

I Still Know What You Visited Last Summer

Leaking browsing history via user interaction and side channel attacks

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Abstract—History sniffing attacks allow web sites to learn about users’ visits to other sites. The major browsers have recently adopted a defense against the current strategies for history sniffing. In a user study with 307 participants, we demonstrate that history sniffing remains feasible via interactive techniques which are not covered by the defense. While these techniques are slower and cannot hope to learn as much about users’ browsing history, we see no practical way to defend against them.

I. INTRODUCTION

Since the creation of the World Wide Web, browsers have made a visual distinction between links to pages their users have already visited, and links to pages their users have not yet visited. CSS allows page authors to control the appearance of this distinction. Unfortunately, that ability, combined with JavaScript’s ability to inspect how a page is rendered, exposes Web users’ browsing history to any site that cares to test a list of URLs that they *might* have visited. This privacy leak has been known since 2002 ([1], [2]), and fixes for it have been being discussed for nearly as long by both browser vendors and security researchers.

In 2010, L. David Baron of Mozilla developed a defense [3] that blocks all known, automated techniques for this attack, while still distinguishing visited from unvisited links and allowing site authors some control over how this distinction is made. The latest versions of Firefox, Chrome, Safari, and IE all adopt this defense. While it is a great step toward closing this privacy leak, in this paper we will demonstrate that it is still possible for a determined attacker to probe browsing history.

Baron’s defense makes no effort to defend against interactive attacks—that is, attacks which trick users into revealing what they see on the screen. In our first experiment, we demonstrate four practical interactive attacks that we have developed. These attacks can probe far fewer links per second than the automated attacks that formerly were possible, but they are still feasible for the small sets of links probed by the exploiters found by Jang et al. [4]. We discuss some potential countermeasures, but as long as a visited/unvisited distinction is being shown at all, it does not seem to us that users can be entirely protected from revealing it to a determined attacker.

Baron’s defense does include protection against side-channel attacks, particularly timing attacks. In our second experiment,

we demonstrate a side-channel attack that remains possible: The dominant color of the computer screen can be made to depend on whether a link is visited. The light of the screen reflects off the victim and his or her surroundings. If the victim possesses a “webcam” (a small computer-controlled video camera, pointed at the victim’s face—this is built into many recent laptops, and is a popular accessory for desktop PCs) it can be used to detect the color of the reflected light. This attack may not be practical for typical sites, if only because users are chary of granting access to their webcams. But like our interactive attacks, we do not believe it can be prevented as long as a visited/unvisited distinction is being shown onscreen.

The rest of this paper is organized as follows. In Section II we introduce the problem of history sniffing; in Section III we describe the automated attacks that were possible until quite recently, and the defense that has now been deployed against it. Section IV covers our primary experiment, demonstrating the feasibility of interactive attacks on browsing history; we also discuss the long-term implications of interactive attacks. Section V describes our second experiment, demonstrating a side-channel attack on history that remains exploitable even with a general defense against automated attacks in place. Section VI covers related work, and Section VII concludes.

II. BACKGROUND

A. The Web platform

The World Wide Web was originally conceived in 1990 as an interface to large collections of static documents (“pages”) [5]. In this paradigm, it is obviously useful for users to be able to tell whether they have seen a particular page before, no matter who is referring to it. NCSA Mosaic, one of the first graphical Web browsers, drew hyperlinks in blue if they referred to a page that had not yet been visited, in purple otherwise [6]; this feature was inherited by Netscape Navigator and has now become customary.

Since its original conception, the Web has evolved into a platform for software applications. At first these relied on server-side processing, but with the invention of JavaScript in the late 1990s, it became possible to run programs inside Web pages. With this capability comes a need for security: applications must not interfere with each other, and malicious software must not be permitted to exploit the user. The Web’s basic security policy is the *same-origin policy* [7], which

partitions the Web by its servers. JavaScript programs can only see data from the HTTP server that produced them; within the client, they can communicate only with other pages produced by the same server. The same-origin policy originally applied only to JavaScript but is progressively being expanded to cover other security decisions that the browser must make [8]. However, it has never applied to hyperlinks. It would diminish the utility of the Web if sites could not link to each other, or even if they could only link to other sites’ “front pages.” Further, since visited-link indications are most useful when you encounter an unfamiliar link to a familiar page, links are marked as visited whether or not they cross origins [9].

In principle, a website should not be able to determine what other sites its visitors have visited. Unfortunately, a combination of innocuous-seeming Web features makes it possible for websites to probe browsing history. This vulnerability was first publicly disclosed by Andrew Clover in a BUGTRAQ mailing list post in February of 2002 [1]. Until recently, browser vendors and the security community believed that it was not being exploited “in the wild,” but Jang et al. [4] discovered 46 popular websites—including one from the Alexa top 100—that definitely probed browsing history and reported what they found to their servers. Many of these sites were using third-party JavaScript libraries designed specifically to probe history. Another 326 sites made “suspicious” use of history information, but might not have been reporting it to their servers.

B. Threat model

Illicit inspection of browsing history is conventionally referred to as *history sniffing*.¹ As will be explained below, history sniffers cannot simply get a list of all URLs their victims have ever visited; they can only ask whether particular URLs have been visited. Therefore, the goal of history sniffers is to learn which of some predetermined set of interesting URLs have been visited by their victims. In principle, there is no limit to the size of this set, but the actual exploiters found by Jang only probed 6 to 220 URLs.

History sniffers have the abilities of web attackers: they control the contents of a website and a DNS domain, and they can get victims to visit their website. For *interactive* sniffing, as the name implies, victims must also be willing to interact with a sniffer’s site in the same ways that they might interact with a legitimate site. History sniffers do not have any of the additional powers of a network attacker: they cannot eavesdrop on, tamper with, or redirect network traffic from victims to legitimate sites (or vice versa), nor can they interfere with domain name lookups. Furthermore, history sniffers cannot install malicious software on their victims’ computers, or take advantage of malware installed by someone else.

C. Attack consequences

What can history sniffers do with the information they glean? There are some benign or even beneficial possibilities. Sites

at grave risk of impersonation (banks, for instance) could use history sniffing to determine whether their users have visited known phishing sites, and if so, warn them that their accounts may have been compromised [9], [11]. Sites could also seed visitors’ history with URLs made up for the purpose, and then use those URLs to re-identify their visitors on subsequent visits; this can foil “pharming” attacks (where attackers redirect traffic for legitimate sites to servers under their control) by making it impossible for attackers to predict the appearance of the sites they wish to impersonate [12]. However, ordinary “cookies” provide the same re-identification capability in an aboveboard, user-controllable fashion. Finally, sites that support federated login (OpenID, Facebook Connect, etc.) can use history sniffing to determine which identity provider a user favors, and thus streamline their login UI [13]. The same principle can be applied to a broad variety of third-party service providers, such as those for social bookmarking, feed subscription, and maps [10].

On the other hand, the actual history sniffers found by Jang appear to be tracking visitors across sites for advertising purposes and/or to determine whether they also visit a site’s competitors. This is very similar to the “tracking cookies” used by many ad networks, which are widely considered to be invasions of privacy [14], but only on the same level as having one’s postal address sold to senders of junk mail. History sniffing could potentially enable much more severe privacy violations, because unlike tracking cookies, it allows the sniffing site to know about visits to sites with which it has no relationship at all. For instance, the government-services websites of a police state could detect whether their visitors have been reading sites that provide uncensored news, and corporate webmail servers could detect whether employees have been visiting a union organizer’s online forum (even if they do this from home) [15]. Knowledge of browsing habits can also connect an identity used on one social network to that used on another [16], defeating users’ efforts to keep them separate so they can maintain contextually appropriate presentations of self [17]. Finally, stepping away from privacy issues, attackers can construct more targeted phishing pages [18], [19] by impersonating only sites that a particular victim is known to visit, or using visual details (such as logos) of those sites in a novel but credible context [9], [11].

We consider the privacy and security costs of history sniffing to outweigh the beneficial possibilities.

III. AUTOMATED ATTACKS

Until recently, it was possible to sniff history automatically, rapidly, and invisibly to users. While the focus of this paper is on the attacks that remain possible today, for context’s sake we begin by explaining how automated attacks worked and how browsers now prevent them.

Web authors wish to control the appearance of their sites; the modern mechanism for this is Cascading Style Sheets (CSS), invented in the late 1990s (contemporaneously with JavaScript). CSS provides control over every aspect of a page’s appearance, including how the distinction between visited and unvisited

¹While the attack has been known since 2002, the phrase “history sniffing” seems to have been coined much later: the earliest use we have found was in 2008 [10].

```

a          { text-decoration: none }
a:link     { color: #A61728 }
a:visited  { color: #707070 }

```

Fig. 1. Example of CSS controlling rendering of links. Each line of code is a *style rule*. Each style rule begins with a *selector*, which controls which HTML elements are affected by the rule. A lone `a` selects all `a` elements, i.e. hyperlinks; `a:link` and `a:visited` select unvisited and visited links, respectively. A brace-enclosed list of *style properties* and their *values* follows; these rules each contain only one property, but there could be many.

links is rendered. Figure 1 shows a sample set of changes to the appearance of links: setting `text-decoration` to `none` disables underlining, and setting `color` changes the color of the text. If the same `#rrggbb` code were given in both the second and third rules, visited and unvisited links would be indistinguishable. Browsers’ default style sheets generally distinguish visited and unvisited links with a color change, but (until recently; see below) a web page’s style sheets could use any CSS style property to make the distinction.

A. Direct sniffing

A JavaScript program can examine and manipulate the page it is embedded within, using a standardized API known as the Document Object Model (DOM) [20]. Most importantly for our purposes, the DOM provides access to the *computed style* of each HTML element. The computed style collects all of the CSS properties that influence the drawing of that element, which may have come from many style rules in different places. Continuing with the example in Figure 1, the computed style for both visited and unvisited links would show the value of `text-decoration` as `none`, but the `color` property would be `#A61728` for unvisited links and `#707070` for visited links. JavaScript can also change the destination of an existing hyperlink, or create entirely new hyperlinks to destinations of its choosing.

Therefore, a malicious site can guess URLs of pages that its visitors might have also visited, create links pointing to those URLs, and determine whether each visitor has indeed visited them by inspecting the links’ computed styles. The malicious site’s style sheets control how the visited/unvisited difference appears in the computed style, so the site knows exactly what to look for. This only allows the malicious site to ask yes/no questions about URLs it can guess; there is no known way for a malicious site to get access to the browser’s complete list of visited URLs. However, the “wild” exploits found by Jang were interested in a small set of other *sites* that their visitors also visited—usually direct competitors and popular social networking sites—so they could use the well-known URLs of those sites’ front pages. Deanonymization attacks [16] can require thousands of history queries per victim, but this is no obstacle; depending on the browser, an attacker can make 10,000 to 30,000 queries per second [15].

B. Indirect sniffing

The attack described above admits a simple defense: the DOM’s computed style API could pretend that all links were being styled as if they were unvisited. However, this is only

the most direct way to detect whether or not a link has been visited. Baron [3] lists two classes of indirect technique for detecting whether a link has been visited:

- *Make visited and unvisited links take different amounts of space, which causes unrelated elements on the page to move; inspect the positions of those other elements.*

The DOM provides information on the position and size of every HTML element on a page; the API for this information is separate from the API for computed style. Many CSS properties can change the size of an element, and the size of an element influences the position of all the elements that will be drawn after it. Therefore, an attacker can make the APIs for position and size reveal whether links are visited, by having the style rules for visited links change the links’ sizes.

With moderate effort, the DOM could be made to pretend that all links are being drawn with the size they would have if they were unvisited. However, adopting the same pretense for element positions would require the browser to lay out the entire page twice, which would be impractical.

- *Make visited and unvisited links cause different images to load.*

The `background-image` style property specifies a URL of an image to load; if it is used in a `:visited` rule limited to one link, that image will be loaded only if that link is visited. The attacker can specify a unique URL on their server for each link to be probed, then route all those URLs to a program that records which links were visited. (The program would always send back an empty image, so the page’s appearance would not be affected.) This technique does not even require JavaScript. It could be defeated by unconditionally loading all images mentioned in style rules, but that would increase page load time and bandwidth consumption for honest websites.

C. Side-channel sniffing

Side channel attacks exist when a system leaks information through a mechanism that wasn’t intended to provide that information, bypassing the system’s security policy. Side channels are difficult to find, and often cannot be eliminated without destroying other desirable characteristics of the system [21]. For instance, when a cache returns a piece of information faster than it could be retrieved from the source, it reveals that someone looked up the same information in the past. We can only prevent this leak by slowing down retrievals from the cache, or partitioning it by user; either method renders the cache less useful.

Timing attacks are the most well-known type of side channel attack. Baron’s essay also considers timing attacks on browsing history: the attacker can make the page take longer to lay out if a link is visited than if it is unvisited, or vice versa. JavaScript has access to the system clock and can force page layout to occur synchronously, so it can easily measure this time. Modern computers’ clocks provide enough precision that even apparently trivial details of rendering, such as whether an area

of color is partially transparent, or whether a line of text is underlined, can produce measurable differences in the time to draw the page. There doesn't even need to be a rendering difference. All current browsers process CSS selectors from right to left [22], so if a style rule such as

```
[class*="abc"] :visited { ... }
```

appears somewhere in the style sheets for a page, layout will take longer if any link on the page is visited.

Timing is by no means the only type of side-channel attack. As an example, in the course of the experiments described in this paper, we discovered a side channel for history sniffing in early beta versions of Firefox 4 (which implements Baron's defense). For some time, Firefox has looked up history database entries in the background, meanwhile drawing the page as it would appear if all links were unvisited. If any of the links turn out to have been visited, the page is redrawn. Changing the target of a link will start this whole process over. So far, there is no problem, because the redraws are invisible to standard JavaScript. However, as an extension for benchmarking and testing, early betas of Firefox 4 would generate a JavaScript event called `MozAfterPaint` every time the browser finished redrawing a page. An attacker could install a handler for this event, repeatedly change the target of a link, and after each change, count the number of times Firefox calls the event handler. If it gets called twice, the current link target is visited. We reported this bug to Mozilla [23], and it was fixed in beta 10 (by removing the extension).

D. Defense

As mentioned previously, in 2010 Baron developed a defense [3] which blocks all known techniques for automated sniffing. To block direct sniffing, the computed style APIs pretend that all links are unvisited. To block indirect and side-channel sniffing, CSS's ability to control the visited/unvisited distinction is limited, so that visited links are always the same size and take the same amount of time to draw as their unvisited counterparts. Style rules applying to links in general, or unvisited links, can still do everything they could before the defense was implemented. Style rules for visited links, however, can only change visible graphical elements (text, background, border, etc.) from one solid color to another solid color. They cannot remove or introduce gradients, and they cannot change the transparency of a color. For example, the style rules shown in Figure 1 still work as designed. However, suppose the `text-decoration` property was moved from the `a` rule to the `a:visited` rule. Older browsers would then underline unvisited links but not visited links, but browsers that implement the defense would underline all links.

It is also necessary to ensure that selector matching takes the same amount of time whether or not any links are visited. To do so, Baron adjusted the algorithm for selector matching a bit. A browser that implements the defense will only do one history lookup per style rule, and it will do it last, after all the other work of selector matching. Thus, the example selector in Section III-C now takes the same amount of time whether

or not any links are visited. Also, a rule that needs more than one lookup, such as

```
:visited + :visited { ... }
```

which is meant to apply to the second of two visited links in a row, will be ignored by a browser that implements the defense (technically, it will never match any elements).

Baron's defense was rapidly adopted by browser vendors; as of this writing, it is included in Firefox 4, Chrome 9, Safari 5, and IE 9 (in order of adoption).

IV. EXPERIMENT 1: INTERACTIVE ATTACKS

Baron's defense makes no attempt to address interactive attacks, where victims' actions on a site reveal their browsing history. Interactive attacks obviously require victims to interact with a malicious site, and cannot hope to probe nearly as many links as the automated attacks that are no longer possible. It might also seem that an interactive attack would be hard to disguise as legitimate interaction. We claim that these are not significant obstacles: we claim that interactive attacks can be disguised as "normal" interactive tasks that users will not find surprising or suspicious, and that they can still probe a useful number of links. To demonstrate these claims, we designed four interactive tasks that could be used to probe browser history, and tested them on people recruited from Amazon's Mechanical Turk service [24].

A. The tasks

All of our tasks operate within the constraints of Baron's defense: they use visited-link styles only to change the color of text or graphics on the screen. They are designed to probe 8 to 100 links each, which is small, but as demonstrated by Jang, not too small for the sites currently making use of automated history exploits. Finally, each task masquerades as an interaction that would not be out of place on a honest website. It is common for web sites to challenge their visitors to perform a task that is relatively easy for a human, but difficult for software [25]. This is to prevent automated abuse of a site ("spam" posts to a message board, for instance). Such challenges are referred to as CAPTCHAs.² The most common type of CAPTCHA is a request to type either a few words, or a string of random letters and numbers, from an image shown on the screen. The text is manipulated to defeat OCR software. Another common type of CAPTCHA is a visual puzzle, to be solved using the mouse; visual puzzles are also commonly presented as true games (that is, intended only to entertain).

Interactive attacks necessarily involve placing hyperlinks on the screen, and then inducing victims to do something with them that will reveal to the attacker which ones are visited links. Hyperlinks have built-in interactive behavior that will reveal that something fishy is going on, if a victim experiments with the page rather than just following the instructions. For instance, clicking on a link (visible or not) will cause the browser to load the link destination; hovering the mouse pointer over a link (again, visible or not) will display the link's destination

²CAPTCHA is a contrived acronym for Completely Automated Public Turing test to tell Computers and Humans Apart.

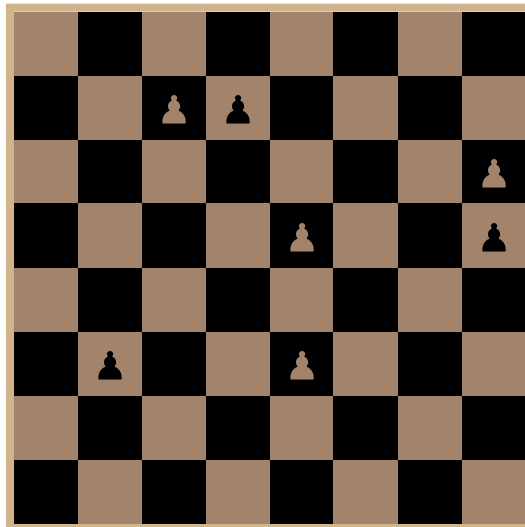
Please type all the words shown below, then press RETURN.

low hang we life alone line cost

Please type the string of characters shown below, then press RETURN. You don't have to match upper and lower case.

FA4A 5ABA A-65 A9-5

Please click on all of the chess pawns.



The large image on the left was assembled from two of the small images on the right: one from the first row and one from the second. Please click on the two small images that make up the large one.

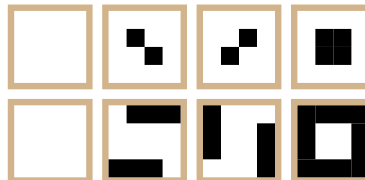
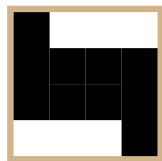


Fig. 2. Our four interactive tasks. Top to bottom: word CAPTCHA, character CAPTCHA, chessboard, and visual matching. Screen shots taken with Safari 4.0.



Fig. 3. 7-segment LCD symbols stacked to test three links per composite character. The - at the bottom is always visible, but the 4, 5, and F are only visible if a URL was visited.

URL somewhere in the browser’s “chrome” (such as the status bar or the URL bar); selecting all the text on the page will reveal text that has been hidden by drawing it with the same color as the background. Fortunately for the attacker, all these inconvenient behaviors can be suppressed by positioning a transparent image over all the hyperlinks.

Figure 2 shows what each of our interactive attacks looked like to a participant in the experiment, including the instructions for each. Note that we did not include the noise, lines, or distortions typical of real CAPTCHAs; image recognition software would have no trouble with any of them. (If we had done this, the tasks would also have been more difficult for our participants.) An attacker determined to make their phony CAPTCHAs look as much like real ones as possible could use SVG transformations to distort the text, and/or include lines and visual noise in the transparent image superimposed on the links to suppress their normal behavior.

1) *Word CAPTCHA*: This is the simplest task. Victims are asked to type several short English words. Each word is a hyperlink to an URL that the attacker wishes to probe; if visited, the word is styled to be drawn in black as usual, but if unvisited, it is drawn in the same color as the background. Thus, victims see only words corresponding to sites they have visited. The attacker must arrange for at least one word to be visible no matter what; otherwise, a victim who has visited *none* of the URLs the attacker is probing will see a blank CAPTCHA and think the site has malfunctioned.

This task is easy to perform, and simple to implement, but can only probe a small number of links, since attackers cannot expect their victims to be willing to type more than a few words. In our study, we used a maximum of ten words, of which one was always visible and one always invisible; thus we could test no more than eight links.

2) *Character CAPTCHA*: This task is very similar to the previous one, but by clever choice of font and symbols, it tests the visitedness of three links per *character* typed. Victims are asked to type what appears to be a string of letters, numbers, and dashes from a restricted character set, in a font that mimics seven-segment LCD symbols. As shown in Figure 3, each visible character is actually *four* characters, superimposed, three of them visible only if an associated link is visited. No

matter which combination of symbols is “on,” their composite will always be a character that the victim can type, and each combination produces a different composite. $4+5 = 9$; $4+F = R$; $5+F = 5$; $4+5+F = 8$. The always-on - is necessary because position within the overall string is meaningful; without it, victims might see a series of blank spaces. In response they would probably type only one space, and that would make the result ambiguous. Again, attackers cannot expect their victims to type more than a few characters, but an eight-character CAPTCHA of this design will probe 24 sites, and a 12-character one will probe 36.

This attack has more technical complications to cope with than the previous one. Hardly anyone has a seven-segment LCD font installed, but this is only a minor hurdle, as all modern browsers implement site-supplied fonts [26]. More seriously, Baron’s history-sniffing defense does not allow visited-link rules to change the transparency of a color. This restriction prevents timing attacks (drawing partial transparency is slower than drawing opaque color) but also makes it harder to compose characters by stacking them. Attackers can work around this restriction by making the characters *always* be nearly (but not entirely) transparent, whether or not they are visited links; this is allowed. They are black if visited and white if unvisited. Each composite segment is thus drawn in a shade of gray. This might be acceptable; if not, attackers could apply an SVG color transformation to map all shades of gray to solid black. Unfortunately, SVG is *not* a universal feature [27]; IE did not support it at all before version 9 (not yet released as of this writing) and no browser implements the complete spec.

3) *Chessboard puzzle*: This task presents a chessboard grid (not necessarily the same size as a standard chessboard) on the screen; some of the squares are occupied by chess pawns. Victims are asked to click on all of the pawns. In fact every square contains a pawn, but each is a hyperlink to a different website, and only the pawns corresponding to visited sites are made visible, using the same technique as for the word CAPTCHA; invisible pawns are the same color as their background. This is technically straightforward; the only complication is that the pawns must be rendered using text or SVG shapes, so their color can be controlled from CSS. Fortunately, Unicode defines dingbats for all the standard chess pieces; in our implementation we used another site-supplied font to ensure that participants got pawns rather than “missing glyph” symbols. An attacker might be able to rely on system fonts for the pawn dingbat, but it’s easy enough to use a site font that there’s no reason not to.

This puzzle is easy for victims to complete, and the grid can be at least ten squares on a side—the only limits are the size of the screen, and victims’ patience—so this attack can test at least 100 links’ visitedness. However, it becomes tedious if there are more than a few visible pawns. Also, if used for a real attack, the page would have no way to tell how many clicks each victim will make, so attackers must resort to a time-out or an explicit “go on” button; either might seem suspicious.

4) *Pattern matching puzzle*: In this task, victims are asked to select two images which, when “assembled,” produce a

composite image. The composite is made up of four SVG shapes, whose fill color depends on the visitedness of four hyperlinks. There are four choices for each of the two images to be selected; together, they exhaust the sixteen possible appearances of the composite image. While this does rely on SVG, it only requires basic drawing features that are universally supported (except by IE).

One encounter with this puzzle tests the visitedness of four links. It could be presented as a brainteaser challenge, giving a malicious site the opportunity to make each victim solve many instances of the puzzle in succession, and so probe many links. It is decidedly more difficult than our other tasks, but it could be made easier by not composing two images, or by adjusting the images to make the correct answer more obvious.

B. Procedure

We constructed a website which would challenge participants to carry out instances of each of the above four tasks. We did not actually sniff history in the implementation of these tasks, because our goal was to prove that these tasks could be performed by a typical user accurately, quickly, and without frustration. If we had implemented genuine history-sniffing attacks, we would not have known the ratio of visited to unvisited links to expect for each prompt, nor would we have been able to detect errors. Instead, we randomly generated task instances corresponding to known proportions of visited and unvisited links. Each participant experienced a fixed number of trials of each task, as indicated in Table I; each trial selected a proportion uniformly at random without replacement from the appropriate column of Table I. The site automatically skipped tasks that would not work with participants’ browsers (notably those that required SVG, for participants using IE).

We recruited 307 participants from Amazon Mechanical Turk for a “user study.” Participants were required to be at least 18 years old, able to see computer graphics and read English, and be using a browser with JavaScript enabled. The precise nature of the study was not revealed until participants visited the site itself. At that point they were told:

We are studying how much information can be extracted from a browser’s history of visited web pages by interactive attacks—that is, attacks that involve your doing something on a website that appears to be innocuous. It used to be possible to probe your browsing history without making you do anything, but browsers are now starting to block those attacks, so interactive probes may become more common in the future.

In this experiment you will carry out some tasks similar to the ones that a malicious site might use to probe your browsing history. These tasks do not actually probe your browsing history; instead we measure how quickly and accurately you can do them. From this, we will be able to infer how much information each of the tasks could extract from your history.

TABLE I
PROPORTIONS OF VISITED LINKS USED FOR EACH TASK.
 N = TOTAL NUMBER OF LINKS, V = NUMBER OF VISITED LINKS.

Word captcha 9 trials	Character captcha 9 trials		Chess 12 trials		Matching 12 trials		
	N	V	N	V	N	V	
10	1	12	3	16	3	4	0
10	1	12	6	16	3	4	0
10	1	12	9	16	5	4	1
10	2	24	6	16	5	4	1
10	2	24	12	16	7	4	1
10	3	24	18	16	7	4	1
10	3	36	9	16	11	4	1
10	3	36	18	16	11	4	1
10	4	36	27	36	3	4	1
10	4	48	12	36	3	4	1
10	4	48	24	36	5	4	2
10	4	48	36	36	5	4	2
10	5	60	15	36	7	4	2
10	5	60	30	36	7	4	2
10	5	60	45	36	11	4	2
10	6			64	3	4	2
10	6			64	3	4	2
10	6			64	5	4	2
10	7			64	5	4	3
10	7			64	7	4	3
10	7			64	7	4	3
10	8			64	11	4	3
10	8			64	11	4	3
10	8					4	3
10	9					4	3
10	9					4	3
10	9					4	3
						4	4
						4	4

All participants completed a consent form and then a short demographic survey (reproduced in Appendix A), after which they were given brief overall instructions:

This experiment is divided into several tasks. To proceed to the first task, click on its heading, which is right below these instructions. When you complete each task, the heading for the next task will become selectable.

The tasks all included their own specific instructions, which are reproduced in Figure 2 above the facsimile of each task. Each task also included a progress bar at the bottom of its screen area (not shown in Figure 2) which indicated the number of trials remaining for that task. When participants reached the end of a subtask, the page showed some graphs of their performance on that task, as a reward (we do not show any of these graphs here, to avoid confusion with our actual analysis). At the very end of the experiment, participants were thanked for their assistance and offered an opportunity to see all of the data collected (in its raw form) before sending it to our server.

The typing tasks gave no feedback until the end, but the clicking tasks indicated errors immediately. In the chessboard task, each pawn turned green when clicked, but if a participant clicked on an empty square, a red X would appear in that square. In the matching task, when a small image was clicked,

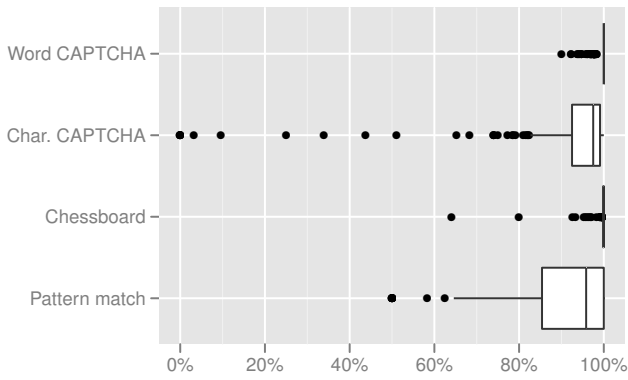


Fig. 4. Overall accuracy rates for the four interactive tasks.

its brown border would turn blue if that was the correct choice, red if not. In both cases, participants had to produce the correct answers before the task would end. A real attack could respond to clicks in a similar fashion, but might not be able to give exactly the same error feedback, because of the limitations on visited-link styles imposed by Baron’s defense. For instance, a version of the chessboard task that really sniffed history could turn visible pawns green when clicked, and could cause red pawns to appear in squares that had been empty before the click, but could *not* convert invisible pawns to visible Xes upon a click.

It was possible for participants to refuse to carry out the typing tasks, by hitting the RETURN key over and over again without typing anything. The matching task could also be skipped, via an explicit “skip this task” button, because our implementation sometimes malfunctioned and we were not able to isolate the bug, so we had to give people a way to move on. The chessboard task, however, could not be skipped or refused.

For comparison purposes, we also ran three automated history-sniffing exploits on all the participants. Less than 13% of the participants were using a browser that blocked these exploits; see Section IV-E below for more on the experiment population. We used *wtikay.com*’s set of 7012 commonly visited URLs (derived from the Alexa top 5000 sites list [15], [28]) for this test; we recorded only the total elapsed time and the number of URLs detected as visited.

C. Results

Not all of the participants completed all of the tasks successfully, but we have usable data from at least 177 participants for each task. Figure 4 shows raw user accuracy rate for all four tasks. The chessboard takes first place in accuracy, with nearly all participants scoring 100% or close to. The word CAPTCHA is substantially easier than the character CAPTCHA; the visual matching task is dead last in terms of *average* accuracy, but the character CAPTCHA has a surprising number of outliers with very poor accuracy. We investigated these, and found that some participants became so frustrated with the task that after a few trials they started hitting RETURN without attempting to type

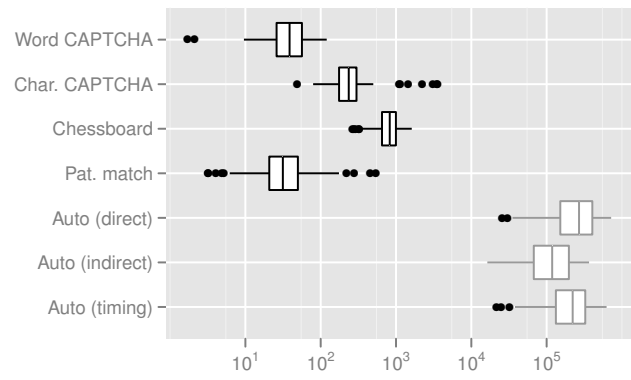


Fig. 5. Queries per minute achieved by the four interactive tasks (black) and three automated exploits (gray).

anything. There are even a few 0% scores, from participants who would not do this task at all. It is well known that strings of meaningless characters are harder to type than strings of words [29], but we did not anticipate this level of frustration.

Figure 5 shows the achievable history-sniffing rate for each task, with the rate of “traditional” automated attacks included for comparison. Of the four interactive tasks, the chessboard puzzle is the clear winner, achieving a median of nearly 1000 queries per minute. It should be remembered that this measurement combines two factors: how fast a victim can do the task, and how many URLs the task encodes. The chessboard scores highly on both counts, but the character CAPTCHA is only in second place because it encodes many URLs. Conversely, the word CAPTCHA is quick to complete, but doesn’t encode many URLs and therefore falls behind on QPM. Matching does poorly on both factors. And, unsurprisingly, all of our interactive tasks are much slower than automated sniffing.

Since our study conditions are artificial, our participants’ performance (either speed or accuracy) does not translate directly to attack effectiveness under “wild” conditions. We challenged participants to carry out dozens of instances of our tasks in quick succession, whereas a real attack would require victims to complete only one instance (except perhaps for the pattern-matching task). However, we did not observe any significant effect of fatigue in our tests, except for the participants who refused to complete all the requested trials of the character CAPTCHA. Some of the errors on the typing tasks were caused by participants entering something completely unexpected, rather than a possible but incorrect answer; in a real attack, if this happened, the attacker would have to default to some assumption about the links it was probing (most likely, that none of them were visited) which might chance to be correct. These effects would tend to make a genuine attack more effective than our results indicate.

On the other hand, our participants were told in advance that their ability to carry out the tasks quickly and accurately was being measured; people are known to perform better on tasks of this nature when they know their performance is being tested

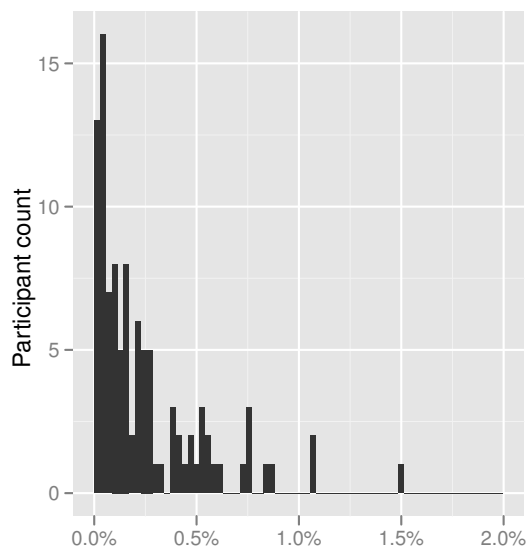


Fig. 6. Histogram of percentage of links visited within `wtikay.com`'s set of 7012 commonly visited URLs (derived from the Alexa top 5000 sites), as measured by an automated history exploit. No participant had visited more than a tiny fraction of these URLs.

(the ‘‘Hawthorne effect’’ [30]). Even if we had made the task conditions mimic a real attack more precisely—perhaps we could have claimed that we were evaluating the usability of new CAPTCHA styles—our participants might have deduced that their performance was being tested. Furthermore, Mechanical Turk workers are paid for every task they complete, so the faster they do tasks, the more money they earn; our participant pool was therefore primed to carry out tasks as quickly and accurately as they could before we ever started talking to them. These effects would tend to make a genuine attack *less* effective than our results indicate. We should not discount the motivation of victims faced with an (apparent) CAPTCHA, however. CAPTCHAs are pure obstacles, so users are motivated to get them out of the way as quickly as possible; users expect to be locked out of the site if they fail to solve the challenge, so they are motivated to solve them correctly.

On the whole, we think our results are a reasonable estimate of the effectiveness of our tasks when used for a real sniffing exploit. Attackers should perhaps worry more about CAPTCHAs causing some fraction of their victims to abandon their efforts to use the site [31]. Even this can be addressed by making the interactive task seem more like a game than an obstacle, and by presenting it after potential victims have already sunk effort into making use of the site.

D. History Density

The chessboard and word CAPTCHA are easier for the victim to complete if they have visited only a few of the links that the attacker is probing. 264 of our participants used a browser that still permits automated history sniffing. Figure 6 shows what percentage of the `wtikay.com` ‘‘top5k’’ link set had been visited by each of them. The percentages are

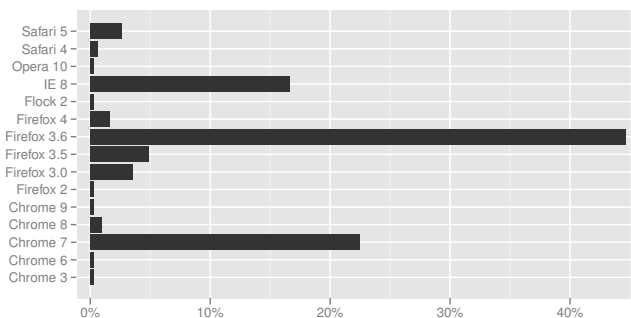


Fig. 8. Browsers used by participants

clearly quite small, so attackers may be able to assume a sparse set of visited links. However, as pointed out by Janc and Olejnik [15], sparseness over this generic link set may not equate to sparseness over a more targeted set—and the link sets found by Jang were quite targeted indeed.

E. Participant Demographics

We asked participants a few general questions about themselves; the results are shown in Figure 7. As the leftmost graph in Figure 7 shows, the study population is strongly skewed to younger users, much more so than the (USA) Internet-using population [32]. Participants also appear more likely than average to own more than one computer, use the Internet frequently, have used computers for more than ten years despite their youth, and to report having at least tried to put together a website before. This is consistent with other analyses of the demographics of Mechanical Turk workers specifically [33], [34]. We expect that our conclusions about interactive tasks remain valid for Internet users at large, since they rely mostly on measurements of basic motor activities (typing, mousing).

Our participants used a wide variety of browsers, with the three most popular being Firefox 3.6, Chrome 7, and IE 8. Despite its place in the top three, less than 20% of participants used IE 8, and no older versions of IE were detected; this also indicates a more technically experienced population than the average. The full breakdown is in Figure 8. We did not record participants’ operating systems, or any other User-Agent data beyond what is shown. Safari 5, Firefox 4, and Chrome 9 are the browsers that, at the time of the study, implemented Baron’s defense against automated history sniffing; users of these browsers made up 13% of our survey population.

F. Discussion

We have shown that interactive attacks on visited-link history are feasible, particularly if the attacker is interested only in a small set of links, as were the real history sniffers found by Jang. If we wish to defend against these attacks we must consider further restricting the functionality of visited-link history—either the circumstances under which links are revealed to be visited, or the capabilities of visited-link styles.

Three of our four interactive attacks relied on making unvisited links invisible by blending them into the background.

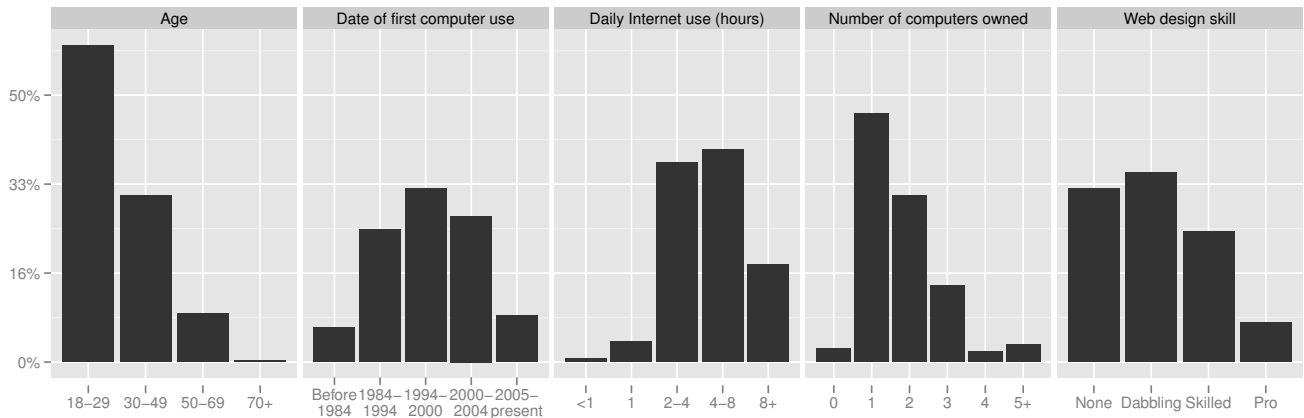


Fig. 7. Demographic breakdown of participants

An obvious defense is to prevent links from being drawn in the same color as the background (whether visited or not). However, merely determining what the background color *is* at any given position can be difficult. Just to give one example, the attacker could make the background of their fake CAPTCHA be partially transparent, then place a box of a contrasting color directly underneath. For efficiency, the browser might prefer to have the computer’s graphics card overlay the text, the partially transparent background, and the colored box, and send the result directly to the screen, but if it needs to know what the color of the background plus the box is before it can draw the text, it cannot do this.

But this is not the real problem with this defense. The real problem is that interactive attacks don’t *need* to make anything invisible. “Type the green words, but not the red words” would be an even more convincing fake CAPTCHA than the one we used. Similarly, the chessboard task could ask the user to click only on red pawns. As long as there is a visible difference on the user’s screen, we see no practical way to prevent a sufficiently determined attacker from getting the user to reveal what it is.

For the most privacy-conscious users, limiting the circumstances under which visited links are revealed might be an appropriate move. In his original BUGTRAQ post describing visited link attacks [1], Clover suggested that links might only be revealed as visited when they refer to documents in the same domain as the current page, but then immediately pointed out that this would render the feature nearly useless. SafeHistory [9] refines this idea: links are revealed as visited if they target a document in the same domain, if the link destination has previously been visited from the current site, or if the current site is on a whitelist of trusted sites. Under this policy, a malicious site cannot learn anything from history sniffing that it could not discover by monitoring clicks on outbound links. It sacrifices what is arguably the most useful case of visited-link indications (when a new-to-the-user site links to a document they have already seen), but to some extent this can be mitigated by use of the whitelist.

Unfortunately, an attacker may still be able to construct an interactive attack on history if *any* links are revealed as visited. With SafeHistory in use, if attackers can predict the location of a link to a site of interest on a whitelisted page, they can draw pictures using `iframes` that show one pixel of the whitelisted page, directly above that link. This is not so farfetched as it might sound: a hyperlink to `facebook.com` appears at a predictable location on the page <http://www.google.com/search?q=facebook.com>, and search engines are obvious candidates for whitelisting. If there is no whitelist, attackers could instead draw their pictures with single-pixel `iframes` of *the sites they want to know about*. Many sites contain links pointing back to their front pages in predictable locations on interior pages, which would count as same-origin and so have their visitedness revealed. (Care must be taken not to disturb the visitedness of the front page, of course.) Of course, attackers using this technique cannot control the colors of visited and unvisited links, but this poses little difficulty: they can either design their interactive attack to work with the colors they get, or they can use an SVG filter to remap the colors as they see fit (as we did in the character CAPTCHA).

Most browsers can be configured not to retain any visited-link history at all, and the “private browsing” mode found in all modern browsers makes this quite convenient. Private browsing was developed to defend users’ privacy against other users of the same computer [35], but it also prevents remote history sniffing attacks. Of course, this comes at the price of not distinguishing visited from unvisited links at all. Alternatively, most browsers can be configured to remember history only until shut down; this mode’s visited-link distinctions are less useful (the user probably remembers what they have visited within the current session) and remote attackers can still detect pages visited within the current session.

V. EXPERIMENT 2: SIDE-CHANNEL ATTACK

Baron’s defense *was* intended to cover all practical side channel attacks on browsing history; many of the restrictions it places on `:visited` are solely to prevent timing attacks.

In Section III-C, we described a practical side channel attack on Firefox 4 beta using the MozAfterPaint event. Unfortunately, this is not the only side channel attack for history detection. We discovered another attack that is technically out of scope for the defense, as it relies on both software and hardware outside the browser’s control, and would be difficult to exploit in practice, but would also be very hard to close.

A. Webcam attacks

Many computers, especially laptops, nowadays come with a built-in video camera aimed at the user. Adobe Flash (not a standard component of the Web, but very common nonetheless) includes a mechanism for activating this camera and gaining direct access to the data stream it produces. Computer screens are backlit, so they illuminate the user and the user’s environment; the color of this light varies with the color of the computer screen. Thus, if the color of an area of the screen depends on whether or not a link has been visited, an attacker could use the camera to detect that color. This attack will work better if the colored area is large and the difference between the visited and unvisited colors is dramatic, but in theory, sophisticated image processing code could detect even small differences.

There are two major obstacles to this attack. First, the Flash runtime will not activate the camera without the user’s permission, and it includes defenses against “clickjacking” attacks that trick the user into granting permission [36], [37]. The attacker would have to make their site appear to have a legitimate use for the camera; for instance, it could present itself as a video chat site. Second, to probe many links, it is necessary to change the color of the link frequently—that is, to make some part of the screen flash, which annoys users even in tiny doses, as the <blink> tag demonstrates. If the color, size, or blink rate are poorly chosen, flashing light can even induce epileptic seizures [38]. However, despite these drawbacks, many online ads already do include blinking effects; an attack disguised as one of these ads might irritate victims enough that they close the offending window, but is unlikely to seem suspicious.

We developed and tested two variants of this attack. In both variants, we made a rectangular box of uniform color be a hyperlink, periodically changed its target, and monitored changes in the average color detected by the camera. We used the least sophisticated image processing algorithm that would work at all; our results should therefore be considered a worst case scenario for the attacker. The QPM ratio and total number of links probed are fixed by the blink rate and runtime of the attack, so we discuss only accuracy below. As with the interactive attacks, we did not actually sniff history; rather, we generated a random sequence of 20 links, of which 10 were known to be visited and 10 known to be unvisited, so that we knew the correct answer for each link and could measure accuracy.

1) *Variant 1*: The first variant was designed to comply with the WCAG standard for seizure safety [38]. This standard limits the maximum area that can be made to blink, maximum blink

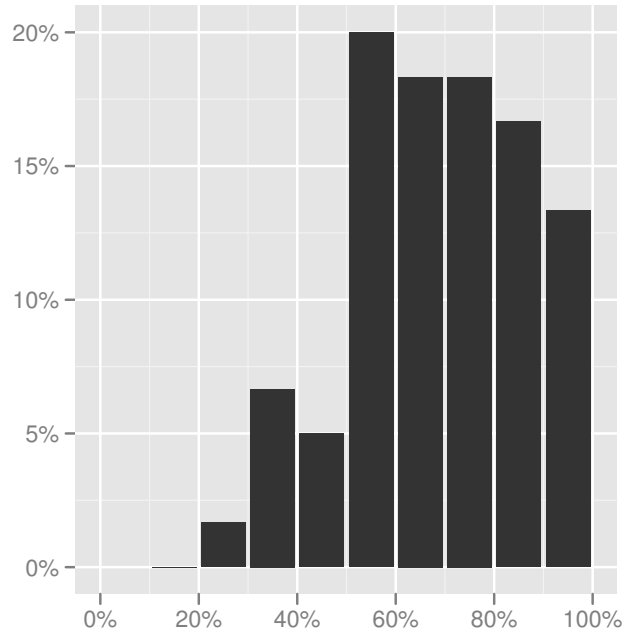


Fig. 9. Histogram of webcam attack (variant 1)’s accuracy rate when presented to participants in the interactive experiment.

rate, and the maximum luminosity difference between flashes; it also requires avoidance of the color red. All these requirements, especially the limits on blinking area and luminosity changes, make detecting the change in reflected light more difficult, but by no means impossible.

2) *Variant 2*: The second variant made the entire browser window flash, and used brighter colors to represent visited and unvisited links. The image processing task is much easier, but it is obvious that something unusual is happening.

B. Results

We tested both variants on ourselves under controlled conditions, using one of the authors’ computers (a Macbook Pro with built-in webcam) in three settings with diverse backgrounds: an office cubicle, a bedroom, and a living room. We also tested the attacks both with one of the authors sitting in front of the computer, and with nobody in the camera’s field of view. We were able to achieve 100% accuracy for both variants in all conditions, provided that the room was well-lit and the person in front of the computer (if any) remained still. In a dark room, accuracy dropped to chance (50%).

The first variant of the webcam attack was also field-tested as an optional task for participants in our interactive experiment. Not all of them had Flash-accessible cameras or were willing to let us use them; of the 307 participants in the interactive experiment, only 60 performed the webcam task. Participants who agreed to perform the task were asked to sit still and watch the screen while it flashed; they did not need to do anything.

As shown in Figure 9, this attack’s accuracy rate is highly variable in the field, often dropping to not much better than

chance. Comparing to our results under controlled conditions, we believe the high error rate is mainly caused by participants moving around during the task. If so, attackers could analyze the video feed and only run the attack during periods when nothing was moving in the camera’s field of view. More sophisticated image processing might also help.

C. Discussion

One might reasonably ask whether this technique is practical enough to be a genuine threat. We think the most serious obstacle in real life would be persuading victims to allow access to their webcams. There are already sites that make legitimate use of the webcam, usually for live two-way chat (the ChatRoulette service [39] is a prominent example). Such sites could plausibly incorporate the WCAG-compliant variant of this attack, disguised as an ad. The more obtrusive variant is likely to make anyone who sees it close the browser immediately, but we think it could still be used on victims who walk away from the computer leaving the malicious site open. It does not take terribly sophisticated image processing to detect when nobody is in the camera’s field of view, and in our controlled tests, the attack works even when the closest reflector is a wall 10 to 20 feet away from the monitor.

We would also like to point out that as the Web platform gains capabilities, other side-channel attacks may become possible. HTML5 already contemplates adding features [40] that would eliminate the need for Adobe Flash in the webcam attack. WebGL [41] allows rendered HTML pages to be processed by shader programs, which are Turing-complete; we speculate that they might be able to detect history-dependent color changes and report them back to the controlling page’s scripts (if only via a timing channel).

VI. RELATED WORK

Privacy attacks have received significant attention recently. Section II covered the existing work on defenses for non-interactive attacks on visited-link history [1], [2], [4], [9], [11], [15], [16]. In this section, we describe related work on privacy attacks that abuse other browser features.

Visited-link state is not the only way to determine whether the user has visited a site. Two other straightforward techniques involve timing attacks on local caches maintained by the browser.

Page cache. Browsers cache resources retrieved from the Web to improve the speed of subsequent page loads. Approximately 60% of HTTP queries are requests for cacheable resources [42]. The cache is global, so by embedding a resource from another site and measuring the time it takes to load, a web page can determine whether that resource is already in the browser’s cache, and thus determine whether the user has visited the other site [43].

DNS cache. Name-to-IP-address mappings retrieved from the DNS are typically cached by the operating system of the computer that made the query, and may also be cached by an intermediate device (such as a network router) for the benefit of other computers on the same network.

Web attackers can induce the browser to perform a DNS lookup and measure the amount of time it takes [43]; local network attackers, able to make queries of a shared DNS cache, can inspect its contents in more detail [44], [45]. The DNS cache can reveal which sites a user has visited, but unlike the page cache, it can also reveal search queries that the user has made, because some browsers (versions of Firefox and Chrome released since 2008 [45]; Safari 5 also adopted the tactic) *prefetch* DNS entries for sites that the user is likely to visit in the future—such as sites linked from a search results page.

Note that both these techniques are destructive—only the very first attempt to determine whether a piece of information is cached will reveal anything interesting, because the attack itself causes the information to be cached. Also, browsers don’t cache information for very long, even in the face of strenuous efforts by site maintainers to make them do so [46], [47] so these attacks are not very reliable and may only reveal short-term history.

Another tactic only applies to sites that users typically remain logged into for long periods (Facebook, Gmail, Twitter, etc.) If an attacker can guess the URL of a resource that is loadable cross-origin but only available to logged-in users, they can attempt to load it and detect failure using the JavaScript `onerror` event. Depending on the site, more information may be available to clever attackers [48]; even if the resource does not generate an HTTP error for users that are not logged in, it may be possible to extract information from it [49].

Client-side state such as cookies [50], [51], Flash Player local shared objects [52], and Web Storage [53] can be used by web sites to re-identify users who have visited a site in the past. They are often used for user authentication and personalization. Some of these mechanisms (notably cookies) allow “third parties” (sites other than the main one the user is interacting with, but that provide some of the resources present in the page) to access client-side state. This third-party state is separate from any state set by the page itself, but if several sites refer to the same resource provider (for instance, an advertising network), that provider can build a profile of a user’s browsing activities. Even if the user regularly clears their cookies, a determined site may be able to re-construct them based on other browser state [54]. Most browsers provide some degree of control over cookies, allowing users to disable third-party cookies altogether, or allow only cookies with an acceptable P3P privacy policy [55]. Unfortunately, these mechanisms are easily circumvented [9], [56].

Finally, many kinds of technological devices possess subtle but measurable variations that allow them to be “fingerprinted,” and browsers are no exception. By tracking information that the browser reveals to all sites, such as `User-Agent` headers, `Accept` headers, screen resolution, time zone, browser plugins, and system fonts, a site can rapidly re-identify users, even without the use of client-side state [57], [58]. Fingerprinting can be used to build a profile of user behavior even if the user tries to clear browser state.

Privacy tools such as Torbutton [59] aim to mitigate or

prevent the above attacks, at the cost of web functionality; this is an acceptable tradeoff for some users. Torbutton is particularly noteworthy for considering and designing against fingerprintability. Private browsing mode [35] can also mitigate some of these attacks, but it was not designed to do so and is less effective than a specialized tool; again, functionality is sacrificed. Ad-blockers [60] prevent many real-world cases of behavior profiling as a side effect, since ad networks are one of the primary users of third-party cookies.

The more well-known providers of third-party tracking cookies often allow users to “opt out” [14], but this is a manual procedure that must be carried out for each tracker. The “Do Not Track” initiative [61] proposes to indicate in HTTP request headers when users do not wish to be tracked; to be effective this would have to be backed up with sanctions against tracking agencies that ignore it, and at present there is no legal framework for such sanctions.

VII. CONCLUSION

Web browsers attempt the difficult balancing act of preserving their users’ privacy and security, while simultaneously exposing as much of their computers’ capabilities as possible to untrusted code from the Internet. In this paper we examined an attack, history sniffing, which appeared as an unintended consequence of the combination of three independently desirable features: visited-link indication to the user, CSS control of all aspects of page appearance, and JavaScript monitoring of page rendering. Automated history sniffing attacks, including timing attacks, have successfully been blocked in the latest browsers by David Baron’s restrictions on visited link styling [3]. However, attacks that involve the user remain possible, as do attacks via side channels outside of the browser’s control.

We developed proofs of concept of six history sniffing exploits that remain possible with Baron’s defense in place: four involving interaction with the user, and two involving detection of the color of the screen with a webcam. We tested our exploits on 307 users from Amazon Mechanical Turk, and found that while they are slower than automated attacks, and less convenient for an attacker, they are practical for small numbers of URLs, in the same range as the “wild” automated exploits found by Jang et al. [4].

All of our exploits, fundamentally, depend only on the browser having revealed a distinction between visited and unvisited links on the computer screen, plus some way for the page to read that information back—via the victim’s eyes and hands, or via a camera controllable by the webpage. As browsers continue to add capabilities to the Web platform, it seems inevitable to us that further ways will appear for malicious pages to discover what only the user should know. Link visitedness is not the only case where browsers try to combine information from mutually distrusting sources into one apparently-seamless “page,” and all those other cases are also problematic for security [62], [63]. We consider finding more reliable ways to make these combinations, without compromising user privacy or cross-site security, an open research problem crucial to the future of the Web.

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Data analysis was done in R [64] with the “ggplot2” graphics package [65].

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APPENDIX A DEMOGRAPHIC SURVEY

This is the demographic survey presented to participants in the interactive experiment. In the actual study, the response choices shown for each question were presented with an HTML drop-down selection widget. Participants were required to answer all questions.

We'd like to know a little bit about you and your experience with computers.

Roughly how old are you?

- 18–29
- 30–49
- 50–69
- 70+

When did you first use a computer?

- Less than 5 years ago
- 5 to 10 years ago
- 10 to 15 years ago
- Before Windows 95
- Before the Macintosh

How long do you spend on the Internet each day?

- Barely at all
- 1 hour
- 2–4 hours
- 4–8 hours
- More than 8 hours

How many computers do you own?

- 0
- 1
- 2
- 3
- 4
- More

Do you know how to program computers or build websites?

- No
- I've tried it a few times
- Yes
- Yes, and I've done it for a living

What kind of mouse are you using?

- Regular mouse
- Trackball
- Touchpad
- Eraser-head mouse
- Other