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L. Nordberg
NORDUnet
D. Gillmor
ACLU
T. Ritter

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Gossiping in CT
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Abstract

The logs in Certificate Transparency are untrusted in the sense that the users of the system don't have to trust that they behave correctly since the behavior of a log can be verified to be correct.

This document tries to solve the problem with logs presenting a "split view" of their operations. It describes three gossiping mechanisms for Certificate Transparency: SCT Feedback, STH Pollination and Trusted Auditor Relationship.

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1. Introduction

The purpose of the protocols in this document, collectively referred to as CT Gossip, is to detect certain misbehavior by CT logs. In particular, CT Gossip aims to detect logs that are providing inconsistent views to different log clients, and logs failing to include submitted certificates within the time period stipulated by MMD.

One of the major challenges of any gossip protocol is limiting damage to user privacy. The goal of CT gossip is to publish and distribute information about the logs and their operations, but not to expose any additional information about the operation of any of the other participants. Privacy of consumers of log information (in particular, of web browsers and other TLS clients) should not be undermined by gossip.

This document presents three different, complementary mechanisms for non-log elements of the CT ecosystem to exchange information about

logs in a manner that preserves the privacy of HTTPS clients. They should provide protective benefits for the system as a whole even if their adoption is not universal.

2. Defining the problem

When a log provides different views of the log to different clients this is described as a partitioning attack. Each client would be able to verify the append-only nature of the log but, in the extreme case, each client might see a unique view of the log.

The CT logs are public, append-only and untrusted and thus have to be audited for consistency, i.e., they should never rewrite history. Additionally, auditors and other log clients need to exchange information about logs in order to be able to detect a partitioning attack (as described above).

Gossiping about log behavior helps address the problem of detecting malicious or compromised logs with respect to a partitioning attack. We want some side of the partitioned tree, and ideally both sides, to see the other side.

Disseminating information about a log poses a potential threat to the privacy of end users. Some data of interest (e.g. SCTs) is linkable to specific log entries and thereby to specific websites, which makes sharing them with others a privacy concern. Gossiping about this data has to take privacy considerations into account in order not to expose associations between users of the log (e.g., web browsers) and certificate holders (e.g., web sites). Even sharing STHs (which do not link to specific log entries) can be problematic - user tracking by fingerprinting through rare STHs is one potential attack (see Section 8.2).

3. Overview

This document presents three gossiping mechanisms: SCT Feedback, STH Pollination, and a Trusted Auditor Relationship.

SCT Feedback enables HTTPS clients to share Signed Certificate Timestamps (SCTs) (Section 3.3 of [RFC-6962-BIS-09]) with CT auditors in a privacy-preserving manner by sending SCTs to originating HTTPS servers, who in turn share them with CT auditors.

In STH Pollination, HTTPS clients use HTTPS servers as pools to share Signed Tree Heads (STHs) (Section 3.6 of [RFC-6962-BIS-09]) with other connecting clients in the hope that STHs will find their way to CT auditors.

HTTPS clients in a Trusted Auditor Relationship share SCTs and STHs with trusted CT auditors directly, with expectations of privacy sensitive data being handled according to whatever privacy policy is agreed on between client and trusted party.

Despite the privacy risks with sharing SCTs there is no loss in privacy if a client sends SCTs for a given site to the site corresponding to the SCT. This is because the site's logs would already indicate that the client is accessing that site. In this way a site can accumulate records of SCTs that have been issued by various logs for that site, providing a consolidated repository of SCTs that could be shared with auditors. Auditors can use this information to detect a misbehaving log that fails to include a certificate within the time period stipulated by its MMD metadata.

Sharing an STH is considered reasonably safe from a privacy perspective as long as the same STH is shared by a large number of other log clients. This safety in numbers can be achieved by only allowing gossiping of STHs issued in a certain window of time, while also refusing to gossip about STHs from logs with too high an STH issuance frequency (see Section 8.2).

4. Terminology

This document relies on terminology and data structures defined in [RFC-6962-BIS-09], including MMD, STH, SCT, Version, LogID, SCT timestamp, CtExtensions, SCT signature, Merkle Tree Hash.

This document relies on terminology defined in [draft-ietf-trans-threat-analysis-03], including Auditing.

4.1. Pre-Loaded vs Locally Added Anchors

Through the document, we refer to both Trust Anchors (Certificate Authorities) and Logs. Both Logs and Trust Anchors may be locally added by an administrator. Unless otherwise clarified, in both cases we refer to the set of Trust Anchors and Logs that come pre-loaded and pre-trusted in a piece of client software.

5. Who gossips with whom

- HTTPS clients and servers (SCT Feedback and STH Pollination)
- HTTPS servers and CT auditors (SCT Feedback and STH Pollination)
- CT auditors (Trusted Auditor Relationship)

Additionally, some HTTPS clients may engage with an auditor who they trust with their privacy:

- HTTPS clients and CT auditors (Trusted Auditor Relationship)

6. What to gossip about and how

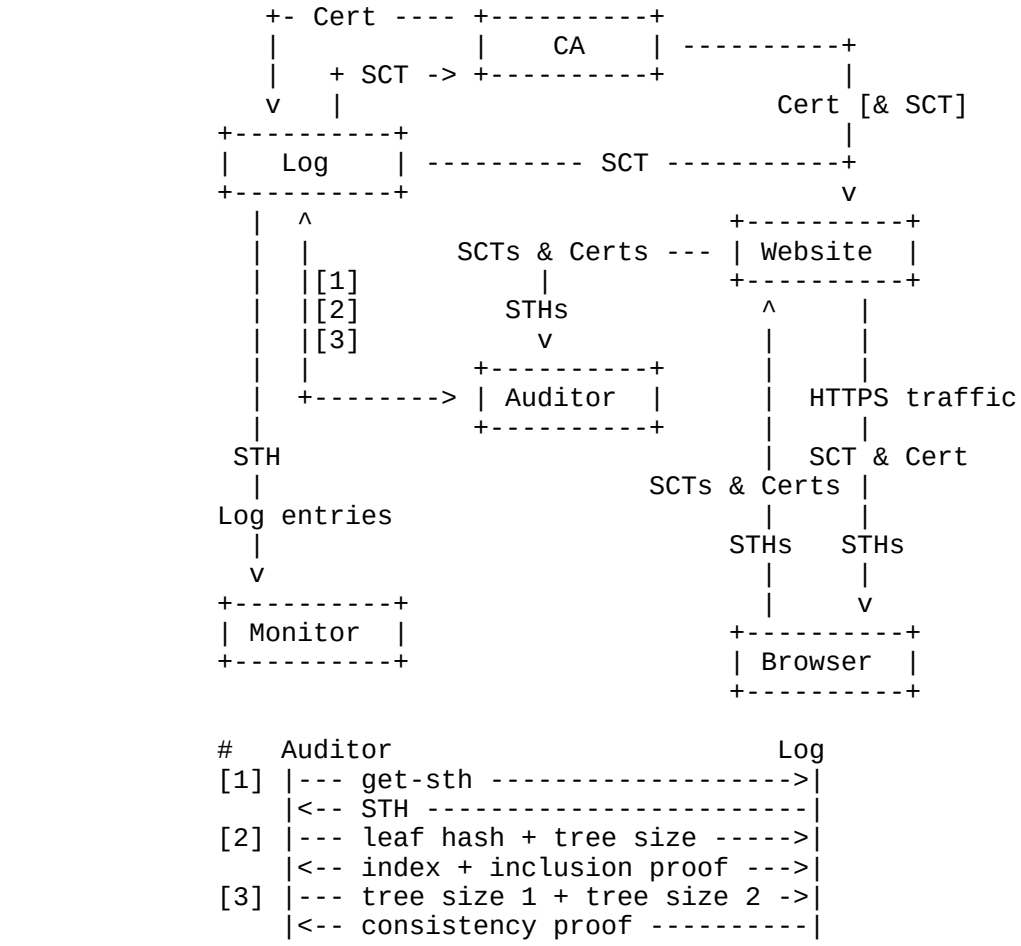
There are three separate gossip streams:

- SCT Feedback - transporting SCTs and certificate chains from HTTPS clients to CT auditors via HTTPS servers.
- STH Pollination - HTTPS clients and CT auditors using HTTPS servers as STH pools for exchanging STHs.
- Trusted Auditor Stream - HTTPS clients communicating directly with trusted CT auditors sharing SCTs, certificate chains and STHs.

It is worthwhile to note that when an HTTPS client or CT auditor interacts with a log, they may equivalently interact with a log mirror or cache that replicates the log.

7. Data flow

The following picture shows how certificates, SCTs and STHs flow through a CT system with SCT Feedback and STH Pollination. It does not show what goes in the Trusted Auditor Relationship stream.



8. Gossip Mechanisms

8.1. SCT Feedback

The goal of SCT Feedback is for clients to share SCTs and certificate chains with CT auditors while still preserving the privacy of the end user. The sharing of SCTs contribute to the overall goal of detecting misbehaving logs by providing auditors with SCTs from many vantage points, making it more likely to catch a violation of a log's MMD or a log presenting inconsistent views. The sharing of certificate chains is beneficial to HTTPS server operators interested in direct feedback from clients for detecting bogus certificates issued in their name and therefore incentivizes server operators to take part in SCT Feedback.

SCT Feedback is the most privacy-preserving gossip mechanism, as it does not directly expose any links between an end user and the sites they've visited to any third party.

HTTPS clients store SCTs and certificate chains they see, and later send them to the originating HTTPS server by posting them to a well-known URL (associated with that server), as described in Section 8.1.2. Note that clients will send the same SCTs and chains to a server multiple times with the assumption that any man-in-the-middle attack eventually will cease, and an honest server will eventually receive collected malicious SCTs and certificate chains.

HTTPS servers store SCTs and certificate chains received from clients, as described in Section 8.1.3. They later share them with CT auditors by either posting them to auditors or making them available via a well-known URL. This is described in Section 8.1.4.

8.1.1. SCT Feedback data format

The data shared between HTTPS clients and servers, as well as between HTTPS servers and CT auditors, is a JSON array [RFC7159]. Each item in the array is a JSON object with the following content:

- x509_chain: An array of PEM-encoded X.509 certificates. The first element is the end-entity certificate, the second certifies the first and so on.

- sct_data: An array of objects consisting of the base64 representation of the binary SCT data as defined in [RFC-6962-BIS-09] Section 3.3.

We will refer to this object as 'sct_feedback'.

The x509_chain element always contains a full chain from a leaf certificate to a self-signed trust anchor.

See Section 8.1.2 for details on what the sct_data element contains as well as more details about the x509_chain element.

8.1.2. HTTPS client to server

When an HTTPS client connects to an HTTPS server, the client receives a set of SCTs as part of the TLS handshake. SCTs are included in the TLS handshake using one or more of the three mechanisms described in [RFC-6962-BIS-09] section 3.4 - in the server certificate, in a TLS extension, or in an OCSP extension. The client MUST discard SCTs that are not signed by a log known to the client and SHOULD store the remaining SCTs together with a locally constructed certificate chain

which is trusted (i.e. terminated in a pre-loaded or locally installed Trust Anchor) in an sct_feedback object or equivalent data structure for later use in SCT Feedback.

The SCTs stored on the client MUST be keyed by the exact domain name the client contacted. They MUST NOT be sent to any domain not matching the original domain (e.g. if the original domain is sub.example.com they must not be sent to sub.sub.example.com or to example.com.) They MUST NOT be sent to any Subject Alternate Names specified in the certificate. In the case of certificates that validate multiple domain names, the same SCT is expected to be stored multiple times.

Not following these constraints would increase the risk for two types of privacy breaches. First, the HTTPS server receiving the SCT would learn about other sites visited by the HTTPS client. Second, auditors receiving SCTs from the HTTPS server would learn information about other HTTPS servers visited by its clients.

If the client later again connects to the same HTTPS server, it again receives a set of SCTs and calculates a certificate chain, and again creates an sct_feedback or similar object. If this object does not exactly match an existing object in the store, then the client MUST add this new object to the store, associated with the exact domain name contacted, as described above. An exact comparison is needed to ensure that attacks involving alternate chains are detected. An example of such an attack is described in [dual-ca-compromise-attack]. However, at least one optimization is safe and MAY be performed: If the certificate chain exactly matches an existing certificate chain, the client MAY store the union of the SCTs from the two objects in the first (existing) object.

If the client does connect to the same HTTPS server a subsequent time, it MUST send to the server sct_feedback objects in the store that are associated with that domain name. However, it is not necessary to send an sct_feedback object constructed from the current TLS session, and if the client does so, it MUST NOT be marked as sent in any internal tracking done by the client.

Refer to Section 11.3 for recommendations for implementation.

Because SCTs can be used as a tracking mechanism (see Section 10.5.2), they deserve special treatment when they are received from (and provided to) domains that are loaded as subresources from an origin domain. Such domains are commonly called ’third party domains’. An HTTPS client SHOULD store SCT Feedback using a ’double-keying’ approach, which isolates third party domains by the first party domain. This is described in [double-keying].

Gossip would be performed normally for third party domains only when the user revisits the first party domain. In lieu of 'double-keying', an HTTPS client MAY treat SCT Feedback in the same manner it treats other security mechanisms that can enable tracking (such as HSTS and HPKP.)

If the HTTPS client has configuration options for not sending cookies to third parties, SCTs of third parties MUST be treated as cookies with respect to this setting. This prevents third party tracking through the use of SCTs/certificates, which would bypass the cookie policy. For domains that are only loaded as third party domains, the client may never perform SCT Feedback; however the client may perform STH Pollination after fetching an inclusion proof, as specified in Section 8.2.

SCTs and corresponding certificates are POSTed to the originating HTTPS server at the well-known URL:

https://<domain>/.well-known/ct-gossip/v1/sct-feedback

The data sent in the POST is defined in Section 8.1.1. This data SHOULD be sent in an already-established TLS session. This makes it hard for an attacker to disrupt SCT Feedback without also disturbing ordinary secure browsing (https://). This is discussed more in Section 11.1.1.

The HTTPS server SHOULD respond with an HTTP 200 response code and an empty body if it was able to process the request. An HTTPS client who receives any other response SHOULD consider it an error.

Some clients have trust anchors or logs that are locally added (e.g. by an administrator or by the user themselves). These additions are potentially privacy-sensitive because they can carry information about the specific configuration, computer, or user.

Certificates validated by locally added trust anchors will commonly have no SCTs associated with them, so in this case no action is needed with respect to CT Gossip. SCTs issued by locally added logs MUST NOT be reported via SCT Feedback.

If a certificate is validated by SCTs that are issued by publicly trusted logs, but chains to a local trust anchor, the client MAY perform SCT Feedback for this SCT and certificate chain bundle. If it does so, the client MUST include the full chain of certificates chaining to the local trust anchor in the x509_chain array. Performing SCT Feedback in this scenario may be advantageous for the broader internet and CT ecosystem, but may also disclose information about the client. If the client elects to omit SCT Feedback, it can

choose to perform STH Pollination after fetching an inclusion proof, as specified in Section 8.2.

We require the client to send the full chain (or nothing at all) for two reasons. Firstly, it simplifies the operation on the server if there are not two code paths. Secondly, omitting the chain does not actually preserve user privacy. The Issuer field in the certificate describes the signing certificate. And if the certificate is being submitted at all, it means the certificate is logged, and has SCTs. This means that the Issuer can be queried and obtained from the log, so omitting the signing certificate from the client's submission does not actually help user privacy.

8.1.3. HTTPS server operation

HTTPS servers can be configured (or omit configuration), resulting in, broadly, two modes of operation. In the simpler mode, the server will only track leaf certificates and SCTs applicable to those leaf certificates. In the more complex mode, the server will confirm the client's chain validation and store the certificate chain. The latter mode requires more configuration, but is necessary to prevent denial of service (DoS) attacks on the server's storage space.

In the simple mode of operation, upon receiving a submission at the sct-feedback well-known URL, an HTTPS server will perform a set of operations, checking on each sct_feedback object before storing it:

1. the HTTPS server MAY modify the sct_feedback object, and discard all items in the x509_chain array except the first item (which is the end-entity certificate)

2. if a bit-wise compare of the sct_feedback object matches one already in the store, this sct_feedback object SHOULD be discarded

3. if the leaf cert is not for a domain for which the server is authoritative, the SCT MUST be discarded

4. if an SCT in the sct_data array can't be verified to be a valid SCT for the accompanying leaf cert, and issued by a known log, the individual SCT SHOULD be discarded

The modification in step number 1 is necessary to prevent a malicious client from exhausting the server's storage space. A client can generate their own issuing certificate authorities, and create an arbitrary number of chains that terminate in an end-entity certificate with an existing SCT. By discarding all but the end-entity certificate, we prevent a simple HTTPS server from storing

this data. Note that operation in this mode will not prevent the attack described in [dual-ca-compromise-attack]. Skipping this step requires additional configuration as described below.

The check in step 2 is for detecting duplicates and minimizing processing and storage by the server. As on the client, an exact comparison is needed to ensure that attacks involving alternate chains are detected. Again, at least one optimization is safe and MAY be performed. If the certificate chain exactly matches an existing certificate chain, the server MAY store the union of the SCTs from the two objects in the first (existing) object. If the validity check on any of the SCTs fails, the server SHOULD NOT store the union of the SCTs.

The check in step 3 is to help malfunctioning clients from exposing which sites they visit. It additionally helps prevent DoS attacks on the server.

[Note: Thinking about building this, how does the SCT Feedback app know which sites it's authoritative for? It will need that amount of configuration at least.]

The check in step 4 is to prevent DoS attacks where an adversary fills up the store prior to attacking a client (thus preventing the client's feedback from being recorded), or an attack where an adversary simply attempts to fill up server's storage space.

The above describes the simpler mode of operation. In the more advanced server mode, the server will detect the attack described in [dual-ca-compromise-attack]. In this configuration the server will not modify the sct_feedback object prior to performing checks 2, 3, and 4.

To prevent a malicious client from filling the server's data store, the HTTPS server SHOULD perform an additional check in the more advanced mode:

- if the x509_chain consists of an invalid certificate chain, or the culminating trust anchor is not recognized by the server, the server SHOULD modify the sct_feedback object, discarding all items in the x509_chain array except the first item

The HTTPS server MAY choose to omit checks 4 or 5. This will place the server at risk of having its data store filled up by invalid data, but can also allow a server to identify interesting certificate or certificate chains that omit valid SCTs, or do not chain to a trusted root. This information may enable an HTTPS server operator

to detect attacks or unusual behavior of Certificate Authorities even outside the Certificate Transparency ecosystem.

8.1.4. HTTPS server to auditors

HTTPS servers receiving SCTs from clients SHOULD share SCTs and certificate chains with CT auditors by either serving them on the well-known URL:

https://<domain>/.well-known/ct-gossip/v1/collected-sct-feedback

or by HTTPS POSTing them to a set of preconfigured auditors. This allows an HTTPS server to choose between an active push model or a passive pull model.

The data received in a GET of the well-known URL or sent in the POST is defined in Section 8.1.1 with the following difference: The x509_chain element may contain only he end-entity certificate, as described below.

HTTPS servers SHOULD share all sct_feedback objects they see that pass the checks in Section 8.1.3. If this is an infeasible amount of data, the server MAY choose to expire submissions according to an undefined policy. Suggestions for such a policy can be found in Section 11.3.

HTTPS servers MUST NOT share any other data that they may learn from the submission of SCT Feedback by HTTPS clients, like the HTTPS client IP address or the time of submission.

As described above, HTTPS servers can be configured (or omit configuration), resulting in two modes of operation. In one mode, the x509_chain array will contain a full certificate chain. This chain may terminate in a trust anchor the auditor may recognize, or it may not. (One scenario where this could occur is if the client submitted a chain terminating in a locally added trust anchor, and the server kept this chain.) In the other mode, the x509_chain array will consist of only a single element, which is the end-entity certificate.

Auditors SHOULD provide the following URL accepting HTTPS POSTing of SCT feedback data:

https://<auditor>/ct-gossip/v1/sct-feedback

Auditors SHOULD regularly poll HTTPS servers at the well-known collected-sct-feedback URL. The frequency of the polling and how to determine which domains to poll is outside the scope of this

document. However, the selection MUST NOT be influenced by potential HTTPS clients connecting directly to the auditor. For example, if a poll to example.com occurs directly after a client submits an SCT for example.com, an adversary observing the auditor can trivially conclude the activity of the client.

8.2. STH pollination

The goal of sharing Signed Tree Heads (STHs) through pollination is to share STHs between HTTPS clients and CT auditors while still preserving the privacy of the end user. The sharing of STHs contribute to the overall goal of detecting misbehaving logs by providing CT auditors with STHs from many vantage points, making it possible to detect logs that are presenting inconsistent views.

HTTPS servers supporting the protocol act as STH pools. HTTPS clients and CT auditors in the possession of STHs can pollinate STH pools by sending STHs to them, and retrieving new STHs to send to other STH pools. CT auditors can improve the value of their auditing by retrieving STHs from pools.

HTTPS clients send STHs to HTTPS servers by POSTing them to the well-known URL:

https://<domain>/.well-known/ct-gossip/v1/sth-pollination

The data sent in the POST is defined in Section 8.2.4. This data SHOULD be sent in an already established TLS session. This makes it hard for an attacker to disrupt STH gossiping without also disturbing ordinary secure browsing (https://). This is discussed more in Section 11.1.1.

On a successful connection to an HTTPS server implementing STH Pollination, the response code will be 200, and the response body is application/json, containing zero or more STHs in the same format, as described in Section 8.2.4.

An HTTPS client may acquire STHs by several methods:

- in replies to pollination POSTs;
- asking logs that it recognizes for the current STH, either directly (v2/get-sth) or indirectly (for example over DNS)
- resolving an SCT and certificate to an STH via an inclusion proof
- resolving one STH to another via a consistency proof

HTTPS clients (that have STHs) and CT auditors SHOULD pollinate STH pools with STHs. Which STHs to send and how often pollination should happen is regarded as undefined policy with the exception of privacy concerns explained below. Suggestions for the policy can be found in Section 11.3.

An HTTPS client could be tracked by giving it a unique or rare STH. To address this concern, we place restrictions on different components of the system to ensure an STH will not be rare.

- HTTPS clients silently ignore STHs from logs with an STH issuance frequency of more than one STH per hour. Logs use the STH Frequency Count metadata to express this ([RFC-6962-BIS-09] sections 3.6 and 5.1).

- HTTPS clients silently ignore STHs which are not fresh.

An STH is considered fresh iff its timestamp is less than 14 days in the past. Given a maximum STH issuance rate of one per hour, an attacker has 336 unique STHs per log for tracking. Clients MUST ignore STHs older than 14 days. We consider STHs within this validity window not to be personally identifiable data, and STHs outside this window to be personally identifiable.

When multiplied by the number of logs from which a client accepts STHs, this number of unique STHs grow and the negative privacy implications grow with it. It’s important that this is taken into account when logs are chosen for default settings in HTTPS clients. This concern is discussed upon in Section 10.5.5.

A log may cease operation, in which case there will soon be no STH within the validity window. Clients SHOULD perform all three methods of gossip about a log that has ceased operation since it is possible the log was still compromised and gossip can detect that. STH Pollination is the one mechanism where a client must know about a log shutdown. A client who does not know about a log shutdown MUST NOT attempt any heuristic to detect a shutdown. Instead the client MUST be informed about the shutdown from a verifiable source (e.g. a software update). The client SHOULD be provided the final STH issued by the log and SHOULD resolve SCTs and STHs to this final STH. If an SCT or STH cannot be resolved to the final STH, clients SHOULD follow the requirements and recommendations set forth in Section 11.1.2.

8.2.1. HTTPS Clients and Proof Fetching

There are two types of proofs a client may retrieve; inclusion proofs and consistency proofs.

An HTTPS client will retrieve SCTs together with certificate chains from an HTTPS server. Using the timestamp in the SCT together with the end-entity certificate and the issuer key hash, it can obtain an inclusion proof to an STH in order to verify the promise made by the SCT.

An HTTPS client will have STHs from performing STH Pollination, and may obtain a consistency proof to a more recent STH.

An HTTPS client may also receive an SCT bundled with an inclusion proof to a historical STH via an unspecified future mechanism. Because this historical STH is considered personally identifiable information per above, the client needs to obtain a consistency proof to a more recent STH.

A client SHOULD perform proof fetching. A client MUST NOT perform proof fetching for any SCTs or STHs issued by a locally added log. A client MAY fetch an inclusion proof for an SCT (issued by a pre-loaded log) that validates a certificate chaining to a locally added trust anchor.

If a client requested either proof directly from a log or auditor, it would reveal the client’s browsing habits to a third party. To mitigate this risk, an HTTPS client MUST retrieve the proof in a manner that disguises the client.

Depending on the client’s DNS provider, DNS may provide an appropriate intermediate layer that obfuscates the linkability between the user of the client and the request for inclusion (while at the same time providing a caching layer for oft-requested inclusion proofs). See [draft-ct-over-dns] for an example of how this can be done.

Anonymity networks such as Tor also present a mechanism for a client to anonymously retrieve a proof from an auditor or log.

Even when using a privacy-preserving layer between the client and the log, certain observations may be made about an anonymous client or general user behavior depending on how proofs are fetched. For example, if a client fetched all outstanding proofs at once, a log would know that SCTs or STHs received around the same time are more likely to come from a particular client. This could potentially go so far as correlation of activity at different times to a single client. In aggregate the data could reveal what sites are commonly visited together. HTTPS clients SHOULD use a strategy of proof fetching that attempts to obfuscate these patterns. A suggestion of such a policy can be found in Section 11.2.

Resolving either SCTs and STHs may result in errors. These errors may be routine downtime or other transient errors, or they may be indicative of an attack. Clients SHOULD follow the requirements and recommendations set forth in Section 11.1.2 when handling these errors in order to give the CT ecosystem the greatest chance of detecting and responding to a compromise.

8.2.2. STH Pollination without Proof Fetching

An HTTPS client MAY participate in STH Pollination without fetching proofs. In this situation, the client receives STHs from a server, applies the same validation logic to them (signed by a known log, within the validity window) and will later pass them to another HTTPS server.

When operating in this fashion, the HTTPS client is promoting gossip for Certificate Transparency, but derives no direct benefit itself. In comparison, a client who resolves SCTs or historical STHs to recent STHs and pollinates them is assured that if it was attacked, there is a probability that the ecosystem will detect and respond to the attack (by distrusting the log).

8.2.3. Auditor Action

CT auditors participate in STH pollination by retrieving STHs from HTTPS servers. They verify that the STH is valid by checking the signature, and requesting a consistency proof from the STH to the most recent STH.

After retrieving the consistency proof to the most recent STH, they SHOULD pollinate this new STH among participating HTTPS servers. In this way, as STHs "age out" and are no longer fresh, their "lineage" continues to be tracked in the system.

8.2.4. STH Pollination data format

The data sent from HTTPS clients and CT auditors to HTTPS servers is a JSON object [RFC7159] with the following content:

- sths - an array of 0 or more fresh SignedTreeHeads as defined in [RFC-6962-BIS-09] Section 3.6.1.

8.3. Trusted Auditor Stream

HTTPS clients MAY send SCTs and cert chains, as well as STHs, directly to auditors. If sent, this data MAY include data that reflects locally added logs or trust anchors. Note that there are

privacy implications in doing so, these are outlined in Section 10.5.1 and Section 10.5.6.

The most natural trusted auditor arrangement arguably is a web browser that is "logged in to" a provider of various internet services. Another equivalent arrangement is a trusted party like a corporation to which an employee is connected through a VPN or by other similar means. A third might be individuals or smaller groups of people running their own services. In such a setting, retrieving proofs from that third party could be considered reasonable from a privacy perspective. The HTTPS client may also do its own auditing and might additionally share SCTs and STHs with the trusted party to contribute to herd immunity. Here, the ordinary [RFC-6962-BIS-09] protocol is sufficient for the client to do the auditing while SCT Feedback and STH Pollination can be used in whole or in parts for the gossip part.

Another well established trusted party arrangement on the internet today is the relation between internet users and their providers of DNS resolver services. DNS resolvers are typically provided by the internet service provider (ISP) used, which by the nature of name resolving already know a great deal about which sites their users visit. As mentioned in Section 8.2.1, in order for HTTPS clients to be able to retrieve proofs in a privacy preserving manner, logs could expose a DNS interface in addition to the ordinary HTTPS interface. A specification of such a protocol can be found in [draft-ct-over-dns].

8.3.1. Trusted Auditor data format

Trusted Auditors expose a REST API at the fixed URI:

https://<auditor>/ct-gossip/v1/trusted-auditor

Submissions are made by sending an HTTPS POST request, with the body of the POST in a JSON object. Upon successful receipt the Trusted Auditor returns 200 OK.

The JSON object consists of two top-level keys: ’sct_feedback’ and ’sths’. The ’sct_feedback’ value is an array of JSON objects as defined in Section 8.1.1. The ’sths’ value is an array of STHs as defined in Section 8.2.4.

Example:

```
{
  'sct_feedback' :
    [
      {
        'x509_chain' :
          [
            '----BEGIN CERTIFICATE---\n
             AAA...',
            '----BEGIN CERTIFICATE---\n
             AAA...',
             ...
          ],
        'sct_data' :
          [
            'AAA...',
            'AAA...',
            ...
          ]
      }, ...
    ],
  'sths' :
    [
      'AAA...',
      'AAA...',
      ...
    ]
}
```

9. 3-Method Ecosystem

The use of three distinct methods for auditing logs may seem excessive, but each represents a needed component in the CT ecosystem. To understand why, the drawbacks of each component must be outlined. In this discussion we assume that an attacker knows which mechanisms an HTTPS client and HTTPS server implement.

9.1. SCT Feedback

SCT Feedback requires the cooperation of HTTPS clients and more importantly HTTPS servers. Although SCT Feedback does require a significant amount of server-side logic to respond to the corresponding APIs, this functionality does not require customization, so it may be pre-provided and work out of the box. However, to take full advantage of the system, an HTTPS server would wish to perform some configuration to optimize its operation:

- Minimize its disk commitment by maintaining a list of known SCTs and certificate chains (or hashes thereof)

- Maximize its chance of detecting a misissued certificate by configuring a trust store of CAs
- Establish a "push" mechanism for POSTing SCTs to CT auditors

These configuration needs, and the simple fact that it would require some deployment of software, means that some percentage of HTTPS servers will not deploy SCT Feedback.

It is worthwhile to note that an attacker may be able to prevent detection of an attack on a webserver (in all cases) if SCT Feedback is not implemented. This attack is detailed in Section 10.1).

If SCT Feedback was the only mechanism in the ecosystem, any server that did not implement the feature would open itself and its users to attack without any possibility of detection.

If SCT Feedback is not deployed by a webserver, malicious logs will be able to attack all users of the webserver (who do not have a Trusted Auditor relationship) with impunity. Additionally, users who wish to have the strongest measure of privacy protection (by disabling STH Pollination Proof Fetching and forgoing a Trusted Auditor) could be attacked without risk of detection.

9.2. STH Pollination

STH Pollination requires the cooperation of HTTPS clients, HTTPS servers, and logs.

For a client to fully participate in STH Pollination, and have this mechanism detect attacks against it, the client must have a way to safely perform Proof Fetching in a privacy preserving manner. (The client may pollinate STHs it receives without performing Proof Fetching, but we do not consider this option in this section.)

HTTPS servers must deploy software (although, as in the case with SCT Feedback this logic can be pre-provided) and commit some configurable amount of disk space to the endeavor.

Logs (or a third party mirroring the logs) must provide access to clients to query proofs in a privacy preserving manner, most likely through DNS.

Unlike SCT Feedback, the STH Pollination mechanism is not hampered if only a minority of HTTPS servers deploy it. However, it makes an assumption that an HTTPS client performs Proof Fetching (such as the DNS mechanism discussed). Unfortunately, any manner that is

anonymous for some (such as clients who use shared DNS services such as a large ISP), may not be anonymous for others.

For instance, DNS requests expose a considerable amount of sensitive information (including what data is already present in the cache) in plaintext over the network. For this reason, some percentage of HTTPS clients may choose to not enable the Proof Fetching component of STH Pollination. (Although they can still request and send STHs among participating HTTPS servers, even when this affords them no direct benefit.)

If STH Pollination was the only mechanism deployed, users that disable it would be able to be attacked without risk of detection.

If STH Pollination was not deployed, HTTPS clients visiting HTTPS Servers who did not deploy SCT Feedback could be attacked without risk of detection.

9.3. Trusted Auditor Relationship

The Trusted Auditor Relationship is expected to be the rarest gossip mechanism, as an HTTPS client is providing an unadulterated report of its browsing history to a third party. While there are valid and common reasons for doing so, there is no appropriate way to enter into this relationship without retrieving informed consent from the user.

However, the Trusted Auditor Relationship mechanism still provides value to a class of HTTPS clients. For example, web crawlers have no concept of a "user" and no expectation of privacy. Organizations already performing network auditing for anomalies or attacks can run their own Trusted Auditor for the same purpose with marginal increase in privacy concerns.

The ability to change one’s Trusted Auditor is a form of Trust Agility that allows a user to choose who to trust, and be able to revise that decision later without consequence. A Trusted Auditor connection can be made more confidential than DNS (through the use of TLS), and can even be made (somewhat) anonymous through the use of anonymity services such as Tor. (Note that this does ignore the de-anonymization possibilities available from viewing a user’s browsing history.)

If the Trusted Auditor relationship was the only mechanism deployed, users who do not enable it (the majority) would be able to be attacked without risk of detection.

If the Trusted Auditor relationship was not deployed, crawlers and organizations would build it themselves for their own needs. By standardizing it, users who wish to opt-in (for instance those unwilling to participate fully in STH Pollination) can have an interoperable standard they can use to choose and change their trusted auditor.

9.4. Interaction

The interactions of the mechanisms is thus outlined:

HTTPS clients can be attacked without risk of detection if they do not participate in any of the three mechanisms.

HTTPS clients are afforded the greatest chance of detecting an attack when they either participate in both SCT Feedback and STH Pollination with Proof Fetching or if they have a Trusted Auditor relationship. (Participating in SCT Feedback is required to prevent a malicious log from refusing to ever resolve an SCT to an STH, as put forward in Section 10.1). Additionally, participating in SCT Feedback enables an HTTPS client to assist in detecting the exact target of an attack.

HTTPS servers that omit SCT Feedback enable malicious logs to carry out attacks without risk of detection. If these servers are targeted specifically, even if the attack is detected, without SCT Feedback they may never learn that they were specifically targeted. HTTPS servers without SCT Feedback do gain some measure of herd immunity, but only because their clients participate in STH Pollination (with Proof Fetching) or have a Trusted Auditor Relationship.

When HTTPS servers omit SCT feedback, it allows their users to be attacked without detection by a malicious log; the vulnerable users are those who do not have a Trusted Auditor relationship.

10. Security considerations

10.1. Attacks by actively malicious logs

One of the most powerful attacks possible in the CT ecosystem is a trusted log that has actively decided to be malicious. It can carry out an attack in two ways:

In the first attack, the log can present a split view of the log for all time. The only way to detect this attack is to resolve each view of the log to the two most recent STHs and then force the log to present a consistency proof. (Which it cannot.) This attack can be detected by CT auditors participating in STH Pollination, as long as

they are explicitly built to handle the situation of a log continuously presenting a split view.

In the second attack, the log can sign an SCT, and refuse to ever include the certificate that the SCT refers to in the tree. (Alternately, it can include it in a branch of the tree and issue an STH, but then abandon that branch.) Whenever someone requests an inclusion proof for that SCT (or a consistency proof from that STH), the log would respond with an error, and a client may simply regard the response as a transient error. This attack can be detected using SCT Feedback, or an Auditor of Last Resort, as presented in Section 11.1.2.

10.2. Dual-CA Compromise

[dual-ca-compromise-attack] describes an attack possible by an adversary who compromises two Certificate Authorities and a Log. This attack is difficult to defend against in the CT ecosystem, and [dual-ca-compromise-attack] describes a few approaches to doing so. We note that Gossip is not intended to defend against this attack, but can in certain modes.

Defending against the Dual-CA Compromise attack requires SCT Feedback, and explicitly requires the server to save full certificate chains (described in Section 8.1.3 as the 'complex' configuration.) After CT auditors receive the full certificate chains from servers, they MAY compare the chain built by clients to the chain supplied by the log. If the chains differ significantly, the auditor SHOULD raise a concern. A method of determining if chains differ significantly is by asserting that one chain is not a subset of the other and that the roots of the chains are different.

[Note: Justification for this algorithm:

Cross-Signatures could result in a different org being treated as the 'root', but in this case, one chain would be a subset of the other.

Intermediate swapping (e.g. different signature algorithms) could result in different chains, but the root would be the same.

(Hitting both those cases at once would cause a false positive though, but this would likely be rare.)

Are there other cases that could occur? (Left for the purposes of reading during pre-Last Call, to be removed by Editor)]

10.3. Censorship/Blocking considerations

We assume a network attacker who is able to fully control the client's internet connection for some period of time, including selectively blocking requests to certain hosts and truncating TLS connections based on information observed or guessed about client behavior. In order to successfully detect log misbehavior, the gossip mechanisms must still work even in these conditions.

There are several gossip connections that can be blocked:

1. Clients sending SCTs to servers in SCT Feedback
2. Servers sending SCTs to auditors in SCT Feedback (server push mechanism)
3. Servers making SCTs available to auditors (auditor pull mechanism)
4. Clients fetching proofs in STH Pollination
5. Clients sending STHs to servers in STH Pollination
6. Servers sending STHs to clients in STH Pollination
7. Clients sending SCTs to Trusted Auditors

If a party cannot connect to another party, it can be assured that the connection did not succeed. While it may not have been maliciously blocked, it knows the transaction did not succeed. Mechanisms which result in a positive affirmation from the recipient that the transaction succeeded allow confirmation that a connection was not blocked. In this situation, the party can factor this into strategies suggested in Section 11.3 and in Section 11.1.2.

The connections that allow positive affirmation are 1, 2, 4, 5, and 7.

More insidious is blocking the connections that do not allow positive confirmation: 3 and 6. An attacker may truncate or drop a response from a server to a client, such that the server believes it has shared data with the recipient, when it has not. However, in both scenarios (3 and 6), the server cannot distinguish the client as a cooperating member of the CT ecosystem or as an attacker performing a Sybil attack, aiming to flush the server's data store. Therefore the fact that these connections can be undetectably blocked does not actually alter the threat model of servers responding to these requests. The choice of algorithm to release data is crucial to

protect against these attacks; strategies are suggested in Section 11.3.

Handling censorship and network blocking (which is indistinguishable from network error) is relegated to the implementation policy chosen by clients. Suggestions for client behavior are specified in Section 11.1.

10.4. Flushing Attacks

A flushing attack is an attempt by an adversary to flush a particular piece of data from a pool. In the CT Gossip ecosystem, an attacker may have performed an attack and left evidence of a compromised log on a client or server. They would be interested in flushing that data, i.e. tricking the target into gossiping or pollinating the incriminating evidence with only attacker-controlled clients or servers with the hope they trick the target into deleting it.

Flushing attacks may be defended against differently depending on the entity (HTTPS client or HTTPS server) and record (STHs or SCTs with Certificate Chains).

10.4.1. STHs

For both HTTPS clients and HTTPS servers, STHs within the validity window SHOULD NOT be deleted. An attacker cannot flush an item from the cache if it is never removed so flushing attacks are completely mitigated.

The required disk space for all STHs within the validity window is 336 STHs per log that is trusted. If 20 logs are trusted, and each STH takes 1 Kilobytes, this is 6.56 Megabytes.

Note that it is important that implementors do not calculate the exact size of cache expected - if an attack does occur, a small number of additional STHs will enter into the cache. These STHs will be in addition to the expected set, and will be evidence of the attack.

If an HTTPS client or HTTPS server is operating in a constrained environment and cannot devote enough storage space to hold all STHs within the validity window it is recommended to use the below Deletion Algorithm Section 11.3.2 to make it more difficult for the attacker to perform a flushing attack.

10.4.2. SCTs & Certificate Chains on HTTPS Servers

An HTTPS server will only accept SCTs and Certificate Chains for domains it is authoritative for. Therefore the storage space needed is bound by the number of logs it accepts, multiplied by the number of domains it is authoritative for, multiplied by the number of certificates issued for those domains.

Imagine a server authoritative for 10,000 domains, and each domain has 3 certificate chains, and 10 SCTs. A certificate chain is 5 Kilobytes in size and an SCT 1 Kilobyte. This yields 732 Megabytes.

This data can be large, but it is calculable. Web properties with more certificates and domains are more likely to be able to handle the increased storage need, while small web properties will not seen an undue burden. Therefore HTTPS servers SHOULD NOT delete SCTs or Certificate Chains. This completely mitigates flushing attacks.

Again, note that it is important that implementors do not calculate the exact size of cache expected - if an attack does occur, the new SCT(s) and Certificate Chain(s) will enter into the cache. This data will be in addition to the expected set, and will be evidence of the attack.

If an HTTPS server is operating in a constrained environment and cannot devote enough storage space to hold all SCTs and Certificate Chains it is authoritative for it is recommended to configure the SCT Feedback mechanism to allow only certain certificates that are known to be valid. These chains and SCTs can then be discarded without being stored or subsequently provided to any clients or auditors. If the allowlist is not sufficient, the below Deletion Algorithm Section 11.3.2 is recommended to make it more difficult for the attacker to perform a flushing attack.

10.4.3. SCTs & Certificate Chains on HTTPS Clients

HTTPS clients will accumulate SCTs and Certificate Chains without bound. It is expected they will choose a particular cache size and delete entries when the cache size meets its limit. This does not mitigate flushing attacks, and such an attack is documented in [gossip-mixing].

The below Deletion Algorithm Section 11.3.2 is recommended to make it more difficult for the attacker to perform a flushing attack.

10.5. Privacy considerations

CT Gossip deals with HTTPS clients which are trying to share indicators that correspond to their browsing history. The most sensitive relationships in the CT ecosystem are the relationships between HTTPS clients and HTTPS servers. Client-server relationships can be aggregated into a network graph with potentially serious implications for correlative de-anonymization of clients and relationship-mapping or clustering of servers or of clients.

There are, however, certain clients that do not require privacy protection. Examples of these clients are web crawlers or robots. But even in this case, the method by which these clients crawl the web may in fact be considered sensitive information. In general, it is better to err on the side of safety, and not assume a client is okay with giving up its privacy.

10.5.1. Privacy and SCTs

An SCT contains information that links it to a particular web site. Because the client-server relationship is sensitive, gossip between clients and servers about unrelated SCTs is risky. Therefore, a client with an SCT for a given server SHOULD NOT transmit that information in any other than the following two channels: to the server associated with the SCT itself; or to a Trusted Auditor, if one exists.

10.5.2. Privacy in SCT Feedback

SCTs introduce yet another mechanism for HTTPS servers to store state on an HTTPS client, and potentially track users. HTTPS clients which allow users to clear history or cookies associated with an origin MUST clear stored SCTs and certificate chains associated with the origin as well.

Auditors should treat all SCTs as sensitive data. SCTs received directly from an HTTPS client are especially sensitive, because the auditor is a trusted by the client to not reveal their associations with servers. Auditors MUST NOT share such SCTs in any way, including sending them to an external log, without first mixing them with multiple other SCTs learned through submissions from multiple other clients. Suggestions for mixing SCTs are presented in Section 11.3.

There is a possible fingerprinting attack where a log issues a unique SCT for targeted log client(s). A colluding log and HTTPS server operator could therefore be a threat to the privacy of an HTTPS client. Given all the other opportunities for HTTPS servers to

fingerprint clients - TLS session tickets, HPKP and HSTS headers, HTTP Cookies, etc. - this is considered acceptable.

The fingerprinting attack described above would be mitigated by a requirement that logs must use a deterministic signature scheme when signing SCTs ([RFC-6962-BIS-09] Section 2.1.4). A log signing using RSA is not required to use a deterministic signature scheme.

Since logs are allowed to issue a new SCT for a certificate already present in the log, mandating deterministic signatures does not stop this fingerprinting attack altogether. It does make the attack harder to pull off without being detected though.

There is another similar fingerprinting attack where an HTTPS server tracks a client by using a unique certificate or a variation of cert chains. The risk for this attack is accepted on the same grounds as the unique SCT attack described above.

10.5.3. Privacy for HTTPS clients performing STH Proof Fetching

An HTTPS client performing Proof Fetching SHOULD NOT request proofs from a CT log that it doesn't accept SCTs from. An HTTPS client SHOULD regularly request an STH from all logs it is willing to accept, even if it has seen no SCTs from that log.

The time between two polls for new STH's SHOULD NOT be significantly shorter than the MMD of the polled log divided by its STH Frequency Count ([RFC-6962-BIS-09] section 5.1).

The actual mechanism by which Proof Fetching is done carries considerable privacy concerns. Although out of scope for the document, DNS is a mechanism currently discussed. DNS exposes data in plaintext over the network (including what sites the user is visiting and what sites they have previously visited) and may not be suitable for some.

10.5.4. Privacy in STH Pollination

An STH linked to an HTTPS client may indicate the following about that client:

- that the client gossips;
- that the client has been using CT at least until the time that the timestamp and the tree size indicate;
- that the client is talking, possibly indirectly, to the log indicated by the tree hash;

o which software and software version is being used.

There is a possible fingerprinting attack where a log issues a unique STH for a targeted HTTPS client. This is similar to the fingerprinting attack described in Section 10.5.2, but can operate cross-origin. If a log (or HTTPS server cooperating with a log) provides a unique STH to a client, the targeted client will be the only client pollinating that STH cross-origin.

It is mitigated partially because the log is limited in the number of STHs it can issue. It must 'save' one of its STHs each MMD to perform the attack.

10.5.5. Privacy in STH Interaction

An HTTPS client may pollinate any STH within the last 14 days. An HTTPS client may also pollinate an STH for any log that it knows about. When a client pollinates STHs to a server, it will release more than one STH at a time. It is unclear if a server may 'prime' a client and be able to reliably detect the client at a later time.

It's clear that a single site can track a user any way they wish, but this attack works cross-origin and is therefore more concerning. Two independent sites A and B want to collaborate to track a user cross-origin. A feeds a client Carol some N specific STHs from the M logs Carol trusts, chosen to be older and less common, but still in the validity window. Carol visits B and chooses to release some of the STHs she has stored, according to some policy.

Modeling a representation for how common older STHs are in the pools of clients, and examining that with a given policy of how to choose which of those STHs to send to B, it should be possible to calculate statistics about how unique Carol looks when talking to B and how useful/accurate such a tracking mechanism is.

Building such a model is likely impossible without some real world data, and requires a given implementation of a policy. To combat this attack, suggestions are provided in Section 11.3 to attempt to minimize it, but follow-up testing with real world deployment to improve the policy will be required.

10.5.6. Trusted Auditors for HTTPS Clients

Some HTTPS clients may choose to use a trusted auditor. This trust relationship exposes a large amount of information about the client to the auditor. In particular, it will identify the web sites that the client has visited to the auditor. Some clients may already share this information to a third party, for example, when using a

server to synchronize browser history across devices in a server-visible way, or when doing DNS lookups through a trusted DNS resolver. For clients with such a relationship already established, sending SCTs to a trusted auditor run by the same organization does not appear to expose any additional information to the trusted third party.

Clients who wish to contact a CT auditor without associating their identities with their SCTs may wish to use an anonymizing network like Tor to submit SCT Feedback to the auditor. Auditors SHOULD accept SCT Feedback that arrives over such anonymizing networks.

Clients sending feedback to an auditor may prefer to reduce the temporal granularity of the history exposure to the auditor by caching and delaying their SCT Feedback reports. This is elaborated upon in Section 11.3. This strategy is only as effective as the granularity of the timestamps embedded in the SCTs and STHs.

10.5.7. HTTPS Clients as Auditors

Some HTTPS clients may choose to act as CT auditors themselves. A Client taking on this role needs to consider the following:

- an Auditing HTTPS client potentially exposes its history to the logs that they query. Querying the log through a cache or a proxy with many other users may avoid this exposure, but may expose information to the cache or proxy, in the same way that a non-Auditing HTTPS Client exposes information to a Trusted Auditor.

- an effective CT auditor needs a strategy about what to do in the event that it discovers misbehavior from a log. Misbehavior from a log involves the log being unable to provide either (a) a consistency proof between two valid STHs or (b) an inclusion proof for a certificate to an STH any time after the log’s MMD has elapsed from the issuance of the SCT. The log’s inability to provide either proof will not be externally cryptographically-verifiable, as it may be indistinguishable from a network error.

11. Policy Recommendations

This section is intended as suggestions to implementors of HTTPS Clients, HTTPS servers, and CT auditors. It is not a requirement for technique of implementation, so long as privacy considerations established above are obeyed.

11.1. Blocking Recommendations

11.1.1. Frustrating blocking

When making gossip connections to HTTPS servers or Trusted Auditors, it is desirable to minimize the plaintext metadata in the connection that can be used to identify the connection as a gossip connection and therefore be of interest to block. Additionally, introducing some randomness into client behavior may be important. We assume that the adversary is able to inspect the behavior of the HTTPS client and understand how it makes gossip connections.

As an example, if a client, after establishing a TLS connection (and receiving an SCT, but not making its own HTTP request yet), immediately opens a second TLS connection for the purpose of gossip, the adversary can reliably block this second connection to block gossip without affecting normal browsing. For this reason it is recommended to run the gossip protocols over an existing connection to the server, making use of connection multiplexing such as HTTP Keep-Alive or SPDY.

Truncation is also a concern. If a client always establishes a TLS connection, makes a request, receives a response, and then always attempts a gossip communication immediately following the first response, truncation will allow an attacker to block gossip reliably.

For these reasons, we recommend that, if at all possible, clients SHOULD send gossip data in an already established TLS session. This can be done through the use of HTTP Pipelining, SPDY, or HTTP/2.

11.1.2. Responding to possible blocking

In some circumstances a client may have a piece of data that they have attempted to share (via SCT Feedback or STH Pollination), but have been unable to do so: with every attempt they receive an error. These situations are:

1. The client has an SCT and a certificate, and attempts to retrieve an inclusion proof - but receives an error on every attempt.

2. The client has an STH, and attempts to resolve it to a newer STH via a consistency proof - but receives an error on every attempt.

3. The client has attempted to share an SCT and constructed certificate via SCT Feedback - but receives an error on every attempt.

4. The client has attempted to share an STH via STH Pollination - but receives an error on every attempt.

5. The client has attempted to share a specific piece of data with a Trusted Auditor - but receives an error on every attempt.

In the case of 1 or 2, it is conceivable that the reason for the errors is that the log acted improperly, either through malicious actions or compromise. A proof may not be able to be fetched because it does not exist (and only errors or timeouts occur). One such situation may arise because of an actively malicious log, as presented in Section 10.1. This data is especially important to share with the broader internet to detect this situation.

If an SCT has attempted to be resolved to an STH via an inclusion proof multiple times, and each time has failed, this SCT might very well be a compromising proof of an attack. However the client MUST NOT share the data with any other third party (excepting a Trusted Auditor should one exist).

If an STH has attempted to be resolved to a newer STH via a consistency proof multiple times, and each time has failed, a client MAY share the STH with an "Auditor of Last Resort" even if the STH in question is no longer within the validity window. This auditor may be pre-configured in the client, but the client SHOULD permit a user to disable the functionality or change whom data is sent to. The Auditor of Last Resort itself represents a point of failure and privacy concerns, so if implemented, it SHOULD connect using public key pinning and not consider an item delivered until it receives a confirmation.

In the cases 3, 4, and 5, we assume that the webserver(s) or trusted auditor in question is either experiencing an operational failure, or being attacked. In both cases, a client SHOULD retain the data for later submission (subject to Private Browsing or other history-clearing actions taken by the user.) This is elaborated upon more in Section 11.3.

11.2. Proof Fetching Recommendations

Proof fetching (both inclusion proofs and consistency proofs) SHOULD be performed at random time intervals. If proof fetching occurred all at once, in a flurry of activity, a log would know that SCTs or STHs received around the same time are more likely to come from a particular client. While proof fetching is required to be done in a manner that attempts to be anonymous from the perspective of the log, the correlation of activity to a single client would still reveal patterns of user behavior we wish to keep confidential. These

patterns could be recognizable as a single user, or could reveal what sites are commonly visited together in the aggregate.

11.3. Record Distribution Recommendations

In several components of the CT Gossip ecosystem, the recommendation is made that data from multiple sources be ingested, mixed, stored for an indeterminate period of time, provided (multiple times) to a third party, and eventually deleted. The instances of these recommendations in this draft are:

- When a client receives SCTs during SCT Feedback, it should store the SCTs and Certificate Chain for some amount of time, provide some of them back to the server at some point, and may eventually remove them from its store

- When a client receives STHs during STH Pollination, it should store them for some amount of time, mix them with other STHs, release some of them them to various servers at some point, resolve some of them to new STHs, and eventually remove them from its store

- When a server receives SCTs during SCT Feedback, it should store them for some period of time, provide them to auditors some number of times, and may eventually remove them

- When a server receives STHs during STH Pollination, it should store them for some period of time, mix them with other STHs, provide some of them to connecting clients, may resolve them to new STHs via Proof Fetching, and eventually remove them from its store

- When a Trusted Auditor receives SCTs or historical STHs from clients, it should store them for some period of time, mix them with SCTs received from other clients, and act upon them at some period of time

Each of these instances have specific requirements for user privacy, and each have options that may not be invoked. As one example, an HTTPS client should not mix SCTs from server A with SCTs from server B and release server B's SCTs to Server A. As another example, an HTTPS server may choose to resolve STHs to a single more current STH via proof fetching, but it is under no obligation to do so.

These requirements should be met, but the general problem of aggregating multiple pieces of data, choosing when and how many to release, and when to remove them is shared. This problem has

previously been considered in the case of Mix Networks and Remailers, including papers such as [trickle].

There are several concerns to be addressed in this area, outlined below.

11.3.1. Mixing Algorithm

When SCTs or STHs are recorded by a participant in CT Gossip and later used, it is important that they are selected from the datastore in a non-deterministic fashion.

This is most important for servers, as they can be queried for SCTs and STHs anonymously. If the server used a predictable ordering algorithm, an attacker could exploit the predictability to learn information about a client. One such method would be by observing the (encrypted) traffic to a server. When a client of interest connects, the attacker makes a note. They observe more clients connecting, and predicts at what point the client-of-interest's data will be disclosed, and ensures that they query the server at that point.

Although most important for servers, random ordering is still strongly recommended for clients and Trusted Auditors. The above attack can still occur for these entities, although the circumstances are less straightforward. For clients, an attacker could observe their behavior, note when they receive an STH from a server, and use javascript to cause a network connection at the correct time to force a client to disclose the specific STH. Trusted Auditors are stewards of sensitive client data. If an attacker had the ability to observe the activities of a Trusted Auditor (perhaps by being a log, or another auditor), they could perform the same attack - noting the disclosure of data from a client to the Trusted Auditor, and then correlating a later disclosure from the Trusted Auditor as coming from that client.

Random ordering can be ensured by several mechanisms. A datastore can be shuffled, using a secure shuffling algorithm such as Fisher-Yates. Alternately, a series of random indexes into the data store can be selected (if a collision occurs, a new index is selected.) A cryptographically secure random number generator must be used in either case. If shuffling is performed, the datastore must be marked 'dirty' upon item insertion, and at least one shuffle operation occurs on a dirty datastore before data is retrieved from it for use.

11.3.2. The Deletion Algorithm

No entity in CT Gossip is required to delete records at any time, except to respect user's wishes such as private browsing mode or clearing history. However, it is likely that over time the accumulated storage will grow in size and need to be pruned.

While deletion of data will occur, proof fetching can ensure that any misbehavior from a log will still be detected, even after the direct evidence from the attack is deleted. Proof fetching ensures that if a log presents a split view for a client, they must maintain that split view in perpetuity. An inclusion proof from an SCT to an STH does not erase the evidence - the new STH is evidence itself. A consistency proof from that STH to a new one likewise - the new STH is every bit as incriminating as the first. (Client behavior in the situation where an SCT or STH cannot be resolved is suggested in Section 11.1.2.) Because of this property, we recommend that if a client is performing proof fetching, that they make every effort to not delete data until it has been successfully resolved to a new STH via a proof.

When it is time to delete a record, it can be done in a way that makes it more difficult for a successful flushing attack to to be performed.

1. When the record cache has reached a certain size that is yet under the limit, aggressively perform proof fetching. This should resolve records to a small set of STHs that can be retained. Once a proof has been fetched, the record is safer to delete.

2. If proof fetching has failed, or is disabled, begin by deleting SCTs and Certificate Chains that have been successfully reported. Deletion from this set of SCTs should be done at random. For a client, a submission is not counted as being reported unless it is sent over a connection using a different SCT, so the attacker is faced with a recursive problem. (For a server, this step does not apply.)

3. Attempt to save any submissions that have failed proof fetching repeatedly, as these are the most likely to be indicative of an attack.

4. Finally, if the above steps have been followed and have not succeeded in reducing the size sufficiently, records may be deleted at random.

Note that if proof fetching is disabled (which is expected although not required for servers) - the algorithm collapses down to 'delete at random'.

The decision to delete records at random is intentional. Introducing non-determinism in the decision is absolutely necessary to make it more difficult for an adversary to know with certainty or high confidence that the record has been successfully flushed from a target.

11.4. Concrete Recommendations

We present the following pseudocode as a concrete outline of our policy recommendations.

Both suggestions presented are applicable to both clients and servers. Servers may not perform proof fetching, in which case large portions of the pseudocode are not applicable. But it should work in either case.

11.4.1. STH Pollination

The STH class contains data pertaining specifically to the STH itself.

```
class STH
{
  uint16   proof_attempts
  uint16   proof_failure_count
  uint32   num_reports_to_thirdparty
  datetime timestamp
  byte[]   data
}
```

The broader STH store itself would contain all the STHs known by an entity participating in STH Pollination (either client or server). This simplistic view of the class does not take into account the complicated locking that would likely be required for a data structure being accessed by multiple threads. Something to note about this pseudocode is that it does not remove STHs once they have been resolved to a newer STH. Doing so might make older STHs within the validity window rarer and thus enable tracking.

```
class STHStore
{
  STH[] sth_list

  //  This function is run after receiving a set of STHs from
  //  a third party in response to a pollination submission
  def insert(STH[] new_sths) {
    foreach(new in new_sths) {
      if(this.sth_list.contains(new))
        continue
      this.sth_list.insert(new)
    }
  }

  //  This function is called to delete the given STH
  //  from the data store
  def delete_now(STH s) {
    this.sth_list.remove(s)
  }

  //  When it is time to perform STH Pollination, the HTTPS client
  //  calls this function to get a selection of STHs to send as
  //  feedback
  def get_pollination_selection() {
    if(len(this.sth_list) < MAX_STH_TO_GOSSIP)
      return this.sth_list
    else {
      indexes = set()
      modulus = len(this.sth_list)
      while(len(indexes) < MAX_STH_TO_GOSSIP) {
        r = randomInt() % modulus
        // Ignore STHs that are past the validity window but not
        // yet removed.
        if(r not in indexes
           && now() - this.sth_list[i].timestamp < TWO_WEEKS)
          indexes.insert(r)
      }

      return_selection = []
      foreach(i in indexes) {
        return_selection.insert(this.sth_list[i])
      }
      return return_selection
    }
  }
}
```

We also suggest a function that will be called periodically in the background, iterating through the STH store, performing a cleaning operation and queuing consistency proofs. This function can live as a member functions of the STHStore class.

```
//Just a suggestion:
#define MIN_PROOF_FAILURES_CONSIDERED_SUSPICIOUS 3

def clean_list() {
  foreach(sth in this.sth_list) {

    if(now() - sth.timestamp > TWO_WEEKS) {
      //STH is too old, we must remove it
      if(proof_fetching_enabled
         && auditor_of_last_resort_enabled
         && sth.proof_failure_count
            > MIN_PROOF_FAILURES_CONSIDERED_SUSPICIOUS) {
        queue_for_auditor_of_last_resort(sth,
                                         auditor_of_last_resort_callback)
      } else {
        delete_now(sth)
      }
    }


    else if(proof_fetching_enabled
            && now() - sth.timestamp > LOG_MMD
            && sth.proof_attempts != UINT16_MAX
            // Only fetch a proof is we have never received a proof
            // before. (This also avoids submitting something
            // already in the queue.)
            && sth.proof_attempts == sth.proof_failure_count) {
      sth.proof_attempts++
      queue_consistency_proof(sth, consistency_proof_callback)
    }
  }
}
```

These functions also exist in the STHStore class.

```
//  This function is called after successfully pollinating STHs
//  to a third party. It is passed the STHs sent to the third
//  party, which is the output of get_gossip_selection(), as well
//  as the STHs received in the response.
def successful_thirdparty_submission_callback(STH[] submitted_sth_list,
                                              STH[] new_sths)
{
  foreach(sth in submitted_sth_list) {
    sth.num_reports_to_thirdparty++
  }

  this.insert(new_sths);
}


//  Attempt auditor of last resort submissions until it succeeds
def auditor_of_last_resort_callback(original_sth, error) {
  if(!error) {
    delete_now(original_sth)
  }
}


def consistency_proof_callback(consistency_proof, original_sth, error) {
  if(!error) {
    insert(consistency_proof.current_sth)
  } else {
    original_sth.proof_failure_count++
  }
}
```

11.4.2. SCT Feedback

The SCT class contains data pertaining specifically to an SCT itself.

```
class SCT
{
  uint16 proof_failure_count
  bool   has_been_resolved_to_sth
  bool   proof_outstanding
  byte[] data
}
```

The SCT bundle will contain the trusted certificate chain the HTTPS client built (chaining to a trusted root certificate.) It also contains the list of associated SCTs, the exact domain it is applicable to, and metadata pertaining to how often it has been reported to the third party.

```
   class SCTBundle
   {
     X509[] certificate_chain
     SCT[]  sct_list
     string domain
     uint32 num_reports_to_thirdparty

     def equals(sct_bundle) {
       if(sct_bundle.domain != this.domain)
         return false
       if(sct_bundle.certificate_chain != this.certificate_chain)
         return false
       if(sct_bundle.sct_list != this.sct_list)
         return false

       return true
     }
     def approx_equals(sct_bundle) {
       if(sct_bundle.domain != this.domain)
         return false
       if(sct_bundle.certificate_chain != this.certificate_chain)
         return false

       return true
     }

     def insert_scts(sct[] sct_list) {
       this.sct_list.union(sct_list)
       this.num_reports_to_thirdparty = 0
     }

     def has_been_fully_resolved_to_sths() {
       foreach(s in this.sct_list) {
         if(!s.has_been_resolved_to_sth && !s.proof_outstanding)
           return false
       }
       return true
     }

     def max_proof_failures() {
       uint max = 0
       foreach(sct in this.sct_list) {
         if(sct.proof_failure_count > max)
           max = sct.proof_failure_count
       }
       return max
     }
   }
```

For each domain, we store a SCTDomainEntry that holds the SCTBundles seen for that domain, as well as encapsulating some logic relating to SCT Feedback for that particular domain. In particular, this data structure also contains the logic that handles domains not supporting SCT Feedback. Its behavior is:

1. When a user visits a domain, SCT Feedback is attempted for it. If it fails, it will retry after a month (configurable). If it succeeds, excellent. SCT Feedback data is still collected and stored even if SCT Feedback failed.

2. After 3 month-long waits between failures, the domain will be marked as failing long-term. No SCT Feedback data will be stored beyond meta-data, but SCT Feedback will still be attempted after month-long waits

3. If at any point in time, SCT Feedback succeeds, all failure counters are reset

4. If a domain succeeds, but then begins failing, it must fail more than 90% of the time (configurable) and then the process begins at (2).

If a domain is visited infrequently (say, once every 7 months) then it will be evicted from the cache and start all over again (according to the suggestion values in the below pseudocode).

[Note: To be certain the logic is correct I give the following test cases which illustrate the intended behavior. Hopefully the code matches!

```
 Succeed 1 Time        num_submissions_attempted=1    num_submissions_succeeded=
1  num_feedback_loop_failures=0
 Fail 10 Times         num_submissions_attempted=11   num_submissions_succeeded=
1  num_feedback_loop_failures=0
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=12   num_submissions_succeeded=
1  num_feedback_loop_failures=1
 ... wait a month ...
 Succeed 1 month later num_submissions_attempted=13   num_submissions_succeeded=
2  num_feedback_loop_failures=0(r) indicates (Reset)
 -> Feedback is attempted regularly.

 Succeed 1 Time        num_submissions_attempted=1    num_submissions_succeeded=
1  num_feedback_loop_failures=0
 Fail 10 Times         num_submissions_attempted=11   num_submissions_succeeded=
1  num_feedback_loop_failures=0
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=12   num_submissions_succeeded=
1  num_feedback_loop_failures=1
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=13   num_submissions_succeeded=
1  num_feedback_loop_failures=2
 ... wait a month ...
 Succeed 1 month later num_submissions_attempted=14   num_submissions_succeeded=
2  num_feedback_loop_failures=0(r)
 -> Feedback is attempted regularly.
```

```
 Succeed 1 Time        num_submissions_attempted=1    num_submissions_succeeded=
1  num_feedback_loop_failures=0
 Fail 10 Times         num_submissions_attempted=11   num_submissions_succeeded=
1  num_feedback_loop_failures=0
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=12   num_submissions_succeeded=
1  num_feedback_loop_failures=1
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=13   num_submissions_succeeded=
1  num_feedback_loop_failures=2
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=14   num_submissions_succeeded=
2  num_feedback_loop_failures=3
 ... clear_old_data() is run every hour ...
                       num_submissions_attempted=0    num_submissions_succeeded=
0  num_feedback_loop_failures=3
                       sct_feedback_failing_longterm=True
 Fail 1 month later    num_submissions_attempted=1    num_submissions_succeeded=
0  num_feedback_loop_failures=4
                       sct_feedback_failing_longterm=True
 ... clear_old_data() is run every hour ...
                       num_submissions_attempted=0(r) num_submissions_succeeded=
0  num_feedback_loop_failures=3
                       sct_feedback_failing_longterm=True
 Succeed 1 month later num_submissions_attempted=2   num_submissions_succeeded=1
  num_feedback_loop_failures=0(r)
                       sct_feedback_failing_longterm=False
 -> Feedback is attempted regularly.

 Note above that the second run of clear_old_data() will reset num_submissions_a
ttempted from 1 to 0.  This is
 CRITICAL. Otherwise, we would have the below bug (where after 10 months of fail
ures, a success would not hit
 the required ratio to keep going)


 //The below represents a bug.
 Succeed 1 Time        num_submissions_attempted=1   num_submissions_succeeded=1
  num_feedback_loop_failures=0
 Fail 10 Times         num_submissions_attempted=11  num_submissions_succeeded=1
  num_feedback_loop_failures=0
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=12  num_submissions_succeeded=1
  num_feedback_loop_failures=1
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=13  num_submissions_succeeded=1
  num_feedback_loop_failures=2
 ... wait a month ...
 Fail 1 month later    num_submissions_attempted=14  num_submissions_succeeded=2
  num_feedback_loop_failures=3
 ... clear_old_data() is run every hour ...
                       num_submissions_attempted=0   num_submissions_succeeded=0
  num_feedback_loop_failures=3
                       sct_feedback_failing_longterm=True
 Fail 1 month later    num_submissions_attempted=1   num_submissions_succeeded=0
  num_feedback_loop_failures=4
                       sct_feedback_failing_longterm=True
 Fail 9 times for 9 months
                       num_submissions_attempted=10  num_submissions_succeeded=0
  num_feedback_loop_failures=13
                       sct_feedback_failing_longterm=True
 Succeed 1 month later num_submissions_attempted=11  num_submissions_succeeded=1
  num_feedback_loop_failures=0(r)
```

```
                        sct_feedback_failing_longterm=False
 -> Feedback is NOT attempted regularly. \]

//Suggestions:
//  After concluding a domain doesn’t support feedback, we try again
```

```
//  after WAIT_BETWEEN_SCT_FEEDBACK_ATTEMPTS amount of time to see if
//  they added support
#define WAIT_BETWEEN_SCT_FEEDBACK_ATTEMPTS                    1 month

//  If we've waited MIN_SCT_FEEDBACK_ATTEMPTS_BEFORE_OMITTING_STORAGE
//  multiplied by WAIT_BETWEEN_SCT_FEEDBACK_ATTEMPTS amount of time, we
//  still attempt SCT Feedback, but no longer bother storing any data
//  until the domain supports SCT Feedback
#define MIN_SCT_FEEDBACK_ATTEMPTS_BEFORE_OMITTING_STORAGE      3

//  If this percentage of SCT Feedback attempts previously succeeded,
//  we consider the domain as supporting feedback and is just having
//  transient errors
#define MIN_RATIO_FOR_SCT_FEEDBACK_TO_BE_WORKING               .10

class SCTDomainEntry
{
  //  This is the primary key of the object, the exact domain name it
  //  is valid for
  string   domain

  //  This is the last time the domain was contacted. For client
  //  operations it is updated whenever the client makes any request
  //  (not just feedback) to the domain. For server operations, it is
  //  updated whenever any client contacts the domain. Responsibility
  //  for updating lies OUTSIDE of the class
  public datetime last_contact_for_domain

  //  This is the last time SCT Feedback was attempted for the domain.
  //  It is updated whenever feedback is attempted - responsibility for
  //  updating lies OUTSIDE of the class
  //  This is not used when this algorithm runs on servers
  public datetime last_sct_feedback_attempt

  //  This is the number of times we have waited an
  //  WAIT_BETWEEN_SCT_FEEDBACK_ATTEMPTS amount of time, and still failed
  //  e.g. 10 months of failures
  //  This is not used when this algorithm runs on servers
  private uint16   num_feedback_loop_failures

  //  This is whether or not SCT Feedback has failed enough times that we
  //  should not bother storing data for it anymore. It is a small function
  //  used for illustrative purposes
  //  This is not used when this algorithm runs on servers
  private bool     sct_feedback_failing_longterm()
    { num_feedback_loop_failures >= MIN_SCT_FEEDBACK_ATTEMPTS_BEFORE_OMITTING_ST
ORAGE }

  //  This is the number of SCT Feedback submissions attempted.
```

```
  //  Responsibility for incrementing lies OUTSIDE of the class
  //  (And watch for integer overflows)
  //  This is not used when this algorithm runs on servers
  public uint16    num_submissions_attempted

  //  This is the number of successful SCT Feedback submissions. This
  //  variable is updated by the class.
  //  This is not used when this algorithm runs on servers
  private uint16   num_submissions_succeeded

  //  This contains all the bundles of SCT data we have observed for
  //  this domain
  SCTBundle[] observed_records


  //  This function can be called to determine if we should attempt
  //  SCT Feedback for this domain.
  def should_attempt_feedback() {
    // Servers always perform feedback!
    if(operator_is_server)
      return true

    // If we have not tried in a month, try again
    if(now() - last_sct_feedback_attempt > WAIT_BETWEEN_SCT_FEEDBACK_ATTEMPTS)
      return true

    // If we have tried recently, and it seems to be working, go for it!
    if((num_submissions_succeeded / num_submissions_attempted) >
       MIN_RATIO_FOR_SCT_FEEDBACK_TO_BE_WORKING)
      return true

    // Otherwise don't try
    return false
  }

  //  For Clients, this function is called after a successful
  //  connection to an HTTPS server, with a single SCTBundle
  //  constructed from that connection's certificate chain and SCTs.
  //  For Servers, this is called after receiving SCT Feedback with
  //  all the bundles sent in the feedback.
  def insert(SCTBundle[] bundles) {
    // Do not store data for long-failing domains
    if(sct_feedback_failing_longterm()) {
      return
    }

    foreach(b in bundles) {
      if(operator_is_server) {
```

```
        if(!passes_validity_checks(b))
          return
      }

      bool have_inserted = false
      foreach(e in this.observed_records) {
        if(e.equals(b))
          return
        else if(e.approx_equals(b)) {
          have_inserted = true
          e.insert_scts(b.sct_list)
        }
      }
      if(!have_inserted)
        this.observed_records.insert(b)
    }
    SCTStoreManager.update_cache_percentage()
  }

  //  When it is time to perform SCT Feedback, the HTTPS client
  //  calls this function to get a selection of SCTBundles to send
  //  as feedback
  def get_gossip_selection() {
    if(len(observed_records) > MAX_SCT_RECORDS_TO_GOSSIP) {
      indexes = set()
      modulus = len(observed_records)
      while(len(indexes) < MAX_SCT_RECORDS_TO_GOSSIP) {
        r = randomInt() % modulus
        if(r not in indexes)
          indexes.insert(r)
      }

      return_selection = []
      foreach(i in indexes) {
        return_selection.insert(this.observed_records[i])
      }

      return return_selection
    }
    else
      return this.observed_records
  }

  def passes_validity_checks(SCTBundle b) {
    //  This function performs the validity checks specified in
    //  {{feedback-srvop}}
  }
}
```

The SCTDomainEntry is responsible for handling the outcome of a submission report for that domain using its member function:

```
//  This function is called after providing SCT Feedback
//  to a server. It is passed the feedback sent to the other party, which
//  is the output of get_gossip_selection(), and also the SCTBundle
//  representing the connection the data was sent on.
//  (When this code runs on the server, connectionBundle is NULL)
//  If the Feedback was not sent successfully, error is True
def after_submit_to_thirdparty(error, SCTBundle[] submittedBundles,
                               SCTBundle connectionBundle)
{
  // Server operation in this instance is exceedingly simple
  if(operator_is_server) {
    if(error)
      return
    foreach(bundle in submittedBundles)
      bundle.num_reports_to_thirdparty++
    return
  }

  // Client behavior is much more complicated
  if(error) {
    if(sct_feedback_failing_longterm()) {
      num_feedback_loop_failures++
    }
    else if((num_submissions_succeeded / num_submissions_attempted)
            > MIN_RATIO_FOR_SCT_FEEDBACK_TO_BE_WORKING) {
      // Do nothing. num_submissions_succeeded will not be incremented
      // After enough of these failures, the ratio will fall beyond
      // acceptable
    } else {
      // The domain has begun its three-month grace period. We will
      // attempt submissions once a month
      num_feedback_loop_failures++
    }
    return
  }
  // We succeeded, so reset all of our failure states
  // Note, there is a race condition here if clear_old_data() is called
  // while this callback is outstanding.
  num_feedback_loop_failures     = 0
  if(num_submissions_succeeded != UINT16_MAX )
    num_submissions_succeeded++


  foreach(bundle in submittedBundles)
  {
```

```
    // Compare Certificate Chains, if they do not match, it counts as a
    // submission.
    if(!connectionBundle.approx_equals(bundle))
      bundle.num_reports_to_thirdparty++
    else {
      // This check ensures that a SCT Bundle is not considered reported
      // if it is submitted over a connection with the same SCTs. This
      // satisfies the constraint in Paragraph 5 of {{feedback-clisrv}}
      // Consider three submission scenarios:
      // Submitted SCTs      Connection SCTs    Considered Submitted
      // A, B                A, B               No - no new information
      // A                   A, B               Yes - B is a new SCT
      // A, B                A                  No - no new information
      if(connectionBundle.sct_list is NOT a subset of bundle.sct_list)
        bundle.num_reports_to_thirdparty++
    }
  }
}
```

Instances of the SCTDomainEntry class are stored as part of a larger class that manages the entire SCT Cache, storing them in a hashmap keyed by domain. This class also tracks the current size of the cache, and will trigger cache eviction.

```
//Suggestions:
#define CACHE_PRESSURE_SAFE                    .50
#define CACHE_PRESSURE_IMMINENT                .70
#define CACHE_PRESSURE_ALMOST_FULL             .85
#define CACHE_PRESSURE_FULL                    .95
#define WAIT_BETWEEN_IMMINENT_CACHE_EVICTION  5 minutes

class SCTStoreManager
{
  hashmap<String, SCTDomainEntry> all_sct_entries
  uint32                          current_cache_size
  datetime                        imminent_cache_pressure_check_performed

  float current_cache_percentage() {
    return current_cache_size / MAX_CACHE_SIZE;
  }

  static def update_cache_percentage() {
    // This function calculates the current size of the cache
    // and updates current_cache_size
    /* ... perform calculations ... */
    current_cache_size = /* new calculated value */

    // Perform locking to prevent multiple of these functions being
    // called concurrently or unnecessarily
    if(current_cache_percentage() > CACHE_PRESSURE_FULL) {
        cache_is_full()
    }

    else if(current_cache_percentage() > CACHE_PRESSURE_ALMOST_FULL) {
      cache_pressure_almost_full()
    }

    else if(current_cache_percentage() > CACHE_PRESSURE_IMMINENT) {
      // Do not repeatedly perform the imminent cache pressure operation
      if(now() - imminent_cache_pressure_check_performed >
          WAIT_BETWEEN_IMMINENT_CACHE_EVICTION) {
        cache_pressure_is_imminent()
      }
    }
  }
}
```

The SCTStoreManager contains a function that will be called periodically in the background, iterating through all SCTDomainEntry objects and performing maintenance tasks. It removes data for domains we have not contacted in a long time. This function is not

```
   intended to clear data if the cache is getting full, separate
   functions are used for that.

 // Suggestions:
 #define TIME_UNTIL_OLD_SUBMITTED_SCTDATA_ERASED     3 months
 #define TIME_UNTIL_OLD_UNSUBMITTED_SCTDATA_ERASED   6 months

 def clear_old_data()
 {
   foreach(domainEntry in all_sct_stores)
   {
     // Queue proof fetches
     if(proof_fetching_enabled) {
       foreach(sctBundle in domainEntry.observed_records) {
         if(!sctBundle.has_been_fully_resolved_to_sths()) {
           foreach(s in bundle.sct_list) {
             if(!s.has_been_resolved_to_sth && !s.proof_outstanding) {
               sct.proof_outstanding = True
               queue_inclusion_proof(sct, inclusion_proof_callback)
             }
           }
         }
       }
     }

     // Do not store data for domains who are not supporting SCT
     if(!operator_is_server
        && domainEntry.sct_feedback_failing_longterm())
     {
       // Note that reseting these variables every single time is
       // necessary to avoid a bug
       all_sct_stores[domainEntry].num_submissions_attempted      = 0
       all_sct_stores[domainEntry].num_submissions_succeeded      = 0
       delete all_sct_stores[domainEntry].observed_records
       all_sct_stores[domainEntry].observed_records               = NULL
     }

     // This check removes successfully submitted data for
     // old domains we have not dealt with in a long time
     if(domainEntry.num_submissions_succeeded > 0
        && now() - domainEntry.last_contact_for_domain
           > TIME_UNTIL_OLD_SUBMITTED_SCTDATA_ERASED)
     {
       all_sct_stores.remove(domainEntry)
     }

     // This check removes unsuccessfully submitted data for
     // old domains we have not dealt with in a very long time
```

```
     if(now() - domainEntry.last_contact_for_domain
        > TIME_UNTIL_OLD_UNSUBMITTED_SCTDATA_ERASED)
     {
       all_sct_stores.remove(domainEntry)
     }

 SCTStoreManager.update_cache_percentage()
 }
```

Inclusion Proof Fetching is handled fairly independently

```
 // This function is a callback invoked after an inclusion proof
 // has been retrieved. It can exist on the SCT class or independently,
 // so long as it can modify the SCT class' members
 def inclusion_proof_callback(inclusion_proof, original_sct, error)
 {
   // Unlike the STH code, this counter must be incremented on the
   // callback as there is a race condition on using this counter in the
   // cache_* functions.
   original_sct.proof_attempts++
   original_sct.proof_outstanding = False
   if(!error) {
     original_sct.has_been_resolved_to_sth = True
     insert_to_sth_datastore(inclusion_proof.new_sth)
   } else {
     original_sct.proof_failure_count++
   }
 }
```

If the cache is getting full, these three member functions of the SCTStoreManager class will be used.

```
// ------------------------------------------------------------------
// This function is called when the cache is not yet full, but is
// nearing it. It prioritizes deleting data that should be safe
// to delete (because it has been shared with the site or resolved
// to a STH)
def cache_pressure_is_imminent()
{
  bundlesToDelete = []
  foreach(domainEntry in all_sct_stores) {
    foreach(sctBundle in domainEntry.observed_records) {

      if(proof_fetching_enabled) {
        // First, queue proofs for anything not already queued.
        if(!sctBundle.has_been_fully_resolved_to_sths()) {
          foreach(sct in bundle.sct_list) {
            if(!sct.has_been_resolved_to_sth
```

```
               && !sct.proof_outstanding) {
              sct.proof_outstanding = True
              queue_inclusion_proof(sct, inclusion_proof_callback)
            }
          }
        }

        // Second, consider deleting entries that have been fully
        // resolved.
        else {
          bundlesToDelete.append( Struct(domainEntry, sctBundle) )
        }
      }

      // Third, consider deleting entries that have been successfully
      // reported
      if(sctBundle.num_reports_to_thirdparty > 0) {
        bundlesToDelete.append( Struct(domainEntry, sctBundle) )
      }
    }
  }

  // Third, delete the eligible entries at random until the cache is
  // at a safe level
  uint recalculateIndex                = 0
  #define RECALCULATE_EVERY_N_OPERATIONS 50

  while(bundlesToDelete.length > 0 &&
        current_cache_percentage() > CACHE_PRESSURE_SAFE) {
    uint rndIndex = rand() % bundlesToDelete.length
    bundlesToDelete[rndIndex].domainEntry.observed_records.remove(bundlesToDelet
e[rndIndex].sctBundle)
    bundlesToDelete.removeAt(rndIndex)

    recalculateIndex++
    if(recalculateIndex % RECALCULATE_EVERY_N_OPERATIONS == 0) {
      update_cache_percentage()
    }
  }

  // Finally, tell the proof fetching engine to go faster
  if(proof_fetching_enabled) {
    // This function would speed up proof fetching until an
    // arbitrary time has passed. Perhaps until it has fetched
    // proofs for the number of items currently in its queue? Or
    // a percentage of them?
    proof_fetch_faster_please()
  }
```

```
  update_cache_percentage();
}

// ----------------------------------------------------------------
// This function is called when the cache is almost full. It will
// evict entries at random, while attempting to save entries that
// appear to have proof fetching failures
def cache_pressure_almost_full()
{
  uint recalculateIndex                = 0
  uint savedRecords                    = 0
  #define RECALCULATE_EVERY_N_OPERATIONS 50

  while(all_sct_stores.length > savedRecords &&
        current_cache_percentage() > CACHE_PRESSURE_SAFE) {
    uint rndIndex1 = rand() % all_sct_stores.length
    uint rndIndex2 = rand() % all_sct_stores[rndIndex1].observed_records.length

    if(proof_fetching_enabled) {
      if(all_sct_stores[rndIndex1].observed_records[rndIndex2].max_proof_failure
s() >
         MIN_PROOF_FAILURES_CONSIDERED_SUSPICIOUS) {
        savedRecords++
        continue
      }
    }

    // If proof fetching is not enabled we need some other logic
    else {
      if(sctBundle.num_reports_to_thirdparty == 0) {
        savedRecords++
        continue
      }
    }

    all_sct_stores[rndIndex1].observed_records.removeAt(rndIndex2)
    if(all_sct_stores[rndIndex1].observed_records.length == 0) {
      all_sct_stores.removeAt(rndIndex1)
    }

    recalculateIndex++
    if(recalculateIndex % RECALCULATE_EVERY_N_OPERATIONS == 0) {
      update_cache_percentage()
    }
  }

  update_cache_percentage();
}
```

```
// ---------------------------------------------------------------
// This function is called when the cache is full, and will evict
// cache entries at random
def cache_is_full()
{
  uint recalculateIndex                = 0
  #define RECALCULATE_EVERY_N_OPERATIONS 50

  while(all_sct_stores.length > 0 &&
        current_cache_percentage() > CACHE_PRESSURE_SAFE) {
    uint rndIndex1 = rand() % all_sct_stores.length
    uint rndIndex2 = rand() % all_sct_stores[rndIndex1].observed_records.length

    all_sct_stores[rndIndex1].observed_records.removeAt(rndIndex2)
    if(all_sct_stores[rndIndex1].observed_records.length == 0) {
      all_sct_stores.removeAt(rndIndex1)
    }


    recalculateIndex++
    if(recalculateIndex % RECALCULATE_EVERY_N_OPERATIONS == 0) {
      update_cache_percentage()
    }
  }

  update_cache_percentage();
}
```

12. IANA considerations

[TBD]

13. Contributors

The authors would like to thank the following contributors for valuable suggestions: Al Cutter, Ben Laurie, Benjamin Kaduk, Josef Gustafsson, Karen Seo, Magnus Ahltorp, Steven Kent, Yan Zhu.

14. ChangeLog

14.1. Changes between ietf-03 and ietf-04

- No changes.

14.2. Changes between ietf-02 and ietf-03

- TBD’s resolved.
- References added.
- Pseduocode changed to work for both clients and servers.

14.3. Changes between ietf-01 and ietf-02

- Requiring full certificate chain in SCT Feedback.
- Clarifications on what clients store for and send in SCT Feedback added.
- SCT Feedback server operation updated to protect against DoS attacks on servers.
- Pre-Loaded vs Locally Added Anchors explained.
- Base for well-known URL’s changed.
- Remove all mentions of monitors - gossip deals with auditors.
- New sections added: Trusted Auditor protocol, attacks by actively malicious log, the Dual-CA compromise attack, policy recommendations,

14.4. Changes between ietf-00 and ietf-01

- Improve language and readability based on feedback from Stephen Kent.
- STH Pollination Proof Fetching defined and indicated as optional.
- 3-Method Ecosystem section added.
- Cases with Logs ceasing operation handled.
- Text on tracking via STH Interaction added.
- Section with some early recommendations for mixing added.
- Section detailing blocking connections, frustrating it, and the implications added.

14.5. Changes between -01 and -02

- STH Pollination defined.
- Trusted Auditor Relationship defined.
- Overview section rewritten.
- Data flow picture added.
- Section on privacy considerations expanded.

14.6. Changes between -00 and -01

- Add the SCT feedback mechanism: Clients send SCTs to originating web server which shares them with auditors.
- Stop assuming that clients see STHs.
- Don’t use HTTP headers but instead .well-known URL’s - avoid that battle.
- Stop referring to trans-gossip and trans-gossip-transport-https - too complicated.
- Remove all protocols but HTTPS in order to simplify - let’s come back and add more later.
- Add more reasoning about privacy.
- Do specify data formats.

15. References

15.1. Normative References

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Authors' Addresses

Linus Nordberg
NORDUnet

Email: linus@nordu.net

Daniel Kahn Gillmor
ACLU

Email: dkg@fifthhorseman.net

Tom Ritter

Email: tom@ritter.vg

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B. Laurie
A. Langley
E. Kasper
E. Messeri
Google
R. Stradling
Comodo

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Certificate Transparency Version 2.0
draft-ietf-trans-rfc6962-bis-25

Abstract

This document describes version 2.0 of the Certificate Transparency (CT) protocol for publicly logging the existence of Transport Layer Security (TLS) server certificates as they are issued or observed, in a manner that allows anyone to audit certification authority (CA) activity and notice the issuance of suspect certificates as well as to audit the certificate logs themselves. The intent is that eventually clients would refuse to honor certificates that do not appear in a log, effectively forcing CAs to add all issued certificates to the logs.

Logs are network services that implement the protocol operations for submissions and queries that are defined in this document.

Status of This Memo

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1. Introduction

Certificate Transparency aims to mitigate the problem of misissued certificates by providing append-only logs of issued certificates. The logs do not need to be trusted because they are publicly auditable. Anyone may verify the correctness of each log and monitor when new certificates are added to it. The logs do not themselves prevent misissue, but they ensure that interested parties (particularly those named in certificates) can detect such misissuance. Note that this is a general mechanism that could be used for transparently logging any form of binary data, subject to some kind of inclusion criteria. In this document, we only describe its use for public TLS server certificates (i.e., where the inclusion criteria is a valid certificate issued by a public certification authority (CA)).

Each log contains certificate chains, which can be submitted by anyone. It is expected that public CAs will contribute all their newly issued certificates to one or more logs; however certificate holders can also contribute their own certificate chains, as can third parties. In order to avoid logs being rendered useless by the submission of large numbers of spurious certificates, it is required that each chain ends with a trust anchor that is accepted by the log. When a chain is accepted by a log, a signed timestamp is returned, which can later be used to provide evidence to TLS clients that the chain has been submitted. TLS clients can thus require that all certificates they accept as valid are accompanied by signed timestamps.

Those who are concerned about misissuance can monitor the logs, asking them regularly for all new entries, and can thus check whether domains for which they are responsible have had certificates issued that they did not expect. What they do with this information, particularly when they find that a misissuance has happened, is beyond the scope of this document. However, broadly speaking, they can invoke existing business mechanisms for dealing with misissued certificates, such as working with the CA to get the certificate revoked, or with maintainers of trust anchor lists to get the CA

removed. Of course, anyone who wants can monitor the logs and, if they believe a certificate is incorrectly issued, take action as they see fit.

Similarly, those who have seen signed timestamps from a particular log can later demand a proof of inclusion from that log. If the log is unable to provide this (or, indeed, if the corresponding certificate is absent from monitors' copies of that log), that is evidence of the incorrect operation of the log. The checking operation is asynchronous to allow clients to proceed without delay, despite possible issues such as network connectivity and the vagaries of firewalls.

The append-only property of each log is achieved using Merkle Trees, which can be used to show that any particular instance of the log is a superset of any particular previous instance. Likewise, Merkle Trees avoid the need to blindly trust logs: if a log attempts to show different things to different people, this can be efficiently detected by comparing tree roots and consistency proofs. Similarly, other misbehaviors of any log (e.g., issuing signed timestamps for certificates they then don't log) can be efficiently detected and proved to the world at large.

1.1. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

1.2. Data Structures

Data structures are defined and encoded according to the conventions laid out in Section 4 of [RFC5246].

1.3. Major Differences from CT 1.0

This document revises and obsoletes the experimental CT 1.0 [RFC6962] protocol, drawing on insights gained from CT 1.0 deployments and on feedback from the community. The major changes are:

- Hash and signature algorithm agility: permitted algorithms are now specified in IANA registries.
- Precertificate format: precertificates are now CMS objects rather than X.509 certificates, which avoids violating the certificate serial number uniqueness requirement in Section 4.1.2.2 of [RFC5280].

- Removed precertificate signing certificates and the precertificate poison extension: the change of precertificate format means that these are no longer needed.

- Logs IDs: each log is now identified by an OID rather than by the hash of its public key. OID allocations are managed by an IANA registry.

- "TransItem" structure: this new data structure is used to encapsulate most types of CT data. A "TransItemList", consisting of one or more "TransItem" structures, can be used anywhere that "SignedCertificateTimestampList" was used in [RFC6962].

- Merkle tree leaves: the "MerkleTreeLeaf" structure has been replaced by the "TransItem" structure, which eases extensibility and simplifies the leaf structure by removing one layer of abstraction.

- Unified leaf format: the structure for both certificate and precertificate entries now includes only the TBSCertificate (whereas certificate entries in [RFC6962] included the entire certificate).

- Log Artifact Extensions: these are now typed and managed by an IANA registry, and they can now appear not only in SCTs but also in STHs.

- API outputs: complete "TransItem" structures are returned, rather than the constituent parts of each structure.

- get-all-by-hash: new client API for obtaining an inclusion proof and the corresponding consistency proof at the same time.

- Presenting SCTs with proofs: TLS servers may present SCTs together with the corresponding inclusion proofs using any of the mechanisms that [RFC6962] defined for presenting SCTs only. (Presenting SCTs only is still supported).

- CT TLS extension: the "signed_certificate_timestamp" TLS extension has been replaced by the "transparency_info" TLS extension.

- Other TLS extensions: "status_request_v2" may be used (in the same manner as "status_request"); "cached_info" may be used to avoid sending the same complete SCTs and inclusion proofs to the same TLS clients multiple times.

- Verification algorithms: added detailed algorithms for verifying inclusion proofs, for verifying consistency between two STHs, and

for verifying a root hash given a complete list of the relevant leaf input entries.

- Extensive clarifications and editorial work.

2. Cryptographic Components

2.1. Merkle Hash Trees

2.1.1. Definition of the Merkle Tree

The log uses a binary Merkle Hash Tree for efficient auditing. The hash algorithm used is one of the log's parameters (see Section 4.1). We have established a registry of acceptable hash algorithms (see Section 10.3). Throughout this document, the hash algorithm in use is referred to as HASH and the size of its output in bytes as HASH_SIZE. The input to the Merkle Tree Hash is a list of data entries; these entries will be hashed to form the leaves of the Merkle Hash Tree. The output is a single HASH_SIZE Merkle Tree Hash. Given an ordered list of n inputs, D_n = {d[0], d[1], ..., d[n-1]}, the Merkle Tree Hash (MTH) is thus defined as follows:

The hash of an empty list is the hash of an empty string:

MTH({}) = HASH().

The hash of a list with one entry (also known as a leaf hash) is:

MTH({d[0]}) = HASH(0x00 || d[0]).

For n > 1, let k be the largest power of two smaller than n (i.e., k < n <= 2k). The Merkle Tree Hash of an n-element list D_n is then defined recursively as

MTH(D_n) = HASH(0x01 || MTH(D[0:k]) || MTH(D[k:n])),

Where || is concatenation and D[k1:k2] = D'_(k2-k1) denotes the list {d'[0] = d[k1], d'[1] = d[k1+1], ..., d'[k2-k1-1] = d[k2-1]} of length (k2 - k1). (Note that the hash calculations for leaves and nodes differ; this domain separation is required to give second preimage resistance).

Note that we do not require the length of the input list to be a power of two. The resulting Merkle Tree may thus not be balanced; however, its shape is uniquely determined by the number of leaves. (Note: This Merkle Tree is essentially the same as the history tree [CrosbyWallach] proposal, except our definition handles non-full trees differently).

2.1.2. Verifying a Tree Head Given Entries

When a client has a complete list of n input "entries" from "0" up to "tree_size - 1" and wishes to verify this list against a tree head "root_hash" returned by the log for the same "tree_size", the following algorithm may be used:

1. Set "stack" to an empty stack.
2. For each "i" from "0" up to "tree_size - 1":
    1. Push "HASH(0x00 || entries[i])" to "stack".
    2. Set "merge_count" to the lowest value ("0" included) such that "LSB(i >> merge_count)" is not set. In other words, set "merge_count" to the number of consecutive "1"s found starting at the least significant bit of "i".
    3. Repeat "merge_count" times:
        1. Pop "right" from "stack".
        2. Pop "left" from "stack".
        3. Push "HASH(0x01 || left || right)" to "stack".
3. If there is more than one element in the "stack", repeat the same merge procedure (Step 2.3 above) until only a single element remains.
4. The remaining element in "stack" is the Merkle Tree hash for the given "tree_size" and should be compared by equality against the supplied "root_hash".

2.1.3. Merkle Inclusion Proofs

A Merkle inclusion proof for a leaf in a Merkle Hash Tree is the shortest list of additional nodes in the Merkle Tree required to compute the Merkle Tree Hash for that tree. Each node in the tree is either a leaf node or is computed from the two nodes immediately below it (i.e., towards the leaves). At each step up the tree (towards the root), a node from the inclusion proof is combined with the node computed so far. In other words, the inclusion proof consists of the list of missing nodes required to compute the nodes leading from a leaf to the root of the tree. If the root computed from the inclusion proof matches the true root, then the inclusion proof proves that the leaf exists in the tree.

2.1.3.1. Generating an Inclusion Proof

Given an ordered list of n inputs to the tree, D_n = {d[0], d[1], ..., d[n-1]}, the Merkle inclusion proof PATH(m, D_n) for the (m+1)th input d[m], 0 <= m < n, is defined as follows:

The proof for the single leaf in a tree with a one-element input list D[1] = {d[0]} is empty:

PATH(0, {d[0]}) = {}

For n > 1, let k be the largest power of two smaller than n. The proof for the (m+1)th element d[m] in a list of n > m elements is then defined recursively as

PATH(m, D_n) = PATH(m, D[0:k]) : MTH(D[k:n]) for m < k; and

PATH(m, D_n) = PATH(m - k, D[k:n]) : MTH(D[0:k]) for m >= k,

The : operator and D[k1:k2] are defined the same as in Section 2.1.1.

2.1.3.2. Verifying an Inclusion Proof

When a client has received an inclusion proof (e.g., in a "TransItem" of type "inclusion_proof_v2") and wishes to verify inclusion of an input "hash" for a given "tree_size" and "root_hash", the following algorithm may be used to prove the "hash" was included in the "root_hash":

1. Compare "leaf_index" against "tree_size". If "leaf_index" is greater than or equal to "tree_size" then fail the proof verification.

2. Set "fn" to "leaf_index" and "sn" to "tree_size - 1".

3. Set "r" to "hash".

4. For each value "p" in the "inclusion_path" array:

   If "sn" is 0, stop the iteration and fail the proof verification.

   If "LSB(fn)" is set, or if "fn" is equal to "sn", then:

   1. Set "r" to "HASH(0x01 || p || r)"

   2. If "LSB(fn)" is not set, then right-shift both "fn" and "sn" equally until either "LSB(fn)" is set or "fn" is "0".

Otherwise:

1. Set "r" to "HASH(0x01 || r || p)"

Finally, right-shift both "fn" and "sn" one time.

5. Compare "sn" to 0. Compare "r" against the "root_hash". If "sn" is equal to 0, and "r" and the "root_hash" are equal, then the log has proven the inclusion of "hash". Otherwise, fail the proof verification.

2.1.4. Merkle Consistency Proofs

Merkle consistency proofs prove the append-only property of the tree. A Merkle consistency proof for a Merkle Tree Hash MTH(D_n) and a previously advertised hash MTH(D[0:m]) of the first m leaves, m <= n, is the list of nodes in the Merkle Tree required to verify that the first m inputs D[0:m] are equal in both trees. Thus, a consistency proof must contain a set of intermediate nodes (i.e., commitments to inputs) sufficient to verify MTH(D_n), such that (a subset of) the same nodes can be used to verify MTH(D[0:m]). We define an algorithm that outputs the (unique) minimal consistency proof.

2.1.4.1. Generating a Consistency Proof

Given an ordered list of n inputs to the tree, D_n = {d[0], d[1], ..., d[n-1]}, the Merkle consistency proof PROOF(m, D_n) for a previous Merkle Tree Hash MTH(D[0:m]), 0 < m < n, is defined as:

PROOF(m, D_n) = SUBPROOF(m, D_n, true)

In SUBPROOF, the boolean value represents whether the subtree created from D[0:m] is a complete subtree of the Merkle Tree created from D_n, and, consequently, whether the subtree Merkle Tree Hash MTH(D[0:m]) is known. The initial call to SUBPROOF sets this to be true, and SUBPROOF is then defined as follows:

The subproof for m = n is empty if m is the value for which PROOF was originally requested (meaning that the subtree created from D[0:m] is a complete subtree of the Merkle Tree created from the original D_n for which PROOF was requested, and the subtree Merkle Tree Hash MTH(D[0:m]) is known):

SUBPROOF(m, D[m], true) = {}

Otherwise, the subproof for m = n is the Merkle Tree Hash committing inputs D[0:m]:

SUBPROOF(m, D[m], false) = {MTH(D[m])}

For m < n, let k be the largest power of two smaller than n. The subproof is then defined recursively.

If m <= k, the right subtree entries D[k:n] only exist in the current tree. We prove that the left subtree entries D[0:k] are consistent and add a commitment to D[k:n]:

SUBPROOF(m, D_n, b) = SUBPROOF(m, D[0:k], b) : MTH(D[k:n])

If m > k, the left subtree entries D[0:k] are identical in both trees. We prove that the right subtree entries D[k:n] are consistent and add a commitment to D[0:k].

SUBPROOF(m, D_n, b) = SUBPROOF(m - k, D[k:n], false) : MTH(D[0:k])

The number of nodes in the resulting proof is bounded above by ceil(log2(n)) + 1.

The : operator and D[k1:k2] are defined the same as in Section 2.1.1.

2.1.4.2. Verifying Consistency between Two Tree Heads

When a client has a tree head "first_hash" for tree size "first", a tree head "second_hash" for tree size "second" where "0 < first < second", and has received a consistency proof between the two (e.g., in a "TransItem" of type "consistency_proof_v2"), the following algorithm may be used to verify the consistency proof:

1. If "first" is an exact power of 2, then prepend "first_hash" to the "consistency_path" array.

2. Set "fn" to "first - 1" and "sn" to "second - 1".

3. If "LSB(fn)" is set, then right-shift both "fn" and "sn" equally until "LSB(fn)" is not set.

4. Set both "fr" and "sr" to the first value in the "consistency_path" array.

5. For each subsequent value "c" in the "consistency_path" array:

   If "sn" is 0, stop the iteration and fail the proof verification.

   If "LSB(fn)" is set, or if "fn" is equal to "sn", then:

   1. Set "fr" to "HASH(0x01 || c || fr)"

Set "sr" to "HASH(0x01 || c || sr)"

2. If "LSB(fn)" is not set, then right-shift both "fn" and "sn" equally until either "LSB(fn)" is set or "fn" is "0".

Otherwise:

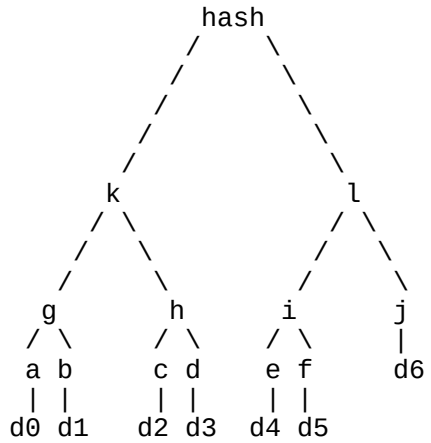
1. Set "sr" to "HASH(0x01 || sr || c)"

Finally, right-shift both "fn" and "sn" one time.

6. After completing iterating through the "consistency_path" array as described above, verify that the "fr" calculated is equal to the "first_hash" supplied, that the "sr" calculated is equal to the "second_hash" supplied and that "sn" is 0.

2.1.5. Example

The binary Merkle Tree with 7 leaves:



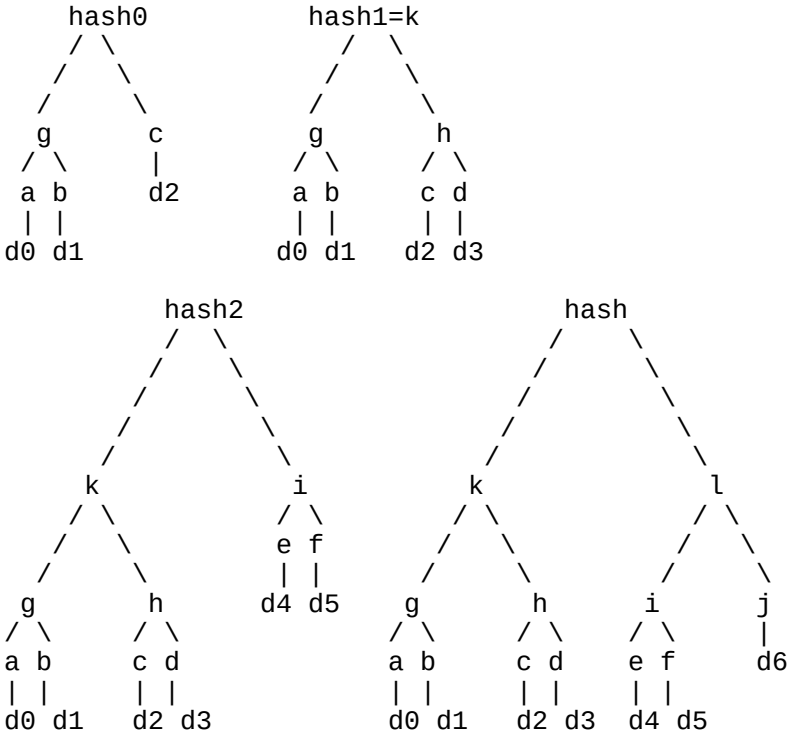
The inclusion proof for d0 is [b, h, l].

The inclusion proof for d3 is [c, g, l].

The inclusion proof for d4 is [f, j, k].

The inclusion proof for d6 is [i, k].

The same tree, built incrementally in four steps:



The consistency proof between hash0 and hash is PROOF(3, D[7]) = [c, d, g, l]. c, g are used to verify hash0, and d, l are additionally used to show hash is consistent with hash0.

The consistency proof between hash1 and hash is PROOF(4, D[7]) = [l]. hash can be verified using hash1=k and l.

The consistency proof between hash2 and hash is PROOF(6, D[7]) = [i, j, k]. k, i are used to verify hash2, and j is additionally used to show hash is consistent with hash2.

2.2. Signatures

Various data structures Section 1.2 are signed. A log MUST use one of the signature algorithms defined in Section 10.4.

3. Submitters

Submitters submit certificates or preannouncements of certificates prior to issuance (precertificates) to logs for public auditing, as described below. In order to enable attribution of each logged certificate or precertificate to its issuer, each submission MUST be

accompanied by all additional certificates required to verify the chain up to an accepted trust anchor. The trust anchor (a root or intermediate CA certificate) MAY be omitted from the submission.

If a log accepts a submission, it will return a Signed Certificate Timestamp (SCT) (see Section 4.8). The submitter SHOULD validate the returned SCT as described in Section 8.1 if they understand its format and they intend to use it directly in a TLS handshake or to construct a certificate. If the submitter does not need the SCT (for example, the certificate is being submitted simply to make it available in the log), it MAY validate the SCT.

3.1. Certificates

Any entity can submit a certificate (Section 5.1) to a log. Since it is anticipated that TLS clients will reject certificates that are not logged, it is expected that certificate issuers and subjects will be strongly motivated to submit them.

3.2. Precertificates

CAs may preannounce a certificate prior to issuance by submitting a precertificate (Section 5.1) that the log can use to create an entry that will be valid against the issued certificate. The CA MAY incorporate the returned SCT in the issued certificate. One example of where the returned SCT is not incorporated in the issued certificate is when a CA sends the precertificate to multiple logs, but only incorporates the SCTs that are returned first.

A precertificate is a CMS [RFC5652] "signed-data" object that conforms to the following profile:

- It MUST be DER encoded.
- "SignedData.version" MUST be v3(3).
- "SignedData.digestAlgorithms" MUST only include the "SignerInfo.digestAlgorithm" OID value (see below).
- "SignedData.encapContentInfo":
  - "eContentType" MUST be the OID 1.3.101.78.
  - "eContent" MUST contain a TBSCertificate [RFC5280] that will be identical to the TBSCertificate in the issued certificate, except that the Transparency Information (Section 7.1) extension MUST be omitted.

- "SignedData.certificates" MUST be omitted.
- "SignedData.crls" MUST be omitted.
- "SignedData.signerInfos" MUST contain one "SignerInfo":
  - "version" MUST be v3(3).
  - "sid" MUST use the "subjectKeyIdentifier" option.
  - "digestAlgorithm" MUST be one of the hash algorithm OIDs listed in Section 10.3.
  - "signedAttrs" MUST be present and MUST contain two attributes:
    - A content-type attribute whose value is the same as "SignedData.encapContentInfo.eContentType".
    - A message-digest attribute whose value is the message digest of "SignedData.encapContentInfo.eContent".
  - "signatureAlgorithm" MUST be the same OID as "TBSCertificate.signature".
  - "signature" MUST be from the same (root or intermediate) CA that will ultimately issue the certificate. This signature indicates the CA's intent to issue the certificate. This intent is considered binding (i.e., misissuance of the precertificate is considered equivalent to misissuance of the corresponding certificate).
  - "unsignedAttrs" MUST be omitted.

"SignerInfo.signedAttrs" is included in the message digest calculation process (see Section 5.4 of [RFC5652]), which ensures that the "SignerInfo.signature" value will not be a valid X.509v3 signature that could be used in conjunction with the TBSCertificate (from "SignedData.encapContentInfo.eContent") to construct a valid certificate.

4. Log Format and Operation

A log is a single, append-only Merkle Tree of submitted certificate and precertificate entries.

When it receives and accepts a valid submission, the log MUST return an SCT that corresponds to the submitted certificate or precertificate. If the log has previously seen this valid

submission, it SHOULD return the same SCT as it returned before (to reduce the ability to track clients as described in Section 11.4). If different SCTs are produced for the same submission, multiple log entries will have to be created, one for each SCT (as the timestamp is a part of the leaf structure). Note that if a certificate was previously logged as a precertificate, then the precertificate's SCT of type "precert_sct_v2" would not be appropriate; instead, a fresh SCT of type "x509_sct_v2" should be generated.

An SCT is the log's promise to append to its Merkle Tree an entry for the accepted submission. Upon producing an SCT, the log MUST fulfil this promise by performing the following actions within a fixed amount of time known as the Maximum Merge Delay (MMD), which is one of the log's parameters (see Section 4.1): * Allocate a tree index to the entry representing the accepted submission. * Calculate the root of the tree. * Sign the root of the tree (see Section 4.10). The log may append multiple entries before signing the root of the tree.

Log operators SHOULD NOT impose any conditions on retrieving or sharing data from the log.

4.1. Log Parameters

A log is defined by a collection of parameters, which are used by clients to communicate with the log and to verify log artifacts.

Base URL: The URL to substitute for <log server> in Section 5.

Hash Algorithm: The hash algorithm used for the Merkle Tree (see Section 10.3).

Signature Algorithm: The signature algorithm used (see Section 2.2).

Public Key: The public key used to verify signatures generated by the log. A log MUST NOT use the same keypair as any other log.

Log ID: The OID that uniquely identifies the log.

Maximum Merge Delay: The MMD the log has committed to.

Version: The version of the protocol supported by the log (currently 1 or 2).

Maximum Chain Length: The longest chain submission the log is willing to accept, if the log chose to limit it.

STH Frequency Count: The maximum number of STHs the log may produce in any period equal to the "Maximum Merge Delay" (see Section 4.10).

Final STH: If a log has been closed down (i.e., no longer accepts new entries), existing entries may still be valid. In this case, the client should know the final valid STH in the log to ensure no new entries can be added without detection. The final STH should be provided in the form of a TransItem of type "signed_tree_head_v2".

[JSON.Metadata] is an example of a metadata format which includes the above elements.

4.2. Accepting Submissions

To avoid being overloaded by invalid submissions, the log MUST NOT accept any submission until it has verified that the submitted certificate or precertificate has a valid signature chain to an accepted trust anchor, using only the chain of intermediate CA certificates provided by the submitter.

Logs SHOULD accept certificates and precertificates that are fully valid according to RFC 5280 [RFC5280] verification rules and are submitted with such a chain. (A log may decide, for example, to temporarily reject valid submissions to protect itself against denial-of-service attacks).

Logs MAY accept certificates and precertificates that have expired, are not yet valid, have been revoked, or are otherwise not fully valid according to RFC 5280 verification rules in order to accommodate quirks of CA certificate-issuing software. However, logs MUST reject submissions without a valid signature chain to an accepted trust anchor. Logs MUST also reject precertificates that do not conform to the requirements in Section 3.2.

Logs SHOULD limit the length of chain they will accept. The maximum chain length is one of the log’s parameters (see Section 4.1).

The log SHALL allow retrieval of its list of accepted trust anchors (see Section 5.7), each of which is a root or intermediate CA certificate. This list might usefully be the union of root certificates trusted by major browser vendors.

4.3. Log Entries

If a submission is accepted and an SCT issued, the accepting log MUST store the entire chain used for verification. This chain MUST include the certificate or precertificate itself, the zero or more intermediate CA certificates provided by the submitter, and the trust anchor used to verify the chain (even if it was omitted from the submission). The log MUST present this chain for auditing upon request (see Section 5.6). This prevents the CA from avoiding blame by logging a partial or empty chain. Each log entry is a "TransItem" structure of type "x509_entry_v2" or "precert_entry_v2". However, a log may store its entries in any format. If a log does not store this "TransItem" in full, it must store the "timestamp" and "sct_extensions" of the corresponding "TimestampedCertificateEntryDataV2" structure. The "TransItem" can be reconstructed from these fields and the entire chain that the log used to verify the submission.

4.4. Log ID

Each log is identified by an OID, which is one of the log's parameters (see Section 4.1) and which MUST NOT be used to identify any other log. A log's operator MUST either allocate the OID themselves or request an OID from the Log ID Registry (see Section 10.7.1). Various data structures include the DER encoding of this OID, excluding the ASN.1 tag and length bytes, in an opaque vector:

```
opaque LogID<2..127>;
```

Note that the ASN.1 length and the opaque vector length are identical in size (1 byte) and value, so the DER encoding of the OID can be reproduced simply by prepending an OBJECT IDENTIFIER tag (0x06) to the opaque vector length and contents.

OIDs used to identify logs are limited such that the DER encoding of their value is less than or equal to 127 octets.

4.5. TransItem Structure

Various data structures are encapsulated in the "TransItem" structure to ensure that the type and version of each one is identified in a common fashion:

```
enum {
    reserved(0),
    x509_entry_v2(1), precert_entry_v2(2),
    x509_sct_v2(3), precert_sct_v2(4),
    signed_tree_head_v2(5), consistency_proof_v2(6),
    inclusion_proof_v2(7),
    (65535)
} VersionedTransType;

struct {
    VersionedTransType versioned_type;
    select (versioned_type) {
        case x509_entry_v2: TimestampedCertificateEntryDataV2;
        case precert_entry_v2: TimestampedCertificateEntryDataV2;
        case x509_sct_v2: SignedCertificateTimestampDataV2;
        case precert_sct_v2: SignedCertificateTimestampDataV2;
        case signed_tree_head_v2: SignedTreeHeadDataV2;
        case consistency_proof_v2: ConsistencyProofDataV2;
        case inclusion_proof_v2: InclusionProofDataV2;
    } data;
} TransItem;
```

"versioned_type" is a value from the IANA registry in Section 10.5 that identifies the type of the encapsulated data structure and the earliest version of this protocol to which it conforms. This document is v2.

"data" is the encapsulated data structure. The various structures named with the "DataV2" suffix are defined in later sections of this document.

Note that "VersionedTransType" combines the v1 [RFC6962] type enumerations "Version", "LogEntryType", "SignatureType" and "MerkleLeafType". Note also that v1 did not define "TransItem", but this document provides guidelines (see Appendix A) on how v2 implementations can co-exist with v1 implementations.

Future versions of this protocol may reuse "VersionedTransType" values defined in this document as long as the corresponding data structures are not modified, and may add new "VersionedTransType" values for new or modified data structures.

4.6. Log Artifact Extensions

```
enum {
    reserved(65535)
} ExtensionType;

struct {
    ExtensionType extension_type;
    opaque extension_data<0..2^16-1>;
} Extension;
```

The "Extension" structure provides a generic extensibility for log artifacts, including Signed Certificate Timestamps (Section 4.8) and Signed Tree Heads (Section 4.10). The interpretation of the "extension_data" field is determined solely by the value of the "extension_type" field.

This document does not define any extensions, but it does establish a registry for future "ExtensionType" values (see Section 10.6). Each document that registers a new "ExtensionType" must specify the context in which it may be used (e.g., SCT, STH, or both) and describe how to interpret the corresponding "extension_data".

4.7. Merkle Tree Leaves

The leaves of a log's Merkle Tree correspond to the log's entries (see Section 4.3). Each leaf is the leaf hash (Section 2.1) of a "TransItem" structure of type "x509_entry_v2" or "precert_entry_v2", which encapsulates a "TimestampedCertificateEntryDataV2" structure. Note that leaf hashes are calculated as HASH(0x00 || TransItem), where the hash algorithm is one of the log's parameters.

```
opaque TBSCertificate<1..2^24-1>;

struct {
    uint64 timestamp;
    opaque issuer_key_hash<32..2^8-1>;
    TBSCertificate tbs_certificate;
    Extension sct_extensions<0..2^16-1>;
} TimestampedCertificateEntryDataV2;
```

"timestamp" is the NTP Time [RFC5905] at which the certificate or precertificate was accepted by the log, measured in milliseconds since the epoch (January 1, 1970, 00:00 UTC), ignoring leap seconds. Note that the leaves of a log's Merkle Tree are not required to be in strict chronological order.

"issuer_key_hash" is the HASH of the public key of the CA that issued the certificate or precertificate, calculated over the DER encoding of the key represented as SubjectPublicKeyInfo [RFC5280]. This is

needed to bind the CA to the certificate or precertificate, making it impossible for the corresponding SCT to be valid for any other certificate or precertificate whose TBSCertificate matches "tbs_certificate". The length of the "issuer_key_hash" MUST match HASH_SIZE.

"tbs_certificate" is the DER encoded TBSCertificate from the submission. (Note that a precertificate's TBSCertificate can be reconstructed from the corresponding certificate as described in Section 8.1.2).

"sct_extensions" matches the SCT extensions of the corresponding SCT.

The type of the "TransItem" corresponds to the value of the "type" parameter supplied in the Section 5.1 call.

4.8. Signed Certificate Timestamp (SCT)

An SCT is a "TransItem" structure of type "x509_sct_v2" or "precert_sct_v2", which encapsulates a "SignedCertificateTimestampDataV2" structure:

```
struct {
    LogID log_id;
    uint64 timestamp;
    Extension sct_extensions<0..2^16-1>;
    opaque signature<0..2^16-1>;
} SignedCertificateTimestampDataV2;
```

"log_id" is this log's unique ID, encoded in an opaque vector as described in Section 4.4.

"timestamp" is equal to the timestamp from the corresponding "TimestampedCertificateEntryDataV2" structure.

"sct_extensions" is a vector of 0 or more SCT extensions. This vector MUST NOT include more than one extension with the same "extension_type". The extensions in the vector MUST be ordered by the value of the "extension_type" field, smallest value first. If an implementation sees an extension that it does not understand, it SHOULD ignore that extension. Furthermore, an implementation MAY choose to ignore any extension(s) that it does understand.

"signature" is computed over a "TransItem" structure of type "x509_entry_v2" or "precert_entry_v2" (see Section 4.7) using the signature algorithm declared in the log's parameters (see Section 4.1).

4.9. Merkle Tree Head

The log stores information about its Merkle Tree in a "TreeHeadDataV2":

```
opaque NodeHash<32..2^8-1>;

struct {
    uint64 timestamp;
    uint64 tree_size;
    NodeHash root_hash;
    Extension sth_extensions<0..2^16-1>;
} TreeHeadDataV2;
```

The length of NodeHash MUST match HASH_SIZE of the log.

"timestamp" is the current NTP Time [RFC5905], measured in milliseconds since the epoch (January 1, 1970, 00:00 UTC), ignoring leap seconds.

"tree_size" is the number of entries currently in the log's Merkle Tree.

"root_hash" is the root of the Merkle Hash Tree.

"sth_extensions" is a vector of 0 or more STH extensions. This vector MUST NOT include more than one extension with the same "extension_type". The extensions in the vector MUST be ordered by the value of the "extension_type" field, smallest value first. If an implementation sees an extension that it does not understand, it SHOULD ignore that extension. Furthermore, an implementation MAY choose to ignore any extension(s) that it does understand.

4.10. Signed Tree Head (STH)

Periodically each log SHOULD sign its current tree head information (see Section 4.9) to produce an STH. When a client requests a log's latest STH (see Section 5.2), the log MUST return an STH that is no older than the log's MMD. However, since STHs could be used to mark individual clients (by producing a new STH for each query), a log MUST NOT produce STHs more frequently than its parameters declare (see Section 4.1). In general, there is no need to produce a new STH unless there are new entries in the log; however, in the event that a log does not accept any submissions during an MMD period, the log MUST sign the same Merkle Tree Hash with a fresh timestamp.

An STH is a "TransItem" structure of type "signed_tree_head_v2", which encapsulates a "SignedTreeHeadDataV2" structure:

```
struct {
    LogID log_id;
    TreeHeadDataV2 tree_head;
    opaque signature<0..2^16-1>;
} SignedTreeHeadDataV2;
```

"log_id" is this log's unique ID, encoded in an opaque vector as described in Section 4.4.

The "timestamp" in "tree_head" MUST be at least as recent as the most recent SCT timestamp in the tree. Each subsequent timestamp MUST be more recent than the timestamp of the previous update.

"tree_head" contains the latest tree head information (see Section 4.9).

"signature" is computed over the "tree_head" field using the signature algorithm declared in the log's parameters (see Section 4.1).

4.11. Merkle Consistency Proofs

To prepare a Merkle Consistency Proof for distribution to clients, the log produces a "TransItem" structure of type "consistency_proof_v2", which encapsulates a "ConsistencyProofDataV2" structure:

```
struct {
    LogID log_id;
    uint64 tree_size_1;
    uint64 tree_size_2;
    NodeHash consistency_path<1..2^16-1>;
} ConsistencyProofDataV2;
```

"log_id" is this log's unique ID, encoded in an opaque vector as described in Section 4.4.

"tree_size_1" is the size of the older tree.

"tree_size_2" is the size of the newer tree.

"consistency_path" is a vector of Merkle Tree nodes proving the consistency of two STHs.

4.12. Merkle Inclusion Proofs

To prepare a Merkle Inclusion Proof for distribution to clients, the log produces a "TransItem" structure of type "inclusion_proof_v2", which encapsulates an "InclusionProofDataV2" structure:

```
struct {
    LogID log_id;
    uint64 tree_size;
    uint64 leaf_index;
    NodeHash inclusion_path<1..2^16-1>;
} InclusionProofDataV2;
```

"log_id" is this log's unique ID, encoded in an opaque vector as described in Section 4.4.

"tree_size" is the size of the tree on which this inclusion proof is based.

"leaf_index" is the 0-based index of the log entry corresponding to this inclusion proof.

"inclusion_path" is a vector of Merkle Tree nodes proving the inclusion of the chosen certificate or precertificate.

4.13. Shutting down a log

Log operators may decide to shut down a log for various reasons, such as deprecation of the signature algorithm. If there are entries in the log for certificates that have not yet expired, simply making TLS clients stop recognizing that log will have the effect of invalidating SCTs from that log. To avoid that, the following actions are suggested:

- Make it known to clients and monitors that the log will be frozen.
- Stop accepting new submissions (the error code "shutdown" should be returned for such requests).
- Once MMD from the last accepted submission has passed and all pending submissions are incorporated, issue a final STH and publish it as one of the log's parameters. Having an STH with a timestamp that is after the MMD has passed from the last SCT issuance allows clients to audit this log regularly without special handling for the final STH. At this point the log's private key is no longer needed and can be destroyed.

- o Keep the log running until the certificates in all of its entries have expired or exist in other logs (this can be determined by scanning other logs or connecting to domains mentioned in the certificates and inspecting the SCTs served).

5. Log Client Messages

Messages are sent as HTTPS GET or POST requests. Parameters for POSTs and all responses are encoded as JavaScript Object Notation (JSON) objects [RFC7159]. Parameters for GETs are encoded as order-independent key/value URL parameters, using the "application/x-www-form-urlencoded" format described in the "HTML 4.01 Specification" [HTML401]. Binary data is base64 encoded [RFC4648] as specified in the individual messages.

Clients are configured with a base URL for a log and construct URLs for requests by appending suffixes to this base URL. This structure places some degree of restriction on how log operators can deploy these services, as noted in [RFC7320]. However, operational experience with version 1 of this protocol has not indicated that these restrictions are a problem in practice.

Note that JSON objects and URL parameters may contain fields not specified here. These extra fields should be ignored.

The <log server> prefix, which is one of the log’s parameters, MAY include a path as well as a server name and a port.

In practice, log servers may include multiple front-end machines. Since it is impractical to keep these machines in perfect sync, errors may occur that are caused by skew between the machines. Where such errors are possible, the front-end will return additional information (as specified below) making it possible for clients to make progress, if progress is possible. Front-ends MUST only serve data that is free of gaps (that is, for example, no front-end will respond with an STH unless it is also able to prove consistency from all log entries logged within that STH).

For example, when a consistency proof between two STHs is requested, the front-end reached may not yet be aware of one or both STHs. In the case where it is unaware of both, it will return the latest STH it is aware of. Where it is aware of the first but not the second, it will return the latest STH it is aware of and a consistency proof from the first STH to the returned STH. The case where it knows the second but not the first should not arise (see the "no gaps" requirement above).

If the log is unable to process a client's request, it MUST return an HTTP response code of 4xx/5xx (see [RFC7231]), and, in place of the responses outlined in the subsections below, the body SHOULD be a JSON structure containing at least the following field:

error_message: A human-readable string describing the error which prevented the log from processing the request.

In the case of a malformed request, the string SHOULD provide sufficient detail for the error to be rectified.

error_code: An error code readable by the client. Other than the generic codes detailed here, each error code is specific to the type of request. Specific errors are specified in the respective sections below. Error codes are fixed text strings.

Error Code	Meaning
not compliant	The request is not compliant with this RFC.

e.g., In response to a request of "/ct/v2/get-entries?start=100&end=99", the log would return a "400 Bad Request" response code with a body similar to the following:

```
{
    "error_message": "'start' cannot be greater than 'end'",
    "error_code": "not compliant",
}
```

Clients SHOULD treat "500 Internal Server Error" and "503 Service Unavailable" responses as transient failures and MAY retry the same request without modification at a later date. Note that as per [RFC7231], in the case of a 503 response the log MAY include a "Retry-After:" header in order to request a minimum time for the client to wait before retrying the request.

5.1. Submit Entry to Log

POST https://<log server>/ct/v2/submit-entry

Inputs:

submission: The base64 encoded certificate or precertificate.

type: The "VersionedTransType" integer value that indicates the type of the "submission": 1 for "x509_entry_v2", or 2 for "precert_entry_v2".

chain: An array of zero or more base64 encoded CA certificates. The first element is the signer of the "submission"; the second certifies the first; etc. The last element of "chain" (or, if "chain" is an empty array, the "submission") either is, or is certified by, an accepted trust anchor.

Outputs:

sct: A base64 encoded "TransItem" of type "x509_sct_v2" or "precert_sct_v2", signed by this log, that corresponds to the "submission".

If the submitted entry is immediately appended to (or already exists in) this log’s tree, then the log SHOULD also output:

sth: A base64 encoded "TransItem" of type "signed_tree_head_v2", signed by this log.

inclusion: A base64 encoded "TransItem" of type "inclusion_proof_v2" whose "inclusion_path" array of Merkle Tree nodes proves the inclusion of the "submission" in the returned "sth".

Error codes:

Error Code	Meaning
bad submission	"submission" is neither a valid certificate nor a valid precertificate.
bad type	"type" is neither 1 nor 2.
bad chain	The first element of "chain" is not the signer of the "submission", or the second element does not certify the first, etc.
bad certificate	One or more certificates in the "chain" are not valid (e.g., not properly encoded).
unknown anchor	The last element of "chain" (or, if "chain" is an empty array, the "submission") both is not, and is not certified by, an accepted trust anchor.
shutdown	The log is no longer accepting submissions.

If the version of "sct" is not v2, then a v2 client may be unable to verify the signature. It MUST NOT construe this as an error. This is to avoid forcing an upgrade of compliant v2 clients that do not use the returned SCTs.

If a log detects bad encoding in a chain that otherwise verifies correctly then the log MUST either log the certificate or return the "bad certificate" error. If the certificate is logged, an SCT MUST be issued. Logging the certificate is useful, because monitors (Section 8.2) can then detect these encoding errors, which may be accepted by some TLS clients.

If the returned "sct" is intended to be provided to clients, then "sth" and "inclusion" (if returned) SHOULD also be provided to clients (e.g., if "type" was 1 then all three "TransItem"s could be embedded in the certificate).

5.2. Retrieve Latest Signed Tree Head

GET https://<log server>/ct/v2/get-sth

No inputs.

Outputs:

sth: A base64 encoded "TransItem" of type "signed_tree_head_v2", signed by this log, that is no older than the log's MMD.

5.3. Retrieve Merkle Consistency Proof between Two Signed Tree Heads

GET https://<log server>/ct/v2/get-sth-consistency

Inputs:

first: The tree_size of the older tree, in decimal.

second: The tree_size of the newer tree, in decimal (optional).

Both tree sizes must be from existing v2 STHs. However, because of skew, the receiving front-end may not know one or both of the existing STHs. If both are known, then only the "consistency" output is returned. If the first is known but the second is not (or has been omitted), then the latest known STH is returned, along with a consistency proof between the first STH and the latest. If neither are known, then the latest known STH is returned without a consistency proof.

Outputs:

consistency: A base64 encoded "TransItem" of type "consistency_proof_v2", whose "tree_size_1" MUST match the "first" input. If the "sth" output is omitted, then "tree_size_2" MUST match the "second" input. If "first" and "second" are equal and correspond to a known STH, the returned consistency proof MUST be empty (a "consistency_path" array with zero elements).

sth: A base64 encoded "TransItem" of type "signed_tree_head_v2", signed by this log.

Note that no signature is required for the "consistency" output as it is used to verify the consistency between two STHs, which are signed.

Error codes:

Error Code	Meaning
first unknown	"first" is before the latest known STH but is not from an existing STH.
second unknown	"second" is before the latest known STH but is not from an existing STH.

See Section 2.1.4.2 for an outline of how to use the "consistency" output.

5.4. Retrieve Merkle Inclusion Proof from Log by Leaf Hash

GET https://<log server>/ct/v2/get-proof-by-hash

Inputs:

hash: A base64 encoded v2 leaf hash.

tree_size: The tree_size of the tree on which to base the proof, in decimal.

The "hash" must be calculated as defined in Section 4.7. The "tree_size" must designate an existing v2 STH. Because of skew, the front-end may not know the requested STH. In that case, it will return the latest STH it knows, along with an inclusion proof to that STH. If the front-end knows the requested STH then only "inclusion" is returned.

Outputs:

inclusion: A base64 encoded "TransItem" of type "inclusion_proof_v2" whose "inclusion_path" array of Merkle Tree nodes proves the inclusion of the chosen certificate in the selected STH.

sth: A base64 encoded "TransItem" of type "signed_tree_head_v2", signed by this log.

Note that no signature is required for the "inclusion" output as it is used to verify inclusion in the selected STH, which is signed.

Error codes:

Error Code	Meaning
hash unknown	"hash" is not the hash of a known leaf (may be caused by skew or by a known certificate not yet merged).
tree_size unknown	"hash" is before the latest known STH but is not from an existing STH.

See Section 2.1.3.2 for an outline of how to use the "inclusion" output.

5.5. Retrieve Merkle Inclusion Proof, Signed Tree Head and Consistency Proof by Leaf Hash

GET https://<log server>/ct/v2/get-all-by-hash

Inputs:

hash: A base64 encoded v2 leaf hash.

tree_size: The tree_size of the tree on which to base the proofs, in decimal.

The "hash" must be calculated as defined in Section 4.7. The "tree_size" must designate an existing v2 STH.

Because of skew, the front-end may not know the requested STH or the requested hash, which leads to a number of cases.

latest STH < requested STH Return latest STH.

latest STH > requested STH Return latest STH and a consistency proof between it and the requested STH (see Section 5.3).

index of requested hash < latest STH Return "inclusion".

Note that more than one case can be true, in which case the returned data is their concatenation. It is also possible for

none to be true, in which case the front-end MUST return an empty response.

Outputs:

inclusion: A base64 encoded "TransItem" of type "inclusion_proof_v2" whose "inclusion_path" array of Merkle Tree nodes proves the inclusion of the chosen certificate in the returned STH.

sth: A base64 encoded "TransItem" of type "signed_tree_head_v2", signed by this log.

consistency: A base64 encoded "TransItem" of type "consistency_proof_v2" that proves the consistency of the requested STH and the returned STH.

Note that no signature is required for the "inclusion" or "consistency" outputs as they are used to verify inclusion in and consistency of STHs, which are signed.

Errors are the same as in Section 5.4.

See Section 2.1.3.2 for an outline of how to use the "inclusion" output, and see Section 2.1.4.2 for an outline of how to use the "consistency" output.

5.6. Retrieve Entries and STH from Log

GET https://<log server>/ct/v2/get-entries

Inputs:

start: 0-based index of first entry to retrieve, in decimal.

end: 0-based index of last entry to retrieve, in decimal.

Outputs:

entries: An array of objects, each consisting of

log_entry: The base64 encoded "TransItem" structure of type "x509_entry_v2" or "precert_entry_v2" (see Section 4.3).

submitted_entry: JSON object representing the inputs that were submitted to "submit-entry", with the addition of the trust anchor to the "chain" field if the submission did not include it.

sct: The base64 encoded "TransItem" of type "x509_sct_v2" or "precert_sct_v2" corresponding to this log entry.

sth: A base64 encoded "TransItem" of type "signed_tree_head_v2", signed by this log.

Note that this message is not signed -- the "entries" data can be verified by constructing the Merkle Tree Hash corresponding to a retrieved STH. All leaves MUST be v2. However, a compliant v2 client MUST NOT construe an unrecognized TransItem type as an error. This means it may be unable to parse some entries, but note that each client can inspect the entries it does recognize as well as verify the integrity of the data by treating unrecognized leaves as opaque input to the tree.

The "start" and "end" parameters SHOULD be within the range 0 <= x < "tree_size" as returned by "get-sth" in Section 5.2.

The "start" parameter MUST be less than or equal to the "end" parameter.

The "chain" field in the "submission" output parameter MUST include the trust anchor that the log used to verify the submission, even if it was omitted in the original submission.

Log servers MUST honor requests where 0 <= "start" < "tree_size" and "end" >= "tree_size" by returning a partial response covering only the valid entries in the specified range. "end" >= "tree_size" could be caused by skew. Note that the following restriction may also apply:

Logs MAY restrict the number of entries that can be retrieved per "get-entries" request. If a client requests more than the permitted number of entries, the log SHALL return the maximum number of entries permissible. These entries SHALL be sequential beginning with the entry specified by "start".

Because of skew, it is possible the log server will not have any entries between "start" and "end". In this case it MUST return an empty "entries" array.

In any case, the log server MUST return the latest STH it knows about.

See Section 2.1.2 for an outline of how to use a complete list of "log_entry" entries to verify the "root_hash".

5.7. Retrieve Accepted Trust Anchors

GET https://<log server>/ct/v2/get-anchors

No inputs.

Outputs:

certificates: An array of base64 encoded trust anchors that are acceptable to the log.

max_chain_length: If the server has chosen to limit the length of chains it accepts, this is the maximum number of certificates in the chain, in decimal. If there is no limit, this is omitted.

6. TLS Servers

TLS servers MUST use at least one of the three mechanisms listed below to present one or more SCTs from one or more logs to each TLS client during full TLS handshakes, where each SCT corresponds to the server certificate. TLS servers SHOULD also present corresponding inclusion proofs and STHs.

Three mechanisms are provided because they have different tradeoffs.

- A TLS extension (Section 7.4.1.4 of [RFC5246]) with type "transparency_info" (see Section 6.4). This mechanism allows TLS servers to participate in CT without the cooperation of CAs, unlike the other two mechanisms. It also allows SCTs and inclusion proofs to be updated on the fly.

- An Online Certificate Status Protocol (OCSP) [RFC6960] response extension (see Section 7.1.1), where the OCSP response is provided in the "CertificateStatus" message, provided that the TLS client included the "status_request" extension in the (extended) "ClientHello" (Section 8 of [RFC6066]). This mechanism, popularly known as OCSP stapling, is already widely (but not universally) implemented. It also allows SCTs and inclusion proofs to be updated on the fly.

- An X509v3 certificate extension (see Section 7.1.2). This mechanism allows the use of unmodified TLS servers, but the SCTs and inclusion proofs cannot be updated on the fly. Since the logs from which the SCTs and inclusion proofs originated won't necessarily be accepted by TLS clients for the full lifetime of the certificate, there is a risk that TLS clients will

subsequently consider the certificate to be non-compliant and in need of re-issuance.

Additionally, a TLS server which supports presenting SCTs using an OCSP response MAY provide it when the TLS client included the "status_request_v2" extension ([RFC6961]) in the (extended) "ClientHello", but only in addition to at least one of the three mechanisms listed above.

6.1. Multiple SCTs

TLS servers SHOULD send SCTs from multiple logs in case one or more logs are not acceptable to the TLS client (for example, if a log has been struck off for misbehavior, has had a key compromise, or is not known to the TLS client). For example:

- If a CA and a log collude, it is possible to temporarily hide misissuance from clients. Including SCTs from different logs makes it more difficult to mount this attack.

- If a log misbehaves, a consequence may be that clients cease to trust it. Since the time an SCT may be in use can be considerable (several years is common in current practice when embedded in a certificate), servers may wish to reduce the probability of their certificates being rejected as a result by including SCTs from different logs.

- TLS clients may have policies related to the above risks requiring servers to present multiple SCTs. For example, at the time of writing, Chromium [Chromium.Log.Policy] requires multiple SCTs to be presented with EV certificates in order for the EV indicator to be shown.

To select the logs from which to obtain SCTs, a TLS server can, for example, examine the set of logs popular TLS clients accept and recognize.

6.2. TransItemList Structure

Multiple SCTs, inclusion proofs, and indeed "TransItem" structures of any type, are combined into a list as follows:

```
opaque SerializedTransItem<1..2^16-1>;

struct {
    SerializedTransItem trans_item_list<1..2^16-1>;
} TransItemList;
```

Here, "SerializedTransItem" is an opaque byte string that contains the serialized "TransItem" structure. This encoding ensures that TLS clients can decode each "TransItem" individually (so, for example, if there is a version upgrade, out-of-date clients can still parse old "TransItem" structures while skipping over new "TransItem" structures whose versions they don't understand).

6.3. Presenting SCTs, inclusions proofs and STHs

In each "TransItemList" that is sent to a client during a TLS handshake, the TLS server MUST include a "TransItem" structure of type "x509_sct_v2" or "precert_sct_v2" (except as described in Section 6.5).

Presenting inclusion proofs and STHs in the TLS handshake helps to protect the client's privacy (see Section 8.1.5) and reduces load on log servers. Therefore, if the TLS server can obtain them, it SHOULD also include "TransItem"s of type "inclusion_proof_v2" and "signed_tree_head_v2" in the "TransItemList".

6.4. transparency_info TLS Extension

Provided that a TLS client includes the "transparency_info" extension type in the ClientHello, the TLS server SHOULD include the "transparency_info" extension in the ServerHello with "extension_data" set to a "TransItemList". The TLS server SHOULD ignore any "extension_data" sent by the TLS client. Additionally, the TLS server MUST NOT process or include this extension when a TLS session is resumed, since session resumption uses the original session information.

6.5. cached_info TLS Extension

When a TLS server includes the "transparency_info" extension in the ServerHello, it SHOULD NOT include any "TransItem" structures of type "x509_sct_v2" or "precert_sct_v2" in the "TransItemList" if all of the following conditions are met:

- The TLS client includes the "transparency_info" extension type in the ClientHello.
- The TLS client includes the "cached_info" ([RFC7924]) extension type in the ClientHello, with a "CachedObject" of type "ct_compliant" (see Section 8.1.7) and at least one "CachedObject" of type "cert".
- The TLS server sends a modified Certificate message (as described in section 4.1 of [RFC7924]).

TLS servers SHOULD ignore the "hash_value" fields of each "CachedObject" of type "ct_compliant" sent by TLS clients.

7. Certification Authorities

7.1. Transparency Information X.509v3 Extension

The Transparency Information X.509v3 extension, which has OID 1.3.101.75 and SHOULD be non-critical, contains one or more "TransItem" structures in a "TransItemList". This extension MAY be included in OCSP responses (see Section 7.1.1) and certificates (see Section 7.1.2). Since RFC5280 requires the "extnValue" field (an OCTET STRING) of each X.509v3 extension to include the DER encoding of an ASN.1 value, a "TransItemList" MUST NOT be included directly. Instead, it MUST be wrapped inside an additional OCTET STRING, which is then put into the "extnValue" field:

```
TransparencyInformationSyntax ::= OCTET STRING
```

"TransparencyInformationSyntax" contains a "TransItemList".

7.1.1. OCSP Response Extension

A certification authority MAY include a Transparency Information X.509v3 extension in the "singleExtensions" of a "SingleResponse" in an OCSP response. All included SCTs and inclusion proofs MUST be for the certificate identified by the "certID" of that "SingleResponse", or for a precertificate that corresponds to that certificate.

7.1.2. Certificate Extension

A certification authority MAY include a Transparency Information X.509v3 extension in a certificate. All included SCTs and inclusion proofs MUST be for a precertificate that corresponds to this certificate.

7.2. TLS Feature X.509v3 Extension

A certification authority SHOULD NOT issue any certificate that identifies the "transparency_info" TLS extension in a TLS feature extension [RFC7633], because TLS servers are not required to support the "transparency_info" TLS extension in order to participate in CT (see Section 6).

8. Clients

There are various different functions clients of logs might perform. We describe here some typical clients and how they should function. Any inconsistency may be used as evidence that a log has not behaved correctly, and the signatures on the data structures prevent the log from denying that misbehavior.

All clients need various parameters in order to communicate with logs and verify their responses. These parameters are described in Section 4.1, but note that this document does not describe how the parameters are obtained, which is implementation-dependent (see, for example, [Chromium.Policy]).

Clients should somehow exchange STHs they see, or make them available for scrutiny, in order to ensure that they all have a consistent view. The exact mechanisms will be in separate documents, but it is expected there will be a variety.

8.1. TLS Client

8.1.1. Receiving SCTs and inclusion proofs

TLS clients receive SCTs alongside or in certificates. TLS clients MUST implement all of the three mechanisms by which TLS servers may present SCTs (see Section 6). TLS clients MAY also accept SCTs via the "status_request_v2" extension ([RFC6961]). TLS clients that support the "transparency_info" TLS extension SHOULD include it in ClientHello messages, with empty "extension_data". TLS clients may also receive inclusion proofs in addition to SCTs, which should be checked once the SCTs are validated.

8.1.2. Reconstructing the TBSCertificate

To reconstruct the TBSCertificate component of a precertificate from a certificate, TLS clients should remove the Transparency Information extension described in Section 7.1.

If the SCT checked is for a precertificate (where the "type" of the "TransItem" is "precert_sct_v2"), then the client SHOULD also remove embedded v1 SCTs, identified by OID 1.3.6.1.4.1.11129.2.4.2 (See Section 3.3. of [RFC6962]), in the process of reconstructing the TBSCertificate. That is to allow embedded v1 and v2 SCTs to co-exist in a certificate (See Appendix A).

8.1.3. Validating SCTs

In addition to normal validation of the server certificate and its chain, TLS clients SHOULD validate each received SCT for which they have the corresponding log's parameters. To validate an SCT, a TLS client computes the signature input by constructing a "TransItem" of type "x509_entry_v2" or "precert_entry_v2", depending on the SCT's "TransItem" type. The "TimestampedCertificateEntryDataV2" structure is constructed in the following manner:

- "timestamp" is copied from the SCT.
- "tbs_certificate" is the reconstructed TBSCertificate portion of the server certificate, as described in Section 8.1.2.
- "issuer_key_hash" is computed as described in Section 4.7.
- "sct_extensions" is copied from the SCT.

The SCT's "signature" is then verified using the public key of the corresponding log, which is identified by the "log_id". The required signature algorithm is one of the log's parameters.

TLS clients MUST NOT consider valid any SCT whose timestamp is in the future.

8.1.4. Fetching inclusion proofs

When a TLS client has validated a received SCT but does not yet possess a corresponding inclusion proof, the TLS client MAY request the inclusion proof directly from a log using "get-proof-by-hash" (Section 5.4) or "get-all-by-hash" (Section 5.5). Note that this will disclose to the log which TLS server the client has been communicating with.

8.1.5. Validating inclusion proofs

When a TLS client has received, or fetched, an inclusion proof (and an STH), it SHOULD proceed to verifying the inclusion proof to the provided STH. The TLS client SHOULD also verify consistency between the provided STH and an STH it knows about.

If the TLS client holds an STH that predates the SCT, it MAY, in the process of auditing, request a new STH from the log (Section 5.2), then verify it by requesting a consistency proof (Section 5.3). Note that if the TLS client uses "get-all-by-hash", then it will already have the new STH.

8.1.6. Evaluating compliance

It is up to a client's local policy to specify the quantity and form of evidence (SCTs, inclusion proofs or a combination) needed to achieve compliance and how to handle non-compliance.

A TLS client MUST NOT evaluate compliance if it did not send both the "transparency_info" and "status_request" TLS extensions in the ClientHello.

8.1.7. cached_info TLS Extension

If a TLS client uses the "cached_info" TLS extension ([RFC7924]) to indicate 1 or more cached certificates, all of which it already considers to be CT compliant, the TLS client MAY also include a "CachedObject" of type "ct_compliant" in the "cached_info" extension. The "hash_value" field MUST be 1 byte long with the value 0.

8.2. Monitor

Monitors watch logs to check that they behave correctly, for certificates of interest, or both. For example, a monitor may be configured to report on all certificates that apply to a specific domain name when fetching new entries for consistency validation.

A monitor needs to, at least, inspect every new entry in each log it watches. It may also want to keep copies of entire logs. In order to do this, it should follow these steps for each log:

1. Fetch the current STH (Section 5.2).

2. Verify the STH signature.

3. Fetch all the entries in the tree corresponding to the STH (Section 5.6).

4. Confirm that the tree made from the fetched entries produces the same hash as that in the STH.

5. Fetch the current STH (Section 5.2). Repeat until the STH changes.

6. Verify the STH signature.

7. Fetch all the new entries in the tree corresponding to the STH (Section 5.6). If they remain unavailable for an extended period, then this should be viewed as misbehavior on the part of the log.

8. Either:

    1. Verify that the updated list of all entries generates a tree with the same hash as the new STH.

    Or, if it is not keeping all log entries:

    1. Fetch a consistency proof for the new STH with the previous STH (Section 5.3).

    2. Verify the consistency proof.

    3. Verify that the new entries generate the corresponding elements in the consistency proof.

9. Go to Step 5.

8.3. Auditing

Auditing ensures that the current published state of a log is reachable from previously published states that are known to be good, and that the promises made by the log in the form of SCTs have been kept. Audits are performed by monitors or TLS clients.

In particular, there are four log behavior properties that should be checked:

- The Maximum Merge Delay (MMD).
- The STH Frequency Count.
- The append-only property.
- The consistency of the log view presented to all query sources.

A benign, conformant log publishes a series of STHs over time, each derived from the previous STH and the submitted entries incorporated into the log since publication of the previous STH. This can be proven through auditing of STHs. SCTs returned to TLS clients can be audited by verifying against the accompanying certificate, and using Merkle Inclusion Proofs, against the log's Merkle tree.

The action taken by the auditor if an audit fails is not specified, but note that in general if audit fails, the auditor is in possession of signed proof of the log's misbehavior.

A monitor (Section 8.2) can audit by verifying the consistency of STHs it receives, ensure that each entry can be fetched and that the STH is indeed the result of making a tree from all fetched entries.

A TLS client (Section 8.1) can audit by verifying an SCT against any STH dated after the SCT timestamp + the Maximum Merge Delay by requesting a Merkle inclusion proof (Section 5.4). It can also verify that the SCT corresponds to the server certificate it arrived with (i.e., the log entry is that certificate, or is a precertificate corresponding to that certificate).

Checking of the consistency of the log view presented to all entities is more difficult to perform because it requires a way to share log responses among a set of CT-aware entities, and is discussed in Section 11.3.

9. Algorithm Agility

It is not possible for a log to change any of its algorithms part way through its lifetime:

Signature algorithm: SCT signatures must remain valid so signature algorithms can only be added, not removed.

Hash algorithm: A log would have to support the old and new hash algorithms to allow backwards-compatibility with clients that are not aware of a hash algorithm change.

Allowing multiple signature or hash algorithms for a log would require that all data structures support it and would significantly complicate client implementation, which is why it is not supported by this document.

If it should become necessary to deprecate an algorithm used by a live log, then the log should be frozen as specified in Section 4.13 and a new log should be started. Certificates in the frozen log that have not yet expired and require new SCTs SHOULD be submitted to the new log and the SCTs from that log used instead.

10. IANA Considerations

The assignment policy criteria mentioned in this section refer to the policies outlined in [RFC5226].

10.1. TLS Extension Type

IANA is asked to allocate an RFC 5246 ExtensionType value for the "transparency_info" TLS extension. IANA should update this extension type to point at this document.

10.2. New Entry to the TLS CachedInformationType registry

IANA is asked to add an entry for "ct_compliant(TBD)" to the "TLS CachedInformationType Values" registry that was defined in [RFC7924].

10.3. Hash Algorithms

IANA is asked to establish a registry of hash algorithm values, named "CT Hash Algorithms", that initially consists of:

Value	Hash Algorithm	OID	Reference / Assignment Policy
0x00	SHA-256	2.16.840.1.101.3.4.2.1	[RFC6234]
0x01 - 0xDF	Unassigned		Specification Required and Expert Review
0xE0 - 0xEF	Reserved		Experimental Use
0xF0 - 0xFF	Reserved		Private Use

10.3.1. Expert Review guidelines

The appointed Expert should ensure that the proposed algorithm has a public specification and is suitable for use as a cryptographic hash algorithm with no known preimage or collision attacks. These attacks can damage the integrity of the log.

10.4. Signature Algorithms

IANA is asked to establish a registry of signature algorithm values, named "CT Signature Algorithms", that initially consists of:

SignatureScheme Value	Signature Algorithm	Reference / Assignment Policy
ecdsa_secp256r1_sha256(0x0403)	ECDSA (NIST P-256) with SHA-256	[FIPS186-4]
ecdsa_secp256r1_sha256(0x0403)	Deterministic ECDSA (NIST P-256) with HMAC-SHA256	[RFC6979]
ed25519(0x0807)	Ed25519 (PureEdDSA with the edwards25519 curve)	[RFC8032]
private_use(0xFE00..0xFFFF)	Reserved	Private Use

10.4.1. Expert Review guidelines

The appointed Expert should ensure that the proposed algorithm has a public specification, has a value assigned to it in the TLS SignatureScheme Registry (that IANA is asked to establish in [I-D.ietf-tls-tls13]) and is suitable for use as a cryptographic signature algorithm.

10.5. VersionedTransTypes

IANA is asked to establish a registry of "VersionedTransType" values, named "CT VersionedTransTypes", that initially consists of:

Value	Type and Version	Reference / Assignment Policy
0x0000	Reserved	[RFC6962] (*)
0x0001	x509_entry_v2	RFCXXXX
0x0002	precert_entry_v2	RFCXXXX
0x0003	x509_sct_v2	RFCXXXX
0x0004	precert_sct_v2	RFCXXXX
0x0005	signed_tree_head_v2	RFCXXXX
0x0006	consistency_proof_v2	RFCXXXX
0x0007	inclusion_proof_v2	RFCXXXX
0x0008 - 0xDFFF	Unassigned	Specification Required and Expert Review
0xE000 - 0xEFFF	Reserved	Experimental Use
0xF000 - 0xFFFF	Reserved	Private Use

(*) The 0x0000 value is reserved so that v1 SCTs are distinguishable from v2 SCTs and other "TransItem" structures.

[RFC Editor: please update 'RFCXXXX' to refer to this document, once its RFC number is known.]

10.5.1. Expert Review guidelines

The appointed Expert should review the public specification to ensure that it is detailed enough to ensure implementation interoperability.

10.6. Log Artifact Extension Registry

IANA is asked to establish a registry of "ExtensionType" values, named "CT Log Artifact Extensions", that initially consists of:

ExtensionType	Status	Use	Reference / Assignment Policy
0x0000 - 0xDFFF	Unassigned	n/a	Specification Required and Expert Review
0xE000 - 0xEFFF	Reserved	n/a	Experimental Use
0xF000 - 0xFFFF	Reserved	n/a	Private Use

The "Use" column should contain one or both of the following values:

- "SCT", for extensions specified for use in Signed Certificate Timestamps.

- "STH", for extensions specified for use in Signed Tree Heads.

10.6.1. Expert Review guidelines

The appointed Expert should review the public specification to ensure that it is detailed enough to ensure implementation interoperability. The Expert should also verify that the extension is appropriate to the contexts in which it is specified to be used (SCT, STH, or both).

10.7. Object Identifiers

This document uses object identifiers (OIDs) to identify Log IDs (see Section 4.4), the precertificate CMS "eContentType" (see Section 3.2), and X.509v3 extensions in certificates (see Section 7.1.2) and OCSP responses (see Section 7.1.1). The OIDs are defined in an arc that was selected due to its short encoding.

10.7.1. Log ID Registry

IANA is asked to establish a registry of Log IDs, named "CT Log ID Registry", that initially consists of:

Value	Log	Reference / Assignment Policy
1.3.101.8192 - 1.3.101.16383	Unassigned	Parameters Required and Expert Review
1.3.101.80.0 - 1.3.101.80.127	Unassigned	Parameters Required and Expert Review
1.3.101.80.128 - 1.3.101.80.*	Unassigned	First Come First Served

All OIDs in the range from 1.3.101.8192 to 1.3.101.16383 have been reserved. This is a limited resource of 8,192 OIDs, each of which has an encoded length of 4 octets.

The 1.3.101.80 arc has been delegated. This is an unlimited resource, but only the 128 OIDs from 1.3.101.80.0 to 1.3.101.80.127 have an encoded length of only 4 octets.

Each application for the allocation of a Log ID should be accompanied by all of the required parameters (except for the Log ID) listed in Section 4.1.

10.7.2. Expert Review guidelines

Since the Log IDs with the shortest encodings are a limited resource, the appointed Expert should review the submitted parameters and judge whether or not the applicant is requesting a Log ID in good faith (with the intention of actually running a CT log that will be identified by the allocated Log ID).

11. Security Considerations

With CAs, logs, and servers performing the actions described here, TLS clients can use logs and signed timestamps to reduce the likelihood that they will accept misissued certificates. If a server presents a valid signed timestamp for a certificate, then the client knows that a log has committed to publishing the certificate. From this, the client knows that monitors acting for the subject of the certificate have had some time to notice the misissue and take some action, such as asking a CA to revoke a misissued certificate, or that the log has misbehaved, which will be discovered when the SCT is audited. A signed timestamp is not a guarantee that the certificate is not misissued, since appropriate monitors might not have checked the logs or the CA might have refused to revoke the certificate.

In addition, if TLS clients will not accept unlogged certificates, then site owners will have a greater incentive to submit certificates to logs, possibly with the assistance of their CA, increasing the overall transparency of the system.

[I-D.ietf-trans-threat-analysis] provides a more detailed threat analysis of the Certificate Transparency architecture.

11.1. Misissued Certificates

Misissued certificates that have not been publicly logged, and thus do not have a valid SCT, are not considered compliant. Misissued certificates that do have an SCT from a log will appear in that public log within the Maximum Merge Delay, assuming the log is operating correctly. As a log is allowed to serve an STH that's up to MMD old, the maximum period of time during which a misissued certificate can be used without being available for audit is twice the MMD.

11.2. Detection of Misissue

The logs do not themselves detect misissued certificates; they rely instead on interested parties, such as domain owners, to monitor them and take corrective action when a misissue is detected.

11.3. Misbehaving Logs

A log can misbehave in several ways. Examples include: failing to incorporate a certificate with an SCT in the Merkle Tree within the MMD; presenting different, conflicting views of the Merkle Tree at different times and/or to different parties; and issuing STHs too frequently. Such misbehavior is detectable and [I-D.ietf-trans-threat-analysis] provides more details on how this can be done.

Violation of the MMD contract is detected by log clients requesting a Merkle inclusion proof (Section 5.4) for each observed SCT. These checks can be asynchronous and need only be done once per certificate. In order to protect the clients' privacy, these checks need not reveal the exact certificate to the log. Instead, clients can request the proof from a trusted auditor (since anyone can compute the proofs from the log) or communicate with the log via proxies.

Violation of the append-only property or the STH issuance rate limit can be detected by clients comparing their instances of the Signed Tree Heads. There are various ways this could be done, for example via gossip (see [I-D.ietf-trans-gossip]) or peer-to-peer

communications or by sending STHs to monitors (who could then directly check against their own copy of the relevant log). Proof of misbehavior in such cases would be: a series of STHs that were issued too closely together, proving violation of the STH issuance rate limit; or an STH with a root hash that does not match the one calculated from a copy of the log, proving violation of the append-only property.

11.4. Preventing Tracking Clients

Clients that gossip STHs or report back SCTs can be tracked or traced if a log produces multiple STHs or SCTs with the same timestamp and data but different signatures. Logs SHOULD mitigate this risk by either:

- Using deterministic signature schemes, or
- Producing no more than one SCT for each distinct submission and no more than one STH for each distinct tree_size. Each of these SCTs and STHs can be stored by the log and served to other clients that submit the same certificate or request the same STH.

11.5. Multiple SCTs

By offering multiple SCTs, each from a different log, TLS servers reduce the effectiveness of an attack where a CA and a log collude (see Section 6.1).

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Appendix A. Supporting v1 and v2 simultaneously

Certificate Transparency logs have to be either v1 (conforming to [RFC6962]) or v2 (conforming to this document), as the data structures are incompatible and so a v2 log could not issue a valid v1 SCT.

CT clients, however, can support v1 and v2 SCTs, for the same certificate, simultaneously, as v1 SCTs are delivered in different TLS, X.509 and OCSP extensions than v2 SCTs.

v1 and v2 SCTs for X.509 certificates can be validated independently. For precertificates, v2 SCTs should be embedded in the TBSCertificate before submission of the TBSCertificate (inside a v1 precertificate, as described in Section 3.1. of [RFC6962]) to a v1 log so that TLS clients conforming to [RFC6962] but not this document are oblivious to the embedded v2 SCTs. An issuer can follow these steps to produce an X.509 certificate with embedded v1 and v2 SCTs:

- Create a CMS precertificate as described in Section 3.2 and submit it to v2 logs.
- Embed the obtained v2 SCTs in the TBSCertificate, as described in Section 7.1.2.
- Use that TBSCertificate to create a v1 precertificate, as described in Section 3.1. of [RFC6962] and submit it to v1 logs.
- Embed the v1 SCTs in the TBSCertificate, as described in Section 3.3 of [RFC6962].
- Sign that TBSCertificate (which now contains v1 and v2 SCTs) to issue the final X.509 certificate.

Authors' Addresses

Ben Laurie
Google UK Ltd.

Email: benl@google.com

Adam Langley
Google Inc.

Email: agl@google.com

Emilia Kasper
Google Switzerland GmbH

Email: ekasper@google.com

Eran Messeri
Google UK Ltd.

Email: eranm@google.com

Rob Stradling
Comodo CA, Ltd.

Email: rob.stradling@comodo.com

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S. Kent
BBN Technologies
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Attack and Threat Model for Certificate Transparency
draft-ietf-trans-threat-analysis-11

Abstract

This document describes an attack model and discusses threats for the Web PKI context in which security mechanisms to detect mis-issuance of web site certificates are being developed. The model provides an analysis of detection and remediation mechanisms for both syntactic and semantic mis-issuance. The model introduces an outline of attacks to organize the discussion. The model also describes the roles played by the elements of the Certificate Transparency (CT) system, to establish a context for the model.

Status of This Memo

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1. Introduction

Certificate transparency (CT) is a set of mechanisms designed to detect, deter, and facilitate remediation of certificate mis-issuance. The term certificate mis-issuance is defined here to encompass violations of either semantic or syntactic constraints. The fundamental semantic constraint for a certificate is that it was issued to an entity that is authorized to represent the Subject (or Subject Alternative) named in the certificate. (It is also assumed that the entity requested the certificate from the CA that issued it.) Throughout the remainder of this document we refer to a semantically mis-issued certificate as "bogus."

A certificate is characterized as syntactically mis-issued (aka erroneous) if it violates syntax constraints associated with the class of certificate that it purports to represent. Syntax constraints for certificates are established by certificate profiles, and typically are application-specific. For example, certificates used in the Web PKI environment might be characterized as domain validation (DV) or extended validation (EV) certificates. Certificates used with applications such as IPsec or S/MIME have different syntactic constraints from those in the Web PKI context.

There are three classes of beneficiaries of CT: certificate Subjects, CAs, and relying parties (RPs). In the initial focus context of CT, the Web PKI, Subjects are web sites and RPs are browsers employing HTTPS to access these web sites. Thee CAs that benefit are issuers of certificates used to authenticate web sites.

A certificate Subject benefits from CT because CT helps detect certificates that have been mis-issued in the name of that Subject. A Subject learns of a bogus certificate (issued in its name), via the Monitor function of CT. The Monitor function may be provided by the Subject itself, i.e., self-monitoring, or by a third party trusted by the Subject. When a Subject is informed of certificate mis-issuance by a Monitor, the Subject is expected to request/demand revocation of the bogus certificate. Revocation of a bogus certificate is the primary means of remedying mis-issuance.

Certificate Revocations Lists (CRLs) [RFC5280] are the primary means of certificate revocation established by IETF standards. Unfortunately, most browsers do not make use of CRLs to check the revocation status of certificates presented by a TLS Server (Subject). Some browsers make use of Online Certificate Status Protocol (OCSP) data [RFC6960] as a standards-based alternative to CRLs. If a certificate contains an Authority Information Access (AIA) extension [RFC5280], it directs a relying party to an OCSP server to which a request can be directed. This extension also may

be used by a browser to request OCSP responses from a TLS server with which it is communicating [RFC6066][RFC6961].

RFC 5280 does not require inclusion of an AIA extension in certificates, so a browser cannot assume that this extension will be present. The Certification Authority and Browser Forum (CABF) baseline requirements and extended validation guidelines do mandate inclusion of this extension in EE certificates (in conjunction with their certificate policies). (See https://cabforum.org for the most recent versions of these policies.)

In addition to the revocation status data dissemination mechanisms specified by IETF standards, most browser vendors employ proprietary means of conveying certificate revocation status information to their products, e.g., via a blacklist that enumerates revoked certificates (EE or CA). Such capabilities enable a browser vendor to cause browsers to reject any certificates on the blacklist. This approach also can be employed to remedy mis-issuance. Throughout the remainder of this document references to certificate revocation as a remedy encompass this and analogous forms of browser behavior, if available. Note: there are no IETF standards defining a browser blacklist capability.

Note that a Subject can benefit from the Monitor function of CT even if the Subject’s certificate has not been logged. Monitoring of logs for certificates issued in the Subject’s name suffices to detect mis-issuance targeting the Subject, if the bogus/erroneous certificate is logged.

A relying party (e.g., browser) benefits from CT if it rejects a bogus certificate, i.e., treats it as invalid. An RP is protected from accepting a bogus certificate if that certificate is revoked, and if the RP checks the revocation status of the certificate. (An RP is also protected if a browser vendor "blacklists" a certificate or "bad-CA-lists" a CA as noted above.) An RP also may benefit from CT if the RP validates an SCT associated with a certificate, and rejects the certificate if the Signed certificate Timestamp (SCT) [I-D.ietf-trans-rfc6962-bis] is invalid. If an RP verified that a certificate that claims to have been logged has a valid log entry, the RP would have a higher degree of confidence that the certificate is genuine. However, checking logs in this fashion imposes a burden on RPs and on logs. Moreover, the existence of a log entry does not ensure that the certificate is not mis-issued. Unless the certificate Subject is monitoring the log(s) in question, a bogus certificate will not be detected by CT mechanisms. Finally, if an RP were to check logs for individual certificates, that would disclose to logs the identity of web sites being visited by the RP, a privacy

violation. Thus this attack model does not assume that all RPs will check log entries.

A CA benefits from CT when it detects a (mis-issued) certificate that represents the same Subject name as a legitimate certificate issued by the CA.

Note that all RPs may benefit from CT even if they do nothing with SCTs. If Monitors inform Subjects of mis-issuance, and if a CA revokes a certificate in response to a request from the certificate's legitimate Subject, then an RP benefits without having to implement any CT-specific mechanisms.

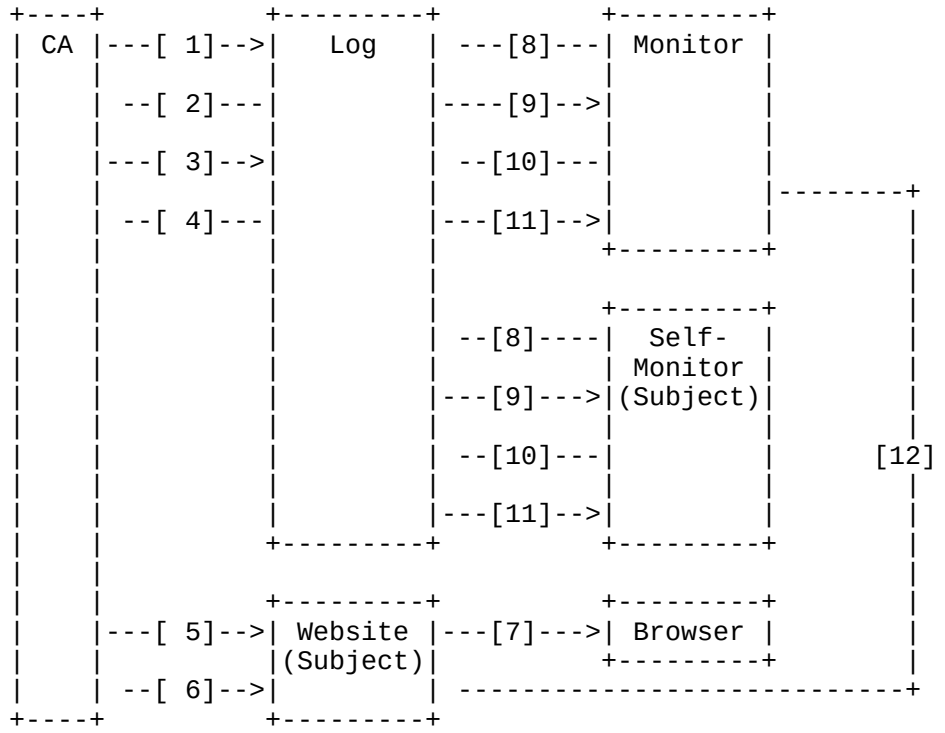
Also note that one proposal [I-D.ietf-trans-gossip] for distributing Audit information (to detect misbehaving logs) calls for a browser to send SCTs it receives to the corresponding website when visited by the browser. If a website acquires an inclusion proof from a log for each (unique) SCT it receives in this fashion, this would cause a bogus SCT to be discovered, and, presumably, trigger a revocation request.

Logging [I-D.ietf-trans-rfc6962-bis] is the central element of CT. Logging enables a Monitor to detect a bogus certificate based on reference information provided by the certificate Subject. Logging of certificates is intended to deter mis-issuance, by creating a publicly-accessible record that associates a CA with any certificates that it mis-issues. Logging does not remedy mis-issuance; but it does facilitate remediation by providing the information needed to enable detection and consequently revocation of bogus certificates in some circumstances.

Auditing is a function employed by CT to detect misbehavior by logs and to deter mis-issuance that is abetted by misbehaving logs. Auditing detects several types of log misbehavior, including failures to adhere to the advertised Maximum Merge Delay (MMD) and Signed Tree Head (STH) frequency count [I-D.ietf-trans-rfc6962-bis] violating the append-only property, and providing inconsistent views of the log to different log clients. The first three of these are relatively easy for an individual auditor to detect, but the last form of misbehavior requires communication among multiple log clients. Monitors ought not trust logs that are detected misbehaving. Thus the Audit function does not detect mis-issuance per se. The CT design identifies audit functions designed to detect several types of misbehavior. However, mechanisms to detect some forms of log misbehavior are not yet standardized.

Figure 1 (below) illustrates the data exchanges among the major elements of the CT system, based on the log specification

[I-D.ietf-trans-rfc6962-bis] and on the assumed behavior of other CT system elements as described above. This Figure does not include the Audit function, because there is not yet agreement on how that function will work in a distributed, privacy-preserving fashion.



[1] Retrieve accepted root certs
[2] accepted root certs
[3] Add chain to log/add PreCertChain to log
[4] SCT
[5] send cert + SCTs (or cert with embedded SCTs)
[6] Revocation request/response (in response to detected mis-issuance)
[7] cert + SCTs (or cert with embedded SCTs)
[8] Retrieve entries from Log
[9] returned entries from log
[10] Retrieve latest STH
[11] returned STH
[12] bogus/erroneous cert notification

Figure 1: Data Exchanges Between Major Elements of the CT System

Certificate mis-issuance may arise in one of several ways. The ways by which CT enables a Subject (or others) to detect and redress mis-issuance depends on the context and the entities involved in the mis-issuance. This attack model applies to use of CT in the Web PKI context. If CT is extended to apply to other contexts, each context will require its own attack model, although most elements of the model described here are likely to be applicable.

Because certificates are issued by CAs, the top level differentiation in this analysis is whether the CA that mis-issued a certificate did so maliciously or not. Next, for each scenario, the model considers whether or not the certificate was logged. Scenarios are further differentiated based on whether the logs and monitors are benign or malicious and whether a certificate's Subject is self-monitoring or is using a third party Monitoring service. Finally, the analysis considers whether a browser is performing checking relevant to CT. The scenarios are organized as illustrated by the following outline:

```
Web PKI CA - malicious vs non-malicious
   Certificate - logged vs not logged
         Log - benign vs malicious
         Third party Monitor - benign vs malicious
         Certificate's Subject - self-monitoring (or not)
         Browser - CT-supporting (or not)
```

The next section of the document briefly discusses threats. Subsequent sections examine each of the cases described above. As noted earlier, the focus here is on the Web PKI context, although most of the analysis is applicable to other PKI contexts.

1.1. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

2. Threats

A threat is defined, traditionally, as a motivated, capable adversary. An adversary who is not motivated to attack a system is not a threat. An adversary who is motivated but not "capable" also is not a threat. Threats change over time; new classes of adversaries may arise, new motivations may come into play, and the capabilities of adversaries may change. Nonetheless, it is useful to document perceived threats against a system to provide a context for understanding attacks. Even if the assumptions about adversaries prove to be incorrect, documenting the assumptions is valuable.

As noted above, the goals of CT are to deter, detect, and facilitate remediation of attacks on the web PKI. Such attacks can enable an attacker to spoof the identity of TLS-enabled web sites. Spoofing enables an adversary to perform many types of attacks, e.g., delivery of malware to a client, reporting bogus information, or acquiring information that a client would not communicate if the client were aware of the spoofing. Such information may include personal identification and authentication information and electronic payment authorization information. Because of the nature of the information that may be divulged (or misinformation or malware that may be delivered), the principal adversaries in the CT context are perceived to be (cyber) criminals and nation states. Both adversaries are motivated to acquire personal identification and authentication information. Criminals are also motivated to acquire electronic payment authorization information.

To make use of forged web site certificates, an adversary must be able to direct a TLS client to a spoofed web site, so that it can present the forged certificate during a TLS handshake. An adversary may achieve this in various ways, e.g., by manipulation of the DNS response sent to a TLS client or via a man-in-the-middle attack. The former type of attack is well within the perceived capabilities of both classes of adversary. The latter attack may be possible for criminals and is certainly a capability available to a nation state within its borders. Nation states also may be able to compromise DNS servers outside their own jurisdiction.

The elements of CT may themselves be targets of attacks, as described below. A criminal organization might compromise a CA and cause it to issue bogus certificates, or it may exert influence over a CA (or CA staff) to do so, e.g., through extortion or physical threat. A CA may be the victim of social engineering, causing it to issue a certificate to an inappropriate Subject. (Even though the CA is not intentionally malicious in this case, the action is equivalent to a malicious CA, hence the use of the term "bogus" here.) A nation state may operate or influence a CA that is part of the large set of "root CAs" in browsers. A CA, acting in this fashion, is termed a "malicious" CA. A nation state also might compromise a CA in another country, to effect issuance of bogus certificates. In this case the (non-malicious) CA, upon detecting the compromise (perhaps because of CT) is expected to work with Subjects to remedy the mis-issuance.

A log also might be compromised by a suitably sophisticated criminal organization or by a nation state. Compromising a log would enable a compromised or rogue CA to acquire SCTs, but log entries would be suppressed, either for all log clients or for targeted clients (e.g., to selected Monitors or Auditors). It seems unlikely that a

compromised, non-malicious, log would persist in presenting multiple views of its data, but a malicious log would.

Finally, note that a browser trust store may include a CA that is intended to issue certificates to enable monitoring of encrypted browser sessions. The inclusion of a trust anchor for such a CA is intended to facilitate monitoring encrypted content, via an authorized man-in-the-middle (MITM) attack. CT is not designed to counter this type of locally-authorized interception.

3. Semantic mis-issuance

3.1. Non-malicious Web PKI CA context

In this section, we address the case where the CA has no intent to issue a bogus certificate.

A CA may have mis-issued a certificate as a result of an error or, in the case of a bogus certificate, because it was the victim of a social engineering attack or an attack such as the one that affected DigiNotar [https://www.vasco.com/company/about_vasco/press_room/news_archive/2011/news_diginotar_reports_any security_incident.aspx]. In the case of an error, the CA should have a record of the erroneous certificate and be prepared to revoke this certificate once it has discovered and confirmed the error. In the event of an attack, a CA may have no record of a bogus certificate.

3.1.1. Certificate logged

3.1.1.1. Benign log

The log (or logs) is benign and thus is presumed to provide consistent, accurate responses to requests from all clients.

If a bogus (pre-)certificate has been submitted to one or more logs prior to issuance to acquire an embedded SCT, or post-issuance to acquire a standalone SCT, detection of this mis-issuance is the responsibility of a Monitor.

3.1.1.1.1. Self-monitoring Subject

If a Subject is tracking the log(s) to which a certificate was submitted, and is performing self-monitoring, then it will be able to detect a bogus (pre-)certificate and request revocation. In this case, the CA will make use of the log entry (supplied by the Subject) to determine the serial number of the bogus certificate, and investigate/revoke it. (See Sections 5.1, 5.2 and 5.3.)

3.1.1.1.2. Benign third party Monitor

If a benign third party monitor is checking the logs to which a certificate was submitted and is protecting the targeted Subject, it will detect a bogus certificate and will alert the Subject. The Subject, in turn, will ask the CA to revoke the bogus certificate. In this case, the CA will make use of the log entry (supplied by the Subject) to determine the serial number of the bogus certificate, and revoke it (after investigation). (See Sections 5.1, 5.2 and 5.3.)

3.1.1.2. Misbehaving log

In this case, the bogus (pre-)certificate has been submitted to one or more logs, each of which generate an SCT for the submission. A misbehaving log probably will suppress a bogus certificate log entry, or it may create an entry for the certificate but report it selectively. (A misbehaving log also could create and report entries for bogus certificates that have not been issued by the indicated CA (hereafter called "fake"). Unless a Monitor validates the associated certificate chains up to roots that it trusts, these fake bogus certificates could cause the Monitors to report non-existent semantic problems to the Subject who would in turn report them to the purported issuing CA. This might cause the CA to do needless investigative work or perhaps incorrectly revoke and re-issue the Subject’s real certificate. Note that for every certificate submitted to a log, the log MUST verify a complete certificate chain up to one of the roots it accepts. So creating a log entry for a fake bogus certificate marks the log as misbehaving.

3.1.1.2.1. Self-monitoring Subject & Benign third party Monitor

If a misbehaving log suppresses a bogus certificate log entry, a Subject performing self-monitoring will not detect the bogus certificate. CT relies on an Audit mechanism to detect log misbehavior, as a deterrent. It is anticipated that logs that are identified as persistently misbehaving will cease to be trusted by Monitors, non-malicious CAs, and by browser vendors. This assumption forms the basis for the perceived deterrent. It is not clear if mechanisms to detect this sort of log misbehavior will be viable.

Similarly, when a misbehaving log suppresses a bogus certificate log entry (or report such entries inconsistently) a benign third party Monitor that is protecting the targeted Subject also will not detect a bogus certificate. In this scenario, CT relies on a distributed Auditing mechanism [I-D.ietf-trans-gossip] to detect log misbehavior, as a deterrent. (See Section 5.6 below.) However, a Monitor (third-party or self) must participate in the Audit mechanism in order to become aware of log misbehavior.

If the misbehaving log has logged the bogus certificate when issuing the associated SCT, it will try to hide this from the Subject (if self-monitoring) or from the Monitor protecting the Subject. It does so by presenting them with a view of its log entries and STH that does not contain the bogus certificate. To other entities, the log presents log entries and an STH that include the bogus certificate. This discrepancy can be detected if there is an exchange of information about the log entries and STH between the entities receiving the view that excludes the bogus certificate and entities that receive a view that includes it, i.e., a distributed Audit mechanism.

If a malicious log does not create an entry for a bogus certificate (for which an SCT has been issued), then any Monitor/Auditor that sees the bogus certificate will detect this when it checks with the log for log entries and STH (see Section 3.1.2.)

3.1.1.3. Misbehaving third party Monitor

A third party Monitor that misbehaves will not notify the targeted Subject of a bogus certificate. This is true irrespective of whether the Monitor checks the logs or whether the logs are benign or malicious/conspiring.

Note that independent of any mis-issuance on the part of the CA, a misbehaving Monitor could issue false warnings to a Subject that it protects. These could cause the Subject to report non-existent semantic problems to the issuing CA and cause the CA to do needless investigative work or perhaps incorrectly revoke and re-issue the Subject’s certificate.

3.1.2. Certificate not logged

If the CA does not submit a pre-certificate to a log, whether a log is benign or misbehaving does not matter. The same is true if a Subject is issued a certificate without an SCT and does not log the certificate itself, to acquire an SCT. Also, since there is no log entry in this scenario, there is no difference in outcome between a benign and a misbehaving third party Monitor. In both cases, no Monitor (self or third-party) will detect a bogus certificate based on Monitor functions and there will be no consequent reporting of the problem to the Subject or by the Subject to the CA based on examination of log entries.

3.1.2.1. Self-monitoring Subject

A Subject performing self-monitoring will be able to detect the lack of an embedded SCT in the certificate it received from the CA, or the lack of an SCT supplied to the Subject via an out-of-band channel. A Subject ought to notify the CA if the Subject expected that its certificate was to be logged. (A Subject would expect its certificate to be logged if there is an agreement between the Subject and the CA to do so, or because the CA advertises that it logs all of the certificates that it issues.) If the certificate was supposed to be logged, but was not, the CA can use the certificate supplied by the Subject to investigate and remedy the problem. In the context of a benign CA, a failure to log the certificate might be the result of an operations error, or evidence of an attack on the CA.

3.1.2.2. CT-enabled browser

If a browser rejects certificates without SCTs (see Section 5.4), CAs may be "encouraged" to log the certificates they issue. This, in turn, would make it easier for Monitors to detect bogus certificates. However, the CT architecture does not describe how such behavior by browsers can be deployed incrementally throughout the Internet. As a result, this attack model does not assume that browsers will reject a certificate that is not accompanied by an SCT. In the CT architecture certificates have to be logged to enable Monitors to detect mis-issuance, and to trigger subsequent revocation [I-D.kent-trans-architecture]. Thus the effectiveness of CT is diminished in this context.

3.2. Malicious Web PKI CA context

In this section, we address the scenario in which the mis-issuance is intentional, not due to error. The CA is not the victim but the attacker.

3.2.1. Certificate logged

3.2.1.1. Benign log

A bogus (pre-)certificate may be submitted to one or more benign logs prior to issuance, to acquire an embedded SCT, or post-issuance to acquire a standalone SCT. The log (or logs) replies correctly to requests from clients.

3.2.1.1.1. Self-monitoring Subject

If a Subject is checking the logs to which a certificate was submitted and is performing self-monitoring, it will be able to detect the bogus certificate and will request revocation. The CA may refuse to revoke, or may substantially delay revoking, the bogus certificate. For example, the CA could make excuses about inadequate proof that the certificate is bogus, or argue that it cannot quickly revoke the certificate because of legal concerns, etc. In this case, the CT mechanisms will have detected mis-issuance, but the information logged by CT may not suffice to remedy the problem. (See Sections 4 and 6.)

A malicious CA might revoke a bogus certificate to avoid having browser vendors take punitive action against the CA and/or to persuade them to not enter the bogus certificate on a vendor-maintained blacklist. However, the CA might provide a "good" OCSP response (from a server it operates) to a targeted browser instance as a way to circumvent the remediation nominally offered by revocation. No component of CT is tasked with detecting this sort of misbehavior by a CA. (The misbehavior is analogous to a log offering split views to different clients, as discussed later. The Audit element of CT is tasked with detecting this sort of attack.)

3.2.1.1.2. Benign third party Monitor

If a benign third party monitor is checking the logs to which a certificate was submitted and is protecting the targeted Subject, it will detect the bogus certificate and will alert the Subject. The Subject will then ask the CA to revoke the bogus certificate. As in 3.2.1.1.1, the CA may or may not revoke the certificate and it might revoke the certificate but provide "good" OCSP responses to a targeted browser instance.

3.2.1.2. Misbehaving log

A bogus (pre-)certificate may have been submitted to one or more logs that are misbehaving, e.g., conspiring with an attacker. These logs may or may not issue SCTs, but will hide the log entries from some or all Monitors.

3.2.1.2.1. Monitors - third party and self

If log entries are hidden from a Monitor (third party or self), the Monitor will not be able to detect issuance of a bogus certificate.

The Audit function of CT is intended to detect logs that conspire to delay or suppress log entries (potentially selectively), based on

consistency checking of logs. (See 3.1.1.2.2.) If a Monitor learns of misbehaving log operation, it alerts the Subjects that it is protecting, so that they no longer acquire SCTs from that log. The Monitor also avoids relying upon such a log in the future. However, unless a distributed Audit mechanism proves effective in detecting such misbehavior, CT cannot be relied upon to detect this form of mis-issuance. (See Section 5.6 below.)

3.2.1.3. Misbehaving third party Monitor

If the third party Monitor that is "protecting" the targeted Subject is misbehaving, then it will not notify the targeted Subject of any mis-issuance or of any malfeasant log behavior that it detects irrespective of whether the logs it checks are benign or malicious/ conspiring. The CT architecture does not include any measures to detect misbehavior by third-party monitors.

3.2.2. Certificate not logged

Because the CA is presumed malicious, it may choose to not submit a (pre-)certificate to a log. This means there is no SCT for the certificate.

When a CA does not submit a certificate to a log, whether a log is benign or misbehaving does not matter. Also, since there is no log entry, there is no difference in behavior between a benign and a misbehaving third-party Monitor. Neither will report a problem to the Subject.

A bogus certificate would not be delivered to the legitimate Subject. So the Subject, acting as a self-Monitor, cannot detect the issuance of a bogus certificate in this case.

3.2.2.1. CT-aware browser

If careful browsers reject certificates without SCTs, CAs may be "encouraged" to log certificates (see section 5.4.) However, the CT architecture does not describe how such behavior by browsers can be deployed incrementally throughout the Internet. As a result, this attack model does not assume that browsers will reject a certificate that is not accompanied by an SCT. Since certificates have to be logged to enable detection of mis-issuance by Monitors, and to trigger subsequent revocation, the effectiveness of CT is diminished in this context.

3.3. Undetected Compromise of CAs or Logs

Sections 3.1 and 3.2 examined attacks in the context of non-malicious and malicious CAs, and benign and misbehaving logs. Another class of attacks might occur in the context of a non-malicious CA and/or a benign log. Specifically these CT elements might be compromised and the compromise might go undetected. Compromise of CAs and logs was noted in Section 2, as was coercion of a CA. As noted there, a compromised CA is essentially a malicious CA, and thus the discussions in Section 3.2 are applicable. Section 3.3 explored the undetected compromise of a CA in the context of attacks designed to issue a bogus certificate that might avoid revocation (because the certificate would appear on distinct certificate paths).

The section focuses on undetected compromise of CAs. Such compromises warrant some additional discussion, since some relying parties may see signed objects issued by the legitimate (non-malicious) CA, others may see signed objects from its compromised counterpart, and some may see objects from both. In the case of a compromised CA or log the adversary is presumed to have access to the private key used by a CA to sign certificates, or used by a log to sign SCTs and STHs. Because the compromise is undetected, there will be no effort by a CA to have its certificate revoked or by a log to shut down the log.

3.3.1. Compromised CA, Benign Log

In the case of a compromised (non-malicious) CA, an attacker uses the purloined private key to generate a bogus certificate (that the compromised CA would not issue). If this certificate is submitted to a (benign) log, then it subject to detection by a Monitor, as discussed in 3.1.1.1. If the bogus certificate is submitted to a misbehaving log, then an SCT can be generated, but there will be no entry for it, as discussed in 3.1.1.2. If the bogus certificate is not logged, then there will be no SCT, and the implications are as described in 3.1.2.

This sort of attack may be most effective if the CA that is the victim of the attack has issued a certificate for the targeted Subject. In this case the bogus certificate will then have the same certification path as the legitimate certificate, which may help hide the bogus certificate. However, means of remedying the attack are independent of this aspect, i.e., revocation can be effected irrespective of whether the targeted Subject received its certificate from the compromised CA.

A compromised (non-malicious) CA may be able to revoke the bogus certificate if it is detected by a Monitor, and the targeted Subject

has been notified. It can do so only when the serial number of the bogus certificate is made known to this CA and assuming that the bogus certificate was not issued with an Authority Information Access (AIA) or CRL Distribution Point (CRL DP) extension that enables only the malicious twin to revoke the certificate. (The AIA extension in the bogus certificate could be used to direct relying parties to an OCSP server controlled by the malicious twin. The CRL DP extension could be used to direct relying parties to a CRL controlled by the malicious twin.) If the bogus certificate contains either extension, the compromised CA cannot effectively revoke it. However, the presence of either of these extensions provides some evidence that an entity other than the compromised CA issued the certificate in question. (If the extensions differ from those in other certificates issued by the compromised CA, that is suspicious.)

If the serial number of the bogus certificate is the same as for a valid, not-expired certificate issued by the CA (to the target or to another Subject), then revocation poses a problem. This is because revocation of the bogus certificate will also invalidate a legitimate certificate. This problem may cause the compromised CA to delay revocation, thus allowing the bogus certificate to remain a danger for a longer time.

The compromised CA may not realize that the bogus certificate was issued by a malicious twin; one occurrence of this sort might be regarded as an error, and not cause the CA to transition to a new key pair. (This assumes that the bogus certificate does not contain an AIA or CRL DP extension that wrests control of revocation from the compromised CA.) If the compromised CA does determine that its private key has been stolen, it probably will take some time to transition to a new key pair, and reissue certificates to all of its legitimate Subjects. Thus an attack of this sort probably will take a while to be remedied.

Also note that the malicious twin of the compromised CA may be capable of issuing its own CRL or OCSP responses, without changing any AIA/CRL DP data present in the targeted certificate. The revocation status data from the evil twin will appear as valid as those of the compromised CA. If the attacker has the ability to control the sources of revocation status data available to a targeted user (browser instance), then the user may not become aware of the attack.

A bogus certificate issued by the malicious CA will not match the SCT for the legitimate certificate, since they are not identical, e.g., at a minimum the private keys do not match. Thus a CT-aware browser that rejects certificates without SCTs (see 3.1.2.2) will reject a bogus certificate created under these circumstances if it is not

logged. If the bogus certificate is detected and logged, browsers that require an SCT will reject the bogus certificate.

3.3.2. Benign CA, Compromised Log

A benign CA does not issue bogus certificates, except as a result of an accident or attack. So, in normal operation, it is not clear what behavior by a compromised log would yield an attack. If a bogus certificate is issued by a benign CA (under these circumstances) is submitted to a compromised (non-malicious) log, then both an SCT and a log entry will be created. Again, it is not clear what additional adverse actions the compromised log would perform to further an attack on CT.

It is worth noting that if a benign CA was attacked and thus issued one or more bogus certificates, then a malicious log might provide split views of its log to help conceal the bogus certificate from targeted users. Specifically, the log would show an accurate set of log entries (and STHs) to most clients, but would maintain a separate log view for targeted users. This sort of attack motivates the need for Audit capabilities based on "gossiping" [I-D.ietf-trans-gossip]. However, even if such mechanisms are employed, they might be thwarted if a user is unable to exchange log information with trustworthy partners.

3.3.3. Compromised CA, Compromised Log

As noted in 3.4.1, an evil twin CA may issue a bogus certificate that contains the same Subject name as a legitimate certificate issued by the compromised CA. Alternatively, the bogus certificate may contain a different name but reuse a serial number from a valid, not revoked certificate issued by that CA.

An attacker who compromises a log might act in one of two ways. It might use the private key of the log only to generate SCTs for a malicious CA or the evil twin of a compromised CA. If a browser checks the signature on an SCT but does not contact a log to verify that the certificate appears in the log, then this is an effective attack strategy. Alternatively, the attacker might not only generate SCTs, but also pose as the compromised log, at least with regard to requests from targeted users. In the latter case, this "evil twin" log could respond to STH requests from targeted users, making appear that the compromised log was offering a split view (thus acting as a malicious log). To detect this attack an Auditor needs to employ a gossip mechanism that is able to acquire CT data from diverse sources, a feature not yet part of the base CT system.

An evil twin CA might submit a bogus certificate to the evil twin of a compromised log. (The same adversary may be controlling both.) The operator of the evil twin log can use the purloined private key to generate SCTs for certificates that have not been logged by its legitimate counterpart. These SCTs will appear valid relative to the public key associated with the legitimate log. However, an STH issued by the legitimate log will not correspond to a tree (maintained by the compromised log) containing these SCTs. Thus checking the SCTs issued by the evil twin log against STHs from the compromised log will identify this discrepancy. As noted above, if an attacker uses the key to generate log entries and respond to log queries, the effect is analogous to a malicious log.)

An Auditor checking for log consistency and with access to bogus SCTs, might conclude that the compromised log is acting maliciously, and is presenting a split view to its clients. In this fashion the compromised log may be shunned and forced to shut down. However, if an attacker targets a set of TLS clients that do not have access to the legitimate log, they may not be able to detect this inconsistency. In this case CT would need to rely on a distributed gossiping audit mechanism to detect the compromise (see Section 5.6).

3.4. Attacks Based on Exploiting Multiple Certificate Chains

Section 3.2 examined attacks in which a malicious CA issued a bogus certificate and either tried to prevent the Subject from detecting the bogus certificate, or reported the bogus certificate as valid, to at least some relying parties, even if the Subject requested revocation. These attacks are limited in that if the bogus certificate is not submitted to a log, then it may not be accepted by CT-aware browsers, and submitting the bogus certificate to a log increases the chances that the CA’s malicious behavior will be detected.

In general, if a CA is discovered to be acting maliciously, its certificates will no longer be accepted, either because its parent will revoke its CA certificate, its CA certificate will be added to browsers’ blacklists, or both. However, a malicious CA may be able to obtain an SCT for each bogus certificate that it issues and continue to have those certificates accepted by relying parties even after its malicious behavior has been detected. It can do this by creating more than one path validation chain for the certificates, as shown in Figure 2.

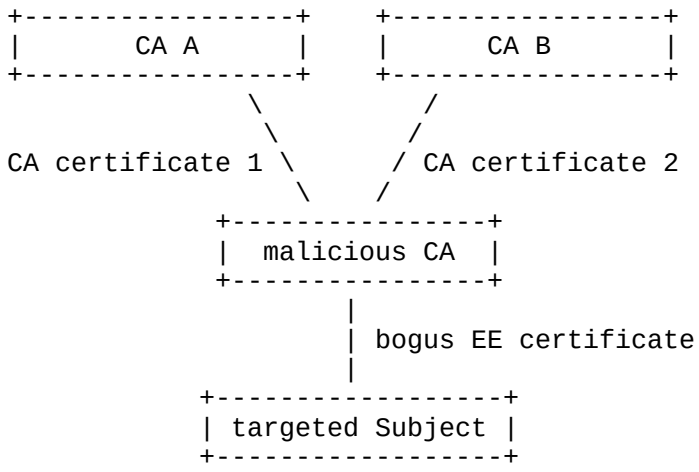


Figure 2: Multiple Certificate Chains for a Bogus Certificate

In Figure 2, the malicious CA has been issued CA certificates by two different parent CAs. The parent CAs may be two different trust anchors, or one or both of them may be an intermediate CA (i.e., it is subordinate to some trust anchor). If both parent CAs are intermediate CAs, they may be subordinate to the same trust anchor or to different trust anchors. The malicious CA may have obtained certificates from the two parents by applying to them for the certificates, or by compromising the parent CAs and creating the certificates without the knowledge of the CAs. If the malicious CA applied for its certificates from these CAs, it may have presented credentials that cause each parent to believe that the parent is dealing with a different CA, despite the fact that the CA name and public key are identical.

Because there are two certificate path validation chains, the malicious CA could provide the chain that includes CA A when submitting a bogus certificate to one or more logs, but an attacker (colluding with the malicious CA) could provide the chain that includes CA B to targeted browsers. If the CA's malicious behavior is detected, then CA A and browser vendors may be alerted (e.g., via the CT Monitor function) and revoke/blacklist CA certificate 1. However, CA certificate 2 does not appear in any logs, and CA A is unaware that CA B has issued a certificate to the malicious CA. Thus those who detected the malicious behavior may not discover the second chain and so may not alert CA B or browser vendors of the need to revoke/blacklist CA certificate 2. In this case, targeted browsers would continue to accept the bogus certificates issued by the malicious CA, since the certificate chain they are provided is valid

and because the SCT issued for the bogus certificate it the same irrespective of which certificate chain is presented.

3.5. Attacks Related to Distribution of Revocation Status

A bogus certificate that has been revoked may still appear valid to a browser under certain circumstances. In part this is because certificate revocation generally depends on the certificate path (chain) used by a relying party when validating a certificate. This is true irrespective of whether revocation is effected via use of a CRL or OCSP. Additionally, an attacker can steer a browser to specific revocation status data via various means, preventing a targeted browser from acquiring accurate revocation status information for a bogus certificate.

The bogus certificate might contain an AIA extension pointing to an OCSP server controlled by the malicious CA (or the attacker). As noted in Section 3.2.1.1.1, the malicious CA could send a "good" OCSP response to a targeted browser instance, even if other parties are provided with a "revoked" response. A TLS server can supply an OCSP response to a browser as part of the TLS handshake [RFC6961], if requested by the browser. A TLS server posing as the entity named in the bogus certificate also could acquire a "good" OCSP response from the malicious CA to effect the attack. Only if the browser relies upon a trusted, third-party OCSP responder, one not part of the collusion, would these OCSP-based attacks fail.

The bogus certificate could contain a CRL distribution point extension instead of an AIA extension. In that case a site supplying CRLs for the malicious CA could supply different CRLs to different requestors, in an attempt to hide the revocation status of the bogus certificate from targeted browser instances. This is analogous to a split-view attack effected by a CT log. However, as noted in Section 3.2.1.1 and 3.2.1.1.1, no element of CT is responsible for detecting inconsistent reporting of certificate revocation status data. (Monitoring in the CT context tracks log entries made by CAs or Subjects. Auditing is designed to detect misbehavior by logs, not by CAs per se.)

The failure of a bogus certificate to be detected as revoked (by a browser) is not the fault of CT. In the class of attacks described above, CT achieves its goal of detecting the bogus certificate when that certificate is logged and a Monitor observes the log entry. Detection is intended to trigger revocation, to effect remediation, the details of which are outside the scope of CT. However the SCT mechanism is intended to assure a relying party that certificate has been logged, is susceptible to being detected as bogus by a Monitor, and presumably will be revoked if detected as such. In the context

of these attacks, because of the way revocation may be implemented, the assurance provided by the SCT may not have the anticipated effect.

This type of attack might be thwarted in several ways. For example, if all intermediate (i.e., CA) certificates had to be logged, then CA certificate 2 might be rejected by CT-aware browsers. If a malicious CA is discovered, a browser vendor might blacklist it by public key (not by its serial number and the name of the parent CA or by a hash of the certificate). This approach to revocation would cause CA certificate 2 to be rejected as well as CA certificate 1. However none of these mechanisms are part of the CT specification [I-D.ietf-trans-rfc6962-bis] nor general IETF PKI standards (e.g., [RFC5280]).

4. Syntactic mis-issuance

4.1. Non-malicious Web PKI CA context

This section analyzes the scenario in which the CA has no intent to issue a syntactically incorrect certificate. As noted in Section 1, we refer to a syntactically incorrect certificate as erroneous.

4.1.1. Certificate logged

4.1.1.1. Benign log

If a (pre)certificate is submitted to a benign log, syntactic mis-issuance can (optionally) be detected, and noted. This will happen only if the log performs syntactic checks in general, and if the log is capable of performing the checks applicable to the submitted (pre)certificate. (A (pre)certificate SHOULD be logged even if it fails syntactic validation; logging takes precedence over detection of syntactic mis-issuance.) If syntactic validation fails, this can be noted in an SCT extension returned to the submitter.

If the (pre)certificate is submitted by the non-malicious issuing CA, then the CA SHOULD remedy the syntactic problem and re-submit the (pre)certificate to a log or logs. If this is a pre-certificate submitted prior to issuance, syntactic checking by a log helps avoid issuance of an erroneous certificate. If the CA does not have a record of the certificate contents, then presumably it was a bogus certificate and the CA SHOULD revoke it.

If a certificate is submitted by its Subject, and is deemed erroneous, then the Subject SHOULD contact the issuing CA and request a new certificate. If the Subject is a legitimate subscriber of the CA, then the CA will either have a record of the certificate content

or can obtain a copy of the certificate from the Subject. The CA will remedy the syntactic problem and either re-submit a corrected (pre-)certificate to a log and send it to the Subject or the Subject will re-submit it to a log. Here too syntactic checking by a log enables a Subject to be informed that its certificate is erroneous and thus may hasten issuance of a replacement certificate.

If a certificate is submitted by a third party, that party might contact the Subject or the issuing CA, but because the party is not the Subject of the certificate it is not clear how the CA will respond.

This analysis suggests that syntactic mis-issuance of a certificate can be avoided by a CA if it makes use of logs that are capable of performing these checks for the types of certificates that are submitted, and if the CA acts on the feedback it receives. If a CA uses a log that does not perform such checks, or if the CA requests checking relative to criteria not supported by the log, then syntactic mis-issuance will not be detected or avoided by this mechanism. Similarly, syntactic mis-issuance can be remedied if a Subject submits a certificate to a log that performs syntactic checks, and if the Subject asks the issuing CA to fix problems detected by the log. (The issuer is presumed to be willing to re-issue the certificate, correcting any problems, because the issuing CA is not malicious.)

4.1.1.2. Misbehaving log or third party Monitor

A log or Monitor that is conspiring with the attacker or is independently malicious, will either not perform syntactic checks, even though it claims to do so, or simply not report errors. The log entry and the SCT for an erroneous certificate will assert that the certificate syntax was verified.

As with detection of semantic mis-issuance, a distributed Audit mechanism could, in principle, detect misbehavior by logs or Monitors with respect to syntactic checking. For example, if for a given certificate, some logs (or Monitors) are reporting syntactic errors and some that claim to do syntactic checking, are not reporting these errors, this is indicative of misbehavior by these logs and/or Monitors.

Note that a malicious log (or Monitor) could report syntactic errors for a syntactically valid certificate. This could result in reporting of non-existent syntactic problems to the issuing CA, which might cause the CA to do needless investigative work or perhaps incorrectly revoke and re-issue the Subject’s certificate.

4.1.1.3. Self-monitoring Subject and Benign third party Monitor

If a Subject or benign third party Monitor performs syntactic checks, it will detect the erroneous certificate and the issuing CA will be notified (by the Subject). If the Subject is a legitimate subscriber of the CA, then the CA will either have a record of the certificate content or can obtain a copy of the certificate from the Subject. The CA SHOULD revoke the erroneous certificate (after investigation) and remedy the syntactic problem. The CA SHOULD either re-submit the corrected (pre)certificate to one or more logs and then send the result to the Subject, or send the corrected certificate to the Subject, who will re-submit it to one or more logs.

4.1.1.4. CT-enabled browser

If a browser rejects an erroneous certificate and notifies the Subject and/or the issuing CA, then syntactic mis-issuance will be detected (see Section 5.) Unfortunately, experience suggests that many browsers do not perform thorough syntactic checks on certificates, and so it seems unlikely that browsers will be a reliable way to detect erroneous certificates. Moreover, a protocol used by a browser to notify a Subject and/or CA of an erroneous certificate represents a DoS potential, and thus may not be appropriate. Additionally, if a browser directly contacts a CA when an erroneous certificate is detected, this is a potential privacy violation, i.e., the CA learns that the browser user is visiting the web site in question. These observations argue for syntactic checking to be performed by other elements of the CT system, e.g., logs and/or Monitors.

4.1.2. Certificate not logged

If a CA does not submit a certificate to a log, there can be no syntactic checking by the log. Detection of syntactic errors will depend on a Subject performing the requisite checks when it receives its certificate from a CA. A Monitor that performs syntactic checks on behalf of a Subject also could detect such problems, but the CT architecture does not require Monitors to perform such checks.

4.2. Malicious Web PKI CA context

This section analyzes the scenario in which the CA’s issuance of a syntactically incorrect certificate is intentional, not due to error. The CA is not the victim but the attacker.

4.2.1. Certificate logged

4.2.1.1. Benign log

Because the CA is presumed to be malicious, the CA may cause the log to not perform checks, in one of several ways. (See [I-D.kent-trans-domain-validation-cert-checks] and [I-D.kent-trans-extended-validation-cert-checks] for more details on validation checks and CCIDs).

1. The CA may assert that the certificate is being issued w/o regard to any guidelines (the "no guidelines" reserved CCID).

2. The CA may assert a CCID that has not been registered, and thus no log will be able to perform a check.

3. The CA may check to see which CCIDs a log declares it can check, and chose a registered CCID that is not checked by the log in question.

4. The CA may submit a (pre-) certificate to a log that is known to not perform any syntactic checks, and thus avoid syntactic checking.

4.2.1.2. Misbehaving log or third party Monitor

A misbehaving log or third party Monitor will either not perform syntactic checks or not report any problems that it discovers. (See 4.1.1.2 for further problems). Also, as noted above, the CT architecture includes no explicit provisions for detecting a misbehaving third-party Monitor.

4.2.1.3. Self-monitoring Subject and Benign third party Monitor

Irrespective of whether syntactic checks are performed by a log, a malicious CA will acquire an embedded SCT, or post-issuance will acquire a standalone SCT. If Subjects or Monitors perform syntactic checks that detect the syntactic mis-issuance and report the problem to the CA, a malicious CA may do nothing or may delay the action(s) needed to remedy the problem.

4.2.1.4. CT-enabled browser

As noted above (4.1.1.4), most browsers fail to perform thorough syntax checks on certificates. Such browsers might benefit from having syntax checks performed by a log and reported in the SCT, although the pervasive nature of syntactically-defective certificates may limit the utility of such checks. (Remember, in this scenario,

the log is benign.) However, if a browser does not discriminate against certificates that do not contain SCTs (or that are not accompanied by an SCT in the TLS handshake), only minimal benefits might accrue to the browser from syntax checks perform by logs or Monitors.

If a browser accepts certificates that do not appear to have been syntactically checked by a log (as indicated by the SCT), a malicious CA need not worry about failing a log-based check. Similarly, if there is no requirement for a browser to reject a certificate that was logged by an operator that does not perform syntactic checks, the fourth attack noted in 4.2.1.1 will succeed as well. If a browser were configured to know which versions of certificate types are applicable to its use of a certificate, the second and third attack strategies noted above could be thwarted.

4.2.2. Certificate is not logged

Since certificates are not logged in this scenario, a Monitor (third-party or self) cannot detect the issuance of an erroneous certificate. Thus there is no difference between a benign or a malicious/conspiring log or a benign or conspiring/malicious Monitor. (A Subject MAY detect a syntax error by examining the certificate returned to it by the Issuer.) However, even if errors are detected and reported to the CA, a malicious/conspiring CA may do nothing to fix the problem or may delay action.

5. Issues Applicable to Sections 3 and 4

5.1. How does a Subject know which Monitor(s) to use?

If a CA submits a bogus certificate to one or more logs, but these logs are not tracked by a Monitor that is protecting the targeted Subject, CT will not remedy this type of mis-issuance attack. If third-party Monitors advertise which logs they track, Subjects may be able to use this information to select an appropriate Monitor (or set thereof). Also, it is not clear whether every third-party Monitor MUST offer to track every Subject that requests protection. If a Subject acts as its own Monitor, this problem is solved for that Subject.

5.2. How does a Monitor discover new logs?

It is not clear how a (self-)Monitor becomes aware of all (relevant) logs, including newly created logs. The means by which Monitors become aware of new logs MUST accommodate self-monitoring by a potentially very large number of web site operators. If there are many logs, it may not be feasible for a (self-) Monitor to track all

of them, or to determine what set of logs suffice to ensure an adequate level of coverage.

5.3. CA response to report of a bogus or erroneous certificate

A CA being presented with evidence of a bogus or erroneous certificate, in the form of a log entry and/or SCT, will need to examine its records to determine if it has knowledge of the certificate in question. It also will likely require the targeted Subject to provide assurances that it is the authorized entity representing the Subject name (subjectAltname) in question. Thus a Subject should not expect immediate revocation of a contested certificate. The time frame in which a CA will respond to a revocation request usually is described in the CPS for the CA. Other certificate fields and extensions may be of interest for forensic purposes, but are not required to effect revocation nor to verify that the certificate to be revoked is bogus or erroneous, based on applicable criteria. The SCT and log entry, because each contains a timestamp from a third party, is probably valuable for forensic purposes (assuming a non-conspiring log operator).

5.4. Browser behavior

If a browser is to reject a certificate that lacks an embedded SCT, or is not accompanied by an SCT transported via the TLS handshake, this behavior needs to be defined in a way that is compatible with incremental deployment. Issuing a warning to a (human) user is probably insufficient, based on experience with warnings displayed for expired certificates, lack of certificate revocation status information, and similar errors that violate RFC 5280 path validation rules [RFC5280]. Unless a mechanism is defined that accommodates incremental deployment of this capability, attackers probably will avoid submitting bogus certificates to (benign) logs as a means of evading detection.

5.5. Remediation for a malicious CA

A targeted Subject might ask the parent of a malicious CA to revoke the certificate of the non-cooperative CA. However, a request of this sort may be rejected, e.g., because of the potential for significant collateral damage. A browser might be configured to reject all certificates issued by the malicious CA, e.g., using a bad-CA-list distributed by a browser vendor. However, if the malicious CA has a sufficient number of legitimate clients, treating all of their certificates as bogus or erroneous still represents serious collateral damage. If this specification were to require that a browser can be configured to reject a specific, bogus or erroneous certificate identified by a Monitor, then the bogus or

erroneous certificate could be rejected in that fashion. This remediation strategy calls for communication between Monitors and browsers, or between Monitors and browser vendors. Such communication has not been specified, i.e., there are no standard ways to configure a browser to reject individual bogus or erroneous certificates based on information provided by an external entity such as a Monitor. Moreover, the same or another malicious CA could issue new bogus or erroneous certificates for the targeted Subject, which would have to be detected and rejected in this (as yet unspecified) fashion. Thus, for now, CT does not seem to provide a way to facilitate remediation of this form of attack, even though it provides a basis for detecting such attacks.

5.6. Auditing - detecting misbehaving logs

The combination of a malicious CA and one or more conspiring logs motivates the definition of an audit function, to detect conspiring logs. If a Monitor protecting a Subject does not see bogus certificates, it cannot alert the Subject. If one or more SCTs are present in a certificate, or passed via the TLS handshake, a browser has no way to know that the logged certificate is not visible to Monitors. Only if Monitors and browsers reject certificates that contain SCTs from conspiring logs (based on information from an auditor) will CT be able to detect and deter use of such logs. Thus the means by which a Monitor performing an audit function detects such logs, and informs browsers must be specified for CT to be effective in the context of misbehaving logs.

Absent a well-defined mechanism that enables Monitors to verify that data from logs are reported in a consistent fashion, CT cannot claim to provide protection against logs that are malicious or may conspire with, or are victims of, attackers effecting certificate mis-issuance. The mechanism needs to protect the privacy of users with respect to which web sites they visit. It needs to scale to accommodate a potentially large number of self-monitoring Subjects and a vast number of browsers, if browsers are part of the mechanism. Even when an Audit mechanism is defined, it will be necessary to describe how the CT system will deal with a misbehaving or compromised log. For example, will there be a mechanism to alert all browsers to reject SCTs issued by such a log? Absent a description of a remediation strategy to deal with misbehaving or compromised logs, CT cannot ensure detection of mis-issuance in a wide range of scenarios.

Monitors play a critical role in detecting semantic certificate mis-issuance, for Subjects that have requested monitoring of their certificates. A monitor (including a Subject performing self-monitoring) examines logs for certificates associated with one or

more Subjects that are being "protected". A third-party Monitor must obtain a list of valid certificates for the Subject being monitored, in a secure manner, to use as a reference. It also must be able to identify and track a potentially large number of logs on behalf of its Subjects. This may be a daunting task for Subjects that elect to perform self-monitoring.

Note: A Monitor must not rely on a CA or RA database for its reference information or use certificate discovery protocols; this information must be acquired by the Monitor based on reference certificates provided by a Subject. If a Monitor were to rely on a CA or RA database (for the CA that issued a targeted certificate), the Monitor would not detect mis-issuance due to malfeasance on the part of that CA or the RA, or due to compromise of the CA or the RA. If a CA or RA database is used, it would support detection of mis-issuance by an unauthorized CA. A Monitor must not rely on certificate discovery mechanisms to build the list of valid certificates since such mechanisms might result in bogus or erroneous certificates being added to the list.

As noted above, Monitors represent another target for adversaries who wish to effect certificate mis-issuance. If a Monitor is compromised by, or conspires with, an attacker, it will fail to alert a Subject to a bogus or erroneous certificate targeting that Subject, as noted above. It is suggested that a Subject request certificate monitoring from multiple sources to guard against such failures. Operation of a Monitor by a Subject, on its own behalf, avoids dependence on third party Monitors. However, the burden of Monitor operation may be viewed as too great for many web sites, and thus this mode of operation ought not be assumed to be universal when evaluating protection against Monitor compromise.

6. Security Considerations

An attack and threat model is, by definition, a security-centric document. Unlike a protocol description, a threat model does not create security problems nor does it purport to address security problems. This model postulates a set of threats (i.e., motivated, capable adversaries) and examines classes of attacks that these threats are capable of effecting, based on the motivations ascribed to the threats. It then analyses the ways in which the CT architecture addresses these attacks.

7. IANA Considerations

None.

8. Acknowledgments

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Author’s Address

Stephen Kent
BBN Technologies
10 Moulton Street
Cambridge, MA 02138
USA

Phone: +1 (617) 873-3988
Email: kent@alum.mit.edu

TRANS (Public Notary Transparency)
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R. Stradling
Comodo CA, Ltd.
E. Messeri
Google UK Ltd.

January 17, 2017

Certificate Transparency: Domain Label Redaction
draft-strad-trans-redaction-01

Abstract

This document defines mechanisms to allow DNS domain name labels that are considered to be private to not appear in public Certificate Transparency (CT) logs, while still retaining most of the security benefits that accrue from using Certificate Transparency.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at http://datatracker.ietf.org/drafts/current/.

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This Internet-Draft will expire on July 21, 2017.

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1. Introduction

Some domain owners regard certain DNS domain name labels within their registered domain space as private and security sensitive. Even though these domains are often only accessible within the domain owner's private network, it's common for them to be secured using publicly trusted Transport Layer Security (TLS) server certificates.

Certificate Transparency v1 [RFC6962] and v2 [I-D.ietf-trans-rfc6962-bis] describe protocols for publicly logging the existence of TLS server certificates as they are issued or observed. Since each TLS server certificate lists the domain names that it is intended to secure, private domain name labels within registered domain space could end up appearing in CT logs, especially as TLS clients develop policies that mandate CT compliance. This seems like an unfortunate and potentially unnecessary privacy leak, because it's the registered domain names in each certificate that are of primary interest when using CT to look for suspect certificates.

TODO: Highlight better the differences between registered domains and subdomains, referencing the relevant DNS RFCs.

2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Redaction Mechanisms

We propose three mechanisms, in increasing order of implementation complexity, to allow certain DNS domain name labels to not appear in public CT logs:

- Using wildcard certificates (Section 3.1) is the simplest option, but it only covers certain use cases.
- Logging a name-constrained intermediate CA certificate in place of the end-entity certificate (Section 3.2) covers more, but not all, use cases.
- Therefore, we define a domain label redaction mechanism (Section 3.3) that covers all use cases, at the cost of considerably increased implementation complexity.

We anticipate that TLS clients may develop policies that impose additional compliancy requirements on the use of the Section 3.2 and Section 3.3 mechanisms.

To ensure effective redaction, CAs and domain owners should note the privacy considerations (Section 5).

TODO(eranm): Do we need to further expand (either here or in the following subsections) on when each of the mechanisms is/isn't suitable?

TODO: Previously, these mechanisms were defined in earlier revisions of CTv2 [I-D.ietf-trans-rfc6962-bis], and nothing was said about compatibility with CTv1. But now, given that these mechanisms have been decoupled from [I-D.ietf-trans-rfc6962-bis], and given that at least one major TLS client has announced a policy of mandatory CT compliance that will almost certainly take effect before CTv2 is widely deployed, we should consider making some or all of these mechnanisms compatible with both CTv1 and CTv2.

3.1. Using Wildcard Certificates

A certificate containing a DNS-ID [RFC6125] of "*.example.com" could be used to secure the domain "topsecret.example.com", without revealing the label "topsecret" publicly.

Since TLS clients only match the wildcard character to the complete leftmost label of the DNS domain name (see Section 6.4.3 of [RFC6125]), a different mechanism is needed when any label other than the leftmost label in a DNS-ID is considered private (e.g., "top.secret.example.com"). Also, wildcard certificates are prohibited in some cases, such as Extended Validation Certificates [EV.Certificate.Guidelines].

3.2. Using a Name-Constrained Intermediate CA

An intermediate CA certificate or intermediate CA precertificate that contains the Name Constraints [RFC5280] extension MAY be logged in place of end-entity certificates issued by that intermediate CA, as long as all of the following conditions are met:

- there MUST be a non-critical extension (OID 1.3.101.76, whose extnValue OCTET STRING contains ASN.1 NULL data (0x05 0x00)). This extension is an explicit indication that it is acceptable to not log certificates issued by this intermediate CA.

- there MUST be a Name Constraints extension, in which:

  * permittedSubtrees MUST specify one or more dNSNames.

  * excludedSubtrees MUST specify the entire IPv4 and IPv6 address ranges.

Below is an example Name Constraints extension that meets these conditions:

```
SEQUENCE {
  OBJECT IDENTIFIER '2 5 29 30'
  BOOLEAN TRUE
  OCTET STRING, encapsulates {
    SEQUENCE {
      [0] {
        SEQUENCE {
          [2] 'example.com'
          }
        }
      [1] {
        SEQUENCE {
          [7] 00 00 00 00 00 00 00 00
          }
        SEQUENCE {
          [7]
            00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
            00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
          }
        }
      }
    }
  }
```

3.2.1. Presenting SCTs, Inclusion Proofs and STHs

Each SCT (and optional corresponding inclusion proof and STH) presented by a TLS server MAY correspond to an intermediate CA certificate or intermediate CA precertificate (to which the server certificate chains) that meets the requirements in Section 3.2. This extends section TBD of CT v2 [I-D.ietf-trans-rfc6962-bis], which specifies that each SCT always corresponds to the server certificate or to a precertificate that corresponds to that certificate.

Each SCT (and optional corresponding inclusion proof and STH) included by a certification authority in a Transparency Information X.509v3 extension in the "singleExtensions" of a "SingleResponse" in an OCSP response MAY correspond to an intermediate CA certificate or intermediate CA precertificate (to which the certificate identified by the "certID" of that "SingleResponse" chains) that meets the requirements in Section 3.2. This extends section TBD of CT v2 [I-D.ietf-trans-rfc6962-bis], which specifies that each SCT always corresponds to the certificate identified by the "certID" of that "SingleResponse" or to a precertificate that corresponds to that certificate.

Each SCT (and optional corresponding inclusion proof and STH) included by a certification authority in a Transparency Information

X.509v3 extension in a certificate MAY correspond to an intermediate CA certificate or intermediate CA precertificate (to which the certificate chains) that meets the requirements in Section 3.2. This extends section TBD of CT v2 [I-D.ietf-trans-rfc6962-bis], which specifies that each SCT always corresponds to a precertificate that corresponds to that certificate.

TODO: Refactor this section to avoid repetition.

3.2.2. Matching an SCT to the Correct Certificate

Before considering any SCT to be invalid, a TLS client MUST attempt to validate it against the server certificate and against each of the zero or more suitable name-constrained intermediates in the chain. These certificates may be evaluated in the order they appear in the chain, or indeed, in any order.

TODO: Shall we specify that there MUST be no more than ONE name-constrained intermediate in the chain?

TODO: Shall we specify that all presented SCTs MUST correspond to the same (end-entity or name-constrained intermediate) certificate?

3.3. Redacting Labels in Precertificates

When creating a precertificate, the CA MAY include a redactedSubjectAltName (Section 3.3.1) extension that contains, in a redacted form, the same entries that will be included in the certificate's subjectAltName extension. When the redactedSubjectAltName extension is present in a precertificate, the subjectAltName extension MUST be omitted (even though it MUST be present in the corresponding certificate).

Wildcard "*" labels MUST NOT be redacted, but one or more non-wildcard labels in each DNS-ID [RFC6125] can each be replaced with a redacted label as follows:

```
  REDACT(label) = prefix || BASE32(index || _label_hash)
    _label_hash = LABELHASH(keyid_len || keyid || label_len || label)
```

"label" is the case-sensitive label to be redacted.

"prefix" is the "?" character (ASCII value 63).

"index" is the 1 byte index of a hash function in the CT hash algorithm registry (section TBD of [I-D.ietf-trans-rfc6962-bis]). The value 255 is reserved.

"keyid_len" is the 1 byte length of the "keyid".

"keyid" is the keyIdentifier from the Subject Key Identifier extension (section 4.2.1.2 of [RFC5280]), excluding the ASN.1 OCTET STRING tag and length bytes.

"label_len" is the 1 byte length of the "label".

"||" denotes concatenation.

"BASE32" is the Base 32 Encoding function (section 6 of [RFC4648]). Pad characters MUST NOT be appended to the encoded data.

"LABELHASH" is the hash function identified by "index".

3.3.1. redactedSubjectAltName Certificate Extension

The redactedSubjectAltName extension is a non-critical extension (OID 1.3.101.77) that is identical in structure to the subjectAltName extension, except that DNS-IDs MAY contain redacted labels (Section 3.3).

When used, the redactedSubjectAltName extension MUST be present in both the precertificate and the corresponding certificate.

This extension informs TLS clients of the DNS-ID labels that were redacted and the degree of redaction, while minimizing the complexity of TBSCertificate reconstruction (Section 3.3.3). Hashing the redacted labels allows the legitimate domain owner to identify whether or not each redacted label correlates to a label they know of.

TODO: Consider the pros and cons of this ’un’redaction feature. If the cons outweigh the pros, switch to using Andrew Ayer’s alternative proposal of hashing a random salt and including that salt in an extension in the certificate (and not including the salt in the precertificate).

Only DNS-ID labels can be redacted using this mechanism. However, CAs can use the Section 3.2 mechanism to allow DNS domain name labels in other subjectAltName entries to not appear in logs.

TODO: Should we support redaction of SRV-IDs and URI-IDs using this mechanism?

3.3.2. Verifying the redactedSubjectAltName extension

If the redactedSubjectAltName extension is present, TLS clients MUST check that the subjectAltName extension is present, that the subjectAltName extension contains the same number of entries as the redactedSubjectAltName extension, and that each entry in the subjectAltName extension has a matching entry at the same position in the redactedSubjectAltName extension. Two entries are matching if either:

- The two entries are identical; or
- Both entries are DNS-IDs, have the same number of labels, and each label in the subjectAltName entry has a matching label at the same position in the redactedSubjectAltName entry. Two labels are matching if either:
  - The two labels are identical; or,
  - Neither label is "*" and the label from the redactedSubjectAltName entry is equal to REDACT(label from subjectAltName entry) (Section 3.3).

If any of these checks fail, the certificate MUST NOT be considered compliant.

3.3.3. Reconstructing the TBSCertificate

Section TBD of [I-D.ietf-trans-rfc6962-bis] describes how TLS clients can reconstruct the TBSCertificate component of a precertificate from a certificate, so that associated SCTs may be verified.

If the redactedSubjectAltName extension (Section 3.3.1) is present in the certificate, TLS clients MUST also:

- Verify the redactedSubjectAltName extension against the subjectAltName extension according to Section 3.3.2.
- Once verified, remove the subjectAltName extension from the TBSCertificate.

4. Security Considerations

4.1. Avoiding Overly Redacted Domain Names

Redaction of domain name labels (Section 3.3) carries the same risks as the use of wildcards (e.g., section 7.2 of [RFC6125]). If the entirety of the domain space below the unredacted part of a domain

name is not registered by a single domain owner (e.g., REDACT(label).com, REDACT(label).co.uk and other [Public.Suffix.List] entries), then the domain name may be considered by clients to be overly redacted.

CAs should take care to avoid overly redacting domain names in precertificates. It is expected that monitors will treat precertificates that contain overly redacted domain names as potentially misissued. TLS clients MAY consider a certificate to be non-compliant if the reconstructed TBSCertificate (Section 3.3.3) contains any overly redacted domain names.

TODO(eranm): Describe how the CT ecosystem would be harmed if the use of redaction becomes too widespread.

5. Privacy Considerations

5.1. Ensuring Effective Redaction

Although the mechanisms described in this document remove the need for private labels to appear in CT logs, they do not guarantee that this will never happen. For example, anyone who encounters a certificate could choose to submit it to one or more logs, thereby rendering the redaction futile.

Domain owners are advised to take the following steps to minimize the likelihood that their private labels will become known outside their closed communities:

- Avoid registering private labels in public DNS.
- Avoid using private labels that are predictable (e.g., "www", labels consisting only of numerical digits, etc). If a label has insufficient entropy then redaction will only provide a thin layer of obfuscation, because it will be feasible to recover the label via a brute-force attack.
- Avoid using publicly trusted certificates to secure private domain space.
- Avoid enabling unrestricted access for DNS zone transfer (AXFR) requests (see section 5 of [RFC5936]).

CAs are advised to carefully consider each request to redact a label using the Section 3.3 mechanism. When a CA believes that redacting a particular label would be futile, we advise rejecting the redaction request. TLS clients may have policies that forbid redaction, so

label redaction should only be used when it’s absolutely necessary and likely to be effective.

6. Acknowledgements

The authors would like to thank Andrew Ayer and TBD for their valuable contributions.

A big thank you to Symantec for kindly donating the OIDs from the 1.3.101 arc that are used in this document.

7. References

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Authors' Addresses

Rob Stradling
Comodo CA, Ltd.

Email: rob.stradling@comodo.com

Eran Messeri
Google UK Ltd.

Email: eranm@google.com

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L. Xia, Ed.
D. Zhang
Huawei
D. Gillmor
CMRG
B. Sarikaya
Huawei USA

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CT for Binary Codes
draft-zhang-trans-ct-binary-codes-04

Abstract

This document proposes a solution extending the Certificate Transparency protocol [I-D.ietf-trans-rfc6962-bis] for transparently logging the software binary codes (BC)or its digest with their signature, to enable anyone to monitor and audit the software provider activity and notice the distribution of suspect software as well as to audit the BC logs themselves. The solution is called "Binary Transparency" in this document.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at http://datatracker.ietf.org/drafts/current/.

Internet-Drafts are draft documents valid for a maximum of six months and may be updated, replaced, or obsoleted by other documents at any time. It is inappropriate to use Internet-Drafts as reference material or to cite them other than as "work in progress."

This Internet-Draft will expire on September 7, 2017.

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1. Introduction

Digital signatures have been widely used in software distributions to prove the authenticity of software. Through verifying signature, an end user can ensure that the gotten software is developed by a legal provider (e.g., Microsoft) and is not tampered during the distribution. If an end user does not have a direct trust relationship with the software provider, an certificate chain to a trust anchor that the user trusts should be provided. That is why many signature mechanisms for software distribution are based on public key infrastructure (PKI). However, signature mechanisms cannot prevent software provider from distributing software either with customized backdoors/drawbacks, or they do not own the right to distribute. Besides, it may be hard for a user to detect the differences between the software it got and the software provided to other users..

This draft describes the Binary Transparency mechanism which extends the Certificate Transparency (CT) protocol specified in [I-D.ietf-trans-rfc6962-bis] to support logging binary codes. A software provider can submit its software Binary Codes (BC) (or digests of codes in order to e.g., save space or avoid violating license restrictions) with associated signature to one or more CT logs. Therefore, a user can easily detect the existence of software BC with customized backdoors, by comparing with the according CT log entries. The software provider can monitor the logs all the time to detect whether there are tempered copies of its software in the log, or its software is submitted into the log by other software providers without authority. In summary, the end users should be informed when all the above situations happen, how to achieve it is beyond the scope of this document.

With this mechanism, when a section of binary codes and associated signature has been submitted to a log, if the provided certificate chain ends with a trust anchor that is accepted by the log, the log will accept it and return the Signed Binary Timestamp (SBT) to the software provider as the evidence of its acceptance provided to the users later. Thus, the users should only trust the software accompanied by SBT, even if it is associated with a proper signature. This approach then forces the software providers to submit their binary codes to logs before distributing them.

Binary Transparency is an extension to Certificate Transparency, which comply with most of the specification in [I-D.ietf-trans-rfc6962-bis]. This document only focuses on the extension part of Binary Transparency mechanisms.

1.1. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

2. Cryptographic Components of Binary Transparency

When applying CT for binary codes, a log is a single, ever-growing, append-only binary Merkle Hash Tree of software BC, with associated signature and certificate chain, complying with the Merkle Hash Tree specification in Section 2 of [I-D.ietf-trans-rfc6962-bis].

3. Motivation Scenarios

The documents disclosed by Edward Snowden have raised the concerns of people on the vulnerability of the network devices to the passive attacks performed by NSA or other organizations. Meanwhile, the

network device vendors are also concerned in their foreign markets because their products are suspected to have customized backdoors for adversaries to perform attacks. It is desired for vendors to publish the design details of the products and provide sufficient facilities for clients to check whether certain hardware or software of a device has been improperly modified. There are various techniques that could be used for this purpose. One way is to force a vendor to submit the binary codes of its firmwares to the public CT logs. Therefore, anyone can verify the correctness of each log entry and monitor when new software BCs are added to it. Specially, customers can easily detect whether the vendor is releasing the same firmware to everyone. In addition, under the assistance of the Binary Transparency, customer will have more confidence on the quality of firmware. Since the same codes are used by different customers all over the world, the drawbacks in firmware will be easier to be detected.

There are similar requirements to detect the customized backdoors or misdistribution in the software market. Besides the software itself, a user may also concern whether there are customized backdoors in the patches. The Binary Transparency can help address such concerns in the same way. In addition, this mechanism can also show some advantages in the scenarios where the signer is not aware that their keys have been compromised. If their update system is required to use a CT log, they have the chance to find out about their compromise.

4. Log Format and Operation Extensions

The software provider can submit the software and the associated signature to any preferred CT logs before distributing it. In some cases, the software provider may select only to submit the signed digest of the software because of the license restriction or the space restriction of log entry. In order to verify the attribution of each log entry, a log SHALL publish a set of certificates that it trusts to benefit an software provider to construct an certificate chain connecting a trust anchor and the certificate containing the key used to sign the software.

A log needs to verify the certificate chain provided by the software provider, and MUST refuse to accept the signed software/digest if the chain cannot lead back to a trusted anchor. If the software/digest and the signature are accepted by a log and an SBT is issued, the log MUST store the entire chain and MUST present this chain for auditing upon request.

Complying with the log format definition in [I-D.ietf-trans-rfc6962-bis], some definitions remain the same: "Log ID", "Merkle

Tree Head", "Signed Tree Head", "Merkle Consistency Proofs", "Merkle Inclusion Proofs", "Shutting down a log"... The other required log format extension for Binary Transparency are specified in the following sections:

4.1. Log Entries

Each software entry in a log MUST include a "BinaryChainEntryV2" structure as below:

```
enum { binary(TBD1), binary_digest(TBD2) } BIN_Signed_Type;

opaque BINARY<1..2^24-1>;
opaque ASN.1Cert<1..2^24-1>;
struct {
   BIN_Signed_Type bin_signed_type;
   BINARY signed_software;
   ASN.1Cert certificate_chain<1..2^24-1>;
} BinaryChainEntryV2;
```

"bin_signed_type" indicates whether the signature is generated based on the software or its digest.

"signed_software" consists a ContentInfo structure specified in CMS[RFC5652]. Specifically, this field includes the binary codes/ digest, the signature, and any other additional information used to describe the software and the issuer publishing the software. The software SHOULD be encapsulated and signed following the ways specified in CMS[RFC5652] . If signed_type is TBD1, the software binary code is encapsulated in this field. If signed_type is TBD2, the SHA-256 digest of software binary code is encapsulated in this field.

"certificate_chain" includes the certificates constructing a chain from the certificate of software provider to a certificate trusted by the log. The first certificate MUST be the certificate of software provider. Each following certificate MUST directly certify the one preceding it. The final certificate MUST either be, or be issued by, a root certificate accepted by the log. If the certificate chain is provided in the "signed_software" field structure, this field is set to empty.

4.2. TransItem Structure

The extended "TransItem" structure is defined as below:

```
    enum {
           reserved(0),
           x509_entry_v2(1), precert_entry_v2(2),
           x509_sct_v2(3), precert_sct_v2(4),
           signed_tree_head_v2(5), consistency_proof_v2(6),
           inclusion_proof_v2(7), x509_sct_with_proof_v2(8),
           precert_sct_with_proof_v2(9), BIN_entry_v2(TBD3),
           BIN_sbt_v2(TBD4), BIN_sbt_with_proof_v2(TBD5),
           (65535)
         } VersionedTransType;



   struct {
           VersionedTransType versioned_type;
           select (versioned_type) {
               case x509_entry_v2: TimestampedCertificateEntryDataV2;
               case precert_entry_v2: TimestampedCertificateEntryDataV2;
               case x509_sct_v2: SignedCertificateTimestampDataV2;
               case precert_sct_v2: SignedCertificateTimestampDataV2;
               case signed_tree_head_v2: SignedTreeHeadDataV2;
               case consistency_proof_v2: ConsistencyProofDataV2;
               case inclusion_proof_v2: InclusionProofDataV2;
               case x509_sct_with_proof_v2: SCTWithProofDataV2;
               case precert_sct_with_proof_v2: SCTWithProofDataV2;
               case BIN_entry_v2: TimestampedBinaryEntryDataV2;
               case BIN_sbt_v2: SignedBinaryTimestampDataV2;
               case BIN_sbt_with_proof_v2: SBTWithProofDataV2;
           } data;
       } TransItem;
```

"versioned_type " is the type of the encapsulated data structure of TransItem. Three new values are added to it -- BIN_entry_v2(TBD3), BIN_sbt_v2(TBD4), BIN_sbt_with_proof_v2(TBD5).

For "data" structure, a new type structure of TimestampedBinaryEntryDataV2 is added.

4.3. Merkle Tree Leaves

Each Merkle Tree leaf is defined as the hash value of a "TransItem" structure of according type. Here, a new type ("BIN_entry_v2") of "TransItem" structure is created, which encapsulates a new "TimestampedBinaryEntryDataV2" structure defined as below:

```
opaque TBSCertificate<1..2^24-1>;
struct {
          uint64 timestamp;
          opaque issuer_key_hash<32..2^8-1>;
          BIN_Signed_Type bin_signed_type;
          TBSSignedSoftware tbs_signed_software;
          SbtExtension sbt_extensions<0..2^16-1>;
        } TimestampedBinaryEntryDataV2;
```

"timestamp" is the NTP Time [RFC5905] at which the software binary code was accepted by the log, measured in milliseconds since the epoch (January 1, 1970, 00:00 UTC), ignoring leap seconds. Note that the leaves of a log's Merkle Tree are not required to be in strict chronological order.

"issuer_key_hash" is the HASH of the public key of the software provider that signed the software, calculated over the DER encoding of the key represented as SubjectPublicKeyInfo [RFC5280]. This is needed to bind the software provider to the software binary code, making it impossible for the corresponding SBT to be valid for any other software whose TBSSignedSoftware matches "tbs_signed_software". The length of the "issuer_key_hash" MUST match HASH_SIZE.

"bin_signed_type" indicates whether the signature is generated based on the software or its digest.

"tbs_signed_software" is the DER encoded TBSSignedSoftware from the "signed_software" in the case of a "BinaryChainEntryV2".

4.4. Structure of the Signed Binary Timestamp

An SBT is a "TransItem" structure of type "bin_sbt_v2", which encapsulates a "SignedBinaryTimestampDataV2" structure:

```
       enum {
              reserved(65535)
            } SbtExtensionType;

         struct {
              SbtExtensionType sbt_extension_type;
              opaque sbt_extension_data<0..2^16-1>;
            } SbtExtension;

         struct {
              LogID log_id;
              uint64 timestamp;
              SbtExtension sbt_extensions<0..2^16-1>;
              digitally-signed struct {
                  TransItem timestamped_entry;
              } signature;
            } SignedBinaryTimestampDataV2;
```

"log_id" is this log’s unique ID, encoded in an opaque vector.

"timestamp" is equal to the timestamp from the "TimestampedBinaryEntryDataV2" structure encapsulated in the "timestamped_entry".

"sbt_extension_type" identifies a single extension from the IANA registry in Section 6. At the time of writing, no extensions are specified.

The interpretation of the "sbt_extension_data" field is determined solely by the value of the "sbt_extension_type" field. Each document that registers a new "sbt_extension_type" must describe how to interpret the corresponding "sbt_extension_data".

"sbt_extensions" is a vector of 0 or more SBT extensions. This vector MUST NOT include more than one extension with the same "sbt_extension_type". The extensions in the vector MUST be ordered by the value of the "sbt_extension_type" field, smallest value first. If an implementation sees an extension that it does not understand, it SHOULD ignore that extension. Furthermore, an implementation MAY choose to ignore any extension(s) that it does understand.

The encoding of the digitally-signed element is defined in [RFC5246].

"timestamped_entry" is a "TransItem" structure that MUST be of type "BIN_entry_v2".

5. Log Client Messages

In Section 5 of [I-D.ietf-trans-rfc6962-bis], a set of messages is defined for clients to query and verify the correctness of the log entries they are interested in. In this document, a new message is defined and an existing message is extended for CT to support Binary Transparency.

5.1. Add Binary Code and Certificate Chain to Log

POST https://<log server>/ct/v1/add-Binary-chain

Inputs:

bin_signed_type: indicates whether the input parameter "software" is constructed by the binary code or its digest.

software: the binary code (or digest), the signature, and the information used to describe the software and the software provider publishing the software, which are encapsulated following the way specified in CMS[RFC5652] . The submitter desires a SBT for this element.

chain: An array of base64-encoded certificates. The first element is the certificate used to sign the binary code (or digest); the second certifies the first and so on to the last, which either is, or is certified by, an accepted trust anchor.If the certificate chain information has been included in the "software" field, this field could be empty.

Outputs:

sbt: A base64 encoded "TransItem" of type "BIN_sbt_v2", signed by this log, that corresponds to the submitted software.

Error codes:

Be identical with the according part in Section 5.1 (Add Chain to Log) of [I-D.ietf-trans-rfc6962-bis].

5.2. Retrieve Entries and STH from Log

```
   GET https://<log server>/ct/v2/get-entries
   Inputs:
      start:  0-based index of first entry to retrieve, in decimal.
      end:  0-based index of last entry to retrieve, in decimal.
   Outputs:
      entries:  An array of objects, each consisting of
      leaf_input:  The base64 encoded "TransItem" structure of type
                   "x509_entry_v2" or "precert_entry_v2" or "BIN_entry_v2"
                   (see Section 4.3).
      log_entry:  The base64 encoded log entry (see Section 4.1).  In the
                  case of an "x509_entry_v2" entry, this is the whole
                  "X509ChainEntry"; and in the case of a "precert_entry_v2",
                  this is the whole "PrecertChainEntryV2"; and in the case of a
                  "BIN_entry_v2", this is the whole "BinaryChainEntryV2".
      sct:  The base64 encoded "TransItem" of type "x509_sct_v2" or "precert_sct
_v2"
            or "BIN_sbt_v2"corresponding to this log entry.
      sth:  A base64 encoded "TransItem" of type "signed_tree_head_v2", signed
            by this log.
```

More details are identical with Section 5.7 of [I-D.ietf-trans-rfc6962-bis].

5.3. Summary

In summary, the above extensions of Binary Transparency enable the software providers, the end users, and anyone to monitor and audit the CT logs to mitigate the possible attacks induced by tampered software, or software misdistribution.

This section gives a brief introduction to all the other aspects of Binary Transparency mechanisms for the reason of completeness, since they comply with the basic CT protocol specification. For more details please refer to the corresponding sections of [I-D.ietf-trans-rfc6962-bis].

Software providers act the same as TLS servers in CT protocol. They present one or more SBTs from one or more logs to each end user while distributing the software, where each SBT corresponds to the software. Software providers SHOULD also present corresponding inclusion proofs and STHs. In which way the software providers present this information is beyond the scope of this document.

The end users of software acts the same as Clients of logs described in CT protocol. They can perform various different functions, such as: get log metadata, exchange STHs they see, receive and validate SBTs, Validate inclusion proofs.

Binary Transparency also provides monitoring and auditing functions with the same algorithms defined for CT protocol.

Binary Transparency supports the same algorithm agility feature for signature algorithm and hash algorithm as CT protocol.

6. Acknowledgements

7. IANA Considerations

To be added.

8. Security Considerations

To be added.

9. References

9.1. Normative References

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9.2. Informative References

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Authors' Addresses

Liang Xia (editor)
Huawei

Email: frank.xialiang@huawei.com

Dacheng Zhang
Huawei

Email: dacheng.zhang@huawei.com

Daniel Kahn Gillmor
CMRG

Email: dkg@fifthhorseman.net

Behcet Sarikaya
Huawei USA
5340 Legacy Dr. Building 3
Plano, TX 75024

Email: sarikaya@ieee.org

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D. Zhang

D. Gillmor
CMRG

D. He
Huawei

B. Sarikaya
Huawei USA

N. Kong

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Certificate Transparency for Domain Name System Security Extensions
draft-zhang-trans-ct-dnssec-03

Abstract

In draft-ietf-trans-rfc6962-bis, a solution (Certificate Transparency) is proposed for publicly logging the existence of Transport Layer Security (TLS) certificates using Merkle Hash Trees. This document proposes a mechanism to extend Certificate Transparency for DNSSEC which publicly logs the DS RRs to notice the issuance of suspect key signing keys.

Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on January 6, 2016.

Table of Contents

1. Introduction

[I-D.ietf-trans-rfc6962-bis] specifies a Certificate Transparency (CT) mechanism to disclosing TLS certificates into public logs. This mechanism benefits the public to monitor the operations in issuing certificates to improper subscribers. The logs do not prevent mis-issuing behavior directly, but the provided public audibility can increase the possibility in detecting the improper behaviors of issuers. The logs are constructed with Merkle Hash Trees to ensure the append-only property, and thus enable anyone to verify the correctness of each log record. Note that CT is a common mechanism although [I-D.ietf-trans-rfc6962-bis] only specifies how to use it to publish TLS server certificates issued by public certificate authorities (CAs).

This document discusses the use of CT in addressing the improper issuance issues in DNSSEC. DNSSEC establishes chains of public keys for clients to assess the validity of DNS resource records. In order to prove the validity of keys used for signing DNS data, DNSSEC uses DNS public key (DNSKEY) RRsets and Delegation Signer (DS) RRsets to form authentication chains for the signed data, with each link in the chains vouching for the next by signing the next. If an authentication chain can be eventually connected to the a trusted DNS key or DS RR, the client then ensures the key for signing the data is legitimate. Unlike PKIX, SDNSEC inherently has strong naming constraints. The owner of a zone can only be allowed to sign the RRs in his zone. Any attempt in signing the RRs in other zones will be easily detected by clients. However, the owner of a zone is dependent on its parent delegation via the DS record to vouch for its DNSKEY. The zone itself is responsible for publishing DS records for the child zones that dependant on it. Misbehavior or compromise of the parent zone directly affects the core DNS security of the child zone. A detailed example is provided in Section 3.

In order to benefit the detection of improper issuance/delegation of DNSSEC keys, this document describes an extension to CT to support logging DSs . The CT logs are publicly auditable, making it possible for anyone to verify the correctness of the log entries and monitor the new DS RR’s appended to the log. The logs do not prevent the parent from issuing DS records that the child disagrees with, but they ensure that interested parties can detect such operations. For instance, For example, a zone owner that has been compromised or compelled by a third party can hijack a child zone to return different DNS data that is indistinguishable from DNSSEC validated data from the child zone by using its own DNSKEY to sign DNS data on behalf of the child zone. It could deliver this modified DNS data to only selected regions or individuals, making this attack very difficult to detect by the legitimate child zone.

In DNSSEC, it is assumed that the keys used for signing RRs or other keys will be properly maintained. This work follows this assumption and the compromise of key signing keys are out of scope of this work. This work assumes the existence of inside attacker. That is, a legal owner of a zone may try to attack or circumvent other zones. However, because the naming constraint feature of DNSSEC, a zone owner in principle can only use its keys to perform attacks on its child zones.

This work reuses most of the messages and data structures specified in [I-D.ietf-trans-rfc6962-bis] and makes necessary extensions for supporting DS RRs. Only the extensions to [I-D.ietf-trans-rfc6962-bis] are presented in this document.

2. Cryptographic Components of Certificate Transparency

The introduce of cryptographic components of CT is in Section 2 of [I-D.ietf-trans-rfc6962-bis]. When applying CT for NDSSEC, a log is a single, ever-growing, append-only Merkle Tree of DS RRs.

3. Motivation Scenario

Assume a zone (foo.bar.example) and its parent zone (bar.example) are owned by different organizations. Follows are the steps of an example attack that the owner of the parent zone could perform on the child zone.

1. Set up a fake foo.bar.example DNS server

2. The owner of parent zone generates a new KSK X1 and ZSK X2 for the fake foo.bar.example DNS server, because it does not know the private key of the KSK of foo.bar.example. The fake server uses the KSK to sign the ZSK and uses the ZSK to sign the fake resource records

3. The owner of parent zone generates a DS record for the KSK record generated in step 2 in order to generate the certificate chain for the records in the fake server.

4. The owner of bar.example signs the DS RR with its zone signing key and publishes it

5. Change the IP address of the DNS server of foo.bar.example in the associated RRs to the IP address of the fake DNS server

The owner of foo.bar.example may try to periodically access the DNS server of bar.example and monitor the RRs on it . However, there could be still a time window between two assessments which can be

taken advantage of by the owner of bar.example to perform a hijacking attack and remove the bogus RRs before the owner of foo.bar.example detects the attack.

In some cases, the parent can even achieve its objectives without publishing the DS RR containing the invalid KSK, which makes the attacks more difficult to detect.

If the owner of bar.example is forced to publish his operations on the public CT logs, the attack introduced above will be detected eventually. Through checking the log, it is easy detect the improper issuance of RRs of his parent zone.

4. Log Format and Operation

As illustrated in Section 3, a zone owner may need to publish multiple RRs in order to hijack the queries to its child zone and re-direct them to another illegal DNS server. However, it is not necessary to publish all those associated RRs to the log. In fact, by publishing the DS RR which is critical in constructing the authentication chain across two zones will be sufficient for helping the public to detect the improper issuance behavior. In this solution, when a zone owner generates a DS RR and delegates a new public key to a child zone, it MUST publish the DS RR at least one CT log in order to allow the public to monitor its behavior. Identical to what is specified in [I-D.ietf-trans-rfc6962-bis], each CT log needs to return a SCT to the zone owner immediately. The SCT will be encapsulated in a SCT RR and published within a DS RR.

The SCT is the log’s promise to incorporate the RR in the Merkle Tree within a fixed amount of time known as the Maximum Merge Delay (MMD). If the log has previously seen the certificate, it MAY return the same SCT as it returned before. DNS servers MUST provide an SCT within a SCT RR. DNSSEC clients will not honor a DS RR that does not have a valid SCT. Therefore it is expected that a zone owner will usually deliver the DS RRs for audit purposes.

4.1. Log Entries

Before publishing a DS RR, a zone owner MUST submit it to one or more preferred logs. In order to enable attribution of each logged RR to its issuer, the log SHALL publish a list of acceptable public keys (or hashes of public keys) of root zone or islands of security. Each submitted DS RR MUST be accompanied by all additional RRs (DNSKEY RRs, DS RRs, and RRSIG RRs) which construct an authentication chain to an accepted root public key.

Logs MUST verify that the authentication chain and make sure it leads back to a trusted public key, using the chain of intermediate DNSKEY RRs and DS RRs provided by the submitter. Logs MUST refuse to publish a DS RR without a valid chain to a trusted key. If a DS RR is accepted and an SCT issued, the accepting log MUST store the entire chain used for verification, including the DS RR itself and including the trusted key used to verify the chain, and MUST present this chain for auditing upon request.

To comply with the certificate entries specified in [I-D.ietf-trans-rfc6962-bis],Each DS RR entry in a log MUST include the following components:

```
 enum { x509_entry(0), precert_entry(1), DSRR_entry(TBD1),(65535) } LogEntryT
ype;

 struct {
     LogEntryType entry_type;
     select (entry_type) {
         case x509_entry: X509ChainEntry;
         case precert_entry: PrecertChainEntry;
         case DSRR_entry:DSRR_Chain_Entry
     } entry;
 } LogEntry;

 opaque DNSSECRR<1..2^24-1>;

 struct {
    DNSSECRR DSRR;
    DNSSECRR DNSSEC_key_chain<0..2^24-1>
 } DSRR_Chain_Entry;
```

"entry_type" is the type of this entry. the type value of a DSRR LogEntry is TBD1.

"DSRR" is the DS RR submitted for auditing.

"DNSSEC_key_chain" is a chain of additional DNSSEC RRs required to verify the DS RR.A typical authentication chain is as follow: Trusted DNSSKEY ->[DS->(DNSKEY)*->DNSKEY]*-> Submitted DS RR, where "*" denotes zero or more sub-chains. (DNSKEY)* indicates that DNSSEC permits additional layers of DNSKEY RRs including the keys for signing other keys within a zone. Each DNSKEY/DS RR in the chain is authenticated by a RRSIG RR. In practice, a RRSIG RR is normally used to sign a DS/DNSKEY RRset. Therefore, not only the DS/DNSKEY RR on the authentication chain but also other records in the RRset SHOULD be provided to the log the verification purpose. Otherwise, the log may have to consult DNS again in order to verify the

authentication chains. Logs SHOULD limit the length of chain they will accept.

4.2. Structure of the Signed Certificate Timestamp

This work reuses the structure of Signed Certificate Timestamp specified in Section 3.3 of [I-D.ietf-trans-rfc6962-bis] but make necessary extensions.

```
 enum { certificate_timestamp(0), tree_hash(1),DSRR_timestamp(TBD2), (255) }
   SignatureType;

 enum { v1(0), (255) }
   Version;

   struct {
       opaque key_id[32];
   } LogID;

  struct {
     opaque issuer_key_hash[32];
     C14N_DSRR dsrr;
   } DSRR;

   opaque CtExtensions<0..2^16-1>;
```

"key_id" and "issuer_key_hash" are defined in Section 3.3 of [I-D.ietf-trans-rfc6962-bis].

dsrr is the submitted DS RR in a canonical form. The canconicalization of a DS RR is described in Section 6.2 of [RFC4304].

```
struct {
    Version sct_version;
    LogID id;
    uint64 timestamp;
    CtExtensions extensions;
    digitally-signed struct {
        Version sct_version;
        SignatureType signature_type = DSRR_timestamp;
        uint64 timestamp;
        LogEntryType entry_type;
        select(entry_type) {
            case x509_entry: ASN.1Cert;
            case precert_entry: PreCert;
            case BIN_entry: BinaryDigest;
            case BINDI_entry: BinaryDigest
        } signed_entry;
       CtExtensions extensions;
    };
} SignedCertificateTimestamp;
```

The encoding of the digitally-signed element is defined in [RFC5246].

"sct_version", "timestamp", "entry_type and extensions" are are identical to what is defined in Section 3.3 of [I-D.ietf-trans-rfc6962-bis].

"signed_entry" is the is DSRR (in the case of a DSRR_entry), as described above.

"extensions" are future extensions to this protocol version (v1). Currently, no extensions are specified.

4.3. Merkle Tree

This specification extends the structure of the Merkle Tree input in Section 3.5 of [I-D.ietf-trans-rfc6962-bis] and enable it to encapsulate DS RR:

```
enum { v1(0), v2(1), (255) }
  LeafVersion;

struct {
    uint64 timestamp;
    LogEntryType entry_type;
    select(entry_type) {
        case x509_entry: ASN.1Cert;
        case precert_entry: PreCert;
        case DSRR_entry: DSRR;
    } signed_entry;
    CtExtensions extensions;
} TimestampedEntry;

struct {
    LeafVersion version;
    TimestampedEntry timestamped_entry;
} MerkleTreeLeaf;
```

The fields in the input are introduced in Section 3.5 of [I-D.ietf-trans-rfc6962-bis].

Open question[dacheng]: We should include the RRs constucting the authenticaiton chain in the input, right?

5. Including the Signed Certificate Timestamp into DNS Security Extensions

In section 3.5 of [I-D.ietf-trans-rfc6962-bis]

5.1. SCT RR

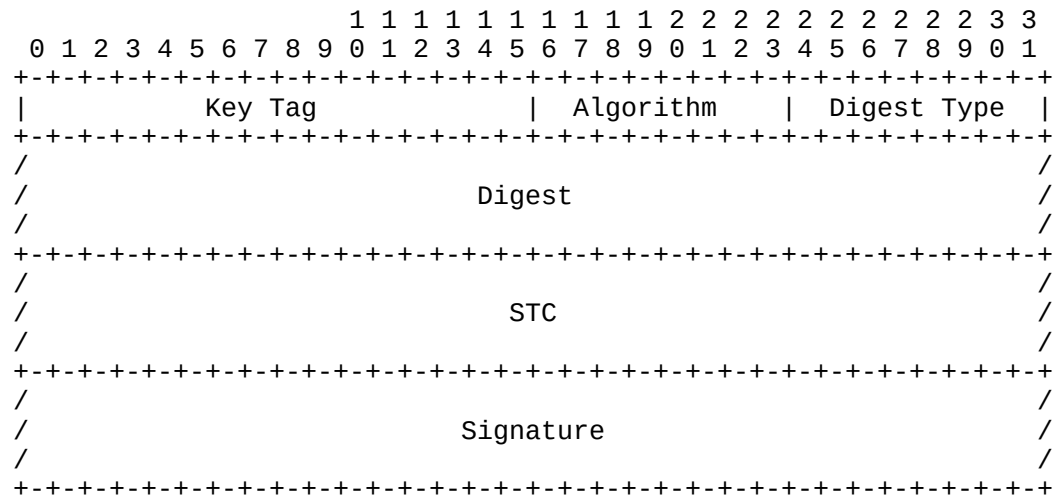
The SCT associated with a DS RR is stored within a STC RR. A DNS server MAY provide multiple SCT RRs for one DS RR.

The type number for the SCT RR is TBD3.

The SCT resource record is class independent.

The life period of SCT RR should not be set in a way that the RR will not be expired before the associated DS RR.

The RDATA portion of an SCT RR is as shown below.



5.1.1. The Key Tag Field

The Key Tag field lists the key tag of the DNSKEY RR referred to by the SCT record, in network byte order. Appendix B of [RFC4034] describes how to compute a Key Tag.

5.1.2. The Algorithm Field

The Algorithm field lists the algorithm number of the DNSKEY RR referred to by the SCT record. Appendix A.1 of [RFC4034] lists the algorithm number types.

5.1.3. The Digest Type Field

The Digest Type field identifies the algorithm used to construct the digest used to identify the DS RR that the SCT RR refers to. Appendix A.2 of [RFC4034] lists the possible digest algorithm types.

5.1.4. The Digest Field

The method of calculating digest is identical to what is specified in Section 5.1.4 of [RFC2065].[RFC4034]

5.1.5. The SCT Field

This field contains the SCT got from the log, encoded in BASE64.

5.1.6. The Signature Field

This field contains the SCT signature associated with the SCT. The Signature field is represented as a Base64 encoding of the signature.

5.2. Operations

After introducing the SCT RR, the verification procedures of DNS data specified in DNSSEC[RFC4305] do not change a lot. However, the correctness of CTS needs to be assessed during checking the validity of a DS RR.

A DS RR needs to be associated with a CTS RR which contains a valid CTS and signed with a proper public key. Otherwise, the DS RR will not be used to construct the authentication chain. The signatures of DS RR and its CTS RR should be stored in different RRSIG RR respectively. In addition, a DNS server will sends CTS RRs and the associated RRSIG RRs to a resolver only when it indicates the support of CT in the request.

6. Log Client Messages

In Section 4 of [I-D.ietf-trans-rfc6962-bis], a set of messages is defined for clients to query and verfiy the correctness of the log entries they are interested in. In this memo, two new messages are defined for CT to support DNSSEC.

6.1. Add DNSSEC RR Chain to Log

POST https://<log server>/ct/v1/add-RR-chain

Inputs:

chain: An array of base64-encoded DNS RR. The first element is the submited DS RR; the second chains to the first and so on to the last, which is a trurst DNSKey RR.

Outputs:

sct_version: The version of the SignedCertificateTimestamp structure, in decimal. A compliant v1 implementation MUST NOT expect this to be 0 (i.e., v1).

id: The log ID, base64 encoded.

timestamp: The SCT timestamp, in decimal.

extensions: An opaque type for future expansion. It is likely that not all participants will need to understand data in this field. Logs should set this to the empty string. Clients should decode the base64-encoded data and include it in the SCT.

signature: The SCT signature, base64 encoded.

6.2. Retrieve Accepted Root DNSKEY RRs

GET https://<log server>/ct/v1/get-root-RRs

No inputs.

Outputs:

RRs: An array of base64-encoded DNSKEY RRs that are acceptable to the log.

7. IANA Considerations

This document specified a new LogEntryType value TBD1 to identify DS RR entry, a new SCT Type value TBD2, and a type number for the SCT DNS RR TBD3.

8. Security Considerations

8.1. Logging Other Types of RRs

This solution only tries to describes a solution to disclose keys for DNSSEC in logs for the public to audit. However, it may be valuable to also log the RRs specified in [RFC1035]. For instance, assume there is an attacker which has compromised the zone authentication key and is able to perform the MITM attack between a resolver and the DNS server of the zone. It is possible for an attacker to transfer a forged RR which is signed with the compromised key. The current solution cannot benefit the detection of this attack in this scenario. However, if the RR is also required to be uploaded to public logs, the condition is changed. If the attacker does not publish the RR to a log, it cannot get the SCT. When the attacker tries to publish the RR to the log, the owner of the zone may detect the problem even if the attacker can provide keys to convince the log to accept the RR.

8.2. Scalability Concerns

The log MAY limit accepting entries where the TTL is too short or the RRSIG times are too far in the future or the past, to avoid spamming the log. It should probably also put a maximum on the number of child zones to avoid getting spammed.

9. Acknowledgements

10. Normative References

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Authors' Addresses

Dacheng Zhang

Email: dacheng.zhang@gmail.com

Daniel Kahn Gillmor
CMRG

Email: dkg@fifthhorseman.net

Danping He
Huawei

Email: ana.hedanping@huawei.com

Behcet Sarikaya
Huawei USA
5340 Legacy Dr. Building 3
Plano, TX 75024

Email: sarikaya@ieee.org

Ning Kong

Email: nkong@cnnic.cn