Quantifying User Password Exposure to Third-Party CDNs

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Abstract. Web services commonly employ Content Distribution Networks (CDNs) for performance and security. As web traffic is becoming 100% HTTPS, more and more websites allow CDNs to terminate their HTTPS connections. This practice may expose a website's user sensitive information such as a user's login password to a third-party CDN. In this paper, we measure and quantify the extent of user password exposure to third-party CDNs. We find that among Alexa top 50K websites, at least 12,451 of them use CDNs and contain user login entrances. Among those websites, 33% of them expose users' passwords to the CDNs, and a popular CDN may observe passwords from more than 40% of its customers. This result suggests that if a CDN infrastructure has a vulnerability or an insider attack, many users' accounts will be at risk. If we assume the attacker is a passive eavesdropper, a website can avoid this vulnerability by encrypting users' passwords in HTTPS connections. Our measurement shows that less than 17% of the websites adopt this countermeasure.

1 Introduction

Content Distribution Networks (CDNs) [37,45] play an important role in improving the performance and security of web services. A CDN caches web pages at servers near end users to reduce retrieval latency. It also blocks malicious requests to defend a web server against various attacks [20]. Currently, many websites employ CDNs provided by third-party companies such as Akamai [1], Cloudflare [3], and Fastly [4].

However, third-party CDNs introduce a considerable security and privacy risk when they serve websites that enable HTTPS [15,17]. HTTPS uses a certificate to certify the domain name of a website. Thus, to make the web pages appear as if they come from the original site, a website has to share its TLS private key [15] or TLS session keys[51] with the CDN. In both cases, a third-party CDN can observe the content of all connections between a website and its users.

In this work, we aim to raise awareness of this security and privacy risk and quantify its severeness from a user's perspective. We choose to measure the extent to which users' website login passwords are exposed to CDNs due to the HTTPS key sharing practice. Although prior research has shown that private key sharing is prevalent on the Internet [15] and HTTPS termination weakens connection security of a great portion of the Internet [17], it is not clear whether websites have taken preliminary countermeasures such as client-side encryption (see § 2) to protect users' passwords in the case of a passive attacker.

We conduct a measurement on Alexa top 50K sites [2] to quantify password exposure to CDNs during the user login procedures. We also measure the deployment of client-side password encryption on websites to understand websites' treatment of users' passwords. Such a large-scale measurement is technically non-trivial, because we need to automate the login procedures on websites with diverse structures to inspect login requests. Thus, we design and implement a framework for automatic login. The framework can detect login elements on a website and collect login requests when it submits credentials to websites.

Our main contributions and findings can be concluded as the following:

- We propose an open-source framework for automatic login [1], which can be applied to other research such as the measurement of authentication methods.
- Our measurement presents that 33.0% of websites that employ CDNs and contain login entrances expose users' passwords in plaintext to their CDNs.
- We find that two popular CDN providers, Cloudflare and Akamai, can observe users' passwords from 44% and 25% of their customers, respectively.
- We find prevalent password exposure in most website categories, including websites whose user accounts should be carefully protected, such as websites related to finance and health. Retail websites substantially benefit from CDNs, but most of them (58%) expose passwords to CDNs.
- Our result shows that less than 17% of the websites encrypt users' passwords when transferring login requests to CDNs, and the top 1,500 websites are more likely to adopt client-side password encryption.

Overall, our measurement points out potential security issues caused by password exposure to CDNs. Even though websites trust CDNs, users may concern about their privacy when CDNs can monitor their private data including passwords. Moreover, CDNs have never been secure enough. Prior work has shown that an attacker can trick some CDNs to cache and reveal other users' private data [19,38,39]. Thus, private data leakage to CDNs may turn into a disaster when attackers or malicious insiders exploit vulnerabilities of CDNs.

2 Background

In this section, we briefly introduce CDNs and HTTPS, and we analyze the security issues when a website with HTTPS employs a CDN. We also discuss two countermeasures adopted by websites in practice to address such issues.

2.1 HTTPS on CDNs

A CDN reduces web retrieval time by directing a client's request to an *edge server* which is hosted by the CDN and geographically close to the user. The

[1] The code is available at `https://github.com/SHiftLin/PAM2023-CDNPassword`

edge server responds to the client with cached content. If the requested content is not cached, the edge server may fetch the content from the *origin server* which is hosted by the website (the CDN's *customer*) and is the initial source of all content. CDNs do not cache private data, as they are usually dynamic.

Modern CDNs are used not only to speed up page loading but also to provide an effective shield against attacks such as DDoS and code injections [20]. A CDN enlarges the serving capability of its customers to prevent volumetric DDoS attacks. It also applies techniques such as IP blocking and rate limiting to block attacks when DDoS happens. For example, Akamai protected its customers from 38,905 separate DDoS attacks from 2014 to 2019 [50]. CDNs also inspect the content of requests and use Web Application Firewall (WAF) to filter out malicious requests such as XSS injection [59] and SQL injection [24].

Unfortunately, CDNs have become a source of vulnerabilities in the HTTPS ecosystem in recent years [15,17]. If a website employs a CDN to represent it to respond to clients' HTTPS requests, it has to share its private key with the CDN. With the private key, the CDN can build HTTPS connections with clients, and clients cannot differentiate between the CDN and the origin server. When a client requests for private data, the CDN will forward the request by terminating the HTTPS connection and building another HTTPS connection with the origin server. Therefore, the CDN becomes a man in the middle when a user's private data are transmitted between the client and the origin server [15].

2.2 Countermeasures in Practice

Two instant but imperfect countermeasures have been deployed by some websites. First, a website can bypass the CDN and send the private requests to the origin server directly. In this countermeasure, a website should use a separate domain or subdomain for the private data, because the CDN possesses the private key of the original domain. We refer to this method as "*CDN bypassing*" in this paper. This method will not affect CDNs' benefit of page loading acceleration, since the private data are not cached by CDNs. However, it eliminates the benefit of having the origin server shielded against DDoS attacks, because the IP address of the origin server is exposed to the public. When attackers can connect to the origin server directly, it is much easier to launch DDoS attacks since the origin server usually cannot construct a DDoS defense as effectively as CDNs [22,54]. Besides DDoS, the CDN cannot inspect the private content to filter out malicious requests, and thus the origin server may suffer from attacks such as code injections.

Another countermeasure is to encrypt private data inside HTTPS connections. The website generates another key pair and delivers the new public key to the client. The client uses the public key to encrypt the private data to be sent out. Therefore, when a CDN forwards the request, the private data are invisible to the CDN. We refer to this method as "*client-side encryption*" in our paper. We observe some websites use this method to protect users' passwords only, as encrypting all private data may introduce too much overhead. However, the client-side encryption only defends against a passive attacker as described in

§ 3. Besides, secure public key delivery is non-trivial when HTTPS connections are already intercepted by a CDN [35]. Delivering another certificate differing from the HTTPS certificate is useless, because a website has to use JavaScript to conduct encryption in current browsers, and the JavaScript code cannot obtain the root certificates of a client to verify a certificate. Without a certificate, if the public key is delivered by a CDN, a CDN with an active attacker (defined in § 3) inside can launch the man-in-the-middle attacks by replacing the public key. If the public key is delivered by the origin server, the origin server is exposed to the public and under the threat of DDoS. In practice, websites use an asynchronous JavaScript call [6] to request for a public key from the origin server and encrypt passwords by JavaScript code.

Despite the defects of these two methods, they preserve users' privacy to some extent. Moreover, if the origin server builds its own DDoS defense or a CDN is assumed to be a passive attacker, these two countermeasures can provide sufficient protection. However, it is unclear about the deployment of these two countermeasures on websites. Thus, we investigate the password exposure to provide a profile of their deployment.

3 Threat Model

We use the threat model proposed by the prior work [35]. We consider the private data in a website as the data can only be accessed by a authenticated user. The users can be authenticated by the traditional password, one-time password (OTP), OAuth [25], certificates, etc. The credentials for authentication are considered as private data as well. We focus on the measurement of the traditional password in this paper.

We considered two types of attackers defined in the prior work [35].

- **Passive attacker:** A CDN behaves honestly to serve the requests, but an attacker inside the CDN may eavesdrop on the transmitted messages. For example, a malicious administer of a CDN cannot change the CDN's behavior but may peek at the transmitted traffic and record users' passwords. Client-side encryption can protect users' password under a passive attacker.
- **Active attacker:** An attacker insider CDN may launch arbitrary attacks including eavesdropping and tampering. Thus, it is more capable than a passive attacker. For example, a CDN may modify or corrupt the cached HTML or JavaScript to disable the client-side encryption so that it can observe users' passwords in the login requests. This may happen when attackers exploit a vulnerability of a CDN. As previously mentioned, CDN-bypassing can defend against an active attacker inside a CDN, but it introduces the vulnerability of DDoS to the origin server.

4 Method

To detect the password exposure, we should inspect a website's login request and the destination. Thus, we need a framework for automatic login in a large-scale measurement. Currently, a website may adopt multiple authentication methods, such as text passwords, OAuth [25], one-time password (OTP). In our measurement, we only consider the method of text passwords.

Based on the existing frameworks [47,31,48], we designed and implemented an automatic login framework that copes with more web pages with diverse structures. In our work, we do not need to successfully log into a website, so the framework merely triggers a failed login and collects the login request. We elaborate on the design and implementation of such a framework in the appendix.

Besides the automatic login framework, we use the method in the prior work [15,27,32,33,35] to discover the CDN usage of a website. This method also helps to inspect the destination of the collected login requests to determine whether the requests are sent to a CDN server.

Some cloud providers will provide both hosting service and CDN service, such as AWS and Azure. In our method, when a request is sent to such a cloud provider, we cannot determine whether the website is using the CDN service or the hosting service. If the password is sent to a hosting service, it should not be considered as an exposure to a CDN. Since our goal is to provide an underestimation of password exposure, our CDN list does not include a CDN service provider that also provides hosting service. As a result, our CDN list contains 9 popular CDNs, namely Cloudflare, Akamai, Fastly, Highwinds, Edgecast, Incapsula, Quantil, CDNetworks, and Limelight.

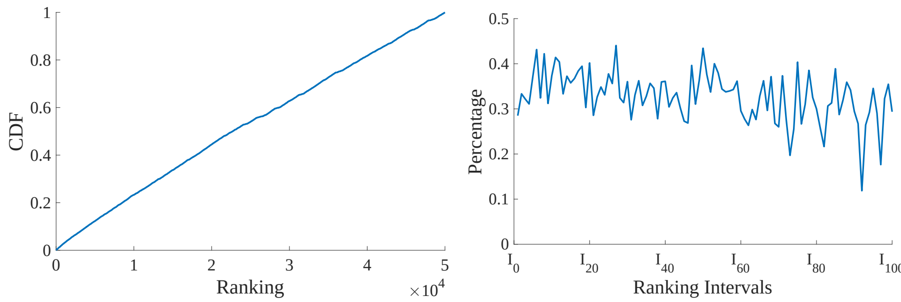
We collected 50k websites from the Alexa ranking list [2] and ran our experiments of automatic login and CDN discovery in Oct. 2020. In our future work, we will set up our experiments as a monitoring platform to observe the evolution of password exposure behavior.

Ethical concerns: We respect user privacy, and our work does not raise ethical concerns. The method of CDN discovery only used public data from the Internet, such as Registration Data Access Protocol (RDAP) [43]. As for the automatic login framework, since we do not require a successful login, we use a randomly generated fake account that is nearly impossible to coincide with existing ones. We skip the websites that require a test of the account existence before submitting the login credentials. We only conduct the login trial once for each website, so we do not overload the websites in our test.

5 Password Exposure

We only consider HTTPS-enabled websites because a website without HTTPS apparently contains major vulnerabilities. In Alexa top 50K sites [2], 42,502 of them enable HTTPS. We run the framework to automatically log into these websites. If the framework submits the fake credentials to a website, we consider it performs a login. The framework performs 17,111 logins in total. In this paper, we focus on these 17,111 websites and call them "login-detected websites".

We detect CDNs employed by these websites according to § 4. Our result shows that 12,451 websites employ CDN service, and we call them "CDN-enabled websites" in this paper. By inspecting their login procedures, we find that 4,114



(a) **CDF** (b) **Percentage**

Fig. 1: (a) Distribution of login-detected websites. (b) Percentages of password-exposed websites among CDN-enabled websites across different ranking intervals. We divide 50K websites into 100 ranking intervals. Each interval contains 500 websites. The x-axis ticks at every 20 intervals.

websites send the login requests with users' passwords in plaintext or Base64 encoding to CDNs. We denote these websites as "password-exposed websites". We discovered that 33% of CDN-enabled websites expose users' passwords to CDNs, demonstrating a potential privacy issue. In this section, we present the results in detail.

5.1 Distribution over Rankings

Since our framework may fail to detect the login forms of some websites, the dataset of login-detected websites is a sample set of all websites that enable logins. We first investigate the distribution of these samples over rankings.

Figure 1a shows the distribution of login-detected websites. A linear relationship between the CDF and ranking shows a uniform distribution of the websites. Therefore, the logins detected by our framework are unbiased in the rankings.

To investigate the relationship between websites' rankings and their preference for password exposure, we divide the rankings into 100 intervals. For an interval I_j, it contains 500 websites ranking in the range of $[1+500*(j-1), 500*j]$. For each interval, we count the password-exposed websites and the CDN-enabled websites, and we compute the percentage of password-exposed websites in CDN-enabled websites.

Figure 1b presents the percentage variation across the intervals. Given the result of unbiased detection in Figure 1a, we can examine the distribution of password exposure on website rankings through Figure 1b. Even though some fluctuations exist, the percentages are overall above 20%, meaning that the password exposure is common across all rankings. Besides, we can find that the most popular websites in the first two intervals have relatively low password exposure percentage. It is because that the top websites are more likely to deploy defense mechanisms, which can be justified by our analysis in § 6.

Table 1: Distribution across CDN providers (a) and website categories(b). The "Percent" column denotes the percentage of password-exposed websites in CDN-enabled websites. We mark notable data with red color.

(a) **CDN providers**

CDN provider	CDN-enabled	Password-exposed	Percent
Cloudflare	6356	2803	44%
Akamai	3280	818	25%
Fastly	1631	291	18%
Highwinds	504	26	5%
Edgecast	241	16	7%
Incapsula	216	142	66%
Quantil	161	10	6%
CDNetworks	32	3	9%
Limelight	30	5	17%

(b) **Website categories**

Category	CDN-enabled	Password-exposed	Percent
Retail	304	175	58%
Internet	231	69	30%
Business	225	72	32%
Entertain	213	76	36%
News	181	62	34%
Finance	159	60	38%
Technology	155	42	27%
Education	145	14	10%
Society	99	31	31%
Travel	79	34	43%
Science	50	18	36%
Sports	49	15	31%
Health	43	17	40%
Reference	36	13	36%

5.2 Distribution over CDN Providers

We also consider how password-exposed websites are distributed among the CDN providers. Table 1a presents the number of password-exposed websites in each CDN provider. As shown in the table, Cloudflare and Akamai are the two most popular CDNs in the world, and they observe the most users' passwords from their customers' requests. More than 40% of Cloudflare's customer websites in our dataset share users' passwords to Cloudflare, and Akamai observes passwords from 25% of its customers. Besides, 66% of websites that use Incapsula expose passwords to the CDN. Some CDNs only observe a small fraction of sensitive traffic, such as Highwinds and Edgecast.

Compared to the other CDN providers, a much larger portion of Cloudflare and Incapsula customers are affected by password exposure. For Cloudflare, the reason may be the difference in request redirection methods. Cloudflare uses anycast for request redirection by default [14], while the other CDNs use DNS redirection [45,37]. As discussed in [35], to enable anycast redirection, a website needs to use Cloudflare as the DNS provider. Such a practice will transfer a website's all DNS records to Cloudflare DNS service, including the resolution to the domain of the login request (*e.g.* DNS A record of `login.example.com`). Cloudflare will conduct anycast redirection for the transferred domains by default. Therefore, the login request is very likely to be terminated by Cloudflare. We verify this inference by checking the DNS provider of password-exposed websites using Cloudflare. We find that 63% of websites that transferred their DNS providers to Cloudflare expose their passwords to Cloudflare, while 83% of websites that use Cloudflare CDN service without transferring their DNS providers do not suffer the password exposure.

As for Incapsula, such a high percentage (66%) may originate from the dynamic content caching provided by Incapsula [8]. Such a service will cache the dynamic content for a short period to improve the performance of webpage loading, which is not enabled by the other CDN providers. Websites using Incapsula may employ this service to cache the dynamic content including the login responses, leading to password exposure.

It is reasonable for websites to trust famous CDN providers and employ their defense against attacks. However, it does not necessarily mean users should also trust CDNs. From the users' perspective, they may be concerned about their private data when it is shared with a third-party CDN. The results also imply a risk of the single point failure of popular CDNs: a malicious insider in a popular CDN may divulge the users' passwords of more than 40% of its customer websites, leading to a large-scale user data leakage.

We reported our findings to three CDN providers, Cloudflare, Akamai, and Fastly. All of them replied to us. They acknowledged the implication of password exposure and claimed that they are trustworthy and will follow the privacy policy [7,10] to secure customers' data. Akamai also explained that they must terminate the TLS connections including those transmitting private data in order to provide protections such as WAF for customers.

5.3 Distribution over Website Categories

We investigate the practice of exposing passwords among different website categories. We collect the website category data from Alexa Top Sites by Category [2]. In 12,451 CDN-enabled websites, 2,010 of them can be classified by the Alexa data. In our dataset, three categories (Government, Recreation, and Home) contain less than 20 CDN-enabled websites, so we consider the dataset is not representative enough for these three categories. Thus, we only use the rest of the 14 categories in our analysis in this section.

Table 1b presents the statistics of CDN usage and password exposure across 14 website categories. As we can see, retail websites employ most CDNs because they need to display many pictures of their products, and CDNs notably accelerate the picture delivery . However, most retail websites (58%) also expose passwords to CDNs. Besides retail websites, more than 40% of websites of travel and health expose users' passwords. We note that a large portion (38%) of finance and health websites which are usually considered to require sophisticated defense divulges users' passwords to CDNs. Moreover, education websites have the least percentage of password exposure. Our results point out that password exposure is prevalent within a wide range of categories, while retail, travel, and health are the most affected website categories.

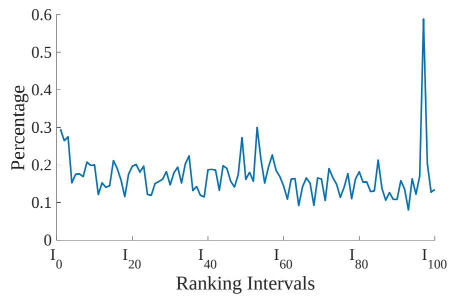


Fig. 2: Percentages of password-encrypted websites among CDN-enabled websites across different ranking intervals. We divide 50K websites into 100 intervals. Each interval contains 500 websites. The x-axis ticks at every 20 intervals.

6 Countermeasures

In this section, we first present the measurement of the countermeasures against password exposure used by current websites. We also discuss possible countermeasures that websites and users can adopt.

6.1 Client-side Encryption and CDN Bypassing

In our measurement, we observe that some websites indeed adopt client-side encryption discussed in § 2.2 to protect users' passwords. For example, `baidu.com`, `dropbox.com`, and `chase.com` deliver public keys by their origin servers. However, such a solution is rarely adopted by the websites. In our measurement, if our framework submits the credentials but cannot find the password in plain text or Base64 encoding in the login request, we consider that the website encrypts the password. Since our framework may fail to login, we have an upper-bound estimation of the deployment of client-side password encryption. Therefore, in our dataset, at most 2,057 (16.5%) out of 12,451 CDN-enabled websites adopt such a solution. We call these websites "password-encrypted websites". This result demonstrates that password encryption is a rare practice on the web.

We investigate the relationship between a website's ranking and password encryption deployment. We used the same method and intervals in Figure 1b, and the results are shown in Figure 2. As we can see, even for the websites that rank top 1,500 (I_0, I_1, and I_2), less than 30% of them encrypt users' passwords. Nevertheless, when compared with other websites with lower ranks, they have a relatively higher percentage of password encryption. However, an outstandingly high percentage exists around the intervals of quite low rankings. We manually inspected websites located in that interval. We found 13 websites of all 20 password-encrypted websites are subdomains of `tmall.com` for different retailers, such as `www.kfc.tmall.com` and `www.lenovo.tmall.com`. Once a user attempts to sign into these subdomain sites, they all direct the user to `tmall.com`. This website is a top electronic shopping website, and it adopts password encryption.

We note that as a preliminary defense, client-side encryption can only defend against passive attackers as described in § 3. However, our measurement shows that most websites including top ones cannot even prevent a passive attacker. If an active attacker exists, CDN bypassing can protect users' privacy, but it exposes origin servers' IP addresses and leave servers at the risk of DDoS. In our measurement, we cannot verify whether the destination of a login request is the origin server through RDAP. We leave the further measurement of CDN bypassing as future work.

6.2 Possible Countermeasures

Besides client-side encryption and CDN bypassing, Password Authenticated Key Exchange (PAKE) [13,21] also prevents password exposure. PAKE protocols, such as SRP [60] and OPAQUE [29], authenticate users without the requirement of revealing passwords in login requests. Moreover, it is proven to be secure during login even when CDNs can launch active attacks. However, PAKE protocols require trust on first use (TOFU), meaning that a secure channel is required during account registration. Therefore, PAKE solves the password exposure issue for web services that do not allow online registration. For example, it can be used in banking industry, as users are required to open a bank account physically at branches. Nevertheless, PAKE is almost never used by websites [21]. The reason may be the difficulty of understanding and implementing PAKE protocols for developers. It may also be because developers usually trust third-party CDNs and are not aware of such a password exposure issue.

From the users' perspective, a user can use OAuth [25] such as using a Google account to sign in to other websites. Because leading tech companies such as Google and Facebook have built their own CDNs, a user's password will not be exposed to a third party during the login. However, more OAuth practices may lead to a severe single-point failure if a user's password of the Google account is leaked. Besides OAuth, users can also adopt two-factor authentication. Even though two-factor authentication cannot prevent passwords from being exposed to third-party CDNs, it prevents accounts from being compromised even when the passwords are exposed to attackers.

These countermeasures can only protect users' passwords. However, users' private data stored on a website may also be divulged to a CDN during the transmission. As private data are much more complicated and diverse than the passwords, developing countermeasures would be harder. Thus, private data leakage may be much more prevalent than password leakage. We leave the measurement of private data leakage as future work.

7 Discussion and Future Work

Our measurement quantifies password exposure to CDNs and suggests potential security issues in current web ecosystem. In this section, we provide suggestions to the security community, users, and the industry.

We need further research on the solutions. As presented in § 2.2, the preliminary strategies of CDN bypassing and client-side encryption can be easily deployed but contain vulnerabilities. Proposed techniques such as Keyless SSL [51,18,40], certificate delegation [34], and mcTLS [42] are ineffective in preserving user privacy. The SGX-based solutions [41,26] can provide comprehensive protection, but it is hard to be deployed on CDNs. InviCloak [35] can achieve the goal of DDoS defense, privacy protection, and instant deployment simultaneously, but it disables the Web Application Firewall (WAF) of CDNs. Therefore, further research on this area is critical to a more secure Internet.

We recommend users adopt two-factor authentication. Two-factor authentication provides additional protection for an account even when the password is stolen by a hacker. Adopting OAuth is debatable as it may lead to the single point of failure although it prevents password exposure as discussed in § 6.2.

Websites should adopt preliminary defense. The results shows that many websites do not apply the minimal defense against password exposure. Despite the preliminary strategies are vulnerable to some attacks, they provide basic protection for users' privacy. Since it is acceptable to assume a passive CDNs in most cases, the client-side encryption usually provides a sufficient protection.

CDN providers should involve in developing and deploying advanced solutions. The widespread of Keyless SSL on Cloudflare demonstrates that a CDN provider plays an important role in the security community [51]. Cooperation from CDN providers can validate researchers' ideas and advance further research. CDNs can also guide their customers to deploy a defense mechanism.

This paper presents the preliminary results of password sharing to third-party CDNS. We propose the following directions as the future work.

1. Augment the existing CDN discovery method to differentiate the hosting service and the CDN service of a cloud provider, as mentioned in § 4.
2. Quantify the adopted or available countermeasures besides the client-side encryption in websites, including CDN bypassing, OAuth, one-time password, two-factor authentication, etc, as mentioned in § 6.
3. Measure private data leakage in websites to understand the security impact of TLS private key sharing from users' perspectives, as mentioned in § 6.
4. Survey the users and website developers to understand their awareness of private data leakage to thrid-party CDNs. Such a survey helps to figure out the reason why countermeasures are not widespread.

8 Related Work

Password security. Password security has attracted attention from many researchers. Lu *et al.* analyzed how websites deploy measures to prevent online password cracking [36]. Wang *et al.* manually inspected 188 websites to characterize the login process and built an extension to inform users of potential password leakage caused by the lack of HTTPS [56]. Acker *et al.* studied the security of password input fields among the Alexa top 100K sites, and they found that 62.8% of the websites with a login page are vulnerable to basic man-in-the-middle attacks [53]. Bonneau *et al.* surveyed the proposals for replacing passwords and pointed out the difficulty of replacing passwords [12]. Peng *et al.* explored how passwords are spread after they are divulged by phishing sites [47]. In addition, many prior works investigated the prevalence of the password reuse problem [46,28,57,49] and its countermeasures [55].

CDN security. Researchers have shown the existence of a wide range of vulnerabilities in CDNs. Mirheidari *et al.*'s measurement shows that private data can be divulged by CDNs through web cache deception [19,38,39]. Nguyen *et al.* presented an attack of poisoning CDN cache with error pages, and five CDN services were vulnerable to such an attack [44]. Besides CDN cache, researchers also presented approaches to disclosing the IP addresses of origin servers hidden behind CDNs, demonstrating insufficient DDoS protection of CDNs [54,30]. Moreover, attackers may utilize a CDN to launch DoS to an origin server or to the CDN itself [52,16,23]. In addition, Durumeric *et al.*'s measurement shows that the HTTPS interception on CDNs may downgrade the TLS version or cipher suites and thus reduce connection security [17].

Solutions to TLS key sharing. A line of research focuses on building keyless CDNs. Cloudflare, Akamai, and Modadugu *et al.* proposed similar solutions called "Keyless SSL", respectively [51,18,40]. Certificate delegation [34] and mcTLS [42] enable a client to recognize the CDN as a delegation of the website. Wei *et al.* [58] and Ahmed *et al.* [11] adopted Trust Executive Environment (TEE) on CDNs for private key management. However, these strategies only prevent the TLS private key sharing, while users' private data are still visible to CDNs. Phoenix [26] and mbTLS [41] extend TEE solutions to fully protect users' private data. However, deploying TEE-based solutions on CDNs may take a long time as it requires upgrades of hardware and operating systems. InviCloak [35] protects users' private data with an additional encryption channel and low overhead, but its adoption by websites in the future remains unclear.

9 Conclusion

In this paper, we conduct a large-scale measurement to quantify user password exposure to third-party CDNs in the web ecosystem. Our results show that 33.0% of CDN-enabled websites expose users' passwords to the CDNs during the login procedures. Retail websites substantially benefit from CDNs but also tend to expose passwords to CDNs. Besides, client-side password encryption is adopted by less than 17% of websites, even though it is simple and effective to a certain extent. Overall, our results suggest that current websites excessively trust CDNs, leading to potential security issues when attackers exploit CDNs' vulnerabilities. We publicly released the code to facilitate future research [9].

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Appendix

We present the detail of our auto-login framework in this section. For each web page, the framework applies four steps to the HTML elements: filtering, classifying, scoring, and submitting credentials. The framework first filters the elements based on tag names and locations. Then it uses keyword frequency as the features to classify filtered elements into three classes: login entrances, account inputs, and password inputs. In each class, it assigns a score to each element according to features extracted from the HTML code. Finally it fills and submits credentials if the login form is found, or it clicks on the login entrance to visit the login page. The elements to interact with are chosen by their scores in each class. The followings paragraphs introduce each step in detail.

1. **Filtering**: When the framework arrives at a page, it starts with filtering out elements that are considered irrelevant to login. Specifically, it selects elements containing one of the following tag names: "input", "button", "label", "a" and "iframe". To reduce element candidates, we assume that a login entrance or a login form should be shown within the area of one and a half of the viewport height from the top of a web page. The rationale of this assumption is that a website should place login elements at positions that are easily accessible to users.
2. **Classifying**: To classify an element into the classes mentioned above, the framework extracts strings from HTML properties and the inner text of the element. It then splits strings into words by camel case and non-word characters. It computes the frequencies of some keywords in the string. The keyword frequencies are regarded as a feature of the element. The framework classifies the element based on these features and heuristic rules. We manually select eleven keywords and construct rules for classification after examining Alexa top 100 sites. One example of the rules is that a login entrance should contain at least one of the keywords related to "login", "account", or "email". To improve the detection accuracy, we also apply some deprecation keywords such as "user guide" and "policy". An element is discarded if it contains any of the deprecation keywords.
3. **Scoring**: While a website usually contains only one login entrance, the framework may classify multiple elements into the login class. Thus, our framework assigns scores to elements. For each element, the framework extracts other features besides keywords, such as the length of inner text and the visibility of element. The framework uses the features to assign a score to each element according to the rules we construct manually. For example, in the class of login entrance, a visible and interactive element receives a higher score than ones that are not. The frequency of a keyword in an element is also factored in the scores. Finally, the framework sorts elements in each class according to their scores.
4. **Submitting Credentials**: If the framework obtains any input element in the account class or the password class, it fills each input element with credentials. Then it uses the keyboard signal, ENTER, to submit fake credentials. If no input field is detected, the framework clicks on the login element

with the highest score and repeats the presented steps on the new web page to detect input fields. The framework collects the login request once it considers a credential submission happens.

Overall, our framework uses heuristic rules to detect login entrances and input fields of credentials. We implement the framework by using Selenium WebDriver [5] to control Chrome. We test our framework on 100 random-selected websites of which 52 enable the login. The results show that our framework successfully submits credentials to 45 of 53 websites, meaning a recall of 84.9%. The framework ignores all 47 websites without a login entrance, meaning a false positive of 0%. The overall detection accuracy is (45+47)/100=92.0%.

Existing automatic login frameworks: Browsers such as Chrome and Firefox can help users automatically fill in the credentials on some web pages. We do not use this function because it relies on the existence of the "autocomplete" attribute in HTML elements, and thus it cannot handle the websites that do not enable this attribute in HTML. Besides the automation of browsers, Peng *et al.* implemented a framework to log into phishing websites automatically [47]. Our framework can handle issues that are common in legitimate sites but rare in phishing sites, such as confusion caused by sign-up forms and pop-ups. Jonker *et al.*. also proposed a framework for post-login security analysis [31]. Our framework shares many similarities with theirs but adds the capability to operate in the presence of HTTP Authentication and reCAPTCHA.

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