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Certificate Transparency Version 2.0
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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.

- submit-entry: new client API, replacing add-chain and add-pre-chain.

- 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:

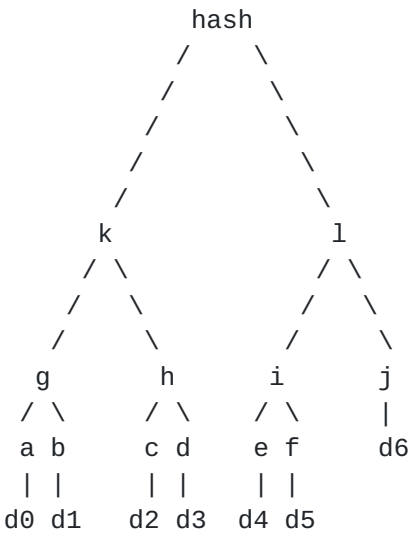
1. Set "sr" to "HASH(0x01 || sr || c)"

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:



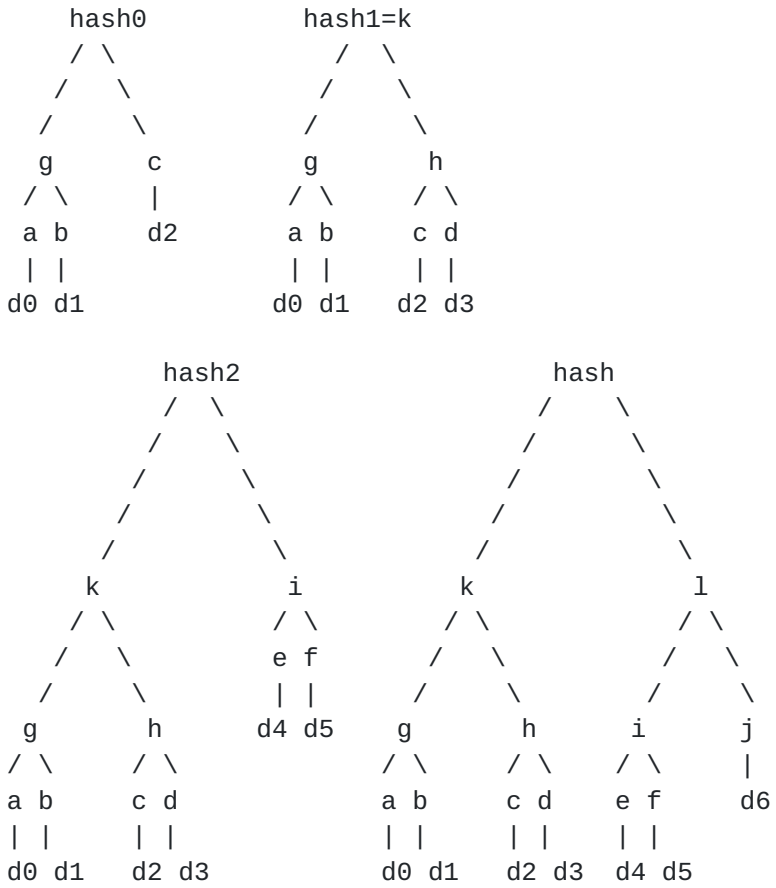
The inclusion proof for d0 is [b, h, l].

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.

- 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 certifier of the "submission"; the second certifies the first; etc. The last element of "chain" (or, if "chain" is an empty array, the "submission") 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 certifier 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 "submission" is an accepted trust anchor whose certifier is neither an accepted trust anchor nor the first element of "chain", then the log MUST return the "unknown anchor" error. A log cannot generate an SCT for a submission if it does not have access to the issuer's public key.

If the returned "sct" is intended to be provided to TLS clients, then "sth" and "inclusion" (if returned) SHOULD also be provided to TLS clients (e.g., if "type" was 2 (for "precert_sct_v2") 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.

Each "submitted_entry" output parameter MUST include the trust anchor that the log used to verify the "submission", even if that trust anchor was not provided to "submit-entry" (see Section 5.1). If the "submission" does not certify itself, then the first element of "chain" MUST be present and MUST certify the "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; issuing STHs too frequently; mutating the signature of a logged certificate; and failing to present a chain containing the certifier of a logged certificate. 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.

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