server. However, the fingerprinter can gradually upload detected values, and a partial fingerprint can leak from the browser.

We chose the heuristic approach as many prior studies [2, 13, 25, 31] proved it to be a viable approach with a very low false-positive rate. JShelter heuristics count calls of JavaScript API endpoints, which are relevant for fingerprinting detection, performed by a web page. FPD is not based on code analyses, so it overcomes any obfuscation of fingerprinting scripts. FPD builds upon recent knowledge in the field:

(1) Iqbal et al. [25] measured the relative prevalence of API keywords in fingerprinting scripts and created a list of APIs using the ratio metric. FPD observes wrappable endpoints that are frequently misused (at least 10 occurrences counted by Iqbal et al.).

(2) Additionally, FPD includes heuristics proposed by Englehardt and Narayanan [13] to detect additional fingerprinting techniques. These techniques often require more steps to produce a fingerprint (e.g. canvas fingerprinting). FPD heuristics use groups to define these steps regardless of the order.

(3) We looked through the source code of fingerprinting tools like FingerprintJS [17], Am I Unique [18] and Cover Your Tracks [19]. Furthermore, we analysed FPMON [15] and DFPM [20]. Finally, we pick all the relevant endpoints and group them by their semantic properties. We further adjusted the weights during testing.

FPD provides a report that summarises FPD findings on the visited web page, see Fig. 2. The report aims to educate users about fingerprinting and clarifies why FPD notified the user and optionally blocked the page. Additionally, the report can be generated from passive observation of a web page (no API blocking). We expect that other researchers will use passive FPD to study fingerprinting in more detail.

![Figure 2: An excerpt from an FPD report on AmlUnique.org. The user can clearly see what APIs the visited page called.](https://coveryourtracks.eff.org/)

We expect that the APIs for fingerprinting will change in time so we designed the heuristics to be as flexible as possible. We expect to run periodic web crawls based on the tools initially developed by Snyder et al. [56] and apply machine learning to FPD.

4.2 JavaScript Shield
JSS focuses on spoofing timestamps (threat T1 and T4), fingerprint modifications (threat T1) and limiting APIs available to visited pages (threat T2). JSS offers three predefined profiles that we expect users should use.

Profile P1 focuses on making the browser appear differently to distinct fingerprinting origins by slightly modifying the results of API calls differently on different domains so that the cross-site fingerprint is not stable [40, 46]. The focus is on applying security countermeasures that are likely not to break web pages. However, as some modifications break some pages. If FPD does not detect fingerprinting attempt, JShelter allows users to apply another profile (P2) that does not apply fingerprinting protections but incorporates other security protections.

Profile P3 focuses on limiting the information provided by the browser by returning fake values from the protected APIs. Some are blocked completely, some provide meaningful but rare values, and others return meaningless values.

P2 and P3 make the user fingerprintable because the results of API calls are generally modified in the same way on all websites and in each session.

JShelter currently modifies 113 APIs, which include APIs considered by previous works of Schwarz et al. [37], Iqbal et al. [25], Snyder et al. [57] and APIs that Apple declined to implement. For each API, we decide its relevance on an individual basis. Usually, we do not modify APIs already explicitly permitted by the user. However, the analysis might provide an example where the user still wants to limit the precision of the API. For example, Geolocation API allows the page to learn a very precise location while the user might be interested in services in the city. Hence, JShelter allows fine-tuning the precision of the Geolocation (and other APIs).
Additionally, the slightest mismatch between the results of two APIs can make the user more visible to fingerprinters [31, 51, 60]. Hence, we consider each protection that we decide to implement in JShelter from the point of fingerprintability, the threat of leaking information about the browser or user and other threats presented in Sect. 2. JShelter tries to mimic a stationary device with consistent and plausible readings.

4.2.1 Farbling-like prevention of browser fingerprinting. JSS applies the same or very similar anti-fingerprinting modifications as Farbling implemented in Brave. Farbling is, in turn, based on Privaricator [40] and FPRandom [46]. JSS modifies the values readable by page scripts with small lies that differ per origin. These little lies result in different websites calculating different fingerprints. Moreover, a previously visited website calculates a different fingerprint in a new browsing session. Consequently, cross-site tracking is more complicated.

Datta et al. [9] evaluated several anti-fingerprinting approaches. Nevertheless, JShelter was not evaluated by Datta et al. as the project did not exist during the time they performed their study. JShelter would not apply many modifications to properties studied by Datta et al. because Datta et al. focused on properties that allow determining browser and operating system versions. We do not see a way to consistently spoof operation system, browser, and the version from a web extension. Consequently, JShelter does not try to partially spoof such information as that would make the browser more fingerprintable. Indeed, Datta et al. found all webextensions not masking more than 50% of the studied attributes. Additionally, Datta et al. [9] prefer the approach of Torbrowser. Their expectation is that one anti-fingerprinting approach "could become nearly universal in the future". We develop JShelter for the current web where it is used only rarely. Furthermore, Datta et al. [9] do not provide a sound comparison of homogeneous fingerprints and little lies as they "assume any modifications of an attribute renders that attribute useless to a tracker". We expect that a fingerprinter can use the spoofed values in the fingerprint so our approach is to confuse the fingerprinter with little lies.

4.2.2 Interaction between JavaScript Shield and Fingerprint Detector. Both JSS and FPD aim to prevent fingerprinting. Both are necessary for JShelter.

- The blocking mode of FPD breaks pages. Users are typically tempted to access the content even when they know they are being fingerprinted. Consequently, they turn FPD off for such pages. JSS ensures that these users are not linkable across origins and sessions.
- JSS profiles P2 and P3 likely provide the same fingerprint for all domains; hence, we strongly advise users of this profile to activate FPD.
- We expect most users to stick with the default profile creating little lies. Future research should validate the current approach. For example, JShelter and Brave create indistinguishable changes to canvas readings. These are sufficient for a fingerprinter that creates a hash of the readings. Nevertheless, an advanced fingerprinter might, for example, read the colours of specific pixels to determine a presence of a font (different fonts produce a different pixel-wise-long output of the same text). As both Brave and JShelter modify only the least significant bit of each colour, the fingerprinter can ignore this bit and get the information on installed fonts. Hence, we believe that FPD is beneficial as it offers additional protections.

4.2.3 Sensors. JShelter tries to simulate a stationary device and consequently completely spoofs the readings of AmbientLight, AbsoluteOrientation, RelativeOrientation, Accelerometer, LinearAcceleration, Gravity, Gyroscope, and Magnetometer sensors. JShelter also spoofs Geolocation API that can be either completely blocked or return a modified location derived from the reading from the original API.

Instead of using the original data, JShelter returns artificially generated values that look like actual sensor readings. Hence the spoofed readings fluctuate around a value that is unique per origin and session. The readings are performed consistently in the same origin tabs, so the same sensor produces the same value in each tab.

We observed sensor readings from several devices to learn the fluctuations of stationary devices in different environments. Most of the sensors have small deviations. However, magnetometer readings have big fluctuations. JShelter simulates Magnetometer fluctuations by using a series of sines for each axis. Each sine has a unique amplitude, phase shift, and period. The number of sines per axis is chosen pseudorandomly. JShelter currently employs 20 to 30 sines for each axis. Nevertheless, the optimal configuration is subject to future research. More sines give less predictable results at the cost of increased computing complexity.

The readings of the acceleration and orientation sensors are generated consistently between each other from an initial device orientation that JShelter generates for each origin and session.

4.2.4 User in Control. The number of modified APIs is high. We expect that users will encounter pages broken by JShelter or that do not work as expected. For example, the user might want to play games with a gamepad device on some pages or make a call on others.

JSS allows each user to fine-tune the protection for each origin. Some users reported that they would prefer to avoid digging into the configuration. Those can disable JSS for the domain with a simple ON/OFF popup switch. More experienced users can react to information provided by FPD and turn off JSS fingerprint protection when the visited site does not behave as a fingerprinter. The most experienced users can fine-tune the behaviour per API group. Figure 3 shows an example of a user accessing a page that allows video calls. The user sees the groups with APIs that have been called by the configured JSS and FPD. The user can react to the configuration. Those can disable JSS for the domain with a simple ON/OFF popup switch.
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al. [37] in Chrome Zero. However, Chrome Zero was a proof-of-concept with no modification in the last four years. Shusterman et al. [54] identified several problems with Chrome Zero:

1. Unprotected prototype chains (issue 1): the original implementation is available through the prototype chain because Chrome Zero protects a wrong property.
2. Delayed JavaScript environment initialisation (issue 2): Current webextension APIs lack a reliable and straightforward way to inject scripts modifying the JavaScript environment before page scripts start running. JShelter and Chrome Zero allow configurable protection that may differ per origin, so they need to load the configuration during each page load. Hence, a naive implementation with asynchronous APIs may allow page scripts to access original, unprotected API calls. Note that once page scripts can access the original API implementation, they can store the unprotected version. There is no way (for a webextension) to reverse the leak.
3. Missed context (issue 3): Chrome Zero does not apply protection in iframes and worker threads.

In addition, Firefox suffers from a long-standing unfixed bug [39] that prevents up to 10% of Firefox webextensions from working correctly on pages whose Content Security Policy (CSP) forbids inline scripts [24] (issue 4).

To cope with issue 1, JShelter needs to identify the correct method to protect. For example, performance.now() yields precise timestamps. However, the method now is not a method of the performance object, but it is rather available through prototype chain from Performance.prototype. We tackle this issue in two steps. (1) Before we implement a protection, we analyse the prototype chain and pick the correct object implementing the property or method to wrap. Left alone, this approach is brittle: it can be broken by changes in the DOM APIs specification or by browser implementation. Therefore, JShelter applies an additional step. (2) The injection code checks at runtime whether the property (or method) is actually implemented as an own property by the object defined in step 1 or if the property is available through the prototype chain. In the latter case, JShelter replaces the correct property by traversing the prototype chain and overriding the step 1 choice.

To overcome issues 2–4, we needed to develop a reliable cross-browser early script injection. As the same issues affect several privacy and security webextensions, we refactored the code from NoScript Security Suite into NSCL and made it publicly available for reusing and contributing back.

NSCL abstracts common functionality shared among security and privacy webextensions. The goal is to minimise the development and maintenance burden on webextension maintainers. Shared common code paths between webextensions lead to more code review. As the browser APIs often provide multiple ways to achieve the same goal, a shared code between webextensions prevents feature mismatches. For example, an attacker can access an API through the window object, an iframe, or a worker. A webextension modifying the API needs to modify each possibility. By modifying only some ways to access the API, the webextension not only gives an attacker the possibility to learn original values offered by the API but also reveals that the browser behaves strangely. Additionally, NSCL provides consistent implementation across multiple browser engines. Hence, developers do not need to study browser-dependent implementation details.

The NSCL tackles issue 2 in its DocStartInjection module\textsuperscript{22}. NSCL allows to preprocess URL-dependent configuration inside a BeforeNavigate event handler. This event is fired every time the browser starts loading a new page. As the event handler has access to the destination URL, JShelter can build a configuration object in advance. Later, the JShelter content script can access the configuration during the document start event (before any page script can run). However, this technique does not always succeed due to race conditions. As a safety net, when the content script finds no configuration object, it calls SyncMessage API to retrieve the correct settings before it is interleaved with concurrent scripts.

To address issue 3, manifest.json (the configuration of the webextension) registers code injection into all the newly created windows, including subframes. Unfortunately, this alone cannot prevent dynamically created windows and frames from being exploited by the originator page to retrieve unwrapped objects as window.open(), contentWindow, and contentDocument.window allow access to a new window object immediately after its creation (synchronously) before any initialisation (including the injection of webextension content script) occurs. To fix this problem, NSCL patchWindow() API modifies window.open(), contentWindow, and contentDocument.window to recursively wrap the newly created window just before it gets returned\textsuperscript{23}.

A further possibility to access unwrapped APIs are subframe windows of all kinds, also immediately available at creation time by indexing their parent window as an unwrappable pseudo array (e.g., window[0] is a synonym of window.frames[0]). The NSCL takes care of this problem by automatically patching all not yet patched window[n] objects every time the DOM structure is modified, potentially creating new windows. This requires accounting for all methods and accessors by which the DOM can be changed in JavaScript and wrapping them\textsuperscript{24}.

Regarding web workers, JShelter disables them by default. The NSCL provides another option: wrapping workers by injecting the wrappers in their own browser context via its patchWorkers() API. The implementation is very complex and still experimental\textsuperscript{25}. It needs more testing before it can be confidently deployed to a general audience.

\textsuperscript{22}https://github.com/hackademix/nscl/blob/20220330/service/DocStartInjection.js
\textsuperscript{23}https://github.com/hackademix/nscl/blob/20220330/content/patchWindow.js#L247
\textsuperscript{24}https://github.com/hackademix/nscl/blob/20220330/content/patchWindow.js#L311
\textsuperscript{25}https://github.com/hackademix/nscl/blob/20220330/content/patchWorkers.js and https://github.com/hackademix/nscl/blob/20220330/service/patchWorkers.js
Finally, NSCL works around issue 4 by leveraging a Firefox-specific privileged API meant to safely share functions and objects between page scripts and WebExtensions. On Chromium, where such API is not available, but injected scripts have no special powers, and therefore, do not need those safety measures, NSCL provides shims to expose a uniform interface for injected code and reduce the burden of cross-browser development.

5 EVALUATION
This section evaluates the different JShelter parts.

5.1 Fingerprinting inconsistencies
Besides a few bugs that we intend to fix, we are aware that a fingerprinter may observe some inconsistencies. For example, JShelter modifies each read canvas. Should the page scripts probe a single-colour-filled canvas, JShelter would introduce small changes in some pixels. Hence, a page script might learn that protection against canvas fingerprinting is in place.

A naive implementation available in earlier JShelter versions modified all canvases of the same size in the same way. Hence a fingerprinter could have created two canvases, one for the fingerprinting and the other to learn what pixels are modified and consequently revert the modifications. We removed the vulnerability before anyone outside our team discovered the issue. Nevertheless, the little lies modifications (see Sect. 4.2.1) have a performance hit. For all APIs that allow obtaining hardware-rendered data like the Canvas, WebGL, and WebAudio APIs, JShelter needs to access all data in two iterations, first to create a hash that controls the modifications in the second iteration. Hence, the same content is deterministically modified the same way, and different content is modified differently.

Consider AudioBuffer.prototype.getChannelData allowing quick access to pulse-code modulation audio buffer data without data copy. A fingerprinter might be interested in a couple of samples only. However, the spoofing mechanism needs to access all data, so the method is much slower (learning that the time of getChannelData takes too long is usable for fingerprinting).

We are not aware of any isolated side-effect that reveals JShelter. For example, page scripts can detect some similar webextensions by calling Function.prototype.toString for the modified APIs. Should toString return the wrapping code modifying the API rather than the original value, it might reveal a unique text as other webextensions modifying the same API call by the same technique will likely use a different code. Nevertheless, we are aware and do not hide that users of JShelter are vulnerable to focused attacks. Our goal is to offer protections indistinguishable from another privacy-improving tool for each modified API. Nevertheless, a focused observer will very likely be always able to learn that a user is using JShelter if they aggregate the observable inconsistencies of all APIs produced by JShelter.

5.2 Timing events
JShelter implements rounding and, by default, randomises the timestamps as Chrome Zero does [37]. In comparison, Firefox Fingerprinting Protection and Tor Browser implement only rounding, which makes the technique visually easily detectable. Compared with Chrome Zero, JShelter modifies all APIs that produce timestamps, including events (see threat T1), geolocation, gamepads, virtual reality and sensors.

Computer clocks do not measure time accurately, but each has a built-in error. Previous research [29, 47, 53] established that such errors are unique to a device and observable on the network. Jireš [26] studied the influence of timestamp rounding (Tor Browser, Firefox Fingerprinting Protection) and rounding and randomisation (JShelter, Chrome Zero). He computed clock skew from rounded timestamps but could not remove the noise from rounded and randomised timestamps. However, this result should be validated; long-lasting (at least tens of minutes) measurements might remove the randomisation noise and reveal the clock skew. Nevertheless, Polčák and Franková [47] observed that timestamps provided by JavaScript are affected by time synchronisations (such as NTP). Hence, we advise combining JShelter round and randomisation with continuous-time synchronisation to hide built-in clock skew.

Biometrics cannot be forgotten or stolen [27]. However, JShelter forges timestamps from all JavaScript timestamp sources consistently. As the biometric feature computation is based on time tracking [27, 43, 44, 64], forged timestamps result in fake biometrical data.

5.3 Sensors
5.3.1 Sensor timestamp loophole. We discovered a loophole in the Sensor.timestamp attribute [27]. The value describes when the last Sensor.onreading event occurred in millisecond precision. We observed that the reported time is the time since the last boot of the device. Exposing such information is dangerous as it allows fingerprinting the user easily as devices boot at different times.

JShelter protects the device by provisioning the time since the browser created the page context (the same value as returned by performance.now()). Such timestamps uniquely identify the reading without leaking anything about a device. Future work can determine if such behaviour appears in the wild. If all devices and browsers incorporate the loophole, we should provide a random boot time.

5.3.2 Fake magnetometer evaluation. Figure 4 shows readings from a real and fake magnetometer. The left part (a) shows a stationary device. The magnetic field is not stable due to small changes in Earth’s magnetic field and other noise. The middle part of the figure (b) shows a device that changed its position several times during the measurement. We analysed traces of sensor readings collected in various locations and environments. Fig. 4 (c) shows readings generated by JShelter fake magnetometer. The values look like actual sensor readings. Nevertheless, the generator uses a series

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[27] Tested with Samsung Galaxy S21 Ultra; Android 11, kernel 5.4.6-215566388-abG998XXX3AUE1, Build/BP1A.200720.012.G998XXX3AUE1, Chrome 94.0.4606.71 and Kiwi (Chromium) 94.0.4606.56 and Xiaomi Redmi Note 5; Android 9, kernel 4.4.156-perf+, Build/9 FKQ1.180901.001, Chrome 94.0.4606.71
of constants whose optimal values should be the subject of future research and improvements.

5.4 Fingerprint Detector Effectivity

The FPD heuristics were designed to keep the number of false positives as low as possible. As FPD can optionally block all subsequent requests by a fingerprinting page, JShelter provides complementary protections, FPD blocks only indisputable fingerprinting attempts. We conducted real-world testing of FPD and refined its detection heuristics accordingly.

regarding testing methodology, we manually visited homepages and login pages of the top 100 websites from the Tranco list. We randomly replaced inaccessible websites by websites from the top 200 list. Before visiting a website, we wiped browser caches and storage to remove previously-stored identifiers. Hence, the visited pages may have deployed fingerprinting scripts more aggressively to identify the user and reinstall the identifier.

To boost the probability of fingerprinting even more, we switched off all protection mechanisms offered by the browser. However, we blocked third-party cookies because our previous experience suggests that the missing possibility to store a permanent identifier tempts trackers to start fingerprinting. We repeated the visits with both Google Chrome and Mozilla Firefox.

We used FPMON, DFPM, and JShelter to find the ground truth. For each visited page, we computed its fingerprinting score. FPMON reports fingerprinting pages with colour. We assigned yellow colour 1 point and red colour 3 points. DFPM reports danger warnings. If DFPM reports one danger warning, we assign 1 point.

Table 1 shows the accuracy and the sum of true positives and true negatives of the tested tools. In total, we tested 98 home pages and 81 login pages; 2 home pages are actually login pages, we removed duplicate login pages, and some sites do not have a login page. JShelter is more accurate in fingerprinting detection when compared with the scenario when FPMON and DFPM have low confidence in fingerprinting detection (they score 1 point). JShelter is slightly worse compared to the scenario in which the other tools are confident that they detected fingerprinting. The differently evaluated pages are typically borderline cases. For example, JShelter does not detect fingerprinting on Google and Facebook login pages, while both FPMON and DFPM detect fingerprinting. As the number of accessed APIs is not high and users would likely turn FPD off for these pages, we do not intend to modify FPD heuristics.

5.5 Network Boundary Shield

5.5.1 Localhost Scanning. Some web pages, like ebay.com, scan (some users) for open local TCP ports to detect bots with open remote desktop access or possibly to create a fingerprint. The web page instructs the browser to connect to the localhost (127.0.0.1) and monitors the errors to detect if the port is opened or closed.

When we first encountered the eBay port scanning case, we knew that this behaviour should trigger NBS as the requests cross network boundaries. We accessed ebay.com, detected the scanning by Web Developer Tools (Fig. 5) and checked that NBS is indeed triggered and works as expected.

When we developed NBS we did not anticipate localhost port scanning. When we first encountered the eBay port scanning case, we knew that this behaviour should trigger NBS as the requests cross network boundaries. We accessed ebay.com, detected the scanning by Web Developer Tools (Fig. 5) and checked that NBS is indeed triggered and works as expected.

5.5.2 Comparison with Private Network Access. Recently, Google announced Private Network Access (PNA) that should become W3C standard. PNA solves the same problem as NBS, but the solution is different. PNA-compatible browsers send HTTP Requests to the local networks with the additional header:

Access-Control-Request-Private-Network: true.

Table 1: Tested Tools Accuracy Based on the Manual Crawl of the Top 100 Web Pages According to the Tranco List.

|                | Home Pages | Login Pages |
|----------------|------------|-------------|
| JShelter       | fingerprinting detected | 96 (98.0%) | 77 (95.1%) |
| FPMON          | red        | 79 (80.6%) | 66 (81.5%) |
|               | red or yellow | 96 (98.0%) | 80 (98.8%) |
| DFPM           | two or more dangers | 70 (71.4%) | 66 (81.5%) |
|               | at least one danger | 98 (100%) | 81 (100%) |

28https://tranco-list.eu/list/23W9/1000000
29https://developer.chrome.com/blog/private-network-access-preflight/
30https://w3c.github.io/private-network-access/
The local resource can allow such access with HTTP reply header Access-Control-Allow-Private-Network: true. If it does not, the browser blocks the access.

NBS works differently. Firefox version leverages DNS API to learn that a public web page tries to access the local network and blocks the request before the browser sends any data. Chromium-based browsers do not support DNS API, so the first request goes through. NBS learns the IP address during the reply processing. NBS blocks any future request before it is made once it learns the IP address during the reply processing. Hence, NBS limits the network bandwidth and prevents any state modification on a local node that may be caused by a request going through, except for the learning phase in Chromium-based browsers. Both approaches solve threat T3; it is up to the user what solution they prefer.

Note that Google plans to fully deploy Chrome PNA in version 113, so Chrome users without JShelter or another webextension with similar capabilities are not protected at the time of the writing of this paper.

5.6 Feedback from users

JShelter is available in addons.mozilla.org, Chrome Store, and Opera Store from the early development stages. We employ the release early, release often strategy, but we do not release early if we are concerned about possible security bugs in the new version.

Some users found JShelter immediately after initial upload to webextension sites. Nevertheless, the number of users increased massively only after an announcement by Free Software Foundation. Figure 6, shows JShelter users in time in Firefox and Chrome. The graph shows that JShelter has an audience and users want to control their browsers. However, many users stopped using the extension after a trial period. The decline in 2021 and 2022 seems to be reverted and JShelter gains users. The trend is clear for Chrome users, the number of new Firefox users is smaller.

Based on the feedback from users, one of the reasons for the decline was that they encountered too many broken or slow pages. After we focused on fixing broken pages the decline slowed down.

Figure 5: eBay web page scanning the local computer for open ports.

Another reason is that users do not understand the little lies fingerprint prevention. They want to hide in the crowd (see Sect. 3.3). The most controversial protection is WebGL vendor, unmasked vendor, renderer, and unmasked renderer spoofing. We do not know any list of real-world strings, and even if we knew, we are not sure if we could avoid inconsistencies. Hence we decided that the threat model defending from a fingerprinter not focused on revealing JShelter users allows for the generation of random strings per origin and session for the little lies JSS profile (see Sect. 4.2).

Some users do not understand the explanation even though we highlight that similar randomly generated strings are already available through MediaDevices.prototype.enumerateDevices, the created profile is unique by design.

A common problem is that users do not understand what JShelter is doing and that several modules work in parallel and can be enabled and configured separately. We tweaked the UI several times to make the UI as straightforward as possible and we added explanations and want to add even more explanations (for example, to the popup window).

JShelter users also reported false-positive NBS detections when using DNS-based filtering programs. Some DNS-based filters return the localhost IP address for any blocked domain. In that case, NBS correctly detects that a public page tries to access a local resource, blocks the request, and notifies the user. We suggest that users reconfigure their DNS blocker to return 0.0.0.0 (invalid address). We also added options to turn notifications completely off as some users do not want to be notified at all. We limited the number of notifications if they are enabled and the web page accesses local nodes during a short time frame. Additionally, we added explanation texts. Users do not report issues with NBS notifications anymore.

Many webextensions report the number of blocked elements in the badge icon. Previous research projects like Chrome Zero depicts currently applied protections. Early JShelter versions reported applied level as well, but the feedback preferred showing the number of blocked elements and using colours. We decided to (1) report the number of accessed API groups and (2) report the likelihood of fingerprinting as a colour starting from shades of green through yellow to shades of red. Figure 7 shows examples of badged icons that received positive reception.
JShelter: Give Me My Browser Back

Figure 7: Interactive badge icons.

6 CONCLUSION

Previous research established that browser security, privacy, and customizability are important topics [5, 12, 20, 31, 36, 37, 47, 61]. The imminent danger of third-party cookie removal forces trackers to employ even more privacy-invading techniques. Real-time bidding leaves users easy targets for various attacks, including gaining information about other applications running on the local computer [42]. Moreover, continuous additions of new JavaScript APIs open new ways for fingerprinting the browsers and gaining additional knowledge about the browser or user preferences and physical environment. One of the major concerns is a need for more effective tools that everyday user wants to use. Current methods to tackle web threats are list-based blockers that might be evaded with a change of URL, specialised browsers, or research-only projects that are quickly abandoned.

In contrast, JShelter is a webextension that can be installed on major browsers and does not require the user to change the browser and routines. We integrate and improve several previous research projects like Chrome Zero [37], little-lies-based fingerprinting prevention [40, 46], and ideas for limiting APIs brought by Web API Manager [57]. JShelter comes with a heuristic-based fingerprint detector and prevents web pages from misusing the browser as a proxy to access the local network and computer. We solved issues with reliable environment modifications that stem from insufficient webextension APIs that open many loopholes that previous research exploited [54]. Nevertheless, at the time of the writing of this paper, JShelter does not allow to use Web Workers, which breaks some pages. Besides JShelter, we introduced NSCL. Both NoScript Security Suite and JShelter include NSCL. Moreover, NSCL is available for other privacy- and security-related webextensions.

In cooperation with Free Software Foundation, we aim for long-term JShelter development; thus, users’ privacy and security should be improved in the future.

7 ACKNOWLEDGEMENT

This project was funded through the NGl0 PET Fund, a fund established by NLnet with financial support from the European Commission’s Next Generation Internet programme, under the aegis of DG Communications Networks, Content and Technology under grant agreement No 825310 as JavaScript Restrictor and JShelter projects. This work was supported in part by the Brno University of Technology grant FIT-S-20-6293 and FIT-S-23-8209. We thank Martin Bednář for capturing Figure 5.

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