

Zero-Knowledge Age Restriction for GNU Taler

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Age restriction in E-commerce

Problem:

Verification of minimum age requirements in e-commerce.

Common solutions:

1. ID Verification
2. Restricted Accounts
3. Attribute-based

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- | | |
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For age-restriction, the lowest level of authority is:

Parents, guardians and caretakers

Our contribution

Design and implementation of an age restriction scheme with the following goals:

1. It ties age restriction to the **ability to pay** (not to ID's)
2. maintains **anonymity of buyers**
3. maintains **unlinkability of transactions**
4. aligns with **principle of subsidiarity**
5. is **practical and efficient**

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Age restriction

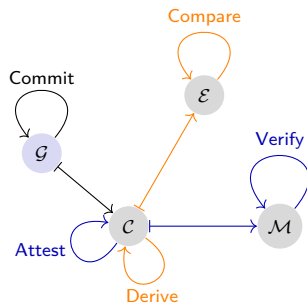
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Note: Scheme is independent of payment service protocol.

Formal Function Signatures

Searching for functions

Commit

Attest

Verify

Derive

Compare

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Commit : $(a, \omega) \mapsto (Q, P)$ $\mathbb{N}_M \times \Omega \rightarrow \mathbb{O} \times \mathbb{P}$,

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$\mathbb{O} = c\mathbb{O}mmitments$, $Q = Q\text{-}mitment$ (commitment), $\mathbb{P} = \mathbb{P}roofs$,

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with $\Omega, \mathbb{P}, \mathbb{O}, \mathbb{T}, \mathbb{B}$ sufficiently large sets.

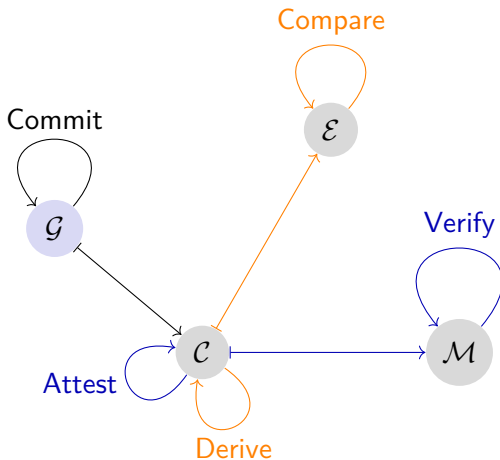
Basic and security requirements are defined later.

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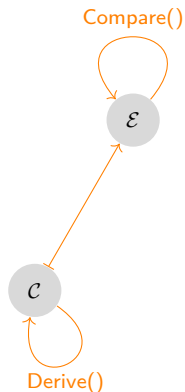
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Age restriction

Naïve scheme

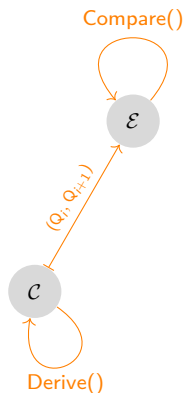


Achieving Unlinkability



Simple use of `Derive()` and `Compare()` is problematic.

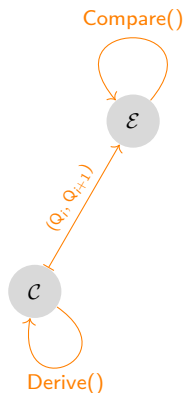
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- ▶ Calling `Derive()` iteratively generates sequence (Q_0, Q_1, \dots) of commitments.
- ▶ Exchange calls `Compare(Q_i, Q_{i+1}, \dots)`

Achieving Unlinkability



Simple use of $Derive()$ and $Compare()$ is problematic.

- ▶ Calling $Derive()$ iteratively generates sequence (Q_0, Q_1, \dots) of commitments.
- ▶ Exchange calls $Compare(Q_i, Q_{i+1}, \dots)$

⇒ **Exchange identifies sequence**

⇒ **Unlinkability broken**

Achieving Unlinkability

Define cut&choose protocol $\text{DeriveCompare}_\kappa$, using $\text{Derive}()$ and $\text{Compare}()$.

Achieving Unlinkability

Define cut&choose protocol **DeriveCompare $_{\kappa}$** , using `Derive()` and `Compare()`.

Sketch:

1. \mathcal{C} derives commitments (Q_1, \dots, Q_{κ}) from Q_0 by calling `Derive()` with blindings $(\beta_1, \dots, \beta_{\kappa})$
2. \mathcal{C} calculates $h_0 := H(H(Q_1, \beta_1) || \dots || H(Q_{\kappa}, \beta_{\kappa}))$
3. \mathcal{C} sends Q_0 and h_0 to \mathcal{E}
4. \mathcal{E} chooses $\gamma \in \{1, \dots, \kappa\}$ randomly
5. \mathcal{C} reveals $h_{\gamma} := H(Q_{\gamma}, \beta_{\gamma})$ and all (Q_i, β_i) , except $(Q_{\gamma}, \beta_{\gamma})$
6. \mathcal{E} compares h_0 and $H(H(Q_1, \beta_1) || \dots || h_{\gamma} || \dots || H(Q_{\kappa}, \beta_{\kappa}))$ and evaluates `Compare`(Q_0, Q_i, β_i).

Note: Scheme is similar to the *refresh* protocol in GNU Taler.

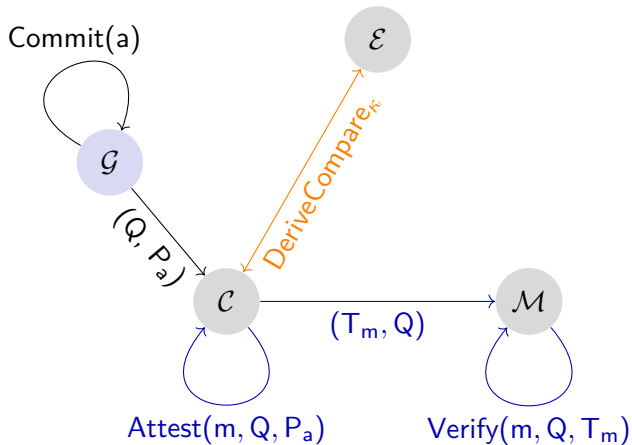
Achieving Unlinkability

With `DeriveCompare κ`

- ▶ \mathcal{E} learns nothing about Q_γ ,
- ▶ trusts outcome with $\frac{\kappa-1}{\kappa}$ certainty,
- ▶ i.e. \mathcal{C} has $\frac{1}{\kappa}$ chance to cheat.

Note: Still need Derive and Compare to be defined.

Refined scheme



Basic Requirements

Candidate functions

(Commit, Attest, Verify, Derive, Compare)

must first meet *basic* requirements:

- ▶ Existence of attestations
- ▶ Efficacy of attestations
- ▶ Derivability of commitments and attestations

Basic Requirements

Formal Details

Existence of attestations

$$\forall_{\substack{a \in \mathbb{N}_M \\ \omega \in \Omega}} : \text{Commit}(a, \omega) =: (Q, P) \implies \text{Attest}(m, Q, P) = \begin{cases} T \in \mathbb{T}, & \text{if } m \leq a \\ \perp & \text{otherwise} \end{cases}$$

Efficacy of attestations

$$\text{Verify}(m, Q, T) = \begin{cases} 1, & \text{if } \exists_{P \in \mathbb{P}} : \text{Attest}(m, Q, P) = T \\ 0 & \text{otherwise} \end{cases}$$

$$\forall_{n \leq a} : \text{Verify}(n, Q, \text{Attest}(n, Q, P)) = 1.$$

etc.

Security Requirements

Candidate functions must also meet *security* requirements. Those are defined via security games:

- ▶ Game: Age disclosure by commitment or attestation
↔ Requirement: Non-disclosure of age
- ▶ Game: Forging attestation
↔ Requirement: Unforgeability of minimum age
- ▶ Game: Distinguishing derived commitments and attestations
↔ Requirement: Unlinkability of commitments and attestations

Meeting the security requirements means that adversaries can win those games only with negligible advantage.

Adversaries are arbitrary polynomial-time algorithms, acting on all relevant input.

Security Requirements

Simplified Example

Game $G_{\mathcal{A}}^{\text{FA}}(\lambda)$ —Forging an attest:

1. $(a, \omega) \xleftarrow{\$} \mathbb{N}_{M-1} \times \Omega$
2. $(Q, P) \leftarrow \text{Commit}(a, \omega)$
3. $(m, T) \leftarrow \mathcal{A}(a, Q, P)$
4. Return 0 if $m \leq a$
5. Return $\text{Verify}(m, Q, T)$

Requirement: Unforgeability of minimum age

$$\forall \mathcal{A} \in \mathfrak{A}(\mathbb{N}_M \times \mathbb{O} \times \mathbb{P} \rightarrow \mathbb{N}_M \times \mathbb{T}) : \Pr \left[G_{\mathcal{A}}^{\text{FA}}(\lambda) = 1 \right] \leq \epsilon(\lambda)$$

Solution: Instantiation with ECDSA

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1. Guardian generates ECDSA-keypairs, one per age (group):

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- ▶ $\vec{Q} := (q_1, \dots, q_M)$ is the *Commitment*,
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3. Guardian gives child $\langle \vec{Q}, \vec{P}_a \rangle$

Instantiation with ECDSA

Definitions of Attest and Verify

Child has

- ▶ ordered public-keys $\vec{Q} = (q_1, \dots, q_M)$,
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To Verify a minimum age m :

Verify the ECDSA-Signature σ with public key q_m .

Instantiation with ECDSA

Definitions of Derive and Compare

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Definitions of Derive and Compare

Child has $\vec{Q} = (q_1, \dots, q_M)$ and $\vec{P} = (p_1, \dots, p_a, \perp, \dots, \perp)$.

To Derive new \vec{Q}' and \vec{P}' : Choose random $\beta \in \mathbb{Z}_g$ and calculate

$$\vec{Q}' := (\beta * q_1, \dots, \beta * q_M),$$

$$\vec{P}' := (\beta p_1, \dots, \beta p_a, \perp, \dots, \perp)$$

Note: $(\beta p_i) * G = \beta * (p_i * G) = \beta * q_i$

$\beta * q_i$ is scalar multiplication on the elliptic curve.

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Exchange gets $\vec{Q} = (q_1, \dots, q_M)$, $\vec{Q}' = (q'_1, \dots, q'_M)$ and β

To Compare, calculate: $(\beta * q_1, \dots, \beta * q_M) \stackrel{?}{=} (q'_1, \dots, q'_M)$

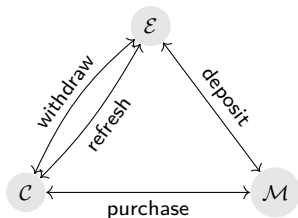
Instantiation with ECDSA

Functions (Commit, Attest, Verify, Derive, Compare)
as defined in the instantiation with ECDSA

- ▶ meet the basic requirements,
- ▶ also meet all security requirements.
Proofs by security reduction, details are in the paper.

GNU Taler

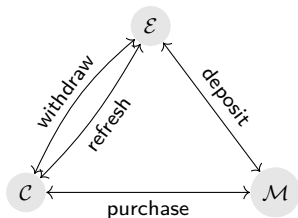
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- ▶ Coins are public-/private key-pairs (C_p, c_s) .
- ▶ Exchange blindly signs $\text{FDH}(C_p)$ with denomination key d_p
- ▶ Verification:

$$1 \stackrel{?}{=} \text{SigCheck}(\text{FDH}(C_p), D_p, \sigma_p)$$

(D_p = public key of denomination and σ_p = signature)

Integration with GNU Taler

Binding age restriction to coins

To bind an age commitment Q to a coin C_p , instead of signing $\text{FDH}(C_p)$, \mathcal{E} now blindly signs

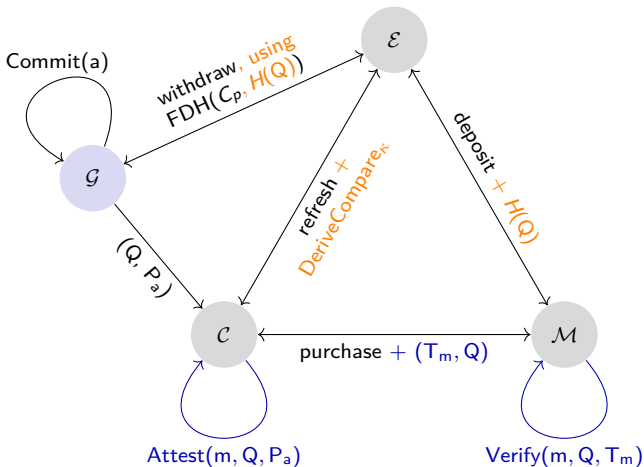
$$\text{FDH}(C_p, H(Q))$$

Verification of a coin now requires $H(Q)$, too:

$$1 \stackrel{?}{=} \text{SigCheck}(\text{FDH}(C_p, H(Q)), D_p, \sigma_p)$$

Integration with GNU Taler

Integrated schemes



Instantiation with Edx25519

Paper also formally defines another signature scheme: Edx25519.

- ▶ Scheme already in use in GNUnet,
- ▶ based on EdDSA (Bernstein et al.),
- ▶ generates compatible signatures and
- ▶ allows for key derivation from both, private and public keys, independently.

Current implementation of age restriction in GNU Taler uses Edx25519.

Discussion

- ▶ Our solution can in principle be used with any token-based payment scheme
- ▶ GNU Taler best aligned with our design goals (security, privacy and efficiency)
- ▶ Subsidiarity requires bank accounts being owned by adults
 - ▶ Scheme can be adapted to case where minors have bank accounts
 - ▶ Assumption: banks provide minimum age information during bank transactions.
 - ▶ Child and Exchange execute a variant of the cut&choose protocol.
- ▶ Our scheme offers an alternative to identity management systems (IMS)

Related Work

- ▶ Current privacy-preserving systems all based on attribute-based credentials (Koning et al., Schanzenbach et al., Camenisch et al., Au et al.)
- ▶ Attribute-based approach lacks support:
 - ▶ Complex for consumers and retailers
 - ▶ Requires trusted third authority
- ▶ Other approaches tie age-restriction to ability to pay ("debit cards for kids")
 - ▶ Advantage: mandatory to payment process
 - ▶ Not privacy friendly

Conclusion

Age restriction is a technical, ethical and legal challenge.

Existing solutions are

- ▶ without strong protection of privacy or
- ▶ based on identity management systems (IMS)

Our scheme offers a solution that is

- ▶ based on subsidiarity
- ▶ privacy preserving
- ▶ efficient
- ▶ an alternative to IMS