Oh, What a Fragile Web We Weave: Third-party Service Dependencies In Modern Webservices and Implications

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Abstract

The recent October 2016 DDoS attack on Dyn served as a wake up call to the security community as many popular and independent webservices (e.g., Twitter, Spotify) were impacted. This incident raises a larger question on the fragility of modern webservices due to their dependence on third-party services. In this paper, we characterize the dependencies of popular webservices on third party services and how these can lead to DoS, RoQ attacks and reduction in security posture. In particular, we focus on three critical infrastructure services: DNS, CDNs, and certificate authorities (CAs). We analyze both direct relationships (e.g., Twitter uses Dyn) and indirect dependencies (e.g., Netflix uses Symantec as OCSP and Symantec in turn uses Verisign for DNS).

Our key findings are: (1) 73.14% of the top 100,000 popular services are vulnerable to reduction in availability due to potential attacks on third-party DNS, CDN, CA services that they exclusively rely on; (2) the use of third-party services is concentrated, so that if the top-10 providers of CDN, DNS and OCSP services go down, they can potentially impact 25%-46% of the top 100K most popular web services; (3) transitive dependencies significantly increase the set of webservices that exclusively depend on popular CDN and DNS service providers, in some cases by ten times (4) targeting even less popular webservices can potentially cause significant collateral damage, affecting up to 20% of the top-100K webservices due to their shared dependencies. Based on our findings, we present a number of key implications and guidelines to guard against such Internet-scale incidents in the future.

1 Introduction

In October 2016, a major managed DNS provider, Dyn, fell victim to a Distributed Denial of Service (DDoS) attack [4]. Dyn hosted the authoritative nameservers for many popular webservices, such as PayPal, Twitter, and Github and as a result they were inaccessible to a sizable part of the East Coast. It turned out that many other webservices were also dependent on Dyn, therefore the incident resulted in a massive impact on the availability of many popular webservices.

This recent incident suggests that the modern webservices ecosystem is perhaps much more fragile than one would expect, and that threat actors are already taking advantage of this. At the same time, this incident also raises many broader questions about the robustness (and fragility) of the web ecosystem:

- How robust or fragile are popular webservices in terms of their dependency on third-party infrastructure services? E.g., do they use any form of redundancy when using third-party services?
- Is the Dyn incident a singular type of occurrence or are there other types of hidden third-party services that are also potential Achilles’ heel for affecting popular webservices?
- Are there more subtle or transitive dependencies between webservices and their third-party providers; e.g., loading webservice Netflix entails third-party service Symantec which in turn depends on Verisign for DNS

In this paper, we systematically address these questions using a measurement-driven approach by analyzing the top 100,000 sites (as defined by the Alexa rankings) [2]. We believe that such a study is timely and significant to understand the security of modern webservices. While there are some key limitations of the types of end-to-end vantage point measurement studies (e.g., we do not have capacity estimates for third-party services, we cannot infer third-party dependencies that are not visible to end hosts, we don’t consider interwebservice dependencies), we believe that our findings are nevertheless valuable and relevant. The answers to the aforementioned questions have key implications both for different stakeholders as we shed light on key bottlenecks that are potential vectors for future large-scale attacks.

Specifically, we focus on three key types of third-party services that most modern webservices rely on and that are critical pieces in the lifetime of a web request: naming (DNS), SSL certificate validation (OCSP), and content delivery (CDN). We analyze two kinds of potential dependencies: (1) direct dependencies of the simple kind found in the Dyn incident where a webservice like Spotify uses Dyn as its DNS provider and (2) indirect or transitive dependencies that consider “multi-hop” ef-
fects; e.g., loading Netflix.com entails loading Symantec which in turn depends on Verisign for DNS.

Our key findings are:
- 73.14% of the top 100,000 popular services are vulnerable to reduction in availability due to potential attacks on third-party DNS, CDN, CA services that they exclusively rely on;
- The use of third-party services is concentrated, so that if the top-10 providers of CDN, DNS and OCSP services go down, they can potentially impact 25%-46% of the most popular web services;
- Transitive dependencies significantly increase the set of webservices that exclusively depend on popular CDN and DNS service providers, in some cases by ten times, and even affect the set of most popular providers;
- Transitive dependencies can introduce even simpler attack capabilities to achieve similar goals. For example, targeting less popular webservices can potentially cause significant collateral damage, affecting up to 20% of the top-100K webservices due to their shared dependencies.

Based on these findings, we derive key implications for future services and attacks. Specifically, we recommend that: (1) webservices seek to increase their robustness by adding more redundancy w.r.t third party services and also be aware of the hidden dependencies of the third-party services they employ and (2) Third-party services increase the transparency in reporting potential attack events and also provide a quantitative understanding of their infrastructure and dependencies to the web services. Finally, we also observe that these have implications for attackers as they can uncover new attack targets for indirectly affecting webservices that can maximize the impact for a fixed amount of attack resources.

2 Background and Motivation

In this section we begin with real-world case studies that highlight three potential threats that webservices (WSes) may face as a result of the dependencies with other third-party services (TPSes). We specifically focus on three types of potential threats in this paper as discussed below.

Denial of Service (DoS) Denial of Service (DoS) occurs when users of a particular service are unable to access it, for reasons such as an attack on it or an internal failure. In 2016, a Distributed Denial of Service (DDoS) attack on a Managed DNS provider called Dyn caused the unavailability of many websites such as Twitter, Spotify, Github etc. Dyn is the authoritative name server of these and many other websites. Authoritative name servers are responsible for name resolutions to a particular zone where a DNS zone is a contiguous namespace for which administrative responsibility has been delegated to a single authority. For example, if a user goes to twitter.com then the authoritative name server for twitter will be responsible for answering queries to twitter.com which in this scenario was Dyn. If the authoritative name server becomes inaccessible as a result of an attack or a bug, it can lead to failed name resolutions for all the domains that rely on it, which makes the clients unable to access those domains. This is what happened in this case where a dependency of multiple WSes on a single provider led to denial of service for all of their users.

Another such incident happened with Cloudflare, a major DNS and CDN provider, when a software bug caused DNS and HTTP requests of some of its customer websites to fail. Similarly, in 2013, Cloudflare effectively disappeared from the Internet due to a router misconfiguration. These incidents show that the dependency of websites on various services become single points of failure in the face of an attack or misconfiguration.

Reduction of Security (RoS) Reduction of Security happens when the security of a WS is compromised, as a result of an attack or misconfiguration. To give an example of such an attack, consider the public-private key cryptography primitives used along with Certificate Authorities (CA’s) used to provide end-to-end confidentiality (encryption) and authentication on the Internet. CA’s signed certificates presented by web services, which clients verify to be valid. CAs can sometimes revoke certificates when they are compromised and one way to do that is to provide an OCSP service, which clients can query to check the validity of a certificate presented by a website. In a recent ROS attack in 2016, users were unable to connect securely to websites which used GlobalSign as their CA, since their OCSP servers mistakenly marked valid certificates for numerous websites as invalid due to a misconfiguration.

Reduction of Quality (RoQ) Reduction of Quality happens when a WS falls victim to performance degradation, resulting in increased page load times for its users as a consequence of different types of throttling or admission control mechanisms. This is not good for a number of reasons, 1) Users eventually stop using the service when they experience poor performance, 2) This results in loss of revenue for the WSes. There can be many ways to do a Reduction of Quality attack. For instance, Stark et al. describes the additional delay that occurs in the TLS handshake when a user validates the status of a certificate by contacting the OCSP server. They show that OCSP validation can cause a mean delay of approximately 500ms. So if these OCSP requests go into timeout, due to high load or unavailability of the OCSP server, it can cause huge performance penalty for the users. Moreover, a certain form of denial of service...
Attacks can also cause huge performance degradations [22] which involves sending a sustained traffic workload that keeps the WS flooded with traffic, without causing DoS but performance degradation to its users. Such kind of attacks, can also exploit the various TPS dependencies that exist in the Internet infrastructure.

Motivating Questions These case studies and incidents spark several natural questions about the state of the web services ecosystem today:
- How pervasive are such dependencies between popular WSes and various TPSes (e.g., DNS, CDN) providers?
- How many of these dependencies are direct and how many of them are hidden or indirect transitive dependencies?
- How robust or fragile is a typical WS today with respect to different types of TPSes?
- Are there other service providers (such as Dyn) that are key points of vulnerability on the Internet, such that an attack on them could lead to significant collateral damage to multiple webservices?

Our goal is to shed light on these questions to better understand the robustness/fragility of the web ecosystem and to provide recommendations for improving their robustness going forward. In the next section, we describe our measurement methodology to collect data about the service dependencies on the Alexa’s top 100,000 WSes and then present our analysis and implications.

3 Preliminaries and Methodology

In this section, we describe our measurement methodology to shed light on the motivating questions listed above. We also define the types of dependencies we focus on in our analysis. We also highlight key limitations of our analysis to help put our results in context.

3.1 Problem Scope and Definitions

To understand the types of services we need to analyze, it is instructive to start by looking at the life cycle of a typical web request as illustrated in Figure 1. When a user makes request to a Web service (WS) such as example.com, the request first goes through a name resolution phase, where the hostname to IP translation is fetched from the authoritative nameserver of example.com. After having the successful resolution, the request then goes through a routing phase to reach example.com server. If the website is using HTTPS, the request goes through a certificate exchange phase. The client then consults the respective OCSP server to validate the certificate. After this, user requests the homepage of example.com and the content of example.com might be hosted by a CDN, and loading the page may entail contacting one or more TPSes as well.

We refer to the origin service (e.g., example.com) as a WSes and non-origin hosted services as TPSes (which can be either infrastructure services such as CDN, DNS, or CA or other WSes).

We can model the observed relationships between the various services as a dependency graph: \( G = (S, D) \), where \( S \) is the set of services and \( D \) is the set of directed edges depicting a dependency between services. Each node in the graph is represented as a tuple: \( s = (name, service type) \), where service type can be a website, CDN, DNS or OCSP. Edges represent s dependencies, denoted as: \( d = (source, target, dependency type) \).

In our analysis, we consider two types of dependencies:

1. Direct Dependency: We say that a service \( s_1 \) has a direct dependency on service \( s_2 \) if \( s_1 \) uses \( s_2 \). It is denoted as \( \langle s_1, s_2, \text{direct} \rangle \).

From a robustness point of view, we are also specifically interested in the notion of exclusive dependency. That is, if service \( s_1 \) has a direct dependency on service \( s_2 \) where \( s_2 \) is of type A and there exists no service \( s_3 \) of the same type A such that \( s_1 \) has direct dependency on \( s_3 \). For example, Figure 2 shows that \( (example.com, \text{website}) \) is directly dependent on both \( (DNS_1, \text{DNS}) \) and \( (DNS_2, \text{DNS}) \) for service type DNS. However, it is exclusively dependent on CDN A for service type CDN.
2. Indirect or Transitive Dependency

If a service $s_1$ has an exclusive dependency on service $s_2$ and $s_2$ has an exclusively dependency on service $s_3$, then we say that $s_1$ has a transitive dependency on service $s_3$.

Figure 3 shows an example of transitive dependencies. If DNS$_1$ fails, this results in the failure of OCSP$_1$ and all the websites exclusively dependent on it are affected as well.

Figure 2: The figure shows that example.com has a direct dependency on DNS$_1$ and DNS$_2$ and exclusive dependency on CDN_A.

3.2 Measurement Methodology

To assess the hidden dependencies among WSes and third party infrastructure providers, we measure the authoritative nameservers (NS), CDNs (if any) and Certificate revocation information (OCSP servers and CRL distribution points) for Alexa’s top 100,000 WSes. Alexa rank is calculated based on the traffic data which includes unique visitors and page views of a particular WS [7]. The traffic across ranks drops roughly exponentially as shown by [1][11]. Therefore, we assume, top 100,000 WSes cover a significant amount of traffic on the Internet. Since Alexa’s rankings change over time, we used a consistent list for all our measurements.

In order to find out the authoritative name servers, we use dig (Domain Information Groper) which is a command line tool to query DNS servers [3]. We issue normal dig queries for the NS (nameserver) records which give the records for authoritative nameservers of these domains. We use Google’s global DNS server [8] to query this information. In order to distinguish between private and TPS DNS providers, we used several indicators such as available lists of Third party DNS providers [12], the number of WSes using a particular DNS provider. However, there is no accurate way to detect if a WS is using a third party DNS provider. We observed 21419 DNS providers in total, 92% of these serve less than 5 WSes in the top 100,000. We do not say anything about these DNS providers and since our analysis concerns the ones that predominantly serve WSes, we looked at all those DNS providers which serve more than 100 WSes. This list included total of 82 DNS providers, which we manually checked to see how many of these provide DNS services and found that 79 of them are Third party DNS providers. These 79 DNS providers cover 58% of the total WSes. Therefore, for our analysis, we only consider these 79 DNS providers to be TPSes. So our analysis might be an under-estimation.

Similarly the information related to OCSP servers and CRL distribution points can be extracted from the certificate of the respective WS. To fetch certificates, we first send a SYN on TCP port 43 to see if the WS supports HTTPS. If we receive a Connection Refused error, then it means the WS does not support HTTPS. Next we initiate an HTTPS connection with it and fetch the certificates. We observed 69 distinct OCSP server and manually checked that 57 of them were TPS. We detected this by looking up how many of these provide CA services to other WSes.

CDN information of a website can be extracted from its canonical (CNAME) records. When a WS uses a CDN, the CNAME that it uses points towards the CDNs. Moreover, some CDNs set custom HTTP headers in the web request. To find the CDNs used by a website, we performed dig CNAME (canonical name) queries on all the links that belong to the same host, in a domain webpage. By looking at these records, we extract the CDNs using some indicators in the CNAME. We also look at HTTP headers to see for any custom headers set by the CDNs. A complete list of these indicators is mentioned here [36]. However, we are not able to detect any CDNs that are not mentioned in this list. We observed 47 distinct CDNs and found that 44 of them are TPS.

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1 We use the terms indirect and transitive interchangeably to refer to this type of dependency throughout the paper.
### 3.3 Limitations

We acknowledge some key limitations of the dataset and measurements to help put our results in perspective:

- First, we only study the interaction of a client with DNS, CA, CDN and other third-party providers for a particular WS that are externally visible. For instance, we will miss dependencies if the interactions are via APIs between the services that are out-of-band; e.g., an ad exchange being contacted while the ad-service is being loaded.

- Second, all of our measurements are conducted from a single vantage point in the US East coast. While we believe this is representative view of the structural dependencies of typical and popular WSes, we might miss region-specific dependencies; e.g., if the content rendered say in Asia-Pacific has a different dependency structure.

- Third, we do not measure the dependencies or robustness with respect to the physical and network infrastructure; e.g., with respect to the physical hosting, or network routing, or physical capacity limitations. Thus, when we present our results as a service being potentially vulnerable it is a capacity- and hosting-agnostic analysis. Such data is proprietary and hard to obtain in practice; we believe that our analysis has value even with this limitation. In particular, as prior attacks have shown it is not unreasonable that the adversary can suitably map the infrastructure and scale their capacity as needed [32, 24].

- Fourth, we do not consider dependencies that might arise from software vulnerabilities; e.g., if the services are running vulnerable versions of web/database servers or content management systems.

- Fifth, we do not focus on dependencies between web-services themselves; e.g., if some third-party widget or scripts are loaded. While this too can have implications for security (e.g., privacy), our focus in this paper is largely on the infrastructure components like DNS, CDN, and CAs. We refer the readers to other related work for analysis of third-party web content [31, 15].

- Finally, we only analyze the dependencies as observed on the landing pages of the popular websites. While we believe this is representative of common workload patterns, we do acknowledge that we do not measure dependencies that may manifest deeper in the content hierarchy.

### 4 Analyzing Direct Dependencies

In this section, we consider the direct dependencies that WSes have on various TPSes. We analyze how robust individual WSes are in using TPSes and also find that a small number of TPSes are critical for a large fraction of WSes.

#### 4.1 Robustness of WSes

**Observation 1:** Third-party services and content are widely used – 76.7% WSes use one or more TPS infrastructure providers and 90.7% of WS entail loading third-party content from other WSes.

| TPSes                   | Percentage of WSes |
|-------------------------|--------------------|
| Ad services             | 62.1               |
| Analytics               | 55                 |
| Overall Third-party     | 90.7               |
| resources               |                    |
| Third-party infrastructure | 76.7             |

**Table 2: Prevalence of TPSes in the top 100k WSes**

Next, we look in greater depth at the specific infrastructure services such as DNS, CDN, and OCSP as they
can have key security implications for the correctness and availability of a given WS.

**Observation 2:** Out of top 100k WSes, 58% use TPS DNS. 96.6% of these WSes are fragile as they have an exclusive dependency on a Third party DNS provider. This constitutes 55.6% of the top 100k WSes.

We begin by analyzing the robustness of WSes in their use of TPS for DNS. For instance, Twitter and Spotify both relied on Dyn for hosting authoritative name services.

For DNS, robustness means that a WS should not have exclusive dependency on any single DNS provider because in case of an attack or any other kind of failure, these will be affected as compared to the ones who use multiple providers.

Figure 4 shows the fraction of WSes that have an exclusive dependency on a single TPS DNS provider. We observed that out of the top 100K sites, 58% WSes used third party DNS providers. 96.6% of them are not robust and have an exclusive dependency on one TPS DNS. We also observe that this percentage fragility of WSes varies across the different popularity rank ranges. WSes that are more popular are marginally more likely to be robust compared to the ones that are less popular. For instance, in the top 100, 33 WSes in total use third party DNS and 50% of them are fragile.

This observation shows that most WSes today do not use TPSes in a robust manner. We also looked at the Dyn incident to analyze the reaction of WSes to the whole incident. Table 3 shows the number of WSes that used Dyn before and after the impact. It can be seen that the prevalent behavior among WSes was to not change anything. However, we see some cases where WSes became robust by having a secondary DNS provider. We also found that the WSes that left, 73% of these went to other TPSes and only 5 of these left Dyn and joined two other TPSes DNS providers. A total of 5 WSes that left shifted to having their own private DNS among the top 10k WSes. We revisit this in Section 6 when we elaborate on recommendations for different stakeholders.

**Observation 3:** Out of the 49.2% WSes which support HTTPS, 96% use TPS OCSPs and roughly 20% use OCSP stapling to lessen this dependency.

An important component of the HTTPS workflow is the use of OCSP or CRL servers to check the validity of the certificate. As observed elsewhere [33, 10], this step can add non-trivial latency to the TLS handshakes and there are several ongoing efforts to speed this protocol [33].

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**Figure 4:** The percentage of WSes that use a TPS DNS provider and are fragile since they exclusively depend on one DNS provider. We plot data for different WSes rank ranges (top 100, top 100,000). More popular WSes (51.5% top 100), are more robust than the less popular ones (96.60%, top 100K).

| Total No. of WSes before | 100 | 1000 | 483 |
|--------------------------|-----|------|-----|
| Total No. of robust WSes before | 11  | 41   | 151 |
| No. of WSes affected     | 8   | 62   | 332 |
| WSes that left           | 3   | 10   | 50  |
| WSes that left and shifted to private | 0   | 1    | 4   |
| WSes that became robust  | 3   | 21   | 74  |
| WSes that did nothing    | 2   | 31   | 208 |

Table 3: The table shows how WSes reacted to the Dyn incident in the top 100, 1000 and 10,000 WSes.

Out of the set of top 100k WSes we analyzed, roughly half (49.2%) support HTTPS. These numbers are consistent with recent reports on the increased adoption of HTTPS. Of this set of WSes that are HTTPS-enabled, almost all of them (96%) rely on TPSes for OCSP.

Now, one well-known approach for a WS to be robust and remove this third party dependency is to use OCSP Stapling [9]. OCSP Stapling effectively allows the WS to bear the resource cost involved in providing OCSP responses by appending a time-stamped OCSP response signed by the CA to the initial TLS handshake, thus eliminating the need for clients to contact the CA.

However, unlike OCSP and CRLs which involve the CA, to support OCSP WS administrators have to enable it. Unfortunately, as we see in Figure 5 only a small fraction of the WSes use OCSP Stapling and are thus...
exposed to potential RoQ and RoS attacks.

Observation 4: 30% of WSes use CDNs, 96.7% of these use TPS CDNs, and 93% of these, have an exclusive dependency on one CDN provider.

Robustness in case of a CDN is similar to that of a DNS provider. A WS should ideally not have an exclusive dependency on one particular CDN. While one CDN might offer 100% uptime, choosing more than one CDN means having a fallback in case of an outage because traffic will get rerouted to the other CDN.

We analyzed the top 100,000 WSes, and observe that roughly 30% of these use some form of CDN, either private (e.g., large providers like Google or Netflix often run their own CDN infrastructure) or TPS CDN services. The vast majority of WSes (96.7%) that use CDNs rely on TPSes, which is unsurprising given the massive infrastructure and management costs associated with operating CDNs. Of these, we find that 93% of them are not robust as shown in figure 6. Similar to DNS, this degree of robustness varies across ranks with more popular WSes being more robust.

Implications We observe that when we combine the sets of WSes that are exclusively dependent on either TPS CDN, OCSP or DNS provider, we get 73.14% of WSes that have a single point of failure. The above observations on the exclusive dependencies on TPSes has key implications for the RoQ, RoS, and DoS attacks we considered in Section 2. For instance, the fragility in $WS \rightarrow DNS$ dependency has key implications for DoS and RoQ for the users as we have seen with the Dyn incident, and 55.6% of WSes are vulnerable to this. The non-robust use of CAs, $WS \rightarrow OCSP$ leads to threats like RoS and RoQ as observed in prior work [33] and 85.2% of WSes that support HTTPS are vulnerable to these kind of attacks. Finally, the exclusive dependency on a single third party CDN $WS \rightarrow CDNs$ can leads to threats like DoS and RoQ and 93.3% of WSes that use CDNs are vulnerable to this. In general, we find that a majority (73.14%) of the top 100k WSes are prone to attacks. In such a scenario, a common dependency among these fragile WSes can cause huge damage.

4.2 Concentration in Third-party services

The previous analysis shows that a large fraction of WSes are not robust in their use of TPSes. Now, what it does not show is whether a large fraction of these WSes rely on the same subset of TPSes or if there is a substantial diversity in this pattern. In this section, we focus on the concentration behavior where a small number of TPSes predominantly offer these services. This type of concentration and the clustering does not bode well as these TPSes become good targets for attacks that can effectively impact a large number of WSes (e.g., Dyn attack took down a large number of popular services).

Observation 5: Top 10 TPS DNS providers cover 37.8% of the top 100k WSes.

Figure 8 shows the fraction of WSes covered by the top-K DNS for different WS popularity ranges. For clarity of presentation, the figure only considers the coverage by analyzing the exclusive dependences of WSes on a
Figure 7: The figure shows dependency graph of top 100k WSes and their DNS providers. The size of DNS provider node is proportional to the number of websites using them. It can be seen that Cloudflare is the major provider for the top 100k WSes.

In total, we observed 21,419 DNS providers in total for our set of WSes. We do see a long-tailed behavior, where 19,650 served less than 5 WSes. However, among the remaining 1769 providers, we see that a small number of providers cover almost 50% of the WSes as seen in Figure 8.

Among these TPS DNS providers, we see that Cloudflare is the major provider and covers almost 17% of the total 100k WSes. However, within the top 100 websites, AWS DNS which is Amazon route 53 DNS service and Dyn are the dominant ones. Furthermore, the contribution of AWS DNS is almost the same across all ranks of WSes. This ranking might be important because more popular WSes carry more traffic and hence can do more damage.

Observation 6: Top 10 TPS CA cover 94.3% of the WSes that support HTTPS. This constitutes 46% of the top 100k WSes.

Figure 8: The figure shows percentage contribution of top 10 DNS providers for different rank ranges (100,100k). The graph only includes exclusive dependency on a particular provider. Websites that use multiple providers are shown as "Multiple". It can be seen that top 10 DNS providers constitute almost 38% of the total WSes.

Figure 9: The figure shows dependency graph of top 100,000 websites and their OCSP providers. The size of OCSP provider node is proportional to the number of websites using them. It can be seen that Comodo is the major CA among all 100k WSes.

Figure 10 shows the percentage distribution of CAs that host OCSP servers for top k websites. In our measurements, we found that the WS $\rightarrow$ CA dependency is always exclusive. In total, we observed 69 unique OCSP servers for our set of WSes. However, from the figure we can see that out of these, just 7 services cover more than 90% of the WSes across each rank range. Among these 7 services, Symantec, GeoTrust, Digicert are the dominant providers across all rank ranges. Interestingly, Comodo which is the most popular service in the overall set, only serves a small number of WSes in top 100. This behavior is similar to Cloudflare in DNS providers. Investigating this further, we found that most of these (88%) of these WSes actually use Cloudflare as their DNS and CDN.
which suggests a hidden correlation as well.

**Observation 7:** Top 10 TPS CDN providers cover 86.4% of the WSes that use CDNs. This constitutes 25.3% of the top 100k WSes.

**Implications** At first glance, the web ecosystem may appear decentralized with a low barrier of entry. However, the reality is that a handful of TPS providers serve most of the popular WSes. As we observed, in case DNS, top 10 providers cover 37.8% of the top 100k WSes. Similarly top 10 CDN providers cover 25.3% of them while top 10 OCSP servers cover 46% of the total 100k WSes. This situation is a bit alarming, considering almost 50% of the top 100k WSes being managed by just 10 providers. Consequently, if these providers are under attack or there is some kind of misconfiguration at their end, then a huge part of the web ecosystem will likely be unavailable or function incorrectly. In fact, these are the high profile targets that attackers (e.g., the Mirai botnet) may consider (and likely already do) as potential targets for future attack campaigns. The top 10 CDNs and DNS might be very food targets for RoQ and DoS attacks. Similarly, top 10 OCSP providers, will be a very good target for RoS and RoQ attacks, particularly if the aim of the attacker is to maximize the total damage caused.

5 Analyzing Transitive Dependencies

During the Dyn incident, many WSes went down. For many of these, the downtime was directly attributed to Dyn; i.e., the ones that had a direct dependency on Dyn. A perhaps less prominent observation was that a few key CDNs, such as Fastly, also were unreachable and consequently any WS that used Fastly was therefore also down. The reason for this was that Fastly was using Dyn, and thus there was an indirect dependency of WSes that

![Figure 10: The figure shows percentage contribution of top 10 CAs that host OCSP servers for WSes in various rank ranges (100,100k). It can be seen that top 10 major providers cover almost 95% of the total HTTPS-enabled WSes.](image)

![Figure 11: The figure shows dependency graph of top 100,000 websites and CDN providers. The size of CDN node is proportional to the number of websites using them. It can be seen that Cloudflare and Akamai are among the two major providers.](image)

![Figure 12: The figure shows percentage contribution of top 10 TPS CDNs for WSes in various rank ranges (100,100k). It can be seen that top 10 major providers cover almost 86% of the total WSes that use CDNs.](image)
used Fastly, on Dyn [5].

Motivated by this observation, we now systematically study the extent of these indirect, potentially “hidden”, and transitive dependencies. To do so, we again focus on the three key TPSes: DNS, CDN, and OCSP, and determine how many of the popular services from each of these categories are dependent on each other (e.g. OCSP \rightarrow DNS, OCSP \rightarrow CDN, etc). We then do a what-if analysis on the potential impact of these indirect dependencies and which TPSes are most critical in case of an attack. We also study how the landscape changes when we consider both indirect and direct dependencies, as compared to direct dependencies alone.

We consider three different kinds of intra-TPS dependencies: OCSP \rightarrow CDN, OCSP \rightarrow DNS and CDN \rightarrow DNS[2] To get this data, we use the same approach that we used for WSES. To find the DNS used by CDNs, we look at the custom CNAMEs set by each CDN for various WSES and from that we extract the CDN domain to perform dig queries on it. Similarly to find the DNS of OCSP servers, we extract the OCSP URL from the certificate and perform dig queries on the host. Furthermore, for finding CDNs used by OCSP servers, we check CNAME for the hosts extracted from the OCSP URL and use the same approach as mentioned in Section [3] We now consider each of them separately. Note that as before, for each of the indirect dependencies, we mark the TPS that another TPS depends on as not robust if it is an exclusive dependency.

### 5.1 Robustness of TPSes

| Dependency         | Total TPS Dependencies | Fragile |
|--------------------|------------------------|---------|
| CDN \rightarrow DNS | 19                     | 16      |
| OCSP \rightarrow DNS | 34                     | 29      |
| OCSP \rightarrow CDN | 18                     | 18      |

Table 4: The table shows for each dependency, the number of provider dependent on TPS provider and the number of fragile provider among them.

Observation 8: 40.4% of CDNs and 49% of OCSP services use a TPS DNS provider. 85% of these CDNs and OCSP services are not robust. Similarly, 33.3% of OCSP providers use a TPS CDN, and 100% of these OCSP services are not robust.

Table [4] provides a summary of our results analyzing these intra-TPS dependencies discussed above.

CDN \rightarrow DNS dependency: CDNs typically have their own DNS infrastructure so that they have more control over where customer traffic gets routed to. However, we found that this was not quite the case. Out of a total 47 observed CDN providers, 19 (40.4%) actually use a TPS, of which 16 (84.2%) are exclusively dependent on a single DNS provider. The two top DNS providers for CDNs are AWS-DNS and Dyn, with AWS DNS serving 9 CDNs. (These CDNs do not provide services to a significant amount of WSES and are not among the major providers.)

OCSP \rightarrow DNS dependency: Out of 69 OCSP providers, 34 of them (49%) use TPS DNS providers, of which 29 (85.2%) were exclusively dependent on a single provider, and thus are not robust. Interestingly, five of these OCSP providers that are not robust rank within the top-10 most used OCSP service providers and are used by 34% of the WSES that support HTTPS.

OCSP \rightarrow CDN dependency: We observed that many CAs host OCSP servers on CDNs for performance gain. Out of the 69 OCSP providers, 18 of them (26.1%) use TPS CDN providers, of which all 18 were exclusive dependencies (100%). 5 of these are among the top 10 OCSP providers and cover 35.3% of the total WSES that support HTTPS.

Implications This is a surprising result that many of these TPSes are themselves interdependent and moreover have non-robust dependencies. This suggests that WSES who rely on these non-robust TPSes may need to take additional safeguards; e.g., either adding a layer of redundancy themselves or switching to other more robust TPSes.

### 5.2 Impact of transitive dependencies

We looked into the transitive dependencies induced by intra-dependency of TPSes. Specifically, we consider four types of transitive dependencies: (1) WSES \rightarrow OCSP \rightarrow DNS; (2) WSES \rightarrow OCSP \rightarrow CDN; (3) WSES \rightarrow CDN \rightarrow DNS; and (4) OCSP \rightarrow CDN \rightarrow DNS. Next, we characterize the impact of such transitive dependencies on the popular WSES.

Observation 9: With indirect dependencies, 37.2% of the top 100,000 WSES are now dependent on just the top-10 CDN providers. Similarly, due to indirect dependencies 56.4% of the top 100,000 WSES are now dependent on the top-10 DNS providers.

Based on these transitive dependencies, next we characterize how the top 100,000 WSES were affected in terms of their robustness. Due to indirect dependencies, 37.6% of the top 100,000 WSES are now dependent on the top-10 CDN providers. In contrast, when considering direct

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[2] The other dependencies do not make sense in practice and naturally do not manifest in the real world.
dependencies only, all CDN providers collectively covered only 30% of the top 100,000 WSes. Note that now, in addition to the direct dependency, a WS can be dependent on a particular CDN provider, via an OCSP.

Similarly, due to indirect dependencies 56.4% of the top 100,000 WSes are now dependent on the top-10 DNS providers. In comparison, 58% of the top 100,000 websites were directly dependent on all third party DNS providers. In other words, with transitive dependencies a significant portion of the most popular websites become dependent on relatively few DNS and CDN service providers, increasing the concentration effects we saw earlier in Section 4.

Figure 13: The figure shows the overall dependency graph of top 100,000 WSes on various TPSes. The size of each node is proportional to their collateral damage. The weight of each edge is proportional to the collateral damage of the source node. The graph also shows intra-TPS dependencies. It can be seen that Akamai DNS, Comodo CA etc are among the major TPS providers.

Observation 10: Transitive dependencies can amplify the total damage caused by a TPS provider and the structure of the top 10 highest impact TPS DNS and CDNs changes when we consider transitive dependencies.

Figure 14 represents a weighted graph showing the transitive relation among various TPSes and WSes, where the edge weights are proportional to the in-degree of the source node (thicker lines means higher weight). The size of each node in the graph is proportional to the number of WSes dependent on them. We next consider each service DNS, CDN and CA and show that transitive dependencies amplify the collateral damage caused by each provider.

Figure 14 shows the top 10 DNS providers after considering indirect dependencies. It also shows their respective impact with only direct dependencies. The x-axis shows the total number of WSes affected. There are two interesting observations from the figure. First, some DNS providers almost have little to no direct effect on their failure but have significant transitive impact; e.g., Verisign DNS and Fastly DNS. These providers would not even show up in the most popular DNS providers if only direct dependencies with WSes were considered. Second, for almost all of these top DNS providers, the transitive impact on them being unavailable affects significantly more WSes than those that directly depend on them. For example, Cloudflare would adversely affect 20.32% WSes when including indirect impact, as compared to 16% WS directly. Similarly, Akamai directly affects 1.3% of WSes. However, with indirect dependency, it can affect 18% of the total WSes which is more than 10X amplification.

Figure 15 similarly compares the number of WSes affected for the top 10 CDN providers, with and without considering transitive dependencies. Similar to the case for third party DNS providers, if some providers (e.g. Akamai and Cloudflare) went down they would adversely affect significantly more WSes indirectly. Akamai being unavailable would affect 15% of WSes when including indirect impact, as compared to 4.5%

Implications We conjecture that some of these providers that are not in the top-k for direct dependencies but appear in the top-k coverage via indirect dependencies are likely less provisioned. This has key implications from an attack perspective as the attackers in the future may be able to have the same volume of impact with significantly fewer resources. This also points to a natural direction for future work—we need to explore the capacity and hosting footprint of these services in greater depth. Also, this information is useful if an attacker wants to amplify a particular kind of attack, for example, consider if the attacker’s goal is to do an RoS attack while maximizing damage, then the attacker could attack an indirect link on which many OCSPs depend etc.

Observation 11: Targeting low-ranked WSes can cause a collateral damage of upto 20% to the top 100k WSes

Finally, we consider a form of collateral damage that could result due to indirect dependencies. Specifically, we consider the collateral damage can be defined as the number of WSes affected as a result of targeting one particular WS. That is, imagine a WS W being subject to a
Figure 14: The figure shows top 10 TPS DNSs and the number of WSes that get affected as a result of direct, direct+transitive dependencies on these providers.

Figure 15: The figure shows top 10 TPS CDNs and the number of WSes that get affected as a result of direct, direct+transitive dependencies on these providers.

DoS attack. Now, suppose this attack impacts the performance and availability of the TPS T that W uses. The impact on T in turn can cause other WSes W’ to also be indirectly impacted because of this attack. We acknowledge that this type of analysis is speculative and there are many caveats here as we assume that T does not have perfect resource isolation across its various customers. We argue that this is in fact quite plausible as not all resources (E.g., network bandwidth inside a datacenter or WAN connectivity from an exchange point) may be multiplexed and there may less-than-perfect isolation. Thus, from a defensive perspective this is a potential attack we need to consider in the future.

For this analysis, we consider the six different attack vectors to attack a WS: three of these arise as a result of direct dependency of WSes on CDNs, DNS and OCSP servers. The other three arise as a result of dependencies among TPSes, and hence, a WS can attacked from an indirect link as well.

Note that since there are a few major TPSes, the collateral damage of all WSes dependent on a particular provider will be same. We calculate the collateral damage associated with all the top 100k WSes, across all the six attack vectors and find the maximum collateral damage associated with each WS. Then we rank these WSes based on their collateral damage. We observed that maximum collateral damage associated with a WS to be 20% of the top 100k WSes. In order to understand, the rank distribution among these WSes, that cause a given collateral damage, we divide top 100k WSes into 10 groups of range 10,000 WSes as shown in figure 16 and see for a given collateral damage, let’s say 20%, how many WSes fall in a particular range group. It can be seen from the graph that roughly 1500 WSes in the rank range of 90k-100k can cause a collateral damage of 20% to the top 100k WSes. The graph shows this trend for the five maximum %age collateral damage observed.

Implications This is important from the WS point of view. Some popular WSes may not want to be co-dependent on a TPS provider, with some low-ranked or highly susceptible to be targeted WSes for instance, in the past there have been attacks on gambling sites [13]. This information can help WSes in making business decisions with robustness in mind.

6 Discussion and Recommendations

Based on our observations and analysis, we discuss key recommendations for different stakeholders.

Web services: The first and obvious recommendation for WSes is that they need to build in more resilience and redundancy when using TPSes. In fact, we already see this happening to some effect as a result of the Dyn incident (see Table 3). A second, and perhaps more sub-
tle recommendation is that WSes may need to analyze the hidden dependencies of the TPSes they use as they maybe indirectly exposed to potential threats. For instance, the types of analysis we have performed can be made available as a neutral service that WSes can query before making business decisions.

Third party services: TPSes (e.g., like Dyn) should be more transparent about the types of attacks they see and also about the potential redundancies they have in place to tackle large-scale attacks. Furthermore, TPSes should also be judicious in how they rely on other TPSes since the transitive dependencies can significantly impact a large fraction of WSes.

Attackers: On the negative side, our findings also have key implications for future attack strategies. The simplest observation is that the attackers can use these results and measurement techniques as a form of reconnaissance to inform their future targets to maximize their return-on-investment. For instance, the attackers may induce a larger impact by attacking less-provisioned TPSes rather than directly attacking well-provisioned WSes. Furthermore, attackers may launch indirect attacks by targeting seemingly unrelated TPSes to create indirect DoS and RoQ attacks for targets of interest. Such indirect attacks may be hard to debug and diagnose and for WSes to defend against since they may not have any direct contractual relationships with the impacted TPSes.

7 Related Work

Our study is related to a rich literature of measurements of the web ecosystem and the Internet infrastructure. However, there is surprisingly little or no systematic analysis of the fragility of the web ecosystem with respect to the TPSes and types of direct and indirect dependencies we report here.

Website complexity and performance: There are several prior works that have analyzed the widespread use of third-party content in popular websites. Butkiewicz et al., study the impact of the complexity of the website as measured in terms of the number of objects and number of third-party objects on the website load time (e.g., [15]). Other work systematically analyzes the critical paths to understand if and how specific content impacts the page load time (e.g., [31]). These are related to a potential RoQ attack; however, our focus is on the infrastructure services at a higher level than individual websites. Other work focuses on the privacy implications of the tracking services that appear on the website (e.g., [31][27][25]). The focus on privacy implications is orthogonal to our work.

Dependency measurement in distributed systems: There are a number of other efforts to understand the dependencies in distributed systems in order to help with performance debugging and diagnosis (e.g., [28]). This type of related work is complementary to our work since they focus on the intra-hosting and internal dependencies rather than the external facing dependencies on third-party services.

Understanding CDN and hosting: Given the large footprint and popular use of CDNs and hosting services, there have been a number of measurement studies to understand CDNs as early as 2001 [26]. For instance, recent work analyzes the hosting infrastructure of popular websites [14]. Other work maps the growing infrastructure and edge deployment by popular content providers (e.g., [17]). Such analysis can complement our analysis especially as we do not consider the hosting infrastructure and capacity bottlenecks of these popular services. This is a natural direction for future work to extend our analysis. Other recent work points out an increasing adoption of DDoS protection services by WSes [23].

Internet-wide measurement: In addition to web measurement, there is also a broader interest in understanding Internet infrastructure. For instance, Zmap [20] and Censys [19] present mechanisms to scan the Internet to understand the open and vulnerable services. Our focus on web infrastructure is complementary to this work.

TLS and certificate measurements: Other work has analyzed the use of TLS, the certificate ecosystem, and the use of Certificate Revocation in the wild (e.g., [18][34][29]). These suggest potential RoS attacks that could be executed via the TPSes we analyze here.

8 Conclusions

This paper was motivated by the recent Dyn incident that led to several popular web services being offline as a result of a DoS attack on the DNS provider. This motivated us to look at the broader landscape of the robustness of modern web services, the dependencies they have on third-party services, as well as more hidden and transitive dependencies via these third-party services. Our analysis paints a somewhat bleak situation on the state of modern web ecosystem: (1) most webservices have little to no redundancy when using third-party infrastructure services (e.g., CDN, DNS, CAs); (2) a small number of thirdparty services could become the Achilles’ heel for the web ecosystem; and (3) considering transitive dependencies can further exacerbate the attack surface and also suggest more opportunities to affect the quality, availability, and security of popular webservices. These observations have key implications and can lead to concrete and actionable recommendation for different stakeholders (i.e.,
attacker, web services, and third-party services). For instance, web and third-party services should understand their effective attack surface via direct and indirect dependencies and build sufficient levels of redundancy, while attackers can leverage these insights to optimally choose targets for maximizing their future impact.

References

[1] Alexa rank a thorough examination. [http://netberry.co.uk/alexa-rank-explained.htm](http://netberry.co.uk/alexa-rank-explained.htm)
[2] Alexa, www.alexa.com. [http://www.alexa.com/](http://www.alexa.com/)
[3] dig: dns lookup utility, howpublished = [https://linux.die.net/man/1/dig](https://linux.die.net/man/1/dig); DNS lookup utility - Linux man page.
[4] Dyn analysis summary of friday october 21 attack. [http://dyn.com/blog/dyn-analysis-summary-of-friday-october-21-attack/](http://dyn.com/blog/dyn-analysis-summary-of-friday-october-21-attack/)
[5] Fastly outage. [https://www.fastly.com/security-advisories](https://www.fastly.com/security-advisories)
[6] Globalsign certificate revocation issue. [https://www.globalsign.com/en/customer-revocation-error/](https://www.globalsign.com/en/customer-revocation-error/)
[7] How are alexa’s traffic rankings determined? [https://support.alexa.com/hc/en-us/articles/200449744-How-are-Alexa-s-traffic-rankings-determined](https://support.alexa.com/hc/en-us/articles/200449744-How-are-Alexa-s-traffic-rankings-determined)
[8] Public dns, google developers. [https://developers.google.com/speed/public-dns/](https://developers.google.com/speed/public-dns/)
[9] Rfc 6961. [https://www.ietf.org/rfc/rfc6961.txt](https://www.ietf.org/rfc/rfc6961.txt)
[10] TLS has exactly one performance problem: it is not used widely enough. [https://istlsfastyet.com/](https://istlsfastyet.com/)
[11] What it takes to be a top 100 website (charts). [http://royal.pingdom.com/2010/07/05/what-it-takes-to-be-a-top-100-website-charts/](http://royal.pingdom.com/2010/07/05/what-it-takes-to-be-a-top-100-website-charts/)
[12] 30 highly reliable free dns hosting services to point a domain to vps. [http://www.servermom.org/free-dns-hosting/](http://www.servermom.org/free-dns-hosting/)
[13] The growing threat of ddos attacks upon gambling sites. [https://www.goldsecurity.com/the-growing-threat-of-ddos-attacks-upon-gambling-sites/](https://www.goldsecurity.com/the-growing-threat-of-ddos-attacks-upon-gambling-sites/)
[14] AGER, B., MAIJHLBAUER, W., SMARAGDAKIS, G., AND UHLIG, S. Web content cartography. In Proc. IMC (2011).
[15] BUTKIEWICZ, M., MADHYASTHA, H. V., AND SEKAR, V. Understanding website complexity: measurements, metrics, and implications. In Proceedings of the 2011 ACM SIGCOMM conference on Internet measurement conference (2011), ACM, pp. 313–328.
[16] BUTKIEWICZ, M., WANG, D., WU, Z., AND MADHYASTHA, H. V. Klotski: Reprioritizing web content to improve user experience on mobile devices.
[17] CALDER, M., FAN, X., HU, Z., GOVINDAN, R., HEIDEMANN, J., AND KATZ-BASSETT, E. Mapping the expansion of google’s serving infrastructure. In Proc. ACM Internet Measurement Conference (IMC) (2013).
[18] CHUNG, T., LIU, Y., CHOFFNES, D., LEVIN, D., MAGGS, B., MISLOVE, A., AND WILSON, C. Measuring and Applying Invalid SSL Certificates: The Silent Majority. In Proc. IMC (2016).
[19] DURUMERIC, Z., ADRIAN, D., MIRIAN, A., BAILEY, M., AND HALDERMAN, J. A. A search engine backed by internet-wide scanning. In Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security (2015), ACM, pp. 542–553.
[20] DURUMERIC, Z., WUSTROW, E., AND HALDERMAN, J. A. Zmap: Fast internet-wide scanning and its security applications. In Usenix Security (2013), vol. 2013.
[21] GRAHAM-CUMMING, J. How and why the leap second affected cloudflare dns. [https://blog.cloudflare.com/how-and-why-the-leap-second-affected-cloudflare-dns](https://blog.cloudflare.com/how-and-why-the-leap-second-affected-cloudflare-dns)
[22] GUIRGUIS, M., BESTAVROS, A., MATTIA, I., AND ZHANG, Y. Reduction of quality (roq) attacks on internet end-systems. In IN-FOCOM 2005. 24th Annual Joint Conference of the IEEE Com-puter and Communications Societies. Proceedings IEEE (2005), vol. 2, IEEE, pp. 1362–1372.
[23] JONKER, M., SPEROTTO, A., VAN RIJSWIJK-DEIJ, R., SADRE, R., AND PRAS, A. Measuring the adoption of ddos protection services. In Proceedings of the 2016 ACM on Internet Measurement Conference (2016).
[24] KANG, M. S., LEE, S. B., AND GLIGOR, V. D. The crossfire attack. In Security and Privacy (SP), 2013 IEEE Symposium on (2013), IEEE, pp. 127–141.
[25] KRISHNAMURTHY, B., AND WILLIS, C. E. Privacy diffusion on the web: A longitudinal perspective. In Proc. WWW (2009).
[26] KRISHNAMURTHY, B., WILLIS, C. E., AND ZHANG, Y. On the use and performance of content distribution networks. In Proc. IMW (2001).
[27] LERNER, A., SIMPSON, A. K., KOHNO, T., AND ROESNER, F. Internet Jones and the Raiders of the Lost Trackers: An Archaeological Study of Web Tracking from 1996 to 2016. In Proc. 25th USENIX Security Symposium, August 2016 (2016).
[28] LI, Z., ZHANG, M., ZHU, Z., GREENBERG, Y. C., A., AND WANG, Y.-M. Webprophet: Automating performance prediction for web services. In Proc. NSDI, 2010 (2010).
[29] LIU, Y., TOME, W., ZHANG, L., CHOFFNES, D., LEVIN, D., MAGGS, B., MISLOVE, A., SCHULMAN, A., AND WILSON, C. An End-to-End Measurement of Certificate Revocation in the Web’s PKI. In Proc. IMC (2015).
[30] PRINCE, M. Cloudflare today’s outage post mortem. [https://blog.cloudflare.com/todays-outage-post-mortem-82515/](https://blog.cloudflare.com/todays-outage-post-mortem-82515/)
[31] ROESNER, F., KOHNO, T., AND WETHERALL, D. Detecting and defending against third-party tracking on the web. In Proceedings of the 9th USENIX conference on Networked Systems Design and Implementation (2012), USENIX Association, pp. 12–12.
[32] SCHNEIDER, B. Someone Is Learning How to Take Down the Internet. [https://www.schneier.com/blog/archives/2016/09/someone_is_lear.html](https://www.schneier.com/blog/archives/2016/09/someone_is_lear.html)
[33] STARK, E., HUANG, L.-S., ISIRANI, D., JACKSON, C., AND BONEH, D. The case for prefetching and prevalidating tls server certificates. In NDSS (2012).
[34] VANDERSLOOT, B., AMANN, J., BERNHARD, M., DURUMERIC, Z., BAILEY, M., AND HALDERMAN, J. A. Towards a Complete View of the Certificate Ecosystem. In Proc. IMC (2016).
[35] WANG, X. S., BALASUBRAMANIAN, A., KRISHNAMURTHY, A., AND WETHERALL, D. Demystify page load performance with wprof. In Proc. of the USENIX conference on Networked Systems Design and Implementation (NSDI) (2013).
[36] WPO-FOUNDATION. Wpo-foundation/webpagetest.
https://github.com/WPO-Foundation/webpagetest/
blob/master/agent/wpthook/cdn.h