Non-Interactive Plaintext (In-)Equality Proofs and Group Signatures with Verifiable Controllable Linkability

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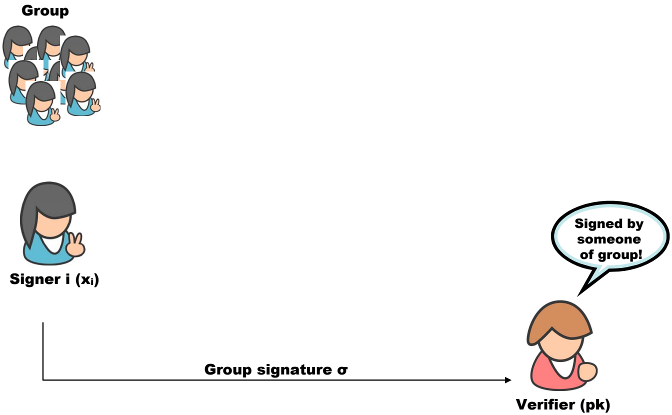
CT-RSA 2016, San Francisco, 2nd March 2016

Group Signature Schemes [CvH91]



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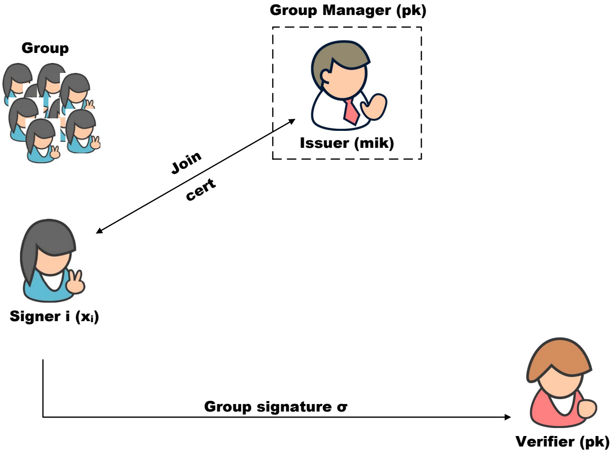

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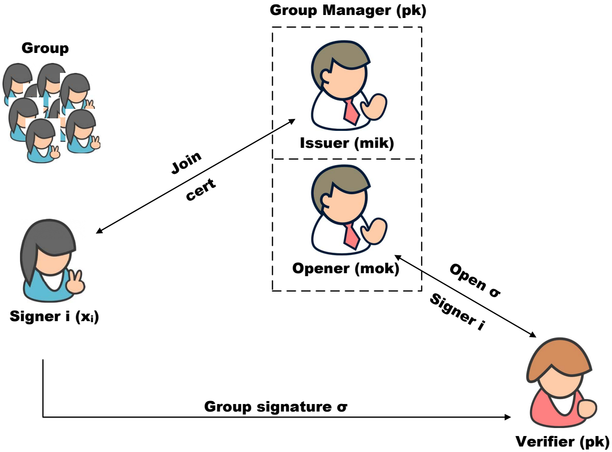
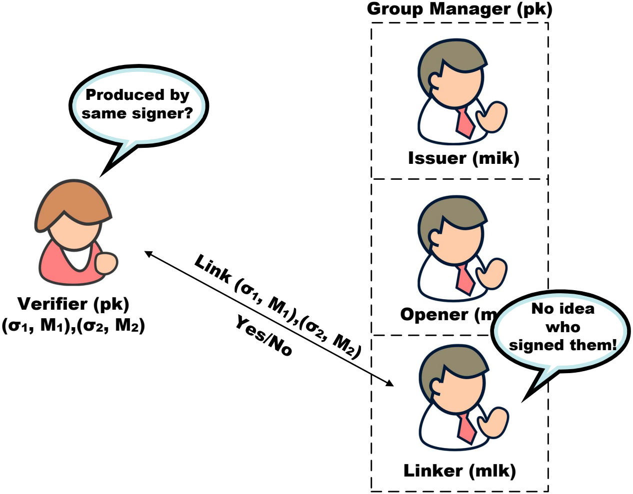


Controllable Linkability [HLhC+11, SSU14]



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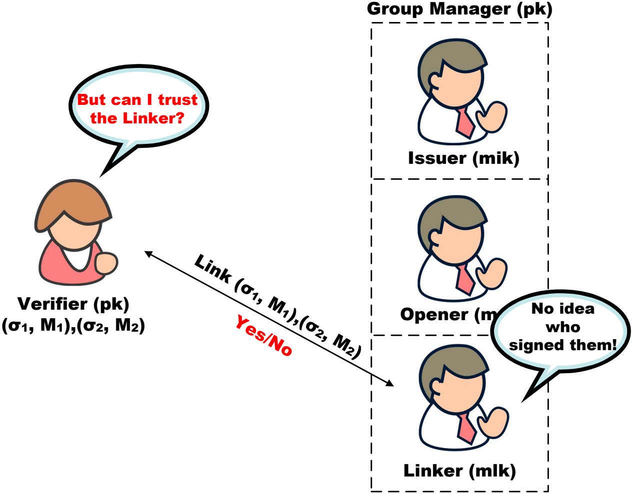

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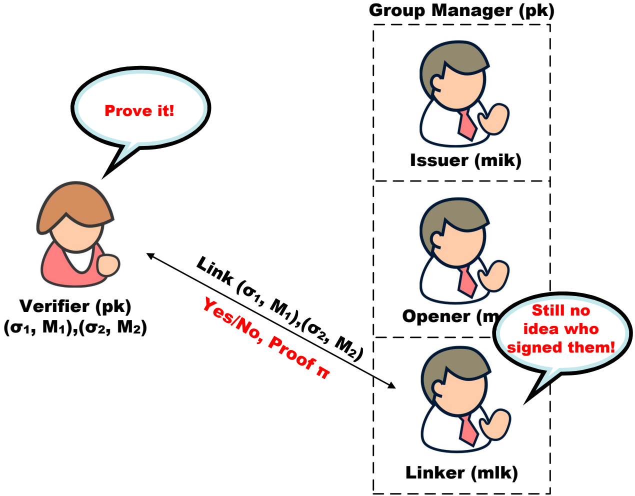

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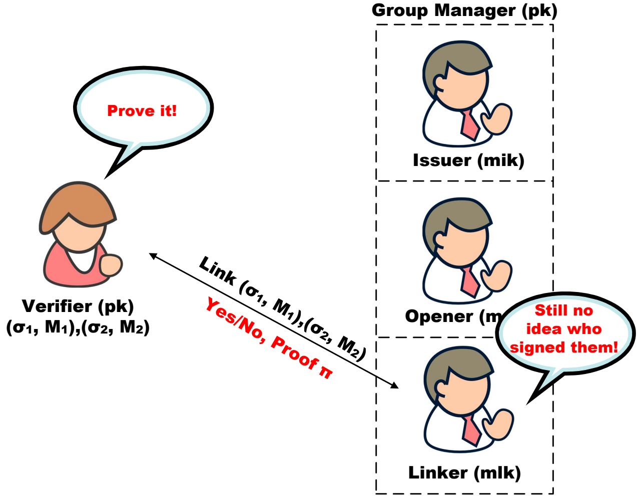

Primitive to prove plaintext (in-)equality

Contributions

1. Model generic proof system for plaintext (in-)equality

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2. Efficient instantiation of this proof system
3. Group signatures with verifiable controllable linkability
4. Extend GSs with verifiable controllable linkability (VCL)

Sign-Encrypt-Prove Paradigm

Basic building blocks

- $\mathcal{DS} = (\mathsf{KG_s}, \mathsf{Sign}, \mathsf{Verify})$

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- User's secret: x_i

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- $gpk \leftarrow (pk_e, pk_s)$, $gmsk \leftarrow sk_e$, $gmik \leftarrow sk_s$

Join

- User's secret: x_i
- Issuer computes: $cert \leftarrow \mathsf{Sign}(gmik, f(x_i))$

Sign-Encrypt-Prove Paradigm I

Sign

- $T \leftarrow \mathrm{Enc}(pk_e, cert)$

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- $\pi \leftarrow SoK\{(x_i, cert) : cert = \mathrm{Sign}(sk_s, f(x_i)) \wedge T = \mathrm{Enc}(pk_e, cert))\}(m)$

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- $\sigma \leftarrow (T, \pi)$

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- "verification of π"

Sign-Encrypt-Prove Paradigm I

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Verify

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Open

- $cert \leftarrow \mathrm{Dec}(sk_e, T)$

Controllable Linkability

Public key encryption with equality tests [Tan12, SSU14]

- Conventional public key encryption scheme

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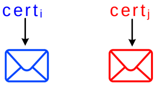
- One-way security for trapdoor holders

$\Rightarrow$ ZK proof of knowledge of trapdoor for VCL

Setting



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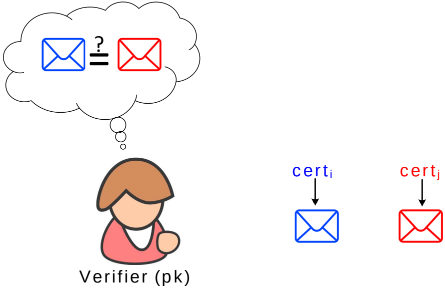

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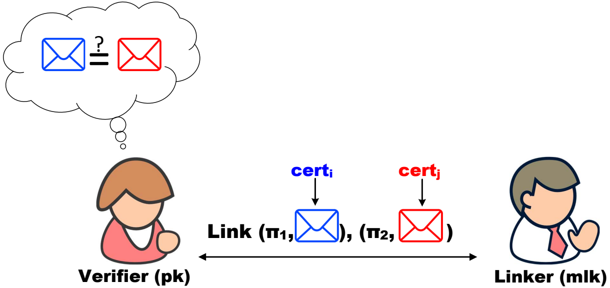

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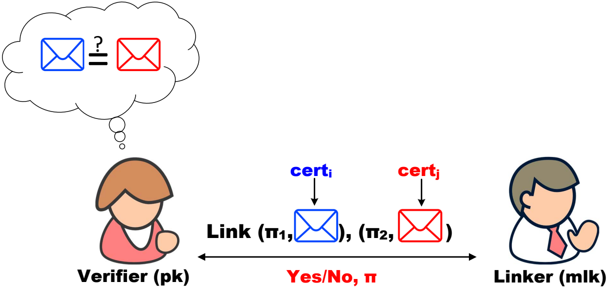

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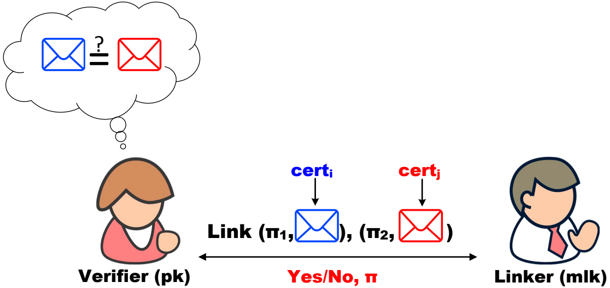

Non-interactive plaintext (in-)equality proofs

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Given any $\mathcal{PKEQ}$ and ciphertexts T and T' under pk

Proof system Π

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Proof system Π

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2. $\mathsf{Com} = 1$ (membership) or $\mathsf{Com} = 0$ (non-membership)
3. Without revealing trapdoor tk

(Non-)Membership Proofs

$\mathsf{Com} = 1$ defines L for membership $((x, w) \in L_R)$

- Witnessed by trapdoor tk
- Standard techniques [GS08]

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- Idea [BCV15]
  - Π_1: Failing membership proof for L_R

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- Efficient instantiations (GS and SPHFs)
- Technicalities: m, r must be known [BCV15]

Smooth Projective Hash Functions (SPHFs)

$w : (x, w) \in R$

Hashing key: hk

Projection key: hp

Verifier

Statement: $x \in L_R$

Prover

$$\xrightarrow{\quad hp \quad}$$

$$H \leftarrow ProjHash(hp, x, w)$$

$$\xleftarrow{\quad H \quad}$$

$$H \stackrel{?}{=} Hash(hk, x)$$

If $x \in L_R : Hash(hk, x) \stackrel{!}{=} ProjHash(hp, x, w)$

(Correctness)

Construction - Non-Membership Proof

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$$\text{Verifier} \xrightarrow{hp} \text{Prover}$$

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$$\pi_1 = Proof((hp, x, H), w)$$

$$\text{Verifier} \xleftarrow{H} \text{Prover}$$

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Construction - Non-Membership Proof

Hashing key: *hk*
Projection key: *hp*

Verifier

Statement: $x \in L_R$

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$$\xrightarrow{\quad hp \quad}$$

$$H \leftarrow ProjHash(hp, x, w)$$

$$\xleftarrow{\quad H, \pi_1 \quad} \qquad \pi_1 = Proof((hp, x, H), w)$$

$$H \overset{?}{\neq} Hash(hk, x) \ \wedge \ Verify((hp, x, H), \pi_1) \overset{?}{=} 1$$

Construction - Non-Membership Proof

Hashing key: hk
Projection key: hp $\longrightarrow$

Verifier

Statement: $x \in L_R$

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$$\xrightarrow{\quad hp \quad}$$

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$\xleftarrow{H, \pi_1}$

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Construction - Non-Membership Proof

Hashing key: hk

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$H' \leftarrow Hash(hk, x)$

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H, π_1 ←

$\pi_1 = Proof((hp, x, H), w)$

Construction - Non-Membership Proof

Hashing key: $\color{red}{hk}$

Projection key: $\color{blue}{hp}$

Verifier

Statement: $x \in L_R$

Prover

$H' \leftarrow Hash(\color{red}{hk}, x)$

$H \leftarrow ProjHash(\color{blue}{hp}, x, w)$

$\pi_1 = Proof((\color{blue}{hp}, x, H), w)$

$$\xleftarrow{\quad H, H', \color{blue}{hp}, \pi_1 \quad}$$

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Construction - Non-Membership Proof

Hashing key: hk

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Statement: $x \in L_R$

Prover

$H' \leftarrow Hash(hk, x)$

$\pi_2 \leftarrow Proof((H' \wedge hp), hk)$

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$\xleftarrow{H, H', hp, \pi_1}$

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$$\xleftarrow{\quad H,\, H',\, hp,\, \pi_1,\, \pi_2 \quad}$$

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Example of Efficient Instantiation

ElGamal with equality tests (as in [SSU14])

- Keypair: $(sk, pk) \leftarrow (x, g^x) \in \mathbb{Z}_p \times \mathbb{G}_1$
- Trapdoor: $(\hat{r}, \hat{r}^x) \in \mathbb{G}_2 \times \mathbb{G}_2$
- Encryption of m: $(g^r, m \cdot g^{x \cdot r}) \in \mathbb{G}_1 \times \mathbb{G}_1$

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Pairing based equality test:

- Ciphertexts: $(g^{r}, m \cdot g^{x \cdot r}), (g^{r'}, m' \cdot g^{x \cdot r'})$

$$m = m' \iff \frac{e(m \cdot g^{x \cdot r}, \hat{r})}{e(g^{r}, \hat{r}^{x})} = \frac{e(m' \cdot g^{x \cdot r'}, \hat{r})}{e(g^{r'}, \hat{r}^{x})}$$

Instantiation of $\Pi_\in$

Com = 1: plaintext equality proof

$$((g^{r}, m \cdot g^{x \cdot r}), (g^{r'}, m' \cdot g^{x \cdot r'}), g^{x}) \in L_{\in} \iff$$

$$\frac{e(m \cdot g^{x \cdot r}, \hat{r})}{e(g^{r}, \hat{r}^{x})} = \frac{e(m' \cdot g^{x \cdot r'}, \hat{r})}{e(g^{r'}, \hat{r}^{x})} \quad \wedge$$

$$e(g, \hat{r}^{x}) = e(g^{x}, \hat{r})$$

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$$e(g, \hat{r}^{x}) = e(g^{x}, \hat{r})$$

$$\prod_{i=1}^{2} e(A_i, \underline{\hat{Y}_i}) = \frac{e(m \cdot g^{x \cdot r} \cdot (m' \cdot g^{x \cdot r'})^{-1}, \hat{r})}{e(g^{r} \cdot g^{-r'}, \hat{r}^{x})} = 1_{\mathbb{G}_T}$$

Instantiation of $\Pi_{\notin}$

Com $=0$: plaintext inequality proof

$$((g^{r}, m \cdot g^{x \cdot r}), (g^{r'}, m' \cdot g^{x \cdot r'}), g^{x}) \in L_{\notin} \iff$$

$$\frac{e(m \cdot g^{x \cdot r}, \hat{r})}{e(g^{r}, \hat{r}^{x})} \neq \frac{e(m' \cdot g^{x \cdot r'}, \hat{r})}{e(g^{r'}, \hat{r}^{x})} \quad \wedge$$

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Instantiation of $\Pi_{\notin}$

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$$e(g, \hat{r}^{x}) = e(g^{x}, \hat{r})$$

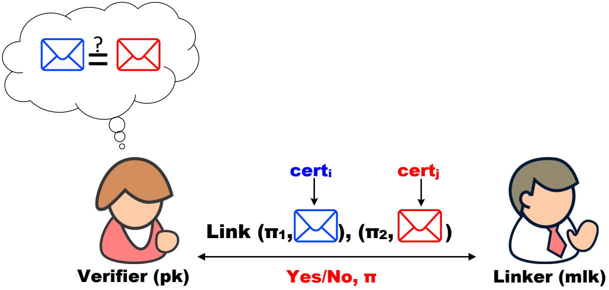
$\Rightarrow$ Our construction for non-membership proofs

NIPEI Proof System

Proof system $\Pi = (\Pi_{\in}, \Pi_{\notin})$

NIPEI Proof System

Proof system $\Pi = (\Pi_{\in}, \Pi_{\notin})$



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GSSs with Verifiable Controllable Linkability

Extended security model for VCL-GS

- Algorithms: Link and $\mathsf{Link}_{\mathsf{Judge}}$
- Property: linking soundness

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Instantiation based on NIPEI

- Link: Π.Proof
- $\text{Link}_{\text{Judge}}$: Π.Verify

Take-Home Message

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- Also works for DLIN and CCA-secure ElGamal variants
  - Compatible with Naor-Yung paradigm (for free)

Take-Home Message

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- Efficient instantiation in the pairing setting
- Also works for DLIN and CCA-secure ElGamal variants
  - Compatible with Naor-Yung paradigm (for free)
- Novel application
  - GSSs with verifiable controllable linkability

Non-Interactive Plaintext (In-)Equality Proofs and Group Signatures with Verifiable Controllable Linkability

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