The Federated Open Key Service (FOKS)

Maxwell Krohn (max@ne43.com)

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Abstract

This paper presents FOKS (Federated Open Key System), a decentralized key management system designed to provide secure and flexible key distribution across federated networks. The basic problem addressed is that of of two parties sharing end-to-end encrypted data across the internet, where both parties have several devices. They might rotate devices, form mutable teams with other users, or even teams of teams in an arbitrary graph. They need to share secret key material to facilitate symmetric encryption, and this material must rotate whenever devices are replaced, or team membership changes. This is a very natural problem but one that still lacks an adequate solution. Morever, we believe key management should not lock users into a particular, walled provider, but instead, should allow for federation and independent management of server resouces, as we see in HTTP and SMTP. We describe the system architecture, security model, and implementation details of a system that achieves secure, federated key exchange, and enables useful applications like end-to-end encrypted data sharing and git hosting.

1 Introduction

2 Threat Model

In FOKS, we consider a threat model similar to that of the Keybase [1], SEAMLess [10] or CONIKs [22] systems. The high level north star is end-to-end secrecy and integrity. Only the clients at the edges of the system should be able to decrypt important data, and only those clients can make authorized changes to the data. Of course, multiple devices per user and mutable groups complicate the picture.

We assume that clients are trustworthy, and behave properly. If this assumption is violated, say, if a client is compromised by a rootkit, then we cannot offer any guarantees.

Users might sometimes lose their devices. In an ideal world, hardware protections would prevent whoever recovered the device from accessing the device's private key material. In the case of hardware keys (like YubiKeys), or backup-keys written on paper, the user has less protection during comrpomise. Regardless, once the user revokes the lost device, keys should rotate so that data is secure going forward (this property is known post-compromise security). In some cases, past data might be safe from the attacker (this property is known as forward-secrecy). but the specifics depend on the trustworthiness of the server (see below). Similarly, revoked keys on lost devices lose their signing power, and other devices will not accept their signatures going forward.

The threat model is here is similar but not exactly the same as Signal's and WhatsApp's, because our applications feature persistent (rather than ephemeral) data. If a new user joins an existing group, or if a user adds a new device, they should be able to access old data, which might be required to reassemble the shared resource. For instance, when Alice adds Bob to a git project,

Bob should see all past commits in the commit history, otherwise the application will break. Thus, we can't guarantee foward-secrecy, since lack of forward secrecy is needed for the application to function properly.

In FOKS, clients pick their servers. They might select for servers that are generally aligned with. They can run their own servers, or pick from third party hosting providers. Users should assume that servers are generally trustworthy, but might suffer comrpomises from time to time. For instance, servers might be running on cloud infrastructure, and the underlying storage, network, or computation might be compromised. Insiders or state actors might have privileged access to the underlying infrascture.

If servers behave honestly, the FOKS system works securely as expected. If servers behave maliciously, they can deny access to data through a variety of mechanisms: they can go offline, they can withoold data, or they can subtly current server-resident data to confuse clients. In this last case, the system's security design should prevent the clients from leaking secrets or accepting unauthorized changes to data. But as in the other more obvious cases, the clients will lose access to their data.

When servers are behaving honestly, they can provide clients with forward-secrecy. That is, if honest servers throw away data encrypted with old keys, an attackets with access to private keys cannot rcannot ecover past data. This property is an improvement over that offered by the Keybase system, which assumed the worst in the case of a comrpomise. If we assume on the other hand that an attacker who steals a private key operates in cohoots with the server, then we cannot offer any guarantees about forward secrecy.

Servers do not trust each other. If one server becomes corrupted, it has no bearing on the other servers in the system. In other words, we assume attackers can stand up their own servers, since anyone in the system can do so.

3 Design

FOKS is a classic client-server system. At a hight level, the clients manage private keys, and the server manages public keys, encryptions of, shared secret keys, and encrypted data. Users generally trust their servers to be online, available and not to intentionally sabotage agreed-upon protocols.

3.1 System Architecture

Much like HTTP or STMP, FOKS clients communicate with one or more servers, depending on where users have accounts. They can safely ignore the other servers in the system. Most communication is between client and server, and there is little if any server-to-server or client-to-client communication. This property simplifies protocol upgrades and network configuration.

Each client can speak for many users, as users can have accounts on different servers, or several accounts on the same server. By analogy, an email client can server multiple emails accounts for the same user concurrently, say one for work and one for personal use. Or a web browser might have different personae (with different cookies, preeferences, passwords and history) for the same user.

Each of the users can of course have multiple devices, like a desktop, a laptop, a phone, and a Yubikey. Additionally, users can have "backup devices", which can be writted down on paper and stored in a safe place. The system recommends at least two devices to prevent data loss. That is, these devices have private keys that decrypt data, and the loss of the last key prevents decryption of the data. Obviously there is a trade-off here: the more devices, the more likely the user will lose

one, or have one stolen; the fewer devices, the more likely the user will lose all devices and therefore access to data. Some optimal middle ground exists, but varies with the users and their behaviors.

3.2 Key Hierarchy

The FOKS key hierarchy sits at the core of the system. It aims to provide users with a sequence of symmetric keys shared across all of their devices, so that they can store data encrypted with the latest key, and can decrypt (and authenticate) data encrypted with older keys when necessary. Similarly, users in a team should share secret keys that users outside their teams cannot see, allowing them to share encrypted data via untrusted FOKS servers.

3.2.1 Device Keys

When a user sits down at a FOKS client to signup or provision a new device for an existing account, she first creates a new key-pair specifically for that device. The private key never leaves the device. She shares the public key with the FOKS server, who eventually selectively shares it with user users. We detail the exact cryptography in Section 4.2.

Hardware keys that support the PIV protocol (like Yubikey version 5 and later) can also be used as device keys. These devices get randomly-generated private keys in the factory, written to one of 20 possible "slots." FOKS users select a slot to use, and the client sends the corresponding public key to the FOKS server. Signing and decryption operations happen on the device against the chose slot.

3.2.2 Per-User Keys (PUKS)

Every user on the FOKS system has one of more per-user keys, or PUKS. A PUKS is a randomly-generated key-pair whose private key is encrypted for each of the device public keys. This way, all current devices can access the current PUK secret key, and perform decryptions or signatures for the current PUK public key. The client makes a new PUK every time the user revokes a device. The system encrypts the old PUK secret keys for the new PUK secret key. This way, a device that has access to the latest PUK can get access easily to all prior PUKs.

Once the PUK sequence is estblished, the system has a convenient way to encrypt a data for all of the user's device — it simply encrypts the data for the user's latest PUK.

3.2.3 Per-Team Keys (PTKs)

Each team has a sequence of per-team-keys, or PTKs, which are analogous to PUKs for users. Upon creation, a team gets a new random PTK. The client performing the creation sends the public part of the PTK to the server. The private part of the PTK is encrypted for each member's latest PUK, and therefore is available on each of the user's devices.

As with PUKs, data that the team shares is encrypted for the team's latest PTK, and all members can decrypt it. As we will see in Section 3.6, teams can join other teams, but the key hierarchy works just the same. When team A joins team B, the secret part of team B's PTK is encrypted for team A's latest PTK, so that all members of team A can decrypt B's PTK, and therefore, all of B's encrypted data.

3.3 Key Roles

FOKS has a notion of a "role" for device keys, PUKs and PTKs. The roles are: owner, admin, and reader, but reader keys have a "visibility level" that varies between -32768 and 32767. There is a

total ordering among key roles, so that owner > admin > reader, and between reader keys, $k_1 > k_2$ iff k_1 has a higher visibility level than k_2.

The important property enforced is that we only encrypt PUK k for device key j if $\mathsf{role}(k) \leq \mathsf{role}(j)$, and similarly, we only encrypt PTK k for PUK j if $\mathsf{role}(k) \leq \mathsf{role}(j)$.

The idea here is that the owners of a group get to see all the keys; the admins can see the admin and reader keys; and the readers can see keys at or below their visiblility level. This configuration allows groups to have lower-privileged members, and for users to have lower-privileged devices. At Keybase, a similar but less-flexible property allows "bots" into teams, so that all the members of the teams can interact with the bots, but the members had channels to communicate that the bots aren't privvy to. For now, all user devices are at the owner role, but we plan to relax this requirement in the future.

3.4 Data Structures

We now have some basic motivation as to what the key system ought to achieve. It ought to allow groups of devices, groups of users, or groups of users and teams to share a secret encryption key. From there, they can share data encrypted (and authenticated) with that key. But the question becomes, how are users formulated from devices, and how are teams formulated from users so that only desired members are in the group, especially if the server behave maliciously?

For instance, a malicious server might fool a user into encrypting secret data for an invalid device, or team administrator into encrypted data for an invalid user.

3.4.1 Signature Chains

FOKS uses the same mechanism as Keybase here — the signature chain (or "sigchain" for short). The sigchain is a series of signed statements that form a cryptographic chain, meaning they can only be replayed in the intended order. Replaying the chain allows a viewer to confirm the chain appears how the author intended and wasn't tampered with, even if the set of signers varies over time. Of course, signers do vary over time as users add and remove devices, or as they add and remove members from teams.

Each user (and team) gets its own sigchain. The sigchain keeps an indellable record of which keys can update the chain, and which PUKs or PTKs are currently active for the user (or team).

Users The first link in a sigchain is called the "eldest" link. For user sigchains, the first device generates this link, generates the first PUK, and then computes a signature over the following data:

- U.1 The hash of the previous link in the chain (nil for the eldest)
- U.2 The current sequence number of the sigchain (which is 1 for the eldest link)
- U.3 A commitment to the next random tree location (see Section 3.4.5)
- U.4 The current Merkle root hash (see Section 3.4.3)
- U.5 The user's ID and the server's host ID (see Section 3.4.6)
- U.6 The user's new PUK public keys
- U.7 The user's new device key
- U.8 A "subchain tree location seed commitment" (see Section 3.4.7)
- U.9 A cryptographic commitment to the user's username (see Section 3.4.8)
- U.10 A cryptographic commitment to the user's device name (picked by the user)

U.11 The role of the new device (currently always owner).

U.12 For Yubikeys, a public "subkey' used to authenticate the client to the server.

The client computes nested signatures first by the new PUKs introduced in Step U.6, and lastly by the user's device key. (Recall that sometimes several PUKs can be introduced at once due to the different possible device roles). The client uploads the whole package as the user's eldest link.

Subsequent links proceed in largely the same way, with a few minor differences. The previous hash (U.1) is the collision-resistent hash of the package uploaded in the previous step. In some cases, like device addition, new PUK public keys (U.6) do not appear. In these cases, no signatures with PUKs are required.

For any link in the chain, a set of devices is authorized to make further updates to the chain. After the first link, the set contains only the first device (sometimes called the "eldest" device). A link can either add a new device, or revoke an existing device, updating the set of authorized devices accordingly. When clients upload new chainlinks, the server enforces valid signatures by authorized devices. When users replay this chain, they perform the same check. This simple mechanism ensures the server can't introduce a bogus device.

Teams A team chain link contains the following fields, many of which are analagous to user chains:

T.1 The hash of the previous link in the chain (nil for the eldest)

T.2 The current sequence number of the sigchain (starting at 1)

T.3 A commitment to the next random tree location

T.4 The current Merkle root hash

T.5 The team's ID and the server's host ID

T.6 The user (or team) ID, host ID, and PUK (or PTK) of the actor making the change

T.7 New PTK public keys

T.8 A set of membership changes

T.9 A "subchain tree location seed commitment"

T.10 A cryptographic commitment to the team's name (optional if not changing)

T.11 The team's "index range" (see 3.6.2)

Since teams can contain both users and other teams, the actor creating or modifying the team can be either a user or a team. In FOKS, a *party* refefes to someone or something that can be in a team, so either a user or a team. In field T.6, the link contains the unique identifier of the party (which is the user or team ID plus the host ID), and also the key making the change. For users, this key is the user's latest PUK at the owner role. For teams, it's the team's latest PTK at the desired source role. That is, consider a teams T where users a and b are owners of T, c is an admin and d is a reader (at visibility level 0). If T creates a new team U with source role of owner, then only users a and b will have access. If T creates the new team with source role of reader, then all users will have access.

FOKS clients and servers enforce these access controls with the key hierachy. In the case of the owners of T creating U, T's owner PTK appears in field T.6 and performs the signature over the chainlink. As T creates U, it makes new PTKs for U. It encrypts the secret keys of these new PTKs for the owner PTK of T. This way, everyone in the owner group of T can now access U's

PTKs. The second example follows similarly, with the readers of T getting access to U's secret PTKs after team creation.

The membership changes field (T.8) contains the following fields for each member being modified:

M.1 The "destination role": the role the member is to have in the team; for removals, this is the role none.

M.2 The member's party and host IDs (a party ID is a user ID or a team ID).

M.3 The source role: the role the member has in its current party.

M.4 The member's public PTK or PUK from its current party.

M.5 The generation number of that PTK or PUK.

M.6 A commitment to a "team removal key" (see Section 3.6.5)

In the case of team creation, member addition, member role upgrade or downgrade, the role in field M.1 is the new role in the target team that the member has after the change is applied. In the case of removal, the role is none.

Note that in field M.4, the public PUK (or PTK) appears directly in the chain, in addition to the ID of that party. Admins and owners are later allowed to make team modifications, and these are the public keys that will sign these modifications. Team readers in particular might lack the permission to load the chains of these users and teams directly, so it's crucial the keys appear directly in the team chain. See Section 3.8 for further details about sigchain visibility.

As alluded to above, owners have ultimate control over the team. They can add and remove members, add other owners, downgrade owners to admins, etc. Admins have more limited control; the have similar control over admins and readers, but cannot: upgrade admins to owners, introduce new members as owners, remove existing owners; or downgrade existing owners. Readers cannot make any team modifications but can of course read team chains, and can access data protected by the reader's PTKs at their level and below.

Teams, unlike users, can include members located on different servers. Above, in item M.2, we include the host ID of the party in the membership change. Remote members cannot be admins or owners, but can be readers. This configuration allows for convenient data sharing across federation boundaries, but simplifies team management relative to an alternative system where remote members can be owners or admins.

Parties making changes to team sign new team chain links much the same way as user devices sign user chain links. First, all new PTKs sign the chain link, and then the acting party's latest PUK or PTK signs the chain link. This PUK or PTK must be the exact key advertised earlier in the chain in the case of link 2 and above. The eldest link is essentially self-signed.

3.4.2 Sigchain Playback

Whenever a client on the time interacts with another party, or even itself, it begins by playing back that party's sigchain. The client connects to the party's home server, downloads any new links it hasn't seen, and ensures the new links play back cleanly on top of links it previously cached. The rules for playback are largely implied by the discussion above, such as:

- All chains start at 1, and have ascending sequence numbers.
- All links should contain the hash of the previous link.

- All links should have valid signatures by devices, PUKs or PTKs that the chain itself authorized. Eldest links are essentially self-signed.
- The role restrictions described in Section 3.4.1 are obeyed in team chains.

Once playback succeeds, the client has a set of devices keys, PUKs and PTKs that can speak on behalf of the party. It also has rosters of devices of members who share that key. From here, useful application work can take over. For instance, in the case of file sharing (whether via Git or via a KV-store interface), a key derived from the most recent PUK or PTK serves as the symmetric key for authenticated encryption. Whenever the PUK or PTK rotates to a new generation, future encryption should use the new key.

3.4.3 Merkle Tree

Section 2 describes the FOKS threat model, and we assume the server can behave maliciously. Sigchains prevent a server from creating new chainlinks out of whole cloth and interleaving those with legitimate links. The protection simply is that the server does not have the private keys the parties use for signing. We assume those never leave the devices they are made on. By these mechanisms, the server cannot extend a chain or replace an inner link. The server can of course create a brand new chain, and might attempt clients into using this chain rather than the one the users intended. This case of "mistaken identity" is one of *naming*, which we cover in Section 3.4.8.

The server can nonetheless *withhold* links at the end of a chain, or show some clients the full chains, and other various subchains, with the hope of forcing them to "fork" the sigchain into 2 incompatible directions. We need a mechanism to force the server's hand into showing a consistent chain tail to all users who request it. This is where the Merkle tree comes in. FOKS servers expose a Merkle Tree that forces the server to commit to a coherent state of the system, across all parties, preventing selective rollback of sigchains.

FOKS uses a Merkle Tree strategy that is a hybrid of Keybase's [1], CONIK's [22] and SEEM-Less's [10], but with a simple novel mechanism introduced to obviate the need for pseudo-random functions. The Merkle tree stores each party's sigchain tail at a leaf in the Merkle tree. The server computes hashes all the way up to the root node. The *root block* contains this tree root hash, a pointer to the previous version of the tree (called the previous "epoch"), a logarithmicly-sized set of pointers to previous roots further back in history, and also the tail of the server's hostchain (see Section 3.4.6). The hash of this root block is now a summary of the entire system. The server attempts to publish root blocks immediately after every sigchain update, but sometimes batches them for efficiency. In general, roots should be produced no more than 15 seconds after a sigchain update to keep clients responsive (since sometimes they need to wait for updates).

3.4.4 Root Chaining

Since many users and teams might be active on a signle FOKS server, the user has no reason to download every root Merkle epoch. Rather, the user will experience long gaps between epochs, especially if going periodically offline. Whenenever a client downloads a root block, say at epoch i, it writes it to local storage. When the client later downloads another root block, call it k, the client enforces that $i < k$. It also sends up the paremeter i, and the server replies with intermediate blocks $j_1, j_2 \ldots j_n$, such that $i < j_1 < \cdots j_n < k$, where block j_a contains a pointer to j_{a-1}, block j_1 contains a pointer to i and block k contains a pointer to j_n. The spacing of the previous pointers in the root block ensures than n is appromixately $\log(k - i)$. Chaining root blocks in this way encourages the server to maintain a consistent, coherent append-only tree. Clients should perform periodic audits of all root blocks to ensure previous-pointer consistency across all epochs.

3.4.5 Location Hiding

For the party p, at sequence number i, the leaf node is a key-value pair, where the key is $H(p, i, t, r_i)$, and the value is the hash of the signature of the last link in the sigchain (the ith). t is an enumerated value that specifies which type of chain for p this is. As we will see in Section 3.4.7, each party has multiple chains. r_i is a random value that was generated when the $(i-1)$ link was published. The $(i-1)$ link contains the value $H(r_i)$ in the field T.3 from Section 3.4.1. This simple mechanism achieves the same end as the PRF in CONIKs and SEEMLess, in that it's unpredictable in the tree where a team's sighcains is stored. This unpredictability prevents data leaks that would otherwise allow the owners of neighboring nodes in the tree to deduce when p's chain advances.

When a client requests a sighchain for party p, the server returns $(n+1)$ paths down from the root of the tree, if the sigchain is n links long. The first n paths point to chain links 1 through n as described above, and the last is a proof that the $(n+1)$ link does not exist. For each path, the server returns neighbors necessary to trace the path back to the tree root. The server also returns the sequence $(r_2, r_3, \ldots r_{n+1})$, so the client can verify they match the commitments in the sigchain. Note the first link location is not randomized with r_1, since there was no 0th link to commit to r_1. However, the eldest link's placements is already essentially random since the party's ID p is generately randomly at the first link (and is predictable thereafter).

3.4.6 Hostchains

Servers maintain hostchains so they can manage and rotate their signig keys, DNS names, and TLS keys. Like team and user chains, hostchains form a cryptographic chain, ensuring they can only be replayed in the intended order, even if modified in transit. Chain links have sequence numbers and contain the cryptographic hashes of previous links. When an administrator creates a new server, they first create a *hostkey*, a signing key-pair. This public key becomes the host's ID. The first chainlin contains this hostkey and several subkeys, one that serves as a TLS CA for the server, and one used to sign *zonefiles* for the server. The *zonefile* contains the DNS names for the server's various services. Subsequent chainlinks can change any of these keys or subkeys, as long as they are signed with keys valid up until that point. clients play these links back to map host IDs to DNS names as they establish connections to new servers.

3.4.7 Subchains

User Settings We have already seen two sigchains: the user chain and the team chain. Each of these chains has a subchain. Users have a *user settings subchain* in addition to the user chain. Currently, this chains contains information about the user's passphrase, which can optionally be used to locally encrypt device keys (see Section 4.3.2). Whenever the user changes her passphrase, she writes a new link to the chain, so that the server cannot roll back her passphrase information to an earlier setting. Chain locations for links i_2 and above are computed as in the user chain itself, but with $t = \mathsf{settings}$ rather than $t = \mathsf{user}$. However, the eldest link is randomized, since otherwise, its location in the tree is predictable given the user ID.

Recall that the eldest user chain link contains a "subchain tree location seed commitment"(U.8). When creating the link, the client software generates a random valaue s, and puts the hash $H(s)$ into the chain link. Then $r_1 = H(s, \mathsf{settings})$, and the Merkle Tree stores the first link of u's user settings chain at location $H(u, 1, \mathsf{settings}, r_1)$. The server knows s, and u knows s, so both can compute and verify the random location of the first link of the user settings chain. But other users who view u's sigchain do not know s and therefore cannot infer if u has a user settings chain or not.

Team Membership Users and teams have a subchain to keep track of which team it is a member of. As we discuss in Section 3.6.4, users need to rotate their teams from time to time based on key rotation events, like device revocation and removals from teams. The general strategy the user follows is to enumerate all teams she is transitively a member of (since recall teams can be members of other teams), and then check each team for staleness, rotating those that are stale. If this membership list were based purely on server trust, a malicious server could withhold team memberships from a user to silent suppress team rotations.[1] Instead of relying on server trust, the client software maintains a list of team memberships as a sigchain, which the server must faithfully synchronize across all of the user's devices. The tree location mechanism here is the same as for user chains, with $t = \mathsf{teamMembership}$. See Section 3.6.5 for more information on team additions and removals, and how the client maintains this subchain.

3.4.8 Naming

The server stores user and team chains at tree locations indexed by user IDs and team IDs respectively. These IDs are large random identitiers, and are not friendly to humans. Users of course need to be able to refer to these parties with convenient names. Morever, parties should have the ability to change names from time-to-time, though not too frequently, as too much churn in naming would complicate the user experience.

Naming in FOKS works as follows. When a user signs up, she first picks a name n, and the software later generates a random user ID u that n will correspond to. The server stores the user ID u at the Merkle Tree location $H(n, 1, \mathsf{name}, nil)$, and the sigchain for u commits to n at U.9. When another user loads u, she looks up the Merkle leaves at location $H(n, 1, \mathsf{name}, nil)$ and $H(n, 2, \mathsf{name}, nil)$, confirming that the first location maps to u, and that the second location is absent from the tree, confirming the name hasn't be remapped. The loader then confirms that the name matches the commitment in u's sigchain.

This system ensures a 1-to-1 mapping between a name n and a user ID u. u can later switch to a new name n' by adding another sigchain link commiting to n' that overrides the earlier commitment to n. The server can likewise later reassign n (though we currently do not allow this) by posting a new user ID u' at tree location $H(n, 2, \mathsf{name}, nil)$.

Team naming works exactly the same way.

3.5 Provisioning

When users sign up for a new FOKS account, they establish a first device. They establish further devices via a process called "provisioning". In provisioning, an existing device signs the device key of the new device, and also sends it the private side of the current PUK. As we saw above, the signatures form a link in the sigchain. The server helps exchanged encrypted PUK keys as "sidecar" data.

3.5.1 Device-to-Device

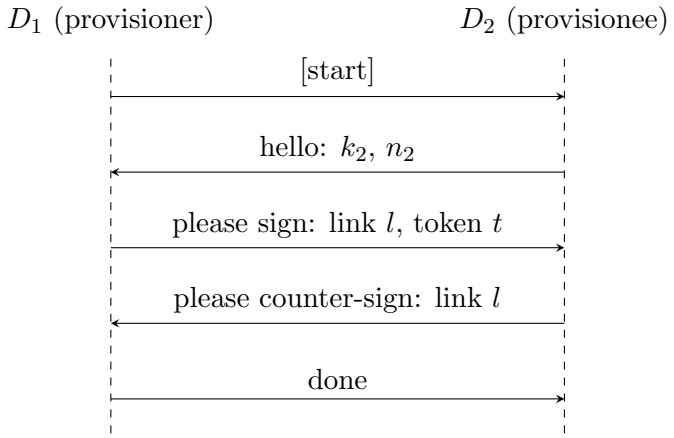
The most complicated case is device-to-device provisioning. A user has an active account on device D_1 and uses it to directly provision device D_2. We call the existing device, D_1, the "provisioner", and the new device, D_2, the "provisionee." Device D_2 generates a new device key k_2 and prompts the user for a device name, which is n_2. Both devices pick random 125-bit session keys, call them

[1] A malicious server could also reject a legitimate team update, but the user's software can alert the user of such a failure.

s_1 and s_2. Both clients show these keys to the user, using a simple encoding scheme we call "high-entropy secret phrase". See Section 4.2.5 for more details. An example might look like:[2]

```
sniff 216 tilt 139 fat 230 patient 228 same 87 burger 13 master
```

To initiate the key exchange protocol, either the user enters s_2 on device D_1 or s_1 on device D_2. In both cases, the message flow is as follows:



The first message, "start", is optional and only needed in the case that s_2 is entered on device D_1. In the "hello" message, the provisionee sends its new key and desired device name over to the provisioner. The provisioner then makes a sigchain link, l, and in the "please sign" message, asks the provisionee to sign it with k_2, the new device key. The provisoner also includes token t so the provisionee can load the user's sigchain from the server. In the "please counter-sign" message, the provisionee returns the signed link and asks the provisioner sign it a second time with k_1, D_1's device key. Finally, the provisioner can post the new signed sigchain link l to the server, including encryption of the latest PUK for k_2 with l. Once the provisionee receives the "done" message, it can load the user's PUKs from the server, and decrypt them with k_2.

Though messages between D_1 and D_2 could use interesting local peer-to-peer protocols, we employ a simpler, more reliable strategy. The FOKS server proxies all of these messages. One device sends a message, while the other polls for the next message in the sequence. Let s^* be the session key that was input on the other device. Both devices encrypt all messages send to the server with the session key s^*, using authenticated encryption.

Some researchers [26] have suggested using a passphrase-authenticated key exchange (PAKE) rather than this simple s_1 / s_2 mechanism. The observation is that the secret phrases, which users have to type until smart-phone apps are built, are quite long and could be much shorter with PAKEs. We considered these constructions but rejected them for FOKS, since we are concerned the PAKEs can be easily DOSed. That is, the provisionee D_2 is not authenticated to the server since the user hasn't logged in on D_2 yet; this login happens naturally as a result of the provisioning process. Thus, there is nothing to stop an attacker from targeting a user and entering bad PAKE codes before the legimiate user can enter the correct code. Such an attack would not break the integrity of the protocol, but could prevent the user from ever successfully provisioning.

[2]The `foks` client running `device assist` one-shotted this secret phrase, and I am pleasantly surprised. When I first used a BBS in 1990, the SYSOP (my friend's older brother) assigned me the handle "Burger Master". I hadn't thought of this in years.

Note that several of these provisioning sessions can happen concurrently on the same the server. D_1 and D_2, with the server's assistance, must separate their messages from other currently active clients. They therefore tag each message in the exchange with the channel identifier $H(s^*)$, where H is a one-way function like SHA2. This channel identifier is unguessable for any malicious clients who do not know s^*, and will clearly be unique across all device pairs.

3.5.2 Yubikey-to-Device and Device-to-Yubikey

Most of the protocol in Section 3.5.1 can be skipped in the case of either provisioning a regular device (a computer or a phone) with a Yubikey, or vice versa. No communication needs to bounce off the server, as the device and the Yubikey can comunicate directly via the local machine. The crux of the protocol, however, remains. For a Yubikey provisioning a new device, the device makes the new link, the device signs the link, and the Yubikey countersigns it. Then the device posts the link (and encrypted PUK keys) to the server. And vice-versa for a device adding a new Yubikey.

3.6 Teams

We covered much of how teams work in Section 3.4.1, largely by analogy to users and devices. There are, however, some important differences, which we cover here in more detail.

3.6.1 Cross-Server Teams

As described in Section 3.4.1, teams are composed of parties that can span multiple federated servers. A team has a home server, which hosts its public keys, encrypted secret keys, sigchain, and Merkle Tree. An importantly, all the admins and owners — those who have the ability to change the team — must be on the same home server. However, team readers can join the team from across the Internet.

Because readers can be local or remote, important team protocols, like addition and removal, must work with more generality, as we cannot assume that the reader and the team have the same home server. Morever, we cannot assume much cooperation among independently administered servers under our thread model (see Section 2).

3.6.2 Cycle Avoidance

One problem in particular the presents itself immediately: potential cycles. Imagine a simple case, with three hosts h_1, h_2 and h_3, and three teams on those host, respectively, t_1, t_2 and t_3. If t_1 adds t_2 as a reader, t_2 adds t_3 as a reader, and t_3 adds t_1 as a reader, there is now a cycle in the team membership graph. That cycles are bad is not immediately obvious, but we must consider what happens in a rekey scenario.

Imagine at the start of the sequence, team t_1 consists of two owners — call then u and v — and no other members. Team t_2 consists of a single owner x, and team t_3 consists a single owner y. Focus on user v, who will eventually be removed. At the start v has access to t_1's reader PTK at generation 1, call it k^1. Next, x adds the readers of t_1 to t_2 as readers. As a result, v gets access via k_1 to t_2's reader PTK, call it k_2. Next, user y adds the readers of t_2 to t_3 as readers, giving v access to t_3's PTK k_3^1 transitively via k_1 and k_2. Finally, u completes the cycle, adding the readers of t_3 to t_1 as readers. Figure 1 shows this initial configuration.

Everything up until now is working as planned, but now consider what happens when u removes v from t_1. What should happen is that all 3 teams should rotate so that v loses access to their most recent reader PTKs. But in practice, this objective cannot be achieved. Playing out the scenario,

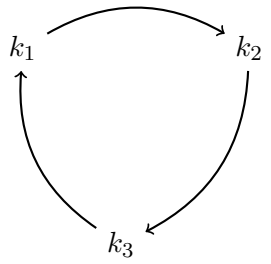


Figure 1: The initial configuration of teams t_1, t_2 and t_3. A link from k to j means that knowing k gives one access to j, i.e., that k is a reader of j.

u rotates t_1's reader PTK from k_1 to k_1'. It encrypts k_1' for k_1 so that the remaining members can still access old data. It also encrypts k_1' for t_2's most recent reader PTK, which remains k_2. See Figure 2 for what this new configuration looks like. One thing to notice immeidately is that any node on the graph is reachable from any other. That is, if user v knows k_1 (which he had access to before u removed him), then he can still decrypt any other key on the graph, including k_1', which he reach via $k_1 \to k_2 \to k_3 \to k_1'$. So in a deep sense, the rotation has failed.

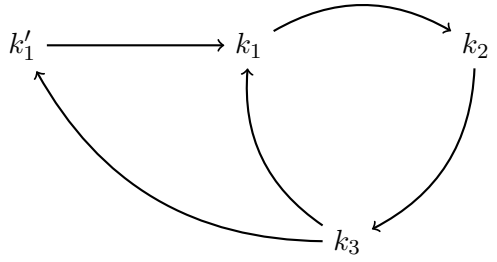


Figure 2: After u removes v from t_1 and rotates t_1's reader PTK to k_1'.

To continue a few more steps, assume t_2 rotates (see Figure 3), and then t_3 rotates (see Figure 4). for the new configuration. The problem remains. Any node in the graph is reachable from any other, and therefore, v can still access the new PTKs for all teams. We can generalize (without proof) that there is no "fixed point" during this decentralized key rotation process, and that no amount of rotation will lock v out of the teams. A different system in which t_1, t_2 and t_3 rotated simultaneously might avoid this problem, but we see no robust way for them to do so if those teams reside on independent servers.

The simplest path forward is to disallow cycles in the global team graph, which seems like a natural constraint. However, enforcing lack of cycles globally is challenging, and seems to require some concept of global locks across the internet. To see why, consider four teams, t_1, t_2, t_3 and t_4, on four different servers. First, t_1 adds t_2 as a reader, and t_3 adds t_4 as a reader. So far so good. If t_2 adds t_3 as a reader, or t_4 adds t_1 as a reader, we still are cycle-free. But if the two additions happen roughly simultaneously, a cycle is formed, and there is no easy way for any of the hosts involves to detect it.

The most blunt and naive solution is for each team to get an "index", which which is simply a natural number. This index cannot change once assigned, and t_1 can only add t_2 iff t_2's index is less than t_1's. This simple rule prevents cycles, but is inflexible and doesn't allow much play in the team graph as the system evolves. FOKS opts for a slightly more flexible solution of a similar flavor. Each team gets a "range" of possible index values, representing bounds on where the team's

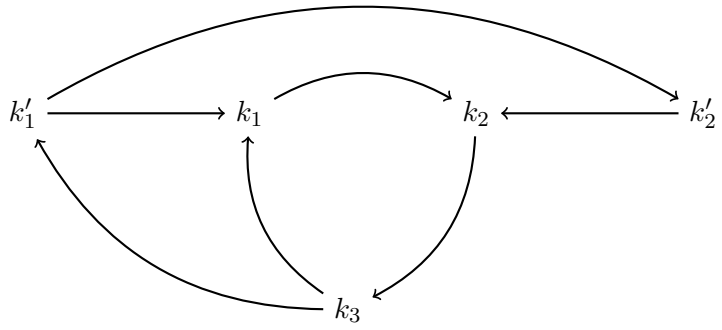


Figure 3: *The Widening Gyre*: After u removes v, t_1 rotates, then t_2 rotates.

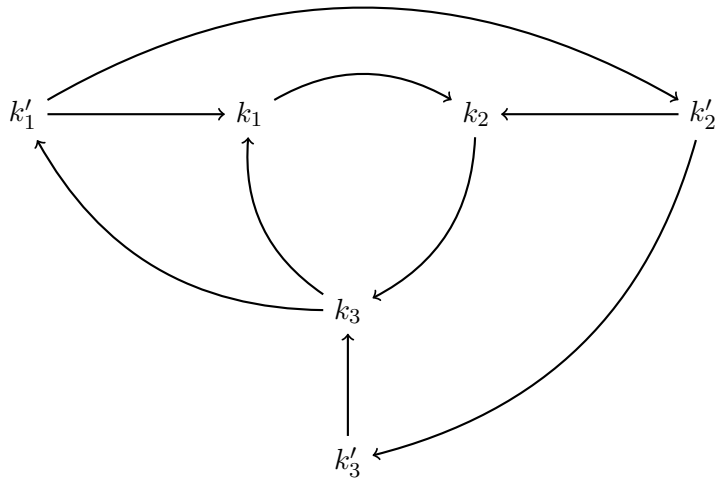


Figure 4: *Things Fall Apart*: After u removes v, t_1 rotates, then t_2 rotates, and finally t_3 rotates.

index will eventually settle. This range in practice is an interval on the positive rational numbers, of the form $[a, b)$, where $a, b \in \mathbb{Q}^+$. b can take on the special value ∞. A team can always restrict its range but can never expand it. The rule for addition then becomes that t_1 can add t_2 iff the lower bound of t_1's range is greater than the upper bound of t_2's range. The rule guarantees that whereever t_1 and t_2's indices eventually settle, t_1's index is greater than t_2's.

All teams get the initial default range of $[1, \infty)$. When a team administrator seeks to add one team to another, she might need to change one or both of the team's ranges. For instance, take teams t_1 and t_2, both at the default range $[1, \infty)$. To add t_1 to t_2 as a reader, the administrator can reduce t_1's range to $[1, 128)$ and team t_2's range to $[128, \infty)$. Now the property above is upheld, since $[1, 128) < [128, \infty)$. Note that it still remains possible to add t_2 to another team or to add another team to t_1 by making appropriate range reductions.

3.6.3 Invitation Sequence

By default, two parties p and q cannot view each other's sigchains, even if on the same server. But p must be able to read q's sigchain in order to compute its current PUKs or PTKs if adding q to a team. So a protocol must be invented to allow p and q to exchange information before the actual join process occurs. There are three general steps: (1) p creates a multi-use invitation token,

which p can share with one or more parties; this invitation exposes the team's name, host and ID to all invitees; (2) q "accepts" this invitation, thereby granting p access to its sigchain; and (3) p "admits" q into the team.

Invite Tokens A team's administrator or owner can create a multi-use invitation token for a team t. First, the administrator creates a team certificate with the fields:

- The team's ID
- The team's Host ID
- The team's current admin PTK
- The current time
- The name of the team
- The team's index range

The adminstrator then signs this certificate payload with both the current PTK, and also the original PTK, whose hash is the team's ID. If the PTK hasn't rotated, then of course only one signature suffices. In totality, the above data and the signatures are quite large, so we introduce one layer of indirection to make them shorter. The administrator posts the signed certificate it's home server, and then formulates an invitattation as: (1) the hash of the above data; and (2) the host's ID. The resulting token can look something like this:

```
YcarI5JTMAVDHG47cb5l1Pp87COqmK6nzf6h12hchVLMMjlplmjC5dky
wwnqlOhuakWkAjzO2zJ6BtxrnOxdZV8NyLby2r16MhCvC
```

Which is small enough to exchange via group text chat.

Accepting Invitations Once a party p receives the invitation to team t (p can be a user or a user acting on behalf of a team), it breaks the token into its two parts, the host ID and the certificate hash. It maps the host ID to a DNS name (see Section 3.7), and then asks the server for the preimage of the hash from the invitation. It checks that the preimage hashes correctly, and then opens the certificate. From here, it checks the signatures described just above. Note that at this point, p is not a member of the team, so cannot read the team's sigchain.

There is therefore an oppoortunity for the team certificate to be partially forged. p can check that that first PTK corresponds to the team ID, so therefore knows that whoever generated this certificate was at one time a team admin. But that administrator might have been removed from the team. Also, the name of the team cannot be checked against the Merkle Tree, so the team's name might be forged. Eventually, once p is admitted into the team, it can check that these fields are correct, and leave the team if not. By accepting the invitation, be it malicious or otherwise, p is primarily giving access to reading its sighcain. It must decide whether or not this is a good idea on the basis of who sent the team invitation in the first place. This problem can recursively be solved in FOKS, by a different team, or by trusted channel on a different platform, like a secure team chat.

If p decides to accept this invitation, there are four subcases to consider:

1. p is a user, and p and t are on the same server. Here, the user p instructs her home server to allow the owners and administrators of t to allow access to her sigchain. The server makes a quick note in the database to honor future accesses. Then p writes a link to its Team Membership Chain (see Section 3.4.7) saying it accepted an invitation to team t.

2. p is a user, and p and t are on different servers. User p contacts its home server and asks that it assue a new "remote view permission token" for the administratos and owners of t. The server sends back this token. p encrypts this token with the PTK it received in the team's certifcate, and then posts this encryption to t's home server. Note that p isn't trusting the server's administrators here, so does not send this token in plaintext. As with the above case, p writes a link to its Team Membership Chain saying it accepted an invitation to t. It also informs t's server that it has accepted the invitation.

3. p is a team, and p and t are on the same server. The actor here is an an administrator or owner of team p. He firsts does a cycle check, checking that the index range of p is less than that of t. The server would reject the addition of p otherwise. The admin/owner now operates analogously to Case 1. First, he instructs the server to allow the admins of t to read p's sigchain. Then, he posts a link to p's Team Membership Chain saying that it has accepted an invitation to t.

4. p is a team, and p and t are on different servers. This case is a hybrid of Cases 2 and 3. As in Case 3, the actor first performs a cycle check. As in Case 2, the actor makes a new review view token for p and posts it to t's home server. Then it writes a link to p's Team Membership Chain as above.

Admitting into Teams For a given team t, the owners and administrators see an inbox of pending accepted invitations. For each of these, the administratos makes a yes/no decision as to whether the team can be admitted into the team, and also what it's role should be in the new team. Recall some restrictions on these roles: (1) remote parties can only be readers; and (2) administrators cannot add new members to teams as owners. In any of the four subcases above, the administrator gets the necessary access to play the accepted party's sigchain; as such, he can put their latest PUK or PTK into the sigchain, and can encrypt t's latest PTK for that PUK or PTK.

Once the party is admitted into the team, it can sign a statement with its PTK or PUK to play the team's sigchain. When it does that for the first time, it updates its Team Memership Chain to show that the accepted invite transitioned to an official admittance.

3.6.4 Team Key Rotations

PTKs must be rotated in two important cases: (1) when a party is removed from a team; and (2) when a member rotates their PTK or PUK. The first case is straightforward, and happens when the administrator performs the removal. In such a case, the adminstrator (or owner) posts a new link to the team's sigchain with the role of `none` for the affected party. The link also contains the new PTKs for the team. The administator also includes new encryption of these PTKs for the remaining members of the team.

The trickier case is the second, since the rotations happen asynchronously. Say that user u is a member of team t_1 which is in turn a member of team t_2. Now say user u revokes a device, mayb because it was lost or stolen. Upon revocation, his PUKs will rotate. Eventually the PTKs for t_1 must rotate, which will eventually trigger a rotation for t_2. But there are several reasons these rotates might not be immediate. Perhaps all the relevant adminstrators (who are authorized to perform the rotations) are offline. Or maybe t_1 or t_2 is hosted on a different server which is currently offline for maintenance. Since it is clear that some cascading team key rotations must be done asynchronously, we simplify the FOKS systems by having *all* team rotations happen asynchronously along the same code paths.

Every FOKS clients polls all reachable teams in a background loop. It starts with teams in the user's team membership chain, then recursively loads all teams and their associated membership chains, in a breadth-first manner. For each team encountered where the user can act as an administrator, either directly or via a team, it checks that all PTKs and PUKs in the team chain are up-to-date. If it finds one that is behind for any member, it will rotate necessary PTKs so they are encrypted for the member's latest keys. Rekeying starts with teams that have the lowest index ranges, and moves upwards, so that cascaing rekeys happen in the right order.

If there are multiple administrators or owners for teams, there is no explicit coordination. Rather, they in effect race to rekey the same teams. However, the FOKS client adds randomness into the traversal order where possible, and randomness into the timing, so chances of collisions are low. If they do happen, the loser of the race will fail to update the team chain (as enforced by the server), will reload the team, and then see it no longer needs to rekey.

Note the importance of the Team Membership Chains in this protocol. The users should not trust the servers to faithfully recount to them which teams they are members of; if they did, dishonest servers could silently supress team rotation through omission. Instead, the Merkle Tree and sigchain append-only properties give users guarantees that servers aren't tampering 1Gwith their view of team memberships.

Also note that to perform this ongoing key rotation process, all team administrators need ongoing access to the sigchain of team's members. Thus, the access tokens and permissions exchanged as part of the team invitation process (see Section 3.6.3) persist in the team as long as mebmers remain.

3.6.5 Removal Keys

When users are removed from teams, they should no longer be able to load the team's sigchain. But what's to stop a server from falselyclaiming the user was removed, thereby preventing the user from rotating the team as described in Section 3.6.4? We here discuss "Team Removal Keys", which allow a team administrator to prove to a removed team member that they were legitimately removed, rather than falsely removed as a malicious server might claim.

Recall from Section 3.4.1 that when administrator add members to teams, they include for each member a commitment to a "team removal key". Here is where this mechanism comes into play. The team removal key is a 32-byte random value, generated anew for each member added to the team. When adding member p to the team, the administrator encrypts this removal key for the other administrators for the team, and also for p's PTK (or PUK, depending if p is a user or a team). The administrator puts both ciphertexts to the server, and writes a commitment to this key into the sigchain link. When p loads the team and plays the sigchain, it writes down this commitment to a local database.

Later, when an administator removes p from the team, p will fail to load new chainlinks from the team, though it should still keep existing chainlinks in its cache. It can now demand "proof" from the server that its removal was legitimate. If indeed it was, the server will send down the ciphertext computed at addition time, and p can decrypt it. It can check this key against the commitment in the team chain that it has written to a local database. It can further check that the administrator MAC'ed a statement with this key, stating that p was removed from the team and the time of the removal. If the decryption of the key fails, or if the key does not match the commitment in the team chain, or if the MAC of the removal statement fails, the software can post a warning to the user's client, saying that it suspects some form of server tampering.

Members p's team removal key is not rotated when p rotates their PTK or PUK; nor is it rotated when the admins or owners of the team change. Lack of rotation opens the window for an attack;

a malicious server collaborating with an attacker who gains access to a stolen device can recover the team removal key and make a false statement that p has been removed from the team. Though it is possible to replace and rotate team removal keys when member PTKs or PUKs change, such rotations create new challenges. If members fall behind the latest team removal keys and then are removed, they will have no commitment to compare the new removal key against, preventing the protocol from workking. We believe the correct trade-off is to keep the original team removal key despite other rotations.

3.7 Beacon Server

3.8 Privacy

Previous systems like Keybase [1] espoused a notion of transparency regarding a user's identity and devices. Any user u is free to load the sigchain of any other user v on the system, and can learn how many devices v has, when those devices were added to v's sigchain, and the names of these devices. Howver, team membership was private, so u could only load team t's sigchain, or learn team t's name, if u is on team t. Zoom's system [13] is derived from Keybase's, by because it caters to enterprise settings, opts for more privacy, obscuring most deatils about user's identities.

As described above, FOKS takes, by default, the more privacy-respecting approach, similar to that of Zoom's system. User u can load v's sigchain only if u allows it. The team invitation flow 3.6.3 is an example of how v shares a view of his sigchain only as required. However, server administrators can configure their server in FOKS to have different policies. A server, for instance, can allow all logged-in users to see each other without need for explicit permissions. A complementary policy might be that v can always directly add u to a team, and if u is unhappy with this situation, he can leave. This configuration might work well for a company-specific server.

Another important privacy feature is how device names are handled. As described in Section 3.4.1, users do not write device names directly into sigchain links. Instead, when provisioning a device name n, the user picks a random 32-byte value r, and publishes $Hmac(n, r)$ into the sigchain. On playback, the server returns r and n, so the user can check it's the same value as intended. If the user later regrets the choice of n, the server can throw n and r away while still allowing playback of the sigchain.

4 Cryptographic Design

Here we describe the important cryptographic decisions at play in the FOKS system. For the most part, our bias is toward simplicity and boring, failure-proof cryptography. For instance, as decribed in Section 3.4.3, we use a vanilla collision-resistant hash function to hide tree locations, rather than the slightly more exotic pseudo-random function approach. The emphasis throughout is on tried-and-true cryptography that will prove as robust as possible to misuse through software bugs.

4.1 The Snowpack Domain-Specific Language

One of the biggest risks in a system like FOKS is signature malleability due to issues like permitting non-canonical encodings [9, 28], lack of clear domain separation [26, 5], or undefined behavior due to parsing and encoding bugs [12].

To address these threats, and at the same time to provide an convenient language for defining RPC protocols, we introduce the Snowpack Language [19], which is influenced by protobufs [16],

Framed Msgpack-RPC as used in Keybase [1] and Cap'n Proto [27]. A further prooperty we insist upon is support for backwards and forwards compatibility. Since FOKS is a federated system, we have no expectations that upgrades will happen in lockstep. The protocol itself must behave well an any number of partially-upgraded configurations.

4.1.1 Structures

By way of example, see Figure 5 for the definition of a sigchain link both for teams and users in the Snowpack language. Any constant of the form `@1` or `0x8fbf37f586b0bc6e` is meant to be *immutable*. Once written down in the protocol, it should never change. For instance, look at the first field in the structure: `chainer @0 : HidingChainer;`. The `@0` indicates that this field will take the 0th slot in the encoded version of the structure. Future editors of this file must never introduce a new field at slot 0 with a different type, as that would cause old clients to fail in decoding. All new fields should be added at the end of the structure. Old clients will ignore fields from the future that they do not know how to decode. Similarly, it is allowable to delete a field. Software with older version of the protocol will get 0 values for the deleted fields. In the Go language, this means `0` for integers, empty strings for strings, empty slices for lists, and nil pointers for optional fields. Of course new clients must consider the impact on older clients to leave 0-ed fields, but the protocol layer itself does not introduce a failure here.

```
  struct GroupChange @0x8fbf37f586b0bc6e {
    chainer @0 : HidingChainer;
    entity @1 : FQEntity;
    signer @2 : GroupChangeSigner;
    changes @3 : List(MemberRole);
    sharedKeys @5 : List(SharedKey);
    metadata @6 : List(ChangeMetadata);
}
```

Figure 5: A sigchain link in the Snowpack language.

Structures like `GroupChange` from Figure 5 are encoded as JSON-style arrays on the wire, with fields written to slots as directed by their `@i`-style positions. Elided fields are written down as `null` values. Before going out to the wire, the JSON-style arrays are encoded with the Msgpack [14] encoding format. Where two possible encodings are possible (e.g., the number `0x2` can be encoded as `0x2` or `0xcd 0x00 0x02`), the shorter encoding is mandated. Note that field names (like `chainer` above) are not sent over the wire, but are available on either end as human-readable references to fields. Thus, it is permitted to rename a field as long as its type doesn't change. We note that serializing using JSON-style dictionaries seems error-prone, since keys can repeat or be ordered in different ways. Snowpack's slot-oriented encoding aims to avoid these styles of ambiguities and to minimize encoding sizes. At the same time, development tools can decode encoded messages without reference to protocol specification files.

4.1.2 Domain Separation

In the definition of the `GroupChange` structure from Figure 5, note the 64-bit integer `0x8fbf37f586b0bc6e`. This is a randomly-generated number that serves as a *domain separator*. We refer to it below as unique type identifier (UTID). Though domain specifiers are optional in the Snowpack language,

when a structure provides it, the snowpack compiler fills in five possible cryptographic operations for the structure:

- `PrefixedHash`(*obj*): The object's UTID is big-endian encoded, then prepended to the object's binary Msgpack encoding. The hash of the combined message is returned.
- `Hmac`(*obj*, *key*): As above, a mesasge is formed out of the object's UTID concatenated with the encoding of the object itself. The combined message is the message input to the MAC function, and the key is passed through as the key.
- `SealIntoSecretBox`(*obj*, *nonce*, *key*): The object's UTID is encoded and conctacted with the supplied *nonce*. The new value is then used as the nonce passed into the encryption algorithm, along with the encoding of *obj* and the supplied *key*.
- `Sign`(*obj*, *key*): The object's UTID is prepended to an encoding of *obj*; the combined message is then used as the message input, passed along to the signature algorithm along with the supplied *key*.

Public key encryption calls into `SealIntoSecretBox` with a random session key, so therefore uses the same domain separation mechanism. Inverse operations for `Hmac`, `SealIntoSecretBox` and `Sign` are also provided; they similarly supply UTIDs where necessary to ensure that verification and decryption succeed.

The programmer must supply their own tooling to generate these UTIDs. Simple CLI tools or editor plugins suffice. However, FOKS provides two mechanisms to guararntee they remain unique across the project. At compile-time, a simple tool examines all input files to guarantee that no UTID contant appears twice. And at runtime, the compiler provides a list of all UTID constants compiled from the protocol input files. The program fails an assertion if it sees any repeats.

4.1.3 Variants

We have seen Snowpack structures in Section 4.1.1. Another important data type is the *variant*, also known as a descriminated union. Figure 6 shows an example from FOKS. The enumerated type `LinkType` has two possible values: `GroupChange` for main chains, and `Generic` for subchains like team membership chains and user settings chains. Based on the switch value, the enumerated type takes the form of a `GroupChange` or `GenericLink` object. Variants have many of the same restrictions as structures: fields specified with '@i'-style slots should never be repurposed, though they can be dropped; also, new type possibilites can be added without breaking the protocol.

```
variant LinkInner switch (t : LinkType) @0xacf9066572a9e7de {
  case GroupChange @0 : GroupChange;
  case Generic @1 : GenericLink;
}
```

Figure 6: A variant in the Snowpack language.

4.2 Cryptographic Primitives

We have tried as much as possible to make boring, unopinionated cryptographic decisions.

4.2.1 Hashing, MAC'ing and Symmetric Encryption

Throughout the system, hashing uses SHA512 truncated to 256 bits [2]. Message authentication codes are with HMAC [18] over SHA512/256. HMAC is used for MAC'ing but also for commitments, and in general, any context where a pair of items are hashed together (one being the "key" and the other being the "data"). Authenticated symmetric encryption uses Salsa20/Poly1305 as implemented by the NaCl [8] library. Sals20 has a 24-byte nonce field, which is often handy when combining with our domain separation strategy with other authenticated data. We throughout refer to encrypting with Salsa20 as `secretBox`'ing, as per the library's conventions.

4.2.2 Signatures and Post-Quantum Encryption

For signing, we use EdDSA with the Ed25519 curve [7]. Public-key encryption is a hybrid of Diffie-Hellman over Curve25519 [6] and MLKEM [23] using a construction similar to X-Wing [3], but with a different binary encoding format and constants. Thus, in practice, all device keys, PUKs, PTKs, and so are are not a single keypair, but rather a triple: an EdDSA keypair, a Curve25519 keypair, and an MLKEM keypair. Wherever public keys are introduced, an EdDSA signature over the Curve25519 and MLKEM public keys is produced to bind them together.

The exact derivation of the hybrid encryption secret key is specified in Snowpack, using the structure shon in Figure 7. Hasn inputs are: the domain separator (UTID); a version number; the shared key exchanged via KEM; the shared Diffie-Hellman key; the receiver's public keys; and the sender's public DH key. Though everywhere in the project we use SHA512/256, here we use SHA3 to follow the spirit of the X-wing specification.

```
struct HybridSecretKeySHA3Payload @0x8a9e327647262289 {
    version @0 : BoxHybridVersion;
    pqKemKey @1 : KemSharedKey;
    dhSharedKey @2 : DHSharedKey;
    rcvr @3 : HEPK; // Hybrid Encryption Public Key = DH + KEM Public keys
    sndr @4 : DHPublicKey;
}
```

Figure 7: Hybrid encryption secret key derivation in the Snowpack language.

4.2.3 Key Derivation

As described just above, each public key in FOKS actually consists of three keypairs. However, a single 32-byte secret seed suffices to generate all three, which simplifies secret key management and backup keys. The key derivation system again uses the Snowpack specification system and simple HMAC-based key derivation. Figure 8 shows the Snowpack structures and variants used. The derived key is the HMAC of the `KeyDerivation` object with the secret 32-byte seed as the key.

For example, to make a new PTK, the team adminstrator picks a random 32-byte seed value. When ever the PTK is used in a symmetric context (like for encrypting older PTKs), the key derivation uses `KeyDerivationType = SecretBoxKey` as an HMAC input. Similarly for using the PTK as a signing key. All derived keys are also 32-bytes with the exception of the ML-KEM key,

```
enum KeyDerivationType {
    // Core types
    Signing @0;
    DH @1;
    SecretBoxKey @2;
    MLKEM @4;
    AppKey @5; // Used for different higher-level applications, like KV Store
}

enum AppKeyDerivationType {
    Enum @0;
    String @1;
}

enum AppKeyEnum {
    KVStore @0;
}

variant KeyDerivation switch (t: KeyDerivationType) @0xd35cdcc95caef674 {
    case MLKEM @4: Uint; // need 2 32-byte values to get a 64-byte seed
    default: void;
}
```

Figure 8: Structures and variants used in key derivation.

which needs 64-bytes. The two halfs of this derived key are generated with the same mechanism, but using `MLKEM=0` and `MLKEM=1` in the `KeyDervitation` object as the HMAC input.

4.2.4 Yubikeys

FOKS supports hardware keys like YubiKey that support the Personal Identity Verification [11] (PIV) standard. This standard allows the device to perform public key cryptopgrahic operations, like ECDSA and Diffie-Hellman over the p256 elliptic curve [24]. Though we have chosen the Ed25519 and Curve25519 curves for use everywhere, we now need to accommodate another curve to fit the PIV standard. Too much "agility" has proven problematic for other systems [21], and we would like to avoid it as much as possible with FOKS, but we make an exception here for a popular hardware standard.

The bigger issue with YubiKeys is: what do to about post-quantum security? To date, we have not seen a wide release of an algorithm like ML-KEM to hardware devices, and even if so, we'd like to support older, widely-deployed hardware.

Since there are no perfect solutions here, we have designed a PQ-secure system around existing PIVs as follows:

1. Extract a "secret" from the PIV module: pick an unused "retired key management" slot (0x82-0x95), and compute g^{x^2} via the ECDH algorithm. Use this value as the seed to create a new ML-KEM keypair. Compute ML-KEM on user's computer after extracting the secret and deriving the keys.

2. Select a different retired key management slot to use for classical ECDH over curve p256. Compute ECDH as usually using the YubiKey's hardware.

3. Combine the secret keys from the previous two steps using the X-wing-style derivation scheme from Section 4.2.3.

An important property of this system is that all of the relevant key material lives on the YubiKey; none lives on the user's computer. The YubiKey is all the user needs to recover important secrets, even if the computer is lost or suffers data loss. Further, this system is no less secure than an encryption scheme without PQ-security, as the classical ECDH computation still happens on the YubiKey as normal. That is, we are not forcing the user to choose between PQ and hardware security. However, this scheme has an important shortcoming. If the user later reuses the key management slot in Step 1 for a different purpose, and exports the public key g^x from the device, the scheme is no longer PQ-secure. A quantum computer could recover x from g^x and then derive the ML-KEM secret key. This shortcoming makes us long for better hardware support for ML-KEM. However, a mitigating factor here is that PIV is an infrequently-used standard (and for instance is way less popular than FIDO2). There are few competing applications using these features and key slots.

4.2.5 High-Entropy Secret Phrase

For backup device keys (which FOKS users can write on pieces of paper), and exchanging provisioning secrets betwewen two computers, FOKS uses a simple encoding scheme called the "high-entropy secret phrase". The pattern is a series of random words, each separated by a random number. All words are chose from the BIP39 wordlist [25]. The exact parameters depend on the application, and are shown in Table 1.

Application	# of Words	# of Numbers	Number Range	Entropy
Provisioning	7	6	$[0, 2^8 - 1]$	$7 \cdot 11 + 6 \cdot 8 = 125$
Backup Device Key	8	7	$[0, 2^{13} - 1]$	$8 \cdot 11 + 7 \cdot 13 = 179$

Table 1: Parameters for high-entropy secret phrases.

4.3 Secret Key Management

Secret keys derives from 32-byte seeds, which never leave the device they are created on (with the possible exception of backup keys, which are written down on paper). We discuss here how the FOKS client stores these secret seeds persistently.

4.3.1 Secure Enclaves

Where possible, FOKS uses OS-specific secure enclaves. This is the simple case. FOKS stores the actual 32-byte seeds in a FOKS-specific keyring file in the user's home directory. For each seed, FOKS picks a random 32-byte key to encrypt with, and, if possible, stores that 32-byte key in the user's OS keyring.

4.3.2 Passphrase-based Management

Though it's not encouragd, FOKS does offer a passphrased-based protection mechanism for secret key seeds. As above, each secret seed gets its own secret-key wrapping material wrapping key

(SKMWK). But instead of storing the SKMWKs in the OS keystore, they are encrypted with a key derived from the user's passphrase. We have important design considerations for this system that make it quite complex:

1. If the user has two computers, A and B, and the user changes his passphrase on A, when B comes online with the old passphrase, it has to decrypt with the new passphrase.

2. Keys encryped for old passphrases need to eventually be migrated to the new passphrase, so that if an attacker gets the old passphrase and all server data, they still can't decrypt the key. Of course this is only possible if that computer B comes back online after the change, but assuming that the property should hold.

3. Passphrae recovery: to change the passphrase and recover keys, it is sufficient to know the latest PUK. Thus, having a backup paper key or a backup YubiKey should suffice to "recover" a passphrase and to allow the user to change it without knowing the old passphrase.

4. As with passphrases, if the PUK is updated, all machines with passphrase-encrypted keys should eventually rotate (when they come online) so that they cannot be decrypted with an old PUK

We describe the process through a small example: two rotations, one due to a PUK rotation, and one due to a passphrase change. The net result is three different configurations (the original, and the two following rotations). The general idea is that we have a new "session" key at every update, which is symmetrically encrypts the SKMWKs. The session key gets encrypted twice: once for a key derived from the current passphrase, and one for the user's PUK. This allows recovery of the SKMWKs with either the passphrase or the PUK:

Key	Epoch 0	Epoch 1	Epoch 2
SKMWK	r_0	r_1	r_2
Session Key	s_0	s_1	s_2
Ephemeral DH Key	t_0	t_1	t_2
Passphrase	p_0	p_0	p_1
PUK	u_0	u_1	u_1

At Epoch 0, we have the initial configuration, which consists of the following three encryptions:

$$e_0 = \mathsf{secretBox}(r_0, s_0)$$
$$f_0 = \mathsf{dhBox}(s_0, \mathsf{publicKey}(p_0), \mathsf{secretKey}(t_0)), \mathsf{publicKey}(t_0)$$
$$g_0 = \mathsf{secretBox}([s_0, \mathsf{publicKey}(p_0)], u_0)$$

e_0 is the encryption of the SKMWK r_0 for the session key s_0. f_0 is the encryption of the session key for the user's current passphrase, p_0. To derive $\mathsf{secretKey}(p_0)$, we employ a simple stretching algorithm and interpret the result as a Curve25519 secret key; then we derive $\mathsf{publicKey}(p_0)$ from the secret key as usual. Finally, g_0 is the encryption of the session key s_0 for the user's current PUK. We include $\mathsf{publicKey}(p_0)$ in the plaintext for reasons we will see shortly. After the client creates encryptions e_0, f_0, and g_0, it sends them up to the server, for later user on this and other devices.

At Epoch 1, we have passphrase stationary at p_0 but the user's PUK is rotated from u_0 to u_1. We will make a SKMWK r_1 and a new session key s_1. s_1 will be encrypted for the user's new PUK

and for the user's existing passphrase. This user might have not have input their passphrase on this machine, and it would annoy the user to prompt for it for a seemingly unrelated operation. For this reason, we included $\mathsf{publicKey}(p_0)$ in the plaintext of g_0, which the user can decrypt with access to the old PUK u_0. The new encryptions are then:

$$
\begin{aligned}
e_1 &= \mathsf{secretBox}([r_0, r_1], s_1) \\
f_1 &= \mathsf{dhBox}(s_1, \mathsf{publicKey}(p_0), \mathsf{secretKey}(t_1)), \mathsf{publicKey}(t_1) \\
g_1 &= \mathsf{secretBox}([s_1, \mathsf{publicKey}(p_0)], u_1)
\end{aligned}
$$

In the next epoch, the user changes their passphrase from p_0 to p_1, and the PUK remains at u_1. The new encryptions are:

$$
\begin{aligned}
e_2 &= \mathsf{secretBox}([r_0, r_1, r_2], s_2) \\
f_2 &= \mathsf{dhBox}(s_2, \mathsf{publicKey}(p_1), \mathsf{secretKey}(t_2)), \mathsf{publicKey}(t_2) \\
g_2 &= \mathsf{secretBox}([s_2, \mathsf{publicKey}(p_1)], u_1)
\end{aligned}
$$

And so on. It might seem at first that there is an unnecssary layer of indirection with using SKMWKs r_i's and session keys s_i's. To see why it's required, consider the case of a device active around passphrase generation p_0, but then turned off for a long time, only to come back online at a much later passphrase generation, say p_9. At this point, the user has forgotten passphrae p_0 and is only expected to know p_9. When they try to unlock secret key materials on this hitherto-mothballed device, they will enter passphrase p_9. The scheme is robust to this scenario. The device pulls f_9 down from the server and derives $\mathsf{secretKey}(p_9)$ from p_9. It can then decrypt f_9 and recover the session key s_9. Then, it pulls e_9 down from the server, and uses it to recover all historical r_i's, including r_0. With r_0, it can decrypt the device's secret key material, encrypted ages ago. After so doing, it discards the encryption with r_0 and then upgrades to an encryption with r_9. This way, going forward, if an attacker steals the device and learns the old passphrase p_0, she cannot recover the secret key material. Decrypting the secret key material requires r_9, which only can be decrypted with the latest passphrase (p_9) or the latest PUK.

5 Applications

The goal of the FOKS system is primarily: for a user or a group of users to agree upon a sequence of cryptographic keys so they can perform authenticated, end-to-end encryption of arbitrary data. As a secondary goal, the system exposes a set of authorized signing keys to sign on behalf of the group, so that changes can be properly attributed. From here, we can build any number of applications.

For instance, one can imagine an MLS system for group messaging [4] where the chat keys are the cryptographic combination (via something like HMAC or SHA3) of: (1) the root of the MLS ratchet tree; and (2) the most current PTKs available for the FOKS group. In this way, one can simultaneously achieve Signal-style forward secrecy and FOKS-style team and device management.

For our first FOKS prototypes, we have focused instead of two important applications: first, at the foundational level, a simple key-value store. Members of the team can put and get key-value pairs to the FOKS server. Keys and values are encrypted with authenticated encryption agains the team's PTKs. A second application, built atop the first, is an end-to-end encrypted Git server, that is compatiable with legacy Git clients. We describe them both below.

5.1 The FOKS Key-Value Store

The FOKS Key-value (KV) store is an end-to-end encrypted key-value store, with a hierchical namespace, local to each party on the system. One can store a value to any key of the form '/a/b/c'; the value can be a few bytes long, or many gigabytes. The system provides simple *put* and *get* operations, but also operations on the namespace, like listing, moving, and deletion of directories. That is, one can perform an operation like `mv /a/b /foo` in roughly O(1) time, without individually mofidying each of the entries stored under `/a/b`. Symlinks are also allowed. Though the system has some important Unix-style file system behaviors, it does not implement full POSIX [17] semantics.

When a user puts a key-value pair into the store, it does so on behalf of a party, whether themselves personally, or a team. It encrypts the key and value with the latest PUK or PTK for the acting party. Of course PTKs and PUKs can rotate after the put happens, so when getting values out of the store, the user might perform a decryption with an older PTK or PUK, depending on the circumstances. We discuss rotation in more detail below as we describe the various operations of the system.

5.1.1 Making a New Directory

The steps for making a new directory for party p operating at role r are as follows:

1. Pick a random 32-byte directory key seed s.
2. Pick a random 16-byte directory ID i.
3. Derive k for application `KVStore` from p's PTK (or PUK) for role r
4. Encrypt s with key k and nonce i.
5. Post the ciphertext and the the directory ID i to the server.

This process creates an new empty directory, floating more or less in space. To link this new directory, we first need to walk to the appropriate place in the key tree, and then modify the parent "directory entry" or *dirent* to point to this new directory. See Section 5.1.2 for more details on the walking process, but for now, assume we have found the appropriate parent directory d. The client gets the directory key seeds for the parent directory d either from the server or from the client's local cache, The client then derivew to keys from this key: a 32-byte HMAC key, and a 32-byte box key. The client can now form a *dirent* with the fields: (1) the new directory ID i; (2) the parent dirent d; (3) the MACs of of the name of directory (the last component of the path), using the MAC key derived just above; (4) the encryption of this name, using the box key derived just above; (5) the version number (which starts at 1); (6) the role required to overwite this entry; and (7) a "binding MAC" of the above fields, using the HMAC key derived for parent directory d. The client posts this dirent up the server, and now the new directory is linked into place. Note, the client can race another client here, in which case there will be conflict over the triple composed of d, the name MAC, and the version number. The client that loses the race should download the winning dirent and potentially try again.

Note that the directory name is MAC'ed and encrypted (using authenticated-encryption) separately. The fields serve two different purposes: the former allows for lookups, where a client knows a path and want to discover which directory (or later, file) it points to; the latter allows for listing, where a client wants to know what is in a directory.

5.1.2 Walking the Namespace

Most operations start with a "walk" of the namespace, from the root down to the desired node. For a path like `/a/b/c` there are of course three directories along the way, and three corresponding dirents. Each party has a designated root directory ID, initialized by the first user of the KV store for this party. The client can fetch this directory with a special RPC, which returns the directory ID and its boxed directory key seeds. To walk down to `/a`, the client MAC's the name `a` with MAC keys derived from these seeds, and then queries the server for the dirent in `/` with the computer MAC, at the greatest version. This dirent, if found, contains a "'binding MAC"', which cryptographically binds the dirents fields together, as MACed by the directory's MAC key. The client verifies this MAC, and if it passes, then the next step in the path is the "value" field of the dirent, which contains the directory ID of `/a`. This process continues until the leaf is reached.

To reduce latency, clients make heavy use of local caching. As they walk, they write down which dirents they passed through and which versinos of those dirents that they saw. At the end of the process, the send up the whole path to the server, asking if any dirent was stale. If so, the clients repeats parts of the walk to get fresh data.

Note there is a special "value" field for "tombstones," which signify that the file at the path was deleted. That value can later be reinsted if a subsequent version of the dirent replaces the tombstone with a value that points to a directory or file.

A dishonest server can withhold fresh dirent versions, which might mask file updates, deletions or creations. Future improvements to this design might include a transparency tree akin to the existing Merkle Trees to force the server to be honest. The throughput and performance of this tree is a challenge that we so far have not tackled.

5.1.3 Creating Small Files

Creating a small file (one less than 2KB) works much like creating a directory. The client:

1. Creates a new random 16-byte file ID.
2. The plaintext is padded to a power of two no less than 32, to hide the exact size of the data.
3. Encrypts the file data with: the KVStore key derived from the current PTK (or PUK) at the given role; and with the file ID as the nonce.
4. Puts the ciphertext to the server
5. Walks the file path down to the correct dirent
6. And writes the dirent pointing to the new file ID.

Small files are immutable. To make an edit to a small file, a client uploads a new small file and replaces the dirent to point to the new file ID.

5.1.4 Creating Large Files

Files bigger than 2KB get a different treatment: each gets its own 32-byte encryption key, and they are chunked into 4MB chunks. When the put commences, the client creates this random 32-byte file key, and encrypts it for the party's latest PTK (or PUK). Each chunk gets encrypted with this key, and a nonce constructed from: (1) the file ID; (2) the chunk's offset; (3) an "is-final" flag; and (4) the unique type ID for chunk nonces. These fields cannot all fit into Salsa20's 24-byte

nonce field, so they are hashed and truncated to 24 bytes. This nonce selection here prevents an evil server from reordering chunks, lying about the end-of-the-file, or mixing-and-matching chunks from different files.

5.1.5 Key Rotations

Given the KV stores persistent data, and new clients and members might need to access old data, there is only so much we can do to prevent data theft if a client device is compromised. Consider this example: Alice is a member of team "Acme" and writes a file `/foo`. Call her device key d, her PUK u_0 and the PTK t_0. The server has access to the sequence of encryptions, starting from the d, through u_0, t_0 and the file key $f.$, that secure the contents of `/foo`. The server *needs* access to these data to broker access to Alice's other devices, and the other members of team Acme. Years pass, and device d is lost, and Alice revokes d after realizing this. Along the way, u_0 has rotated to u_6, and the latest Acme PTK is now t_{100}. And let's say all along, the FOKS clients of ACME members rotate the encryptions stored in the KV store to use the latest PTKs. An evil server who recovers device d can still acceess the file `/foo`, despite all the well-intenioned rotations, because it kept the original encryption of `/foo`, encrypted with the original keys, and disobeyed commands to throw away the ciphertext. In other words, if the server doesn't cooperate, there is only so much that can be done to protect old data after a device compromise. Of course, future data is safe in this scenario.

The Keybase system takes the stance that rotating old file system data is not worth it, due to scenario described above. If we assume the server is semi-honest, that is, if it sometimes (or always!) throws away old ciphertexts, then we still made security gains by rotating file system data, even if the server later becomes evil.

The FOKS KV Store leaves the door open to later perform these reencryptions, though so far we have not implemented it. Clients should periodically sweep over all keys and values, reencrypt them for the latest PTKs (or PUKs), and instruct the server to discard the old ciphertexts. Due to per-file keys for large files, there is no need to download and reupload large file data. Instead, it suffices to reencrypt the file key.

There is no limit to the number of active entries in a directory, so we cannot assume a directory will be rotated all at once. Thus, we allow for two valid directory key seeds per directory. As the reencryption process sweeps across the directory, more dirents use the new key, and fewer use the old, until the old key can be retired.

5.1.6 Garbage Collection

In its current form, the FOKS KV store does not perform any garbage collection, opting instead to keep prior versions of values available indefinitely. We plan to implement deletion in future versions so users can reclaim quota.

5.2 The FOKS Git Server

FOKS includes an application written atop the KV store, which implements an end-to-end encrypted (and authenticated) Git Server. FOKS URLs for a user looks like this:

```
foks://acme.host/alice/tango-proj
```

Where `acme.host` is the FOKS server, `alice` is the user's username, and `tango-proj` is the name of the repository. And for a team:

```
foks://acme.host/t:interns/whiskey-proj
```

Where `t:interns` is the team name. Users of the system clone `git clone` this URL and then push and pull as they would a conventional Git server. Data is written through to the FOKS server at `acme.host`, into its KV-store, of course end-to-end encrypted and authenticated so that the server cannot read or modify the data.

5.2.1 The Git Remote Helper Protocol

FOKS's git integration is built with the Git Remote Helper Protocol [15]. This protocol allows Git to interact with remote storage systems other than its native SSH and HTTP protocols. When Git encounters a URL with a custom scheme like `foks://`, it looks for an executable named `git-remote-foks` in the system path. Git then launches this helper process and communicates with it using a simple text-based protocol.

The protocol consists of Git sending commands like `capabilities`, `list`, `push`, and `fetch`, and the helper responding with success/failure and data. The helper translates between Git's object model and whatever remote storage system it interfaces with.

The more helper must deeply understand Git's object model. The helper gives commands of the form:

```
push refs/heads/main:refs/heads/main
```

The helper starts at the commit refered to by `refs/heads/main`, then walks the commit tree backwards until it finds objects that the server already has. Then it must push the missing objects up to the server, then remap the references to point to the HEAD commit.

Much work has been done to optimize such protocols. Servers in particular can scan the objects they have in their database to assist the client in figuring out the smallest set of objects possible. Unfortunately, in our case, the FOKS server is of little help, since it doesn't know the names of the objects (i.e., their SHA1 hashes). Instead, it sees MACs of these hashes, and also encryptions. And for good reason. The server should not know these content hashes, since knowing them would allow the server to deduce, in important cases, the contents of those objects.

To achieve reasonable performance, while maintaining compatibility with the Git protocol, the FOKS git system makes aggressive use of *packfiles* and *packfile indices*. When clients push, they eagerly pack objects into packfiles, and send these packfiles up to the server. A packfile, in Git, actually consists of two files: the *packfile* itself, which is a compressed concatenation of multiple objects; and the *packfile index*, which contains among other fields, a list of all objects contained in the packfile.

When a client fetches a new HEAD from the server, the algorithm is roughly:

1. Fetch all packfile indices from the server
2. Fetch the HEAD object from the KV store
3. Travese the commit graph starting from the HEAD object:
   (a) If the next object is in the packfile index, fetch the packfile from the KV store.
   (b) Otherwise, fetch the object from the KV store.

The assumption here is that clients pack objects along with other objects that future clients will need to pull together. As long as this assumption roughly holds, clients that pull can avoid costly round-trips and instead can efficiently download batches of objects via packfiles.

6 Related Work

The initial inspiration for FOKS is the SUNDR project [20], which first originated the idea of a fork-consistent blockchain of edits facilitated by a untrusted server. Like Keybase [1], FOKS applies this basic architecture to the problem of key distribution, rather than the data those keys might secure. Many other projects have riffed on this, from CONIKS [22], to the SEAMless [10] work out of Microsoft Research, to the widespread adoption of Key Transparency Signal, WhatsApp and iMessage. The question of federation has largely been ignored, as these sytems all shared the basic architecture of a single upstream server.

7 Conclusion

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