Spook.js: Attacking Chrome Strict Site Isolation via Speculative Execution

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***Abstract*—The discovery of the Spectre attack in 2018 has sent shockwaves through the computer industry, affecting processor vendors, OS providers, programming language developers, and more. Because web browsers execute untrusted code while potentially accessing sensitive information, they were considered prime targets for attacks and underwent significant changes to protect users from speculative execution attacks. In particular, the Google Chrome browser adopted the *strict site isolation* policy that prevents leakage by ensuring that content from different domains is not shared in the same address space.**

The perceived level of risk that Spectre poses to web browsers stands in stark contrast with the paucity of published demonstrations of the attack. Before mid-March 2021, there was no public proof-of-concept demonstrating leakage of information that is otherwise inaccessible to an attacker. Moreover, Google's leaky.page, the only current proof-of-concept that can read such information, is severely restricted to only a subset of the address space and does not perform cross-website accesses.

In this paper, we demonstrate that the absence of published attacks does not indicate that the risk is mitigated. We present Spook.js, a JavaScript-based Spectre attack that can read from the entire address space of the attacking webpage. We further investigate the implementation of strict site isolation in Chrome, and demonstrate limitations that allow Spook.js to read sensitive information from *other* webpages. We further show that Spectre adversely affects the security model of extensions in Chrome, demonstrating leaks of usernames and passwords from the LastPass password manager. Finally, we show that the problem also affects other Chromium-based browsers, such as Microsoft Edge and Brave.

I. Introduction

Recent computer trends have significantly changed the way we use and distribute software. Rather than downloading installation packages, users now prefer to "live in their browser", where software is seamlessly downloaded, compiled, optimized, and executed merely by accessing a URL. Despite its humble origins, the browser is no longer a simple GUI for rendering text documents, but instead is more akin to a "mini operating system", complete with its own execution engines, compilers, memory allocators, and API calls to underlying hardware features. Perhaps most importantly, the browser has evolved into a highly trusted component in almost any user-facing computer system, holding more secret data than any other computer program except the operating system.

Concurrently with the rise in importance of the browser, the rapid growth in complexity of computer systems over the past decades has resulted in numerous hardware security vulnerabilities [2, 6, 12, 21, 22, 24, 26, 27, 29, 48, 49, 50, 58, 69, 70, 71, 74, 75, 77]. Here, the attacker artificially induces contention on various system resources, aiming to cause faults or recover information across security boundaries. Perhaps the most known incident of this kind was the discovery of Spectre [31] and Meltdown [36], which Google dubbed as a watershed moment in computer security [41].

Recognizing the danger posed by browser-based transient-execution attacks, Google has attempted to harden Chrome against Spectre. Introducing the concept of strict site isolation [56], Google's main idea is to isolate websites based on their domains, rendering mutually distrusting pages in different memory address spaces. Aiming to further hinder memory exposure attacks, Google elected to keep its JavaScript code in 32-bit mode, effectively partitioning the renderer's address space into multiple disjoint 4 GB heaps. It is hoped that even if a memory disclosure vulnerability is exploited, the use of 32-bit pointers will confine the damage to a single heap [19]. Thus, given the heuristic nature of these countermeasures, in this paper we ask the following questions:

Is Chrome's strict site isolation implementation sufficient to mitigate browser-based transient-execution attacks? In particular, how can an attacker mount a transient execution attack that recovers sensitive information, despite Google's strict site isolation and 32-bit sandboxing countermeasures?

A. Our Contribution

In this paper, we present Spook.js, a new transient-execution attack capable of extracting sensitive information despite Chrome's strict site isolation architecture. Moreover, Spook.js can overcome Chrome's 32-bit sandboxing countermeasures,

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reading the entire address space of the rendering process. Additionally, we demonstrate a gap between Chrome's effective top-level plus one (eTLD+1)-based consolidation policy and the same-origin policy typically used for web security. The discrepancy can result in mutually distrusting security domains residing in the same address space, allowing one subdomain to attack another. In addition, we show that Chromium-based browsers such as Edge and Brave are also vulnerable to Spook.js. We further show that Firefox's strict site isolation follows a similar eTLD+1 consolidation policy, but we leave the task of porting Spook.js to Firefox to future work.

Escaping 32-Bit Boundaries via Speculative Type Confusion. Although it executes in 64-bit mode, Chrome uses 32-bit addressing for its JavaScript architecture. This limits the information available to most Spectre-based techniques, as even a (speculative) out-of-bounds array index cannot escape the 4 GB heap boundary. To overcome this issue, Spook.js uses a type confusion attack that allows it to target the entire address space. At a high level, our attack confuses the execution engine to speculatively execute code intended for array access on a tailored malicious object. The malicious object is designed to place attacker-controlled fields where the code expects a 64-bit pointer, allowing a speculative access to arbitrary addresses. To the best of our knowledge, this is the first use of a type confusion attack to achieve pointer widening.

Avoiding Deoptimization Events via Speculative Hiding. Even if a type confusion attack is successful, the type of the malicious object does not match the expected array type. In response to such a mismatch, Chrome deoptimizes the array access code which Spook.js exploits, preventing subsequent applications of the attack. We overcome this issue by performing the entire type confusion attack under speculation, running the attack inside a mispredicted `if` statement.

Consequently, Chrome is completely oblivious to the type-confusion attack and its type mismatch, and does not deoptimize the code used for array access. This allows us to run our attack across multiple iterations, reading a large amount of data from the address space of the rendering process. Finally, while this speculative hiding technique suggested in past works [9, 18, 36, 40], to the best of our knowledge this is the first application of this technique for hiding browser deoptimization events.

Applicability to Multiple Architectures. With the basic blocks of our attack in place, we proceed to show the feasibility of Spook.js across multiple architectures, including CPUs made by Intel, AMD, and Apple. For Intel and Apple, we find that Spook.js can leak data at rates of around 500 bytes per second, with around 96% accuracy. For AMD, we obtain similar leak rates assuming a perfect L3 eviction primitive for AMD's non-inclusive cache hierarchy, the construction of which we leave to future work.

Security Implications of eTLD+1 Based Consolidation. Having established the feasibility of reading arbitrary addresses from Chrome's rendering processes, we now turn our attention to the eTLD+1 address space consolidation policy. Rather than using the same-origin policy, which considers two resources to be mutually trusting if their entire domain names match, Chrome uses a more relaxed policy that consolidates address spaces based on their eTLD+1 domains.

We show that this difference is significant, demonstrating how a malicious webpage (e.g., a user's homepage) located on some domain can recover information from login-protected domain pages displayed in adjacent tabs. Here, we show that a personal page uploaded to a university domain can recover login-protected information from the university HR portal displayed in adjacent tabs, including contact information, bank account numbers, and paycheck data. Going beyond displayed information, we show how Spook.js can recover login credentials both from Chrome's built-in password manager and from LastPass, a popular third-party extension.

Exploiting Unintended Uploads. Tackling the case where a malicious presence on a domain is not possible, we show that user-uploaded cloud content is often automatically transferred between different domains of the same provider. Specifically, we show how content uploaded to a `google.com` domain is actually stored by Google on `googleusercontent.com`, where it can be consolidated with personal webpages created on Google Sites. Empirically demonstrating this attack, we show the recovery of an image uploaded to a `google.com` domain through a malicious Google Sites webpage.

Exploiting Malicious Extensions. Aside from website consolidation, we port Spook.js into a malicious Chrome extension which requires no permissions. We show that Chrome fails to properly isolate extensions, allowing one extension to speculatively read the memory of other extensions. We empirically demonstrate this on the LastPass extension, recovering both website-specific credentials as well as the vault's master password (effectively breaching the entire account). Because the problem stems from the browser policy, it is not specific to LastPass and is likely to affect other password managers and extensions. In response to our disclosure, Google introduced the option to avoid consolidating extensions [14].

Summary of Contributions. In this paper we make the following contributions:

- We weaponize speculative execution attacks on the Chrome browser, demonstrating Spook.js, an attack that can read from arbitrary addresses within the rendering process's address space (Section IV).
- We explore the limitations of Chrome's strict site isolation and demonstrate that consolidating websites into the same address space is risky, even when performed only in very restricted scenarios (Section V).
- We study the implications of Spook.js on the security model of extensions in Chrome. We demonstrate that an unprivileged attacker can recover the list of usernames and used passwords from a leading password manager (Section VI).
- We show that Chromium-based browsers, such as Microsoft Edge and Brave, are also vulnerable (Section VII).

B. Responsible Disclosure and Ethics

Disclosure. We shared a copy of the submission with the security teams of Intel, AMD, Chrome, Tumblr, LastPass, and

Atlassian. Experiments performed on university systems were coordinated with the university's IT department and with its Chief Security Officer.

Ethics. Some of our experiments require placing attack code on publicly-accessible webpages. To limit access to such pages and prevent capability leaks and potential 0-days in the wild, we ensured that no links to attack pages were placed in any webpage, and that attack pages were only activated if the browser presents a specific cookie that we manually placed in it. Data collection and inspection were done on a local machine, and never on external servers.

II. Background

A. Caches

To bridge the gap between the fast execution core and the slower memory, processors store recently accessed memory in fast caches. Most modern caches are set associative, meaning that the cache is divided into a number of sets, each of which is further divided into a fixed number of ways. Each way can store a fixed-size block of data, also called a cache line, which is typically 64 bytes on modern machines.

The Cache Hierarchy. The memory subsystem of modern CPUs often consists of a hierarchy of caches, which in a typical Intel CPU consists of three levels. Each core has two L1 caches, one for data and one for instructions, and one unified L2 cache. Additionally, the CPU has a last level cache (LLC), which is shared between all of the cores. When accessing memory, the processor first checks if the data is in L1. If not, the search continues down the hierarchy. In many Intel CPUs, the LLC is inclusive, i.e., its contents are a superset of all of the L1 and L2 caches in the cores it serves.

Cache Attacks. Timing access to memory can reveal information on the status of the cache, giving rise to side-channel attacks, which extract information by monitoring the cache state. Cache-based side-channel attacks have been demonstrated against cryptographic schemes [2, 10, 17, 37, 43, 48, 59, 77] and other secret or sensitive data [22, 62, 64, 65, 76].

B. Speculative Execution

To further improve performance, processors execute instructions out-of-order. That is, instructions are executed as soon as their data dependencies are satisfied, even if preceding instructions have not yet completed execution. In case of branches whose condition cannot be fully determined, the processor tries to predict the branch outcome based on its prior behavior and speculatively execute instructions in the predicted target. Finally, in case of a misprediction, speculatively executed instructions become transient [36]. In this case, the processor drops all results computed by incorrect transient execution and resumes execution from the correct target address.

The disclosure of the Spectre [31] and Meltdown [36] attacks demonstrated that, contrary to contemporary beliefs, transient execution can have severe security implications. While the processor disposes of results computed by transient instructions, the effects of transient execution on microarchitectural components, including caches, are not reversed. Transient-execution attacks exploit this effect by triggering incorrect transient execution, accessing information which is leaked via microarchitectural channels. Since the initial discovery of transient-execution attacks, many variants [8] have emerged, including variants of Spectre [29, 31, 34, 39] and of Meltdown [9, 36, 38, 54, 61, 69, 70, 71, 72].

C. Microarchitectural Attacks in Browsers

Side-channel techniques have also been demonstrated using code running in sandboxed browser environments. Here, browser-based cache attacks have been used to classify user activity [47, 64, 65], and even extract cryptographic keys [16]. Attacks exploiting abnormal timings on denormal floating-point values have been used for pixel stealing attacks [3, 32, 33] while Rowhammer-induced bit flips were also demonstrated using browser-based code [11, 15, 23]. Finally, browser-based transient-execution memory read primitives using JavaScript code have also been demonstrated [31, 39, 41], albeit without extracting sensitive information.

Eviction Set Construction. Cache attacks in JavaScript often require the ability to evict a value out of the cache. However, without native functionalities such as `clflush`, the attacker has to exploit the cache architecture for evictions. For the L1 data cache, eviction sets can be constructed using page offsets, as any two elements that have the same page offset belong to the same eviction set. However, as there is no heuristic for mapping elements to L3 eviction sets, a more sophisticated approach is required. Vila et al. [73] describes a method for generating L3 eviction sets in the Chrome browser.

Leaky.page. Google has recently released `leaky.page`, a JavaScript-based Spectre Proof-of-Concept (PoC) which demonstrates recovering out-of-bounds information using Spectre v1 techniques [20]. More specifically, leaky.page first locates an instance of a `TypedArray` JavaScript object, whose length information and data pointer reside in different cache lines. It then evicts the array's length from the L1 cache, forcing speculation past the array length check upon array access. At the same time, the cache line containing the array's data pointer is not flushed and remains cached. Hence the attacker can perform a transient out-of-bounds array access, leaking the obtained data via a cache channel.

We note, however, that the use of 32-bit array indices in JavaScript limits the effectiveness of leaky.page to the 4 GB heap containing the `TypedArray` object. This limitation is significant, as sensitive information (e.g., cookies, passwords, HTML DOM, etc.) is often located in different heaps and thus remains out of leaky.page's reach.

Rage Against The Machine Clear. In a concurrent independent work, Ragab et al. [53] demonstrated a new transient-execution attack against Firefox. At a high level, Ragab et al. [53] construct a read primitive for 64-bit addresses by injecting arbitrary floating-point values in a transient-execution window created by a floating-point machine clear. Using this technique, they demonstrate a PoC of a transient type confusion attack on Firefox, with all the mitigations enabled, allowing an attacker to read arbitrary memory addresses.

However, we note that the attack of Ragab et al. [53] significantly differs from Spook.js. In particular, their attack is a variant of LVI [70], which exploits the floating-point unit and is therefore classified as a Meltdown-type attack. In contrast, Spook.js is a Spectre-type attack, exploiting incorrect branch prediction in the JavaScript type check to trigger speculative type confusion. Finally, Ragab et al. [53] constructs a 64-bit read primitive but does not extract sensitive information.

D. Strict Site Isolation

The ever-increasing complexity of the Internet has forced major design changes in modern browsers. Rather than using a single monolithic process, browsers adopted a multi-process architecture where multiple unprivileged rendering processes render untrusted and potentially malicious webpages [1, 46, 55, 78]. In addition to the increased stability from crashes offered by this design, using unprivileged rendering processes compartmentalizes the browser, limiting the reach of attacks that exploit vulnerabilities in the browser's rendering engine.

Site Isolation. Instead of grouping webpages arbitrarily into rendering processes, strict site isolation [56] aims to group them based on the location they are served from, such that mutually distrusting domains are separated. The deployment of strict site isolation was accelerated following the demonstration of transient-execution attacks in browsers [31, 39].

eTLD+1 Consolidation. Chrome's strict site isolation uses the effective top-level domain plus one sub-domain (eTLD+1) as the definition of a security boundary, and ensures that multiple webpages are rendered by the same process only if they are all served from locations that share the same eTLD+1. For example, Chrome will separate `example.com` and `example.net` as their top-level-domains, `.net` and `.com`, are different. `example.com` and `attacker.com` are also separated into different processes due to a difference in their first sub-domains (`example` and `attacker`). Finally, `store.example.com` and `corporate.example.com` are allowed to share the same process since they both share the same eTLD+1, `example.com`.

Origin Isolation. We note that Chrome could have opted for a stricter isolation, using the website's entire origin. However, origin isolation might break a non-negligible amount of websites, as 13.4% of page loads modify their origin via `document.domain` [56]. Finally, Chrome's process consolidation is not only limited to websites but also includes mutually distrusting extensions. See Section VI.

E. Chrome's Address Space Organization

Despite being a 64-bit application, Chrome still uses 32-bit values to represent object pointers and array indices. More specifically, array indices are viewed as a 32-bit offset from the array's starting address, while 32-bit pointers represent the offset from a fixed base address in memory, which is often termed as the object's heap. Although this design increases complexity, the smaller pointer size achieves a 20% reduction in Chrome's memory footprint [63].

Partitions. Consequently, Chrome is limited to allocating objects within a span of 4 GB, referred by Chrome as partitions. Chrome allocates objects into partitions based on the object type. Additionally, Google claims that this partition design also improves browser security, as linear overflows cannot corrupt data outside their corresponding partition [19].

Chrome Object Layout. When allocating buffer-like objects, Chrome follows a two-stage process. First, it allocates the memory required for the buffer storing the object's content. Then, it allocates a metadata structure, which holds a pointer to the object's content buffer (called the `back-pointer`), as well as additional information such as the object's `type-id` and the buffer length. Finally, certain JavaScript data structures, such as `Uint8Arrays`, often have their metadata structure and content's buffer located in two different heaps. In this case, the object must use a 64-bit `back-pointer` to be able to point outside the partition holding the object's metadata. See Figure 1.

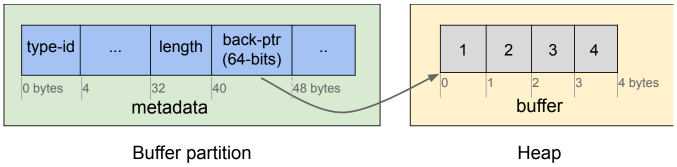


Figure 1: Representation of a Uint8Array array(1,2,3,4) object with data pointer in a different heap.

F. Chrome's Optimizer

Being a weakly typed language, JavaScript functions might be executed on arguments of different types. For example, `function f(x,y) {return x+y;}` can be used to add two integers, two floats, or even concatenate strings. Given the numerous different ways that the same high-level code might be used at runtime, the bytecode generated by Chrome must support multiple use cases, rendering it inefficient.

To improve performance, Chrome dynamically modifies the generated code once its run-time use cases are known. More specifically, Chrome executes the JavaScript bytecode while recording statistics regarding the inputs to certain operations. Based on the collected statistics, Chrome uses the TurboFan [68] compiler to generate highly optimized machine code, using a technique called speculative optimization [42]. Here, Chrome essentially assumes that future runs will use input types similar to past runs, and specializes the code to handle these cases. Finally, in case a code optimized for a specific input type is executed with a different type, it is deoptimized back to the generic yet less efficient version.

III. Threat Model

Unless stated otherwise, in this paper we target Chrome version 89 in its default configuration, with strict site isolation enabled. For the website-based attacks described in this paper, we follow a threat model similar to the related-domain attacker model of [5, 66], and assume that the attacker is able to upload JavaScript code to a page with the same eTLD+1 domain as the targeted page. In Section V we present several examples of such scenarios, including personal pages on popular platforms. We further assume that the attacker's page is rendered in the victim's browser. Finally, for the malicious extension attacks in Section VI, we assume that the victim has downloaded and installed an attacker-controlled Chrome extension.

IV. Spook.js: Mounting Speculative Execution Attacks in Chrome

We now present Spook.js, a JavaScript-based transient-execution attack that can recover information across security domains running concurrently in the Chrome browser. In addition to defeating all side-channel countermeasures deployed in Chrome (e.g., low-resolution timer), Spook.js overcomes several key challenges left open in previous works.

[$\mathcal{C}_1$] Strict Site Isolation. Strict site isolation prevents cross-site attacks. Website consolidation suggests an avenue for overcoming the challenge, but there is a need for a repeatable procedure that lets the attacker consolidate sites.

[$\mathcal{C}_2$] Array Index Limitations. The use of 32-bit array indices in JavaScript restricts bounds check bypasses to recover values only from the same JavaScript heap. To retrieve all sensitive information, the attacker needs to be able to transiently access the full address space.

[$\mathcal{C}_3$] Deoptimization. In our attacks, inducing mis-speculation also causes deoptimization that prevents multi-round attacks. For a successful attack, the attacker needs to cause mis-speculation without causing deoptimization.

[$\mathcal{C}_4$] Limited Speculation Window. Overcoming [$\mathcal{C}_2$] and [$\mathcal{C}_3$] requires a long speculation window. The attacker needs a consistent method that ensures that the processor does not detect mis-speculation before the transient code has the opportunity to retrieve the sensitive data and transmit it.

A. *Overcoming* [$\mathcal{C}_1$]*: Obtaining Address Space Consolidation*

To mount Spectre-type attacks, the attacker and target websites should reside in the same address space. Chrome's strict site isolation feature aims to prevent cross-domain attacks by segregating security domains into different address spaces. However, Chrome does consolidate websites with the same eTLD+1 domain into the same process. We now discuss how an attacker can exploit this consolidation to achieve co-residency between the attacker and target pages.

Exploiting iframes. We first observe it is possible to achieve consolidation by embedding iframes containing sensitive content originating from the same eTLD+1 domain as the attacker's page. For example, the attacker's page, `attacker.example.com` can contain an invisible iframe rendering content from `accounts.example.com`. If the targeted user is already logged in to `accounts.example.com`, the embedded iframe may contain sensitive personal information.

While effective, this method cannot operate on pages that refuse to be rendered inside embedded iframes, e.g., through setting `X-Frame-Options` to `deny`. Because many attacks exploit weaknesses in iframes, setting this option is a recommended security measure and is employed by many websites.

Obtaining Cross Tab Consolidation. When experiencing memory pressure, Chrome attempts to reduce its memory consumption by consolidating websites running in different tabs, provided that these have the same eTLD+1. Thus, a tab rendering `attacker.example.com` might be consolidated with another tab rendering `accounts.example.com`. Moreover, we observe that once consolidation occurs, Chrome tends to add newly-opened websites sharing the same eTLD+1 domain, rather than create a new process for them.

Abusing `window.open`. Finally, we observe that Chrome tends to consolidate pages opened using the JavaScript `window.open()` API, when these share the eTLD+1 domain of the opener. Thus, code running on `attacker.example.com` can use `window.open` to open `accounts.example.com` in a new tab. While not stealthy, this method seems particularly reliable and does not require memory pressure to obtain consolidation.

Experimental Results. We measure the effectiveness of each of the consolidation approaches described above using Chrome 89.0.4389 (latest at the time of writing) on a machine featuring an Intel i7-7600U CPU and 8 GB of RAM, running Ubuntu 20.04. We find that embedded iframes are always consolidated if they have the same eTLD+1 domain as the website embedding them. Likewise, we achieve perfectly reliable consolidation with `window.open`.

To benchmark cross-tab consolidation under memory pressure, we simultaneously opened websites from Alexa's top US list in different tabs. We find that simultaneously opening 17 out of Alexa's top-20 websites forces Chrome to begin consolidation where possible. Finally, we find that the number of open websites depends on the machine's memory size. Specifically, on a similar machine with 16 GB, we need to open 33 sites concurrently before consolidation occurs.

B. *Overcoming* [$\mathcal{C}_2$]*: Breaking 32-bit Boundaries via Speculative Type Confusion*

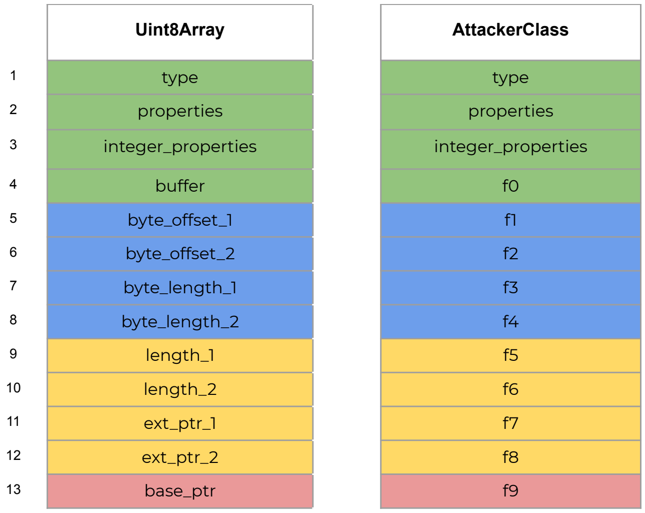
As described in Section II-E, Chrome uses a pointer compression technique that allows it to represent array indices and object pointers using 32-bit integers, partitioning the address space into 4 GB partitions. For an attacker trying to use Spectre v1 techniques to read information outside of the allocated array size, Chrome's 32-bit representation seems to limit the scope of the recovered information to a single 4 GB heap, leaving the rest of the address space out of reach.

In this section, we overcome this limitation using speculative type confusion, building a primitive that allows transient reading from arbitrary 64-bit addresses. While type confusion techniques have been previously outlined [25, 30, 41], to the best of our knowledge, this is the first demonstration of type confusion attacks against Spectre-hardened Chrome.

To mount our attacks, we first inspected the memory layout of common JavaScript objects, looking for an object with a 64-bit back pointer. We found that `TypedArrays` satisfy this requirement, as shown in Figure 1. While any `TypedArray` object can be potentially used with our technique, in the sequel we focus on `Uint8Arrays`, confusing Chrome's code for

```
1  UInt8Array-access(array, index){
2    // type Check
3    if(array.type !== UInt8Array){
4      goto interpreter; // Wrong type
5    }
6    //compute array length
7    len = array.length
8    // length Check
9    if (index >= len) {
10       goto interpreter; // Out of Bounds
11   }
12   //compute array back_ptr
13   back_ptr = array.ext_ptr+
   ↪   ((array.base_ptr+heap_ptr)&0xFFFFFFFF);
14   //do memory access
15   return back_ptr[index];
16 }
```

Listing 1: Pseudocode of operations performed by Chrome's JavaScript engine during array accesses.



	Uint8Array	AttackerClass
1	type	type
2	properties	properties
3	integer_properties	integer_properties
4	buffer	f0
5	byte_offset_1	f1
6	byte_offset_2	f2
7	byte_length_1	f3
8	byte_length_2	f4
9	length_1	f5
10	length_2	f6
11	ext_ptr_1	f7
12	ext_ptr_2	f8
13	base_ptr	f9

Figure 2: Memory layout of objects of `Uint8Array` (left) and `AttackerClass` (right). All words are 4 bytes (32 bits). For clarity, 64-bit fields are split to two 32-bit words.

performing array accesses and causing it to transiently operate on attacker-controlled `AttackerClass` objects.

Performing Array Operations. Consider the following JavaScript array declaration: `var arr = new Uint8Array(10)`. To implement `arr[index]`, the Chrome JavaScript engine performs the sequence of operations outlined in Listing 1, which the Chrome optimizer specializes to handle `Uint8Arrays`. Specifically, the code first checks if the array type is `Uint8Array` (Line 3). If it is, the code verifies that `index` is within the array bounds (Line 9). Following the success of these checks, the code constructs a pointer to the array backing store (Line 13), which it dereferences at offset `index` (Line 15). If either of the checks in Lines 3 or 9 fails, the execution engine raises an exception, diverting control to the JavaScript interpreter.

`Uint8Array` Memory Layout. The left half of Figure 2 shows the memory layout of a `Uint8Array` object. It starts with a three-field object header, specifying the object type and other properties. The header is followed by several fields, which describe the array. We focus on `length`, which specifies the number of elements in the array, and the two fields, `ext_ptr` and `base_ptr`, which are combined to get the pointer to the backing store. (Two fields are needed for legacy reasons.) We note that while `length` and `ext_ptr` are each 64 bits wide, we show each of them as two 32-bit words in Figure 2 (left) for clarity.

A Malicious Memory Layout. Unlike published Spectre v1 attacks, which exploit misprediction of a bounds check, our attack exploits type confusion by causing misprediction after a type check. For the attack, we cause transient execution of the `Uint8Array` array access code on an object other than a `Uint8Array`. By carefully aligning the fields of the malicious object, we can achieve transient accesses to arbitrary 64-bit memory locations.

The right side of Figure 2 contrasts the layout of the malicious object with that of `Uint8Array`. The `AttackerClass` object consists of ten 32-bit integer fields named `f0`–`f9`. We note, in particular, that `f5` and `f6` align with the `length` field of the array, `f7` and `f8` align with `ext_ptr`, and `f9` aligns with `base_ptr`.

Type Confusion. Type confusion operates by training the processor to predict that the object processed by Listing 1 is a `Uint8Array` and then calling the code with an `AttackerClass` object whose layout is shown in Figure 2 (right). The crux of the attack is that during transient execution following a misprediction of the type check in Line 3 of Listing 1, the code accesses the fields of `AttackerClass` object but interprets them as fields of `Uint8Array`.

In particular, the code interprets the values of `f7`–`f9` as if they were `ext_ptr` and `base_ptr`. Thus, by controlling `f7`–`f9` an attacker can control the memory address accessed under speculation. Specifically, Line 13 of Listing 1 shows how the values of `ext_ptr` and `base_ptr` are combined with the global `heap_ptr` to calculate the pointer to the backing store. Because Chrome tends to align heaps to 4 GB boundaries, the 32 least significant bits of `heap_ptr` are typically all zero. Hence, by setting the values of `f7` and `f8` to the low and high words of the desired address, and setting `f9` to zero, the computed value of `back_ptr` is the desired address. If the value of `index` is also set to zero, the transient execution will result in accessing the desired address. Setting `index` to zero also helps to avoid the need to speculate over the test in Line 9 of Listing 1. All the attacker needs to do is to set `f5` and `f6` so that when they are interpreted as a 64-bit `length`, they yield a non-zero value, e.g., 1.

Delaying Type Resolution. Our type confusion attack relies on mispredicting the branch at Line 3 of Listing 1. To allow transient execution past the branch, we need to delay the determination of the branch condition. Typically, such delays can be achieved by evicting the data that the condition evaluates from the cache. In our case, we evict the `type` field of the `AttackerClass` object. At the same time to compute the fake backing store pointer, the CPU should have transient access to fields `f7`–`f9` of the `AttackerClass` object before the type-checking branch is resolved. Thus, for a successful

```
 1  // Setup
 2  let objArray = new Array(128);
 3  for (let i=0; i<64; i++) {
 4    objArray[i] = new Uint8Array(0x20);
 5    objArray[64+i] = new AttackerClass(i);
 6    garbageCollector();
 7  }
 8  let malIndex = findSplitAttackObj(objArray);
 9  let malObject = objArray[malIndex];
10  let arguments;
11  let scratch = 0;
12  malObject.f0 = 1;
13
14  // Training
15  arguments = [0, 0];
16  for(let i=0; i<10000; i++) gadget();
17
18  // Attack
19  arguments = [malIndex, 0];
20  malObject.f5 = 1; // length_1
21  malObject.f6 = 0; // length_2
22  malObject.f7 = Lower32BitsOfAddress;
23  malObject.f8 = Upper32BitsOfAddress;
24  malObject.f9 = 0;
25  evict(malObject.f0);
26  gadget();
27  cacheChannel.receive()
28
29  // Attack Gadget
30  function gadget(){
31    let arrIndex, elemIndex = arguments;
32    if(arrIndex < malObject.f0) {
33      let arr = objArray[arrIndex];
34      let val = arr[elemIndex]; // byte
35      cacheChannel.leak(val);
36      return val;
37    }
38    return scratch;
39  }
```

Listing 2: An example of our speculative type confusion primitive, including code inserted by the JavaScript engine.

attack, we need an AttackerClass object that straddles two cache lines. In Section IV-D we describe how to achieve this layout and how we evict the type field from the cache.

C. Overcoming [$\mathcal{C}_3$]*: Avoiding Deoptimization Events via Speculation*

In the previous section, we show how we can perform type confusion with the compiler-generated code in Listing 1. We now demonstrate how an attacker can exploit type confusion to construct a generic read primitive. The main complication is that the attacker must not only control speculative execution at the processor, but also ensure that Chrome's optimizing compiler does not modify the code as it runs.

Listing 2 presents the JavaScript code for the attack, which consists of four main stages that we now describe.

Setup. The attack relies on speculatively swapping a malicious object of AttackerClass for a Uint8Array. The setup stage prepares all the variables needed for the attack. It initializes an array of objects objArray, setting some of the entries to Uint8Array and others to objects of AttackerClass (Lines 1–5). Line 6 triggers Chrome's garbage collector (similar to [20]) by allocating 50 1 MB buffers and allowing each buffer to go out of scope immediately. The garbage collector then compacts the heap and reallocates the previously-initialized objects, placing them in contiguous memory locations. Finally, we recall from Section IV-B that the attack requires finding a malicious object that is split over two cache lines. We find such an object in Line 8 of Listing 2. Due to its complexity, we defer the discussion of this procedure and its interaction with the garbage collector to Section IV-D.

We keep two different references to the malicious object: a direct reference in malObject (Line 9) and an indirect reference malIndex, via its index in objArray. Finally, the setup declares variables used by the gadget and sets malObject.f0 to 1. We note that we assume the field f0 is in the same cache line as the malicious object's type.

Training. In Lines 15–16, we perform the training stage of the attack. We first set the arguments of the gadget to ensure that the accessed object is a Uint8Array. Specifically, the gadget expects two values in the variable arguments.[1] The first argument is an index to the array objArray, which can be either an object of AttackerClass or a Uint8Array. In the case that the pointed object is a Uint8Array, the gadget's second argument is the Uint8Array index. Setting the first argument to 0 implies that the gadget uses the object in objArray[0], which is a Uint8Array.

After setting the arguments, the training stage invokes the gadget 10000 times (Line 16). During these invocations, Chrome's optimizer observes the gadget's execution, and detects that it always processes a Uint8Array object. Consequently, the optimizer specializes the gadget's array access to that case, using Listing 1 to perform the array access in Line 34. Moreover, the CPU's branch predictor observes the branches in the gadget and in the array access code, and sets their prediction to match a valid Uint8Array object.

Attack. In the attack stage, we first set the arguments to refer to our malicious object (Line 19). We then set the fields f5–f9, which correspond to the length, ext_ptr, and base_ptr of a Uint8Array (see Figure 2). Specifically we set f5, f6 to have the value 1 when interpreted as array length, f7, f8 to point to the desired 64-bit address when interpreted as ext_ptr, and f9 which is interpreted as base_ptr to zero.[2]We then evict the cache line that contains f0 (and the malicious object's type) from the cache and invoke the gadget. When the gadget returns, we retrieve the leaked value from the cache side-channel (Line 27), completing the attack.

Attack Gadget. The core of the attack occurs when the gadget function is executed on a malObject of type AttackerClass, after being specialized to handle Uint8Arrays. As Line 19 of Listing 2 passes malIndex, Line 33 results in arr being malObject of type AttackerClass. Next, as the array access in Line 34

[1] We pass the arguments using a global variable because we find that using function parameters increases the noise in the cache side-channel, which we use to retrieve the leaked values.

[2] This is a simplified description for brevity. See Appendix B for a thorough description.

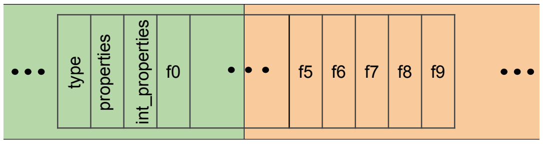


Figure 3: A malicious object split across cache lines.

of Listing 2 is specialized to handle access to `Uint8Arrays`, executing this line using `malObject` triggers the speculative type confusion attack described in Section IV-B. In particular, the address encoded in `malObject.f7` and `malObject.f8` is dereferenced, resulting in `val` being populated with that address's contents. Finally, Line 35 transmits `val` via a cache side-channel, where it is recovered in Line 27.

Deoptimization Hazard. Recall that the compiler specializes the array access in Line 34 of Listing 2 based on the observing `Uint8Array` accesses during the training phase. When the type confusion attack executes, the type check (Line 3 of Listing 1) recognizes the mismatch between `Uint8Array` and `AttackerClass`, aborts the specialized code, and alerts Chrome that other types may be used. Consequently, Chrome deoptimizes the array reference, revoking the specialization. Unfortunately, unspecialized code is not vulnerable to our type confusion attack, requiring us to re-train the optimizer for the next attack iteration. This will significantly reduce the overall byte rate of the attack.

Avoiding Deoptimization. To overcome this challenge, we adapt the speculative hiding technique previously used in native code [9, 18, 36, 40], to the context of the browser, and use branch misprediction to hide JavaScript type-mismatch events. Specifically, we wrap the attack code in a conditional block (Line 32 of Listing 2). The condition checks that the object index is less than the value of the field `f0` of the malicious object, which we have previously set to 1 (Line 12). Hence, the attack code is only executed architecturally when the index is zero and the refered object is `Uint8Array`. However, during the attack stage, the branch predictor mispredicts the condition as true, inducing a speculative execution of the entire type confusion attack code, including the type check. Moreover, because evaluating the condition depends on the value of `f0`, which has been evicted from the cache (Line 25), the processor cannot detect the misprediction until after the attack completes. When the procesor detects the misprediction, it reverts any changes to the architectural state resulting from executing Lines 32–37, and proceeds to Line 38. In this case, the type mismatch only happens transiently under speculation and is never committed to the CPU's architectural state. Thus, Chrome is never alerted to the mismatch and does not deoptimize the code in Listing 1 and Listing 2.

D. Overcoming [$\mathcal{C}_4$]*: Obtaining Deep Speculation via L3 Evictions*

The attack described in Listing 2 requires a malicious object of type `AttackerClass`, where the attacker can evict `malObject`'s `type` and `f0` field from the cache while keeping fields `f5–f9` inside the cache. The cache line boundary lies anywhere between `f0` and `f5` (see Figure 3). We now describe our technique for finding a malicious object at the desired cache layout, as well as how to flush its `type` from the cache. We first find eviction sets for all of the LLC sets and then use them to locate an appropriate malicious object and evict its type (Line 1).

```
1  LLCEvictionSets = GenerateLLCEvictionSets();
2
3  for(let i=64; i<128; i++){
4    candidate = objectList[i];
5    for(evictionSet in LLCEvictionSets){
6      access(candidate.f0);  // cache f0
7      evictionSet.evict();
8      let m = isEvicted(candidate.f0);
9      access(candidate.f5);  // cache f5
10     evictionSet.evict();
11     let h = isEvicted(candidate.f5);
12     if(m && !h){
13       malIndex = i;
14       break;
15 } } }
```

Listing 3: Finding an `AttackerClass` whose memory layout straddles two cache lines.

Use of Memory Compaction. We recall Lines 3–6 in Listing 2, which trigger Chrome's garbage collection after each allocation of an `AttackerClass` object. As a side effect of garbage collection, Chrome reallocates `AttackerClass` objects, compacting them to have a 4 B aligned contiguous memory layout. Next, as the size of each `AttackerClass` object is 52 B, the continuous memory layout of `AttackerClass` objects ensures that there exists an object whose `f0` and `f5` straddle two 64 B cache lines.

Finding a Split Object and a Corresponding Eviction Set. Listing 3 shows the code for identifying an appropriate malicious object and a matching eviction set that evicts the object type. The code first generates eviction sets for all of the LLC's sets, using the code of Vila et al. [73] (Line 1) with the `findall` setting. Empirically, this results in obtaining 99% of the eviction sets, which is sufficient to run our attack.

Listing 3 then tests each of the `AttackerClass` objects generated in Line 5 of Listing 2 to see if any has the desired layout. For each candidate, the test iterates over all of the eviction sets (Line 5), testing whether the eviction set evicts the candidate's `f0` but not its `f5` field. When an appropriate `AttackerClass` object is found, the code records its index in `malIndex` (Line 13), to be used in the attack of Listing 2.

Eviction Test. Testing whether a field has been evicted is done by measuring the time to access it. However, as part of hardening the browser against microarchitectural attacks, Chrome has reduced the resolution of its timer API [52]. Thus, instead of using `performance.now()`, we take the approach of Schwarz et al. [60], and implement a counting web worker thread using a `SharedArrayBuffer`. We note that following the discovery of Spectre [4], Chrome disabled the `SharedArrayBuffer` API [4], but ironically re-enabled it after strict site isolation was deployed.

The Need For LLC Eviction. Rather than using LLC eviction sets, leaky.page [20] (the Google PoC) uses L1 evictions. While constructing L1 eviction sets is far simpler and is more reliable than constructing LLC eviction sets, we have to resort to using the LLC. Specifically, we observe that if we only evict `malObject.f0` from the L1 cache but not from the LLC, our attack consistently fails. We believe that the reason is the length of the speculation window (the number of instructions executed before the processor detects mis-speculation). When the field `malObject.f0` is only evicted from the L1 cache, the processor retrieves it from the L2 cache within about 10 cycles. When the field is evicted from the LLC, it is retrieved from the main memory, taking over 100 cycles. We conjecture that our attack needs to speculatively execute more instructions than fit within the speculation window provided by L1 misses, requiring the longer, more complex, LLC misses.

E. End-to-End Attack Performance

So far, we have described a combination of techniques that enable an attacker's webpage to recover the contents of any address in its rendering process. We now evaluate the effectiveness of our techniques across several generations of processors, including CPUs made by Intel, AMD, and Apple.

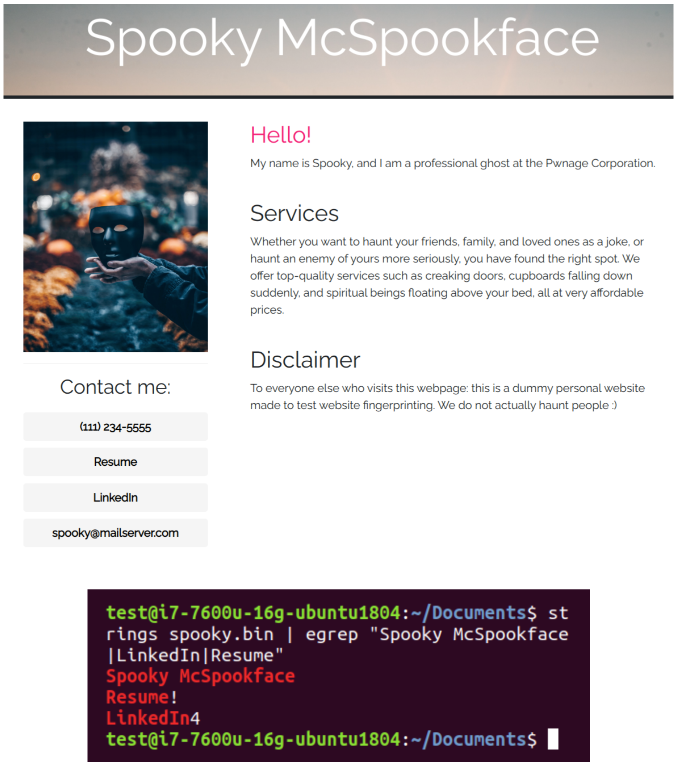
Attack Setup. On Intel and Apple processors, we run Spook.js on unmodified Chrome 89.0.4389.114. For our benchmark, we initialize a 10 KB memory region with a known (random) content and then use Spook.js to leak it.

Eviction Set Based Results. Table I shows a summary of our findings, averaging over 20 attack attempts. As can be seen, Spook.js leaks 500 B/sec on Intel processors ranging from the 6th to the 9th generation, while maintaining above 96% accuracy. On the Apple M1, Spook.js achieves a leakage rate of 450 B/sec with 99% accuracy.

Processor	Architecture	Eviction Method	Leakage	Error
Apple M1	M1	Eviction Sets	451 B/s	0.99%
Intel i7 6700K	Skylake	Eviction Sets	533 B/s	0.32%
Intel i7 7600U	Kaby Lake	Eviction Sets	504 B/s	0.97%
Intel i5 8250U	Kaby Lake R	Eviction Sets	386 B/s	3.93%
Intel i7 8559U	Coffee Lake	Eviction Sets	579 B/s	1.84%
Intel i9 9900K	Coffee Lake R	Eviction Sets	488 B/s	3.76%
AMD TR 1800X	Zen 1	clflush	591 B/s	0.02%
AMD R5 4500U	Zen 2	clflush	590 B/s	0.06%
AMD R7 5800X	Zen 3	clflush	604 B/s	0.08%

Table I: Spook.js performance across different architectures.

Failing to Evict. Unfortunately, on AMD's Zen architecture, we could not construct LLC eviction sets. As Spook.js requires the larger speculation window offered by LLC eviction, we were unable to run end-to-end Spook.js experiments on AMD systems. To evaluate the core speculative type confusion attack without constructing eviction sets, we instrumented V8 to expose the `clflush` instruction. As Table I shows, Spook.js achieves a rate of around 500 B/sec, demonstrating that if an efficient LLC eviction mechanism is found, Spook.js will be applicable to AMD. We leave the development of such eviction techniques to future work.



Spooky McSpookface

Hello!

My name is Spooky, and I am a professional ghost at the Pwnage Corporation.

Services

Whether you want to haunt your friends, family, and loved ones as a joke, or haunt an enemy of yours more seriously, you have found the right spot. We offer top-quality services such as creaking doors, cupboards falling down suddenly, and spiritual beings floating above your bed, all at very affordable prices.

Disclaimer

To everyone else who visits this webpage: this is a dummy personal website made to test website fingerprinting. We do not actually haunt people :)

Contact me:

(111) 234-5555

Resume

LinkedIn

spooky@mailserver.com

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ st
rings spooky.bin | egrep "Spooky McSpookface
|LinkedIn|Resume"
Spooky McSpookface
Resume!
LinkedIn4
test@i7-7600u-16g-ubuntu1804:~/Documents$ █
```

Figure 4: (top) Example of a victim webpage. (bottom) Leakage of parts of the victim webpage's text.

V. Attack Scenarios

In this section, we turn our attention to the implications of Spook.js. We investigate multiple real-world scenarios in which the attack retrieves secret or sensitive information.

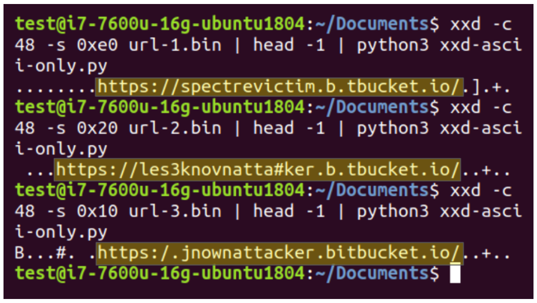
Experimental Setup. We perform all of the experiments in this section using a ThinkPad X1 laptop equipped with an Intel i7-7600U CPU and running Ubuntu 18.04. Next, unless stated otherwise, we use an unmodified Chrome version 89.0.4389. Finally, we leave all of Chrome's settings in their default configuration with all default countermeasures against side-channel attacks enabled.

Obtaining Consolidation. We recall the results from Section IV-A, where Chrome consolidates websites into the same renderer process based on their eTLD+1 domains. More specifically, as noted in Section IV-A, Chrome will consolidate websites into the same renderer process either naturally due to tab pressure (33 tabs for 16GB machine) or due to the attacker opening the target page using the `window.open` API call.

A. Website Identification

In our first scenario, we assume the attacker created a malicious page containing Spook.js code on a public hosting service. The attacker further managed to convince the victim to open an *unknown* page from the same hosting service, e.g., the victim opens their personal page. While the contents of most of the pages on the public hosting service are publicly accessible, the information about which pages the victim has open is private and should not be accessible to the attacker.

Attack Setup. To demonstrate how Spook.js violates the victim's privacy, we perform the attack on bitbucket.io, a Git-based hosting service. To mount our attack, we hosted an attacker webpage with the Spook.js code on bitbucket.io. We also created three sample personal pages on bitbucket.io, see Figure 4 (top). Following Bitbucket's naming convention, the URLs of the four pages follow the pattern https://username.bitbucket.io/, making these eligible for consolidation. The ground truth usernames for our three sample personal pages were {`spectrevictim`, `lessknownattacker`, `knownattacker`}.



```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c
48 -s 0xe0 url-1.bin | head -1 | python3 xxd-asci
i-only.py
........https://spectrevictim.b.tbucket.io/.].+.
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c
48 -s 0x20 url-2.bin | head -1 | python3 xxd-asci
i-only.py
 ...https://les3knovnatta#ker.b.tbucket.io/..+..
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c
48 -s 0x10 url-3.bin | head -1 | python3 xxd-asci
i-only.py
B...#. .https:/.jnownattacker.bitbucket.io/..+..
test@i7-7600u-16g-ubuntu1804:~/Documents$ █
```

Figure 5: Leakage of currently open bitbucket.io subdomains. The parts corresponding to the URLs are highlighted.

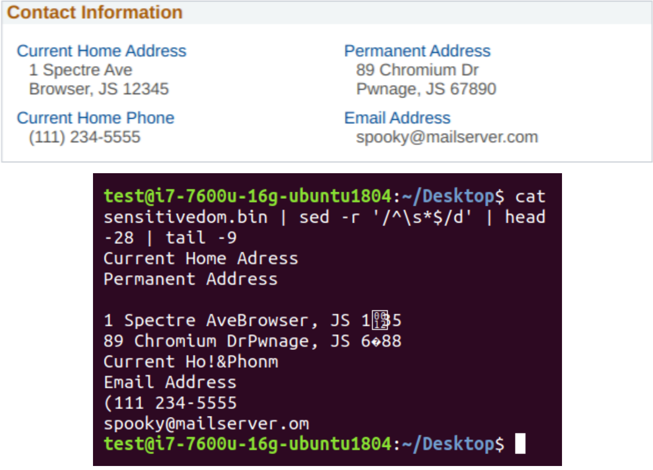
Experimental Results. After opening the four websites in four tabs, we consolidated all of the Bitbucket pages in one renderer process using the tab-pressure technique from Section IV-A. We then used Spook.js to leak the memory space of the renderer process. Inspecting the result, we recovered a list of the URLs for the tabs being rendered; see Figure 5. While the contents of our sample victim pages are public, the list of bitbucket.io websites simultaneously viewed by the user is private and should not be accessible to a malicious page hosted on bitbucket.io. Finally, we achieved similar results using `window.open` instead of tab pressure.

B. Recovering Sensitive DOM Information

In the second scenario, we consider a protected subdomain, which presents private data to an authenticated user. As an example, we exploited the structure of the website of our university, which at the time of writing hosts its main page, single sign-on (SSO) page, and internal portal page on the same eTLD+1 domain as personal webpages.

Attack Setup. Coordinating with the University's IT department, we hosted code performing Spook.js on a personal webpage (e.g., https://web.dpt.example.edu/~user/).With the author's account logged in, we visited three pages in the internal human resources portal, https://portal.example.edu/, on separate tabs. Each page contained the author's contact information and direct deposit account. See Figure 6 (top) and Figure 7 (top). (To protect the author's privacy, we edited the local copy of the DOM before mounting the attack.)

Experimental Results. After opening the three tabs, we also opened the page hosting Spook.js in the same window. Following its eTLD+1 consolidation policy, Chrome consolidated all four tabs into the same address space, allowing us to read sensitive values directly from the process's address space. See Figure 6 (bottom) and Figure 7 (bottom).



Contact Information

Current Home Address
1 Spectre Ave
Browser, JS 12345

Permanent Address
89 Chromium Dr
Pwnage, JS 67890

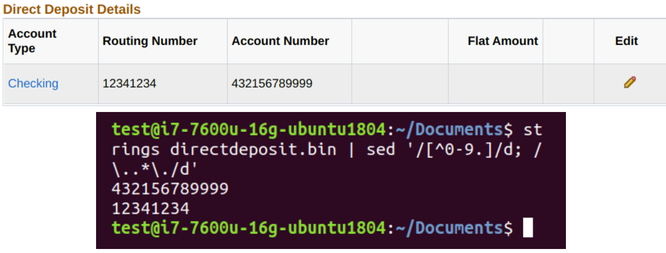
Current Home Phone
(111) 234-5555

Email Address
spooky@mailserver.com

```
test@i7-7600u-16g-ubuntu1804:~/Desktop$ cat
sensitivedom.bin | sed -r '/^\s*$/d' | head
-28 | tail -9
Current Home Adress
Permanent Address

1 Spectre AveBrowser, JS 1□5
89 Chromium DrPwnage, JS 6�88
Current Ho!&Phonm
Email Address
(111 234-5555
spooky@mailserver.om
test@i7-7600u-16g-ubuntu1804:~/Desktop$ █
```

Figure 6: (top) Contact information page displayed of the university website, edited to show anonymized information. (bottom) Leakage of contact information using Spook.js.



Direct Deposit Details

Account Type	Routing Number	Account Number		Flat Amount		Edit
Checking	12341234	432156789999				✎

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ st
rings directdeposit.bin | sed '/[^0-9.]/d; /
\..*\./d'
432156789999
12341234
test@i7-7600u-16g-ubuntu1804:~/Documents$ █
```

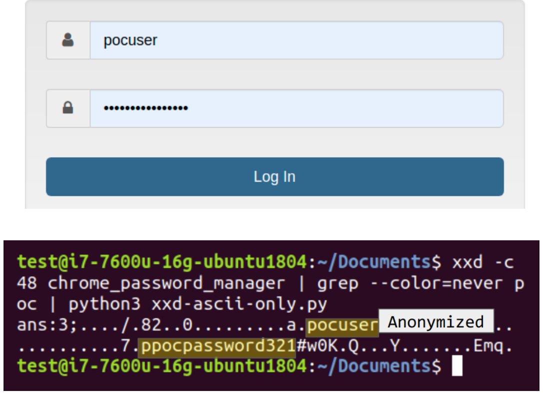
Figure 7: (top) The direct deposit settings page of the university website, edited to show anonymized information. (bottom) Leakage of bank account and routing number.

C. Attacking Credential Managers

We now demonstrate the security implications of Spook.js on popular credential managers, which automatically populate the login credentials associated with a website, often without any user interaction. Moreover, we show that credentials can be recovered even without the user submitting them by pressing the login (or any other) button, as merely populating the credentials into their corresponding fields brings them into the address space of the rendering process.

Attacking Chrome. We use the previous two-tab setup where the login page (https://weblogin.example.edu/), and the internal attacker page (https://web.dpt.example.edu/~user/) are hosted by the university and rendered by the same process. We assume that the credentials for https://weblogin.example.edu/ are already saved with Chrome's password manager, and it populates them as shown in Figure 8 (top). The bottom part of the figure shows Spook.js recovering the auto-populated credentials without requiring any user action.

Attacking LastPass. Next, we used a similar setup, but this time with LastPass version 4.69.0 to autofill the passwords (instead of Chrome's password manager). In addition to ob-

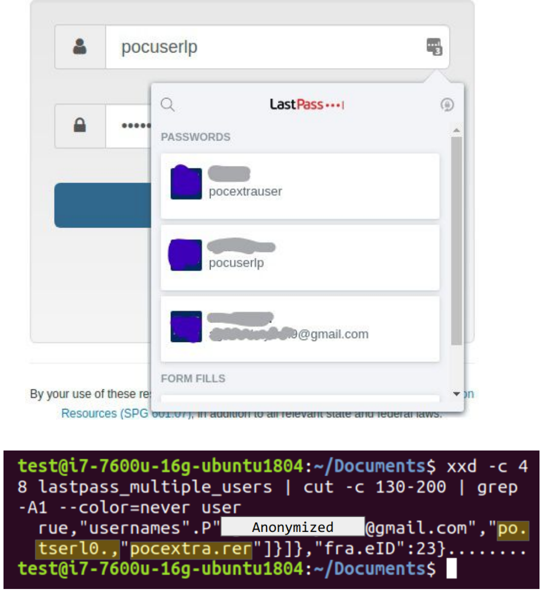


pocuser

••••••••••••••••

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c
48 chrome_password_manager | grep --color=never p
oc | python3 xxd-ascii-only.py
ans:3;..../.82..0.........a.pocuser Anonymized ..
..........7.ppocpassword321#w0K.Q...Y.......Emq.
test@i7-7600u-16g-ubuntu1804:~/Documents$ 
```

Figure 8: (top) Credential autofill by Chrome's password manager into the university's login page. (bottom) Leaked credentials using Spook.js.



pocuserlp

•••••

[redacted]
pocextrauser

[redacted]
pocuserlp

[redacted]
[redacted]@gmail.com

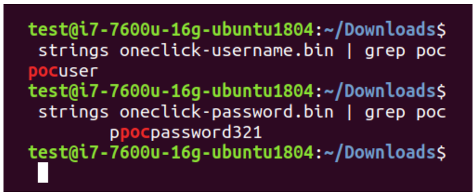
By your use of these re... on Resources (SPG ...), in addition to all relevant state and federal laws.

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c 4
8 lastpass_multiple_users | cut -c 130-200 | grep
-A1 --color=never user
  rue,"usernames".P"   Anonymized   @gmail.com","po.
  tserl0.,"pocextra.rer"]}]},"fra.eID":23}........
test@i7-7600u-16g-ubuntu1804:~/Documents$ 
```

Figure 9: (top) Multiple accounts managed by LastPass. (bottom) Using Spook.js to leak the list of associated accounts.

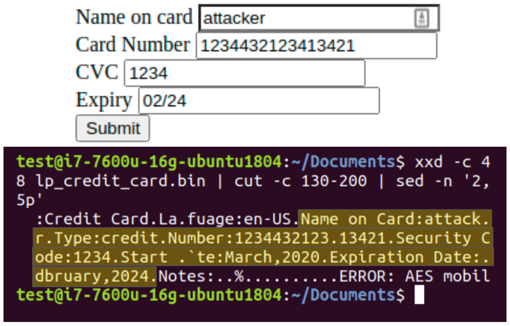
taining similar password leaking results as in Figure 8, we were also able to get multiple account usernames associated with the website. More specifically, Figure 9 (top) shows multiple credentials that we associated with university's login site. As the list of accounts resides in the address space of the rendering process, it can be recovered using Spook.js. See Figure 9 (bottom).

One-Click Credential Recovery. We take the previous attack a step further, showing that credentials can sometimes be recovered as soon as the victim opened our malicious webpage, without the need to assume any simultaneously opened tabs. This was made possible by two observations; firstly, while the pages of most of the university's authenticated portals refused to load inside an iframe (presumably due to security reasons), this was not the case for the login page. Secondly, while Chrome's built-in password manager required the user to click inside the iframe to fill their credentials, LastPass autofilled them without any user interaction, even when the iframe was not visible. Taking advantage of this, we added an iframe with the CSS `display:none;` to the personal webpage hosting the attack code (https://web.dpt.example.edu/~user/). As explained in Section IV-A, the main frame of the webpage and the iframe shared an eTLD+1, and thus were rendered by the same process. By doing so, we recovered the same credentials from Figure 8 as shown in Figure 10, yet without the victim visiting the login page voluntarily or knowingly.



```
test@i7-7600u-16g-ubuntu1804:~/Downloads$
 strings oneclick-username.bin | grep poc
pocuser
test@i7-7600u-16g-ubuntu1804:~/Downloads$
 strings oneclick-password.bin | grep poc
        ppocpassword321
test@i7-7600u-16g-ubuntu1804:~/Downloads$
 
```

Figure 10: Leaked credentials from an invisible iframe.



Name on card attacker
Card Number 1234432123413421
CVC 1234
Expiry 02/24

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c 4
8 lp_credit_card.bin | cut -c 130-200 | sed -n '2,
5p'
  :Credit Card.La.fuage:en-US.Name on Card:attack.
  r.Type:credit.Number:1234432123.13421.Security C
  ode:1234.Start .`te:March,2020.Expiration Date:.
  dbruary,2024.Notes:..%..........ERROR: AES mobil
test@i7-7600u-16g-ubuntu1804:~/Documents$ 
```

Figure 11: (top) Credit card information populated by LastPass. (bottom) Using Spook.js to leak credit card information.

Extracting Credit Cards. In addition to passwords, credential managers such as LastPass can be used to manage credit card information, autofilling it when authorized by the user. Using a setup similar to attacking login credentials, we were able to read the victim's card information shown in Figure 11 (top) after it was populated on a payment page with the same eTLD+1 domain as the attacker's page. See Figure 11 (bottom). Finally, similar credit-card recovery results were also obtained when attacking Chrome's credit card autofill feature.

D. Attacking Tumblr

We now combine the previous techniques used to recover sensitive information from a webpage's DOM and to recover autofilled credentials to deploy an attack on Tumblr. Tumblr is a microblogging platform and social network with 327 million unique visitors as of January 2021 [67].

Attack Setup. The Tumblr platform hosts a user blog in domain name `username.tumblr.com` and the login page is located at `tumblr.com/login`. Furthermore, the account settings page is located at `tumblr.com/settings/account`. As observed previously, this design choice is dangerous, because login pages and user-operated blogs that share the eTLD+1 can be consolidated. While users cannot freely add JavaScript to blog posts, they can inject JavaScript code into the `tumblr.com` domain by customizing the blog's theme template at the raw HTML level.

More specifically, Tumblr's cross-origin resource sharing (CORS) header disallowed importing scripts from a different origin, while Tumblr's content security policy (CSP) header prevented us from creating `Blob` objects. Despite this, Tumblr's CSP header allowed data URLs and the `eval` function, allowing us to embed the attack code as inline JavaScript inside a URL. We used Chrome 90.0.4430 for this attack, after we observed Chrome 89 refusing to call `eval` although the CSP header allowed it explicitly.

Attack Results. In a similar setup as before, we created a malicious blog on Tumblr's platform containing Spook.js attack code. We achieved consolidation in two ways. The first was via memory pressure as before, while the second technique was a two-click attack similar to our one-click credential recovery with LastPass. A one-click attack was not possible because both the login and account settings pages refused to render in an iframe, and Chrome treated a `window.open` from the DOM of our blog as a pop-up, blocking it unless allowed explicitly by the victim. However, with a `window.open` from an `onclick` attribute added to the blog's HTML body, consolidation became possible if the victim clicked anywhere on the blog. We note that Chrome did not block the 'pop-up' this time because it was user-initiated.

After both ways of consolidation, we were able to exfiltrate the credentials shown in Figure 12 (top) once they were injected into the login page's DOM by LastPass, see Figure 12 (bottom). In addition, Figure 13 (top) shows the list of all blogs owned by the user, which is not publicly available. We could leak this information from the DOM of account settings page as shown in Figure 13 (bottom).

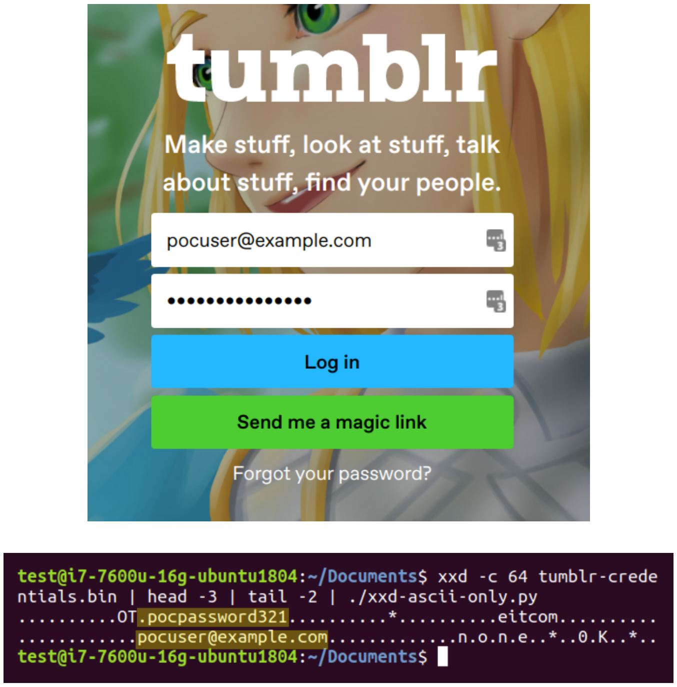
E. Exploiting Unintended Content Uploads

Our attacks so far assumed that the attacker's webpage is directly present on the domain to which the content was originally uploaded. We now depart from this assumption, showing that content uploaded to one domain is sometimes silently transferred to another, allowing Spook.js to recover it.

Google Sites. As an example of such a case, we use Google Sites, which allows users to create their own personal webpage and embed HTML containing JavaScript under `https://sites.google.com/site/username/`. Google Sites then runs the user-supplied code in a sandboxed iframe, which hosts the code under `https://prefix.googleusercontent.com`. As we are unable to obtain a presence on the `google.com` domain, Spook.js cannot affect other `google.com` pages directly, as these are located on different eTLD+1 domains and thus will never be consolidated with the attacker's page.

However, exploring Google services, we have observed that Google hosts more than personal webpages on `googleusercontent.com`. More specifically, Google seems to be using the `googleusercontent` domain as a storage location, automatically uploading emailed attachments, images, and thumbnails for Google Drive documents.

Google Photos. Focusing on Google Photos, we have discovered that all images uploaded (or automatically synchronized) to this service are actually hosted on the `googleusercontent.com` domain. When viewing images through `https://photos.google.com/`, the page loads the images from `googleusercontent.com` via `img` tags,


tumblr
Make stuff, look at stuff, talk about stuff, find your people.

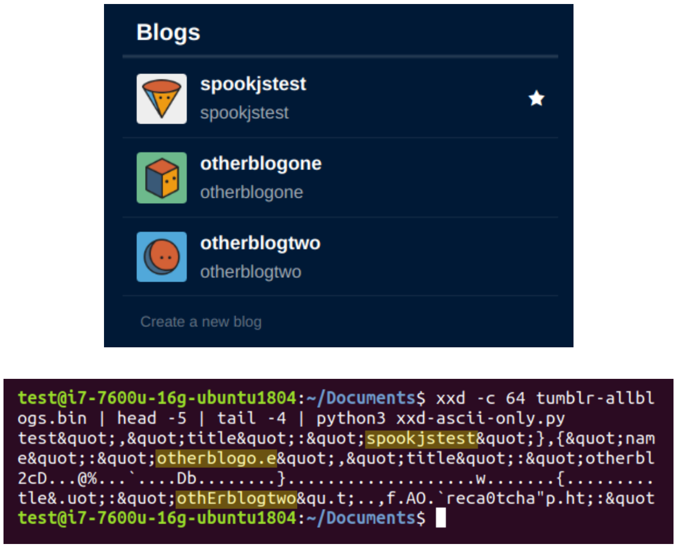
pocuser@example.com

•••••••••••••••

Log in
Send me a magic link
Forgot your password?

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c 64 tumblr-crede
ntials.bin | head -3 | tail -2 | ./xxd-ascii-only.py
..........OT.pocpassword321..........*..........eitcom..........
............pocuser@example.com.............n.o.n.e..*..0.K..*..
test@i7-7600u-16g-ubuntu1804:~/Documents$ 
```

Figure 12: (top) Tumblr's login page with credentials autofilled by LastPass. (bottom) Recovered username and password.



Blogs

spookjstest
spookjstest ★

otherblogone
otherblogone

otherblogtwo
otherblogtwo

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c 64 tumblr-allbl
ogs.bin | head -5 | tail -4 | python3 xxd-ascii-only.py
test&quot;,&quot;title&quot;:&quot;spookjstest&quot;},{&quot;nam
e&quot;:&quot;otherblogo.e&quot;,&quot;title&quot;:&quot;otherbl
2cD...@%...`....Db........}...................w........{.........
tle&.uot;:&quot;othErblogtwo&qu.t;..,f.AO.`reca0tcha"p.ht;:&quot
test@i7-7600u-16g-ubuntu1804:~/Documents$ 
```

Figure 13: (top) The list of all blogs owned by an account, which is visible only to the owner of the account. (bottom) Recovered list with blog names in highlights.

which are not consolidated into the process responsible for rendering pages hosted on `googleusercontent.com`.

Nevertheless, consolidation does occur in case the target elects for additional ways of viewing the image via options available through the right-click menu. For example, if the target loads the image in a new tab, the image will come directly from `googleusercontent.com`, making the tab eligible for consolidation in case of tab pressure. Likewise, in case the target opens the image through a link or QR code received from another person, the image will also be rendered by a consolidable `googleusercontent.com` tab.

Attack Setup and Results. We created a webpage on `sites.google.com` that contains Spook.js attack code. Next, we opened the attacker's Google site in one tab, and opened an image from the target's private Google Workspace (G Suite) in another tab, where the image was automatically uploaded by Google on `googleusercontent.com`. After obtaining consolidation due to tab pressure, we used Spook.js to recover the image. See Figure 14.

VI. Exploiting Malicious Extensions

Moving away from the security implications of website consolidation, in this section, we look at the security implications of consolidating Chrome extensions. At a high level, Chrome allows users to install JavaScript-based extensions that modify the browser's default behavior, such as blocking ads, applying themes to websites, managing passwords, etc.

Extension Permissions. To assist in this task, Chrome uses a permissions model, providing extensions with capabilities beyond that of regular JavaScript code executed by a website. To secure these privileged capabilities from websites and other less privileged extensions, it is important that extensions are correctly isolated from each other and from websites.

The LastPass Extension. To demonstrate the security implications of consolidating Chrome extensions, we use the LastPass Chrome extension, which is a popular credential manager for syncing credentials across multiple devices belonging to the same user. When the user logs into Chrome's LastPass extension, the extension fetches a vault of encrypted passwords stored on LastPass' cloud and decrypts it using a key derived from the user's password [35]. Furthermore, we empirically observed that LastPass decrypts passwords only when it has to populate the credentials into a website while retaining all the usernames in plaintext in memory.

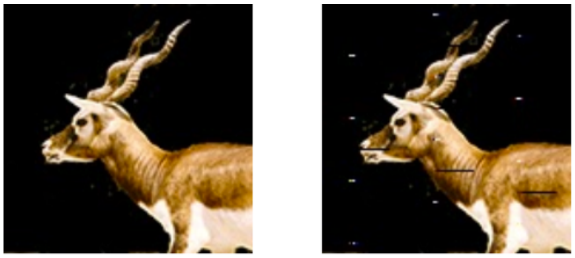
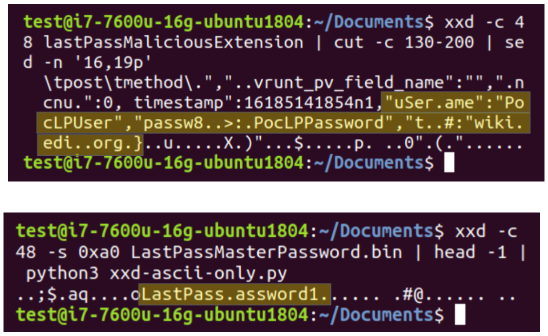


Figure 14: (left) An image of an antelope uploaded to Google Photos. (right) A reconstructed image from the leaked data.



```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c 4
8 lastPassMaliciousExtension | cut -c 130-200 | se
d -n '16,19p'
  \tpost\tmethod\.","..vrunt_pv_field_name":"",".n
  cnu.":0, timestamp":16185141854n1,"uSer.ame":"Po
  cLPUser","passw8..>:.PocLPPassword","t..#:"wiki.
  edi..org.}..u.....X.)"...$.....p. ..0".(."......
test@i7-7600u-16g-ubuntu1804:~/Documents$
```

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c
48 -s 0xa0 LastPassMasterPassword.bin | head -1 |
 python3 xxd-ascii-only.py
..;$.aq....oLastPass.assword1...... .#@...... ..
test@i7-7600u-16g-ubuntu1804:~/Documents$
```

Figure 15: (top) Recovered login credential of wikipedia.org populated by LastPass. (bottom) Recovered master password of LastPass' vault (originally `LastPassPassword1#`).

Attack Setup and Results. We use Chrome with the LastPass v4.69.0 extension, signing into our LastPass account. We also port Spook.js into a malicious Chrome extension that requires no permissions and install it on our system. As the system was already under tab pressure (as described in Section IV-A), we observed that Chrome had immediately consolidated our malicious extension with LastPass. We can now use LastPass to log in to any website, which triggers LastPass to decrypt and populate the website's credentials. Since Spook.js is running in the same process as the LastPass extension, we can leak the decrypted credentials, thereby violating Chrome's extension security model. See Figure 15 (top). Going beyond credentials for specific websites, we were also able to leak the vault's master password, which allows the attacker to compromise all of the vault's accounts; see Figure 15 (bottom).

VII. Attacking Additional Browsers

We now move to investigate Spook.js on other Chromium-based browsers, namely Micrsoft Edge and Brave. Edge is the default browser shipped with Windows 10 (5% desktop market share [28]), whereas Brave is a popular privacy-oriented browser that aims to block ads and trackers [7]. As both of these browsers are based on Chromium, they inherit the strict site isolation policy and its security limitations.

We experimentally observe that the consolidation techniques of Section IV-A are effective in both browsers. Measuring the effectiveness of Spook.js on both browsers, in Table II we see that, in both browsers, Spook.js achieves leakage rates similar to those obtained on Chrome.

Processor	Browser	Leakage Rate	Error Rate
Intel i7 6700k (Skylake)	Brave v89.1.22.71 Edge v89.0.774.76	504 B/s 381 B/s	1.25% 4.88%

Table II: Spook.js performance on Brave and Edge

Finally, we test the experimental implementation of strict site isolation on Firefox [44] using Firefox Nightly 89.0a1[45], build date April 12, 2021. Similar to Chrome, we observe consolidation with tab pressure and `window.open`. However, due to significant JavaScript engine differences, we stop short of implementing Spook.js on Firefox.

VIII. Conclusions

In this paper, we presented Spook.js, a new transient execution attack capable of recovering sensitive information despite Chrome's strict site isolation countermeasure. The fundamental weakness that Spook.js exploits is the differences in the security models of strict site isolation and the rest of the web ecosystem at large. On the one hand, strict site isolation considers any two resources served from the same eTLD+1 to always be in the same security domain. On the other hand, the rest of the web enjoys a much finer-grained definition of the security domain, often known as the same-origin policy. The same-origin policy only considers two resources are to be in the same security domain if the entire domain name is identical. As we show in Section V, the different definitions for a security domain have manifested as vulnerabilities in real world websites, that can be practically exploited by Spook.js.

A. Countermeasures

We now discuss several mitigation strategies for Spook.js.

Separating User JavaScript. Spook.js relies on consolidating two endpoints of the same website into the same process, one which executes attacker-controlled JavaScript and another which contains sensitive data. Website operators can protect their users from Spook.js by using different domains to serve each endpoint. While this technique is already used for separating user content from operator content, it is insufficient in cases where user-provided JavaScript is served from the same domain as other sensitive user-provided content. We propose to extend this idea, such that user-provided JavaScript content is served from one domain while all other user-provided content is served from another domain. This countermeasure can be immediately adopted by website operators to protect their users from JavaScript-based attacks such as Spook.js.

Origin Isolation. Browser vendors might choose to align the definition of security domains in strict site isolation with those used by the rest of the web. A straightforward approach is to consider the entire domain name for strict site isolation rather than relying on eTLD+1. However, origin isolation might break a non-negligible amount of websites, as 13.4% of page loads modify their origin via `document.domain` [56].

The Public Suffix List (PSL). Maintained by Mozilla, the PSL [13] is a list of domain names under which users can directly register names, even if these are not true top-level domains. Examples of list entries include `.com`, `.co.uk`, and also `github.io`. Recognizing that attackers can directly register sub-domains under the domains in the PSL, Chrome will not consolidate pages in case their eTLD+1 domain is present in the PSL. In particular, `x.publicsuffix.com` and `y.publicsuffix.com` will be treated as different sites and never be consolidated.

Thus, we recommend that web services hosting personal websites ensure proper isolation by adding their domain to the PSL. In particular, our attacks on `bitbucket.io` and `tumblr.com` in Section V were made possible due to the absence of both vendors from the PSL. Finally, we note that Tumblr's absence from the PSL was reported previously by [66] while `bitbucket.io` was added to the PSL following our disclosure.

Strict Extension Isolation. Despite the strict site isolation policy, Chrome still consolidates two extensions if the number of extensions reaches one-third of the total process limit [57]. This policy essentially allows extensions to mount transient execution attacks against each other, as we demonstrated in Section VI. Next, as a consequence of our work, Google deployed strict extension isolation [14], which prevents the consolidation of two extensions. While experimental, this can be manually enabled on Chrome 92, preventing malicious extensions from reading other extensions using Spook.js.

Speculation Hardening. At a high level, Spook.js is a type confusion attack which is possible as the CPU speculates past the object's type check. Thus, an incomplete but easy to implement countermeasure is to prevent such speculation by placing an `lfence` instruction after type checks. Next, pointer poisoning [51] is a technique that masks every data pointer with a random constant, specific to the object's type. This prevents speculative type confusion attacks, as an incorrect value will be unmasked in case of a type mismatch.

B. Limitations

Limitation of Targets. To deploy Spook.js, the attacker must upload Spook.js JavaScript code to the target website's domain. While Section V presents many such attack scenarios, Spook.js currently does not work across unrelated domains. Given the plethora of transient-execution attacks discovered and the complexity of modern browsers, it is not clear that unrelated domains are protected from each other.

Limitation of Architecture As described in Section IV-E, we cannot mount end-to-end Spook.js on AMD systems due to our inability to reliably evict the machine's LLC cache. We leave the task of adapting the attack to the AMD Zen architecture to future work.

Attacking Firefox. Similarly to Chrome, Firefox's strict site isolation implementation also consolidates websites based on their eTLD+1 domain. While we successfully induced consolidation on Firefox, the JavaScript execution engine is significantly different from Chrome's. Thus, we leave the task of demonstrating Spook.js on Firefox to future work.

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APPENDIX

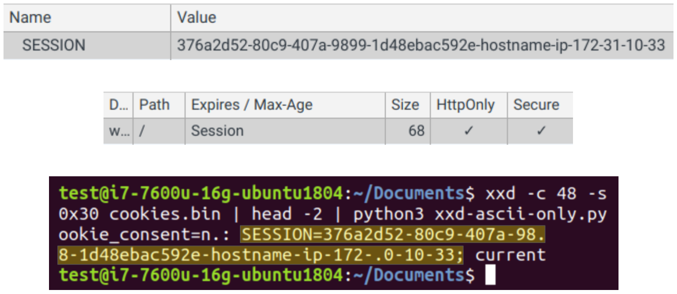
A. Reading Login Information

Going beyond information present on the document's DOM, we repeated our attack on our university's website, but this time targeting session cookies.

Attack Setup. We replicated the previous scenario's two-tab setup, where the Spook.js page (https://web.dpt.example.edu/~user/), and internal portal page (https://portal.example.edu/, after logging in) were rendered using two different tabs but shared the same Chrome rendering process.

Experimental Results. Our initial approach was to use Chrome's debugging tools in order to locate the metadata of the `document.cookie` object and dump the memory pointed to by its `back-pointer`, as shown in Figure 1. While we were able to read cookies associated with the portal page, the session cookie containing login information was marked as `HttpOnly`, and thus normally inaccessible from JavaScript. However, we discovered a different region in the address space of Chrome's rendering process that contains the session cookie, and successfully dumped it with Spook.js. See Figure 16.

Leakage Root Cause. We note that our observations regarding `HttpOnly` cookies seem to contradict an explicit security goal of Chrome's strict site isolation, as Google's strict site isolation paper explicitly states that `HttpOnly` cookies are not delivered to renderer processes [56, Section 5.1]. Reporting our findings to Google, this was discovered to be a bug in Chrome, where the debugging tools accidentally copy the cookie's contents into the address space of the rendering process. While this does make our cookie extraction attack weaker, we note that this attack is still dangerous, as the user can be enticed to manually open Chrome's developer tools.



Name	Value
SESSION	376a2d52-80c9-407a-9899-1d48ebac592e-hostname-ip-172-31-10-33

D...	Path	Expires / Max-Age	Size	HttpOnly	Secure
w...	/	Session	68	✓	✓

```
test@i7-7600u-16g-ubuntu1804:~/Documents$ xxd -c 48 -s
0x30 cookies.bin | head -2 | python3 xxd-ascii-only.py
ookie_consent=n.: SESSION=376a2d52-80c9-407a-98.
8-1d48ebac592e-hostname-ip-172-.0-10-33; current
test@i7-7600u-16g-ubuntu1804:~/Documents$
```

Figure 16: (top) Session cookie for the university's portal page displayed using Chrome's developer tools. (bottom) Leakage of the session cookie.

B. Value Tagging

Along with Pointer Compression, the V8 JavaScript engine uses a technique called Value Tagging [63] that allows code to operate on integers without requiring any indirection. It achieves this by squeezing integers into the same 32-bit space occupied by pointers to objects. The least significant bit is used to distinguish whether the 32-bit space encodes an integer or a pointer to an object. For integers, the least significant bit is set to zero and the remaining 31 bits encode a 31-bits integer. For pointers to objects, the JavaScript engine ensures that objects are always aligned to a multiple of two bytes (i.e. the least significant bit of an object pointer is always zero). To encode a pointer the least significant bit is set to one, and the offset for any access involving the pointer is decremented by one. This encoding allows code that performs operations on integers to avoid indirection and does not require an additional field to identify the type of the value.

We abuse Value Tagging to directly set the memory of an object by storing 31-bit integers in specific properties of the object. However, Value Tagging represents two practical challenges for our attack. The first is that we must undo any encoding applied to values, this can be done by shifting any desired value to the right by one bit. The second is that we cannot set the least significant bit of any property. However, because we use two properties to represent a 64-bit address there are two bits of the address bit 1 and bit 33 that we cannot set, these correspond to the least significant bit of each property. We overcome this challenge with `ext_pointer` and `index`. We access addresses that have bit 1 set by using an index when performing an array access on our type-confused object. To accesses addresses that have bit 33 set, we abuse the addition of `ext_pointer` with `base_pointer` and `index` when performing an array access to cause an overflow that sets bit 33. We set `ext_pointer` to 0X7FFFFFFF, after encoding it will have the value 0XFFFFFFFE, and we set `index` to 2. When these values are added together it causes an overflow and sets bit 33 of the address during the array access. These ideas can be combined to access addresses where bit 33 and bit 1 are set, we follow the same procedure to set bit 33 but set `index` to 3.