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PREVENTION OF PASSIVE BROWSER FINGERPRINT- ING

PREVENCE PŘEDÁVÁNÍ PASIVNÍHO OTISKU PROHLÍŽEČE

TERM PROJECT

SEMESTRÁLNÍ PROJEKT

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Abstract

This diploma thesis aims to design a new protection layer against passive browser fingerprinting, which complements existing protection against active fingerprinting in the JShelter web extension. The protection layer changes the values of selected HTTP headers and modifies the web browser environment to avoid inconsistencies.

Abstrakt

Cílem této diplomové práce je navrhnout novou vrstvu ochrany proti pasivnímu otisku prohlížeče, která komplementuje již existující ochranu proti aktivnímu otisku ve webovém rozšíření JShelter. Navržená ochranná vrstva upravuje hodnoty vybraných HTTP hlaviček a zároveň modifikuje prostředí webového prohlížeče aby zamezila případným nekonzistencím.

Keywords

fingerprint, browser fingerprint, passive browser fingerprint, privacy protection, web extension, JShelter, JavaScript, HTTP

Klíčová slova

digitální otisk, otisk prohlížeče, pasivní otisk prohlížeče, obrana soukromí, webové rozšíření, JShelter, JavaScript, HTTP

Reference

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Prevention of Passive Browser Fingerprinting

Declaration

Prohlašuji, že jsem tuto bakalářskou práci vypracoval samostatně pod vedením pana X... Další informace mi poskytli... Uvedl jsem všechny literární prameny, publikace a další zdroje, ze kterých jsem čerpal.

.....
Jozef Hruška
April 1, 2023

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Chapter 1

Introduction

Although more than 30 years have passed since the invention of the web back in 1989 [11], it is still an integral part of our lives, possibly more than ever before. People worldwide use the web daily to work, learn, consume content and connect with others. Every day our smartphones, tablets, laptops, or even smartwatches and fridges connect to the web.

This diverse ecosystem of devices created a need to identify users who use them uniquely. The ability to uniquely identify a user on a single device or across multiple devices allows applications to personalize the content they provide or improve their security. One of the methods of user identification is browser fingerprinting, the collection of data from the browser to create a fingerprint of the device. Just as a person's fingerprint can uniquely identify that specific person, given that we have enough data, we can uniquely identify a device and its user and act on this information.

However, gathering this kind of data can be considered a violation of privacy [10], which is the primary motivation behind creating privacy-first browsers and browser extensions to fight against fingerprinting. One of the browser extensions set on improving privacy is JSshelter¹ which focuses on preventing active fingerprinting.

Active fingerprinting is a method of obtaining a fingerprint, typically by running JavaScript code to collect data from browser APIs [17]. The other variant is passive fingerprinting, in which the data is collected solely from network traffic, for example, HTTP headers.

This work aims to design and implement a browser extension to prevent the collection of passive fingerprints by altering data in HTTP requests and explore possibilities of integrating this protection into JSshelter. It is important to note that the altered data must be consistent with the data obtainable through active fingerprinting methods. Otherwise, the fingerprinting application could recognize an attempt to mitigate the effects of fingerprinting.

Fingerprinting is an ever-evolving field. Chapter 3 describes its nature, history, and different approaches to collecting a fingerprint. The last two sections of chapter 3 provide an outlook on threats and opportunities fingerprinting brings to the table because, as we know, nothing is purely black and white.

As this work explores the capabilities of mitigating fingerprinting with the help of browser extensions, the following chapter 2.4 gives the reader an insight into the inner working of extensions.

¹JSshelter is an anti-malware browser extension to mitigate potential threats from JavaScript, including fingerprinting [3] (Available at <https://jsshelter.org/>).

Finally, the last chapter 5 proposes a design of passive fingerprinting protection that works consistently with active solutions to keep user-observable side effects to a minimum.

1.1 Definitions

- **Fingerprint:** A collection of device-specific characteristics gathered for the purpose of identification.
- **Fingerprinting:** The process of collecting the device information (data) to compute a fingerprint. Terms fingerprinting, device fingerprinting, and browser fingerprinting will be used interchangeably in the following chapters.
- **Fingerprinter:** An application performing fingerprinting, typically on a third-party remote server.

Chapter 2

Web browsers

In this chapter, the first section, 2.4.1, describes the WebExtensions API exposed by a browser to give extensions more capabilities. Recently, significant changes to the ecosystem of extensions were announced with the introduction of Manifest V3, described in section ???. The last section, 4, is dedicated to the JShelter extension on which this work builds.

2.1 History of web browsers

Web browsers have come a long way since the early days of the World Wide Web. From their humble beginnings as basic applications for viewing text-only web pages, modern browsers have evolved into the powerful tools we know today. Following paragraphs outline the evolution of browsers, highlighting a few of the most significant features added over the years.

The first browser, named WorldWideWeb¹, was created at CERN by Tim Berners-Lee only a year after he published the first World Wide Web proposal [11]. The very early browser aimed to demonstrate how the user-facing layer of the WWW (browsers) could work in the future. The browser was only available on the NeXTSTEP² operating system and had limited features.

One of the earliest features added to browsers was support for images. The Mosaic browser³, released in 1993, was the first to allow users to view images on the web, followed by support for tables, which allowed for more complex web page layouts.

As the web gained popularity, developers needed a way to make web pages more interactive and dynamic. The birth of JavaScript programming language addressed this need. JavaScript was first introduced in 1995⁴ by Netscape Communications Corporation to add interactivity to static HTML pages. Since then, it has become one of the world's most widely used programming languages, with a vast ecosystem of libraries and frameworks⁵.

Nowadays, web browsers expose a variety of JavaScript APIs that allow web developers to interact with the browser and its underlying components, such as the operating system or even the hardware. While it is true that these APIs gave the developers much-needed possibilities, they come at the cost of compromised privacy, described in detail in the following chapters.

¹<https://worldwideweb.cern.ch>

²<https://en.wikipedia.org/wiki/NeXTSTEP>

³[https://en.wikipedia.org/wiki/Mosaic_\(web_browser\)](https://en.wikipedia.org/wiki/Mosaic_(web_browser))

⁴https://en.wikipedia.org/wiki/Netscape_Navigator_2

⁵<https://www.npmjs.com/>

2.2 JavaScript

In its original form, JavaScript is a client-side language executed in the user's web browser rather than on a web server [14]. It allows applications to respond to user actions in real time without making a round trip to the server. However, the rise of popularity and the fact that JavaScript is a relatively developer-friendly language meant that, eventually, runtimes that allowed running JavaScript outside the browser emerged. The most popular JavaScript runtimes include Node.js⁶, Deno⁷, or Bun⁸.

2.2.1 ECMAScript

As the web was rapidly gaining popularity, developers started using JavaScript to create dynamic and interactive web pages. However, there was no standardization for the language, meaning different browsers implemented JavaScript differently. This made it difficult for developers to create web applications that worked consistently across different platforms and browsers [14].

In 1996, Netscape Communications Corporation, the company behind the Netscape Navigator web browser, submitted JavaScript to ECMA International⁹. This standards organization develops and maintains standards for several technologies, including programming languages. The goal was to create a standardized language version that could be implemented across different platforms and browsers.

ECMA International established a committee to develop a standardized scripting language, which was initially called ECMA-262. The standard's first version, ECMAScript 1, was released in June 1997. Since then, ECMAScript has undergone several revisions, the latest being ECMAScript 2022. Each standard version adds new features and capabilities to the language while maintaining backward compatibility with previous versions [14].

Although ECMAScript is technically the correct name for the language, JavaScript is used in the following chapters as the industry uses this name predominantly.

2.2.2 Web APIs

Web applications can use JavaScript Web APIs to interact with various web browser features and functionality. The number of available APIs depends on the browser. For example, at the time of the writing, Firefox had more than 100 APIs¹⁰, with more APIs still being added. Here is a short selection of Web APIs important to the topic of this thesis [19, 25]:

- **Canvas API:** Provides a way to dynamically create and manipulate graphics and animations in a web page using JavaScript.
- **Navigator:** Provides information about the web browser or user agent in which the code runs.
- **Web Audio API:** Provides advanced audio processing and synthesis capabilities, allowing developers to create interactive audio experiences on the web.

⁶<https://nodejs.org/>

⁷<https://deno.land/>

⁸<https://bun.sh/>

⁹<https://www.ecma-international.org/>

¹⁰<https://developer.mozilla.org/en-US/docs/Web/API>

- **WebGL:** Allows for creating and rendering interactive 3D and 2D graphics within a web browser using the computer’s graphics hardware capabilities.

All the APIs listed above are commonly used in fingerprinting to identify devices and their users uniquely [17]. Fingerprinting, the main focus of this thesis, is described more in-depth in the following chapter.

2.3 HTTP

HTTP (Hypertext Transfer Protocol) is a request-response protocol that allows web browsers to request resources from web servers and to receive responses that include the requested resources [22].

When a user types a URL into a web browser’s address bar, the browser sends an HTTP request to the server hosting the resource. This request typically contains information such as the request’s method, the URL of the requested resource, and any HTTP headers or other metadata associated with the request. The server then resolves the request and sends a response containing the response status code and body, among other things.

Web applications can also ask the browser to send HTTP requests on their behalf with the help of XMLHttpRequest (XHR)¹¹ or Fetch API¹² APIs. Web applications commonly transfer only minimal HTML and JavaScript with the first request to improve performance. Once loaded, this skeleton can load additional resources if needed.

2.3.1 Headers

The client and the server use HTTP headers¹³ to transfer additional information with the HTTP request or response. Headers consist of a case-insensitive name and a value separated by a colon (“:”). HTTP defines standardized headers for content negotiation, authentication, or passing additional context [24]. The protocol also allows the use of entirely custom headers.

When an application sends a request, the browser automatically includes default headers. Web applications can add additional headers or overwrite the default ones.

2.4 Browser extensions

Browser extensions, or add-ons, can modify and enhance the capability of a browser [6]. Users install extensions for various reasons, such as to increase security or productivity, remove ads, or modify the browser UI to their liking. Each browser implements extensions slightly differently, but to a large extent, most browsers follow the WebExtensions API standard.

This section describes the WebExtensions API standard mentioned before and the recently introduced Manifest V3, which significantly affects the ecosystem of browser extensions.

¹¹<https://developer.mozilla.org/en-US/docs/Web/API/XMLHttpRequest>

¹²https://developer.mozilla.org/en-US/docs/Web/API/Fetch_API

¹³<https://developer.mozilla.org/en-US/docs/Web/HTTP/Headers>

2.4.1 WebExtensions API

WebExtensions API, first introduced by Google in chromium-based browsers, is a set of special-purpose APIs the browser provides to installed extensions. Firefox¹⁴, Safari¹⁵, and Opera¹⁶ have become widely compatible with the WebExtensions API, making it the standard across all major web browsers. This broad adoption allowed developers to create cross-browser extensions with minor changes to the original codebase.

WebExtensions API provides a wide range of functionality for building browser extensions, including access to browser tabs and windows, manipulating web pages and user settings, and interacting with other extensions and websites [2].

WebExtension API differs from the standard JavaScript Web APIs described in the previous section. Applications use the standard Web APIs to interact with the content and functionality of a web page. In contrast, extensions use the WebExtensions APIs to interact with the browser itself. Some of the interfaces provided by the WebExtensions API are [2]:

- **Cookies API:** Allows to query and modify cookies. Extensions can also configure a callback function browser calls whenever a particular cookie changes.
- **DeclarativeNetRequest API:** Allows to block or modify network requests by specifying declarative rules. This API allows extensions to modify requests without giving them direct access to their content.
- **History API:** Allows interaction with the browser's record of previously visited pages. Extensions can add, remove, and query for URLs in the browser's history.
- **Tabs API:** Allows interaction with the browser's tab system. Extensions can create new, modify, or rearrange existing tabs.

The WebExtensions API is easy to use and provides consistent interfaces and functionality across different browsers. Lately, a push for increased security and privacy rules for extensions resulted in Manifest V3, described more in-depth in the following section.

2.4.2 Browser extension architecture

Extensions, in their essence, are lightweight software modules that are running in the browser. Every extension acts independently from the browser and all other installed extensions. Like regular web pages, extensions are developed using HTML, CSS, and JavaScript.

A typical architecture of a browser extension consists of several components that work together to achieve the desired functionality. These components include [2]:

- **Manifest file:** A required JSON file in the root of the extension source directory that contains metadata about the extension, such as its name, version, description, and permissions. It also defines the various components of the extension and their roles.
- **Service workers (background scripts):** JavaScript files that run in the background and handle the core logic of the extension. They manage persistent states, listen for browser events, and interact with Web APIs.

¹⁴<https://developer.mozilla.org/en-US/docs/Mozilla/Add-ons/WebExtensions>

¹⁵https://developer.apple.com/documentation/safariservices/safari_web_extensions

¹⁶<https://dev.opera.com/extensions/apis>

- **Content scripts:** JavaScript files that run in the context of a web page and have access to the DOM of that page. They enable the extension to read or modify the content of web pages and interact with user actions. Content scripts run in an isolated environment, limiting their access to the same-origin policy of the web page.
- **Popups:** An optional user interface that provides a quick and easy way for users to interact with the extension. It usually appears when a user clicks on the extension's icon in the browser toolbar. Popups are transient and close when they lose focus.
- **Options:** An optional user interface that allows users to configure the settings and preferences of the extension. The options page is accessible through the browser's extension management interface.

In summary, the typical architecture of a browser extension involves a Manifest file that points to other files this extension defines.

Manifest file

The Manifest file is the only file that must be present in every extension. The file must have the name 'manifest.json' and be in the extension's root directory.

Out of all the configuration fields the Manifest file supports, only three of these fields are mandatory, according to the Manifest file format documentation¹⁷:

- **manifest_version:** An integer value specifying the version of the Manifest file. Since June 2022, the only allowed value by the Chrome Web Store¹⁸ has been "3" for all newly added extensions. The January 2024 deadline, when the Chrome Web Store stops accepting updates to existing Manifest V2 extensions, has been postponed, meaning there is no official date for the end of life of Manifest V2.
- **name:** A plain text string identifying the extension in the Chrome Web Store and the Browser UI.
- **version:** A version string consisting of one to three integers separated by dots. Version numbers must be strictly incremental as the browser uses them to decide whether an extension should be updated.

Apart from the three mandatory fields, the Manifest file supports a wide range of other configuration options, including:

- **action:** An object defining the extension's button in the browser's toolbar. Clicking on this button opens the popup if the extension defines it. Otherwise, clicking this button will dispatch an event to the extension's background scripts.
- **background:** Used to include one or more background scripts. For newer Manifest V3 extensions, this configuration field is used to include service worker scripts. Extension service workers do not run on the main thread, meaning they do not interfere with extension content.

¹⁷<https://developer.chrome.com/docs/extensions/mv3/manifest/>

¹⁸<https://chrome.google.com/webstore/category/extensions>

- **permissions:** An array of string keys specifying the granular permissions the extension requires. The browser informs the user what permissions the extension requires during installation.

In January 2022, the Chrome Web Store began the long-awaited transition to the new version of the Manifest file, Manifest V3. The Manifest V3 represents one of the most significant shifts in the extensions platform since its launch [2]. According to the team behind the Chrome browser, it is an answer to raising concerns about privacy, security, and performance of browser extensions. The most notable changes compared to its predecessor Manifest V2 are [2]:

- **Service workers:** Manifest V3 replaces background pages¹⁹ with extension service workers, similar to traditional web service workers.
- **Network request modification:** In the outgoing Manifest V2, extensions could intercept and modify requests procedurally. In contrast, in the Manifest V3, extensions have to define rules and ask the browser engine to modify requests on their behalf. The primary motivation behind this change was privacy, as extensions could previously access requests with little or no limitations.
- **Support for Promises:** The Chrome team added Promise support to some WebExtensions APIs so that extension developers can use modern JavaScript features such as promise chains or async/await patterns.

Although welcomed from a privacy-concerned standpoint, these changes made it more difficult for developers to create extensions to protect from fingerprinting, mainly because of the network request modification differences.

```

1  [
2    {
3      "id": 10,
4      "priority": 2,
5      "action": {
6        "type": "modifyHeaders",
7        "responseHeaders": [
8          {
9            "header": "h1",
10           "operation": "remove"
11         },
12         {
13           "header": "h2",
14           "operation": "set",
15           "value": "v2"
16         },
17         {
18           "header": "h3",
19           "operation": "append",
20           "value": "v3"
21         }

```

¹⁹Manifest V2 extensions used background pages to run a single persistent script to manage tasks, or a state of the extension [1].

```

22     ]
23   },
24   "condition": {
25     "urlFilter": "headers.com/123",
26     "resourceTypes": ["main_frame"]
27   }
28 }
29 ]

```

Listing 2.1: An example of a declarative rule which modifies selected response headers [2].

Listing 2.1 shows an example of the new declarative rule syntax. The rule defined above modifies request headers, specifically removing a header named `h1`, changing the value of `h2`, and adding a new header, `h3`.

At the time of the writing, Manifest V2 extensions are transitioning to Manifest V3. Although no official date is set²⁰, the Chrome Web Store will eventually stop accepting updates to old Manifest V2 extensions. For this reason and to avoid confusion, this thesis will only consider Manifest V3 in the following chapters.

Service workers

Extension service workers represent a significant update in how browser extensions handle background tasks, focusing on enhancing security, privacy, and performance. Replacing the previously used background scripts, service workers offer more efficient resource management, better offline capabilities, and improved security features for browser extensions. This shift aligns with the ongoing evolution of web technologies²¹ and the need for a more secure and reliable foundation for extension development.

Service workers are event-driven, meaning they only run when needed, unlike persistent background scripts [2]. This reduction in resource consumption improves the overall performance of the browser. Additionally, service workers can cache resources and intercept network requests, enabling them to work efficiently even when the user is offline. This feature can enhance the responsiveness and reliability of extensions, even under poor network conditions.

Enhanced security is another significant benefit of service workers in Manifest V3 extensions. Running in a separate thread from the main browser process and having a limited scope, service workers help reduce the attack surface of extensions. With a more restrictive API surface compared to background pages, the risks associated with potential security vulnerabilities are minimized. Introducing service workers in Manifest V3 offers a more secure, efficient, and reliable foundation for developing browser extensions.

Service workers cannot access the DOM API as they are running in a separate thread. Extensions that want to modify the DOM must do so in an alternative API, such as the Offscreen API²².

Content scripts

Extension content scripts are an essential component of browser extensions that enable interaction with web pages displayed in the browser. They provide a means for the exten-

²⁰<https://developer.chrome.com/docs/extensions/migrating/mv2-sunset/>

²¹<https://developer.chrome.com/docs/extensions/mv3/intro/platform-vision/>

²²<https://developer.chrome.com/docs/extensions/reference/offscreen/>

sion to read or modify the content of a web page, access the DOM, and manipulate CSS styles. Content scripts bridge the gap between the isolated extension environment and the web pages it aims to enhance, enabling a wide range of functionality, from modifying the appearance of a website to implementing custom features.

Content scripts run in the context of the web pages they are injected into but maintain a separate JavaScript environment [2]. This separation ensures that content scripts do not directly interact with the JavaScript running on the web page, preventing potential conflicts or security issues. Despite the separation, content scripts can still communicate with the web page's JavaScript using custom events or other messaging mechanisms²³.

To use content scripts in a browser extension, developers must declare them in the extension's manifest file, specifying which scripts to inject and the conditions under which they should be injected, such as the URL patterns of the target web pages. Once configured, the browser extension can seamlessly augment or modify web pages, providing users with customized experiences and extended functionality tailored to their needs.

Popups

Extension popups are standalone HTML documents associated with the extension's button in the browser toolbar [2]. When a user clicks the button, the browser will show a popup. Popups are closed when a user either outside the popup or again on the extension's toolbar button.

Like standard web pages, the popup's HTML document can import external CSS and JavaScript files. Unlike standard web pages, however, the popup can access the WebExtensions API exposed by the browser. Of course, the extension can only access the APIs requested in the Manifest file.

Browsers wrap popups in a wrapper element to match the visual styling across all extensions. This wrapper element resizes automatically to fit the content of the popup, and extensions cannot modify their shape or other styles.

²³https://developer.chrome.com/docs/extensions/mv3/content_scripts/#host-page-communication

Chapter 3

Browser fingerprinting

Fingerprinting is a process of obtaining information about a user's device to construct a digital marker called a fingerprint. Applications can construct a fingerprint from various characteristics, such as information about the device hardware, operating system, and browser, or seemingly unimportant information, such as installed fonts or a language preference. Given that the selected characteristics are uncommon, either individually or in combination with others, applications can track devices until the characteristics change enough to affect the fingerprint.

Browser fingerprinting is a subcategory where the application tries to create a fingerprint from the information available in a browser [17]. As the main focuses of this theses are browsers and browser extensions, the term fingerprinting will be used predominantly over browser fingerprinting for ease of reading. Contrary to other identification techniques like cookies that rely on a unique identifier (ID) directly stored inside the browser, browser fingerprinting is qualified as entirely stateless. It does not leave any trace as it does not require storing information inside the browser [17].

The characteristics to construct a fingerprint may be collected either actively, typically by running a JavaScript code inside a browser, or passively by monitoring the network communication. Most characteristics commonly used for fingerprinting are obtainable only through the browser Web APIs [27]. For this reason, the majority of available anti-fingerprinting solutions focus primarily on mitigating the active fingerprinting.

The first section, 3.1, briefly tells the history of browser fingerprinting, from the time it was explored for the first time to its current form. Section 3.3 describes the most common fingerprinting countermeasures, and the third section, 3.4, compares the active and passive fingerprinting approaches fingerprinting applications use to collect data. The last section, 3.2, summarizes the threats and opportunities fingerprinting brings to the table.

3.1 History of browser fingerprinting

Laperdrix et al. [17] provide excellent insight into the history of browser fingerprinting. In 2009, Johnathan R. Mayer investigated [18] if remote servers could exploit the differences presented by browsers to deanonymize or uniquely identify their users. He conducted an experiment where he collected the contents of the `Navigator`, `Screen`, `Navigator.plugins`, and `Navigator.mimeTypes` objects of browsers that connected to the website of his experiment. Once collected, the contents were concatenated, hashed using the MD5 algorithm, and sent to a remote server for storage. Of 1328 clients, he uniquely identified 1278 (96.23%).

However, he added that the scale of his experiment was too small to draw any meaningful conclusions and that the hashing-based algorithm masks which properties contributed to the uniqueness.

A year later, in 2010, Peter Eckersley pushed the research of fingerprinting further when he conducted a Panopticlick experiment [13]. He obtained over 470 thousand fingerprints in this experiment, uniquely identifying 83.6%. The number of identified browsers was even higher if browsers supported Flash or Java. Out of these browsers, he was able to identify 94.2% uniquely.

Since these two works were published, fingerprinting became a standard in the industry thanks to easy-to-use solutions like FingerprintJS¹, which has an open-source core. This broad and rapid adoption of fingerprinting practices brought severe security and privacy implications [10], resulting in the growing popularity of solutions focusing on mitigating fingerprinting.

3.2 Understanding the impacts of fingerprinting

The practice of fingerprinting is widely recognized for its potential invasion of privacy. However, its impacts are not simply positive or negative like many things in life. This chapter explores the various effects of fingerprinting, including both its benefits and drawbacks. Additionally, real-world examples are provided to illustrate these impacts in practice.

3.2.1 Benefits of fingerprinting

The ability to uniquely identify a device and, by extension, its owner allows third parties to modify the behavior of their services and applications. One essential application of browser fingerprinting is to enhance security and user experiences.

Specifically, applications can utilize fingerprinting for payment fraud prevention and detection [9]. By doing so, they can block users who attempt to use stolen credit, debit, or checking information to make illicit transactions. In this context, fingerprinting serves as an additional layer of protection for both businesses and consumers, ensuring that financial transactions remain secure and trustworthy.

3.2.2 Drawbacks of fingerprinting

Fingerprinting, despite its numerous benefits, has gained popularity primarily due to its potential to violate users' privacy [10]. Tracking individuals over extended periods is possible until the device's characteristics change sufficiently to alter the fingerprint. This pervasive surveillance capability has raised concerns about balancing utility and personal privacy.

When a person is being tracked, applications can display advertisements or products tailored to the user based on their browsing history and online activity. This targeted marketing approach is designed to boost business sales, but it further highlights the potential intrusion of privacy associated with fingerprinting.

3.3 Fingerprinting countermeasures

Although not straightforward, to a certain degree, it is possible to fight against fingerprinting. Fingerprinting countermeasures are typically categorized followingly [15, 20]:

¹<https://fingerprint.com>

- **Creating a homogenous fingerprint:** Fingerprinting tries to find differences between devices to identify them. Hypothetically, if every device in the world had the same characteristics (and thus the same fingerprint), identification would not be possible because each device would be indistinguishable from others. However, every valuable device characteristic exposed to the fingerprinting application must be the same to create absolute homogeneity. If one or more characteristics differ, the anonymity set breaks into smaller ones, making the identification possible again. As Mayer discovered in his work [18], systems with fewer customization options create larger anonymity sets due to the need for more differentiating characteristics.
- **Altering the fingerprint for each domain to prevent cross-domain tracking:** Values of characteristics commonly used to construct a fingerprint are adjusted for each domain, making tracking the device across multiple domains challenging. Algorithms performing these adjustments are doing so in a seemingly random way to avoid being detected by the fingerprinting application.
- **Altering the fingerprint for each session to prevent cross-session tracking:** Similar to the previous cross-domain countermeasure, but values of characteristics are changed for each browsing session. In other words, the fingerprint is different whenever the browser is closed and reopened again. Compared to the previous cross-domain countermeasure, the fingerprint typically changes less frequently.
- **Detecting and blocking fingerprinting:** Protection tools implementing this countermeasure attempt to detect fingerprinting in real-time, block access to the Web APIs commonly misused for fingerprinting, or limit the page's ability to upload the fingerprint. This approach is strict and potentially intrusive as it can limit the functionality of the visited application, or, in the worst scenario, it could break the page completely.

A common practice for applications implementing these countermeasures is combining two or more categories for better overall protection [15]. The type of application is also significant. Usually, the closer the algorithm is to the operating system's core, the more capabilities it has to fight fingerprinting. Browser extensions are more restricted than browsers, which are more restricted than the operating system.

It is also important to note that it is very complicated to counter fingerprinting fully. The process of collecting the fingerprint can be detected, but it is impossible to verify if changes made to the data affected the fingerprint. Current protection tools are only mitigating the threat rather than eradicating it completely.

3.4 Approaches to fingerprinting

Based on the type of data collected, browser fingerprinting can be categorized as either passive or active [15]. This section briefly explains both, including examples of inconsistencies caused by incorrect manipulation done by protection tools that the fingerprinting application can detect.

3.4.1 Active fingerprinting

When a fingerprinting application has to explicitly run code to obtain the data to construct a fingerprint, it is considered active fingerprinting [15]. Examples of such code are

port scanning executed on a remote machine or JavaScript code executed inside the target device's browser.

```
Mozilla/5.0 (Macintosh; Intel Mac OS X 10_15_7) AppleWebKit/605.1.15 (KHTML,
like Gecko) Version/15.6 Safari/605.1.15
```

Listing 3.1: An example of Safari User-Agent string.

Running a JavaScript code in a browser is a potent tool to collect data about the software and hardware on the device. Modern browsers provide Web APIs to give websites native-like capabilities, often allowing developers to access detailed data about the system's underlying components [27]. A commonly misused Web API is the Navigator² interface which represents the state and the identity of the user agent running the script. Another example is the Screen³ interface which represents a screen, usually the one on which the current window is being rendered. Scripts often collect binary data to complement the textual data collected from other Web APIs. For example, it is typical for a fingerprinting application to use the Canvas API⁴ to draw an image to test how the system renders text, emojis, or shapes. Even slight differences in the rendered image can help the fingerprinting application identify the device [27].

Name	Source (JavaScript API)	Example value
Available memory	<code>Navigator.deviceMemory</code>	8
Battery level	<code>BatteryManager.level</code>	0.94
Cookies enabled	<code>Navigator.cookieEnabled</code>	true
Number of log. processors	<code>Navigator.hardwareConcurrency</code>	8
Preferred languages	<code>Navigator.languages</code>	["en-US", "en-GB"]
PDF display support	<code>Navigator.pdfViewerEnabled</code>	true
Screen width	<code>Screen.width</code>	1920
Screen height	<code>Screen.height</code>	1080
User-Agent string	<code>Navigator.userAgent</code>	See listing 3.1.

Table 3.1: An example of data available from JavaScript APIs of a browser.

Table 3.1 shows a few examples of information obtainable through browser APIs. The fingerprinting applications prefer characteristics that change less frequently or are entirely static. For example, the battery percentage will likely change often, which can affect the resulting fingerprint. On the other hand, the number of logical processors will remain the same for the device unless it is virtualized or the user replaces its CPU.

3.4.2 Passive fingerprinting

Passive fingerprinting collects information needed to create a browser fingerprint from data observable in network traffic. As the name suggests, this approach does not require running

²<https://developer.mozilla.org/en-US/docs/Web/API/Navigator>

³<https://developer.mozilla.org/en-US/docs/Web/API/Screen>

⁴https://developer.mozilla.org/en-US/docs/Web/API/Canvas_API

a script directly in the browser, but instead, it only consumes incoming network traffic and picks the information it needs.

Passive fingerprinting typically collects data from HTTP request headers or other parts of incoming network traffic [15]. Network requests include fewer suitable characteristics than active fingerprinting with access to browser Web APIs. However, fingerprinting is not observable from the device as there is no need to execute a script in the browser. This lack of observability makes it very complicated to detect passive fingerprinting.

Name	Source (HTTP/HTTPS header)	Example value
Available memory	Device-Memory	8
Content encoding	Content-Encoding	gzip, deflate, br
Preferred languages	Accept-Language	en-US,en-GB,en;q=0.9
Referer address	Referer	https://amiunique.org/
User-Agent string	Navigator.userAgent	See listing 3.1.

Table 3.2: An example of data available in HTTP request headers.

Table 3.2 shows examples of data directly available in request headers typically used in passive fingerprinting.

3.4.3 Inconsistencies

Fingerprinting countermeasures described in section 3.3 often modify browser characteristics to affect the fingerprint and confuse the fingerprinter. However, some characteristics are fully or partially obtainable by both active and passive fingerprinting. In other words, these characteristics have multiple data sources. When a characteristic has multiple data sources, protections manipulating its value must apply these modifications to all data sources to avoid introducing inconsistent (conflicting) pieces of information. A piece of inconsistent information has a valid but conflicting value between various data sources [27].

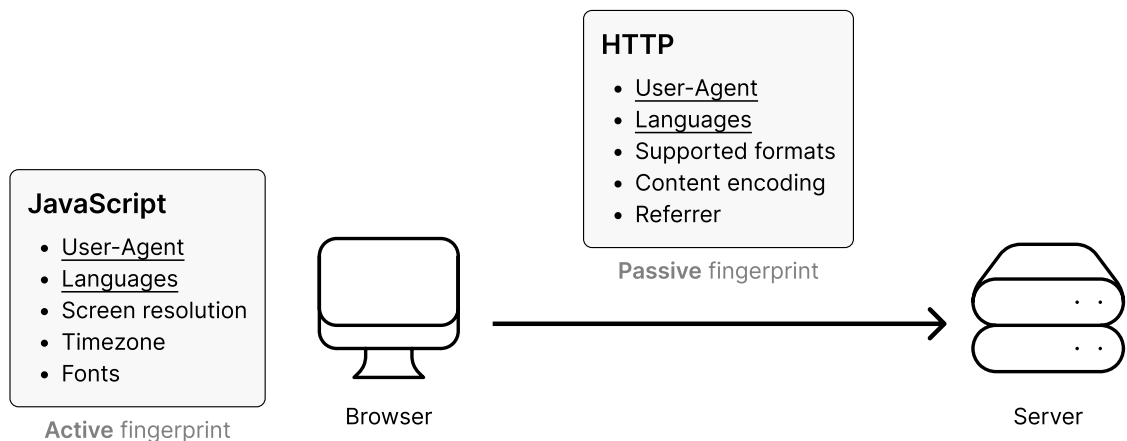


Figure 3.1: A scheme highlighting common properties obtainable with active and passive fingerprinting.

Among the examples shown in tables 3.1 and 3.2 are characteristics with multiple data sources, namely the available memory, preferred languages, and the User-Agent string. Values of specific characteristics, such as the available memory or the User-Agent string, are one-to-one copies meaning the countermeasure algorithm can apply the same transformation to all data sources. However, this is not the case for the values of preferred languages characteristic. Preferred languages transferred in HTTP headers include the quality factor⁵ for each language tag, but this value is absent in the version obtainable from the browser Web API. Tables 3.1 and 3.2 illustrate this difference. An algorithm cannot apply the same transformation for all data sources as it has to be aware of these differences in representation.

Suppose a countermeasure algorithm misapplies the transformation to a data source, or the data source is left unchanged entirely. In that case, the fingerprinting application can detect and act on this attempt at fingerprint manipulation.

⁵Quality weights or quality values are used in HTTP headers to specify the order of priority in a comma-separated list (https://developer.mozilla.org/en-US/docs/Glossary/Quality_values).

Chapter 4

JShelter

In 2019, Martin Timko designed and implemented a proof of concept browser extension called “Javascript Restrictor” as a part of his master’s thesis [26]. Inspired by his work, Libor Polčák et al. [15] created JShelter, a browser extension focused 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 surrounding physical environment and location. JShelter offers versions for three major browsers - Firefox, Chrome, and Opera.

4.0.1 JavaScript Shield

The pivotal protection feature of JShelter is the JavaScript Shield [4], which modifies the behavior of the JavaScript environment of the browser. JShelter provides fake information to confuse fingerprinters and make webpage-triggered attacks harder or impossible.

The JavaScript Shield internally consists of small independent pieces of code called wrappers, which modify the original behavior of JavaScript APIs available in the browser. The behavior of wrappers can be categorized followingly [4]:

- **Precision reduction:** The original value is unnecessarily precise for most use cases. JavaScript Shield modifies the values so that typical and essential use cases are unaffected.
- **Providing fake information:** Some wrappers provide fake information mostly to confuse fingerprinters. For example, canvas wrappers modify the image so that the exact instructions produce a different result in each session and for each domain.
- **Hiding information:** JavaScript Shield hides information from selected browser APIs that are generally unnecessary or have little use. Depending on the API, it might return an error, an empty value, or block the API completely.

To modify the values of the browser characteristics, the JavaScript Shield uses a technique called *farbling* [15]. This technique is based on the implementation of farbling in Brave [12], which has its roots in previous privacy research, including the PriVaricator [20] and FPRandom [16].

Farbling first deterministically generates a per-session, per-eTLD+1¹ seed. This seed is later used to slightly randomize the output of web APIs typically used for fingerprint-

¹eTLD+1 is a part of a domain name, including TLD, eTLD and one more domain part (More on <https://jfhmr.me/what-is-an-etld+-1/>).

ing. The way a seed is generated makes cross-site and cross-session tracking difficult for fingerprinting applications.

Chapter 5

Design proposal

This work aims to design and implement a new protective shield for the JShelter extension that can misrepresent information commonly used for passive fingerprinting. The first section of this chapter emphasizes the importance of avoiding alterations that could disrupt the user experience. Each of the following sections describes a selected HTTP header, proposes a modification to its value, the advantages and disadvantages of this modification, and necessary changes to the browser APIs to maintain consistency.

5.1 Minimizing undesired side effects

Whenever a user loads a webpage, the browser is responsible for constructing the outgoing HTTP request. Headers included in these requests provide valuable additional information servers use to decide on the response. By default, browsers set the headers according to their best knowledge to maximize speed and compatibility.

Protections that modify header values have to do so carefully. No matter how small the change is, it can affect the server's response. For example, English is the prevalent language used on the web. To make the fingerprint look more homogenous, the protection could modify the `Accept-Language` header to report English as the preferred language. However, the user may need help understanding the content if the server reacts and actually returns a website in English.

On the other side, the change has to be significant enough to affect the device's fingerprint. In the end, it is all about balance. Each protection is designed to avoid such unintended errors while keeping the capability to confuse fingerprinters.

5.2 Fingerprinting protections

The browser extension comprises several independent modules, each implementing passive fingerprinting protection for a single HTTP header or a group of HTTP headers. This separation of concerns allows users to enable only some protections while keeping others disabled.

5.2.1 HTTP header: `Accept`

The `Accept` request HTTP header indicates which content types the client can understand, expressed as MIME types [5]. It is possible to add or remove MIME types to affect

the fingerprint. However, the server may react to this modification and respond with an unexpected and incompatible response body.

```
Accept: text/html, application/xhtml+xml, application/xml;q=0.9, image/webp,
*/*;q=0.8
```

Listing 5.1: An example of Accept header contents [5].

The protection algorithm removes certain MIME types, which do not result in incompatibility, but only a slight performance hit. For example, eliminating modern image formats such as `image/webp` and forcing the browser to use older image formats is possible. This transformation would affect the header value (and, transitively, the device's fingerprint) without potentially breaking the website.

Consistency

Browsers no longer offer a standard API for quickly checking supported MIME types. The `Navigator.mimeType` API that partially allows this check has been deprecated and removed from the relevant web standards [7]. A fingerprinting application could maintain a list of browser versions and supported MIME types which it would use to compare with the MIME types in the `Accept` HTTP

Maintaining consistency but also checking the consistency is not trivial when it comes to the supported MIME types. Therefore, no browser API modifications are necessary.

5.2.2 Accept-Language

The `Accept-Language` request HTTP header indicates the natural language and locale that the client prefers [5]. It is a list of language tags separated by commas (“,”). A language tag consists of a 2-3 letter base tag that identifies the language, optionally followed by a dash (“-”) and a subtag, usually specifying the country or the region where the language is used. Language tags can optionally have a quality value (weight) represented by a decimal number separated from the tag by a semicolon (“;”).

```
Accept-Language: fr-CH, fr;q=0.9, en;q=0.8, de;q=0.7, *;q=0.5
```

Listing 5.2: An example of Accept-Language header contents [5].

Modifying the `Accept-Language` header is not straightforward because the web server might respond with content in a different language than the user requested. The protection only makes minor changes and works in two modes:

- **Generalization:** Language regions (subtags) are removed, and only the base language tags are kept unchanged. Listing 5.3 shows the result of generalization for the `Accept-Language` header in listing 5.2. The algorithm also deduplicates language tags and updates quality values after it removes the language regions.
- **Randomization:** Language regions (subtags) are changed for multiregional languages like English or Spanish. Listing 5.4 shows the randomization result for the `Accept-Language` header in listing 5.2.

The reasoning behind these transformations is that the difference between language forms is usually manageable for the users. For example, changing “en-US” (United States English) to “en-GB” (Great Britain English) might get noticed by users, but they would still understand the content.

```
Accept-Language: fr, en;q=0.9, de;q=0.8, *;q=0.5
```

Listing 5.3: The result of the “generalization” mode transformation of listing 5.2.

```
Accept-Language: fr-BE, fr;q=0.9, en;q=0.8, de;q=0.7, *;q=0.5
```

Listing 5.4: The result of the “randomization” mode transformation of listing 5.2.

Consistency

The client-preferred languages are also available through the `Navigator` interface under the `Navigator.languages` property. The languages are ordered the same way as in the `Accept-Language` header but without the quality value (weight). The first language in `Navigator.languages` is also extracted to the `Navigator.language` property. Any change to the `Accept-Language` HTTP header must be reflected in these two properties of the `Navigator` interface.

5.2.3 Device-Memory

The `Device-Memory` request header indicates the approximate amount of available RAM on the client device. The possible values this header can carry are 0.25, 0, 5, 1, 2, 4, and 8 [5]. Even though this header is still experimental, it is already implemented by the Chrome browser.

The protection algorithm randomly picks one of the possible values and uses it as the value of the `Device-Memory` header.

Consistency

The value of the `Device-Memory` header is also accessible through the `Navigator.deviceMemory` property. Any transformation to the `Device-Memory` header must be copied to this property.

5.2.4 User-Agent

The `User-Agent` request HTTP header is a string that lets servers and network peers identify the application, operating system, vendor, and version of the requesting user agent [5]. The value of this header varies depending on the operating system and browser type and version, making it a valuable fingerprint component.

```
Mozilla/5.0 (X11; Linux x86_64) AppleWebKit/537.36 (KHTML, like Gecko)  
Chrome/51.0.2704.103 Safari/537.36
```

Listing 5.5: An example of Chrome User-Agent string [8].

```
Mozilla/5.0 (iPhone; CPU iPhone OS 13_5_1 like Mac OS X) AppleWebKit/605.1.15  
(KHTML, like Gecko) Version/13.1.1 Mobile/15E148 Safari/604.1
```

Listing 5.6: An example of Safari User-Agent string (mobile version) [8].

Figures 5.5 and 5.6 show examples of **User-Agent** strings of Chrome and Safari, which according to Statcounter GlobalStats¹, are the top two browsers with the highest market share of 64.62% and 18.29%, respectively. These examples indicate that some browsers and operating systems have version numbers following the semantic versioning specification[23] or its variation. Semantic versioning in the most recent version 2 is composed of three segments separated by a dot (“.”), where:

- The first segment (**MAJOR**) is incremented when an incompatibility, such as a breaking API change, is introduced.
- The second segment (**MINOR**) is incremented when new functionality is added while maintaining backward compatibility.
- The last segment (**PATCH**) is incremented for all other changes, for example, a bug fix or code refactoring.

Based on the observation that some software versions in the **User-Agent** string follow the semantic versioning specification, we can assume that:

1. Given two version numbers differ only in the last segment (**PATCH**), we know these software builds should have the same functionalities, meaning they should be indistinguishable for the user.
2. A change (either an increment or a decrement) of the (**PATCH**) segment value would likely affect the device’s fingerprint. However, at the same time, it is unlikely that the change would cause any undesired side effects.

The protection cannot apply changes at random, as this could introduce invalid version numbers that have yet to be released. Invalid version numbers could be used by the fingerprinting application to discover an attempt at fingerprint manipulation. Instead, the extension keeps a list of previously released versions gathered from the changelog² of the specific software product. The algorithm then randomly selects a suitable version that only differs in the **PATCH** segment and should have the same functionality as the original version.

Consistency

The **User-Agent** string can also be accessed through the JavaScript **Navigator** interface. This value is identical to the one transmitted in the **User-Agent** HTTP header when a client makes a request to a web server. To maintain consistency between the two sources of the **User-Agent** string, applying the same transformation or parsing logic to the value obtained from **Navigator.userAgent** is crucial. This consistency ensures that the information is treated uniformly and helps to prevent a potential discovery by comparing the strings.

¹Statcounter GlobalStats collects statistics from more than 1.5 million sites with yearly views ranging from 5 to 6 billion. These statistics are available at <https://gs.statcounter.com/>.

²Software products typically maintain a list of published versions. For example, the changelog of Chrome is available at <https://chromereleases.googleblog.com/search/label/Stable%20updates.>

5.2.5 Extra HTTP header

One of the valuable characteristics used to construct a fingerprint is the list of all headers present in a request. Most requests share standard headers like those mentioned in previous sections X, Y, and Z. However, it is common for HTTP requests to include less standard, even custom³ headers.

`Accept, Accept-Encoding, Accept-Language, Connection, Cookie, Host, User-Agent`

Listing 5.7: An example of a list of headers present in an HTTP request.

The protection adds a new header to the HTTP request to alter the list and order of headers and transitively the device’s fingerprint. Additionally, if the newly added header is custom and not standardized by the protocol, this change would likely not affect the response.

5.3 Graphical user interface

The popup is the only graphical user interface the extension exposes. This view contains preferences users can use to change the behavior of the fingerprinting protections.

The preferences are split into three tabs (views). This division allows for more prominent controls and descriptive hints that help users understand what each option does. The first two tabs contain preferences for the most influential HTTP headers, **User-Agent** and **Accept-Language**. The last tab groups other, less significant protections, such as **Device-Memory**.

Each protection can be enabled or disabled individually from others. When enabled, a preview field will appear under the protection’s preferences. The preview field shows the header value as it will be sent in future outgoing requests and is updated automatically according to the selected preferences.

Modern operating systems have the option to switch the user interface to a dark mode which complements the standard light color scheme. The extension’s popup view and every component it renders are made in light and dark variants. The extension automatically switches between these variants based on the operating system’s active color scheme.

³Until 2012, developers tended to prefix custom headers with “X-” to differentiate them from standardized headers, but this naming convention has been officially discouraged in RFC6648 [21].

Bibliography

- [1] *Chrome Developers - Manifest V2* [online]. Google LLC [cit. 2022-12-30]. Available at: <https://developer.chrome.com/docs/extensions/mv2/>.
- [2] *Chrome Developers - WebExtensions API reference* [online]. Google LLC [cit. 2022-12-30]. Available at: <https://developer.chrome.com/docs/extensions/mv3/>.
- [3] *JShelter* [online]. JShelter [cit. 2022-12-30]. Available at: <https://jshelter.org/>.
- [4] *JShelter - JavaScript Shield* [online]. JShelter [cit. 2022-12-30]. Available at: <https://jshelter.org/levels/>.
- [5] *Mozilla Developer Network* [online]. Mozilla Corporation [cit. 2022-12-30]. Available at: <https://developer.mozilla.org/>.
- [6] *Mozilla Developer Network - Browser extensions* [online]. Mozilla Corporation [cit. 2022-12-30]. Available at: <https://developer.mozilla.org/en-US/docs/Mozilla/Add-ons/WebExtensions>.
- [7] *Mozilla Developer Network - Navigator Web API* [online]. Mozilla Corporation [cit. 2023-01-9]. Available at: <https://developer.mozilla.org/en-US/docs/Web/API/Navigator>.
- [8] *Mozilla Developer Network - User-Agent HTTP header* [online]. Mozilla Corporation [cit. 2022-12-30]. Available at: <https://developer.mozilla.org/en-US/docs/Web/HTTP/Headers/User-Agent>.
- [9] *Use Cases* [online]. FingerprintJS, Inc. [cit. 2022-12-30]. Available at: <https://fingerprint.com/use-cases/>.
- [10] ARTICLE 29 WORKING PARTY. Opinion 9/2014 on the application of Directive 2002/58/EC to device fingerprinting. [online]. European Commission. [cit. 2022-12-30]. Available at: https://ec.europa.eu/justice/article-29/documentation/opinion-recommendation/files/2014/wp224_en.pdf.
- [11] BERNERS LEE, T. *Information Management: A Proposal* [online]. 1989 [cit. 2022-12-30]. Available at: <https://www.w3.org/History/1989/proposal.html>.
- [12] BRAVE PRIVACY TEAM. *Brave browsers - Fingerprinting defenses 2.0* [online]. Brave Software, Inc. [cit. 2023-01-10]. Available at: <https://brave.com/privacy-updates/4-fingerprinting-defenses-2.0/>.
- [13] ECKERSLEY, P. How Unique is Your Web Browser? In:.. Berlin, Heidelberg: Springer-Verlag, 2010 [cit. 2022-12-30]. PETS'10. ISBN 3642145264.

- [14] FLANAGAN, D. *JavaScript: the Definitive Guide : Activate Your Web Pages*. O'Reilly Media, Incorporated, 2011 [cit. 2023-02-19]. Available at: <https://ebookcentral.proquest.com/lib/vutbrno/detail.action?docID=686420>.
- [15] L. POLČÁK, G. M. R. H. and MCMAHON, M. *JShelter: Give Me My Browser Back*. arXiv, 2022 [cit. 2022-12-30]. DOI: 10.48550/ARXIV.2204.01392. Available at: <https://arxiv.org/abs/2204.01392>.
- [16] LAPERDRIX, P., BAUDRY, B. and MISHRA, V. FPRandom: Randomizing core browser objects to break advanced device fingerprinting techniques. In: *ESSoS 2017 - 9th International Symposium on Engineering Secure Software and Systems*. Bonn, Germany: [b.n.], July 2017 [cit. 2023-01-6]. Available at: <https://hal.inria.fr/hal-01527580>.
- [17] LAPERDRIX, P., BIELOVA, N., BAUDRY, B. and AVOINE, G. Browser Fingerprinting: A survey. arXiv. 2019, [cit. 2022-12-30]. DOI: 10.48550/ARXIV.1905.01051. Available at: <https://arxiv.org/abs/1905.01051>.
- [18] MAYER, J. R. *Any person... a pamphleteer*. 2009. Master's thesis. Princeton University. Available at: <https://jonathanmayer.org/publications/thesis09.pdf>.
- [19] MUELLER, J. P. *Security for Web Developers : Using JavaScript, HTML, and CSS*. O'Reilly Media, Incorporated, 2015 [cit. 2023-03-05]. Available at: <https://ebookcentral.proquest.com/lib/vutbrno/detail.action?docID=4333783>.
- [20] NIKIFORAKIS, N., JOOSEN, W. and LIVSHITS, B. PriVaricator: Deceiving Fingerprinters with Little White Lies. In: *Proceedings of the 24th International Conference on World Wide Web*. Republic and Canton of Geneva, CHE: International World Wide Web Conferences Steering Committee, 2015 [cit. 2023-01-6]. WWW '15. DOI: 10.1145/2736277.2741090. ISBN 9781450334693. Available at: <https://doi.org/10.1145/2736277.2741090>.
- [21] P. SAINT ANDRE, D. C. and NOTTINGHAM, M. *Deprecating the "X-" Prefix and Similar Constructs in Application Protocols* [Internet Requests for Comments]. RFC. RFC Editor, june 2012 [cit. 2023-01-6]. Available at: <https://www.rfc-editor.org/rfc/rfc6648>.
- [22] PASQUALI, S. *Mastering Node.js*. Packt Publishing, Limited, 2011 [cit. 2023-02-19]. Available at: <https://ebookcentral.proquest.com/lib/vutbrno/detail.action?docID=1389335>.
- [23] PRESTON WERNER, T. *Semantic Versioning Specification* [online]. [cit. 2022-12-30]. Available at: <https://semver.org>.
- [24] R. FIELDING, M. N. E. and J. RESCHKE, E. *HTTP Semantics* [Internet Requests for Comments]. RFC. RFC Editor, june 2022 [cit. 2023-01-6]. Available at: <https://www.rfc-editor.org/rfc/rfc7231>.
- [25] SCHAUER, M. *Oblíbenost JavaScriptových API internetového prohlížeče*. Brno, CZ, 2021. Diplomová práce. Vysoké učení technické v Brně, Fakulta informačních technologií. Available at: <https://www.fit.vut.cz/study/thesis/23312/>.

- [26] TIMKO, M. *Vylepšení rozšíření pro omezení volání JavaScriptu*. Brno, CZ, 2019. [cit. 2022-12-30]. Diplomová práce. Vysoké učení technické v Brně, Fakulta informačních technologií. Available at: <https://www.fit.vut.cz/study/thesis/21824/>.
- [27] VONDRÁČEK, T. *Získávání informací o uživateli na webových stránkách*. Brno, CZ, 2021. [cit. 2022-01-08]. Diplomová práce. Vysoké učení technické v Brně, Fakulta informačních technologií. Available at: <https://www.fit.vut.cz/study/thesis/23972/>.