Zero-Knowledge Age Restriction for GNU Taler

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September 26, 2022

ESORICS 2022

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Age restriction in E-commerce

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Verification of minimum age requirements in e-commerce.

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2. Restricted Accounts
3. Attribute-based

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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 subsidiartiy**
5. is **practical and efficient**

Age restriction

Assumptions and scenario

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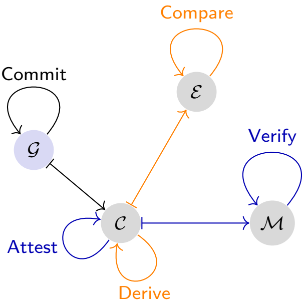

Note: Scheme is independent of payment service protocol.

Formal Function Signatures

Searching for functions

- Commit
- Attest
- Verify
- Derive
- Compare

Formal Function Signatures

Searching for functions with the following signatures

$$\begin{aligned} &\text{Commit}: && (\mathsf{a}, \omega) \mapsto (\mathsf{Q}, \mathsf{P}) && \mathbb{N}_\mathsf{M} \times \Omega \to \mathbb{O} \times \mathbb{P}, \\ &\text{Attest} \\ &\text{Verify} \\ &\text{Derive} \\ &\text{Compare} \end{aligned}$$

Mnemonics:
$\mathbb{O} =$ *c$\mathbb{O}$mmitments*, $\mathsf{Q} =$ *Q-mitment* (commitment), $\mathbb{P} = \mathbb{P}$*roofs*,

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Derive

Compare

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\text{Derive}: &\quad (Q, P, \omega) \mapsto (Q', P', \beta) & \mathbb{O} \times \mathbb{P} \times \Omega \to \mathbb{O} \times \mathbb{P} \times \mathbb{B},\\
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\text{Derive}: && (\mathsf{Q}, \mathsf{P}, \omega) &\mapsto (\mathsf{Q}', \mathsf{P}', \beta) && \mathbb{O} \times \mathbb{P} \times \Omega \to \mathbb{O} \times \mathbb{P} \times \mathbb{B}, \\
\text{Compare}: && (\mathsf{Q}, \mathsf{Q}', \beta) &\mapsto b && \mathbb{O} \times \mathbb{O} \times \mathbb{B} \to \mathbb{Z}_2,
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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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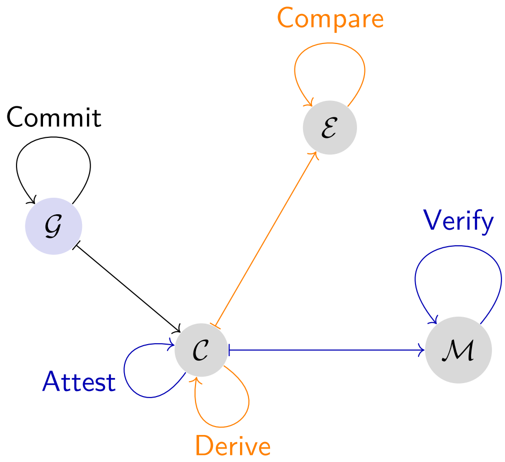
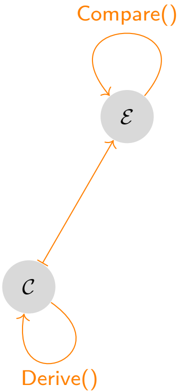
Age restriction

Naïve scheme



Achieving Unlinkability



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

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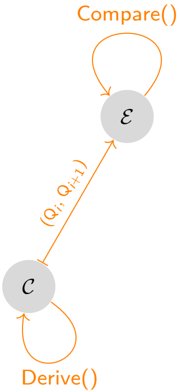

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- Calling Derive() iteratively generates sequence $(Q_0, Q_1, \dots)$ of commitments.
- Exchange calls Compare$(Q_i, Q_{i+1}, .)$

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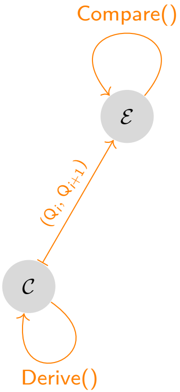

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- Calling Derive() iteratively generates sequence $(Q_0, Q_1, \ldots)$ of commitments.
- Exchange calls Compare$(Q_i, Q_{i+1}, .)$

$\Longrightarrow$ **Exchange identifies sequence**

$\Longrightarrow$ **Unlinkability broken**

Achieving Unlinkability

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

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Sketch:

1. $\mathcal{C}$ derives commitments $(\mathsf{Q}_1, \ldots, \mathsf{Q}_\kappa)$ from Q_0 by calling Derive() with blindings $(\beta_1, \ldots, \beta_\kappa)$
2. $\mathcal{C}$ calculates $h_0 := H(H(\mathsf{Q}_1, \beta_1)|| \ldots ||H(\mathsf{Q}_\kappa, \beta_\kappa))$
3. $\mathcal{C}$ sends Q_0 and h_0 to $\mathcal{E}$
4. $\mathcal{E}$ chooses $\gamma \in \{1, \ldots, \kappa\}$ randomly
5. $\mathcal{C}$ reveals $h_\gamma := H(\mathsf{Q}_\gamma, \beta_\gamma)$ and all (Q_i, β_i), except $(\mathsf{Q}_\gamma, \beta_\gamma)$
6. $\mathcal{E}$ compares h_0 and $H(H(\mathsf{Q}_1, \beta_1)||...||h_\gamma||...||H(\mathsf{Q}_\kappa, \beta_\kappa))$ and evaluates Compare$(\mathsf{Q}_0, \mathsf{Q}_i, \beta_i)$.

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

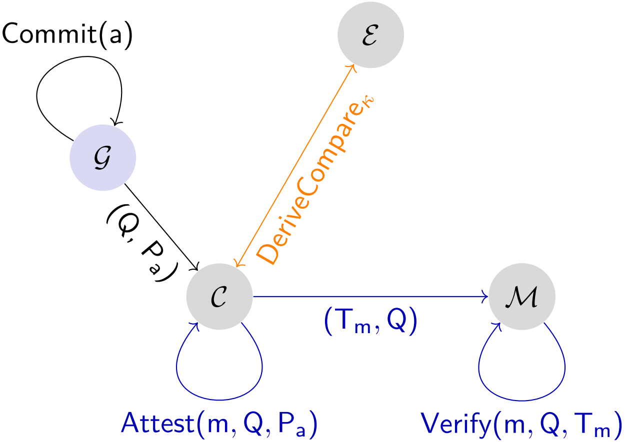
Achieving Unlinkability

With DeriveCompare$_\kappa$

- $\mathcal{E}$ 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

$$(\text{Commit}, \text{Attest}, \text{Verify}, \text{Derive}, \text{Compare})$$

must first meet *basic* requirements:

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

Basic Requirements

Formal Details

Existence of attestations

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

Efficacy of attestations

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

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

etc.

Security Requirements

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

- Game: Age disclosure by commitment or attestation

$\leftrightarrow$ Requirement: Non-disclosure of age

- Game: Forging attestation

$\leftrightarrow$ Requirement: Unforgeability of minimum age

- Game: Distinguishing derived commitments and attestations

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

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

Requirement: Unforgeability of minimum age

$$\underset{\mathcal{A} \in \mathfrak{A}(\mathbb{N}_{\mathsf{M}} \times \mathbb{O} \times \mathbb{P} \to \mathbb{N}_{\mathsf{M}} \times \mathbb{T})}{\forall} : \Pr\left[G_{\mathcal{A}}^{\mathsf{FA}}(\lambda) = 1 \right] \leq \epsilon(\lambda)$$

Solution: Instantiation with ECDSA

To Commit to age (group) 'a'

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

$$\langle (q_1, p_1), \ldots, (q_\mathrm{M}, p_\mathrm{M}) \rangle$$

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2. Guardian then **drops** all private keys p_i for $i > \mathrm{a}$:

$$\Big\langle (q_1, p_1), \ldots, (q_\mathrm{a}, p_\mathrm{a}), (q_{\mathrm{a}+1}, \bot), \ldots, (q_\mathrm{M}, \bot) \Big\rangle$$

- $\vec{\mathrm{Q}} := (q_1, \ldots, q_\mathrm{M})$ is the *Commitment*,
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3. Guardian gives child $\langle \vec{\mathsf{Q}}, \vec{\mathsf{P}}_\mathsf{a} \rangle$

Instantiation with ECDSA

Definitions of Attest and Verify

Child has

- ordered public-keys $\vec{\mathsf{Q}} = (q_1, \ldots, q_\mathsf{M})$,
- (some) private-keys $\vec{\mathsf{P}} = (p_1, \ldots, p_\mathsf{a}, \perp, \ldots, \perp)$.

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To Attest a minimum age $m \leq a$:

Sign a message with ECDSA using private key p_m

Instantiation with ECDSA

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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

Child has $\vec{\mathsf{Q}} = (q_1, \ldots, q_\mathsf{M})$ and $\vec{\mathsf{P}} = (p_1, \ldots, p_\mathsf{a}, \bot, \ldots, \bot)$.

Instantiation with ECDSA

Definitions of Derive and Compare

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

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

$$\vec{Q}' := \big(\beta * q_1, \ldots, \beta * q_M\big),$$
$$\vec{P}' := \big(\beta p_1, \ldots, \beta p_a, \bot, \ldots, \bot\ \big)$$

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

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

Instantiation with ECDSA

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Exchange gets $\vec{\mathrm{Q}} = (q_1, \dots, q_\mathrm{M})$, $\vec{\mathrm{Q}}' = (q'_1, \dots, q'_\mathrm{M})$ and β

To Compare, calculate: $(\beta * q_1, \dots, \beta * q_\mathrm{M}) \stackrel{?}{=} (q'_1, \dots, q'_\mathrm{M})$

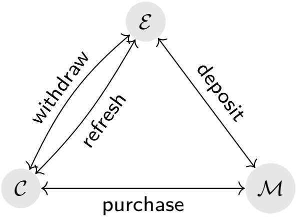
Instantiation with ECDSA

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

https://www.taler.net



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- Based on Chaum's blind signatures
- Allows for change and refund (F. Dold)
- Privacy preserving: anonymous and unlinkable payments

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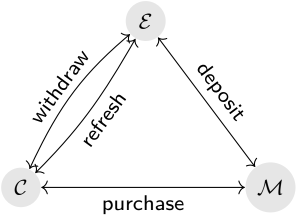

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- Coins are public-/private key-pairs (C_p, c_s).
- Exchange blindly signs $\text{FDH}(C_p)$ with denomination key d_p
- Verification:

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

(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 $\mathrm{FDH}(C_p)$, $\mathcal{E}$ now blindly signs

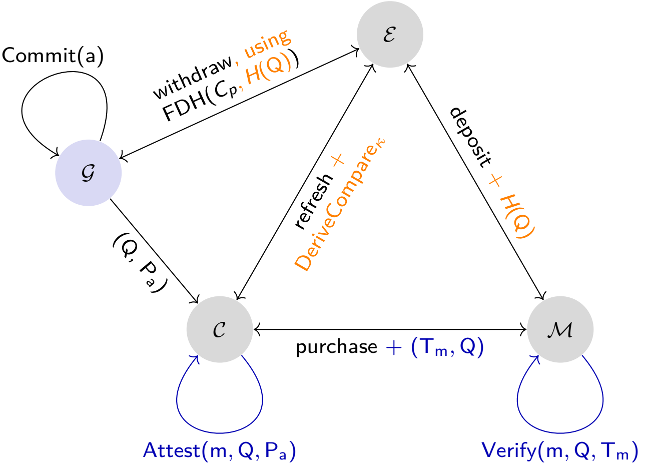
$$\mathrm{FDH}(C_p, H(\mathrm{Q}))$$

Verfication of a coin now requires $H(\mathrm{Q})$, too:

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

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-perserving 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