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Problems with the Public Key Infrastructure (PKI) for the World Wide Web

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Abstract

This document describes the technical and non-technical problems with the current Public Key Infrastructure (PKI) used for the World Wide Web. Some potential technical improvements are considered, and some non-technical approaches to improvements are discussed.

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Table of Contents

1. Introduction 2
2. Very Brief Description of the Web PKI 2
3. Technical Improvements to the Web PKI 3
3.1. Weak Cryptographic Algorithms or Short Public Keys . . . 3
3.2. Certificate Status Checking 4
3.2.1. Short-lived Certificates 5
3.2.2. CRL Distribution Points 5
3.2.3. Proprietary Revocation Checks 5
3.2.4. OCSP Stapling 5
3.3. Surprising Certificates 6
3.3.1. Certificate Authority Authorization (CAA) 7
3.3.2. HTTP Public Key Pinning (HPKP) 8
3.3.3. HTTP Strict Transport Security (HSTS) 8
3.3.4. DNS-Based Authentication of Named Entities (DANE) . . 9
3.3.5. Certificate Transparency 10
3.4. Automation for Server Administrators 10
4. Policy and Process Improvements to the Web PKI 11
4.1. Determination of the Trusted Certificate Authorities . . 11
4.2. Governance Structures for the Web PKI 12
5. Other Considerations for Improving the Web PKI 13
6. Security Considerations 13
7. IANA Considerations 13
8. References 13
8.1. Normative References 13
8.2. Informative References 13
Appendix A. Acknowledgements 16
Appendix B. IAB Members at the Time of Approval 16
Authors' Addresses 16

1. Introduction

There are many technical and non-technical problems with the current Public Key Infrastructure (PKI) used for the World Wide Web. This document describes these problems, considers some potential technical improvements, and discusses some non-technical approaches to improvements.

The Web PKI makes use of certificates as described in RFC 5280 [RFC5280]. These certificates are primarily used with Transport Layer Security (TLS) RFC 5246 [RFC5246].

2. Very Brief Description of the Web PKI

Certificates are specified in [RFC5280]. Certificates contain, among other things, a subject name and a public key, and they are digitally signed by the Certification Authority (CA). Certificate users

require confidence that the private key associated with the certified public key is owned by the named subject. A certificate has a limited valid lifetime.

The architectural model used in the Web PKI includes:

EE: End Entity -- the subject of a certificate -- certificates are issued to Web Servers, and certificates are also issued to clients that need mutual authentication.

CA: Certification Authority -- the issuer of a certificate -- issues certificates for Web Servers and clients.

RA: Registration Authority -- an optional system to which a CA delegates some management functions such as identity validation or physical credential distribution.

CAs are responsible for indicating the revocation status of the certificates that they issue throughout the lifetime of the certificate. Revocation status information may be provided using the Online Certificate Status Protocol (OCSP) [RFC2560], certificate revocation lists (CRLs) [RFC5280], or some other mechanism. In general, when revocation status information is provided using CRLs, the CA is also the CRL issuer. However, a CA may delegate the responsibility for issuing CRLs to a different entity.

The enrollment process used by a CA makes sure that the subject name in the certificate is appropriate and that the subject actually holds the private key. Proof of possession of the private key is often accomplished through a challenge-response protocol.

3. Technical Improvements to the Web PKI

Over the years, many technical improvements have been made to the Web PKI. This section discusses sever problems and the technical problems that have been made to address them. This history sets the stage for suggestions for additional improvements in other sections of this document.

3.1. Weak Cryptographic Algorithms or Short Public Keys

Over the years, the digital signature algorithms, one-way hash functions, and public key sizes that are considered strong have changed. This is not a surprise. Cryptographic algorithms age; they become weaker with time. As new cryptanalysis techniques are developed and computing capabilities improve, the work factor to break a particular cryptographic algorithm will reduce. For this reason, the algorithms and key sizes used in the Web PKI need to

migrate over time. A reasonable choice of algorithm or key size needs to be evaluated periodically, and a transition may be needed before the expected lifetime expires.

The browser vendors have been trying to manage algorithm and key size transitions, but a long-lived trust anchor or intermediate CA certificate can have a huge number of subordinate certificates. So, removing a one because it uses a weak cryptographic algorithm or a short public key can have a significant impact.

As a result, some valid trust anchors and certificates contain cryptographic algorithms after weakness has been discovered and widely known. Similarly, valid trust anchors and certificates contain public keys after computational resources available to attackers have rendered them too weak. We have seen a very successful migration away from certificates that use the MD2 or MD5 one-way hash functions. However, there are still a great number of certificates that use SHA-1 and 1024-bit RSA public keys, and these should be replaced.

Today, the algorithms and key sizes used by a CA to sign certificates with a traditional lifespan should offer 112 to 128 bits of security. SHA-256 is a widely studied one-way hash function that meets this requirement. RSA with a public key of at least 2048 bits or ECDSA with a public key of at least 256 bits are widely studied digital signature algorithms that meet this requirement.

3.2. Certificate Status Checking

Several years ago, many browsers do not perform certificate status checks by default. That is, browsers did not check whether the issuing CA has revoked the certificate unless the user explicitly adjusted a setting to enable this feature. This check can be made by fetching the most recent certificate revocation list (CRL) RFC 5280 [RFC5280], or this check can use the Online Certificate Status Protocol (OCSP) RFC 6960 [RFC6960]. The location of the CRL or the OCSP responder is usually found in the certificate itself. Either one of these approaches add latency. The desire to provide a snappy user experience is a significant reason that this feature was not turned on by default.

Certificate status checking needs to be used at all times. Several techniques have been tried by CAs and browsers to make certificate status checking more efficient. Many CAs are using of Content Delivery Networks (CDNs) by CAs to deliver CRLs and OCSP responses, resulting in very high availability and low latency. Yet, browser vendors are still reluctant to perform standard-based status checking by default for every session.

3.2.1. Short-lived Certificates

Short-lived certificates are an excellent way to reduce the need for certificate status checking. The shorter the life of the certificate, the less time there is for anything to go wrong. If the lifetime is short enough, policy might allow certificate status checking can be skipped altogether. In practice, implementation of short-lived certificates requires automation to assist web server administrators, which is a topic that is discussed elsewhere in this document.

3.2.2. CRL Distribution Points

The certificate revocation list distribution point (CRLDP) certificate extension RFC 5280 [RFC5280] allows a CA to control the maximum size of the CRLs that they issue. This helps in two ways. First, the amount of storage needed by the browser to cache CRLs is reduced. Second, and more importantly, the amount of time it takes to download a CRL can be scoped, so that the amount of time needed to fetch any single CRL is reasonable.

Few CAs take advantage of the CRLDP certificate extension to limit the size of CRLs. In fact, there are several CAs that publish extremely large CRLs. Browsers never want to suffer the latency associated with large CRLs, and some ignore the CRLDP extension when it is present. Browsers tend to avoid the use of CRLs altogether.

3.2.3. Proprietary Revocation Checks

Some browser vendors provide a proprietary mechanism for revocation checking. These mechanisms obtain revocation status information once per day for the entire Web PKI in a very compact form. No network traffic is generated at the time that a certificate is being validated, so there is no latency associated with revocation status checking. The browser vendor infrastructure performs daily checks of the Web PKI, and then the results are assembled in a proprietary format and made available to the browser. These checks only cover the trust anchor store for that browser vendor, so any trust anchors added by the user cannot be checked in this manner.

3.2.4. OCSP Stapling

Browsers can avoid transmission of CRLs altogether by using the Online Certificate Status Protocol (OCSP) RFC 6960 [RFC6960] to check the validity of web server certificates. The TLS Certificate Status Request extension is defined in Section 8 of RFC 6066 [RFC6066]. In addition, RFC 6961 [RFC6961] defines the TLS Multiple Certificate Status Request extension, which allows the web server to provide

status information about its own certificate and also the status of intermediate certificates in the certification path. By including this extension in the TLS handshake, the browser asks the web server to provide an OCSP response in addition to its certificate. This approach greatly reduces the number of round trips by the browser to check the status of each certificate in the path. In addition, the web server can cache the OCSP response for a period of time, avoiding additional latency. Even in the cases where the web server needs to contact the OCSP responder, the web server usually has a higher bandwidth connection than the browser to do so.

The provision of the time-stamped OCSP response in the TLS handshake is referred to as "stapling" the OCSP response to the TLS handshake. If the browser does not receive a stapled OCSP response, it can contact the OCSP responder directly. In addition, the MUST_STAPLE feature [TLSFEATURE] can be used to insist that OCSP stapling be used.

When every browser that connects to a high volume website performs its own OCSP lookup, the OCSP responder must handle a real-time response to every browser. OCSP stapling can avoid enormous volumes of OCSP requests for certificates of popular websites, so stapling can significantly reduce the cost of providing an OCSP service.

OCSP stapling can also improve user privacy, since the web server, not the browser, contacts the OCSP responder. In this way, the OCSP responder is not able to determine which browsers are checking the validity of certificate for websites.

Many web site are taking advantage of OCSP sampling. At the time of this writing, browser venders report that about 12% the the transactions use OCSP sampling, and the number is on the rise.

3.3. Surprising Certificates

All of the CAs in the trust store are equally trusted for the entire domain name space, so any CA can issue for any domain name. In fact, there have been certificates issued by CAs that are surprising to the legitimate owner of a domain. The domain name owner is surprised because they did not request the certificates. They are initially unaware that a CA has issued a certificate that contains their domain name, and once the surprising certificate is discovered, it can be very difficult for the legitimate domain name owner to get it revoked. Further, browsers and other relying parties cannot distinguish a certificate that the legitimate domain name owner requested from an surprising one.

Since all of the CAs in the trust store are equally trusted, any CA can issue a certificate for any domain name. There are known cases where attackers have thwarted the CA protections and issued certificates that were then used to mount attacks against the users of that web site [FOXIT]. For this reason, all of the CAs listed in the trust store must be very well protected.

The Baseline Requirements produced by the CA/Browser Forum [CAB2014] tell CAs the checks that need to be performed before a certificate is issued. In addition, WebTrust [WEBTRUST] provides the audit requirements for CAs, and browser vendors will remove a CA from the trust anchor store if successful audit reports are not made available.

When a CA issues a certificate to a subordinate CA, the inclusion of widely supported certificate extensions can reduce set of privileges given to the sub-CA. This aligns with the traditional security practice of least privilege, where only the privileges needed to perform the envisioned tasks are provided. However, many sub-CAs have certificates that pass along the full powers of the CA, creating additional high-pay-off targets for attackers, and these sub-CAs may not be held to the same certificate issuance requirements and audit requirement as the parent CA.

Some major implementations have not fully implemented the mechanisms necessary to reduce sub-CA privileges. For example, RFC 5280 [RFC5280] includes the specification of name constraints, and the CA/Browser Forum guidelines [CAB2014] encourage the use dNSNames in permittedSubtrees within the name Constraints extension. Despite this situation, one major browser does not support name constraints, and as a result, CAs are reluctant to use them. Further, global CAs are prepared to issue certificates within every top-level domain, including ones that are newly-approved. It is not practical for these global CAs to use name constraints in their sub-CA certificates.

As a result of procedural failures or attacks, surprising certificates are being issued. Several mechanisms have been defined to avoid the issuance of surprising certificates or prevent browsers from accepting them.

3.3.1. Certificate Authority Authorization (CAA)

The Certificate Authority Authorization (CAA) [RFC6844] DNS resource record allows a domain administrator to specify one or more CA that is authorized to issue certificates that include the domain name. Then, a trustworthy CA will refuse to issue a certificate for a

domain name that has a CAA resource record that does not explicitly name the CA.

To date, only one major CA performs this check, and there is no indication that other CAs are planning to add this check in the near future.

3.3.2. HTTP Public Key Pinning (HPKP)

HTTP Public Key Pinning (HPKP) [RFC7469] allows a web server to instruct browsers to remember the server's public key fingerprints for a period of time. The fingerprint is a one-way hash of the subject public key information in the certificate. The Public-Key-Pins header provides a maximum retention period, fingerprints of the web server certificate, and optionally fingerprints for backup certificates. The act of saving of the fingerprints is referred to as "pinning". During pin lifetime, browsers require that the same web server present a certificate chain that includes a public key that matches one of the retained fingerprints. This prevents impersonation of the website with a surprising certificate.

A website can choose to pin the CA certificate so that the browser will accept only valid certificates for the website domain that are issued by that CA. Alternatively, the website can choose to pin their own certificate and at least one backup certificate in case the current certificate needs to be replaced due to a compromised server.

Some browser vendors also pin certificates by hardcoding fingerprints of very well known websites.

When HPKP is used, browsers may be able to detect a man-in-the-middle. Sometimes the man-in-the-middle is an attacker, and other times a service provider purposefully terminates the TLS at a location other than the web server. One example became very public in February 2012 when Trustwave admitted that it had issued a subordinate CA certificate for use by a company to inspect corporate network traffic [LC2012]. When HPKP is used, the browser user will be notified if the key-pining is violated, unless the violating certificate can be validated to a locally installed trust anchor. In this situation, the browser is assuming that the user intended to explicitly trust the certificate.

3.3.3. HTTP Strict Transport Security (HSTS)

HTTP Strict Transport Security (HSTS) [RFC6797] is a security policy mechanism that protects secure websites against downgrade attacks, and it greatly simplifies protection against cookie hijacking. The presence of the Strict-Transport-Security header tells browsers that

all interactions with this web server should never use HTTP without TLS, providing protection against eavesdropping and active network attacks.

When a web server includes the Strict-Transport-Security header, the browser is expected to do two things. First, the browser automatically turns any insecure links into secure ones. For instance, "http://mysite.example.com/mypage/" will be changed to "https://mysite.example.com/mypage/". Second, if the TLS Handshake results in some failure, such as the certificate cannot be validated, then an error message is displayed and the user is denied access the web application.

3.3.4. DNS-Based Authentication of Named Entities (DANE)

The DNS-Based Authentication of Named Entities (DANE) [RFC6698] allows domain administrators to specify the raw public keys or certificates that are used by web servers in their domain. DANE leverages the DNS Security Extensions (DNSSEC) [RFC4034][RFC4035], which provides digital signatures over DNS zones that are validated with keys that are bound to the domain name of the signed zone. The keys associated with a domain name can only be signed by a key associated with the parent of that domain name. For example, the DNSSEC keys for "www.example.com" can only be signed by the DNSSEC keys for "example.com". Therefore, a malicious actor can only compromise the keys of their own subdomains. Like the Web PKI, DNSSEC relies on public keys used to validate chains of signatures, but DNSSEC has a single root domain as opposed to a multiplicity of trusted CAs.

DANE binds raw public keys or certificates to DNS names. The domain administrator is the one that vouches for the binding of the public key or the certificate to the domain name by adding the TSLA records to the zone and then signing the zone. In this way, the same administrator is responsible for managing the DNS names themselves and associated public keys or certificates with those names. DANE restricts the scope of assertions that can be made, forcing them to be consistent with the DNS naming hierarchy.

In addition, DNSSEC reduces opportunities for redirection attacks by binding the domain name to the public key or certificate.

Some Web PKI certificates are being posted in TLSA records, but browsers expect to receive the the server certificate in the TLS handshake, and there is little incentive to confirm that the received certificate matches the one posted in the DNS. For this reason, work has begun on a TLS extension that will allow the DNSSEC-protected

information to be provided in the handshake, which will eliminate the latency [TLSCHAIN].

3.3.5. Certificate Transparency

Certificate Transparency (CT) [RFC6962] offers a mechanism to detect mis-issued certificates, and once detected, administrators and CAs can take the necessary actions to revoke the mis-issued certificates.

When requesting a certificate, the administrator can request the CA to include an embedded Signed Certificate Timestamp (SCT) in the certificate to ensure that their legitimate certificate is logged with one or more CT log.

An administrator, or another party acting on behalf of the administrator, is able to monitor one or more CT log to which a pre-certificate or certificate is submitted, and detect the logging of a pre-certificate or certificate that contains their domain name. When such a pre-certificate or certificate is detected, the CA can be contacted to to get the mis-issued certificate revoked.

In the future, a browser may choose to reject certificates that do not contain an SCT, and potentially notify the website administrator or CA when they encounter such a certificate. Such reporting will help detect mis-issuance of certificates and lead to their revocation.

3.4. Automation for Server Administrators

There have been several attempts to provide automation for routine tasks that are performed by web server administrators, such as certificate renewal. For example, some commercial tools offer automated certificate renewal and installation [DCEI][SSLM]. Also, at least one proposal was brought to the IETF that allows a web server automate obtaining and renewing certificates [PHBOB]. Without automation, there are many manual steps involved in getting a certificate from a CA, and to date none of these attempts at automation have not enjoyed widespread interoperability and adoption. There are at least two ways that this impacts web security. First, many web sites do not have a certificate at all. The cost, time, and effort are too great for the system administrator to go through the effort, especially if the web site does not offer anything for purchase. Second, once a certificate is obtained, a replacement is not obtained until the current one expires. Automation can reduce the amount of time that an administrator needs to dedicate to certificate management, and it can make certificate renewal timely and automatic.

The IETF ACME working group [ACMEWG] is working on protocols that will provide system administrators an automated way to enroll and renew their certificates. The expectation is that these specifications will lead to widely available and interoperable tools for system administrators. The expectation is that these protocols and tools will be supported by all web server environments and CAs, which will greatly reduce complexity and cost.

4. Policy and Process Improvements to the Web PKI

As with many technologies, the issues and complexities associated with Web PKI use and deployment are just as much policy and process as technical. These have evolved over time as well. This section discusses the ways that business models and operational policies and processes impact the Web PKI.

4.1. Determination of the Trusted Certificate Authorities

A very basic question for users of the Web PKI is "Who do you trust?" The system for determining which CAs are added to or removed from the trust store in browsers has been perceived by some as opaque and confusing. As mentioned earlier, the CA/Browser Forum has developed baseline requirements for the management and issuance of certificates [CAB2014] for individual CAs. However, the process by which an individual CA gets added to the trust store for each of the major browsers is not straightforward. The individual browser vendors determine what should and should not be trusted by including those trusted CAs in their trust store. They do this by leveraging the AICPA/CICA WebTrust Program for Certification Authorities [WEBTRUST]. This program provides auditing requirements and a trust mark for CAs. Failure to pass an audit can result in the CA being removed from the trust store.

Once the browser has shipped, how does a user know which CAs are trusted or what has changed recently. For an informed user, information about which CAs have been added to or deleted from the browser trust store can be found in the release notes. Users can also examine the policies of the various CAs which would have been developed and posted for the WebTrust Program. However, this may be considered a fairly high barrier for the average user. There are also options to make local modifications by educated users, but there is little understanding about the implications of these choices. How does an individual, organization, or enterprise really determine if a particular CA is trustworthy? Do the default choices inherited from the browser vendors truly represent the organization's trust model? What constitutes sufficiently bad behavior by a CA to cause removal from the trust store?

One form of bad behavior by CAs is the mis-issuance of certificates. This mis-issuance can be either an honest mistake by the CA, malicious behavior by the CA, or a case where an external party has duped the CA into the mis-issuance. When a CA has delegated authority to a sub-CA, and then the sub-CA issued bad certificates either unintentionally or maliciously, the CA is able to deny responsibility for the actions of the sub-CA. However, the CA may be the only party that can revoke the sub-CA certificate to protect the overall Web PKI.

Another complication with CAs and the trust store maintained by the browser vendor is an enterprise managed PKI. For example, the US Department of Defense operates its own PKI. In this case, the enterprise maintains its own PKI for the exclusive use of the enterprise itself. A bridge CA may be used to connect related enterprises. The complication in this approach is that the revocation mechanisms don't work with any additions that have been made by the enterprise. See Section 3.2.3 on proprietary revocation checks.

What constitutes sufficiently bad behavior by a CA to cause removal from the trust store? The guidelines provided by the WebTrust program [WEBTRUST] provide a framework, but the implications of removing a CA can be significant. There may be a few very large CAs that are critical to significant portions of Internet infrastructure. Removing one of these trusted CAs can have a significant impact on a large cross section of Internet users.

4.2. Governance Structures for the Web PKI

There are a number of organizations that play significant roles in the operation of the Web PKI, including the CAB Forum, the WebTrust Program, and the browser vendors. These organizations act on behalf of the entire Internet community. Transparency in these operations is vital to basic trust in the Web PKI. As one example, in the past the CAB Forum was perceived as being a closed forum; however, some changes were made to the operational procedures to allow more visibility if not actual participation in the process [CAB1.2]. How do we ensure that these processes continue to evolve in an open, inclusive, and transparent manner? Currently, as the name implies, the CAB Forum members represent CAs and browser vendors. How do we ensure that relying parties a voice in this forum?

Since the Web PKI is widespread, applications beyond the World Wide Web are making use of the Web PKI. For example, the Web PKI is used to secure the connections between SMTP servers. In these environments, the browser-centric capabilities are unavailable. For example, see Section 3.2.3 on proprietary revocation checks. The

current governance structure does not provide a way for these other applications to participate. How do we ensure that these other applications get a voice in this forum?

5. Other Considerations for Improving the Web PKI

Other factors impact the usability and reliability of the Web PKI. One factor is time synchronization. As time synchronization infrastructure is made more secure, this infrastrucre will require the use of certificates to authenticate time servers. However, certificate infrastructure is reliant on quality time synchronization as well, creating a boot strapping issue.

6. Security Considerations

Many people find browser error messages related to certificates confusing. Good man-machine interfaces are always difficult, but in this situation users are unable to understand the risks that they are accepting by clicking "okay". This aspect of browser usability needs to be improved for users to make better security choices.

7. IANA Considerations

None.

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Appendix A. Acknowledgements

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Appendix B. IAB Members at the Time of Approval

{{{ RFC Editor: Please add the names to the IAB members at the time that this document is put into the RFC Editor queue. }}}

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