ETH zürich

Applied Crypto Group
D-INFK

Security Analysis of Proton Key Transparency

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Master Thesis Final

Outline

1. Motivation
2. ProtonKT Architecture
3. Security Analysis

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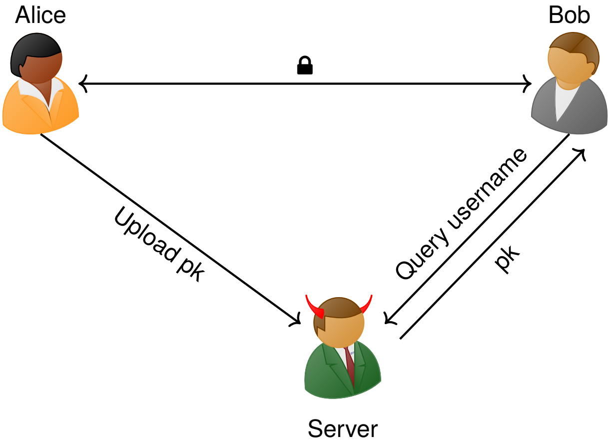
3. Security Analysis

Internet Messaging

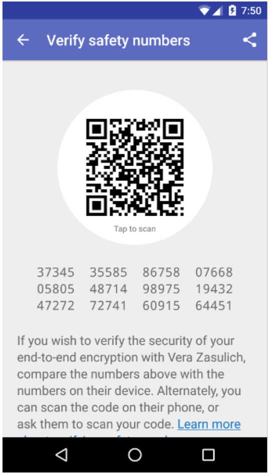


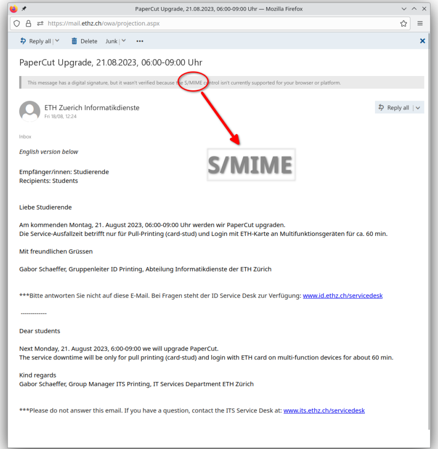
A Key Directory is just a Database

Username	Public Key
alice	~~pkA~~ pkEve
bob	pkB

```
UPDATE table_keys SET pk="pkEve" WHERE username="alice";
```

Existing Solutions: Out-of-Band || Certificates





Key Transparency Goals

Goal 1: make key verification automatic

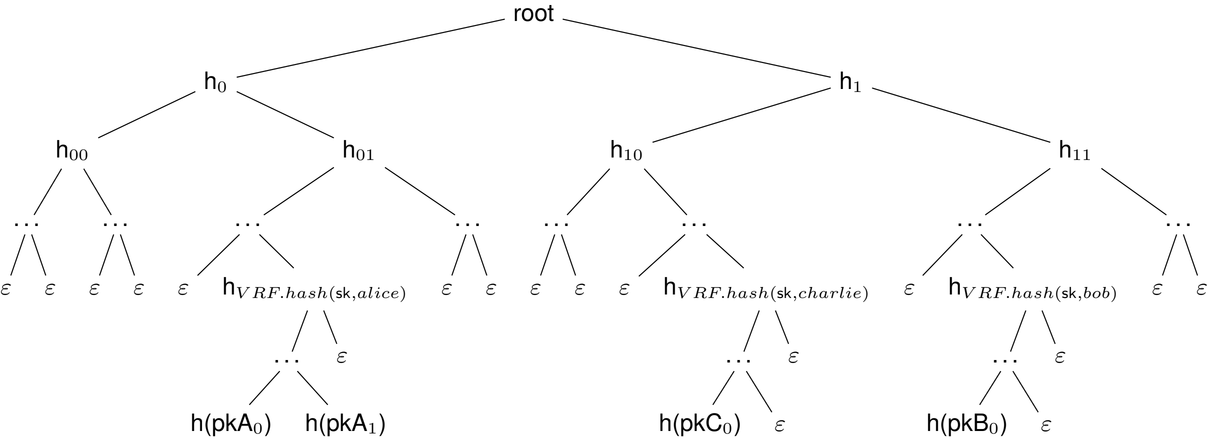
Goal 2: make server behaviour auditable (“transparent”)

Key Transparency in the Real World

- Keybase (docs), Zoom (Whitepaper)
- WhatsApp (blog , Stanford Security Seminar talk)
- Apple iMessage (blog)
- IETF Working Group
- Proton (this talk)

Outline

Build a Merkle Hash Tree from the Key Directory



$$leafindex = VRF.verify(\mathsf{pk}, \mathsf{label}, \pi_{vrf}) \mid\mid \mathsf{rev}$$

Verifiable Random Function (VRF)

$$(\mathsf{sk}, \mathsf{pk}) \leftarrow VRF.kgen()$$

$$\beta \leftarrow VRF.hash(\mathsf{sk}, \alpha)$$

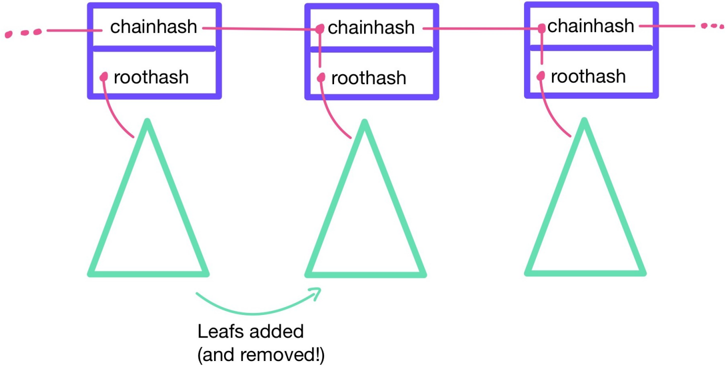
$$\pi \leftarrow VRF.prove(\mathsf{sk}, \alpha)$$

$$\beta / \perp \leftarrow VRF.verify(\mathsf{pk}, \alpha, \pi)$$

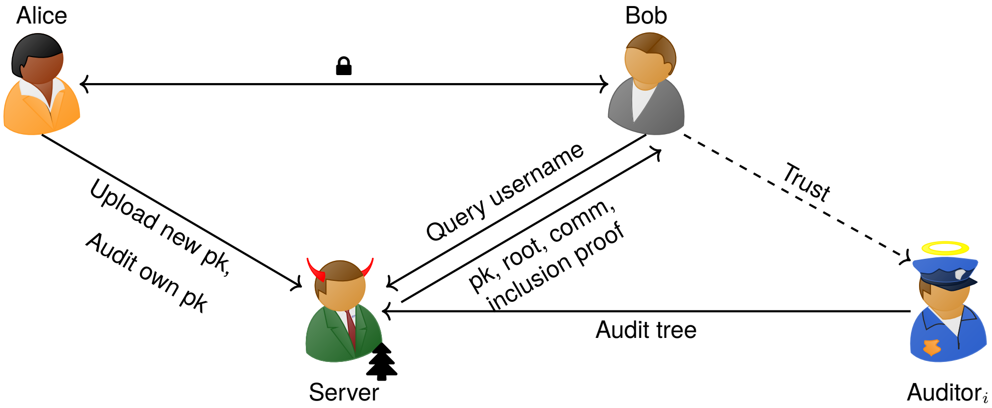
Properties: Pseudorandomness, Collision Resistance, Uniqueness

Trees Across Epochs

$$chainhash_i = h(chainhash_{i-1} \,||\, roothash_i)$$



System Overview and Roles



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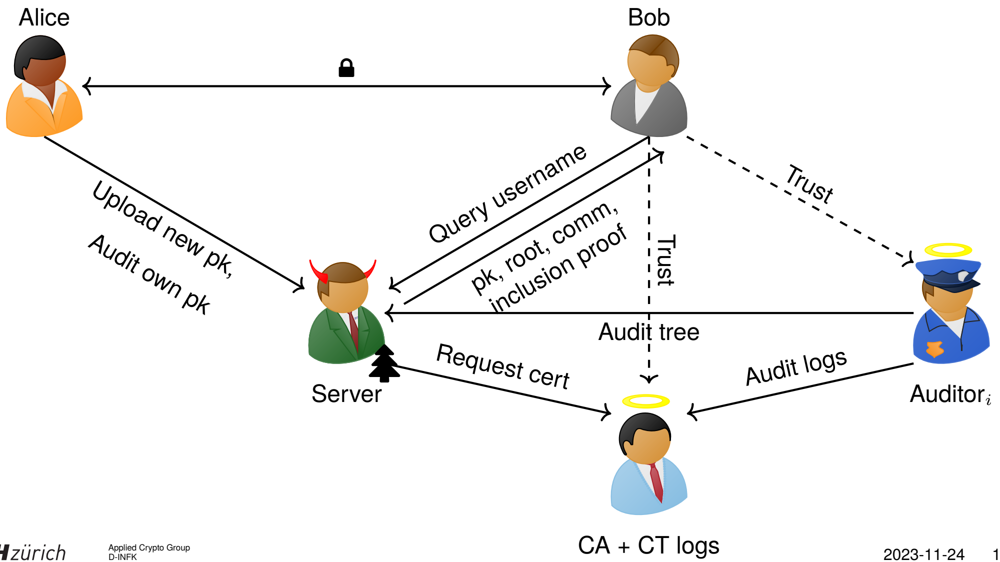
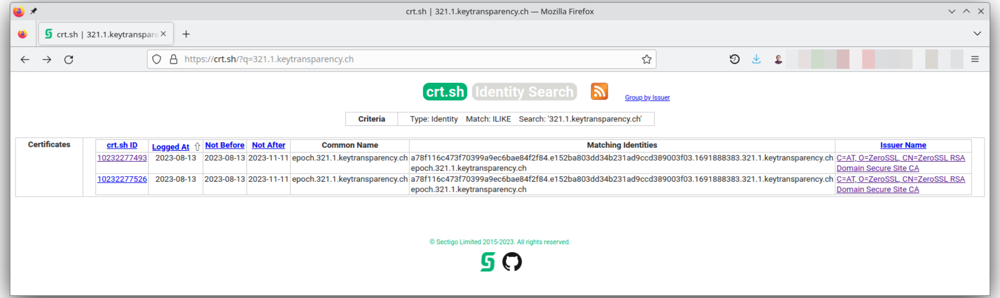


Committing to the Tree Root

`chainhash[0:32].chainhash[32:64].timestamp.epochid.1.keytransparency.ch.`



Tree Leaves

- $leafindex = VRF.verify(\mathsf{pk}, \mathsf{label}, \pi_{vrf}) \mid\mid \mathsf{rev}$
- $\mathsf{val}_{abs} = \emptyset$
- $\mathsf{val}_{incl} = \{keylist,\ minEpochId\}$
- $\mathsf{val}_{obs} = \{ObsolenceToken,\ minEpochId\}$

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- $leafhash_{abs} = \varepsilon$
- $leafhash_{incl} = h\Big(h(keylist) \mid\mid minEpochId\Big)$
- $leafhash_{obs} = h\Big(h(ObsolenceToken) \mid\mid minEpochId\Big)$

Deletions

Deletion of leaf rev allowed $\iff$ leaf $\mathsf{rev}+1$ inserted ≥ 90 days ago

$$\{keylist_1,\, minEpochId_1\}, \{ObsolenceToken_2,\, minEpochId_2\}, \{keylist_3,\, minEpochId_3\}, \ldots$$

ProtonKT Subprotocols (simplified)

- ProtonKT.RequestInsertion(label, $keylist$)
- ProtonKT.Publish($\{$label$_i$, $keylist_i\}_i$)

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- ProtonKT.SelfAudit($roothash_t$, label, $keylist$)
- ProtonKT.PromiseAudit($roothash_t, promises$)
- ProtonKT.ExtAudit()

Outline

Security Properties

Consistency: for a given $(\mathsf{label}, \mathsf{rev})$, we agree on (τ, val).

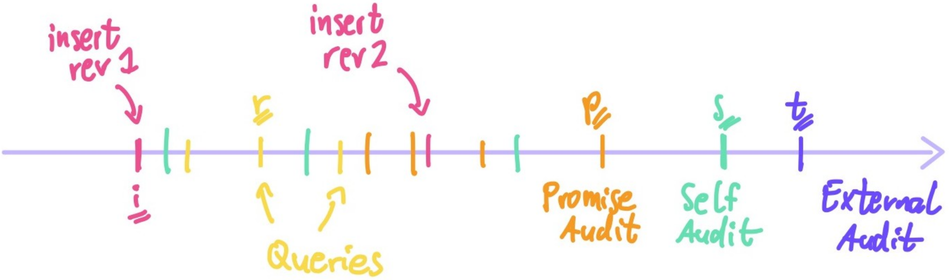
Consistency between queries and Self Audits $\implies$ correctness of keys

Security Property: Query-to-SelfAudit Consistency

We say that ProtonKT provides *Query-to-SelfAudit Consistency*, if

- whenever there was a successful External Audit of epoch t
- and client A runs a successful Self Audit SA for its label at epoch $s \leq t$ and SA passes with $latestRev \geq \mathsf{rev}$,
- and prior to epoch t A has run a successful Self Audit at least once every $\mathsf{DeletionParam}$ (e.g. every 90 days),
- and a query Q for label in epoch $r \leq t$ returned outcome $O = (\tau, \mathsf{rev}, \mathsf{val})$,
- and – if Q returned O as a promise P – there was a successful Promise Audit that sees P at an epoch p with $r < p \leq t$,
- then client A agrees that $(\tau, \mathsf{rev}, \mathsf{val})$ is the expected outcome for rev.

Security Property: Query-to-SelfAudit Consistency



Adversary Model

The adversary can:

- Control the network (active network adversary, Dolev-Yao). Reorder, replay, drop, insert, modify messages.
- Corrupt the KT server. Insert, modify, delete leaves in the Merkle tree.

The adversary cannot:

- Break SHA-256 collision resistance, break ECVRF uniqueness.
- Prevent External Auditors from seeing all CT log entries.

Manual Analysis of Query-to-SelfAudit Consistency

Analysis goal 1: server cannot equivocate on root hash.

- Assume two executions Q, U of $\mathsf{ProtonKT.QueryEpoch}(t)$ accepted $roothash_t^Q \neq roothash_t^U$. Also assume an External Audit passed.
- Then there must exist $chainhash_t^Q = h(chainhash_{t-1}^Q || roothash_t^Q)$ and $cert^Q$, and same for U.

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- *Case 1* $(chainhash_t^Q \neq chainhash_t^U)$*:* Then $cert^Q \neq cert^U$. But these certs must be in CT logs. Then the External Audit finds the equivocation. If it doesn't, then a CT log was malicious or the auditor does not have a global view of CT.

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- *Case 2 ($chainhash_t^Q = chainhash_t^U$):* Then we have $(pch||rh) \neq (pch'||rh')$ such that $h(pch||rh) = h(pch'||rh')$. Contradiction to SHA-256 collision resistance.

CA/CT can Discredit the Server

Problem:

`chainhash[0:32].chainhash[32:64].timestamp.epochid.1.keytransparency.ch.`

`chainhash'[0:32].chainhash'[32:64].timestamp.epochid.1.keytransparency.ch.`

CA + CT logs

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CA + CT logs

Possible solution:

`sig[0:32].sig[32:64].sig[64:96].sig[96:128].epochid.1.keytransparency.ch.`

Manual Analysis of Query-to-SelfAudit Consistency

Analysis goal 2: Query-to-SelfAudit (part of it)

- Assume a query and a Self Audit disagree on the outcome for rev:

  $$O^Q = (\tau^Q, \mathsf{rev}, \mathsf{val}^Q) \neq (\tau^A, \mathsf{rev}, \mathsf{val}^A) = O^A$$

  Also assume an External Audit passed.

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  Also assume an External Audit passed.
- *Case 1 ($idx^Q \neq idx^A$):*
  Let leaf index $idx^Q = VRF.verify(\mathsf{sk}, \mathsf{label}, \pi^Q)||\mathsf{rev}$, and
  $idx^A = VRF.verify(\mathsf{sk}, \mathsf{label}, \pi^A)||\mathsf{rev}$.
  But $VRF.verify(\mathsf{sk}, \mathsf{label}, \pi^Q) \neq VRF.verify(\mathsf{sk}, \mathsf{label}, \pi^A)$ contradicts uniqueness of ECVRF.

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  But $VRF.verify(\mathsf{sk}, \mathsf{label}, \pi^Q) \neq VRF.verify(\mathsf{sk}, \mathsf{label}, \pi^A)$ contradicts uniqueness of ECVRF.
- *Case 2 (Q and SA at same epoch):* By non-equivocation, Q and SA agree on $roothash_t$.
  (Case for different epochs: omitted.)

Manual Analysis of Query-to-SelfAudit Consistency

Analysis goal 2: Query-to-SelfAudit (part of it, continued)

$$O^Q = (\tau^Q, \mathsf{rev}, \mathsf{val}^Q) \neq (\tau^A, \mathsf{rev}, \mathsf{val}^A) = O^A$$

So far: same tree root hash, same leaf index.

- *Case 3 ($leafhash^Q_{idx} \neq leafhash^A_{idx}$):* Hash collision on the path to the root.

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    - *Case 4.1.0 ($\tau^Q = abs, \tau^A = abs$):* $O^Q = O^A$, done.
    - *Case 4.1.1 ($\tau^Q = abs, \tau^A \neq abs$):* Absence has $\mathsf{val}_{abs} = \varepsilon$ but inclusion/absence have values.
    - *Case 4.1.2 ($\tau^Q \neq abs, \tau^A = abs$):* same.

Manual Analysis of Query-to-SelfAudit Consistency

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    - *Case 4.1.2 ($\tau^Q \neq abs, \tau^A = abs$):* same.
    - *Case 4.1.3 ($\tau^Q = incl, \tau^A = obs$):* Then $\mathsf{val}^Q \stackrel{\text{Def}}{=} \{keylist, minEpochId\} = \{ObsolenceToken, minEpochId\} \stackrel{\text{Def}}{=} \mathsf{val}^A$.
      I.e. Q interprets the first field as a keylist and A as an ObsolenceToken.
      This is a contradiction to the fact that the algorithms check that the keylist is JSON-encoded and that ObsolenceToken is a non-empty hex value.
    - *Case 4.1.4 ($\tau^Q = obs, \tau^A = incl$):* same.

Better Leaf Hashes

- $leafhash_{incl} = h\Big(h(keylist) \mid\mid minEpochId\Big)$
- $leafhash_{obs} = h\Big(h(ObsolenceToken) \mid\mid minEpochId\Big)$

Better Leaf Hashes

- $leafhash_{incl} = h\big(h(keylist) \mid\mid minEpochId\big)$
- $leafhash_{obs} = h\big(h(ObsolenceToken) \mid\mid minEpochId\big)$

- $leafhash^{proposed}_{incl} = h\big(h(``1'' \mid\mid keylist) \mid\mid minEpochId\big)$
- $leafhash^{proposed}_{obs} = h\big(h(``2'' \mid\mid ObsolenceToken) \mid\mid minEpochId\big)$

Server can Delay Promise Audit

```
if (promise.expectedMinEpochID > currentEpoch.EpochID) {
return LocalStorageAuditStatus.RetryLater;
}

/* ... only further down the Maximum Merge Delay is checked ... */
if (isTimestampTooOld(promise.creationTimestamp)) {
throwKTError('promise was ignored beyond MMD');
}
```

Formal Analysis of Query-to-SelfAudit Consistency

- Used new Tamarin festures (subterm, natural numbers).
- Tried to prove Query-to-SelfAudit Consistency but ran into a limitation of how Tamarin handles induction.
- Still a useful exercise to understand the protocol better, to find gaps in your understanding.

Conclusion

- ProtonKT Specification
- Adversary Model, Security Property
- Manual Analysis
- Formal Analysis with dead-end
- Recommendations: sign chainhash in CT to prevent discrediting, make type explicit in leaf hash, server could delay Promise Audit forever

Questions?

Formal Analysis of Query-to-SelfAudit Consistency

```
rule CT_Insert:
[ In(<epoch_id, chainhash>) ]
--[ CtInsertChainhash(epoch_id, chainhash) ]->
[ !CT(epoch_id, chainhash) ]
```

Tamarin Prover

Model 1: Tree as Persistent Facts.

```
!TreeLeaf($label, val, %rev, %min_epoch_id)
```

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Model 2: Trees as Terms.

```
roothash = h( <'head', h(ut_0), h(ut_1), ..., h(ut_n), 'tail'> )
ut = < $label, <%n, val_n>, ..., <%3, val_3>, <%2, 'empty'>, 'rest' >
```

$\Longrightarrow$ Only 3 levels, not binary, but more tree-ish.

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Model 1: Tree as Persistent Facts.

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```

$\Longrightarrow$ Only 3 levels, not binary, but more tree-ish.

We didn't find a proof, we ran into a limitation of Tamarin's induction mechanism.

Proving Query-to-SelfAudit Consistency with Tamarin

Problem: Query and Self Audit can happen in different epochs $r \neq s$, w.l.o.g. $r < s$.
Recall: $chainhash_i = h(chainhash_{i-1} \,||\, roothash_i)$
Thus: $chainhash_r \sqsubset chainhash_s$
To reason about the leaves, we need to reason about how the tree(s) evolved, thus we need to reason about the chainhashes.

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Lemma:

```
"All ch1 ch2 #i #j. Ch(ch1)@i & Ch(ch2)@j ==> ch1 << ch2"
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```

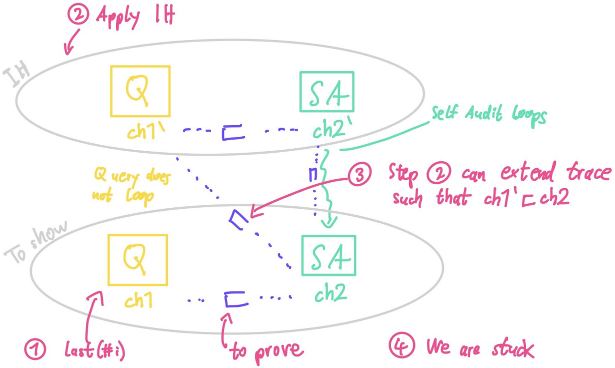
Induction hypothesis:

```
"All ch1 ch2 #i #j. Ch(ch1)@i & Ch(ch2)@j ==> ch1 << ch2 | last(#i) | last(#j)"
```

We cannot avoid induction because Self Audit and External Audit loop (over revisions and over epochs).

Case Split on Induction

IH: `"All ch1 ch2 #i #j. Ch(ch1)@i & Ch(ch2)@j ==> ch1 << ch2 | last(#i) | last(#j)"`



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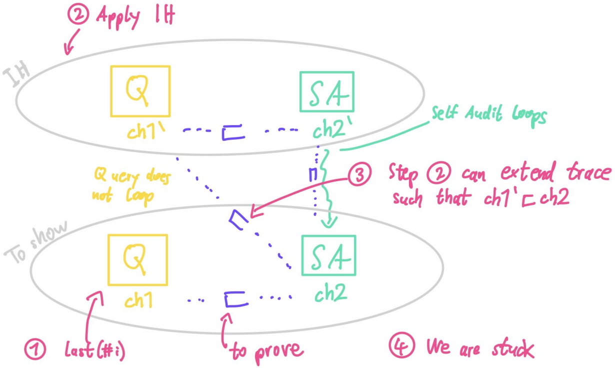

We would like:

`"All ch1 ch2 #j. Ch(ch2)@j & ch1 << ch2 ==> Ex #i. Ch(ch1)@i"`

But `ch1` is not guarded, i.e. invalid Tamarin syntax.