Privacy-Preserving Age Verification Using Zero-Knowledge Proofs

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Problem & Goal

- Online services need age checks without exposing personal data. (Privacy, tracking, over-collection)
- Goal: Prove "age $\geq$ threshold" and validity, with **no identity leakage** and **unlinkability**.
- Approach: Combine Pedersen commitments, BBS+ signatures (BLS12-381), Bulletproofs, and RSA-accumulator revocation.

Schnorr Profs of Knowledge

Goal: Prove knowledge of x such that $X = g^x \pmod{p}$ without revealing x.

- **Setup:** Public parameters (g, p, q) where g generates a group of prime order q.
- **Prover:** Chooses random $y \in \mathbb{Z}_q$, sends $Y = g^y$.
- **Verifier:** Sends random challenge $c \in \mathbb{Z}_q$.
- **Prover:** Responds with $r = y + cx \pmod{q}$.
- **Verifier:** Checks $g^r \stackrel{?}{=} Y X^c$.

Properties: Zero-knowledge (no leak of x), sound (cannot cheat without knowing x), and efficient.

Pedersen Commitment

$$C = g^m h^r \quad \text{in a group of prime order } q.$$

- **Commit:** Choose random $r \in \mathbb{Z}_q$ and compute C as above.
- **Reveal:** Send (m, r) to open the commitment.
- **Verify:** Check that $C = g^m h^r$.

Properties: Perfectly hiding (no information about m), computationally binding (cannot change m once committed).

BBS+ Signatures (BLS12-381)

Overview

- A **BBS+ signature** allows signing multiple messages at once.
- Later, the holder can reveal only selected messages and still prove the signature is valid known as **selective disclosure**.
- Built on **pairing-based cryptography** using the **BLS12-381** curve for 128-bit security.

Core Idea

- The issuer signs a set of messages $\{m_i\}$ producing a compact signature (A, e).
- Verification uses a pairing equation that ensures integrity of all signed messages.
- During disclosure, the holder can generate a zero-knowledge proof that convinces a verifier the signature is valid—without revealing hidden messages.

Bulletproofs (Range Proofs)

Prove $0 \leq v < 2^n$ without revealing v.

Compact (log-size) proof, no trusted setup.

Overview

- **Bulletproofs** are short, non-interactive **range proofs**.
- Based on **inner product arguments** for efficiency.
- No trusted setup, fully transparent.

Uses

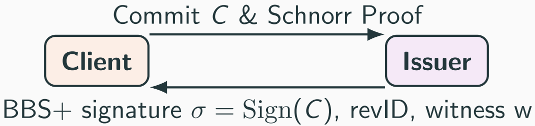
- Confidential transactions (e.g., Monero, Bitcoin).
- Showing age or value in a valid range.
- Proving credentials (e.g., not expired).

Protocol Overview

- Three parties: **Issuer**, **Client**, **Verifier**.
- Core idea: single commitment with hidden attributes, certified by BBS+, and proven with ZK subproofs.

$$C = g_1^{m_{\text{birth}}} \, g_2^{m_{\text{exp}}} \, g_3^{x_d} \, h^r .$$

Issuance Phase (Flow)



Equations:

$$C = g_1^{m_{\text{birth}}} g_2^{m_{\text{exp}}} g_3^{x_d} h^r, \quad \sigma = \text{BBS+Sign}(C). \;;$$

Client stores:

- The issued credential $(C, \sigma, \text{revID}, w)$
- The private randomness r and hidden attributes $(m_{\text{birth}}, m_{\text{exp}}, x_d)$

Verification Phase (1/2): Client-side preparation

Client **Verifier**

Randomize credential & initialize proofs

- Randomize commitment and signature: $C' = C \cdot h^{r'}, \quad \sigma' = \mathrm{ReRand}(\sigma, r')$
- Prepare BBS+ proof of knowledge (PoK) over hidden attributes $(m_{\mathrm{birth}}, m_{\mathrm{exp}}, x_d, r)$.
- Set up Bulletproof witnesses:

$$t_{\mathrm{age}} = \mathrm{age} - \mathrm{threshold}, \quad t_{\mathrm{exp}} = \mathrm{expiry\_date} - \mathrm{today}.$$

  Target: prove $t_{\mathrm{age}} \geq 0$ and $t_{\mathrm{exp}} \geq 0$ via range proofs.
- Compute revocation handle $e =$SHA-256(x_d) and fetch its accumulator witness w to generate a non-membership proof yet with pedersen: $U = g^e h^r$.

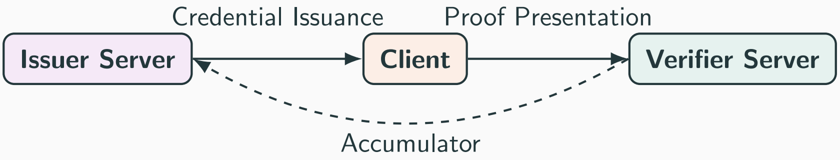
Verification Phase (2/2): Build and send proofs

$$\text{Client} \xrightarrow[]{\substack{\text{Randomized } (C', \sigma') \\ \text{BBS+, PoK (hidden attrs),} \\ \text{Bulletproof}(t_{\text{age}} \geq 0),\ \text{Bulletproof}(t_{\text{exp}} \geq 0), \\ \text{Accumulator non-membership proof for revID}}} \text{Verifier}$$

Proof bundle:

- $\Pi_{\text{BBS+}}$: PoK linking (C', σ') to hidden messages. (AND-composed)
- Π_{age}: Bulletproof that $t_{\text{age}} \geq 0$.
- Π_{exp}: Bulletproof that $t_{\text{exp}} \geq 0$.
- Π_{acc}: Non-membership of revID in accumulator.

System Overview (Entities & Roles)



Roles:

- **Issuer:** Issues credentials, manages RSA accumulator (revocation list), publishes public parameters.
- **Client:** Holds credentials, generates ZK proofs (BBS+, Bulletproofs, revocation).
- **Verifier:** Validates proofs, checks non-revocation.

System Design & Implementation

Architecture

- All components in **Go**; lightweight REST APIs; thin JS UI.
- Client runs local Go backend; cryptography stays off the browser.
- Verifier caches issuer params; enforces freshness & replay protection.

Packages

- `pkg/crypto`: Pedersen, BBS+ on BLS12-381.
- `pkg/protocol`: Bulletproofs, serialization, verification.
- `pkg/revocation`: RSA accumulator, witnesses.

Security & Performance (Highlights)

- **Zero-knowledge**: proofs reveal no personal data.
- **Unlinkability**: re-randomization; no static identifiers.
- **Unforgeability**: BBS+ on BLS12-381.
- **Revocation privacy**: only revoked IDs in accumulator.

Future Work

- Bind credentials to device secrets/biometrics for anti-sharing.
- Native mobile SDKs (Android, iOS).
- Threshold issuers and decentralized identifiers.
- Cross-authority scaling with common identifiers.

Conclusion

- Practical, privacy-preserving age checks without identity disclosure.
- Compact ZK composition: Pedersen + BBS+ + Bulletproofs + RSA accumulator.
- Efficient on BLS12-381 with a clean Go-based architecture.