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The Messaging Layer Security (MLS) Protocol

Abstract

Messaging applications are increasingly making use of end-to-end security mechanisms to ensure that messages are only accessible to the communicating endpoints, and not to any servers involved in delivering messages. Establishing keys to provide such protections is challenging for group chat settings, in which more than two clients need to agree on a key but may not be online at the same time. In this document, we specify a key establishment protocol that provides efficient asynchronous group key establishment with forward secrecy and post-compromise security for groups in size ranging from two to thousands.

Discussion Venues

This note is to be removed before publishing as an RFC.

Source for this draft and an issue tracker can be found at https://github.com/mlswg/mls-protocol.

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 25 June 2021.

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1. Introduction

DISCLAIMER: This is a work-in-progress draft of MLS and has not yet seen significant security analysis. It should not be used as a basis for building production systems.

RFC EDITOR: PLEASE REMOVE THE FOLLOWING PARAGRAPH The source for this draft is maintained in GitHub. Suggested changes should be submitted as pull requests at https://github.com/mlswg/mls-protocol. Instructions are on that page as well. Editorial changes can be managed in GitHub, but any substantive change should be discussed on the MLS mailing list.

A group of users who want to send each other encrypted messages needs a way to derive shared symmetric encryption keys. For two parties, this problem has been studied thoroughly, with the Double Ratchet emerging as a common solution [doubleratchet] [signal]. Channels implementing the Double Ratchet enjoy fine-grained forward secrecy as well as post-compromise security, but are nonetheless efficient enough for heavy use over low-bandwidth networks.

For a group of size greater than two, a common strategy is to unilaterally broadcast symmetric "sender" keys over existing shared symmetric channels, and then for each member to send messages to the group encrypted with their own sender key. Unfortunately, while this improves efficiency over pairwise broadcast of individual messages and provides forward secrecy (with the addition of a hash ratchet), it is difficult to achieve post-compromise security with sender keys. An adversary who learns a sender key can often indefinitely and passively eavesdrop on that member's messages. Generating and distributing a new sender key provides a form of post-compromise security with regard to that sender. However, it requires computation and communications resources that scale linearly with the size of the group.

In this document, we describe a protocol based on tree structures that enable asynchronous group keying with forward secrecy and post-compromise security. Based on earlier work on "asynchronous ratcheting trees" [art], the protocol presented here uses an asynchronous key-encapsulation mechanism for tree structures. This mechanism allows the members of the group to derive and update shared keys with costs that scale as the log of the group size.

1.1. Change Log

RFC EDITOR PLEASE DELETE THIS SECTION.

draft-11

- Include subtree keys in parent hash (*)
- Pin HPKE to draft-07 (*)
- Move joiner secret to the end of the first key schedule epoch (*)
- Add an AppAck proposal
- Make initializations of transcript hashes consistent

draft-10

- Allow new members to join via an external Commit (*)
- Enable proposals to be sent inline in a Commit (*)
- Re-enable constant-time Add (*)
- Change expiration extension to lifetime extension (*)
- Make the tree in the Welcome optional (*)
- PSK injection, re-init, sub-group branching (*)
- Require the initial init_secret to be a random value (*)
- Remove explicit sender data nonce (*)
- Do not encrypt to joiners in UpdatePath generation (*)
- Move MLSPlaintext signature under the confirmation tag (*)
- Explicitly authenticate group membership with MLSPLaintext (*)
- Clarify X509Credential structure (*)
- Remove uneeded interim transcript hash from GroupInfo (*)
- IANA considerations
- Derive an authentication secret
- Use Extract/Expand from HPKE KDF
- Clarify that application messages MUST be encrypted

draft-09

- Remove blanking of nodes on Add (*)
- Change epoch numbers to uint64 (*)
- Add PSK inputs (*)
- Add key schedule exporter (*)
- Sign the updated direct path on Commit, using "parent hashes" and one signature per leaf (*)
- Use structured types for external senders (*)
- Redesign Welcome to include confirmation and use derived keys (*)
- Remove ignored proposals (*)
- Always include an Update with a Commit (*)
- Add per-message entropy to guard against nonce reuse (*)
- Use the same hash ratchet construct for both application and handshake keys (*)
- Add more ciphersuites
- Use HKDF to derive key pairs (*)
- Mandate expiration of ClientInitKeys (*)
- Add extensions to GroupContext and flesh out the extensibility story (*)
- Rename ClientInitKey to KeyPackage

draft-08

- Change ClientInitKeys so that they only refer to one ciphersuite (*)
- Decompose group operations into Proposals and Commits (*)
- Enable Add and Remove proposals from outside the group (*)
- Replace Init messages with multi-recipient Welcome message (*)
- Add extensions to ClientInitKeys for expiration and downgrade resistance (*)
- Allow multiple Proposals and a single Commit in one MLSPlaintext (*)

draft-07

- Initial version of the Tree based Application Key Schedule (*)
- Initial definition of the Init message for group creation (*)
- Fix issue with the transcript used for newcomers (*)
- Clarifications on message framing and HPKE contexts (*)

draft-06

- Reorder blanking and update in the Remove operation (*)
- Rename the GroupState structure to GroupContext (*)
- Rename UserInitKey to ClientInitKey
- Resolve the circular dependency that draft-05 introduced in the confirmation MAC calculation (*)
- Cover the entire MLSPlaintext in the transcript hash (*)

draft-05

- Common framing for handshake and application messages (*)
- Handshake message encryption (*)
- Convert from literal state to a commitment via the "tree hash" (*)
- Add credentials to the tree and remove the "roster" concept (*)
- Remove the secret field from tree node values

draft-04

- Updating the language to be similar to the Architecture document
- ECIES is now renamed in favor of HPKE (*)
- Using a KDF instead of a Hash in TreeKEM (*)

draft-03

- Added ciphersuites and signature schemes (*)
- Re-ordered fields in UserInitKey to make parsing easier (*)
- Fixed inconsistencies between Welcome and GroupState (*)
- Added encryption of the Welcome message (*)

draft-02

- Removed ART (*)
- Allowed partial trees to avoid double-joins (*)
- Added explicit key confirmation (*)

draft-01

- Initial description of the Message Protection mechanism. (*)
- Initial specification proposal for the Application Key Schedule using the per-participant chaining of the Application Secret design. (*)
- Initial specification proposal for an encryption mechanism to protect

Application Messages using an AEAD scheme. (*)

- Initial specification proposal for an authentication mechanism of Application Messages using signatures. (*)
- Initial specification proposal for a padding mechanism to improving protection of Application Messages against traffic analysis. (*)
- Inversion of the Group Init Add and Application Secret derivations in the Handshake Key Schedule to be ease chaining in case we switch design. (*)
- Removal of the UserAdd construct and split of GroupAdd into Add and Welcome messages (*)
- Initial proposal for authenticating handshake messages by signing over group state and including group state in the key schedule (*)
- Added an appendix with example code for tree math
- Changed the ECIES mechanism used by TreeKEM so that it uses nonces generated from the shared secret

draft-00

- Initial adoption of draft-barnes-mls-protocol-01 as a WG item.

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

Client: An agent that uses this protocol to establish shared cryptographic state with other clients. A client is defined by the cryptographic keys it holds.

Group: A collection of clients with shared cryptographic state.

Member: A client that is included in the shared state of a group, hence has access to the group's secrets.

Key Package: A signed object describing a client's identity and capabilities, and including a hybrid public-key encryption (HPKE [I-D.irtf-cfrg-hpke]) public key that can be used to encrypt to that client.

Initialization Key (InitKey): A key package that is prepublished by a client, which other clients can use to introduce the client to a new group.

Signature Key: A signing key pair used to authenticate the sender of a message.

Terminology specific to tree computations is described in Section 5.

We use the TLS presentation language [RFC8446] to describe the structure of protocol messages.

3. Basic Assumptions

This protocol is designed to execute in the context of a Service Provider (SP) as described in [I-D.ietf-mls-architecture]. In particular, we assume the SP provides the following services:

- A signature key provider which allows clients to authenticate protocol messages in a group.

- A broadcast channel, for each group, which will relay a message to all members of a group. For the most part, we assume that this channel delivers messages in the same order to all participants. (See Section 13 for further considerations.)
- A directory to which clients can publish key packages and download key packages for other participants.

4. Protocol Overview

The goal of this protocol is to allow a group of clients to exchange confidential and authenticated messages. It does so by deriving a sequence of secrets and keys known only to members. Those should be secret against an active network adversary and should have both forward secrecy and post-compromise security with respect to compromise of any members.

We describe the information stored by each client as *state*, which includes both public and private data. An initial state is set up by a group creator, which is a group containing only itself. The creator then sends *Add* proposals for each client in the initial set of members, followed by a *Commit* message which incorporates all of the *Adds* into the group state. Finally, the group creator generates a *Welcome* message corresponding to the Commit and sends this directly to all the new members, who can use the information it contains to set up their own group state and derive a shared secret. Members exchange Commit messages for post-compromise security, to add new members, and to remove existing members. These messages produce new shared secrets which are causally linked to their predecessors, forming a logical Directed Acyclic Graph (DAG) of states.

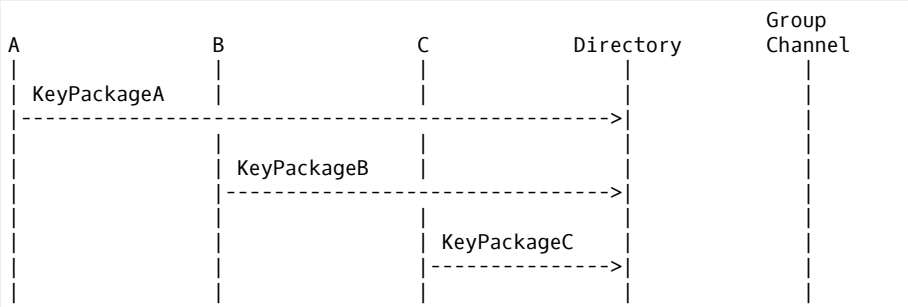
The protocol algorithms we specify here follow. Each algorithm specifies both (i) how a client performs the operation and (ii) how other clients update their state based on it.

There are three major operations in the lifecycle of a group:

- Adding a member, initiated by a current member;
- Updating the leaf secret of a member;
- Removing a member.

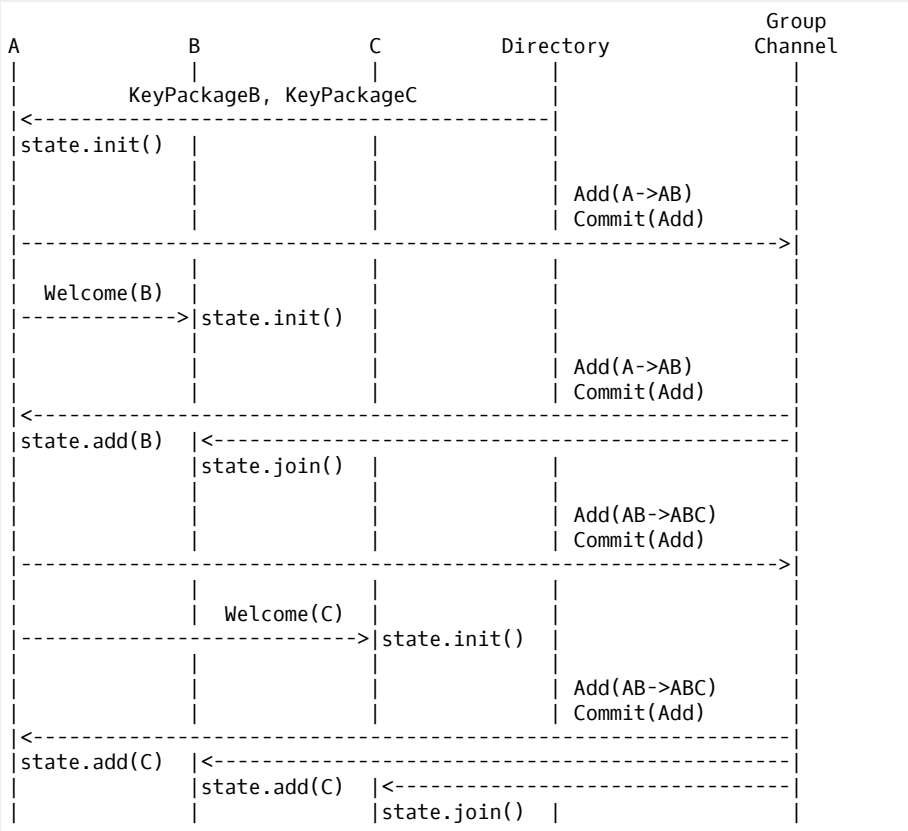
Each of these operations is "proposed" by sending a message of the corresponding type (Add / Update / Remove). The state of the group is not changed, however, until a Commit message is sent to provide the group with fresh entropy. In this section, we show each proposal being committed immediately, but in more advanced deployment cases an application might gather several proposals before committing them all at once.

Before the initialization of a group, clients publish InitKeys (as KeyPackage objects) to a directory provided by the Service Provider.



When a client A wants to establish a group with B and C, it first initializes a group state containing only itself and downloads KeyPackages for B and C. For each member, A generates an Add and Commit message adding that member, and broadcasts them to the group. It also generates a Welcome message and sends this directly to the new member (there's no need to send it to the group). Only after A has received its Commit message back from the server does it update its state to reflect the new member's addition.

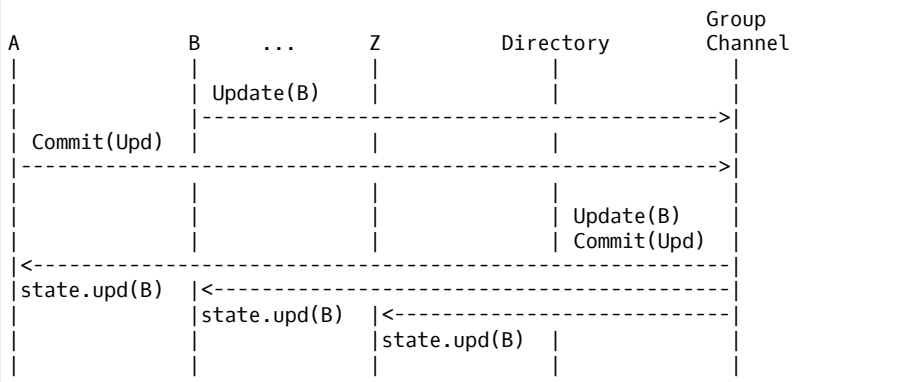
Upon receiving the Welcome message and the corresponding Commit, the new member will be able to read and send new messages to the group. Messages received before the client has joined the group are ignored.



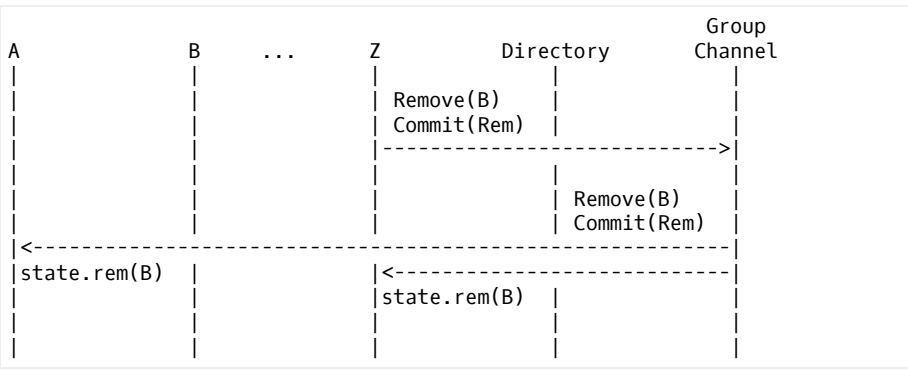
Subsequent additions of group members proceed in the same way. Any member of the group can download a KeyPackage for a new client and broadcast an Add message that the current group can use to update their state, and a Welcome message that the new client can use to initialize its state.

To enforce the forward secrecy and post-compromise security of messages, each member periodically updates their leaf secret. Any member can update this information at any time by generating a fresh KeyPackage and sending an Update message followed by a Commit message. Once all members have processed both, the group's secrets will be unknown to an attacker that had compromised the sender's prior leaf secret.

Update messages should be sent at regular intervals of time as long as the group is active, and members that don't update should eventually be removed from the group. It's left to the application to determine an appropriate amount of time between Updates.



Members are removed from the group in a similar way. Any member of the group can send a Remove proposal followed by a Commit message, which adds new entropy to the group state that's known to all except the removed member. Note that this does not necessarily imply that any member is actually allowed to evict other members; groups can enforce access control policies on top of these basic mechanism.



5. Ratchet Trees

The protocol uses "ratchet trees" for deriving shared secrets among a group of clients.

5.1. Tree Computation Terminology

Trees consist of *nodes*. A node is a *leaf* if it has no children, and a *parent* otherwise; note that all parents in our trees have precisely two children, a *left* child and a *right* child. A node is the *root* of a tree if it has no parents, and *intermediate* if it has both children and parents. The *descendants* of a node are that node, its children, and the descendants of its children, and we say a tree *contains* a node if that node is a descendant of the root of the tree. Nodes are *siblings* if they share the same parent.

A *subtree* of a tree is the tree given by the descendants of any node, the *head* of the subtree. The *size* of a tree or subtree is the number of leaf nodes it contains. For a given parent node, its *left subtree* is the subtree with its left child as head (respectively *right subtree*).

All trees used in this protocol are left-balanced binary trees. A binary tree is *full* (and *balanced*) if its size is a power of two and for any parent node in the tree, its left and right subtrees have the same size.

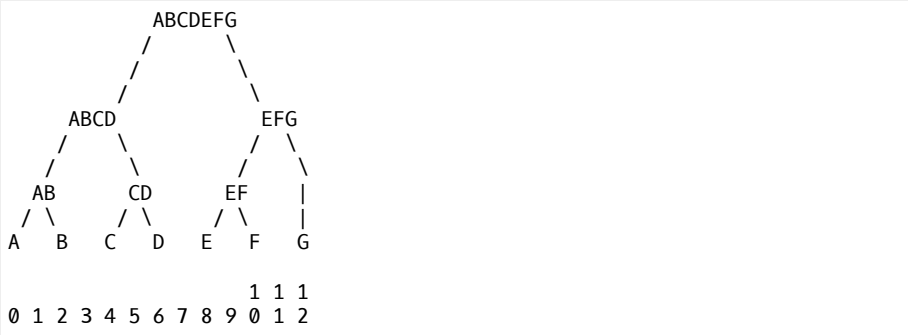
A binary tree is *left-balanced* if for every parent, either the parent is balanced, or the left subtree of that parent is the largest full subtree that could be constructed from the leaves present in the parent's own subtree. Given a list of `n` items, there is a unique left-balanced binary tree structure with these elements as leaves.

(Note that left-balanced binary trees are the same structure that is used for the Merkle trees in the Certificate Transparency protocol [I-D.ietf-trans-rfc6962-bis].)

The *direct path* of a root is the empty list, and of any other node is the concatenation of that node's parent along with the parent's direct path. The *copath* of a node is the node's sibling concatenated with the list of siblings of all the nodes in its direct path, excluding the root.

For example, in the below tree:

- The direct path of C is (CD, ABCD, ABCDEFG)
- The copath of C is (D, AB, EFG)



Each node in the tree is assigned a *node index*, starting at zero and running from left to right. A node is a leaf node if and only if it has an even index. The node indices for the nodes in the above tree are as follows:

- 0 = A
- 1 = AB
- 2 = B
- 3 = ABCD
- 4 = C
- 5 = CD
- 6 = D
- 7 = ABCDEFG
- 8 = E
- 9 = EF
- 10 = F
- 11 = EFG
- 12 = G

The leaves of the tree are indexed separately, using a *leaf index*, since the protocol messages only need to refer to leaves in the tree. Like nodes, leaves are numbered left to right. The node with leaf index `k` is also called the `k-th` leaf. Note that given the above numbering, a node is a leaf node if and only if it has an even node index, and a leaf node's leaf index is half its node index. The leaf

indices in the above tree are as follows:

- 0 = A
- 1 = B
- 2 = C
- 3 = D
- 4 = E
- 5 = F
- 6 = G

5.2. Ratchet Tree Nodes

A particular instance of a ratchet tree is defined by the same parameters that define an instance of HPKE, namely:

- A Key Encapsulation Mechanism (KEM), including a `DeriveKeyPair` function that creates a key pair for the KEM from a symmetric secret
- A Key Derivation Function (KDF), including `Extract` and `Expand` functions
- An AEAD encryption scheme

Each node in a ratchet tree contains up to five values:

- A private key (only within the member's direct path, see below)
- A public key
- An ordered list of leaf indices for "unmerged" leaves (see Section 5.3)
- A credential (only for leaf nodes)
- A hash of certain information about the node's parent, as of the last time the node was changed (see Section 7.4).

The conditions under which each of these values must or must not be present are laid out in Section 5.3.

A node in the tree may also be *blank*, indicating that no value is present at that node. The *resolution* of a node is an ordered list of non-blank nodes that collectively cover all non-blank descendants of the node.

- The resolution of a non-blank node comprises the node itself, followed by its list of unmerged leaves, if any
- The resolution of a blank leaf node is the empty list
- The resolution of a blank intermediate node is the result of concatenating the resolution of its left child with the resolution of its right child, in that order

For example, consider the following tree, where the "_" character represents a blank node:

```
        _
      /   \
    /       \
  _          CD[C]
 / \        / \
A   _      C   D

0 1 2 3 4 5 6
```

In this tree, we can see all of the above rules in play:

- The resolution of node 5 is the list [CD, C]

- The resolution of node 2 is the empty list []
- The resolution of node 3 is the list [A, CD, C]

Every node, regardless of whether the node is blank or populated, has a corresponding *hash* that summarizes the contents of the subtree below that node. The rules for computing these hashes are described in Section 7.5.

5.3. Views of a Ratchet Tree

We generally assume that each participant maintains a complete and up-to-date view of the public state of the group's ratchet tree, including the public keys for all nodes and the credentials associated with the leaf nodes.

No participant in an MLS group knows the private key associated with every node in the tree. Instead, each member is assigned to a leaf of the tree, which determines the subset of private keys it knows. The credential stored at that leaf is one provided by the member.

In particular, MLS maintains the members' views of the tree in such a way as to maintain the *tree invariant*:

```
The private key for a node in the tree is known to a member of
the group only if that member's leaf is a descendant of
the node.
```

In other words, if a node is not blank, then it holds a public key. The corresponding private key is known only to members occupying leaves below that node.

The reverse implication is not true: A member may not know the private keys of all the intermediate nodes they're below. Such a member has an *unmerged* leaf. Encrypting to an intermediate node requires encrypting to the node's public key, as well as the public keys of all the unmerged leaves below it. A leaf is unmerged when it is first added, because the process of adding the leaf does not give it access to all of the nodes above it in the tree. Leaves are "merged" as they receive the private keys for nodes, as described in Section 5.4.

5.4. Ratchet Tree Evolution

A member of an MLS group advances the key schedule to provide forward secrecy and post-compromise security by providing the group with fresh key material to be added into the group's shared secret. To do so, one member of the group generates fresh key material, applies it to their local tree state, and then sends this key material to other members in the group via an UpdatePath message (see Section 7.7) . All other group members then apply the key material in the UpdatePath to their own local tree state to derive the group's now-updated shared secret.

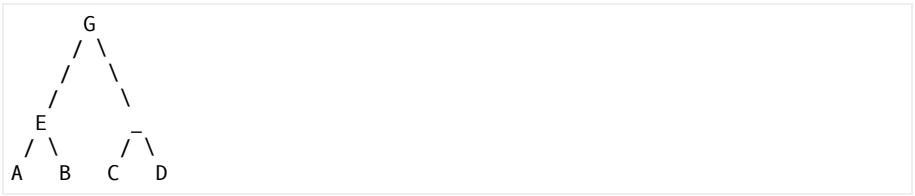
To begin, the generator of the UpdatePath updates its leaf KeyPackage and its direct path to the root with new secret values. The HPKE leaf public key within the KeyPackage MUST be derived from a freshly generated HPKE secret key to provide post-compromise security.

The generator of the UpdatePath starts by sampling a fresh random value called "leaf_secret", and uses the leaf_secret to generate their leaf HPKE key pair (see Section 7) and to seed a sequence of "path secrets", one for each ancestor of its leaf. In this setting, path_secret[0] refers to the node directly above the leaf, path_secret[1] for its parent, and so on. At each step, the path secret is used to

derive a new secret value for the corresponding node, from which the node's key pair is derived.

```
leaf_node_secret = DeriveSecret(leaf_secret, "node")
path_secret[0] = DeriveSecret(leaf_secret, "path")

path_secret[n] = DeriveSecret(path_secret[n-1], "path")
node_secret[n] = DeriveSecret(path_secret[n], "node")

leaf_priv, leaf_pub = KEM.DeriveKeyPair(leaf_node_secret)
node_priv[n], node_pub[n] = KEM.DeriveKeyPair(node_secret[n])
```

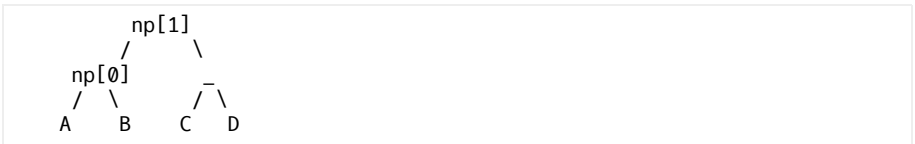
For example, suppose there is a group with four members:



If member B subsequently generates an UpdatePath based on a secret "leaf_secret", then it would generate the following sequence of path secrets:

```
path_secret[1] --> node_secret[1] --> node_priv[1], node_pub[1]
     ^
     |
path_secret[0] --> node_secret[0] --> node_priv[0], node_pub[0]
     ^
     |
leaf_secret    --> leaf_node_secret --> leaf_priv, leaf_pub
                                        ~> leaf_key_package
```

After applying the UpdatePath, the tree will have the following structure, where "np[i]" represents the node_priv values generated as described above:



After performing these operations, the generator of the UpdatePath MUST delete the leaf_secret.

5.5. Synchronizing Views of the Tree

After generating fresh key material and applying it to ratchet forward their local tree state as described in the prior section, the generator must broadcast this update to other members of the group in a Commit message, who apply it to keep their local views of the tree in sync with the sender's. More specifically, when a member commits a change to the tree (e.g., to add or remove a member), it transmits an UpdatePath message containing a set of public and encrypted private values for intermediate nodes in the direct path of a leaf. The other members of the group use these values to update their view of the tree, aligning their copy of the tree to the sender's.

To transmit this update, the sender broadcasts to the group the following information for each node in the direct path of the leaf, including the root:

- The public key for the node
- Zero or more encrypted copies of the path secret corresponding to the node

The path secret value for a given node is encrypted for the subtree corresponding to the parent's non-updated child, that is, the child on the copath of the leaf node. There is one encrypted path secret for each public key in the resolution of the non-updated child.

The recipient of a path update processes it with the following steps:

1. Compute the updated path secrets.
   - Identify a node in the direct path for which the local member is in the subtree of the non-updated child.
   - Identify a node in the resolution of the copath node for which this node has a private key.
   - Decrypt the path secret for the parent of the copath node using the private key from the resolution node.
   - Derive path secrets for ancestors of that node using the algorithm described above.
   - The recipient SHOULD verify that the received public keys agree with the public keys derived from the new path_secret values.
2. Merge the updated path secrets into the tree.
   - For all updated nodes,
     - Replace the public key for each node with the received public key.
     - Set the list of unmerged leaves to the empty list.
     - Store the updated hash of the node's parent (represented as a ParentNode struct), going from root to leaf, so that each hash incorporates all the nodes above it. The root node always has a zero-length hash for this value.
   - For nodes where an updated path secret was computed in step 1, compute the corresponding node key pair and replace the values stored at the node with the computed values.

For example, in order to communicate the example update described in the previous section, the sender would transmit the following values:

Public Key	**Ciphertext(s)**
pk(ns[1])	E(pk(C), ps[1]), E(pk(D), ps[1])
pk(ns[0])	E(pk(A), ps[0])

Table 1

In this table, the value pk(ns[X]) represents the public key derived from the node secret X, whereas pk(X) represents the public leaf key for user X. The value E(K, S) represents the public-key encryption of the path secret S to the public key K.

After processing the update, each recipient MUST delete outdated key material, specifically:

- The path secrets used to derive each updated node key pair.
- Each outdated node key pair that was replaced by the update.

6. Cryptographic Objects

6.1. Ciphersuites

Each MLS session uses a single ciphersuite that specifies the following primitives to be used in group key computations:

- HPKE parameters:
  - A Key Encapsulation Mechanism (KEM)
  - A Key Derivation Function (KDF)
  - An AEAD encryption algorithm
- A hash algorithm
- A signature algorithm

MLS uses draft-07 of HPKE [I-D.irtf-cfrg-hpke] for public-key encryption. The `DeriveKeyPair` function associated to the KEM for the ciphersuite maps octet strings to HPKE key pairs.

Ciphersuites are represented with the CipherSuite type. HPKE public keys are opaque values in a format defined by the underlying protocol (see the Cryptographic Dependencies section of the HPKE specification for more information).

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

The signature algorithm specified in the ciphersuite is the mandatory algorithm to be used for signatures in MLSPlaintext and the tree signatures. It MUST be the same as the signature algorithm specified in the credential field of the KeyPackage objects in the leaves of the tree (including the InitKeys used to add new members).

The ciphersuites are defined in section Section 16.1.

6.2. Credentials

A member of a group authenticates the identities of other participants by means of credentials issued by some authentication system, like a PKI. Each type of credential MUST express the following data in the context of the group it is used with:

- The public key of a signature key pair matching the SignatureScheme specified by the CipherSuite of the group
- The identity of the holder of the private key

Credentials MAY also include information that allows a relying party to verify the identity / signing key binding.

Additionally, Credentials SHOULD specify the signature scheme corresponding to each contained public key.

```
// See RFC 8446 and the IANA TLS SignatureScheme registry
uint16 SignatureScheme;

// See IANA registry for registered values
uint16 CredentialType;

struct {
    opaque identity<0..2^16-1>;
    SignatureScheme signature_scheme;
    opaque signature_key<0..2^16-1>;
} BasicCredential;

struct {
    opaque cert_data<0..2^16-1>;
} Certificate;

struct {
    CredentialType credential_type;
    select (Credential.credential_type) {
        case basic:
            BasicCredential;

        case x509:
            Certificate chain<1..2^32-1>;
    };
} Credential;
```

A BasicCredential is a raw, unauthenticated assertion of an identity/key binding. The format of the key in the `public_key` field is defined by the relevant ciphersuite: the group ciphersuite for a credential in a ratchet tree, the KeyPackage ciphersuite for a credential in a KeyPackage object.

For X509Credential, each entry in the chain represents a single DER-encoded X509 certificate. The chain is ordered such that the first entry (chain[0]) is the end-entity certificate and each subsequent certificate in the chain MUST be the issuer of the previous certificate. The algorithm for the `public_key` in the end-entity certificate MUST match the relevant ciphersuite.

For ciphersuites using Ed25519 or Ed448 signature schemes, the public key is in the format specified [RFC8032]. For ciphersuites using ECDSA with the NIST curves P-256 or P-521, the public key is the output of the uncompressed Elliptic-Curve-Point-to-Octet-String conversion according to [SECG].

Note that each new credential that has not already been validated by the application MUST be validated against the Authentication Service.

7. Key Packages

In order to facilitate asynchronous addition of clients to a group, it is possible to pre-publish key packages that provide some public information about a user. KeyPackage structures provide information about a client that any existing member can use to add this client to the group asynchronously.

A KeyPackage object specifies a ciphersuite that the client supports, as well as providing a public key that others can use for key agreement. The client's signature key can be updated throughout the lifetime of the group by sending a new KeyPackage with a new Credential. However, the identity MUST be the same in both Credentials and the new Credential MUST be validated by the authentication service.

When used as InitKeys, KeyPackages are intended to be used only once and SHOULD NOT be reused except in case of last resort. (See Section 15.4). Clients

MAY generate and publish multiple InitKeys to support multiple ciphersuites.

KeyPackages contain a public key chosen by the client, which the client MUST ensure uniquely identifies a given KeyPackage object among the set of KeyPackages created by this client.

The value for hpke_init_key MUST be a public key for the asymmetric encryption scheme defined by cipher_suite. The whole structure is signed using the client's signature key. A KeyPackage object with an invalid signature field MUST be considered malformed. The input to the signature computation comprises all of the fields except for the signature field.

```
enum {
    reserved(0),
    mls10(1),
    (255)
} ProtocolVersion;

// See IANA registry for registered values
uint16 ExtensionType;

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

struct {
    ProtocolVersion version;
    CipherSuite cipher_suite;
    HPKEPublicKey hpke_init_key;
    Credential credential;
    Extension extensions<8..2^32-1>;
    opaque signature<0..2^16-1>;
} KeyPackage;
```

KeyPackage objects MUST contain at least two extensions, one of type `capabilities`, and one of type `lifetime`. The `capabilities` extension allow MLS session establishment to be safe from downgrade attacks on the parameters described (as discussed in Section 10), while still only advertising one version / ciphersuite per KeyPackage.

As the `KeyPackage` is a structure which is stored in the Ratchet Tree and updated depending on the evolution of this tree, each modification of its content MUST be reflected by a change of its signature. This allow other members to control the validity of the KeyPackage at any time and in particular in the case of a newcomer joining the group.

7.1. Client Capabilities

The `capabilities` extension indicates what protocol versions, ciphersuites, and protocol extensions are supported by a client.

```
struct {
    ProtocolVersion versions<0..255>;
    CipherSuite ciphersuites<0..255>;
    ExtensionType extensions<0..255>;
} Capabilities;
```

This extension MUST be always present in a KeyPackage. Extensions that appear in the `extensions` field of a KeyPackage MUST be included in the `extensions` field of the `capabilities` extension.

7.2. Lifetime

The `lifetime` extension represents the times between which clients will consider a KeyPackage valid. This time is represented as an absolute time, measured in seconds since the Unix epoch (1970-01-01T00:00:00Z). A client MUST NOT use the data in a KeyPackage for any processing before the `not_before` date, or after the `not_after` date.

```
uint64 not_before;
uint64 not_after;
```

Applications MUST define a maximum total lifetime that is acceptable for a KeyPackage, and reject any KeyPackage where the total lifetime is longer than this duration.

This extension MUST always be present in a KeyPackage.

7.3. KeyPackage Identifiers

Within MLS, a KeyPackage is identified by its hash (see, e.g., Section 11.2.2). The `key_id` extension allows applications to add an explicit, application-defined identifier to a KeyPackage.

```
opaque key_id<0..2^16-1>;
```

7.4. Parent Hash

Consider a ratchet tree with a parent node P and children V and S. The parent hash of P changes whenever an `UpdatePath` object is applied to the ratchet tree along a path traversing node V (and hence also P). The new "Parent Hash of P (with Co-Path Child S)" is obtained by hashing P's `ParentHashInput` struct using the resolution of S to populate the `original_child_resolution` field. This way, P's Parent Hash fixes the new HPKE public keys of all nodes on the path from P to the root. Furthermore, for each such key PK the hash also binds the set of HPKE public keys to which PK's secret key was encrypted in the commit packet that anounced the `UpdatePath` object.

```
struct {
    HPKEPublicKey public_key;
    opaque parent_hash<0..255>;
    HPKEPublicKey original_child_resolution<0..2^32-1>;
} ParentHashInput;
```

The Parent Hash of P with Co-Path Child S is the hash of a `ParentHashInput` object populated as follows. The field `public_key` contains the HPKE public key of P. If P is the root, then `parent_hash` is set to a zero-length octet string. Otherwise `parent_hash` is the Parent Hash of P's parent with P's sibling as the co-path child.

Finally, `original_child_resolution` is the array of `HPKEPublicKey` values of the nodes in the resolution of S but with the `unmerged_leaves` of P omitted. For example, in the ratchet tree depicted in Section 5.2 the `ParentHashInput` of node 5 with co-path child 4 would contain an empty `original_child_resolution` since 4's resolution includes only itself but 4 is also an unmerged leaf of 5. Meanwhile, the `ParentHashInput` of node 5 with co-path child 6 has an array

with one element in it: the HPKE public key of 6.

7.4.1. Using Parent Hashes

The Parent Hash of P appears in three types of structs. If V is itself a parent node then P's Parent Hash is stored in the `parent_hash` fields of both V's `ParentHashInput` struct and V's `ParentNode` struct. (The `ParentNode` struct is used to encapsulate all public information about V that must be conveyed to a new member joining the group as well as to define the Tree Hash of node V.)

If, on the other hand, V is a leaf and its KeyPackage contains the `parent_hash` extension then the Parent Hash of P (with V's sibling as co-path child) is stored in that field. In particular, the extension MUST be present in the `leaf_key_package` field of an `UpdatePath` object. (This way, the signature of such a KeyPackage also serves to attest to which keys the group member introduced into the ratchet tree and to whom the corresponding secret keys were sent. This helps prevent malicious insiders from constructing artificial ratchet trees with a node V whose HPKE secret key is known to the insider yet where the insider isn't assigned a leaf in the subtree rooted at V. Indeed, such a ratchet tree would violate the tree invariant.)

7.4.2. Verifying Parent Hashes

To this end, when processing a Commit message clients MUST recompute the expected value of `parent_hash` for the committer's new leaf and verify that it matches the `parent_hash` value in the supplied `leaf_key_package`. Moreover, when joining a group, new members MUST authenticate each non-blank parent node P. A parent node P is authenticated by performing the following check:

- Let L and R be the left and right children of P, respectively
- If L.parent_hash is equal to the Parent Hash of P with Co-Path Child R, the check passes
- If R is blank, replace R with its left child until R is either non-blank or a leaf node
- If R is a leaf node, the check fails
- If R.parent_hash is equal to the Parent Hash of P with Co-Path Child L, the check passes
- Otherwise, the check fails

The left-child recursion under the right child of P is necessary because the expansion of the tree to the right due to Add proposals can cause blank nodes to be interposed between a parent node and its right child.

7.5. Tree Hashes

To allow group members to verify that they agree on the public cryptographic state of the group, this section defines a scheme for generating a hash value (called the "tree hash") that represents the contents of the group's ratchet tree and the members' KeyPackages. The tree hash of a tree is the tree hash of its root node, which we define recursively, starting with the leaves.

As some nodes may be blank while others contain data we use the following struct to include data if present.

```
struct {
    uint8 present;
    select (present) {
        case 0: struct{};
        case 1: T value;
    }
} optional<T>;
```

The tree hash of a leaf node is the hash of leaf's `LeafNodeHashInput` object which might include a Key Package depending on whether or not it is blank.

```
struct {
    uint32 node_index;
    optional<KeyPackage> key_package;
} LeafNodeHashInput;
```

Note that the `node_index` field contains the index of the leaf among the nodes in the tree, not its index among the leaves; `node_index = 2 * leaf_index`.

Now the tree hash of any non-leaf node is recursively defined to be the hash of its `ParentNodeTreeHashInput`. This includes an optional `ParentNode` object depending on if the node is blank or not.

```
struct {
    HPKEPublicKey public_key;
    opaque parent_hash<0..255>;
    uint32 unmerged_leaves<0..2^32-1>;
} ParentNode;

struct {
    uint32 node_index;
    optional<ParentNode> parent_node;
    opaque left_hash<0..255>;
    opaque right_hash<0..255>;
} ParentNodeTreeHashInput;
```

The `left_hash` and `right_hash` fields hold the tree hashes of the node's left and right children, respectively.

7.6. Group State

Each member of the group maintains a GroupContext object that summarizes the state of the group:

```
struct {
    opaque group_id<0..255>;
    uint64 epoch;
    opaque tree_hash<0..255>;
    opaque confirmed_transcript_hash<0..255>;
    Extension extensions<0..2^32-1>;
} GroupContext;
```

The fields in this state have the following semantics:

- The `group_id` field is an application-defined identifier for the group.
- The `epoch` field represents the current version of the group key.
- The `tree_hash` field contains a commitment to the contents of the group's ratchet tree and the credentials for the members of the group, as described in Section 7.5.

- The `confirmed_transcript_hash` field contains a running hash over the messages that led to this state.

When a new member is added to the group, an existing member of the group provides the new member with a Welcome message. The Welcome message provides the information the new member needs to initialize its GroupContext.

Different changes to the group will have different effects on the group state. These effects are described in their respective subsections of Section 11.1. The following general rules apply:

- The `group_id` field is constant
- The `epoch` field increments by one for each Commit message that is processed
- The `tree_hash` is updated to represent the current tree and credentials
- The `confirmed_transcript_hash` is updated with the data for an MLSPlaintext message encoding a Commit message in two parts:

```
struct {
    opaque group_id<0..255>;
    uint64 epoch;
    Sender sender;
    ContentType content_type = commit;
    Commit commit;
    opaque signature<0..2^16-1>;
} MLSPlaintextCommitContent;

struct {
    MAC confirmation_tag;
} MLSPlaintextCommitAuthData;

interim_transcript_hash_[0] = ""; // zero-length octet string

confirmed_transcript_hash_[n] =
    Hash(interim_transcript_hash_[n] ||
        MLSPlaintextCommitContent_[n]);

interim_transcript_hash_[n+1] =
    Hash(confirmed_transcript_hash_[n] ||
        MLSPlaintextCommitAuthData_[n]);
```

Thus the `confirmed_transcript_hash` field in a GroupContext object represents a transcript over the whole history of MLSPlaintext Commit messages, up to the confirmation tag field in the current MLSPlaintext message. The confirmation tag is then included in the transcript for the next epoch. The interim transcript hash is passed to new members in the GroupInfo struct, and enables existing members to incorporate a Commit message into the transcript without having to store the whole MLSPlaintextCommitAuthData structure.

As shown above, when a new group is created, the `interim_transcript_hash` field is set to the zero-length octet string.

7.7. Update Paths

As described in Section 11.2, each MLS Commit message may optionally transmit a KeyPackage leaf and node values along its direct path. The path contains a public key and encrypted secret value for all intermediate nodes in the path above the leaf. The path is ordered from the closest node to the leaf to the root; each node MUST be the parent of its predecessor.

```
struct {
    opaque kem_output<0..2^16-1>;
    opaque ciphertext<0..2^16-1>;
} HPKECiphertext;

struct {
    HPKEPublicKey public_key;
    HPKECiphertext encrypted_path_secret<0..2^32-1>;
} UpdatePathNode;

struct {
    KeyPackage leaf_key_package;
    UpdatePathNode nodes<0..2^32-1>;
} UpdatePath;
```

For each `UpdatePathNode`, the resolution of the corresponding copath node MUST be filtered by removing all new leaf nodes added as part of this MLS Commit message. The number of ciphertexts in the `encrypted_path_secret` vector MUST be equal to the length of the filtered resolution, with each ciphertext being the encryption to the respective resolution node.

The HPKECiphertext values are computed as

```
kem_output, context = SetupBaseS(node_public_key, "")
ciphertext = context.Seal(group_context, path_secret)
```

where `node_public_key` is the public key of the node that the path secret is being encrypted for, group_context is the current GroupContext object for the group, and the functions `SetupBaseS` and `Seal` are defined according to [I-D.irtf-cfrg-hpke].

Decryption is performed in the corresponding way, using the private key of the resolution node and the ephemeral public key transmitted in the message.

8. Key Schedule

Group keys are derived using the `Extract` and `Expand` functions from the KDF for the group's ciphersuite, as well as the functions defined below:

```
ExpandWithLabel(Secret, Label, Context, Length) =
    KDF.Expand(Secret, KDFLabel, Length)

Where KDFLabel is specified as:

struct {
    uint16 length = Length;
    opaque label<7..255> = "mls10 " + Label;
    opaque context<0..2^32-1> = Context;
} KDFLabel;

DeriveSecret(Secret, Label) =
    ExpandWithLabel(Secret, Label, "", KDF.Nh)
```

The value `KDF.Nh` is the size of an output from `KDF.Extract`, in bytes. In the below diagram:

- KDF.Extract takes its salt argument from the top and its IKM argument from the left
- DeriveSecret takes its Secret argument from the incoming arrow

When processing a handshake message, a client combines the following

information to derive new epoch secrets:

- The init secret from the previous epoch
- The commit secret for the current epoch
- The GroupContext object for current epoch

Given these inputs, the derivation of secrets for an epoch proceeds as shown in the following diagram:

```
                  init_secret_[n-1]
                        |
                        V
    commit_secret -> KDF.Extract
                        |
                        V
                  DeriveSecret(., "joiner")
                        |
                        V
                   joiner_secret
                        |
                        V
psk_secret (or 0) -> KDF.Extract
                        |
                        +--> DeriveSecret(., "welcome")
                        |    = welcome_secret
                        |
                        V
                  ExpandWithLabel(., "epoch", GroupContext_[n], KDF.Nh)
                        |
                        V
                   epoch_secret
                        |
                        +--> DeriveSecret(., <label>)
                        |    = <secret>
                        |
                        V
                  DeriveSecret(., "init")
                        |
                        V
                  init_secret_[n]
```

A number of secrets are derived from the epoch secret for different purposes:

Secret	Label
`sender_data_secret`	"sender data"
`encryption_secret`	"encryption"
`exporter_secret`	"exporter"
`authentication_secret`	"authentication"
`external_secret`	"external"
`confirmation_key`	"confirm"
`membership_key`	"membership"
`resumption_secret`	"resumption"

Table 2

The "external secret" is used to derive an HPKE key pair whose private key is held by the entire group:

```
external_priv, external_pub = KEM.DeriveKeyPair(external_secret)
```

The public key `external_pub` can be published as part of the `PublicGroupState` struct in order to allow non-members to join the group using an external commit.

8.1. External Initialization

In addition to initializing a new epoch via KDF invocations as described above, an MLS group can also initialize a new epoch via an asymmetric interaction using the external key pair for the previous epoch. This is done when an new member is joining via an external commit.

In this process, the joiner sends a new `init_secret` value to the group using the HPKE export method. The joiner then uses that `init_secret` with information provided in the PublicGroupState and an external Commit to initialize their copy of the key schedule for the new epoch.

```
kem_output, context = SetupBaseS(external_pub, PublicGroupState)
init_secret = context.export("MLS 1.0 external init secret", KDF.Nh)
```

Members of the group receive the `kem_output` in an ExternalInit proposal and preform the corresponding calculation to retrieve the `init_secret` value.

```
context = SetupBaseR(kem_output, external_priv, PublicGroupState)
init_secret = context.export("MLS 1.0 external init secret", KDF.Nh)
```

In both cases, the `info` input to HPKE is set to the PublicGroupState for the previous epoch, encoded using the TLS serialization.

8.2. Pre-Shared Keys

Groups which already have an out-of-band mechanism to generate shared group secrets can inject those into the MLS key schedule to seed the MLS group secrets computations by this external entropy.

Injecting an external PSK can improve security in the case where having a full run of updates across members is too expensive, or if the external group key establishment mechanism provides stronger security against classical or quantum adversaries.

Note that, as a PSK may have a different lifetime than an update, it does not necessarily provide the same Forward Secrecy (FS) or Post-Compromise Security (PCS) guarantees as a Commit message.

Each PSK in MLS has a type that designates how it was provisioned. External PSKs are provided by the application, while recovery and re-init PSKs are derived from the MLS key schedule and used in cases where it is necessary to authenticate a member's participation in a prior group state. In particular, in addition to external PSK types, a PSK derived from within MLS may be used in the following cases:

- Re-Initialization: If during the lifetime of a group, the group members decide to switch to a more secure ciphersuite or newer protocol version, a PSK can be used to carry entropy from the old group forward into a new group with the desired parameters.
- Branching: A PSK may be used to bootstrap a subset of current group

members into a new group. This applies if a subset of current group members wish to branch based on the current group state.

The injection of one or more PSKs into the key schedule is signaled in two ways: 1) as a `PreSharedKey` proposal, and 2) in the `GroupSecrets` object of a Welcome message sent to new members added in that epoch.

```
enum {
  reserved(0),
  external(1),
  reinit(2),
  branch(3),
  (255)
} PSKType;

struct {
  PSKType psktype;
  select (PreSharedKeyID.psktype) {
    case external:
      opaque psk_id<0..255>;

    case reinit:
      opaque psk_group_id<0..255>;
      uint64 psk_epoch;

    case branch:
      opaque psk_group_id<0..255>;
      uint64 psk_epoch;
  }
  opaque psk_nonce<0..255>;
} PreSharedKeyID;

struct {
    PreSharedKeyID psks<0..2^16-1>;
} PreSharedKeys;
```

On receiving a Commit with a `PreSharedKey` proposal or a GroupSecrets object with the `psks` field set, the receiving Client includes them in the key schedule in the order listed in the Commit, or in the `psks` field respectively. For resumption PSKs, the PSK is defined as the `resumption_secret` of the group and epoch specified in the `PreSharedKeyID` object. Specifically, `psk_secret` is computed as follows:

```
struct {
    PreSharedKeyID id;
    uint16 index;
    uint16 count;
} PSKLabel;

psk_input_[i] = KDF.Extract(0, psk_[i])
psk_secret_[i] = ExpandWithLabel(psk_input_[i], "derived psk", PSKLabel,
KDF.Nh)
psk_secret     = psk_secret_[0] || ... || psk_secret_[n-1]
```

The `index` field in `PSKLabel` corresponds to the index of the PSK in the `psk` array, while the `count` field contains the total number of PSKs.

8.3. Secret Tree

For the generation of encryption keys and nonces, the key schedule begins with the `encryption_secret` at the root and derives a tree of secrets with the same structure as the group's ratchet tree. Each leaf in the Secret Tree is associated with the same group member as the corresponding leaf in the ratchet tree.

Nodes are also assigned an index according to their position in the array representation of the tree (described in Appendix A). If N is a node index in the Secret Tree then left(N) and right(N) denote the children of N (if they exist).

The secret of any other node in the tree is derived from its parent's secret using a call to DeriveTreeSecret:

```
DeriveTreeSecret(Secret, Label, Node, Generation, Length) =
    ExpandWithLabel(Secret, Label, TreeContext, Length)

Where TreeContext is specified as:

struct {
    uint32 node = Node;
    uint32 generation = Generation;
} TreeContext;
```

If N is a node index in the Secret Tree then the secrets of the children of N are defined to be:

```
tree_node_[N]_secret
        |
        |
        +--> DeriveTreeSecret(., "tree", left(N), 0, KDF.Nh)
        |    = tree_node_[left(N)]_secret
        |
        +--> DeriveTreeSecret(., "tree", right(N), 0, KDF.Nh)
             = tree_node_[right(N)]_secret
```

The secret in the leaf of the Secret Tree is used to initiate two symmetric hash ratchets, from which a sequence of single-use keys and nonces are derived, as described in Section 8.4. The root of each ratchet is computed as:

```
tree_node_[N]_secret
        |
        |
        +--> DeriveTreeSecret(., "handshake", N, 0, KDF.Nh)
        |    = handshake_ratchet_secret_[N]_[0]
        |
        +--> DeriveTreeSecret(., "application", N, 0, KDF.Nh)
             = application_ratchet_secret_[N]_[0]
```

8.4. Encryption Keys

As described in Section 9, MLS encrypts three different types of information:

- Metadata (sender information)
- Handshake messages (Proposal and Commit)
- Application messages

The sender information used to look up the key for content encryption is encrypted with an AEAD where the key and nonce are derived from both `sender_data_secret` and a sample of the encrypted message content.

For handshake and application messages, a sequence of keys is derived via a "sender ratchet". Each sender has their own sender ratchet, and each step along the ratchet is called a "generation".

A sender ratchet starts from a per-sender base secret derived from a Secret Tree, as described in Section 8.3. The base secret initiates a symmetric hash ratchet which generates a sequence of keys and nonces. The sender uses the

j-th key/nonce pair in the sequence to encrypt (using the AEAD) the j-th message they send during that epoch. Each key/nonce pair MUST NOT be used to encrypt more than one message.

Keys, nonces, and the secrets in ratchets are derived using DeriveTreeSecret. The context in a given call consists of the index of the sender's leaf in the ratchet tree and the current position in the ratchet. In particular, the node index of the sender's leaf in the ratchet tree is the same as the node index of the leaf in the Secret Tree used to initialize the sender's ratchet.

```
ratchet_secret_[N]_[j]
      |
      +--> DeriveTreeSecret(., "nonce", N, j, AEAD.Nn)
      |    = ratchet_nonce_[N]_[j]
      |
      +--> DeriveTreeSecret(., "key", N, j, AEAD.Nk)
      |    = ratchet_key_[N]_[j]
      |
      V
DeriveTreeSecret(., "secret", N, j, KDF.Nh)
= ratchet_secret_[N]_[j+1]
```

Here, AEAD.Nn and AEAD.Nk denote the lengths in bytes of the nonce and key for the AEAD scheme defined by the ciphersuite.

8.5. Deletion Schedule

It is important to delete all security-sensitive values as soon as they are *consumed*. A sensitive value S is said to be *consumed* if

- S was used to encrypt or (successfully) decrypt a message, or if
- a key, nonce, or secret derived from S has been consumed. (This goes for values derived via DeriveSecret as well as ExpandWithLabel.)

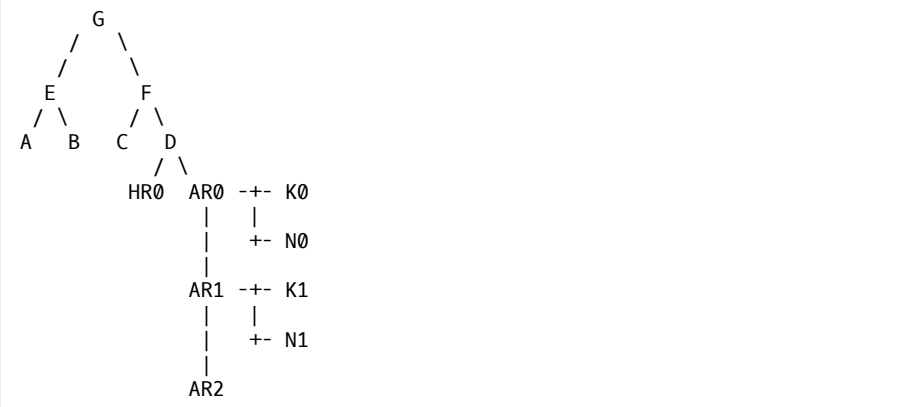
Here, S may be the `init_secret`, `commit_secret`, `epoch_secret`, `encryption_secret` as well as any secret in a Secret Tree or one of the ratchets.

As soon as a group member consumes a value they MUST immediately delete (all representations of) that value. This is crucial to ensuring forward secrecy for past messages. Members MAY keep unconsumed values around for some reasonable amount of time to handle out-of-order message delivery.

For example, suppose a group member encrypts or (successfully) decrypts an application message using the j-th key and nonce in the ratchet of node index N in some epoch n. Then, for that member, at least the following values have been consumed and MUST be deleted:

- the `commit_secret`, `joiner_secret`, `epoch_secret`, `encryption_secret` of that epoch n as well as the `init_secret` of the previous epoch n-1,
- all node secrets in the Secret Tree on the path from the root to the leaf with node index N,
- the first j secrets in the application data ratchet of node index N and
- `application_ratchet_nonce_[N]_[j]` and `application_ratchet_key_[N]_[j]`.

Concretely, suppose we have the following Secret Tree and ratchet for participant D:



Then if a client uses key K1 and nonce N1 during epoch n then it must consume (at least) values G, F, D, AR0, AR1, K1, N1 as well as the key schedule secrets used to derive G (the `encryption_secret`), namely `init_secret` of epoch n-1 and `commit_secret`, `joiner_secret`, `epoch_secret` of epoch n. The client MAY retain (not consume) the values K0 and N0 to allow for out-of-order delivery, and SHOULD retain AR2 for processing future messages.

8.6. Exporters

The main MLS key schedule provides an `exporter_secret` which can be used by an application as the basis to derive new secrets called `exported_value` outside the MLS layer.

```
MLS-Exporter(Label, Context, key_length) =
       ExpandWithLabel(DeriveSecret(exporter_secret, Label),
                       "exporter", Hash(Context), key_length)
```

Each application SHOULD provide a unique label to `MLS-Exporter` that identifies its use case. This is to prevent two exported outputs from being generated with the same values and used for different functionalities.

The exported values are bound to the group epoch from which the `exporter_secret` is derived, hence reflects a particular state of the group.

It is RECOMMENDED for the application generating exported values to refresh those values after a Commit is processed.

8.7. Resumption Secret

The main MLS key schedule provides a `resumption_secret` which can provide extra security in some cross-group operations.

The application SHOULD specify an upper limit on the number of past epochs for which the `resumption_secret` may be stored.

There are two ways in which a `resumption_secret` can be used: to re-initialize the group with different parameters, or to create a sub-group of an existing group as detailed in Section 8.2.

Resumption keys are distinguished from exporter keys in that they have specific use inside the MLS protocol, whereas the use of exporter secrets may be decided by an external application. They are thus derived separately to avoid key material reuse.

8.8. State Authentication Keys

The main MLS key schedule provides a per-epoch `authentication_secret`. If one of the parties is being actively impersonated by an attacker, their `authentication_secret` will differ from that of the other group members. Thus, members of a group MAY use their `authentication_secrets` within an out-of-band authentication protocol to ensure that they share the same view of the group.

9. Message Framing

Handshake and application messages use a common framing structure. This framing provides encryption to ensure confidentiality within the group, as well as signing to authenticate the sender within the group.

The two main structures involved are MLSPlaintext and MLSCiphertext. MLSCiphertext represents a signed and encrypted message, with protections for both the content of the message and related metadata. MLSPlaintext represents a message that is only signed, and not encrypted. Applications MUST use MLSCiphertext to encrypt application messages and SHOULD use MLSCiphertext to encode handshake messages, but MAY transmit handshake messages encoded as MLSPlaintext objects in cases where it is necessary for the Delivery Service to examine such messages.

```
enum {
    reserved(0),
    application(1),
    proposal(2),
    commit(3),
    (255)
} ContentType;

enum {
    reserved(0),
    member(1),
    preconfigured(2),
    new_member(3),
    (255)
} SenderType;

struct {
    SenderType sender_type;
    uint32 sender;
} Sender;

struct {
    opaque mac_value<0..255>;
} MAC;

struct {
    opaque group_id<0..255>;
    uint64 epoch;
    Sender sender;
    opaque authenticated_data<0..2^32-1>;

    ContentType content_type;
    select (MLSPlaintext.content_type) {
        case application:
          opaque application_data<0..2^32-1>;

        case proposal:
          Proposal proposal;

        case commit:
          Commit commit;
    }

    opaque signature<0..2^16-1>;
    optional<MAC> confirmation_tag;
    optional<MAC> membership_tag;
} MLSPlaintext;

struct {
    opaque group_id<0..255>;
    uint64 epoch;
    ContentType content_type;
    opaque authenticated_data<0..2^32-1>;
    opaque encrypted_sender_data<0..255>;
    opaque ciphertext<0..2^32-1>;
} MLSCiphertext;
```

The field `confirmation_tag` MUST be present if `content_type` equals commit. Otherwise, it MUST NOT be present.

External sender types are sent as MLSPlaintext, see Section 11.1.8 for their use.

The remainder of this section describes how to compute the signature of an MLSPlaintext object and how to convert it to an MLSCiphertext object for `member` sender types. The steps are:

- Set group_id, epoch, content_type and authenticated_data fields from the MLSPlaintext object directly
- Identify the key and key generation depending on the content type

- Encrypt an MLSCiphertextContent for the ciphertext field using the key identified and MLSPlaintext object
- Encrypt the sender data using a key and nonce derived from the `sender_data_secret` for the epoch and a sample of the encrypted MLSCiphertextContent.

Decryption is done by decrypting the sender data, then the message, and then verifying the content signature.

The following sections describe the encryption and signing processes in detail.

9.1. Content Authentication

The `signature` field in an MLSPlaintext object is computed using the signing private key corresponding to the public key, which was authenticated by the credential at the leaf of the tree indicated by the sender field. The signature covers the plaintext metadata and message content, which is all of MLSPlaintext except for the `signature`, the `confirmation_tag` and `membership_tag` fields. If the sender is a member of the group, the signature also covers the GroupContext for the current epoch, so that signatures are specific to a given group and epoch.

```
struct {
    select (MLSPlaintextTBS.sender.sender_type) {
        case member:
            GroupContext context;
    }

    opaque group_id<0..255>;
    uint64 epoch;
    Sender sender;
    opaque authenticated_data<0..2^32-1>;

    ContentType content_type;
    select (MLSPlaintextTBS.content_type) {
        case application:
          opaque application_data<0..2^32-1>;

        case proposal:
          Proposal proposal;

        case commit:
          Commit commit;
    }
} MLSPlaintextTBS;
```

The `membership_tag` field in the MLSPlaintext object authenticates the sender's membership in the group. For an MLSPlaintext with a sender type other than `member`, this field MUST be omitted. For messages sent by members, it MUST be present and set to the following value:

```
struct {
  MLSPlaintextTBS tbs;
  opaque signature<0..2^16-1>;
  optional<MAC> confirmation_tag;
} MLSPlaintextTBM;

membership_tag = MAC(membership_key, MLSPlaintextTBM);
```

Note that the `membership_tag` only needs to be computed for MLSPlaintext messages that will be sent over the wire, and isn't needed for those that will be

encrypted and transmitted as MLSCiphertext messages.

9.2. Content Encryption

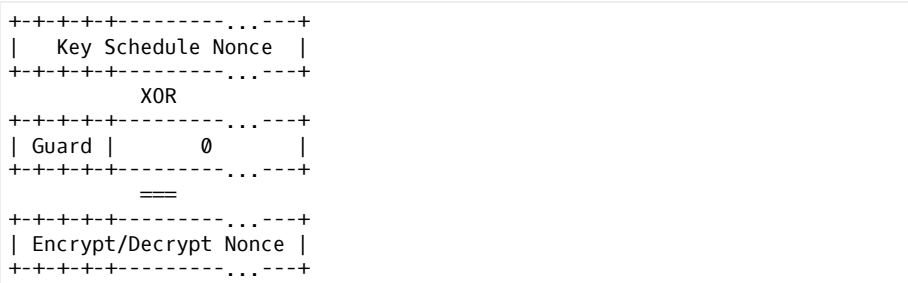
The `ciphertext` field of the MLSCiphertext object is produced by supplying the inputs described below to the AEAD function specified by the ciphersuite in use. The plaintext input contains the content and signature of the MLSPlaintext, plus optional padding. These values are encoded in the following form:

```
struct {
    select (MLSCiphertext.content_type) {
        case application:
          opaque application_data<0..2^32-1>;

        case proposal:
          Proposal proposal;

        case commit:
          Commit commit;
    }

    opaque signature<0..2^16-1>;
    optional<MAC> confirmation_tag;
    opaque padding<0..2^16-1>;
} MLSCiphertextContent;
```

In the MLS key schedule, the sender creates two distinct key ratchets for handshake and application messages for each member of the group. When encrypting a message, the sender looks at the ratchets it derived for its own member and chooses an unused generation from either the handshake or application ratchet depending on the content type of the message. This generation of the ratchet is used to derive a provisional nonce and key.

Before use in the encryption operation, the nonce is XORed with a fresh random value to guard against reuse. Because the key schedule generates nonces deterministically, a client must keep persistent state as to where in the key schedule it is; if this persistent state is lost or corrupted, a client might reuse a generation that has already been used, causing reuse of a key/nonce pair.

To avoid this situation, the sender of a message MUST generate a fresh random 4-byte "reuse guard" value and XOR it with the first four bytes of the nonce from the key schedule before using the nonce for encryption. The sender MUST include the reuse guard in the `reuse_guard` field of the sender data object, so that the recipient of the message can use it to compute the nonce to be used for decryption.



The Additional Authenticated Data (AAD) input to the encryption contains an object of the following form, with the values used to identify the key and nonce:

```
struct {
    opaque group_id<0..255>;
    uint64 epoch;
    ContentType content_type;
    opaque authenticated_data<0..2^32-1>;
} MLSCiphertextContentAAD;
```

9.3. Sender Data Encryption

The "sender data" used to look up the key for the content encryption is encrypted with the ciphersuite's AEAD with a key and nonce derived from both the `sender_data_secret` and a sample of the encrypted content. Before being encrypted, the sender data is encoded as an object of the following form:

```
struct {
    uint32 sender;
    uint32 generation;
    opaque reuse_guard[4];
} MLSSenderData;
```

MLSSenderData.sender is assumed to be a `member` sender type. When constructing an MLSSenderData from a Sender object, the sender MUST verify Sender.sender_type is `member` and use Sender.sender for MLSSenderData.sender.

The `reuse_guard` field contains a fresh random value used to avoid nonce reuse in the case of state loss or corruption, as described in Section 9.2.

The key and nonce provided to the AEAD are computed as the KDF of the first `KDF.Nh` bytes of the ciphertext generated in the previous section. If the length of the ciphertext is less than `KDF.Nh`, the whole ciphertext is used without padding. In pseudocode, the key and nonce are derived as:

```
ciphertext_sample = ciphertext[0..KDF.Nh-1]

sender_data_key = ExpandWithLabel(sender_data_secret, "key",
ciphertext_sample, AEAD.Nk)
sender_data_nonce = ExpandWithLabel(sender_data_secret, "nonce",
ciphertext_sample, AEAD.Nn)
```

The Additional Authenticated Data (AAD) for the SenderData ciphertext is all the fields of MLSCiphertext excluding `encrypted_sender_data`:

```
struct {
    opaque group_id<0..255>;
    uint64 epoch;
    ContentType content_type;
} MLSSenderDataAAD;
```

When parsing a SenderData struct as part of message decryption, the recipient MUST verify that the sender field represents an occupied leaf in the ratchet tree. In particular, the sender index value MUST be less than the number of leaves in the tree.

10. Group Creation

A group is always created with a single member, the "creator". The other members are added when the creator effectively sends itself an Add proposal

and commits it, then sends the corresponding Welcome message to the new participants. These processes are described in detail in Section 11.1.1, Section 11.2, and Section 11.2.2.

The creator of a group MUST take the following steps to initialize the group:

- Fetch KeyPackages for the members to be added, and select a version and ciphersuite according to the capabilities of the members. To protect against downgrade attacks, the creator MUST use the `capabilities` extensions in these KeyPackages to verify that the chosen version and ciphersuite is the best option supported by all members.
- Initialize a one-member group with the following initial values:
  - Ratchet tree: A tree with a single node, a leaf containing an HPKE public key and credential for the creator
  - Group ID: A value set by the creator
  - Epoch: 0
  - Tree hash: The root hash of the above ratchet tree
  - Confirmed transcript hash: the zero-length octet string
  - Interim transcript hash: the zero-length octet string
  - Init secret: a fresh random value of size `KDF.Nh`
- For each member, construct an Add proposal from the KeyPackage for that member (see Section 11.1.1)
- Construct a Commit message that commits all of the Add proposals, in any order chosen by the creator (see Section 11.2)
- Process the Commit message to obtain a new group state (for the epoch in which the new members are added) and a Welcome message
- Transmit the Welcome message to the other new members

The recipient of a Welcome message processes it as described in Section 11.2.2.

In principle, the above process could be streamlined by having the creator directly create a tree and choose a random value for first epoch's epoch secret. We follow the steps above because it removes unnecessary choices, by which, for example, bad randomness could be introduced. The only choices the creator makes here are its own KeyPackage, the leaf secret from which the Commit is built, and the intermediate key pairs along the direct path to the root.

10.1. Linking a New Group to an Existing Group

A new group may be tied to an already existing group for the purpose of re-initializing the existing group, or to branch into a sub-group. Re-initializing an existing group may be used, for example, to restart the group with a different ciphersuite or protocol version. Branching may be used to bootstrap a new group consisting of a subset of current group members, based on the current group state.

In both cases, the `psk_nonce` included in the `PreSharedKeyID` object must be a randomly sampled nonce of length `KDF.Nh` to avoid key re-use.

10.1.1. Sub-group Branching

If a client wants to create a subgroup of an existing group, they MAY choose to include a `PreSharedKeyID` in the `GroupSecrets` object of the Welcome message choosing the `psktype` `branch`, the `group_id` of the group from which a subgroup

is to be branched, as well as an epoch within the number of epochs for which a `resumption_secret` is kept.

11. Group Evolution

Over the lifetime of a group, its membership can change, and existing members might want to change their keys in order to achieve post-compromise security. In MLS, each such change is accomplished by a two-step process:

1. A proposal to make the change is broadcast to the group in a Proposal message
2. A member of the group or a new member broadcasts a Commit message that causes one or more proposed changes to enter into effect

The group thus evolves from one cryptographic state to another each time a Commit message is sent and processed. These states are referred to as "epochs" and are uniquely identified among states of the group by eight-octet epoch values. When a new group is initialized, its initial state epoch is 0x0000000000000000. Each time a state transition occurs, the epoch number is incremented by one.

11.1. Proposals

Proposals are included in an MLSPlaintext by way of a Proposal structure that indicates their type:

```
enum {
    reserved(0),
    add(1),
    update(2),
    remove(3),
    psk(4),
    reinit(5),
    external_init(6),
    app_ack(7),
    (255)
} ProposalType;

struct {
    ProposalType msg_type;
    select (Proposal.msg_type) {
        case add:           Add;
        case update:        Update;
        case remove:        Remove;
        case psk:           PreSharedKey;
        case reinit:        ReInit;
        case external_init: ExternalInit;
        case app_ack:       AppAck;
    };
} Proposal;
```

On receiving an MLSPlaintext containing a Proposal, a client MUST verify the signature on the enclosing MLSPlaintext. If the signature verifies successfully, then the Proposal should be cached in such a way that it can be retrieved by hash (as a ProposalOrRef object) in a later Commit message.

11.1.1. Add

An Add proposal requests that a client with a specified KeyPackage be added to the group.

```
struct {
    KeyPackage key_package;
} Add;
```

The proposer of the Add does not control where in the group's ratchet tree the new member is added. Instead, the sender of the Commit message chooses a location for each added member and states it in the Commit message.

An Add is applied after being included in a Commit message. The position of the Add in the list of proposals determines the leaf index `index` where the new member will be added. For the first Add in the Commit, `index` is the leftmost empty leaf in the tree, for the second Add, the next empty leaf to the right, etc.

- If necessary, extend the tree to the right until it has at least index + 1 leaves
- For each non-blank intermediate node along the path from the leaf at position `index` to the root, add `index` to the `unmerged_leaves` list for the node.
- Set the leaf node in the tree at position `index` to a new node containing the public key from the KeyPackage in the Add, as well as the credential under which the KeyPackage was signed

11.1.2. Update

An Update proposal is a similar mechanism to Add with the distinction that it is the sender's leaf KeyPackage in the tree which would be updated with a new KeyPackage.

```
struct {
    KeyPackage key_package;
} Update;
```

A member of the group applies an Update message by taking the following steps:

- Replace the sender's leaf KeyPackage with the one contained in the Update proposal
- Blank the intermediate nodes along the path from the sender's leaf to the root

11.1.3. Remove

A Remove proposal requests that the client at a specified index in the tree be removed from the group.

```
struct {
    uint32 removed;
} Remove;
```

A member of the group applies a Remove message by taking the following steps:

- Replace the leaf node at position `removed` with a blank node
- Blank the intermediate nodes along the path from the removed leaf to the root

11.1.4. PreSharedKey

A PreSharedKey proposal can be used to request that a pre-shared key be injected into the key schedule in the process of advancing the epoch.

```
struct {
    PreSharedKeyID psk;
} PreSharedKey;
```

The `psktype` of the pre-shared key MUST be `external` and the `psk_nonce` MUST be a randomly sampled nonce of length `KDF.Nh`. When processing a Commit message that includes one or more PreSharedKey proposals, group members derive `psk_secret` as described in Section 8.2, where the order of the PSKs corresponds to the order of the `PreSharedKey` proposals in the Commit.

11.1.5. ReInit

A ReInit proposal represents a request to re-initialize the group with different parameters, for example, to increase the version number or to change the ciphersuite. The re-initialization is done by creating a completely new group and shutting down the old one.

```
struct {
    opaque group_id<0..255>;
    ProtocolVersion version;
    CipherSuite cipher_suite;
    Extension extensions<0..2^32-1>;
} ReInit;
```

A member of the group applies a ReInit proposal by waiting for the committer to send the Welcome message and by checking that the `group_id` and the parameters of the new group corresponds to the ones specified in the proposal. The Welcome message MUST specify exactly one pre-shared key with `psktype = reinit`, and with `psk_group_id` and `psk_epoch` equal to the `group_id` and `epoch` of the existing group after the Commit containing the `reinit` Proposal was processed. The Welcome message may specify the inclusion of other pre-shared keys with a `psktype` different from `reinit`.

If a ReInit proposal is included in a Commit, it MUST be the only proposal referenced by the Commit. If other non-ReInit proposals have been sent during the epoch, the committer SHOULD prefer them over the ReInit proposal, allowing the ReInit to be resent and applied in a subsequent epoch. The `version` field in the ReInit proposal MUST be no less than the version for the current group.

11.1.6. ExternalInit

An ExternalInit proposal is used by new members that want to join a group by using an external commit. This propsal can only be used in that context.

```
struct {
  opaque kem_output<0..2^16-1>;
} ExternalInit;
```

A member of the group applies an ExternalInit message by initializing the next epoch using an init secret computed as described in Section 8.1. The `kem_output` field contains the required KEM output.

11.1.7. AppAck

An AppAck proposal is used to acknowledge receipt of application messages. Though this information implies no change to the group, it is structured as a Proposal message so that it is included in the group's transcript by being included in Commit messages.

```
struct {
    uint32 sender;
    uint32 first_generation;
    uint32 last_generation;
} MessageRange;

struct {
    MessageRange received_ranges<0..2^32-1>;
} AppAck;
```

An AppAck proposal represents a set of messages received by the sender in the current epoch. Messages are represented by the `sender` and `generation` values in the MLSCiphertext for the message. Each MessageRange represents receipt of a span of messages whose `generation` values form a continuous range from `first_generation` to `last_generation`, inclusive.

AppAck proposals are sent as a guard against the Delivery Service dropping application messages. The sequential nature of the `generation` field provides a degree of loss detection, since gaps in the `generation` sequence indicate dropped messages. AppAck completes this story by addressing the scenario where the Delivery Service drops all messages after a certain point, so that a later generation is never observed. Obviously, there is a risk that AppAck messages could be suppressed as well, but their inclusion in the transcript means that if they are suppressed then the group cannot advance at all.

The schedule on which sending AppAck proposals are sent is up to the application, and determines which cases of loss/suppression are detected. For example:

- The application might have the committer include an AppAck proposal whenever a Commit is sent, so that other members could know when one of their messages did not reach the committer.
- The application could have a client send an AppAck whenever an application message is sent, covering all messages received since its last AppAck. This would provide a complete view of any losses experienced by active members.
- The application could simply have clients send AppAck proposals on a timer, so that all participants' state would be known.

An application using AppAck proposals to guard against loss/suppression of application messages also needs to ensure that AppAck messages and the Commits that reference them are not dropped. One way to do this is to always encrypt Proposal and Commit messages, to make it more difficult for the Delivery Service to recognize which messages conatain AppAcks. The application can also have clients enforce an AppAck schedule, reporting loss if an AppAck is not received at the expected time.

11.1.8. External Proposals

Add and Remove proposals can be constructed and sent to the group by a party that is outside the group. For example, a Delivery Service might propose to remove a member of a group who has been inactive for a long time, or propose

adding a newly-hired staff member to a group representing a real-world team. Proposals originating outside the group are identified by a `preconfigured` or `new_member` SenderType in MLSPlaintext.

ReInit proposals can also be sent to the group by a `preconfigured` sender, for example to enforce a changed policy regarding MLS version or ciphersuite.

The `new_member` SenderType is used for clients proposing that they themselves be added. For this ID type the sender value MUST be zero and the Proposal type MUST be Add. The MLSPlaintext MUST be signed with the private key corresponding to the KeyPackage in the Add message. Recipients MUST verify that the MLSPlaintext carrying the Proposal message is validly signed with this key.

The `preconfigured` SenderType is reserved for signers that are pre-provisioned to the clients within a group. If proposals with these sender IDs are to be accepted within a group, the members of the group MUST be provisioned by the application with a mapping between these IDs and authorized signing keys. Recipients MUST verify that the MLSPlaintext carrying the Proposal message is validly signed with the corresponding key. To ensure consistent handling of external proposals, the application MUST ensure that the members of a group have the same mapping and apply the same policies to external proposals.

An external proposal MUST be sent as an MLSPlaintext object, since the sender will not have the keys necessary to construct an MLSCiphertext object.

11.2. Commit

A Commit message initiates a new epoch for the group, based on a collection of Proposals. It instructs group members to update their representation of the state of the group by applying the proposals and advancing the key schedule.

Each proposal covered by the Commit is included by a ProposalOrRef value, which identifies the proposal to be applied by value or by reference. Proposals supplied by value are included directly in the Commit object. Proposals supplied by reference are specified by including the hash of the MLSPlaintext in which the Proposal was sent, using the hash function from the group's ciphersuite. For proposals supplied by value, the sender of the proposal is the same as the sender of the Commit. Conversely, proposals sent by people other than the committer MUST be included by reference.

```
enum {
  reserved(0),
  proposal(1)
  reference(2),
  (255)
} ProposalOrRefType;

struct {
  ProposalOrRefType type;
  select (ProposalOrRef.type) {
    case proposal:  Proposal proposal;
    case reference: opaque hash<0..255>;
  }
} ProposalOrRef;

struct {
    ProposalOrRef proposals<0..2^32-1>;
    optional<UpdatePath> path;
} Commit;
```

A group member that has observed one or more proposals within an epoch MUST send a Commit message before sending application data. This ensures, for example, that any members whose removal was proposed during the epoch are actually removed before any application data is transmitted.

The sender of a Commit MUST include all valid proposals that it has received during the current epoch. Invalid proposals include, for example, proposals with an invalid signature or proposals that are semantically invalid, such as an Add when the sender does not have the application-level permission to add new users. If there are multiple proposals that apply to the same leaf, the committer chooses one and includes only that one in the Commit, considering the rest invalid. The committer MUST prefer any Remove received, or the most recent Update for the leaf if there are no Removes. If there are multiple Add proposals for the same client, the committer again chooses one to include and considers the rest invalid.

The Commit MUST NOT combine proposals sent within different epochs. In the event that a valid proposal is omitted from the next Commit, the sender of the proposal SHOULD retransmit it in the new epoch.

A member of the group MAY send a Commit that references no proposals at all, which would thus have an empty `proposals` vector. Such a Commit resets the sender's leaf and the nodes along its direct path, and provides forward secrecy and post-compromise security with regard to the sender of the Commit. An Update proposal can be regarded as a "lazy" version of this operation, where only the leaf changes and intermediate nodes are blanked out.

The `path` field of a Commit message MUST be populated if the Commit covers at least one Update or Remove proposal. The `path` field MUST also be populated if the Commit covers no proposals at all (i.e., if the proposals vector is empty). The `path` field MAY be omitted if the Commit covers only Add proposals. In pseudocode, the logic for validating a Commit is as follows:

```
hasUpdates = false
hasRemoves = false

for i, id in commit.proposals:
    proposal = proposalCache[id]
    assert(proposal != null)

    hasUpdates = hasUpdates || proposal.msg_type == update
    hasRemoves = hasRemoves || proposal.msg_type == remove

if len(commit.proposals) == 0 || hasUpdates || hasRemoves:
  assert(commit.path != null)
```

To summarize, a Commit can have three different configurations, with different uses:

1. An "empty" Commit that references no proposals, which updates the committer's contribution to the group and provides PCS with regard to the committer.
2. An "add-only" Commit that references only Add proposals, in which the path is optional. Such a commit provides PCS with regard to the committer only if the path field is present.
3. A "full" Commit that references proposals of any type, which provides FS with regard to any removed members and PCS for the committer and any updated members.

A member of the group creates a Commit message and the corresponding Welcome message at the same time, by taking the following steps:

- Construct an initial Commit object with the `proposals` field populated from Proposals received during the current epoch, and an empty `path` field.
- Generate a provisional GroupContext object by applying the proposals referenced in the initial Commit object, as described in Section 11.1. Update proposals are applied first, followed by Remove proposals, and then finally Add proposals. Add proposals are applied in the order listed in the `proposals` vector, and always to the leftmost unoccupied leaf in the tree, or the right edge of the tree if all leaves are occupied.
  - Note that the order in which different types of proposals are applied should be updated by the implementation to include any new proposals added by negotiated group extensions.
  - PreSharedKey proposals are processed later when deriving the `psk_secret` for the Key Schedule.
- Decide whether to populate the `path` field: If the `path` field is required based on the proposals that are in the commit (see above), then it MUST be populated. Otherwise, the sender MAY omit the `path` field at its discretion.
- If populating the `path` field: Create an UpdatePath using the new tree. Any new member (from an add proposal) MUST be exluded from the resolution during the computation of the UpdatePath. The GroupContext for this operation uses the `group_id`, `epoch`, `tree_hash`, and `confirmed_transcript_hash` values in the initial GroupContext object. The `leaf_key_package` for this UpdatePath must have a `parent_hash` extension.
  - Assign this UpdatePath to the `path` field in the Commit.
  - Apply the UpdatePath to the tree, as described in Section 5.5. Define `commit_secret` as the value `path_secret[n+1]` derived from the `path_secret[n]` value assigned to the root node.
- If not populating the `path` field: Set the `path` field in the Commit to the null optional. Define `commit_secret` as the all-zero vector of the same length as a `path_secret` value would be.
- If one or more PreSharedKey proposals are part of the commit, derive the `psk_secret` as specified in Section 8.2, where the order of PSKs in the derivation corresponds to the order of PreSharedKey proposals in the `proposals` vector. Otherwise, set `psk_secret` to a zero-length octet string.
- Construct an MLSPlaintext object containing the Commit object. Sign the MLSPlaintext using the current epoch's GroupContext as context. Use the signature, the `commit_secret` and the `psk_secret` to advance the key schedule and compute the `confirmation_tag` value in the MLSPlaintext.
- Update the tree in the provisional state by applying the direct path
- Construct a GroupInfo reflecting the new state:
  - Group ID, epoch, tree, confirmed transcript hash, and interim transcript hash from the new state
  - The confirmation_tag from the MLSPlaintext object
  - Sign the GroupInfo using the member's private signing key
  - Encrypt the GroupInfo using the key and nonce derived from the `joiner_secret` for the new epoch (see Section 11.2.2)

- For each new member in the group:
  - Identify the lowest common ancestor in the tree of the new member's leaf node and the member sending the Commit
  - If the `path` field was populated above: Compute the path secret corresponding to the common ancestor node
  - Compute an EncryptedGroupSecrets object that encapsulates the `init_secret` for the current epoch and the path secret (if present).
- Construct a Welcome message from the encrypted GroupInfo object, the encrypted key packages, and any PSKs for which a proposal was included in the Commit. The order of the `psks` MUST be the same as the order of PreSharedKey proposals in the `proposals` vector.
- If a ReInit proposal was part of the Commit, the committer MUST create a new group with the parameters specified in the ReInit proposal, and with the same members as the original group. The Welcome message MUST include a `PreSharedKeyID` with `psktype` `reinit` and with `psk_group_id` and `psk_epoch` corresponding to the current group and the epoch after the commit was processed.

A member of the group applies a Commit message by taking the following steps:

- Verify that the `epoch` field of the enclosing MLSPlaintext message is equal to the `epoch` field of the current GroupContext object
- Verify that the signature on the MLSPlaintext message verifies using the public key from the credential stored at the leaf in the tree indicated by the `sender` field.
- Verify that all PSKs specified in any PreSharedKey proposals in the `proposals` vector are available.
- Generate a provisional GroupContext object by applying the proposals referenced in the initial Commit object, as described in Section 11.1. Update proposals are applied first, followed by Remove proposals, and then finally Add proposals. Add proposals are applied in the order listed in the `proposals` vector, and always to the leftmost unoccupied leaf in the tree, or the right edge of the tree if all leaves are occupied.
  - Note that the order in which different types of proposals are applied should be updated by the implementation to include any new proposals added by negotiated group extensions.
- Verify that the `path` value is populated if the `proposals` vector contains any Update or Remove proposals, or if it's empty. Otherwise, the `path` value MAY be omitted.
- If the `path` value is populated: Process the `path` value using the ratchet tree the provisional GroupContext, to update the ratchet tree and generate the `commit_secret`:
  - Apply the UpdatePath to the tree, as described in Section 5.5, and store `leaf_key_package` at the Committer's leaf.
  - Verify that the KeyPackage has a `parent_hash` extension and that its value matches the new parent of the sender's leaf node.
  - Define `commit_secret` as the value `path_secret[n+1]` derived from the `path_secret[n]` value assigned to the root node.

- If the `path` value is not populated: Define `commit_secret` as the all-zero vector of the same length as a `path_secret` value would be.
- Update the new GroupContext's confirmed and interim transcript hashes using the new Commit.
- If the `proposals` vector contains any PreSharedKey proposals, derive the `psk_secret` as specified in Section 8.2, where the order of PSKs in the derivation corresponds to the order of PreSharedKey proposals in the `proposals` vector. Otherwise, set `psk_secret` to 0.
- Use the `commit_secret`, the `psk_secret`, the provisional GroupContext, and the init secret from the previous epoch to compute the epoch secret and derived secrets for the new epoch.
- Use the `confirmation_key` for the new epoch to compute the confirmation tag for this message, as described below, and verify that it is the same as the `confirmation_tag` field in the MLSPlaintext object.
- If the above checks are successful, consider the updated GroupContext object as the current state of the group.
- If the Commit included a ReInit proposal, the client MUST NOT use the group to send messages anymore. Instead, it MUST wait for a Welcome message from the committer and check that
  - The `version`, `cipher_suite` and `extensions` fields of the new group corresponds to the ones in the `ReInit` proposal, and that the `version` is greater than or equal to that of the original group.
  - The `psks` field in the Welcome message includes a `PreSharedKeyID` with `psktype = reinit`, and `psk_epoch` and `psk_group_id` equal to the epoch and group ID of the original group after processing the Commit.

The confirmation tag value confirms that the members of the group have arrived at the same state of the group:

```
MLSPlaintext.confirmation_tag =
    MAC(confirmation_key, GroupContext.confirmed_transcript_hash)
```

11.2.1. External Commits

External Commits are a mechanism for new members (external parties that want to become members of the group) to add themselves to a group, without requiring that an existing member has to come online to issue a Commit that references an Add Proposal.

Whether existing members of the group will accept or reject an External Commit follows the same rules that are applied to other handshake messages.

New members can create and issue an External Commit if they have access to the following information for the group's current epoch:

- group ID
- epoch ID
- ciphersuite
- public tree hash
- interim transcript hash
- group extensions
- external public key

This information is aggregated in a `PublicGroupState` object as follows:

```
struct {
    CipherSuite cipher_suite;
    opaque group_id<0..255>;
    uint64 epoch;
    opaque tree_hash<0..255>;
    opaque interim_transcript_hash<0..255>;
    Extension extensions<0..2^32-1>;
    HPKEPublicKey external_pub;
    uint32 signer_index;
    opaque signature<0..2^16-1>;
} PublicGroupState;
```

Note that the `tree_hash` field is used the same way as in the Welcome message. The full tree can be included via the `ratchet_tree` extension Section 11.3.

The signature MUST verify using the public key taken from the credential in the leaf node at position `signer_index`. The signature covers the following structure, comprising all the fields in the PublicGroupState above `signer_index`:

```
struct {
    opaque group_id<0..255>;
    uint64 epoch;
    opaque tree_hash<0..255>;
    opaque interim_transcript_hash<0..255>;
    Extension extensions<0..2^32-1>;
    HPKEPublicKey external_pub;
} PublicGroupStateTBS;
```

This signature authenticates the HPKE public key, so that the joiner knows that the public key was provided by a member of the group. The fields that are not signed are included in the key schedule via the GroupContext object. If the joiner is provided an inaccurate data for these fields, then its external Commit will have an incorrect `confirmation_tag` and thus be rejected.

The information in a PublicGroupState is not deemed public in general, but applications can choose to make it available to new members in order to allow External Commits.

External Commits work like regular Commits, with a few differences:

- External Commits MUST reference an Add Proposal that adds the issuing new member to the group
- External Commits MUST contain a `path` field (and is therefore a "full" Commit)
- External Commits MUST be signed by the new member. In particular, the signature on the enclosing MLSPlaintext MUST verify using the public key for the credential in the `leaf_key_package` of the `path` field.
- An external commit MUST reference no more than one ExternalInit proposal, and the ExternalInit proposal MUST be supplied by value, not by reference. When processing a Commit, both existing and new members MUST use the external init secret as described in Section 8.1.
- The sender type for the MLSPlaintext encapsulating the External Commit MUST be `new_member`
- If the Add Proposal is also issued by the new member, its member SenderType MUST be `new_member`

11.2.2. Welcoming New Members

The sender of a Commit message is responsible for sending a Welcome message to any new members added via Add proposals. The Welcome message provides the new members with the current state of the group, after the application of the Commit message. The new members will not be able to decrypt or verify the Commit message, but will have the secrets they need to participate in the epoch initiated by the Commit message.

In order to allow the same Welcome message to be sent to all new members, information describing the group is encrypted with a symmetric key and nonce derived from the `joiner_secret` for the new epoch. The `joiner_secret` is then encrypted to each new member using HPKE. In the same encrypted package, the committer transmits the path secret for the lowest node contained in the direct paths of both the committer and the new member. This allows the new member to compute private keys for nodes in its direct path that are being reset by the corresponding Commit.

If the sender of the Welcome message wants the receiving member to include a PSK in the derivation of the `epoch_secret`, they can populate the `psks` field indicating which PSK to use.

```
struct {
  opaque group_id<0..255>;
  uint64 epoch;
  opaque tree_hash<0..255>;
  opaque confirmed_transcript_hash<0..255>;
  Extension extensions<0..2^32-1>;
  MAC confirmation_tag;
  uint32 signer_index;
  opaque signature<0..2^16-1>;
} GroupInfo;

struct {
  opaque path_secret<1..255>;
} PathSecret;

struct {
  opaque joiner_secret<1..255>;
  optional<PathSecret> path_secret;
  optional<PreSharedKeys> psks;
} GroupSecrets;

struct {
  opaque key_package_hash<1..255>;
  HPKECiphertext encrypted_group_secrets;
} EncryptedGroupSecrets;

struct {
  ProtocolVersion version = mls10;
  CipherSuite cipher_suite;
  EncryptedGroupSecrets secrets<0..2^32-1>;
  opaque encrypted_group_info<1..2^32-1>;
} Welcome;
```

The client processing a Welcome message will need to have a copy of the group's ratchet tree. The tree can be provided in the Welcome message, in an extension of type `ratchet_tree`. If it is sent otherwise (e.g., provided by a caching service on the Delivery Service), then the client MUST download the tree before processing the Welcome.

On receiving a Welcome message, a client processes it using the following steps:

- Identify an entry in the `secrets` array where the `key_package_hash` value corresponds to one of this client's KeyPackages, using the hash indicated by the `cipher_suite` field. If no such field exists, or if the ciphersuite indicated in the KeyPackage does not match the one in the Welcome message, return an error.
- Decrypt the `encrypted_group_secrets` using HPKE with the algorithms indicated by the ciphersuite and the HPKE private key corresponding to the GroupSecrets. If a `PreSharedKeyID` is part of the GroupSecrets and the client is not in possession of the corresponding PSK, return an error.
- From the `joiner_secret` in the decrypted GroupSecrets object and the PSKs specified in the `GroupSecrets`, derive the `welcome_secret` and using that the `welcome_key` and `welcome_nonce`. Use the key and nonce to decrypt the `encrypted_group_info` field.

```
welcome_nonce = KDF.Expand(welcome_secret, "nonce", AEAD.Nn)
welcome_key = KDF.Expand(welcome_secret, "key", AEAD.Nk)
```

- Verify the signature on the GroupInfo object. The signature input comprises all of the fields in the GroupInfo object except the signature field. The public key and algorithm are taken from the credential in the leaf node at position `signer_index`. If this verification fails, return an error.
- Verify the integrity of the ratchet tree.
  - Verify that the tree hash of the ratchet tree matches the `tree_hash` field in the GroupInfo.
  - For each non-empty parent node, verify that exactly one of the node's children are non-empty and have the hash of this node set as their `parent_hash` value (if the child is another parent) or has a `parent_hash` extension in the KeyPackage containing the same value (if the child is a leaf). If either of the node's children is empty, and in particular does not have a parent hash, then its respective children's `parent_hash` values have to be considered instead.
  - For each non-empty leaf node, verify the signature on the KeyPackage.
- Identify a leaf in the `tree` array (any even-numbered node) whose `key_package` field is identical to the the KeyPackage. If no such field exists, return an error. Let `index` represent the index of this node among the leaves in the tree, namely the index of the node in the `tree` array divided by two.
- Construct a new group state using the information in the GroupInfo object. The new member's position in the tree is `index`, as defined above. In particular, the confirmed transcript hash for the new state is the `prior_confirmed_transcript_hash` in the GroupInfo object.
  - Update the leaf at index `index` with the private key corresponding to the public key in the node.
  - If the `path_secret` value is set in the GroupSecrets object: Identify the lowest common ancestor of the leaves at `index` and at `GroupInfo.signer_index`. Set the private key for this node to the private key derived from the `path_secret`.
  - For each parent of the common ancestor, up to the root of the tree, derive a new path secret and set the private key for the node to the private key derived from the path secret. The private key MUST be the private key

that corresponds to the public key in the node.

- Use the `joiner_secret` from the GroupSecrets object to generate the epoch secret and other derived secrets for the current epoch.
- Set the confirmed transcript hash in the new state to the value of the `confirmed_transcript_hash` in the GroupInfo.
- Verify the confirmation tag in the GroupInfo using the derived confirmation key and the `confirmed_transcript_hash` from the GroupInfo.
- Use the confirmed transcript hash and confirmation tag to compute the interim transcript hash in the new state.

11.3. Ratchet Tree Extension

By default, a GroupInfo message only provides the joiner with a commitment to the group's ratchet tree. In order to process or generate handshake messages, the joiner will need to get a copy of the ratchet tree from some other source. (For example, the DS might provide a cached copy.) The inclusion of the tree hash in the GroupInfo message means that the source of the ratchet tree need not be trusted to maintain the integrity of tree.

In cases where the application does not wish to provide such an external source, the whole public state of the ratchet tree can be provided in an extension of type `ratchet_tree`, containing a `ratchet_tree` object of the following form:

```
enum {
    reserved(0),
    leaf(1),
    parent(2),
    (255)
} NodeType;

struct {
    NodeType node_type;
    select (Node.node_type) {
        case leaf:   KeyPackage key_package;
        case parent: ParentNode node;
    };
} Node;

optional<Node> ratchet_tree<1..2^32-1>;
```

The presence of a `ratchet_tree` extension in a GroupInfo message does not result in any changes to the GroupContext extensions for the group. The ratchet tree provided is simply stored by the client and used for MLS operations.

If this extension is not provided in a Welcome message, then the client will need to fetch the ratchet tree over some other channel before it can generate or process Commit messages. Applications should ensure that this out-of-band channel is provided with security protections equivalent to the protections that are afforded to Proposal and Commit messages. For example, an application that encrypts Proposal and Commit messages might distribute ratchet trees encrypted using a key exchanged over the MLS channel.

12. Extensibility

This protocol includes a mechanism for negotiating extension parameters similar to the one in TLS [RFC8446]. In TLS, extension negotiation is one-to-one: The client offers extensions in its ClientHello message, and the server expresses its choices for the session with extensions in its ServerHello and

EncryptedExtensions messages. In MLS, extensions appear in the following places:

- In KeyPackages, to describe client capabilities and aspects of their participation in the group (once in the ratchet tree)
- In the Welcome message, to tell new members of a group what parameters are being used by the group
- In the GroupContext object, to ensure that all members of the group have the same view of the parameters in use

In other words, clients advertise their capabilities in KeyPackage extensions, the creator of the group expresses its choices for the group in Welcome extensions, and the GroupContext confirms that all members of the group have the same view of the group's extensions.

This extension mechanism is designed to allow for secure and forward-compatible negotiation of extensions. For this to work, implementations MUST correctly handle extensible fields:

- A client that posts a KeyPackage MUST support all parameters advertised in it. Otherwise, another client might fail to interoperate by selecting one of those parameters.
- A client initiating a group MUST ignore all unrecognized ciphersuites, extensions, and other parameters. Otherwise, it may fail to interoperate with newer clients.
- A client adding a new member to a group MUST verify that the KeyPackage for the new member contains extensions that are consistent with the group's extensions. For each extension in the GroupContext, the KeyPackage MUST have an extension of the same type, and the contents of the extension MUST be consistent with the value of the extension in the GroupContext, according to the semantics of the specific extension.
- If any extension in a GroupInfo message is unrecognized (i.e., not contained in the corresponding KeyPackage), then the client MUST reject the Welcome message and not join the group.
- The extensions populated into a GroupContext object are drawn from those in the GroupInfo object, according to the definitions of those extensions.

Note that the latter two requirements mean that all MLS extensions are mandatory, in the sense that an extension in use by the group MUST be supported by all members of the group.

This document does not define any way for the parameters of the group to change once it has been created; such a behavior could be implemented as an extension.

13. Sequencing of State Changes

Each Commit message is premised on a given starting state, indicated by the `epoch` field of the enclosing MLSPlaintext message. If the changes implied by a Commit messages are made starting from a different state, the results will be incorrect.

This need for sequencing is not a problem as long as each time a group member sends a Commit message, it is based on the most current state of the group. In practice, however, there is a risk that two members will generate Commit messages simultaneously, based on the same state.

When this happens, there is a need for the members of the group to deconflict the simultaneous Commit messages. There are two general approaches:

- Have the Delivery Service enforce a total order
- Have a signal in the message that clients can use to break ties

As long as Commit messages cannot be merged, there is a risk of starvation. In a sufficiently busy group, a given member may never be able to send a Commit message, because he always loses to other members. The degree to which this is a practical problem will depend on the dynamics of the application.

It might be possible, because of the non-contributivity of intermediate nodes, that Commit messages could be applied one after the other without the Delivery Service having to reject any Commit message, which would make MLS more resilient regarding the concurrency of Commit messages. The Messaging system can decide to choose the order for applying the state changes. Note that there are certain cases (if no total ordering is applied by the Delivery Service) where the ordering is important for security, ie. all updates must be executed before removes.

Regardless of how messages are kept in sequence, implementations MUST only update their cryptographic state when valid Commit messages are received. Generation of Commit messages MUST NOT modify a client's state, since the endpoint doesn't know at that time whether the changes implied by the Commit message will succeed or not.

13.1. Server-Enforced Ordering

With this approach, the Delivery Service ensures that incoming messages are added to an ordered queue and outgoing messages are dispatched in the same order. The server is trusted to break ties when two members send a Commit message at the same time.

Messages should have a counter field sent in clear-text that can be checked by the server and used for tie-breaking. The counter starts at 0 and is incremented for every new incoming message. If two group members send a message with the same counter, the first message to arrive will be accepted by the server and the second one will be rejected. The rejected message needs to be sent again with the correct counter number.

To prevent counter manipulation by the server, the counter's integrity can be ensured by including the counter in a signed message envelope.

This applies to all messages, not only state changing messages.

13.2. Client-Enforced Ordering

Order enforcement can be implemented on the client as well, one way to achieve it is to use a two step update protocol: the first client sends a proposal to update and the proposal is accepted when it gets 50%+ approval from the rest of the group, then it sends the approved update. Clients which didn't get their proposal accepted, will wait for the winner to send their update before retrying new proposals.

While this seems safer as it doesn't rely on the server, it is more complex and harder to implement. It also could cause starvation for some clients if they keep failing to get their proposal accepted.

14. Application Messages

The primary purpose of the Handshake protocol is to provide an authenticated group key exchange to clients. In order to protect Application messages sent among the members of a group, the Application secret provided by the Handshake key schedule is used to derive nonces and encryption keys for the Message Protection Layer according to the Application Key Schedule. That is, each epoch is equipped with a fresh Application Key Schedule which consist of a tree of Application Secrets as well as one symmetric ratchet per group member.

Each client maintains their own local copy of the Application Key Schedule for each epoch during which they are a group member. They derive new keys, nonces and secrets as needed while deleting old ones as soon as they have been used.

Application messages MUST be protected with the Authenticated-Encryption with Associated-Data (AEAD) encryption scheme associated with the MLS ciphersuite using the common framing mechanism. Note that "Authenticated" in this context does not mean messages are known to be sent by a specific client but only from a legitimate member of the group. To authenticate a message from a particular member, signatures are required. Handshake messages MUST use asymmetric signatures to strongly authenticate the sender of a message.

14.1. Message Encryption and Decryption

The group members MUST use the AEAD algorithm associated with the negotiated MLS ciphersuite to AEAD encrypt and decrypt their Application messages according to the Message Framing section.

The group identifier and epoch allow a recipient to know which group secrets should be used and from which Epoch secret to start computing other secrets and keys. The sender identifier is used to identify the member's symmetric ratchet from the initial group Application secret. The application generation field is used to determine how far into the ratchet to iterate in order to reproduce the required AEAD keys and nonce for performing decryption.

Application messages SHOULD be padded to provide some resistance against traffic analysis techniques over encrypted traffic. [CLINIC] [HCJ16] While MLS might deliver the same payload less frequently across a lot of ciphertexts than traditional web servers, it might still provide the attacker enough information to mount an attack. If Alice asks Bob: "When are we going to the movie ?" the answer "Wednesday" might be leaked to an adversary by the ciphertext length. An attacker expecting Alice to answer Bob with a day of the week might find out the plaintext by correlation between the question and the length.

Similarly to TLS 1.3, if padding is used, the MLS messages MUST be padded with zero-valued bytes before AEAD encryption. Upon AEAD decryption, the length field of the plaintext is used to compute the number of bytes to be removed from the plaintext to get the correct data. As the padding mechanism is used to improve protection against traffic analysis, removal of the padding SHOULD be implemented in a "constant-time" manner at the MLS layer and above layers to prevent timing side-channels that would provide attackers with information on the size of the plaintext. The padding length length_of_padding can be chosen at the time of the message encryption by the sender. Recipients can calculate the padding size from knowing the total size of the ApplicationPlaintext and the length of the content.

14.2. Restrictions

During each epoch senders MUST NOT encrypt more data than permitted by the security bounds of the AEAD scheme used.

Note that each change to the Group through a Handshake message will also set a new `encryption_secret`. Hence this change MUST be applied before encrypting any new application message. This is required both to ensure that any users removed from the group can no longer receive messages and to (potentially) recover confidentiality and authenticity for future messages despite a past state compromise.

14.3. Delayed and Reordered Application messages

Since each Application message contains the group identifier, the epoch and a message counter, a client can receive messages out of order. If they are able to retrieve or recompute the correct AEAD decryption key from currently stored cryptographic material clients can decrypt these messages.

For usability, MLS clients might be required to keep the AEAD key and nonce for a certain amount of time to retain the ability to decrypt delayed or out of order messages, possibly still in transit while a decryption is being done.

15. Security Considerations

The security goals of MLS are described in [I-D.ietf-mls-architecture]. We describe here how the protocol achieves its goals at a high level, though a complete security analysis is outside of the scope of this document.

15.1. Confidentiality of the Group Secrets

Group secrets are partly derived from the output of a ratchet tree. Ratchet trees work by assigning each member of the group to a leaf in the tree and maintaining the following property: the private key of a node in the tree is known only to members of the group that are assigned a leaf in the node's subtree. This is called the *ratchet tree invariant* and it makes it possible to encrypt to all group members except one, with a number of ciphertexts that's logarithmic in the number of group members.

The ability to efficiently encrypt to all members except one allows members to be securely removed from a group. It also allows a member to rotate their keypair such that the old private key can no longer be used to decrypt new messages.

15.2. Authentication

The first form of authentication we provide is that group members can verify a message originated from one of the members of the group. For encrypted messages, this is guaranteed because messages are encrypted with an AEAD under a key derived from the group secrets. For plaintext messages, this is guaranteed by the use of a `membership_tag` which constitutes a MAC over the message, under a key derived from the group secrets.

The second form of authentication is that group members can verify a message originated from a particular member of the group. This is guaranteed by a digital signature on each message from the sender's identity key.

15.3. Forward Secrecy and Post-Compromise Security

Post-compromise security is provided between epochs by members regularly updating their leaf key in the ratchet tree. Updating their leaf key prevents group secrets from continuing to be encrypted to previously compromised public keys.

Forward-secrecy between epochs is provided by deleting private keys from past version of the ratchet tree, as this prevents old group secrets from being re-derived. Forward secrecy *within* an epoch is provided by deleting message encryption keys once they've been used to encrypt or decrypt a message.

Post-compromise security is also provided for new groups by members regularly generating new InitKeys and uploading them to the Delivery Service, such that compromised key material won't be used when the member is added to a new group.

15.4. InitKey Reuse

InitKeys are intended to be used only once. That is, once an InitKey has been used to introduce the corresponding client to a group, it SHOULD be deleted from the InitKey publication system. Reuse of InitKeys can lead to replay attacks.

An application MAY allow for reuse of a "last resort" InitKey in order to prevent denial of service attacks. Since an InitKey is needed to add a client to a new group, an attacker could prevent a client being added to new groups by exhausting all available InitKeys.

15.5. Group Fragmentation by Malicious Insiders

It is possible for a malicious member of a group to "fragment" the group by crafting an invalid UpdatePath. Recall that an UpdatePath encrypts a sequence of path secrets to different subtrees of the group's ratchet trees. These path secrets should be derived in a sequence as described in Section 5.4, but the UpdatePath syntax allows the sender to encrypt arbitrary, unrelated secrets. The syntax also does not guarantee that the encrypted path secret encrypted for a given node corresponds to the public key provided for that node.

Both of these types of corruption will cause processing of a Commit to fail for some members of the group. If the public key for a node does not match the path secret, then the members that decrypt that path secret will reject the commit based on this mismatch. If the path secret sequence is incorrect at some point, then members that can decrypt nodes before that point will compute a different public key for the mismatched node than the one in the UpdatePath, which also causes the Commit to fail. Applications SHOULD provide mechanisms for failed commits to be reported, so that group members who were not able to recognize the error themselves can reject the commit and roll back to a previous state if necessary.

Even with such an error reporting mechanism in place, however, it is still possible for members to get locked out of the group by a malformed commit. Since malformed Commits can only be recognized by certain members of the group, in an asynchronous application, it may be the case that all members that could detect a fault in a Commit are offline. In such a case, the Commit will be accepted by the group, and the resulting state possibly used as the basis for further Commits. When the affected members come back online, they will reject the first commit, and thus be unable to catch up with the group.

Applications can address this risk by requiring certain members of the group to

acknowledge successful processing of a Commit before the group regards the Commit as accepted. The minimum set of acknowledgements necessary to verify that a Commit is well-formed comprises an acknowledgement from one member per node in the UpdatePath, that is, one member from each subtree rooted in the copath node corresponding to the node in the UpdatePath.

16. IANA Considerations

This document requests the creation of the following new IANA registries:

- MLS Ciphersuites (Section 16.1)
- MLS Extension Types (Section 16.2)
- MLS Credential Types (Section 16.3)

All of these registries should be under a heading of "Messaging Layer Security", and assignments are made via the Specification Required policy [RFC8126]. See Section 16.4 for additional information about the MLS Designated Experts (DEs).

RFC EDITOR: Please replace XXXX throughout with the RFC number assigned to this document

16.1. MLS Ciphersuites

A ciphersuite is a combination of a protocol version and the set of cryptographic algorithms that should be used.

Ciphersuite names follow the naming convention:

```
CipherSuite MLS_LVL_KEM_AEAD_HASH_SIG = VALUE;
```

Where VALUE is represented as a sixteen-bit integer:

```
uint16 CipherSuite;
```

Component	Contents
MLS	The string "MLS" followed by the major and minor version, e.g. "MLS10"
LVL	The security level
KEM	The KEM algorithm used for HPKE in TreeKEM group operations
AEAD	The AEAD algorithm used for HPKE and message protection
HASH	The hash algorithm used for HPKE and the MLS transcript hash
SIG	The Signature algorithm used for message authentication

Table 3

The columns in the registry are as follows:

- Value: The numeric value of the ciphersuite
- Name: The name of the ciphersuite
- Recommended: Whether support for this extension is recommended by the IETF MLS WG. Valid values are "Y" and "N". The "Recommended" column is

assigned a value of "N" unless explicitly requested, and adding a value with a "Recommended" value of "Y" requires Standards Action [RFC8126]. IESG Approval is REQUIRED for a Y->N transition.

- Reference: The document where this ciphersuite is defined

Initial contents:

Value	Name	Recommended
0x0000	RESERVED	N/A
0x0001	MLS10_128_DHKEMX25519_AES128GCM_SHA256_Ed25519	Y
0x0002	MLS10_128_DHKEMP256_AES128GCM_SHA256_P256	Y
0x0003	MLS10_128_DHKEMX25519_CHACHA20POLY1305_SHA256_Ed25519	Y
0x0004	MLS10_256_DHKEMX448_AES256GCM_SHA512_Ed448	Y
0x0005	MLS10_256_DHKEMP521_AES256GCM_SHA512_P521	Y
0x0006	MLS10_256_DHKEMX448_CHACHA20POLY1305_SHA512_Ed448	Y
0xff00 - 0xffff	Reserved for Private Use	N/A

Table 4

All of these ciphersuites use HMAC [RFC2104] as their MAC function, with different hashes per ciphersuite. The mapping of ciphersuites to HPKE primitives, HMAC hash functions, and TLS signature schemes is as follows [I-D.irtf-cfrg-hpke] [RFC8446]:

Value	KEM	KDF	AEAD	Hash	Signature
0x0001	0x0020	0x0001	0x0001	SHA256	ed25519
0x0002	0x0010	0x0001	0x0001	SHA256	ecdsa_secp256r1_sha256
0x0003	0x0020	0x0001	0x0003	SHA256	ed25519
0x0004	0x0021	0x0003	0x0002	SHA512	ed448
0x0005	0x0012	0x0003	0x0002	SHA512	ecdsa_secp521r1_sha512
0x0006	0x0021	0x0003	0x0003	SHA512	ed448

Table 5

The hash used for the MLS transcript hash is the one referenced in the ciphersuite name. In the ciphersuites defined above, "SHA256" and "SHA512" refer to the SHA-256 and SHA-512 functions defined in [SHS].

It is advisable to keep the number of ciphersuites low to increase the chances clients can interoperate in a federated environment, therefore the ciphersuites only inlcude modern, yet well-established algorithms. Depending on their

requirements, clients can choose between two security levels (roughly 128-bit and 256-bit). Within the security levels clients can choose between faster X25519/X448 curves and FIPS 140-2 compliant curves for Diffie-Hellman key negotiations. Additionally clients that run predominantly on mobile processors can choose ChaCha20Poly1305 over AES-GCM for performance reasons. Since ChaCha20Poly1305 is not listed by FIPS 140-2 it is not paired with FIPS 140-2 compliant curves. The security level of symmetric encryption algorithms and hash functions is paired with the security level of the curves.

The mandatory-to-implement ciphersuite for MLS 1.0 is `MLS10_128_DHKEMX25519_AES128GCM_SHA256_Ed25519` which uses Curve25519 for key exchange, AES-128-GCM for HPKE, HKDF over SHA2-256, and Ed25519 for signatures.

Values with the first byte 255 (decimal) are reserved for Private Use.

New ciphersuite values are assigned by IANA as described in Section 16.

16.2. MLS Extension Types

This registry lists identifiers for extensions to the MLS protocol. The extension type field is two bytes wide, so valid extension type values are in the range 0x0000 to 0xffff.

Template:

- Value: The numeric value of the extension type
- Name: The name of the extension type
- Message(s): The messages in which the extension may appear, drawn from the following list:
  - KP: KeyPackage messages
  - GI: GroupInfo objects
- Recommended: Whether support for this extension is recommended by the IETF MLS WG. Valid values are "Y" and "N". The "Recommended" column is assigned a value of "N" unless explicitly requested, and adding a value with a "Recommended" value of "Y" requires Standards Action [RFC8126]. IESG Approval is REQUIRED for a Y->N transition.
- Reference: The document where this extension is defined

Initial contents:

Value	Name	Message(s)	Recommended	Reference
0x0000	RESERVED	N/A	N/A	RFC XXXX
0x0001	capabilities	KP	Y	RFC XXXX
0x0002	lifetime	KP	Y	RFC XXXX
0x0003	key_id	KP	Y	RFC XXXX
0x0004	parent_hash	KP	Y	RFC XXXX

Table 6

Value	Name	Message(s)	Recommended	Reference
0x0005	ratchet_tree	GI	Y	RFC XXXX
0xff00 - 0xffff	Reserved for Private Use	N/A	N/A	RFC XXXX

16.3. MLS Credential Types

This registry lists identifiers for types of credentials that can be used for authentication in the MLS protocol. The extension type field is two bytes wide, so valid extension type values are in the range 0x0000 to 0xffff.

Template:

- Value: The numeric value of the credential type
- Name: The name of the credential type
- Recommended: Whether support for this extension is recommended by the IETF MLS WG. Valid values are "Y" and "N". The "Recommended" column is assigned a value of "N" unless explicitly requested, and adding a value with a "Recommended" value of "Y" requires Standards Action [RFC8126]. IESG Approval is REQUIRED for a Y->N transition.
- Reference: The document where this extension is defined

Initial contents:

Value	Name	Recommended	Reference
0x0000	RESERVED	N/A	RFC XXXX
0x0001	basic	Y	RFC XXXX
0x0002	x509	Y	RFC XXXX
0xff00 - 0xffff	Reserved for Private Use	N/A	RFC XXXX

Table 7

16.4. MLS Designated Expert Pool

Specification Required [RFC8126] registry requests are registered after a three-week review period on the MLS DEs' mailing list: mls-reg-review@ietf.org, on the advice of one or more of the MLS DEs. However, to allow for the allocation of values prior to publication, the MLS DEs may approve registration once they are satisfied that such a specification will be published.

Registration requests sent to the MLS DEs mailing list for review SHOULD use an appropriate subject (e.g., "Request to register value in MLS Bar registry").

Within the review period, the MLS DEs will either approve or deny the registration request, communicating this decision to the MLS DEs mailing list and IANA. Denials SHOULD include an explanation and, if applicable, suggestions as to how to make the request successful. Registration requests that are undetermined for a period longer than 21 days can be brought to the IESG's attention for resolution using the iesg@ietf.org mailing list.

Criteria that SHOULD be applied by the MLS DEs includes determining whether the proposed registration duplicates existing functionality, whether it is likely to be of general applicability or useful only for a single application, and whether the registration description is clear. For example, the MLS DEs will apply the

ciphersuite-related advisory found in Section 6.1.

IANA MUST only accept registry updates from the MLS DEs and SHOULD direct all requests for registration to the MLS DEs' mailing list.

It is suggested that multiple MLS DEs be appointed who are able to represent the perspectives of different applications using this specification, in order to enable broadly informed review of registration decisions. In cases where a registration decision could be perceived as creating a conflict of interest for a particular MLS DE, that MLS DE SHOULD defer to the judgment of the other MLS DEs.

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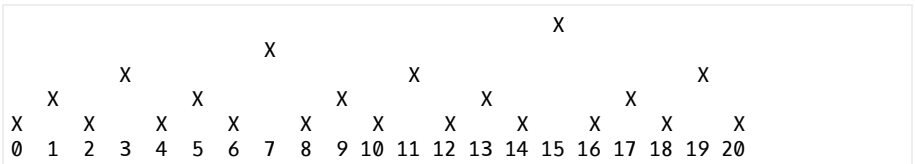
Appendix A. Tree Math

One benefit of using left-balanced trees is that they admit a simple flat array representation. In this representation, leaf nodes are even-numbered nodes, with the n-th leaf at 2*n. Intermediate nodes are held in odd-numbered nodes. For example, an 11-element tree has the following structure:



This allows us to compute relationships between tree nodes simply by manipulating indices, rather than having to maintain complicated structures in memory, even for partial trees. The basic rule is that the high-order bits of parent and child nodes have the following relation (where x is an arbitrary bit string):

```
parent=01x => left=00x, right=10x
```

The following python code demonstrates the tree computations necessary for MLS. Test vectors can be derived from the diagram above.

```
# The exponent of the largest power of 2 less than x. Equivalent to:
#   int(math.floor(math.log(x, 2)))
def log2(x):
    if x == 0:
        return 0

    k = 0
    while (x >> k) > 0:
        k += 1
    return k-1

# The level of a node in the tree. Leaves are level 0, their parents are
# level 1, etc. If a node's children are at different levels, then its
# level is the max level of its children plus one.
def level(x):
    if x & 0x01 == 0:
        return 0

    k = 0
    while ((x >> k) & 0x01) == 1:
        k += 1
    return k

# The number of nodes needed to represent a tree with n leaves.
def node_width(n):
    if n == 0:
        return 0
    else:
        return 2*(n - 1) + 1

# The index of the root node of a tree with n leaves.
def root(n):
    w = node_width(n)
    return (1 << log2(w)) - 1

# The left child of an intermediate node. Note that because the tree is
# left-balanced, there is no dependency on the size of the tree.
def left(x):
    k = level(x)
    if k == 0:
        raise Exception('leaf node has no children')

    return x ^ (0x01 << (k - 1))

# The right child of an intermediate node. Depends on the number of
# leaves because the straightforward calculation can take you beyond the
# edge of the tree.
def right(x, n):
    k = level(x)
    if k == 0:
        raise Exception('leaf node has no children')

    r = x ^ (0x03 << (k - 1))
    while r >= node_width(n):
        r = left(r)
    return r

# The immediate parent of a node. May be beyond the right edge of the
# tree.
def parent_step(x):
    k = level(x)
    b = (x >> (k + 1)) & 0x01
    return (x | (1 << k)) ^ (b << (k + 1))

# The parent of a node. As with the right child calculation, we have to
# walk back until the parent is within the range of the tree.
def parent(x, n):
    if x == root(n):
        raise Exception('root node has no parent')

    p = parent_step(x)
    while p >= node_width(n):
```

```
        p = parent_step(p)
    return p

# The other child of the node's parent.
def sibling(x, n):
    p = parent(x, n)
    if x < p:
        return right(p, n)
    else:
        return left(p)

# The direct path of a node, ordered from leaf to root.
def direct_path(x, n):
    r = root(n)
    if x == r:
        return []

    d = []
    while x != r:
        x = parent(x, n)
        d.append(x)
    return d

# The copath of a node, ordered from leaf to root.
def copath(x, n):
    if x == root(n):
        return []

    d = direct_path(x, n)
    d.insert(0, x)
    d.pop()
    return [sibling(y, n) for y in d]

# The common ancestor of two nodes is the lowest node that is in the
# direct paths of both leaves.
def common_ancestor_semantic(x, y, n):
    dx = set([x]) | set(direct_path(x, n))
    dy = set([y]) | set(direct_path(y, n))
    dxy = dx & dy
    if len(dxy) == 0:
        raise Exception('failed to find common ancestor')

    return min(dxy, key=level)

# The common ancestor of two nodes is the lowest node that is in the
# direct paths of both leaves.
def common_ancestor_direct(x, y, _):
    # Handle cases where one is an ancestor of the other
    lx, ly = level(x)+1, level(y)+1
    if (lx <= ly) and (x>>ly == y>>ly):
      return y
    elif (ly <= lx) and (x>>lx == y>>lx):
      return x

    # Handle other cases
    xn, yn = x, y
    k = 0
    while xn != yn:
       xn, yn = xn >> 1, yn >> 1
       k += 1
    return (xn << k) + (1 << (k-1)) - 1
```

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