



# A User-Oriented Approach and Tool for Security and Privacy Protection on the Web

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## Abstract

We introduce a novel approach to protecting the privacy of web users. We propose to monitor the behaviors of JavaScript code within a web origin based on the source of the code, i.e., code origin, to detect and prevent malicious actions that would compromise users' privacy. Our code-origin policy enforcement approach not only advances the conventional same-origin policy standard but also goes beyond the "all-or-nothing" contemporary ad-blockers and tracker-blockers. In particular, our monitoring mechanism does not rely on browsers' network request interception and blocking as in existing blockers. In contrast, we monitor the code that reads or sends user data sent out of the browser to enforce fine-grained and context-aware policies based on the origin of the code. We implement a proof-of-concept prototype and perform practical evaluations to demonstrate the effectiveness of our approach. Our experimental results evidence that the proposed method can detect and prevent data leakage channels not captured by the leading tools such as Ghostery and uBlock Origin. We show that our prototype is compatible with major browsers and popular real-world websites with promising runtime performance. Although implemented as a browser extension, our approach is browser-agnostic and can be integrated into the core of a browser as it is based on standard JavaScript.

**Keywords** User centric · Privacy · Web security · Online tracking

## Introduction

Privacy is a big challenge and risk for Internet users [7, 32], mostly due to the presence of online trackers on almost all websites [18, 34]. These trackers typically collect users' sensitive information such as personal data, browsing history, activities, and interests [39], mostly without the awareness of users [39, 41]. Standard web security mechanisms such as same-origin policy [47] or Content-Security-Policy (CSP) [69] could not prevent these privacy risks since the trackers, either from the first or third parties, are included by the developers [42]. Do Not Track (DNT) [70] is a mechanism to prevent tracking by sending an HTTP header indicating that a browser does not want to be tracked. Although most web browsers support DNT, there is currently no policy or mechanism about how a website has to respond upon receiving a DNT header. This technical issue of DNT leaves it an ineffective solution for security on the web [6].

Advanced users concerning their privacy usually adopt browser-based blocking tools for privacy protection such as ad- or tracker blocker extensions [39, 68]. While these tools are effective in blocking third-party trackers [42], there are

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a couple of limitations in these mechanisms. First, existing blocking browser extensions only enforce the “all-or-nothing” rule. This rule either blocks or allows a tracker or an ad network based on a URL defined in a filter list, generally identified by the tool or set by users [5]. This blocking approach creates challenges and dilemmas for users as they do not know if they should block an ad or a tracker [39]. Also, several studies show that not every user wants to block ads or trackers [9, 67], and a big crowd desire advanced methods to control their footprint [1, 35]. Second, the existing blocking mechanisms implemented in browser-based extensions face several technical issues outlined below.

The first technical issue is that the implementation of the blocking mechanism is browser dependent. Extensions usually implement the blocking mechanism by intercepting all network requests from a web page and blocking it if the URL is in a filter list [14, 42]. This method relies on a web API `webRequest` provided by major browsers [24, 46], which developers have to follow the requirements of a specific browser. For example, recently, Google has just announced to replace their `webRequest` API by the `declarativeNetRequest` API together with the Manifest specification V3 [14, 63]. This change will restrict the functionality of many of the current blockers on the marketplace. For example, it limits the maximum number of rules and domains that can be blocked by extensions like uBlock Origin [63]. Another technical issue is that extensions are dependent on the filter list predefined by developers. Therefore, new trackers or other third-party content are not captured or blocked by these extensions. For example, in [73], the authors demonstrated that existing extensions could not catch requests that utilize a DNS CNAME alias to prevent detection. Our experiments also confirm this technical issue. As demonstrated in "[Privacy leakage detection and prevention](#)", popular extensions such as Ghostery and uBlock Origin do not detect trackers and data leakage channels simulated in our test suite.

The limitations discussed above motivate us to develop a novel approach to protecting web users. Different from existing tools that block a particular network request, our method is to monitor the code execution in a browser. Our code monitoring goal is to ensure that users' sensitive information cannot be leaked to the outside of a browser without users' concerns. As JavaScript is the language executed in browsers to perform all of the activities on a web page, we propose to intercept critical privacy-related JavaScript operations. In particular, we intercept JavaScript operations that can read data belonging to the user, e.g., cookies, and can send it to the Internet. We then define and enforce context-aware policies on these operations to prevent possible privacy leakages. Our proposed method also stands from the state-of-the-art of JavaScript monitoring by tracking the origin of the code, i.e., where the code comes. From this

origin tracking mechanism, we can enforce distinct policies for each origin of the code. This mechanism advances (and in contrast to) the traditional same-origin policy [47], which treats all the code, even included from an external server, within a web page as the same origin. We originally presented this approach in our preliminary work [30] with the following contributions:

- We introduced a novel approach to controlling the behaviors of JavaScript code within a web page to detect and prevent potential privacy leakage.
- We implemented a proof-of-concept prototype as a browser extension, named MyWebGuard. Our MyWebGuard tool monitors the source of data and the sinks where the data can be sent to detect potential data leakage precisely. Our mechanism contrasts with existing blocking browser extensions that only focus on the web request interception with a static filter list.
- We performed evaluations and report practical experimental results on various aspects. Our approach is browser-agnostic, as it is compatible with major browsers. We showed that our prototype implementation could detect and prevent potential data leakage while preserving the web page functionality. We also reported the performance overhead of our prototype that is quite low for popular real-world websites.

In this article, we have made improvements to extend our MyWebGuard prototype [30] with the following additional contributions:

- We have developed a new mechanism to store the predefined policies in the browser and allow users to personalize policies via a user interface. To this end, we have revised the policy specification to allow the runtime parameters can be stored consistently in the browser local storage, rather than in memory as in the previous design. We have implemented the enforcement code accordingly so that it reflects the new design.
- We have performed and reported new significant experiments on performance by measuring the microbenchmark of selected operations to get the time difference of a webpage with and without our extension.

We organize the rest of this article as follows. In the next section, we review the background, including the landscape of browsers and their security, browser extension, and web security standards. We survey the literature and discuss related work compared with our work in "[Related work](#)". In "[Proposed approach](#)", we describe our technical approach and the design of our method. We present our prototype implementation in "[Implementation](#)". In "[Evaluation and discussions](#)", we demonstrate our evaluations and discuss the

experimental results. Section "[Conclusions and future work](#)" concludes our contributions and outlines the future work.

## Background and Related Work

### Security and Privacy in Browsers

In this subsection, we review the landscape of existing browsers and their security and privacy features. We relate these features to our work.

There are many browsers in the industry in the landscape of existing browsers. Google Chrome is currently the most popular browser with a 63.91% market share, following by Apple Safari, and Mozilla Firefox (cf. <https://gs.statcounter.com/browser-market-share>). There are also more niche browsers, such as Chromium and Brave. Almost all browsers have and implement security and privacy standards to ensure degrees of users' privacy either by default or within the browser settings. Among popular browsers, Google Chrome is considered as a leader in browser security with automatic updates and a Web Authentication API [10]. However, due to its closed-source structure and Google's incident for collecting user information, some users feel that Google has the incentive to break its stance on privacy [8]. Microsoft Edge uses sandboxing to contain browser processes, and it retains Internet Explorer's filtering of suspicious websites. However, Edge has not retained IE's tracking protection, and biannual updates can leave plenty of time for attackers to utilize unpatched exploits [44]. Mozilla Firefox offers users a wide range of security features that are comparable to Chrome. These include add-on warnings, malware protection, content blocking, and filtering of reported malicious websites. Thanks to its open source, users can be confident that their browser is functioning without the inclusion of malicious code [50].

Looking at more niche browsers that advertise a greater emphasis on user privacy, Chromium retains the positives of Chrome while being open source [10]. Privacy concerns with Chromium include the lack of automatic updates that could leave some users open to attacks, and WebRTC leaks are a concern since it cannot be disabled without third-party software [8]. Brave is a relatively new browser that focuses heavily on privacy; features include a built-in ad-blocker, chrome extension functionality, and fingerprinting blocker, to name a few. While Brave is still new and gains limited market share of browsers, its open-source structure and firm stance on privacy are gearing it up to be a strong contender in the browser landscape [8].

Although our work is to build a tool added-on in a browser, our approach can be integrated into a browser to enhance its security and privacy features for protecting web users.

### Browser Extensions

A browser extension is an open-source software module, developed using web technology, i.e., HTML, CSS, and JavaScript, to be integrated into a browser by users. When loading a web page, a browser also loads and executes installed extensions enabled for that web page [49]. Therefore, JavaScript code in a browser extension has the same privilege as the web page, i.e., it can access and modify the data or content of the web page [49]. A typical extension contains a manifest specification in JSON format, HTML pages, and JavaScript files. A browser extension can access general web APIs, available for every web page, and a special set of JavaScript APIs provided by browsers but are not available for web pages. For example, Google Chrome and Opera browsers provide the extension API (<https://developer.chrome.com/extensions>), which is also supported in other major browsers such as Firefox or Microsoft Edge [49].

In this work, we develop our tool as a browser extension. In "[Related work](#)", we survey and discuss related work in browser extensions and their security.

### Web and JavaScript Security

Our work focuses on the security and privacy of web pages within a browser. Therefore, server-side security such as SQL Injection, command injection, or denial-of-service attacks is out-of-scope of this work. In this subsection, we briefly review the web page security model and JavaScript security standards, including Same-Origin Policy and Content Security Policy.

Nowadays, almost all web pages contain JavaScript code. Statistics in [71] show that 95.2% of all websites contain JavaScript code. Among these, websites include JavaScript code from external third-party servers. These facts are evidenced in a survey of the Alexa Top 10,000 websites, which reveals that 88.45% of them include at least one third-party JavaScript library [53]. The work also exposes some contents in the trusted libraries of these sites that can be compromised. They later identify four newly discovered vulnerabilities that could be used in attacks. The work also reviews the effectiveness of proposed solutions for protecting web applications that utilize third-party content.

In principle, JavaScript code in a web page is loaded and executed by a browser within a JavaScript engine. JavaScript code can interact with users, modify the web content, and access (read/write) data stored in a browser such as cookies. Browsers enforce the same-origin policy to ensure that JavaScript code from one origin cannot access the data that belong to other origins.

## Same-Origin Policy

The same-origin policy (SOP) is a critical web security standard that prevents JavaScript code from one origin from accessing data of other origins [47]. An origin in the web is identified by the scheme, host, and port of a URL. The SOP does not apply to the code included in a web page but sourced from a third-party server. For example, if a web page from <https://mywebguard-host.github.io> (the host) includes JavaScript code from <https://thirdparty.com>, e.g., using `<script src="https://thirdparty.com/script.js"></script>`, then the script code from <https://thirdparty.com/script.js> is executed in the host web page and has the same origin as the host. This policy means that the external code can access data that belong to that host. This issue is a known limitation of SOP as identified in the literature, e.g., [51, 55, 62]. Our work addresses this drawback by tracking where the code comes from and enforce different policies for different code origin.

## Content Security Policy

Content-security-policy (CSP) [69] is a web standard that functions to prevent code injection attacks such as cross-site scripting (XSS). This prevention is based on a whitelist of trusted content that can be rendered and executed by the browser. The CSP can be used to prevent data leakage to external domains, not in the whitelist. However, it cannot prevent potential privacy leakage to whitelisted domains, as we investigated in this work. Moreover, there has also been a surge in the attempts to study the CSP. In [72], the authors explore how challenges presented by CSP lead to a low adoption rate among the Alexa Top 1M. The results show that the inclusion of CSP lags other security headers, and CSP policies are often ineffective at preventing content injection attacks like XSS. Additionally, they also suggest an improvement in CSP that could increase its use on the web.

## Related Work

Below, we survey the literature on topics related to our work, including JavaScript security and browser-based tools and approaches. We also discuss how our work advances the state-of-the-art.

## JavaScript Security

In the past decade, there are many research works and proposals focused on the topic of JavaScript security. In 2007, BrowserShield [59] was introduced as a JavaScript security solution by vulnerability-driven filtering dynamic HTML in web pages. The BrowserShield system rewrites web pages to secure vulnerabilities relied on embedded scripts. Caja [23,

45] is a similar approach developed at Google. Google Caja allows passive data to become active content and rewrites scripts into an object-capability language to ensure that their operations are safe on a webpage. In [36], Maffei et al. design language-based methods that websites use to filter untrusted JavaScript. They also propose a foundation for language-based filtering that addresses website vulnerabilities. Phung et al. [56] introduce a lightweight self-protecting JavaScript approach to controlling the behaviors of JavaScript code to prevent potential attacks. Meyerovich and Livshits [43] present a new design, termed ConScript, that empowers to host webpages byways of fine-grained security policies. These policies are to constrain executed code to protect against vulnerabilities opened when untrusted JavaScript codes appear. In [55], Phung et al. introduce a new approach to enforcing security policies on untrusted third-party ad content, referred to as FlashJaX. Their design, FlashJaX, addresses the problem of vulnerability assessment sites that are mixed by JavaScript with Adobe ActionScript content.

There are also other JavaScript security proposals; however, they focus on advertisement networks. For example, ADSafe [13] is a safe subset of JavaScript for ads. Ad developers must follow this subset so that an ad can be included in a hosting web page; otherwise, it will be rejected. In [57], Politz et al. propose a lightweight and efficient technique to verify sandbox sources that utilize ADSafe to demonstrate the system's effectiveness by securing previously unknown weakness within ADSafe rooted in sandboxing. And, Finifter et al. [20] examine a vulnerability found among one-third of the Alexa Top 100, accessible via ADSafe-verified advertisements. This vulnerability is rooted in third parties exploiting prototype objects of the hosting page. The authors propose a JavaScript subset that retains static verification while upgrading security. Furthermore, in [26], there is a development of an online advertising system, referred to as Privad, that aims to secure user privacy while still allowing advertisers to serve targeted ads. This design focuses on improving user's browser experience through increased speeds over other online advertising systems, presenting microbenchmarks and informal analysis of Privad's privacy properties. In addition to these studies, Fredrikson and Livshits [21] present RePriv, a tracker implemented as a browser extension to collect user interests and share them with third parties with the user's permission. This paper also shows how RePriv can collect user interests to personalize the content on various websites with high quality and keep a low overhead, as well as preserve user privacy.

Information flow control in JavaScript to prevent potential leakages in web pages, similar to our work, has also been studied in the literature. For instance, in [12], the authors present a web system supported by an inlined information flow control monitor as well as an evaluation of that monitor. This application uses "mashups" of JavaScript code, which



is one of the most common types of code in many web apps today. Hedin et al. [28] introduce JSFlow as a method for tracking the information flow of JavaScript on sites that utilizes third-party code, deploying it as a browser extension. Through the utilization of JSFlow, they also indicate the different main policies of sharing sensitive user information on websites.

JavaScript security is still an emerging topic in recent years. For example, in 2018, the authors in [58] provide a comprehensive survey of existing client-side web application security solutions that consider desirable features and develop a framework for specifying and enforcing security policies for JavaScript web applications, namely GUARDIA. In [51], Musch et al. propose a *ScriptProtect* framework that instruments third-party JavaScript code to prevent the string-to-code conversions to protect the first-party origin from potential XSS attacks.

Although the works mentioned above provide possible solutions to secure JavaScript code in web pages, they aim to be used at the development phase. In contrast, our work aims at a tool that end-users can use to protect their privacy.

### Browser-Based Tools and Approaches for Security and Privacy

In addition to the research works on JavaScript security, there are many studies on browser extension design problems in recent years [39]. Tracker-blocking browser extensions offer the best protection strategy against online tracking but have certain side effects, such as defending users from malvertising and active URL hijacking attacks [38]. In [60], the authors examine different blocking strategies in browsers and found that Ghostery was the most efficient browser extension for preventing trackers on the Alexa top 500 websites. Although these browser extensions provide a tool for web users to protect themselves from possible attacks, their technical approaches are different from our work, as we discuss in detail below.

In [3], the authors propose a new approach to blocking malicious third-party content achieved through an analysis of inclusion sequences constructed from an in-browser vantage point and implemented with EXCISION in a modified Chromium browser. Many experiments conducted in [4] simulate how advisement and analytics companies bypass ad-block extensions and how a bug with chrome web request help to block the extension from functioning. They base on the evaluation of the bug fix in different states to indicate that some companies still use WebSocket in troubleshooting like serving advertisements, infiltrating the DOM, and fingerprinting. In [54], a stock web browser is modified to fake browser fingerprints. It is a promising method to hind stateful and stateless tracking; however, it relies on browser vendors adopting the technology.

In addition, Bashir et al. [5] develop a methodology for detecting ad exchange information flow (both client and server sides) by leveraging retargeted ads. Also, in [2], the authors propose a new approach (referred to as ORIGIN-TRACER) to determining the source of content modifications done by over-privileged browser extensions or other third-party content. They indicate that this approach statistically improves users' ability to recognize injected advertisements through the use of visual indicators while incurring a modest overhead. In [25], the authors present a framework for the verification of browser extensions to ensure they are secure and not over-privileged. Ter et al. [66] also provide an approach to synthesizing abstract behavioral models from XPCOM interfaces. Their method invokes sequences of extensions obtained by the runtime interface invoking approach. This approach requires the preparatory implementation of a behavior monitoring system. It also proposes to define the vulnerable behavior sequence patterns. This paper's design is used to guide the testing process adopted on sequence matching methods for detecting the security and reliability vulnerability of extensions.

In [15], Dhawan and Ganapathy present an in-browser system for tracking information-flow to analyze JavaScript-based browser extensions and identify their violations. In [74], they design *Expector*, a system for identifying chrome extensions that serve malicious ads, utilizing this system to detect extensions that inject ads or participate in malvertising. In [29], the authors propose a preliminary extension system design for protecting users' privacy from malicious extensions. Their method is also based on the idea of mandatory access control. Moreover, the authors in [65] study a comprehensive new model for extension security that aims to redress the shortcomings of existing extension mechanisms. Their proposed model works through the use of a logic-based specification language. The language describes fine-grained access control and data flow policies that govern an extension's privilege over web content. This model verifies extensions through analysis and includes a module for converting safe extensions into a form that allows for the execution of safety checks at runtime.

There are also other research studies focusing on the interaction between a browser extension and the security policy. For instance, in [27], Hausknecht *et al.* examine why browser extension's interaction with Content Security Policy is one reason for its slow adoption. They also classify three types of vulnerabilities arising from the interaction between extensions and CSP, proposing a solution, and providing a case study as a proof-of-concept. Besides, the authors in [64] explore browser extension discovery and the invasive nature of both websites and extensions. Roesner et al. [61] and Mayer and Mitchell [40] investigate the web tracking. The former is with a focus on the technical implementation and functions of trackers, and the latter one is with the focus on

the policy debate over trackers. In [16], the authors explore the ability of browsers to be uniquely identified through fingerprinting. They implement a fingerprinting algorithm to estimate future success rates and discuss the privacy threats and implications posed by fingerprinting.

Likewise, in [52], the authors propose a new client-side JavaScript framework to check the integrity, origin, authentication, and risks of all JavaScript third-party resources, evaluating the solution through implementation. Moreover, in [42], the authors provide insight into the landscape of tracker blocker tools. Wills and Uzunoglu [73] explore the effectiveness of ad-blocking tools. In [31], Iqbal *et al.* study a graph-based machine learning approach to blocking ads and tracker. They create a graph representation used to trace relationships between page contents (HTML structure, network requests, JavaScript behavior of the webpages) and (third-party) ads/trackers. Besides, the authors in [33] investigate a framework that manages which security mechanism is active to cut down on high overheads created by outdated security solutions.

## Proposed Approach

### Overview

The objective of our method is to monitor the JavaScript code execution and stop a JavaScript operation if it violates a given policy. To this end, we intercept JavaScript operations, including property access and method calls, to enforce policies. In our enforcement code, we track the actual caller of the operation (we termed it `code_origin`) and apply a specific policy for each code origin. Listing 1 illustrates the overview of our technical approach in pseudo-code, where we implement the interception within an anonymous function. Code within an anonymous function is to ensure that any code outside of the scope cannot access our code. In the next subsection, we describe our interception method, how we track the code origin, and how we enforce policies for each code origin.

## JavaScript Interception

We review the JavaScript operations and categorize them into three different types: method calls, object creation and access, and property access. For each type of operation, we propose to intercept as follows.

### Method Calls

Method calls are functions belonging to a global object. For example, `document.getElementById(...)` is a method call, which invokes the `getElementById` function of the `document` global object. For each method call, we wrap the original reference and its aliases by capturing any available prototype inheritance chain of the reference. We leverage a prior library [37] that implements these types of wrapping for our approach. In Sect. 4, we elaborate more details of this approach.

### Property Access

A property is a field of an object that can be accessed (read or write) by JavaScript code. As these properties, for example, `document.cookie`, may contain sensitive data of users, we need to mediate the access to them. To this end, we leverage the `Object.defineProperty(...)` API (standardized in ECMAScript 5 and still supported in later versions [17]) to define the handler functions whenever a property is read (get) or write (set). Simplified code (for brevity) in Listing 2 illustrates this mediation process for the `document.cookie` property.

**Listing 1** The overview of our technical approach in pseudo-code.

```
(function(){
  let reference = original;
  let code_origin = getCodeOrigin(...);
  original = wrapper(){
    if (PolicyCheck(code_origin, reference_name, arguments))
      execute(reference);
  } // the wrapping
})();
```

**Listing 2** Simplified code of mediating the access to document.write

```

var desc= Object.getOwnPropertyDescriptor(Document.prototype,
                                     "cookie");
//assert the desc object and its prototype chain
Object.defineProperty(document, "cookie", {get: function(){
    var code_origin = getCodeOrigin(new Error().stack);
    if (originAllowed(code_origin, "cookie")) {
        setOriginSourceRead(code_origin, "cookie");
        return desc.get.call(document);
    }
    return;
},
set: function(val){ desc.set.call(document, val); },
enumerable : false,
configurable : false
});

```

## Object Creation and Access

There are several JavaScript operations that are based on object creation. For example, the “new Image(…)” operation creates a new image object (HTMLImageElement) that can be appended to a web page to display an image. In our observations and experiments, in some cases, although this object creation operation returns the same object type as an equivalent function call (for example, new Image(…) (object creation) and document.createElement(“img”) (method call) both return an HTMLImageElement object), wrapping the object prototype alone, e.g., HTMLImageElement.prototype, does not capture the object creation operation and, therefore, cannot control the property access to this newly created object. For this reason, we manually create a wrapper class for each original class and mediate the access to the wrapper class using the Proxy object, standardized in ECMAScript 6 [17] and define a specific policy each access operation. Listing 3 demonstrates an implementation example for mediating the “new Image(…)” operation.

## Tracking the Source (Origin) of the Code

A web page nowadays includes typically JavaScript code that can be sourced from different servers [53]. Browsers enforce the same-origin policy to ensure that JavaScript code comes from one origin (specified by the protocol, host, and port of an URL) cannot access the credentials of other origins [47]. However, the same-origin policy treats all code included in a web page as the same origin even though the code comes from an external web site [47, 51, 62]. Several prior works, e.g., [22, 55], recognize this security issue and propose new approaches to enforcing different policies for JavaScript within a web page but is sourced from external servers. For example, FlashJax [55] provides a new JavaScript API to load and execute JavaScript under a principal and enforces principal-based policies for external JavaScript code. However, FlashJax requires web developers to use this new JavaScript API on the web page; thus, it is not applicable for a browser-based tool. In our work, we leverage the call stack of JavaScript language to trace the source of the code, i.e., from which origin (scheme, host, port) the code is included. We term this source of the code as code

**Listing 3** Simplified code of mediating the access to new Image(..)

```

var imgPolicy = {
    get: function(obj, prop) { /* policies for get */},
    set: function(obj, prop, value) { /* policies for set */}
};
var OriginalImage = Image;
class ImageWrapper {
    constructor(height, width) {
        var imgObject = new OriginalImage(height, width);
        imgObject = new Proxy(imgObject, imgPolicy);
        return imgObject;
    }
}
Image = ImageWrapper;

```

origin. We note that our code origin concept is different from the web origin term usually used in the same-origin policy [47]. To track the code origin at runtime when we want to enforce a policy, we create a new `Error` object (`new Error().stack`) to get its stack and trace the top of the stack to get the code origin (We notice that a similar approach has been introduced in [51]; however, our implementation is independent and concurrently with that work). Our experiments demonstrate that this code origin tracing method can keep track of exactly where a JavaScript operation is invoked. The usage of this approach has already been illustrated in Listing 2.

### Context-Aware and Code Origin-Based Policies

We wish to define and enforce more precise policies that can detect and prevent possible information leakage channels as we can trace the origin of the code. The ideal method is to encode information flow policies. However, this approach requires new language constructors with new browser implementation [28]. In this work, we propose to control the information flow at the endpoints. This method means that we monitor the operations that read from sensitive data sources or send information to the outside of a browser. When a sending operation is called, we check whether confidential information was read. As we can keep track of the code origin, we can enforce policies that depend on the code origin. We can also consult the user and let the user decide to allow or deny a data send operation that might be suspicious.

### User-Centric Policies

Our approach allows users to customize the policy settings so that their privacy protection can be personalized. Users can define and customize their privacy at fine-grained levels, allowing for more than an “all-or-nothing” approach to privacy. Users can opt for a relaxed, moderate, or strict level of privacy for groups of related API, which in turn affects the enforcement of the context-aware security policies. For example, the `document.getElementById` group of functions could be a privacy risk if it is allowed to be accessed by all code origins on a page. A user who selects the strict policy would not allow these methods to be accessed at all, while a user utilizing the moderate level of security would only allow code from first-party origins to use these functions. This approach allows for the tailoring of a user’s experience and privacy on the web, according to how much they want to make accessible. Another way that users can customize their policy settings is through blacklisting origins that they do not trust. This method is made easy through an intuitive user interface accessible through the extensions popup menu.

## Implementation

We realize our proposed method in a JavaScript library and deploy it into a browser extension to develop a self-protecting tool for web users. In this section, we describe our JavaScript library, the concrete policies we have implemented, and how we develop a browser extension that leverages our library.

### JavaScript Monitoring Library

We implement our method by developing a JavaScript library to intercept JavaScript operations that might cause privacy leakage. Our library must be executed first in a web page to ensure that it can keep the original references to the intercepted operations.

We divide our interception implementation into three types: (1) data source access: operations can get sensitive data; (2) data sink channels: operations can send data to the outside of a browser. We detail each type below.

#### Data Source Access

The data sources in a web page include the cookie, HTML local storage, browsing history, location, the values of form elements, and the web page contents [40, 56]. These data can be accessed by method calls or property read. We implement each type of data source read according to the approach presented in “JavaScript interception”. For each operation, we check whether the code origin is allowed to read the data. If allowed, we mark that the code origin has read the data by update the corresponding state. The code in Listing 2 (in “JavaScript interception”) illustrates this interception implementation method for a property access of a data source (cookie). In Listing 4, we demonstrate the interception implementation of a data source using a method call (`localStorage.getItem()`). In this code, `monitorMethod` is a wrapping interface implementing the wrapping approach for method calls presented in “Proposed approach”. We list the common data source read operations implemented in our library in Table 1 (`document.getElementById*` in the first row stand for

**Table 1** Operations can access users’ data

Operation	Type	Data source
<code>document.getElementById*</code>	Method call	Page contents
<code>localStorage.getItem</code>	Method call	Local storage
<code>document.cookie</code>	Property access	Cookies
<code>window.history</code>	Property access	Browsing history
<code>navigator.geolocation.getCurrentPosition</code>	Method call	Location



getElementById, getElementsByTagName, getElementsByClassName).

include assigning an URL source to an object such as Frame, IFrame, Image, Script, and Form, Ajax, and

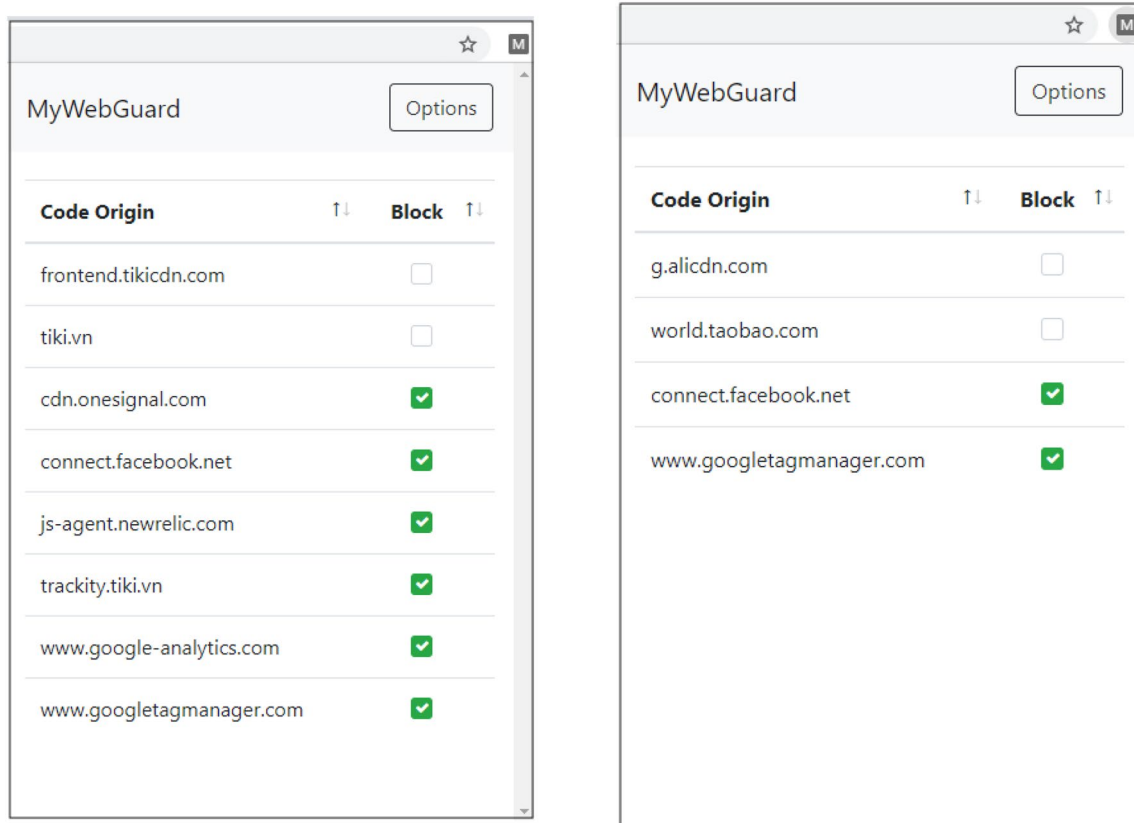
**Listing 4** Interception implementation of a method call accessing a data source

```
function localStorage_getItem_policy(args, proceed, obj) {
  var itemID = args[0];
  var code_origin = getCodeOrigin(new Error().stack);
  if (originAllowed(code_origin, "localStorage",
    "getItem", itemID)) {
    setOriginSourceRead(code_origin, "localStorage");
    return proceed(); //execute the method call
  }
  return; //supress the method call
}
monitorMethod(localStorage, "getItem",
  localStorage_getItem_policy);
```

### Data Sink Channels

We consider the channels where data can be sent from a browser to outside. We do not consider the attack scenarios that are aware by end-users, such as redirection, as this is out of the scope of our work. Generally speaking, these data channels are HTTP requests sent from a browser [47]. JavaScript operations that can generate a HTTP request

WebSocket. We note that WebSocket is not an actual HTTP request yet allows browsers to open two-way interactive communication to a server to send and receive messages asynchronously [48]. In the past, tracking companies have leverage WebSocket to circumvent the blocking mechanism in ad-blockers [4]. We intercept these channels using the approach for object creation presented in "JavaScript interception". Also, we intercept method calls, for example,



**Fig. 1** MyWebGuard user interfaces on <https://tiki.vn> (left) and <https://world.taobao.com> (right)

`document.createElement(...)` that create these objects and enforce the same policy as the object creation interception. We stop a data send operation if it violates policy.

### MyWebGuard: A Privacy Protection Tool in Browsers

In principle, our approach can be implemented and deployed either at the server or client side. However, as we aim to develop a tool for web users, we opt to implement a browser extension using our library. As discussed earlier, our method requires that the interception library run first before a web page is loaded. To this end, we put our JavaScript library code within the `innerHTML` property of a script object and append it to the current page. We perform experiments to confirm that our code is executed before any other code in a web page.

settings; otherwise, our enforcement code is broken. The technical challenge is that there is no such support in browsers for in separation. As we load our code at the webpage context in an extension to monitor webpage actions, it is not possible to communicate back and forward between the policy code and the extension code to update the policy settings and runtime parameters. We solve this challenge by designing a new mechanism where we use content scripts to exchange data between our policy code in webpages and the extension. Content scripts are the only files that run in the context of web pages that can read data from and pass information to their parent extension. Consequently, we share the data between our monitoring code and the content script periodically, then send them to the extension. The user-defined rules are loaded in the webpage context within an anonymous function to prevent malicious code from modifying it or from bypassing our mechanism. The rules will

**Listing 5** Injection of our code in a browser extension

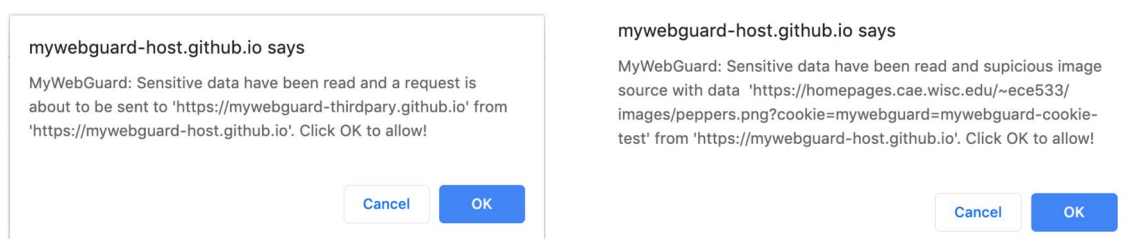
```
var mywebguard = document.createElement("script");
mywebguard.innerHTML = `
(function() {
  //the full JavaScript interception library here
  //...
})();`;
document.documentElement.appendChild(mywebguard);
```

We develop a proof-of-concept user interface to allow users to customize the policies at runtime. Figure 1 illustrates the user interface of our current prototype where users can customize the code execution from a webpage. We note that the code origins in these interfaces examples are dynamically loaded based on the code execution from these domains at runtime.

To support user policy customization, we need to store the policies in the browser so that it can be permanently saved crossing browsing sessions. On the other hand, we must prevent the webpage code from modifying these policy

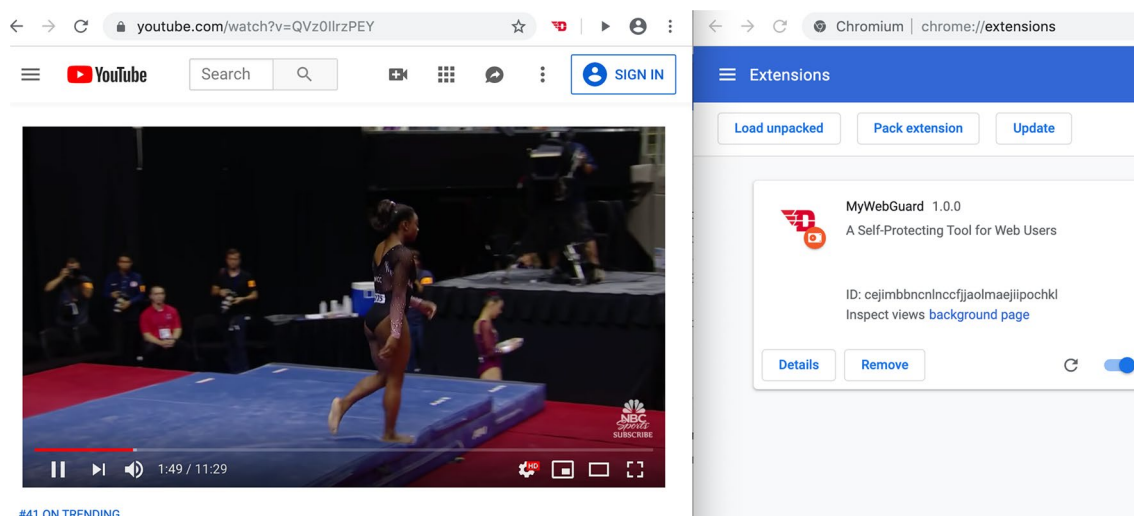
be rendered in the user interface at runtime. When a policy is customized or updated by the user, it will be synchronized between the extension and the webpage context so that the updated policies are refreshed in both sides of webpage and the local storage in the browser.

Implemented as a JavaScript library, our method should be able to be deployed in any browsers as an extension. In this implementation prototype, we develop our MyWebGuard extension and evaluate it in Chromium family, including Google Chrome, Chromium, and Brave. In the future, we explore to deploy our library in other major browsers.

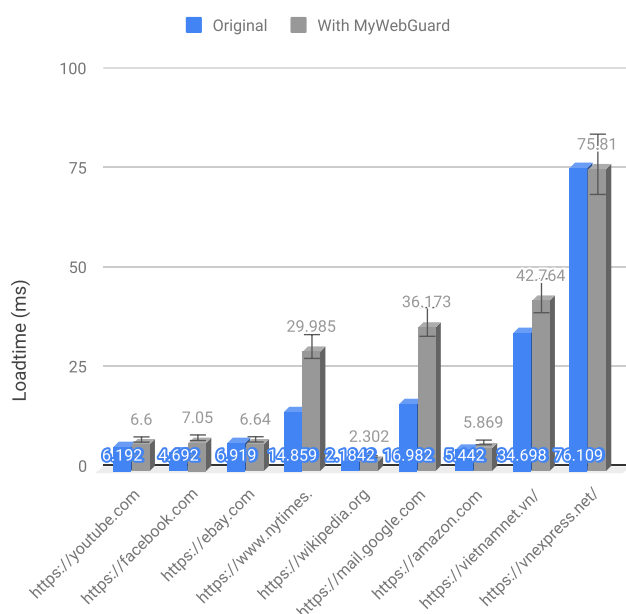


**Fig. 2** MyWebGuard can detect and prevent potential information leakage that is ignored by Ghostery and uBlock Origin extensions





**Fig. 5** Youtube video can be played functionally with MyWebGuard extension in Chromium



**Fig. 6** Load time overhead of MyWebGuard in actual websites

a Youtube video can play when our extension is turned on in Chromium.

We also measured if our extension slows down the load time of actual websites. We tested this by getting the load time numbers in the Network debug in a Chromium browser for top websites in Alexa and several Vietnamese news, with and without our extension. We disabled alert and debug messages and loaded each website ten times to get the average numbers. Figure 6 illustrates the load time overhead of our extension over ten popular websites. As we can see from this graph, our MyWebGuard tool does not pose a great slow down in load time. The average slow down ratio is 1.33, but

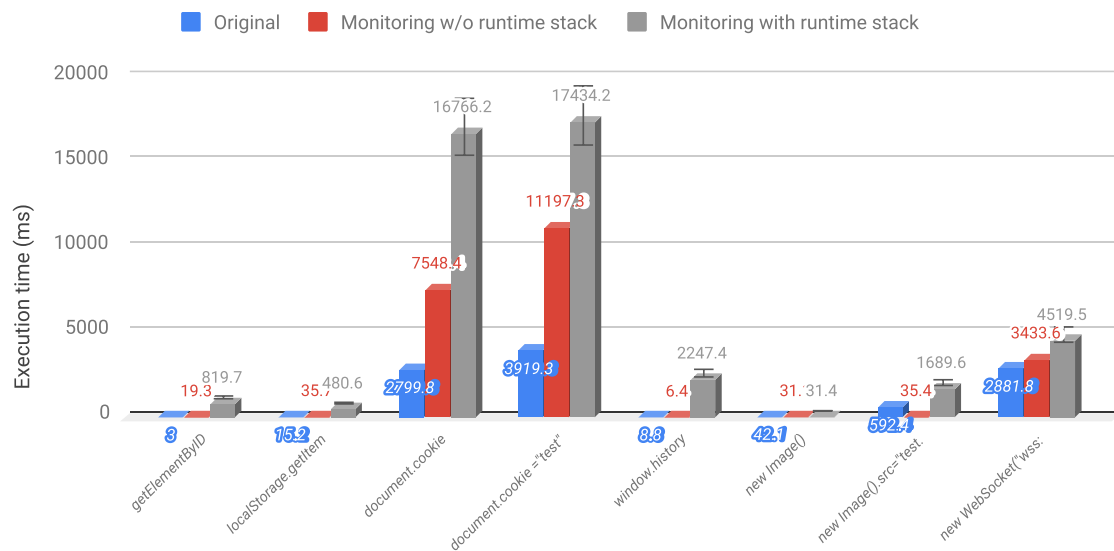
in some cases, the load time is even faster with our extension. For example, the slow down for <https://ebay.com> and <https://vnexpress.net> is 0.95 and 0.99, respectively. This improvement might be because some wrapped operations can be executed faster than the original ones, as reported in the literature [55]. We note that we test <https://facebook.com> and <https://mail.google.com> in logged-in sessions because the content of these web pages are too light to test without logged-in. In several cases, such as <https://www.nytimes.com> and <https://mail.google.com>, the load time is almost doubled. We examine these pages and notice that this might be due to the large number, e.g., hundreds of HTTP requests that the page has sent to remote servers.

## Performance Overhead

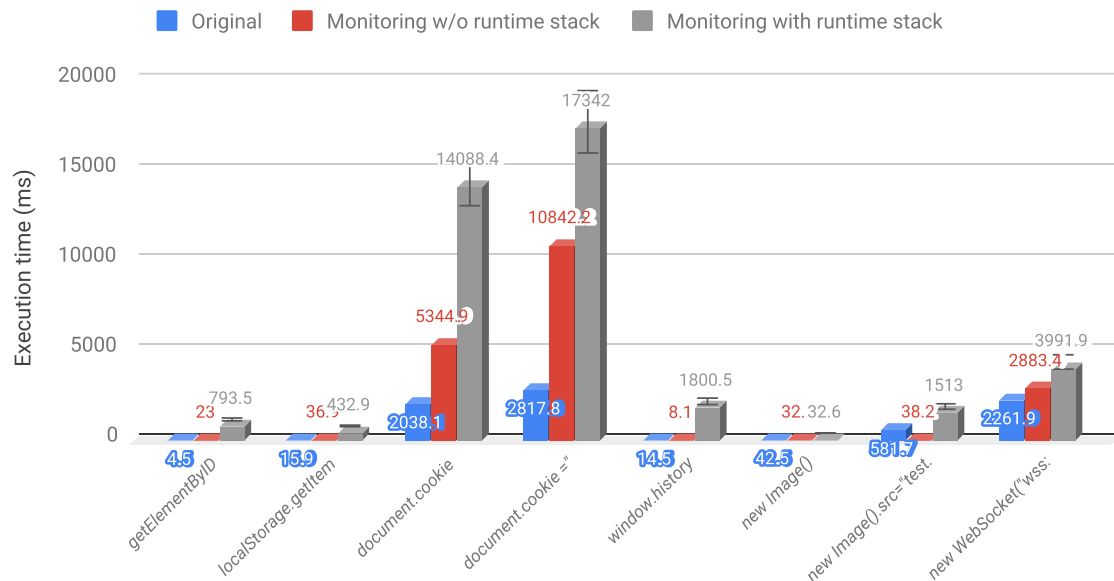
We evaluated the performance overhead of our prototype by measuring the microbenchmarks of each operation. We created a webpage to test every single operation. To get precise results, we loop each operation 10,000 times. We measure the execution time without and with our extension. We also remove the code origin tracing and measure the overhead.

Besides looking out for anomalies and to get unbiased results, we test every case by running the host web page ten times and get the average execution time. Figures 7 and 8 show the visualization of the overhead in Chromium and Brave browsers, respectively.

The slowdown ratios vary depending on an operation. As we can observe from Figs. 7 and 8, the overhead of *getElement\**, *window.history* is quite high while the one of *new Image*, *new WebSocket* is very small or even negative (faster). The average slowdown for the operation tests is 71.98 times in Chromium and 43.24 in Brave. While these average numbers are similar to ratio overhead of



**Fig. 7** Microbenchmark visualization of MyWebGuard in Chromium browser



**Fig. 8** Microbenchmark visualization of MyWebGuard in Brave browser

BrowserShield [59], it is very high compared to similar approaches such as [55, 56], which was average 6.33 times. We take a deeper look into the code and observe that the runtime stack used to track the code origin might cause this high overhead. We revise our code to remove the code origin tracking and perform the tests again. Experimental results confirm our observations: the overhead without runtime stack or the operation tests is 2.13 times in Chromium and 2.07 in Brave. With the upcoming release of zero-cost stack trace [11], we are optimistic about our code origin-based approach for policy enforcement.

## Discussion

Our implementation and evaluation demonstrated that our proposed approach is efficient in detecting and preventing potential privacy leakages on the web based on the code origin. Implemented as an inclined reference monitor [19], our enforcement mechanism, in general, can enforce security policies, which can prevent potential malicious actions. This means that our approach can detect malicious code that violates the defined security policies. Although we have not emphasized on security policies in this work, our approach,



in principle, can enforce such policies, e.g., discussed in [43, 56] to prevent malicious code.

Our MyWebGuard's design allows users to customize the policies via a user interface (GUI). In our current proof-of-concept GUI prototype, it enables users to block or allow code from a code origin. In general, as discussed in Sect. 3.5, we support user-centric policies that provide the flexibility for users to set more fine-grained policies rather than block/unblock mechanisms. This flexibility allows users to relax some certain scripts based on their actions. However, we leave this for future work. In some cases, we rely on the user to decide if a cross-origin information flow, i.e., potential privacy leakage, is allowed. However, we note that this detection mechanism is based on the code behaviors, which is different from traditional filtering approaches that load or block the entire code from a remote domain. In the future, we can reduce the number of such alert messages or avoid them by deploying default security and privacy policy patterns that are to automatically detect and prevent behaviors known as privacy leakage in the literature.

## Conclusions and Future Work

In this paper, we have presented MyWebGuard, a user-centric approach, and a tool to protect the privacy of web users. MyWebGuard can enforce context-aware and code origin-based policies to prevent privacy leakage channels that cannot be captured by existing tools in the industry. The evaluations of our prototype implementation evidence that our novel enforcement method can effectively protect the privacy of web users yet pose lightweight overhead on popular real-world websites.

Our current prototype allows end-users to customize their privacy preferences. In the future, we plan to extend and refine the security policy specification so that they are focused on privacy protection while requiring fewer actions from end-users. We will perform large-scale evaluations of our tool on top websites and investigate whether our tool interferes with co-existing browser extensions. We also plan to leverage machine learning to produce practical policies that protect users but do not break legitimate third-party code. Our objective is to provide a robust and mature tool that web users can use to protect their privacy in the real world. We also want to explore the effectiveness of our approach when built-in into a browser.

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## Compliance with Ethical Standards

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