FROST Research Updates

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What is FROST?

- **<u>F</u>**lexible **<u>R</u>**ound-**<u>O</u>**ptimized **<u>S</u>**chnorr **<u>T</u>**hreshold **<u>S</u>**ignatures [Komlo & Goldberg, 2020]

eprint.iacr.org/2020/852

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  1. PedPop: Distributed Key Generation (DKG)

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    1. PedPop: Distributed Key Generation (DKG)
    2. Two-round threshold signing that is concurrently secure

eprint.iacr.org/2020/852

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- **F**lexible **R**ound-**O**ptimized **S**chnorr **T**hreshold **S**ignatures [Komlo & Goldberg, 2020]
    1. PedPop: Distributed Key Generation (DKG)
    2. Two-round threshold signing that is concurrently secure
- Designed to solve needs in the Zcash ecosystem; now adopted as an industry standard

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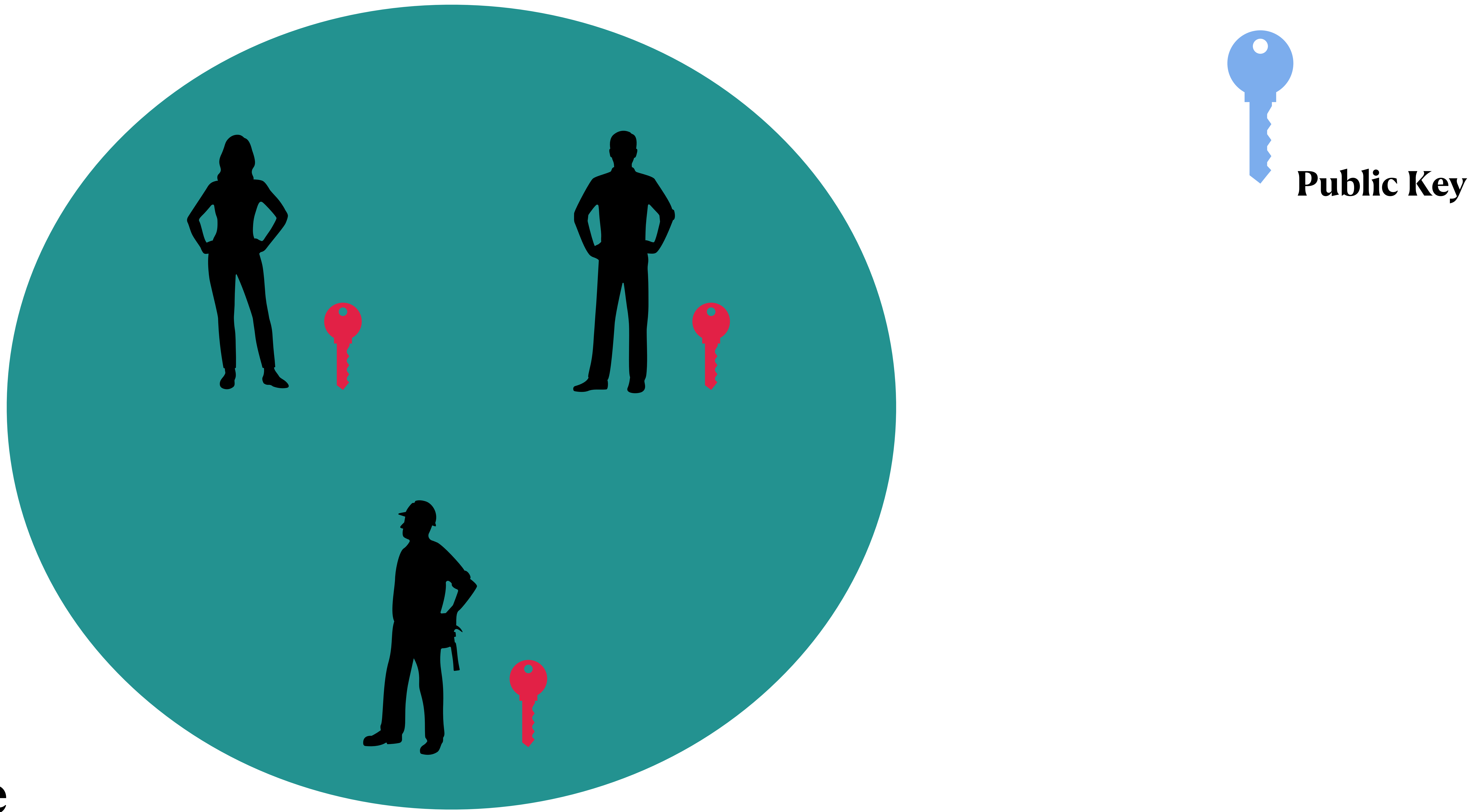
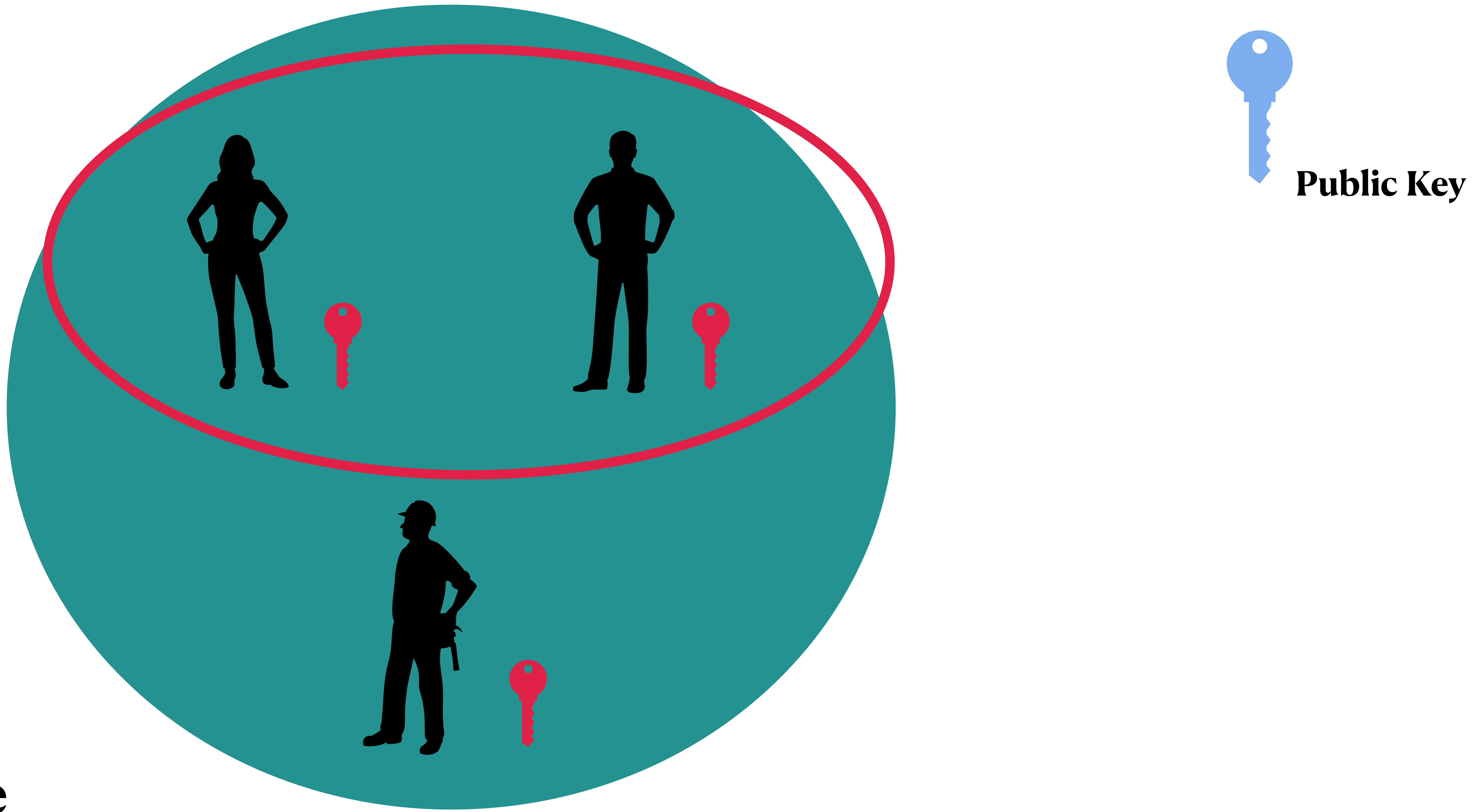
What are Threshold Signatures?



(2,3) Example

What are Threshold Signatures?



(2,3) Example

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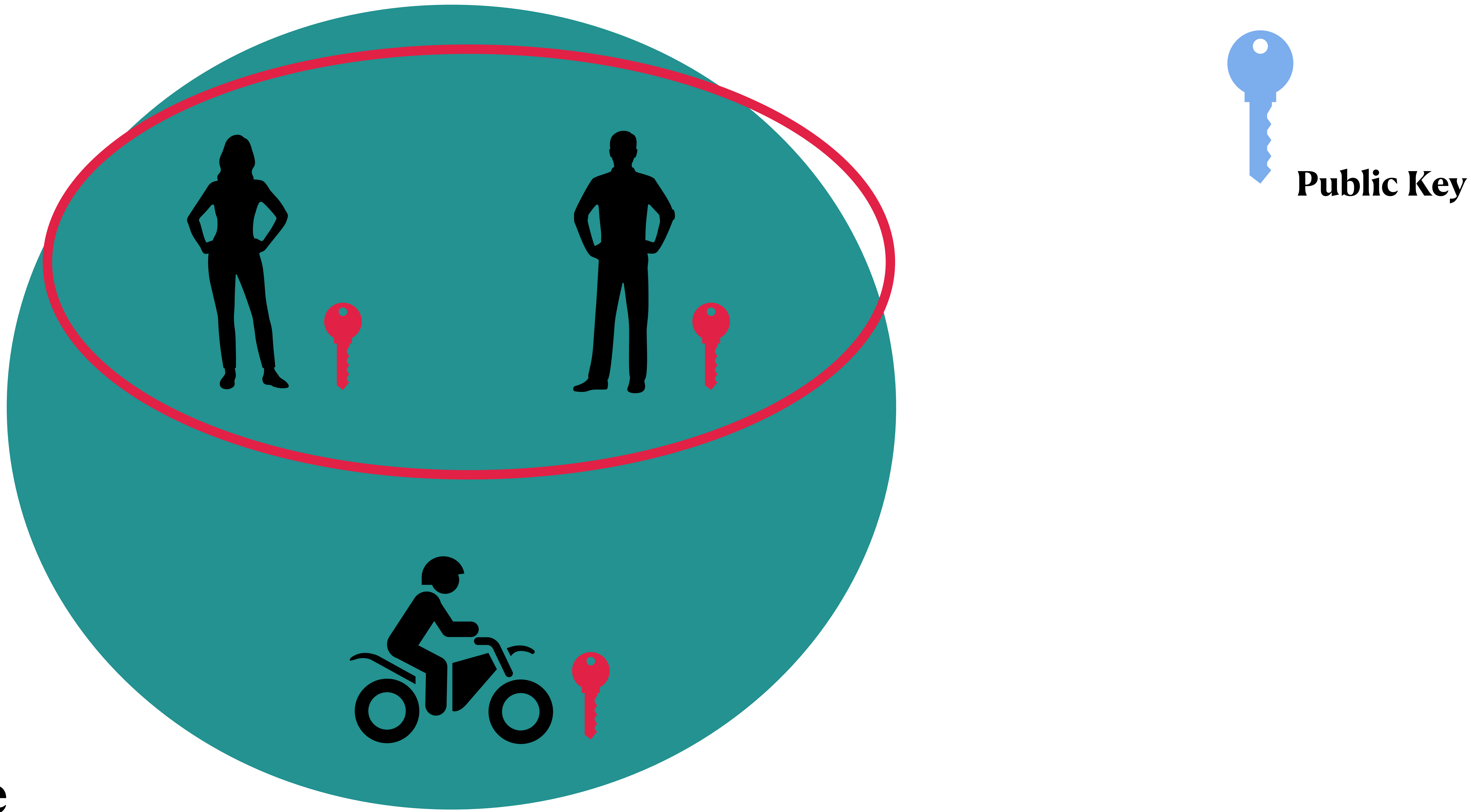
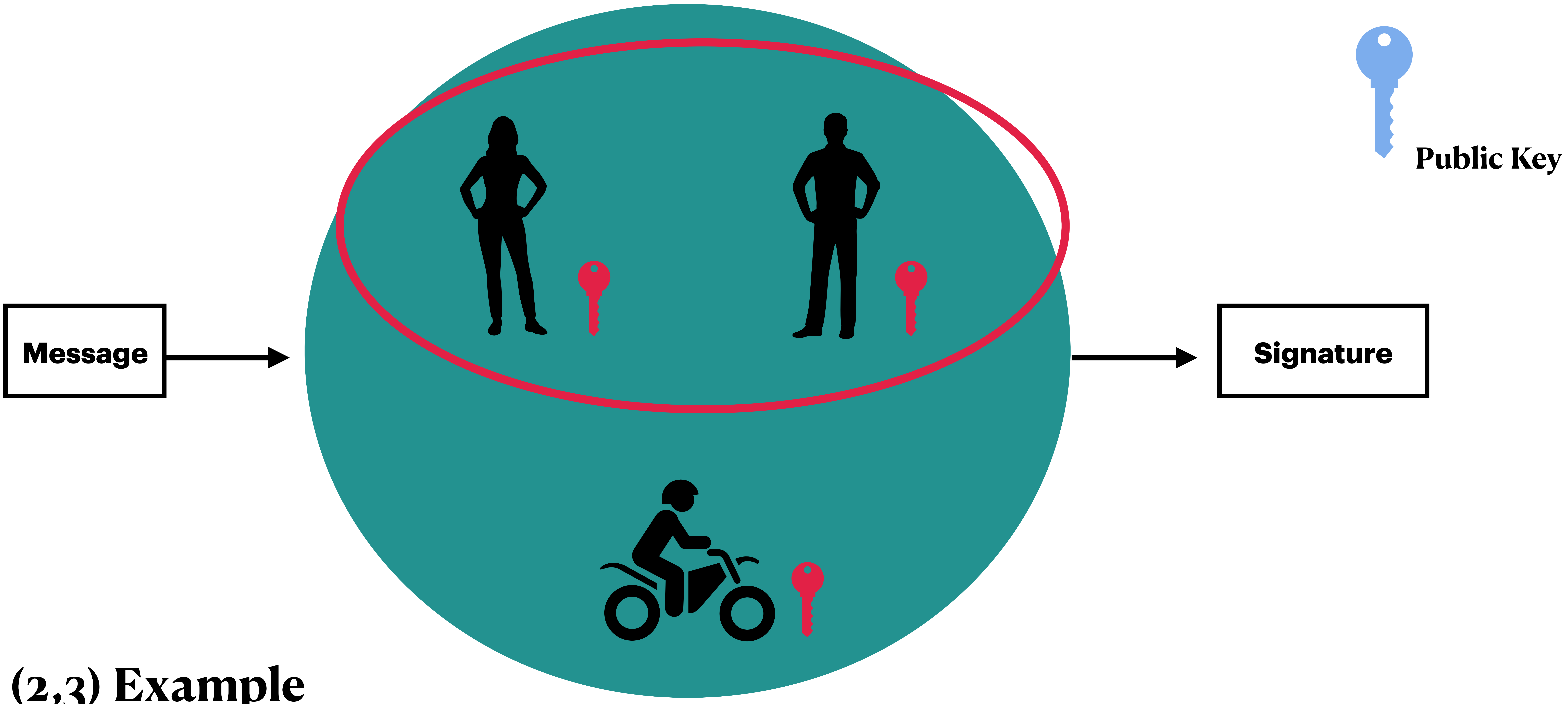


(2,3) Example

What are Threshold Signatures?



(2,3) Example

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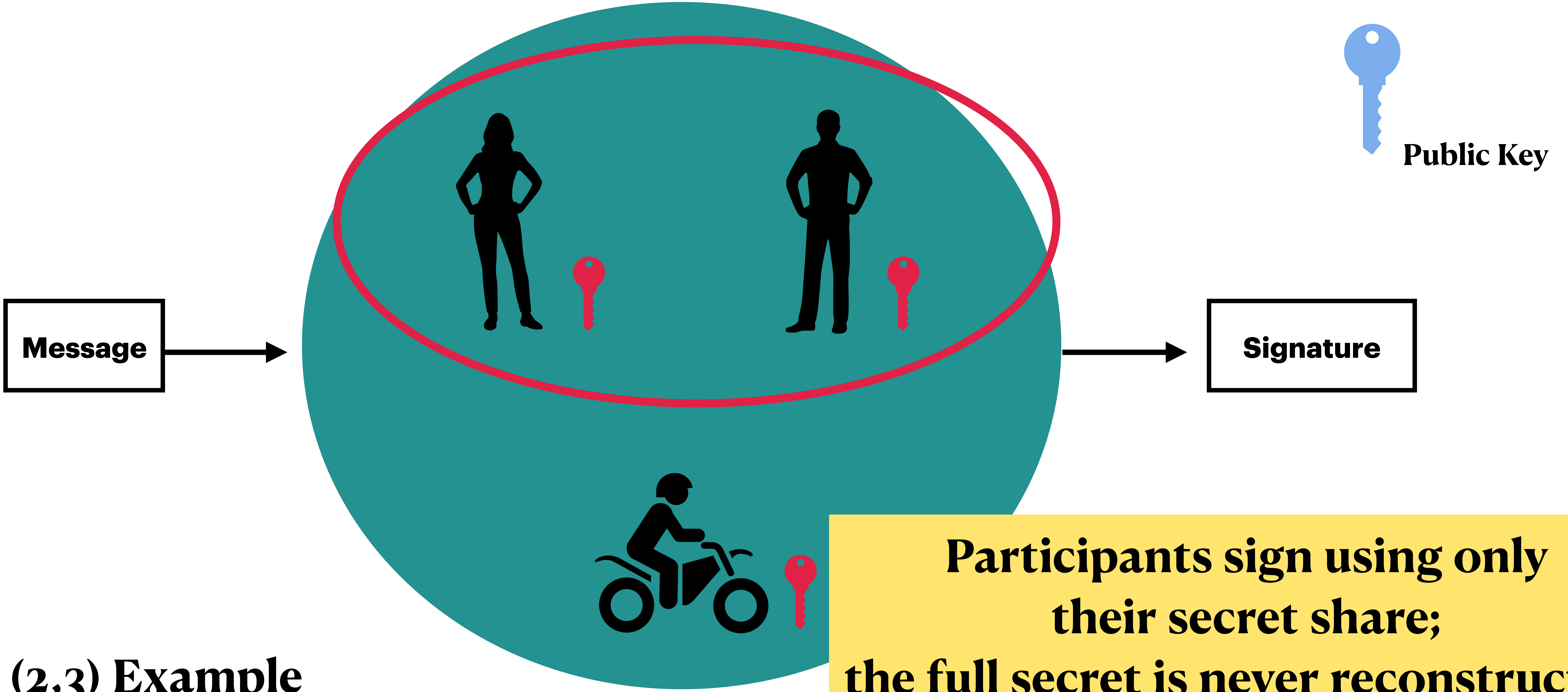
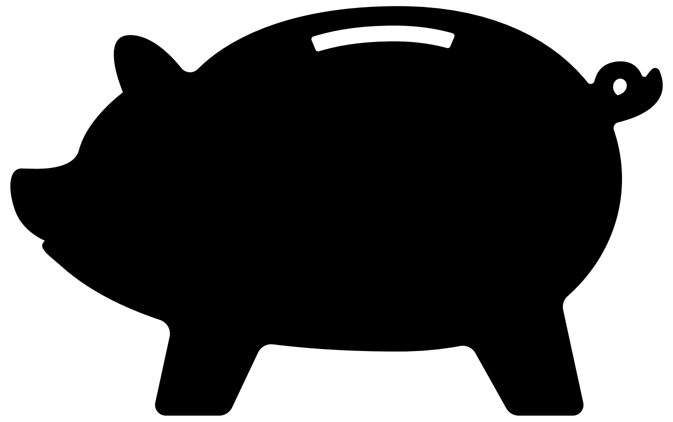


(2,3) Example

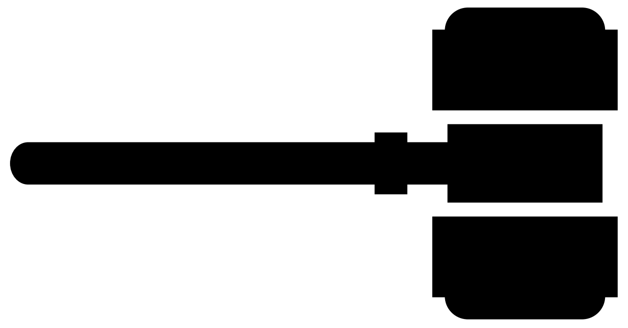
Participants sign using only their secret share; the full secret is never reconstructed!

Uses for Threshold Signatures

Banks and Exchanges



Cryptocurrency Wallets



Trust Authorities (CAs)

Where was FROST Last Year?

Paper Published (FROST1)

Presented to NIST

IETF Draft Started

Where is FROST *Now?*

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Where is FROST *Now?*

5+ Implementations

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Additional Security Proofs

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Robust FROST (ROAST)

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Where is FROST *Now?*

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Threshold BLS & PedPop

Where is FROST *Now?*

- 5+ Implementations
- Optimized FROST2
- Robust FROST (ROAST)
- Paper Published (FROST1)
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- IETF Draft Started
- Unlinkable FROST
- Additional Security Proofs
- IETF Draft Almost Done
- Threshold BLS & PedPop

Where is FROST *Now?*

5+ Implementations

Optimized FROST2

Practical use!

Robust FROST (ROAST)

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Threshold BLS & PedPop

How to Prove Schnorr Assuming Schnorr: Security of Multi- and Threshold Signatures

Elizabeth Crites, Chelsea Komlo, Mary Maller

eprint.iacr.org/2021/1375

(Single-Party) Schnorr Signature Scheme

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To generate a key pair:

$$sk \xleftarrow{\$} \mathbb{F}\ ;\ \ PK \leftarrow g^{sk}$$

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To sign a message m:

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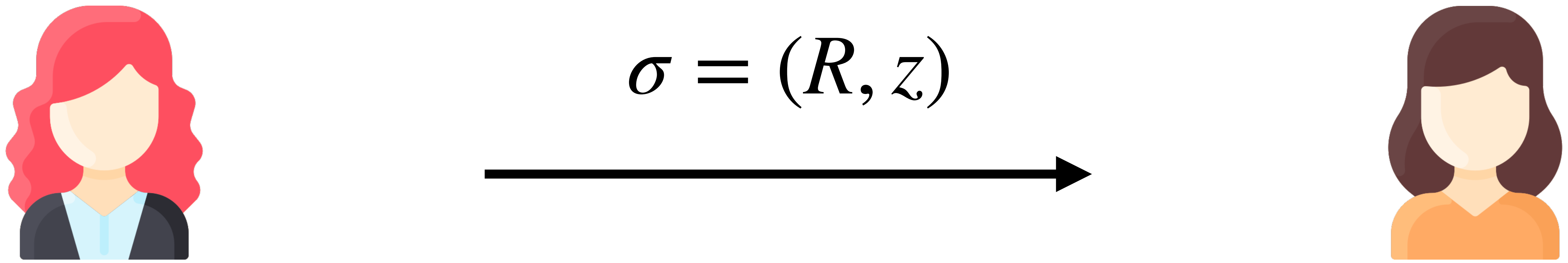
$$c \leftarrow H(PK, m, R)$$

$$z \leftarrow r + c\,sk$$

(Single-Party) Schnorr Signature Scheme



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(Single-Party) Schnorr Signature Scheme

$$\xrightarrow{\sigma = (R, z)}$$

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To sign a message m:

$$r \xleftarrow{\$} \mathbb{F}\ ;\ \ R \leftarrow g^{r}$$

$$c \leftarrow H(PK, m, R)$$

$$z \leftarrow r + csk$$

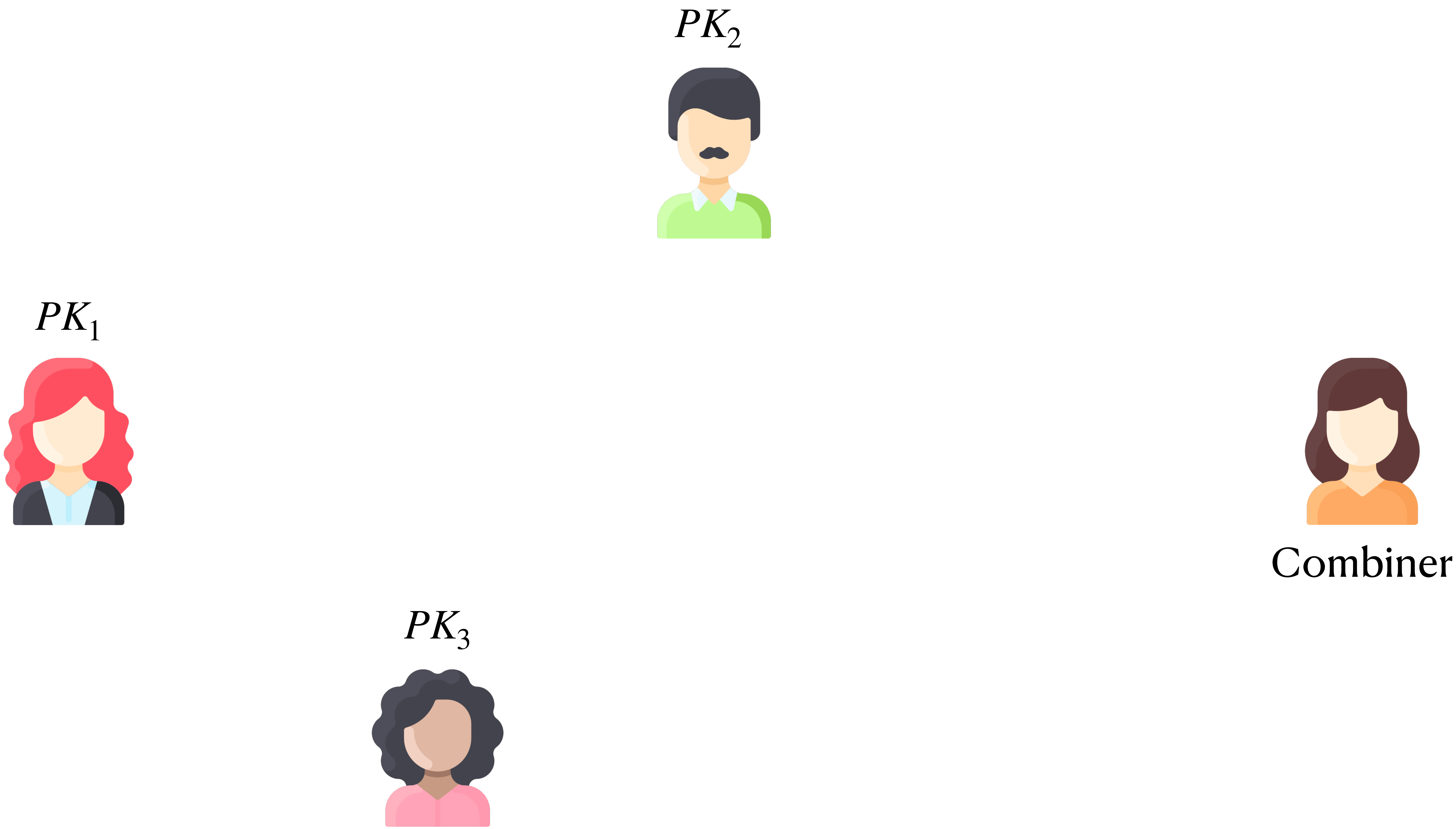
To verify (PK, σ, m):

$$c \leftarrow H(PK, m, R)$$

$$R \cdot PK^{c} \stackrel{?}{=} g^{z}$$

output accept/reject

Attempt: Multi-Party Schnorr



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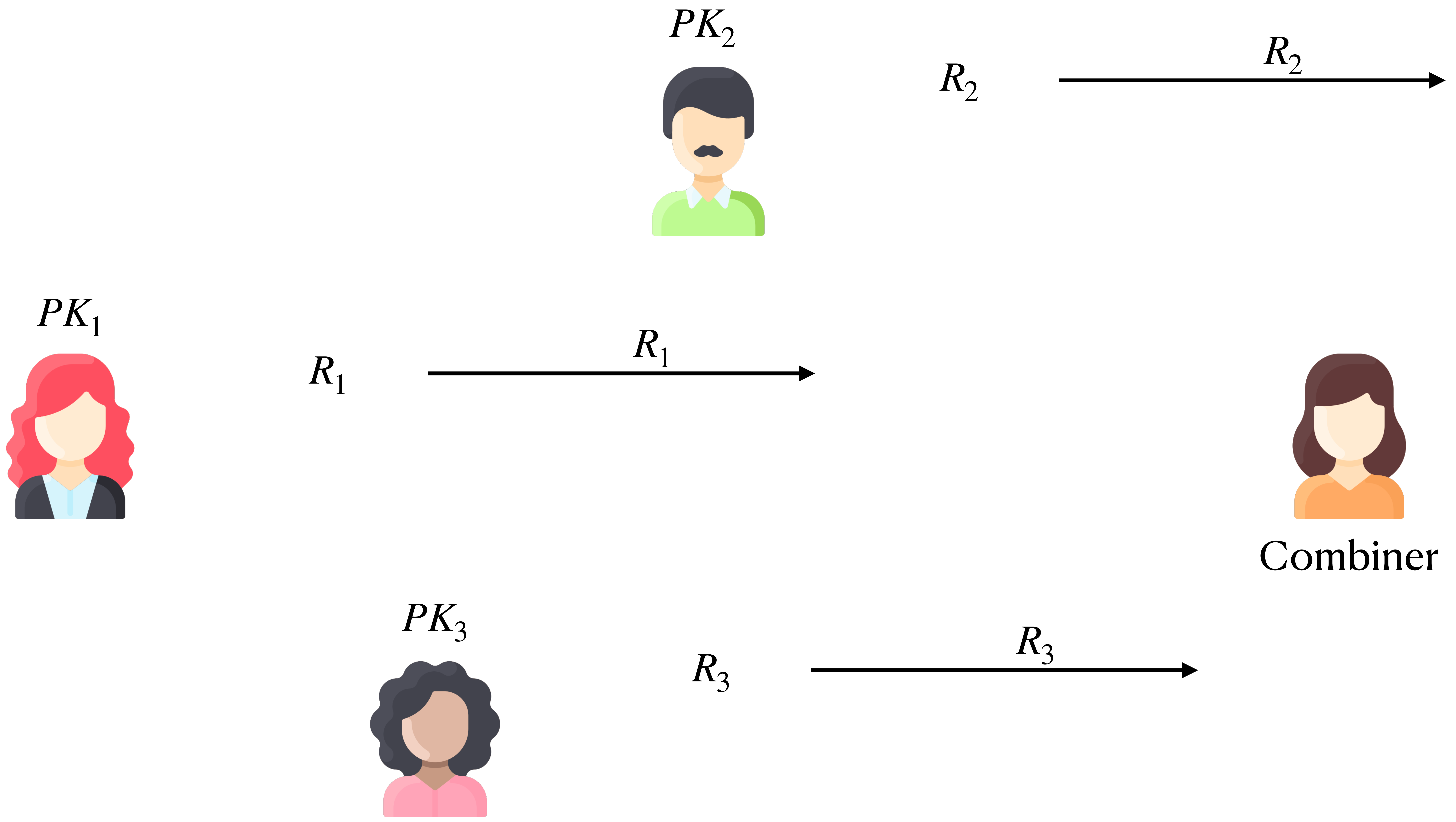


Attempt: Multi-Party Schnorr

PK_2

R_2

$z_2 \leftarrow r_2 + csk_2$

$\xrightarrow{R_2}$

$\xleftarrow{c}$

w/ proof of possession of sk_j

PK_1

R_1

$z_1 \leftarrow r_1 + csk_1$

$\xrightarrow{R_1}$

$\xleftarrow{c}$

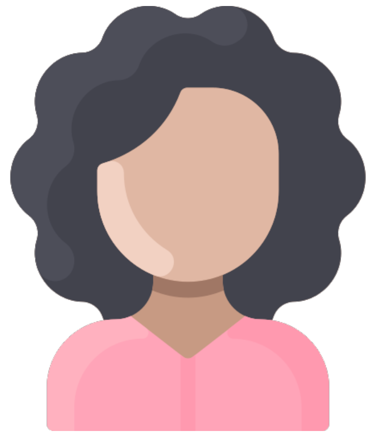
$\tilde{PK} = PK_1 PK_2 PK_3$

$\tilde{R} = R_1 R_2 R_3$

$c \leftarrow H(\tilde{PK}, m, \tilde{R})$

Combiner

PK_3



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Combiner

w/ proof of possession of sk_j

$$\tilde{PK} = PK_1 PK_2 PK_3$$
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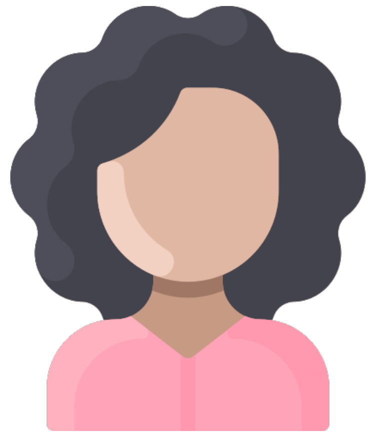
PK_3



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$z_2 \leftarrow r_2 + csk_2$

$\xrightarrow{R_2}$

$\xleftarrow{c}$

$\xrightarrow{z_2}$

w/ proof of possession of sk_j

PK_1

R_1

$z_1 \leftarrow r_1 + csk_1$

$\xrightarrow{R_1}$

$\xleftarrow{c}$

$\xrightarrow{z_1}$

Combiner

$$\tilde{PK} = PK_1 PK_2 PK_3$$
$$\tilde{R} = R_1 R_2 R_3$$
$$c \leftarrow H(\tilde{PK}, m, \tilde{R})$$
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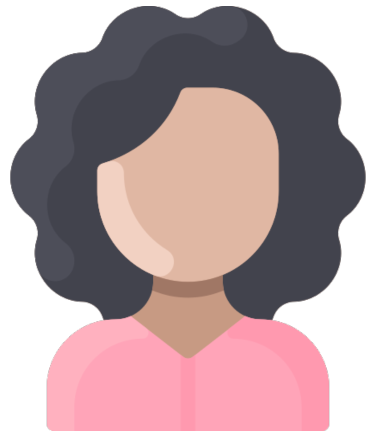
$$\sigma = (\tilde{R}, z)$$

PK_3



R_3

$z_3 \leftarrow r_3 + csk_3$

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$\xleftarrow{c}$

$\xrightarrow{z_3}$

Verify $(\tilde{PK}, \sigma, m)$:

$$c \leftarrow H(\tilde{PK}, m, \tilde{R})$$
$$\tilde{R} \cdot \tilde{PK}^c \stackrel{?}{=} g^z$$

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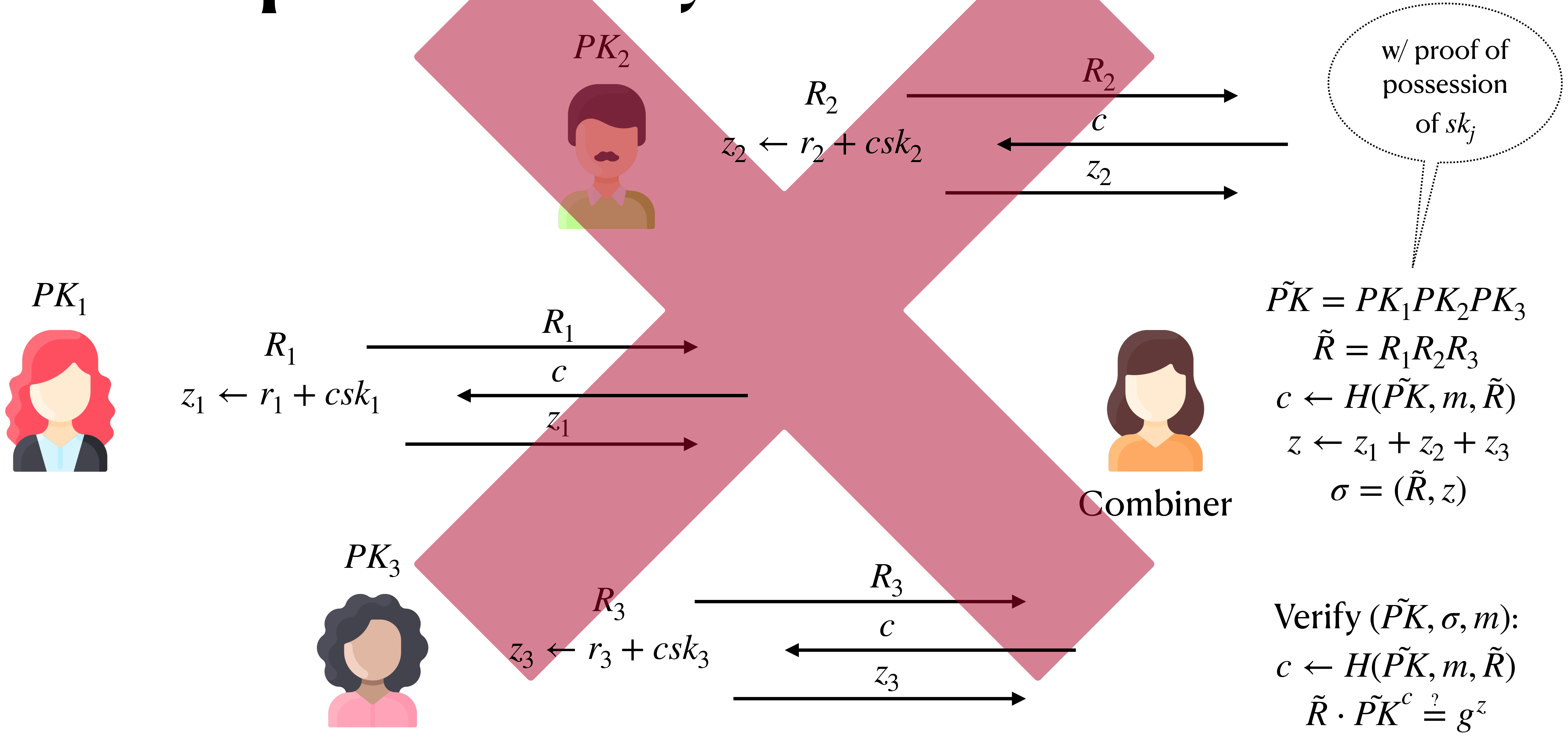
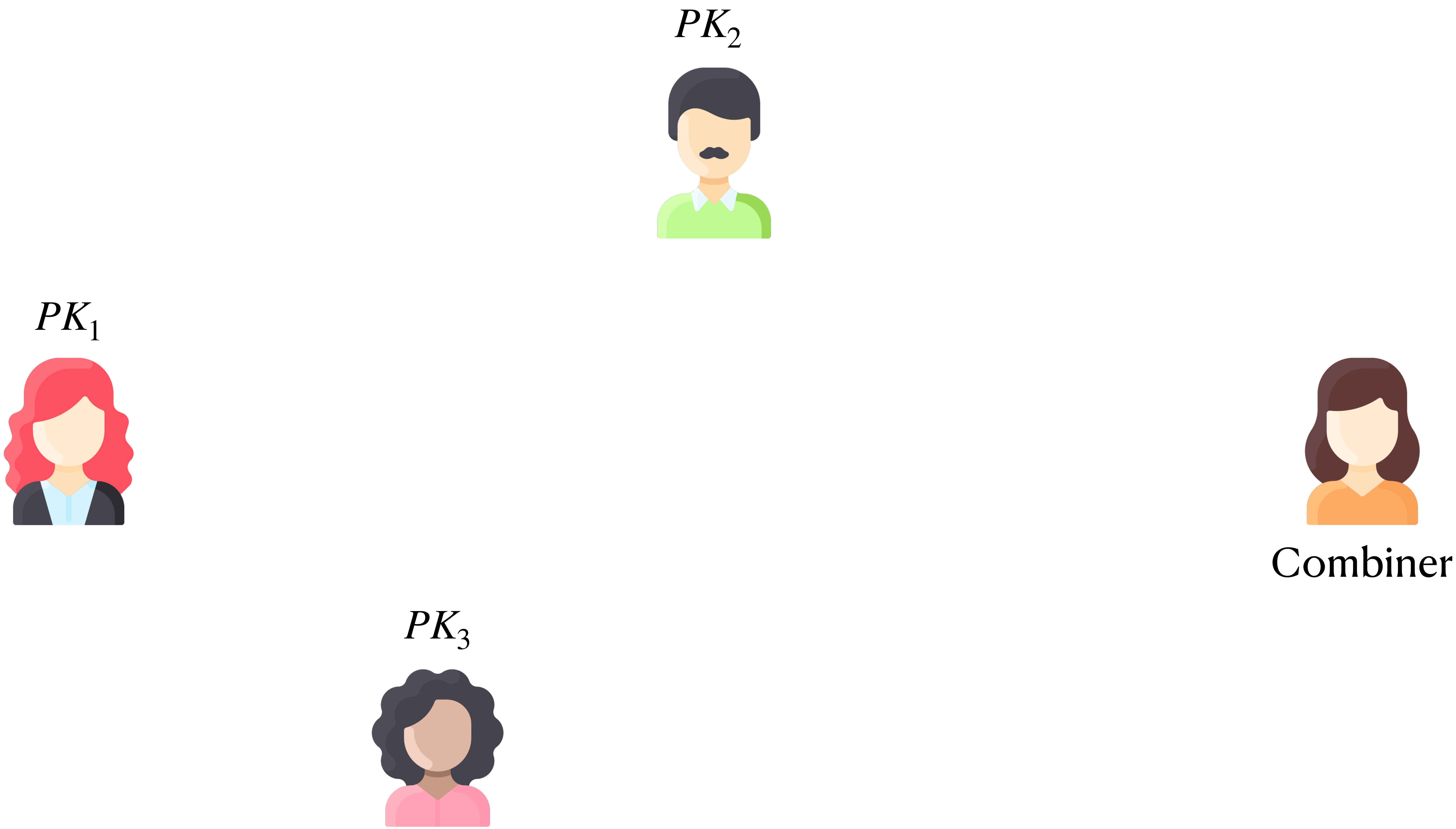


ROS Attack

- ROS problem originally stated in [Schnorr91]
- Drijvers et al. [DEFKLNS19] show how to break unforgeability
- confirmed polynomial-time attack by Benhamouda et al. [BLOR20]
- concurrent attack:
    - adversary opens multiple signing sessions at once
    - sees honest nonces first and makes its nonce a function of them
    - forges signature

Fix #1: 3 Rounds



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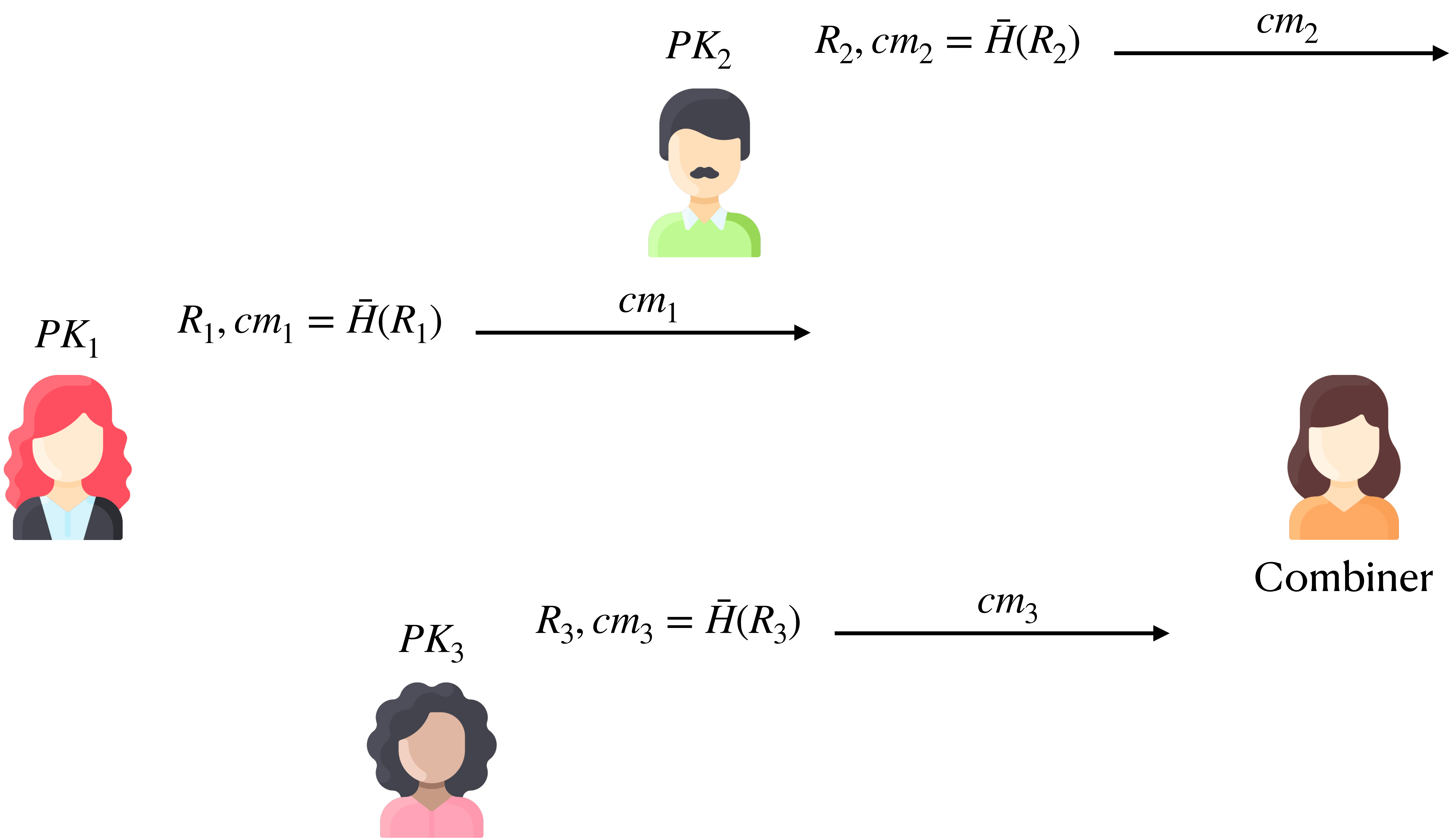

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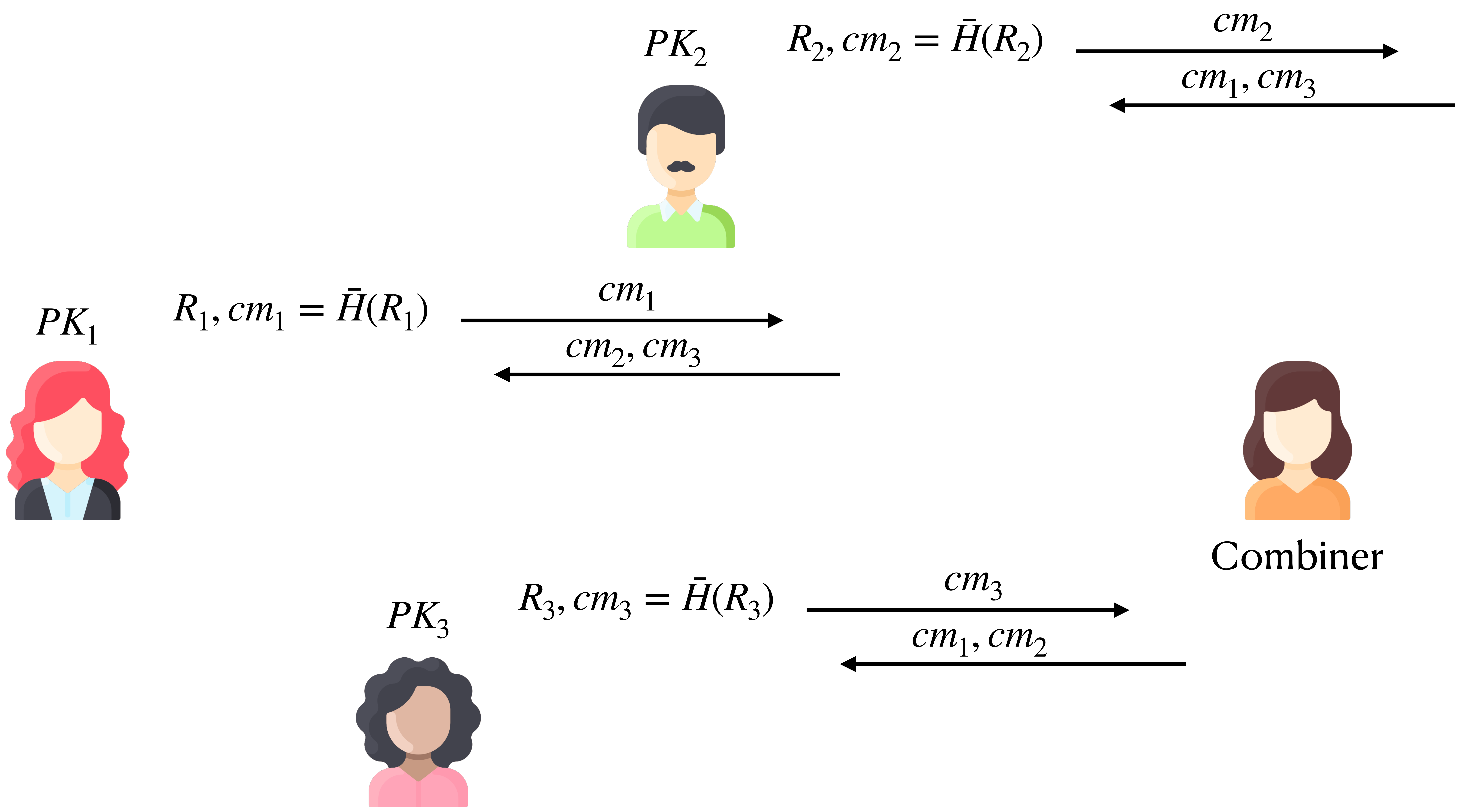

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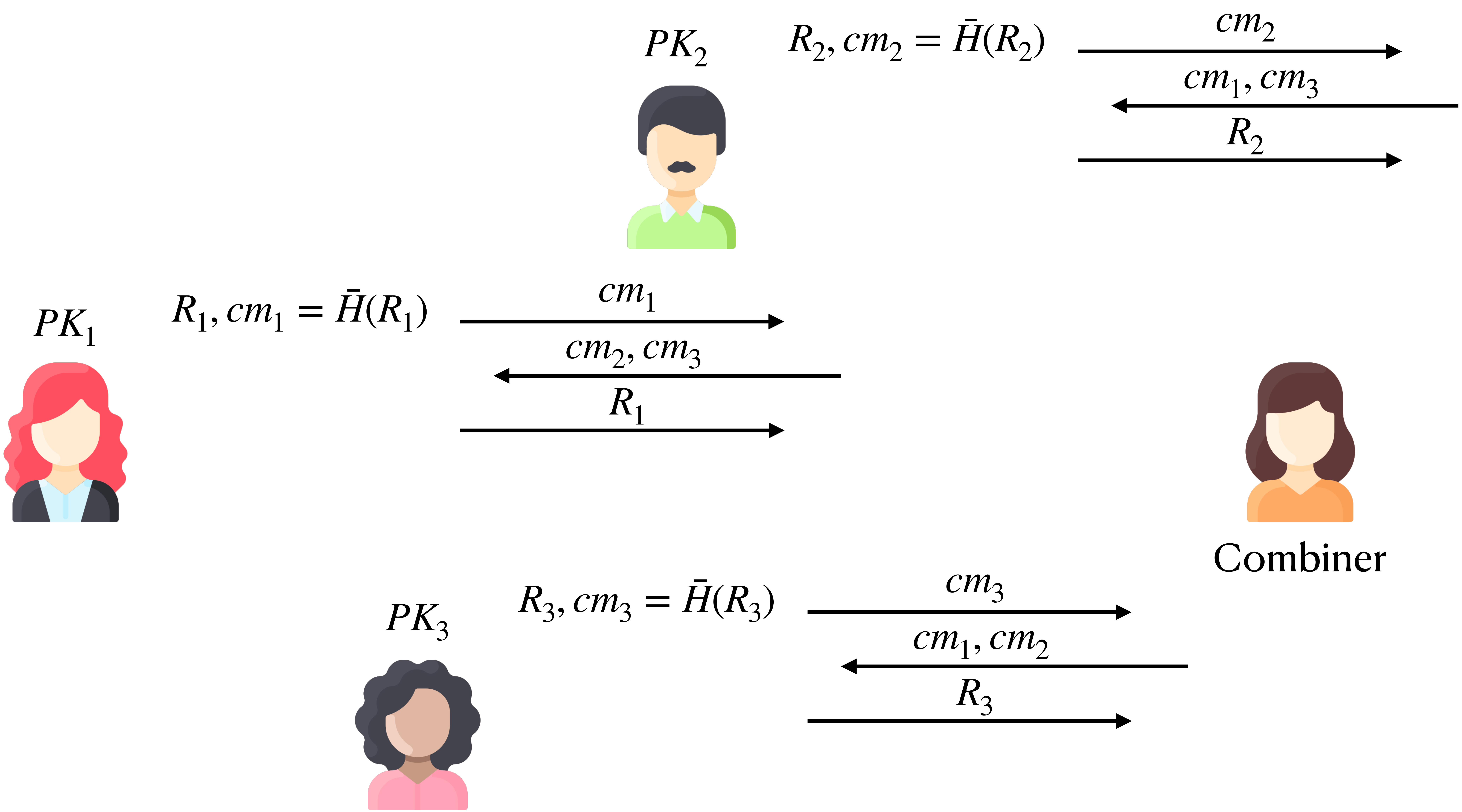

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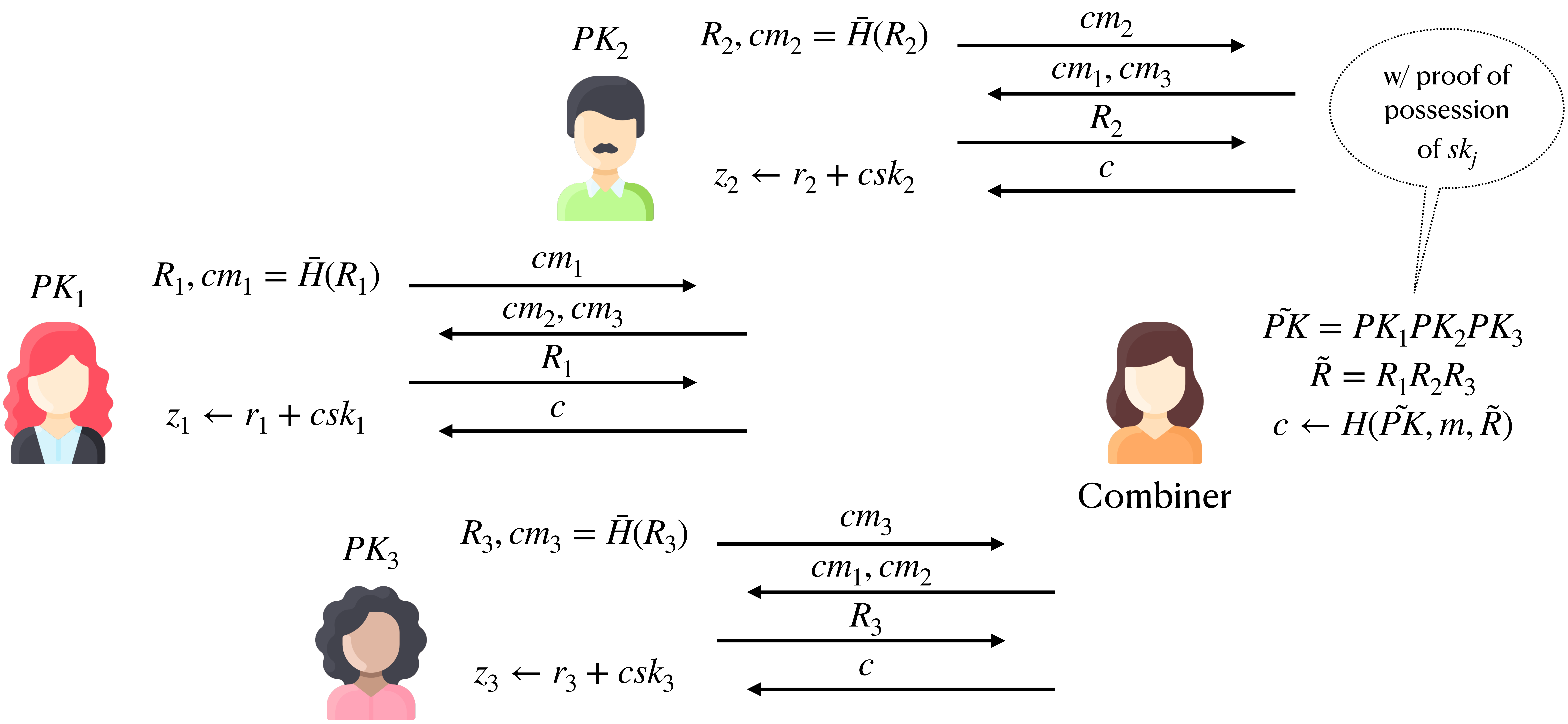

Fix #1: 3 Rounds

PK_2

$R_2, cm_2 = \bar{H}(R_2)$ $\xrightarrow{cm_2}$

$\xleftarrow{cm_1, cm_3}$

$\xrightarrow{R_2}$

$z_2 \leftarrow r_2 + csk_2$ $\xleftarrow{c}$

$\xrightarrow{z_2}$

PK_1

$R_1, cm_1 = \bar{H}(R_1)$ $\xrightarrow{cm_1}$

$\xleftarrow{cm_2, cm_3}$

$\xrightarrow{R_1}$

$z_1 \leftarrow r_1 + csk_1$ $\xleftarrow{c}$

$\xrightarrow{z_1}$

PK_3

$R_3, cm_3 = \bar{H}(R_3)$ $\xrightarrow{cm_3}$

$\xleftarrow{cm_1, cm_2}$

$\xrightarrow{R_3}$

$z_3 \leftarrow r_3 + csk_3$ $\xleftarrow{c}$

$\xrightarrow{z_3}$

Combiner

w/ proof of possession of sk_j

$\tilde{PK} = PK_1 PK_2 PK_3$

$\tilde{R} = R_1 R_2 R_3$

$c \leftarrow H(\tilde{PK}, m, \tilde{R})$

$z \leftarrow z_1 + z_2 + z_3$

$\sigma = (\tilde{R}, z)$

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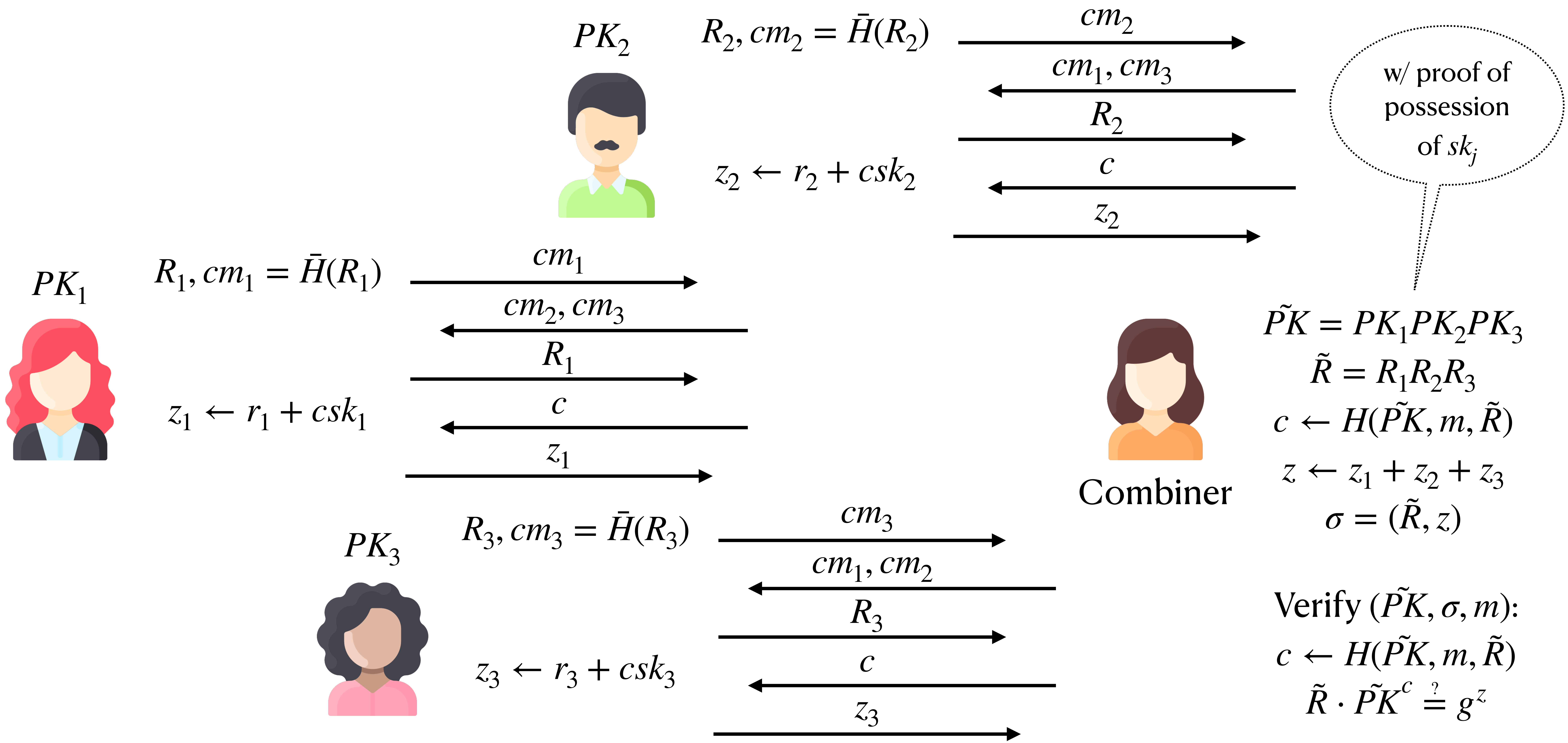
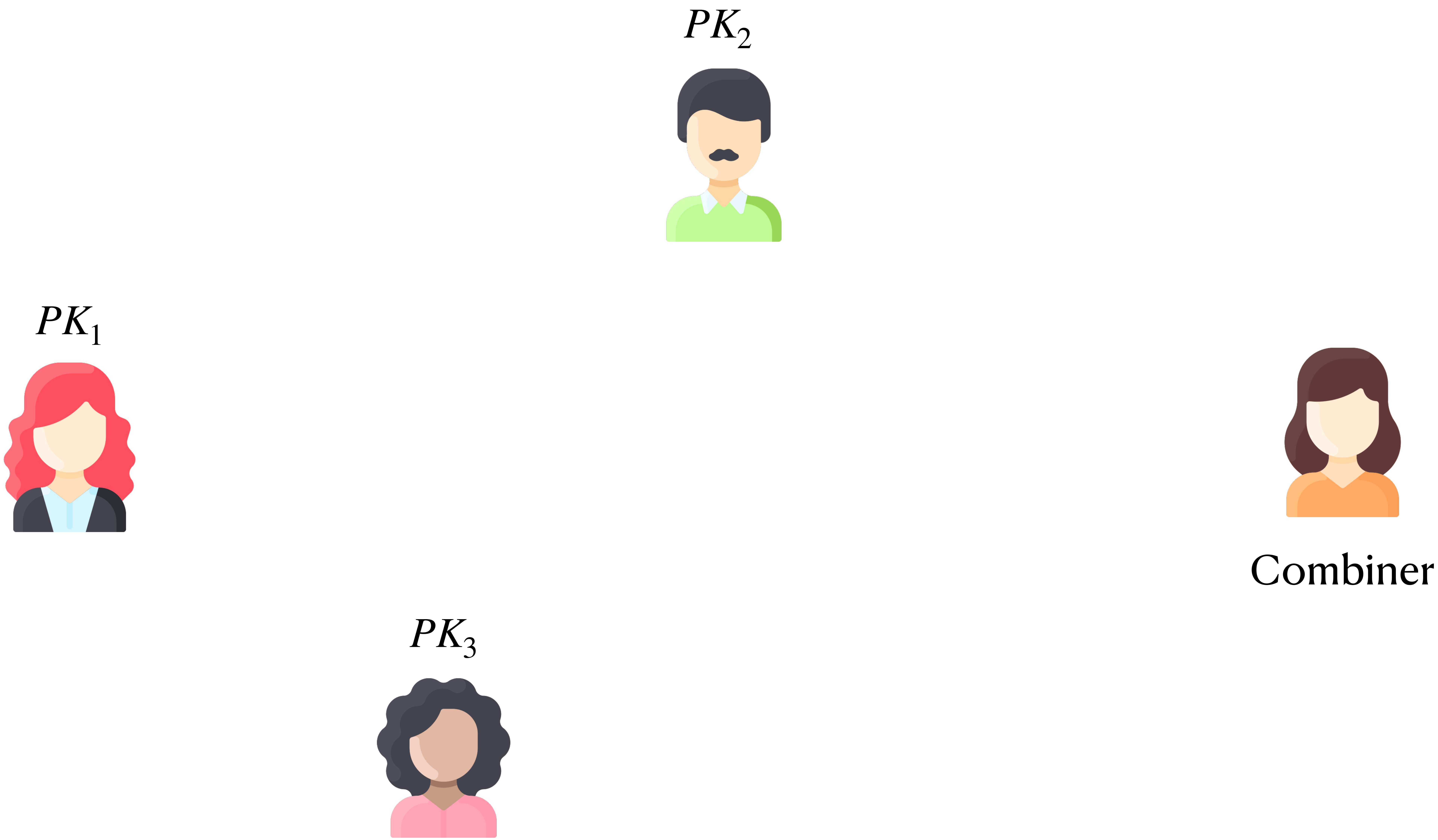


"How to Prove Schnorr Assuming Schnorr"

Elizabeth Crites, Chelsea Komlo, Mary Maller

- Our Contributions:
  - 3-round (n,n) multisignature SimpleMuSig (with PoP of keys)
  - 3-round (t,n) threshold signature SimpleTSig (with PedPoP)

Fix #2: 2 Nonces (“FROST”)



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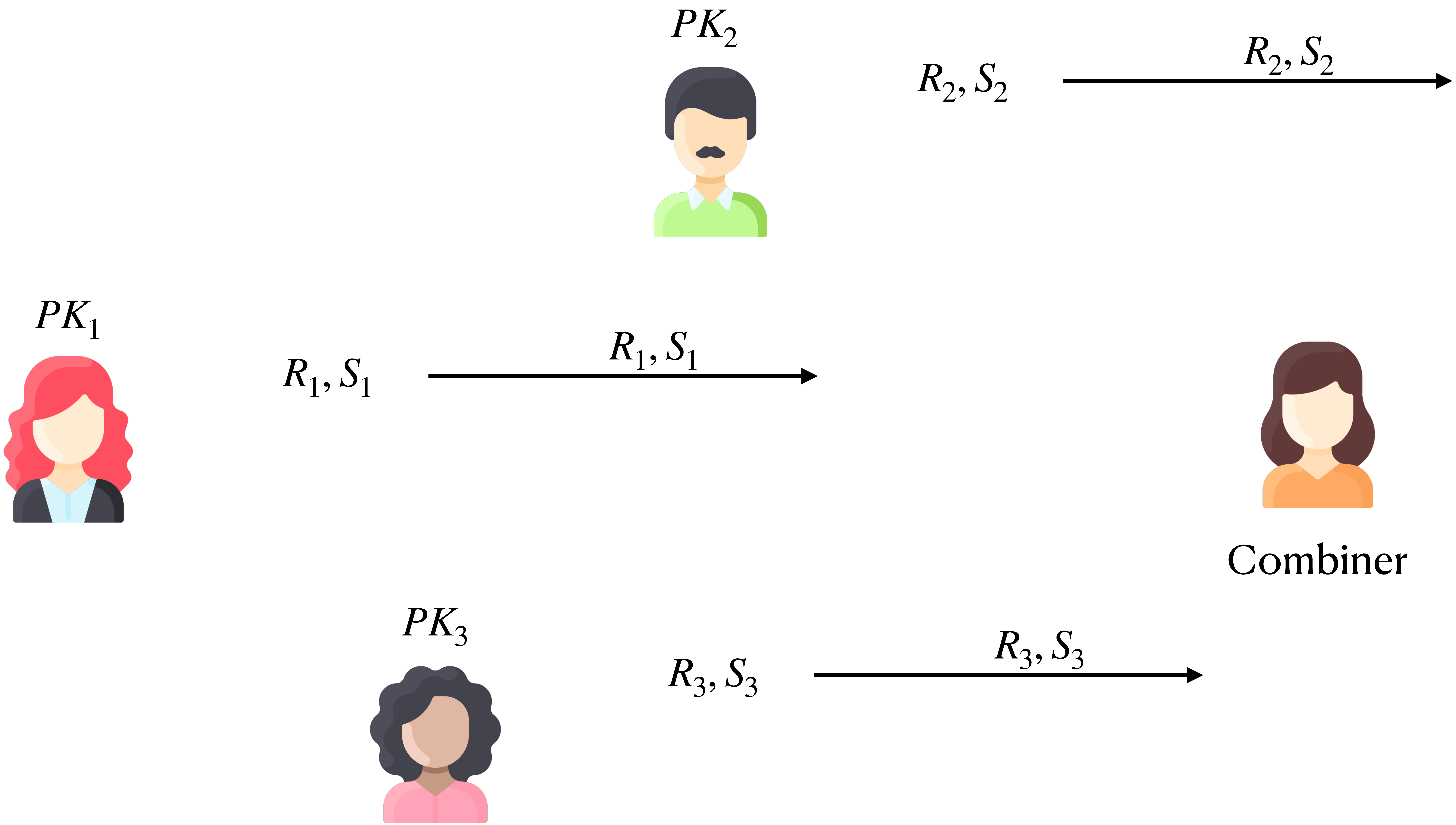

Fix #2: 2 Nonces ("FROST")

PK_2

R_2, S_2 $\xrightarrow{R_2, S_2}$

$z_2 \leftarrow r_2 + a_2 s_2 + c sk_2$ $\xleftarrow{c}$

PK_1

R_1, S_1 $\xrightarrow{R_1, S_1}$

$z_1 \leftarrow r_1 + a_1 s_1 + c sk_1$ $\xleftarrow{c}$

PK_3

R_3, S_3 $\xrightarrow{R_3, S_3}$

$z_3 \leftarrow r_3 + a_3 s_3 + c sk_3$ $\xleftarrow{c}$

w/ proof of possession of sk_j

$$\tilde{PK} = PK_1 PK_2 PK_3$$
$$a_j = \tilde{H}(j, \tilde{PK}, m, \{R_j, S_j\}_1^3)$$
$$\tilde{R} = \Pi_1^3 R_j S_j^{a_j}$$
$$c \leftarrow H(\tilde{PK}, m, \tilde{R})$$

Combiner

Fix #2: 2 Nonces (“FROST”)

w/ proof of possession of sk_j

PK_2

R_2, S_2 $\xrightarrow{R_2, S_2}$

$z_2 \leftarrow r_2 + a_2 s_2 + c sk_2$ $\xleftarrow{c}$

$\xrightarrow{z_2}$

PK_1

R_1, S_1 $\xrightarrow{R_1, S_1}$

$z_1 \leftarrow r_1 + a_1 s_1 + c sk_1$ $\xleftarrow{c}$

$\xrightarrow{z_1}$

Combiner

$$\tilde{PK} = PK_1 PK_2 PK_3$$
$$a_j = \tilde{H}(j, \tilde{PK}, m, \{R_j, S_j\}_1^3)$$
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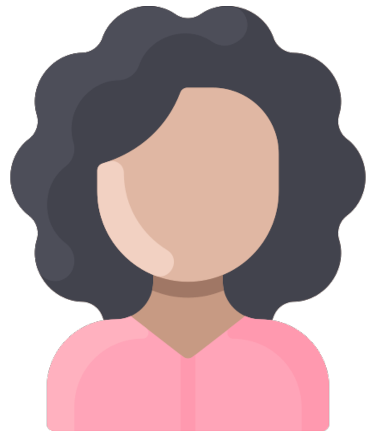
$$\sigma = (\tilde{R}, z)$$

PK_3



R_3, S_3 $\xrightarrow{R_3, S_3}$

$z_3 \leftarrow r_3 + a_3 s_3 + c sk_3$ $\xleftarrow{c}$

$\xrightarrow{z_3}$

Fix #2: 2 Nonces ("FROST")

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R_2, S_2 $\xrightarrow{R_2, S_2}$

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$\xrightarrow{z_2}$

PK_1

R_1, S_1 $\xrightarrow{R_1, S_1}$

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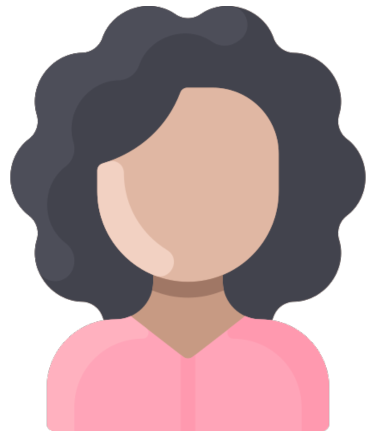
$\xrightarrow{z_1}$

PK_3



R_3, S_3 $\xrightarrow{R_3, S_3}$

$z_3 \leftarrow r_3 + a_3 s_3 + c sk_3$ $\xleftarrow{c}$

$\xrightarrow{z_3}$

Combiner

w/ proof of possession of sk_j

$$\tilde{PK} = PK_1 PK_2 PK_3$$
$$a_j = \tilde{H}(j, \tilde{PK}, m, \{R_j, S_j\}_1^3)$$
$$\tilde{R} = \Pi_1^3 R_j S_j^{a_j}$$
$$c \leftarrow H(\tilde{PK}, m, \tilde{R})$$
$$z \leftarrow z_1 + z_2 + z_3$$
$$\sigma = (\tilde{R}, z)$$

Verify $(\tilde{PK}, \sigma, m)$:

$$c \leftarrow H(\tilde{PK}, m, \tilde{R})$$
$$\tilde{R} \cdot \tilde{PK}^c \stackrel{?}{=} g^z$$

Fix #3: 2 Nonces ("FROST2")

PK_2

R_2, S_2

$z_2 \leftarrow r_2 + as_2 + csk_2$

$\xrightarrow{R_2, S_2}$

$\xleftarrow{c}$

$\xrightarrow{z_2}$

w/ proof of possession of sk_j

PK_1

R_1, S_1

$z_1 \leftarrow r_1 + as_1 + csk_1$

$\xrightarrow{R_1, S_1}$

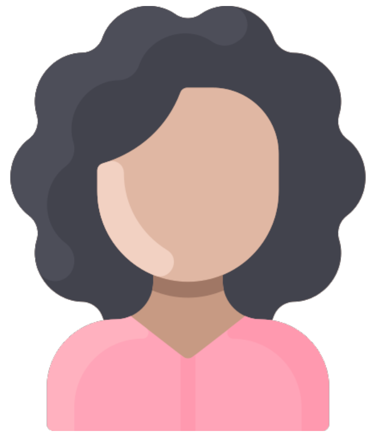
$\xleftarrow{c}$

$\xrightarrow{z_1}$

Combiner

$$\widetilde{PK} = PK_1 PK_2 PK_3$$
$$a = \tilde{H}(\widetilde{PK}, m, \{R_j, S_j\}_1^3)$$
$$\tilde{R} = \Pi_1^3 R_j S_j^a$$
$$c \leftarrow H(\widetilde{PK}, m, \tilde{R})$$
$$z \leftarrow z_1 + z_2 + z_3$$
$$\sigma = (\tilde{R}, z)$$

PK_3



R_3, S_3

$z_3 \leftarrow r_3 + as_3 + csk_3$

$\xrightarrow{R_3, S_3}$

$\xleftarrow{c}$

$\xrightarrow{z_3}$

Verify $(\widetilde{PK}, \sigma, m)$:

$$c \leftarrow H(\widetilde{PK}, m, \tilde{R})$$
$$\tilde{R} \cdot \widetilde{PK}^c \stackrel{?}{=} g^z$$

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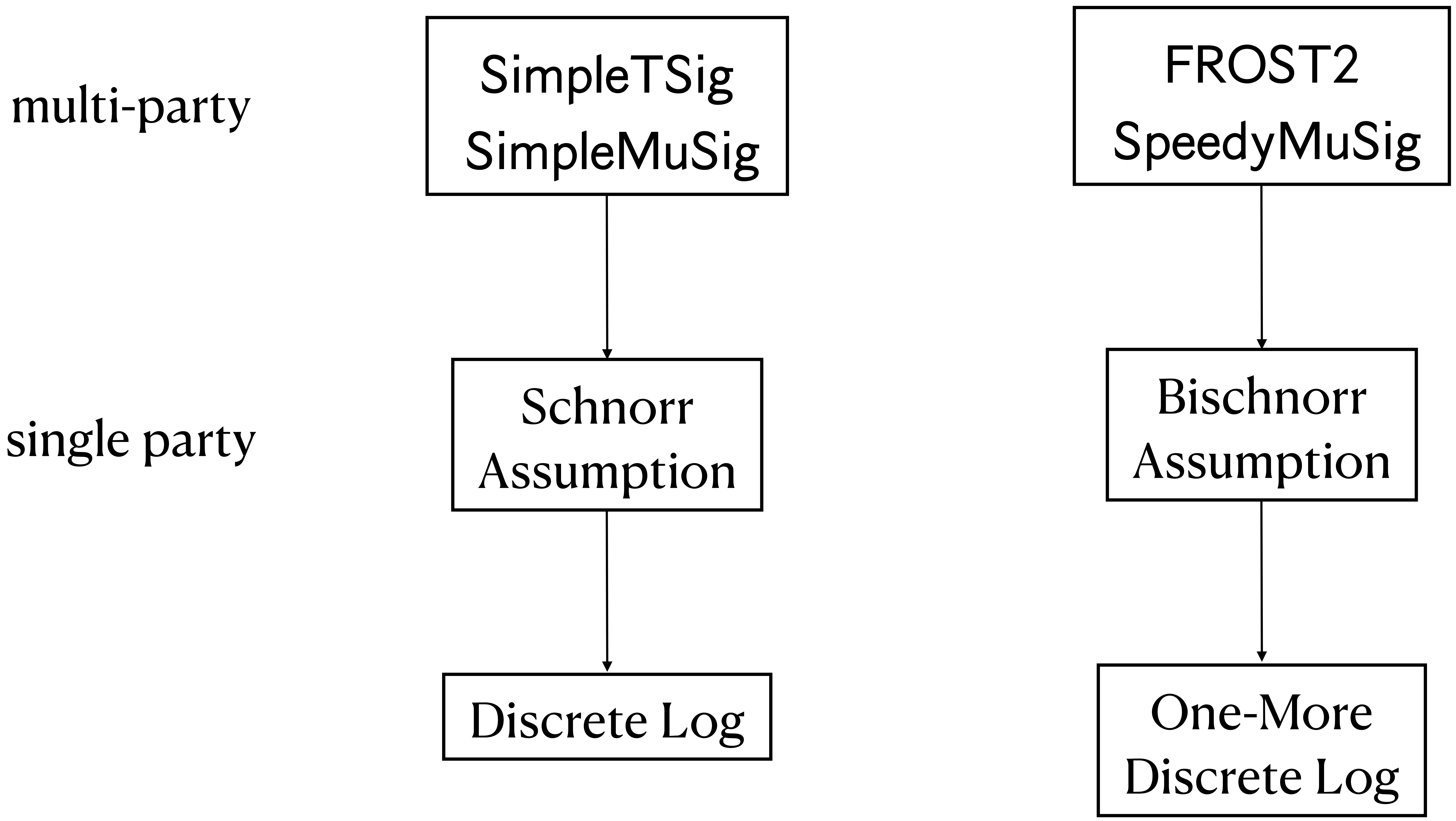
- Our Contributions:
  - 3-round (n,n) multisignature SimpleMuSig (with PoP of keys)
  - 3-round (t,n) threshold signature SimpleTSig (with PedPoP)
  - optimized 2-round (n,n) multisignature SpeedyMuSig (with PoP of keys)
  - optimized 2-round (t,n) threshold signature FROST2 (with PedPoP)
    - reduces exponentiations from at least t to one
  - new proving framework

Proving the Security of Multi-Party Schnorr

- Security reductions for multi-party signatures have two moving parts:
  1. Simulating honest users interacting with the adversary
  2. Extracting a solution to some hard problem from the adversary's responses
- Idea: Separate the two parts for a more modular reduction

Proving the Security of Multi-Party Schnorr



“Stronger Security for Non-Interactive Threshold Signatures”

Mihir Bellare, Stefano Tessaro, Chenzhi Zhu

- Merged with our paper for CRYPTO 2022

eprint.iacr.org/2022/833

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- Merged with our paper for CRYPTO 2022
- Hierarchy of notions of unforgeability for threshold signatures

eprint.iacr.org/2022/833

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- Merged with our paper for CRYPTO 2022
- Hierarchy of notions of unforgeability for threshold signatures
- Independent proofs for unforgeability of FROST1 and FROST2 in ROM/OMDL

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“Stronger Security for Non-Interactive Threshold Signatures”

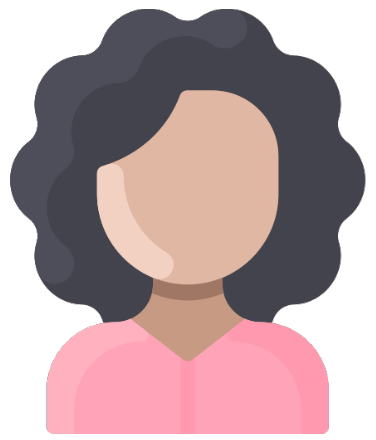
Mihir Bellare, Stefano Tessaro, Chenzhi Zhu

- Merged with our paper for CRYPTO 2022
- Hierarchy of notions of unforgeability for threshold signatures
- Independent proofs for unforgeability of FROST1 and FROST2 in ROM/OMDL
- Finds FROST2 to be malleable with respect to the signing set

eprint.iacr.org/2022/833

- γ = Lagrange coefficient for signing set (1, 3, 4),
- δ = Lagrange coefficient for signing set (1, 2, 3) / γ

PK_3, PK_4



Corrupt

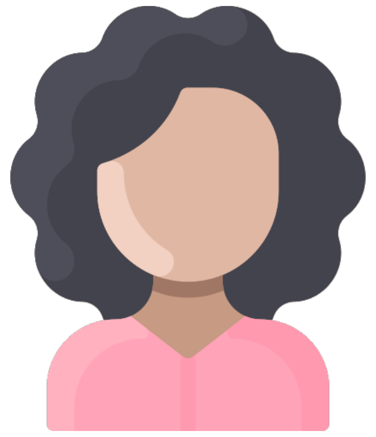
Honest

PK_2

PK_1

- γ = Lagrange coefficient for signing set (1, 3, 4),
- δ = Lagrange coefficient for signing set (1, 2, 3) / γ

PK_3, PK_4



Corrupt

PK_2

Honest

$R_2 = g^{r_2}, S_2 = g^{s_2}$ $\xrightarrow{R_2, S_2}$

Begin signing protocol with signers (1, 2, 3)

PK_1

$R_1 = g^{r_1}, S_1 = g^{s_1}$ $\xrightarrow{R_1, S_1}$

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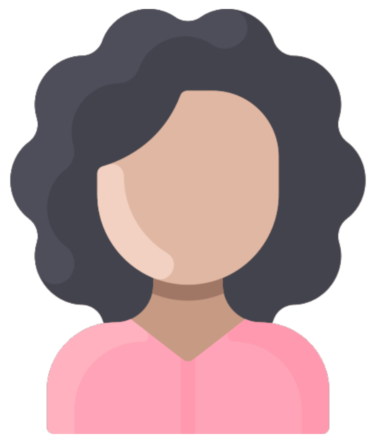

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PK_1

$R_1 = g^{r_1}, S_1 = g^{s_1}$ $\xrightarrow{R_1, S_1}$

$$R_3 = (R_1)^{\delta-1} \cdot (R_2)^{-1}$$

$$S_3 = (S_1)^{\delta-1} \cdot (S_2)^{-1}$$

$\xleftarrow{R_3, S_3}$

$$R = \prod_{i=1}^{3} R_i \cdot (S_i)^a$$

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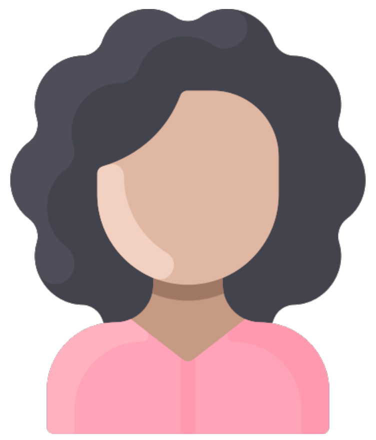

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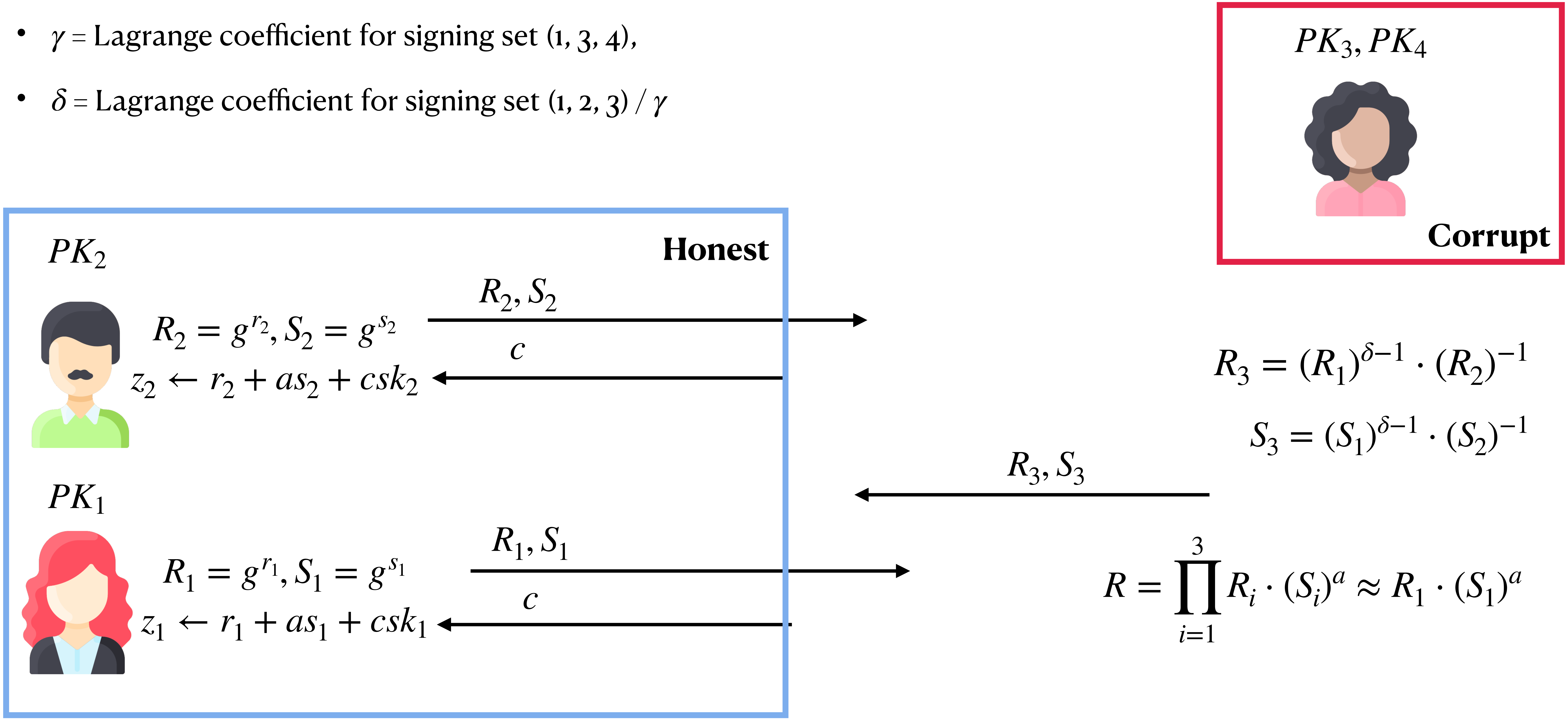

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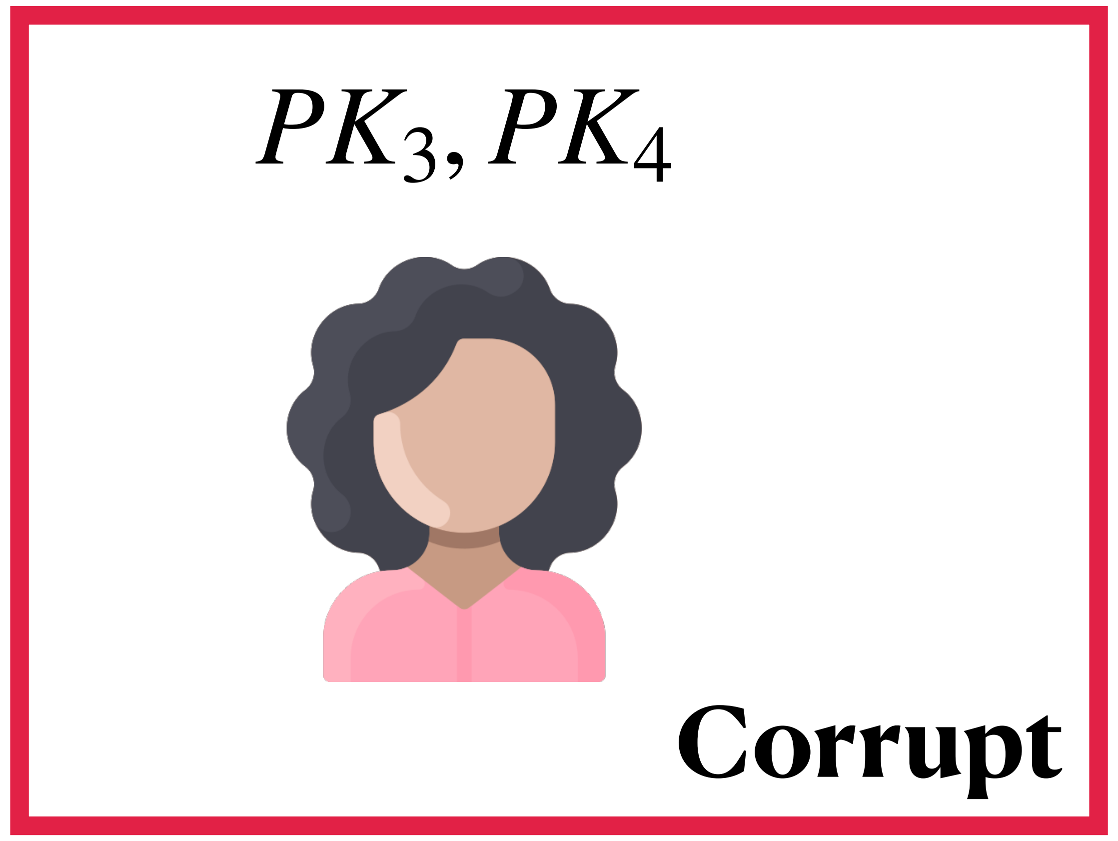

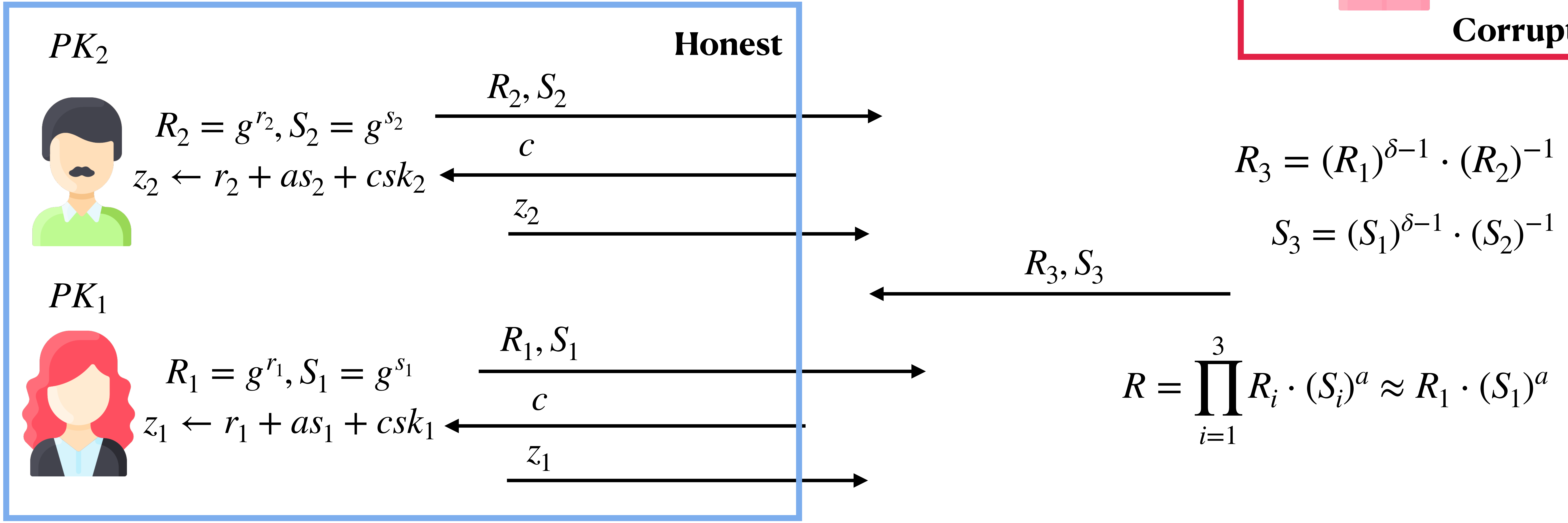

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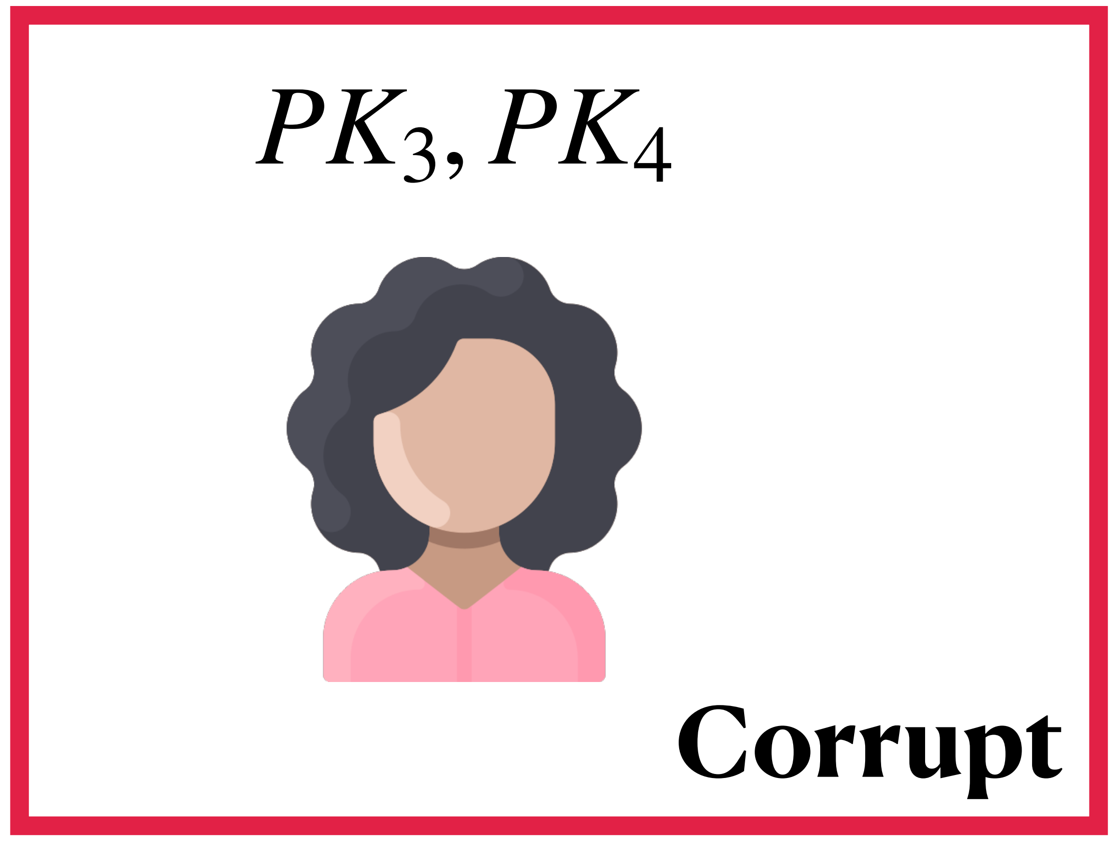

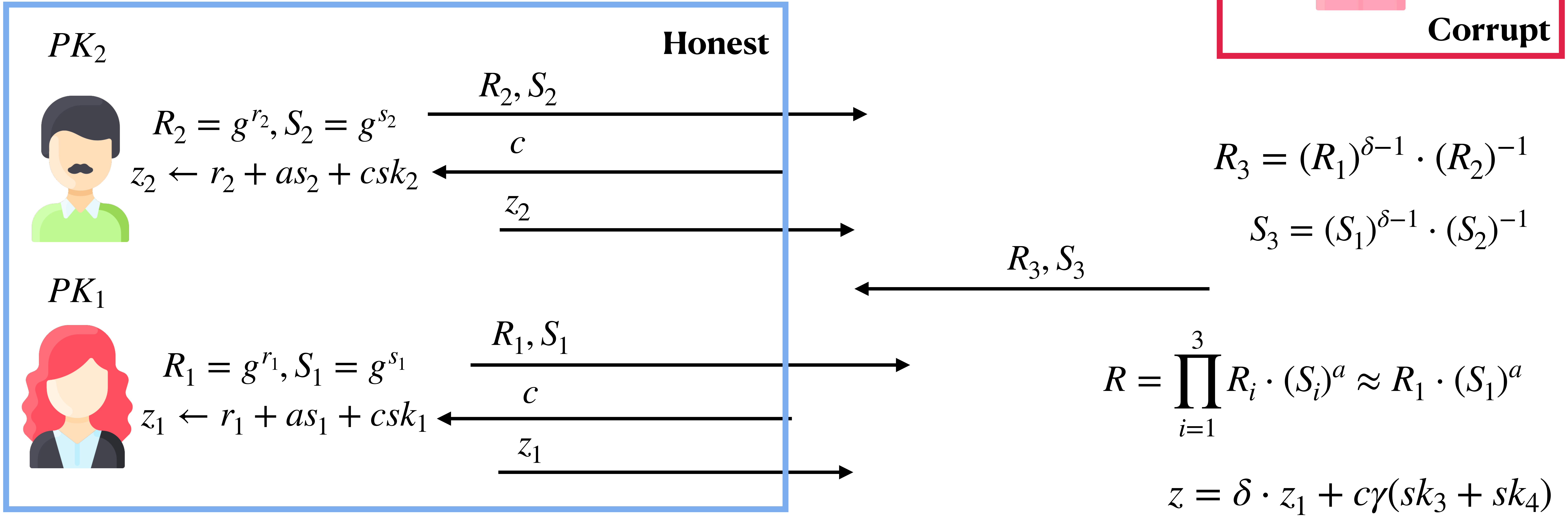

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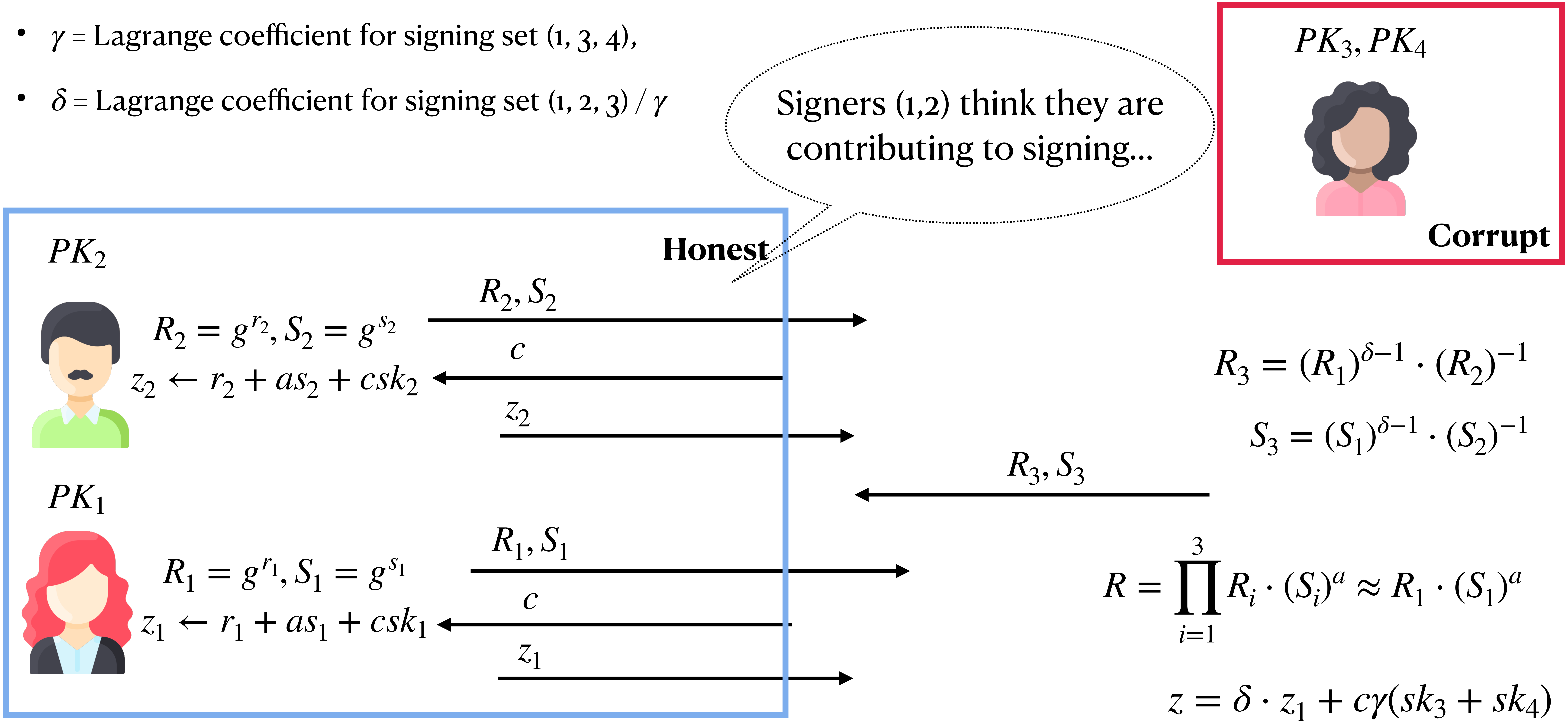

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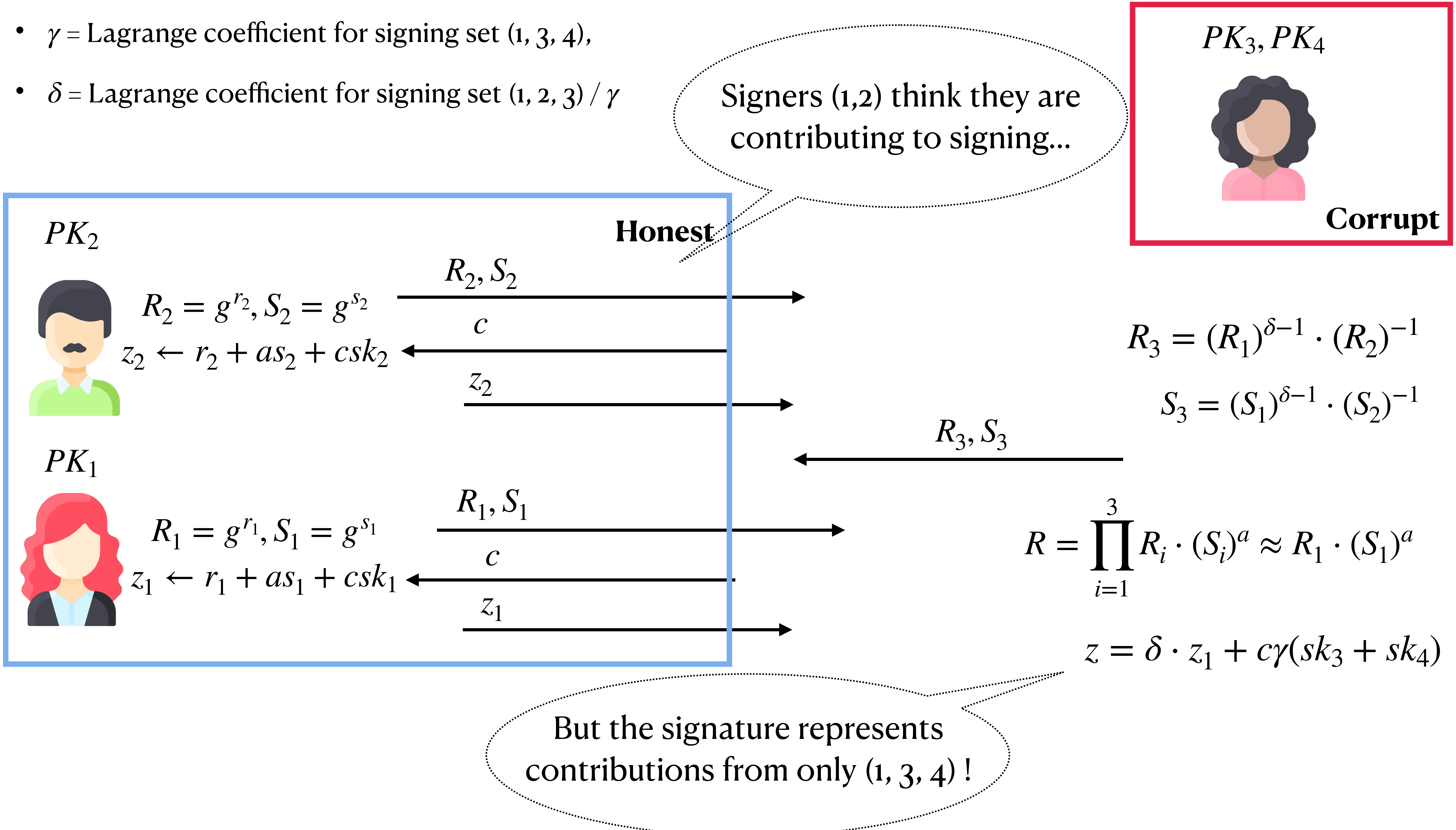

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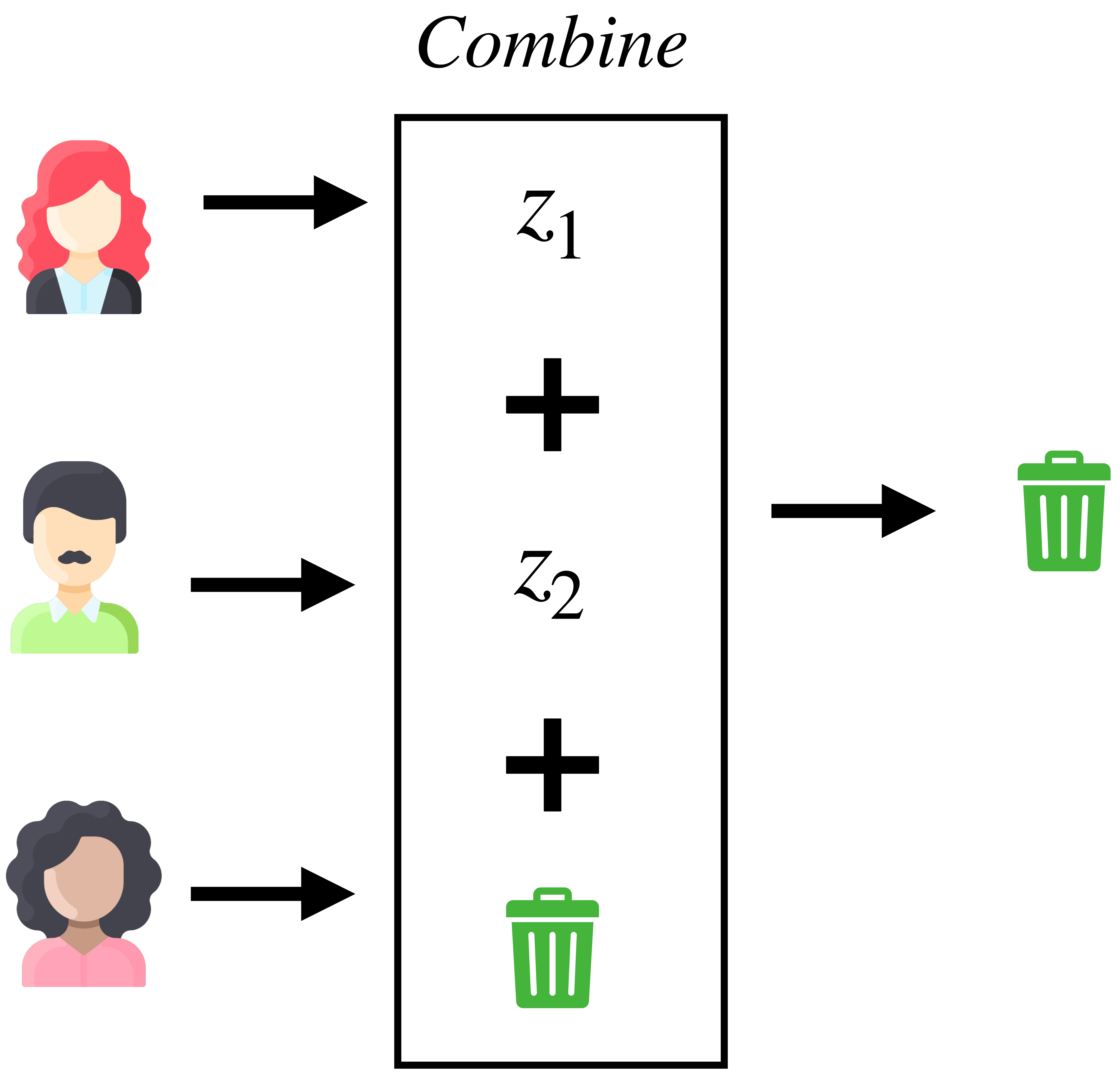
- FROST2 may be of interest for performance critical settings.

FROST & Robustness

- **Robustness**: the protocol succeeds so long as at least t players participate honestly.



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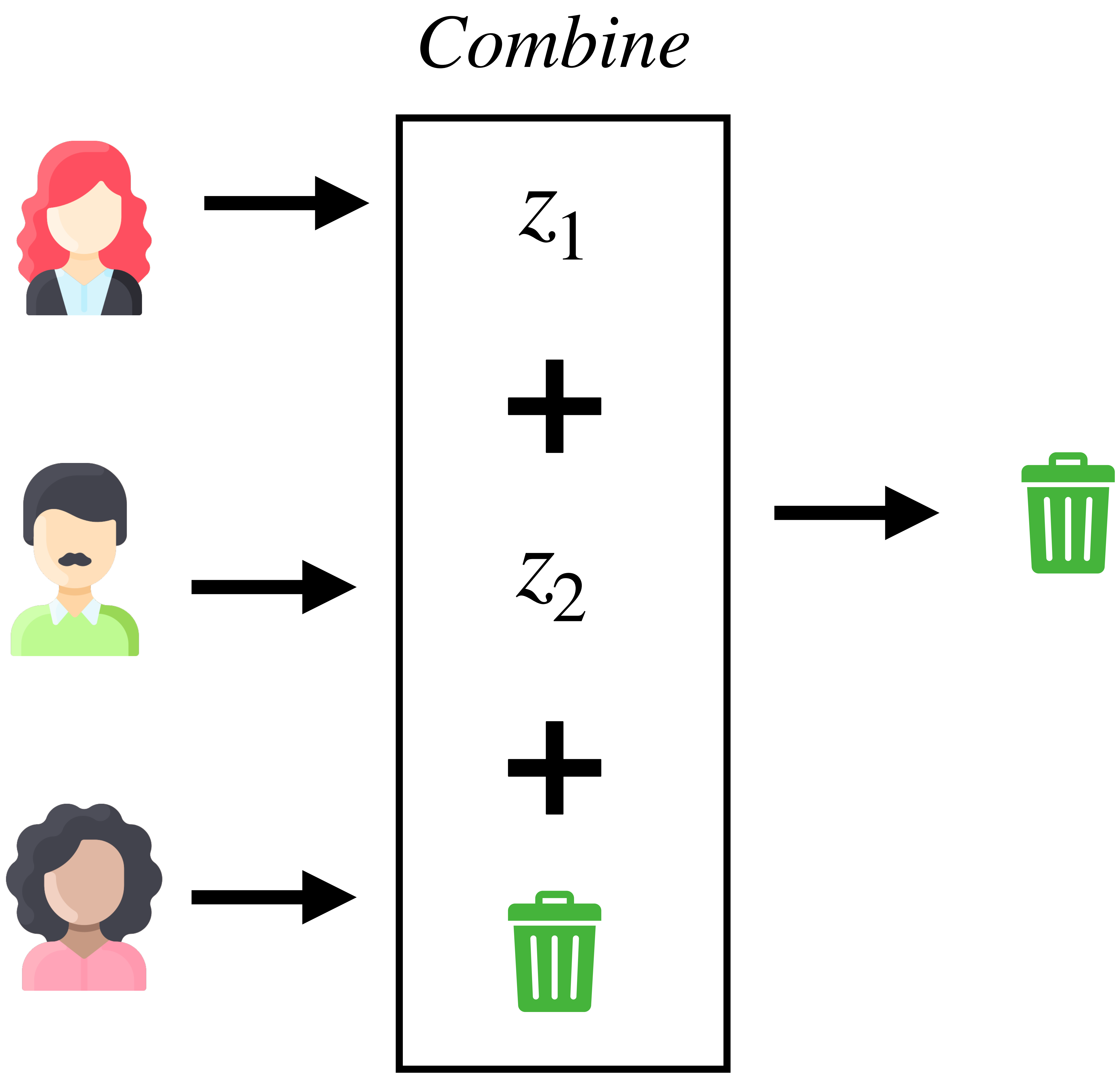

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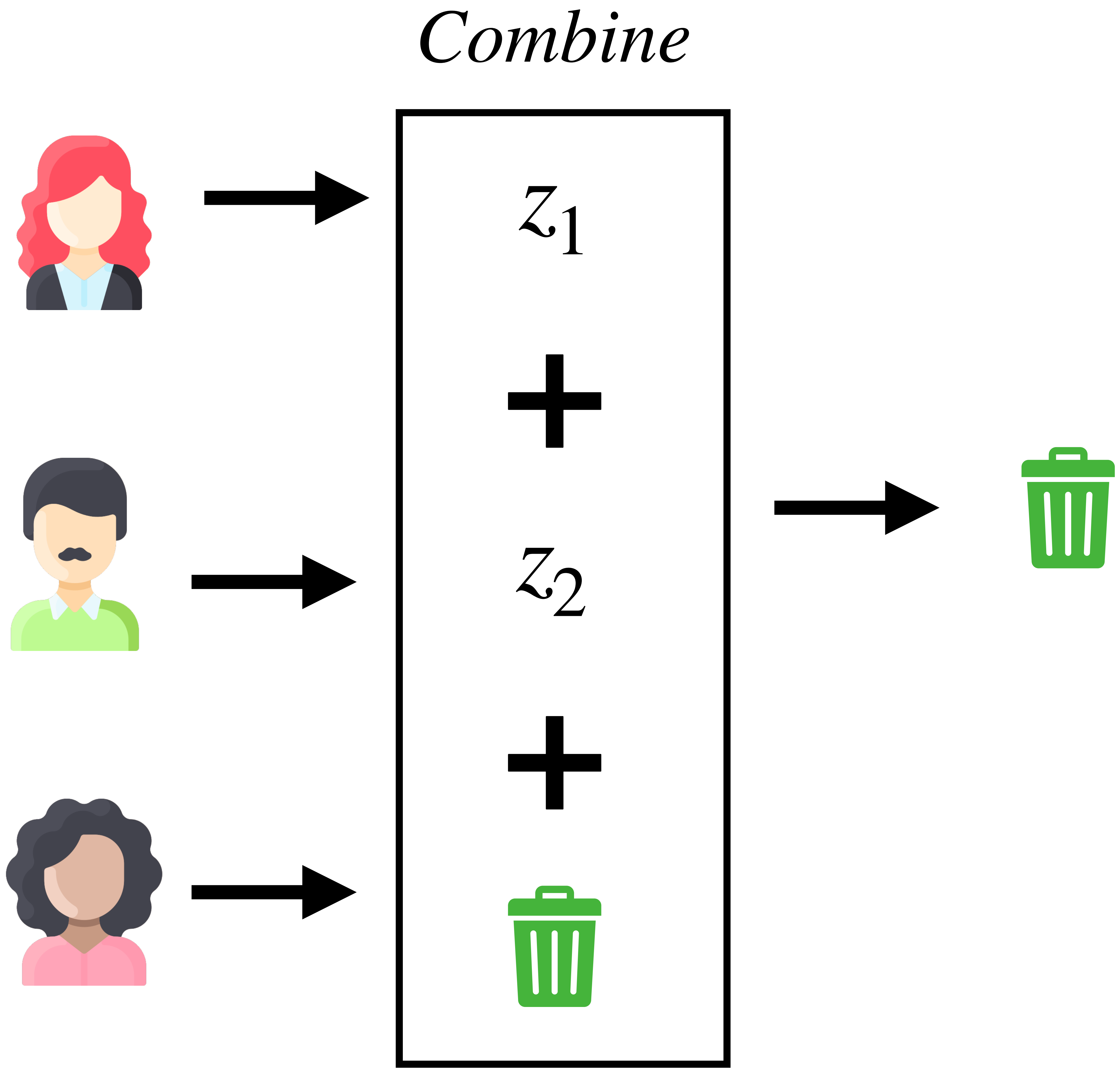

FROST & Robustness

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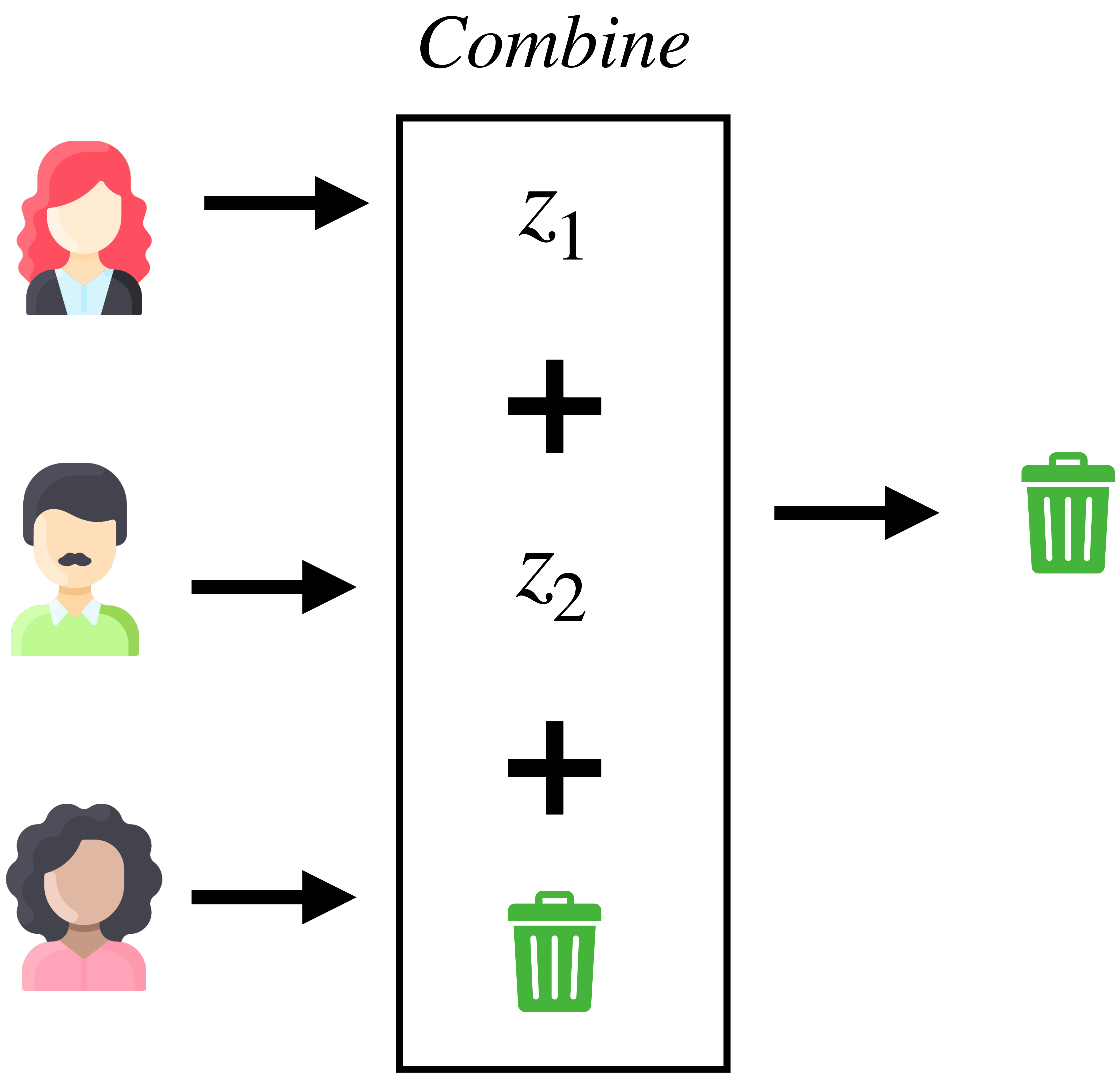
- Example: n=3, t=2
- If even one FROST signer issues garbage, the resulting signature is garbage and the protocol must be re-run (even if more than two signed).



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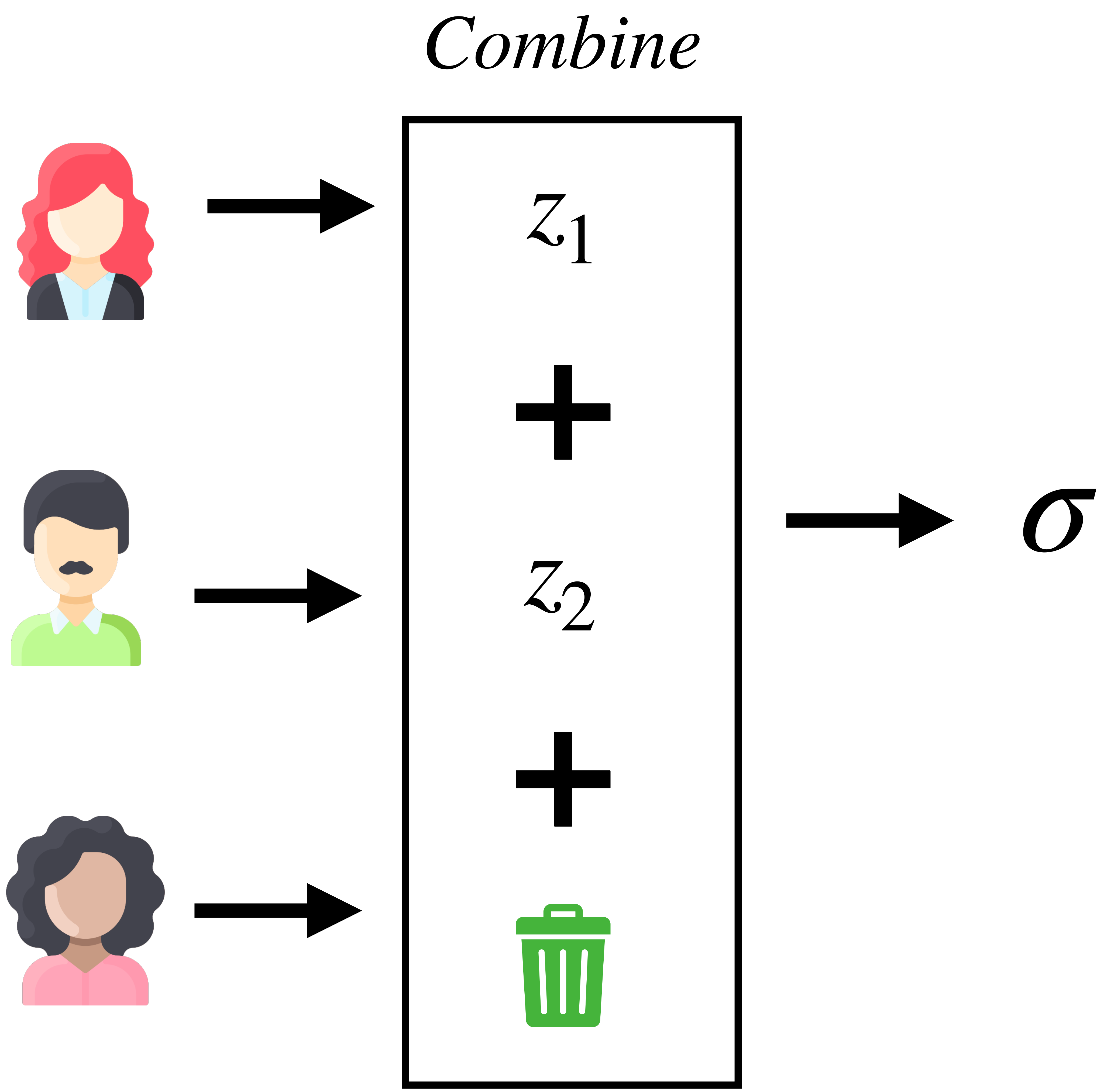
- ROAST defines a wrapper protocol to make FROST robust.

eprint.iacr.org/2022/550



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- Improves on the trivial solution of maintaining $\binom{n}{t}$ concurrent sessions to $n - t + 1$

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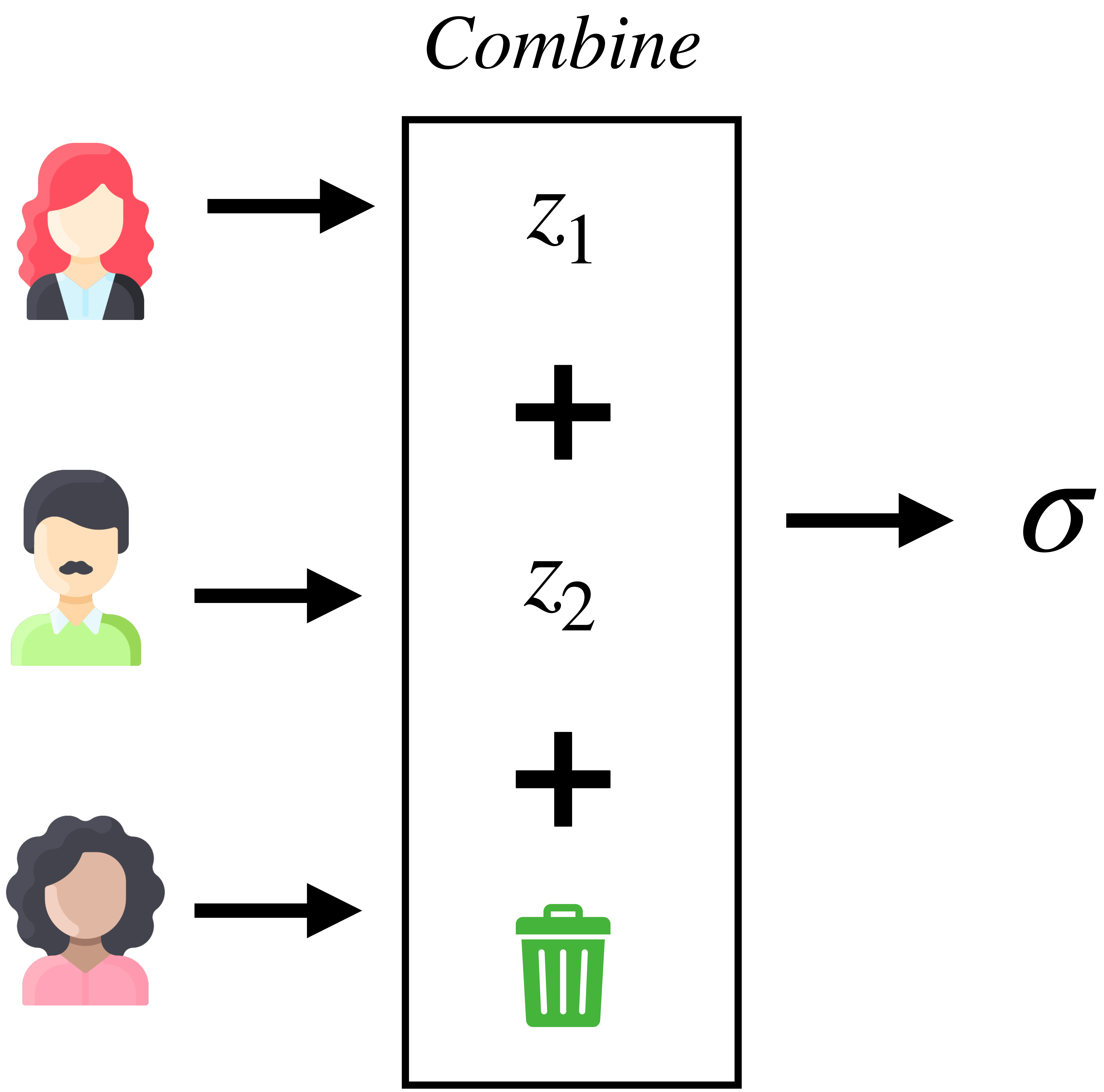
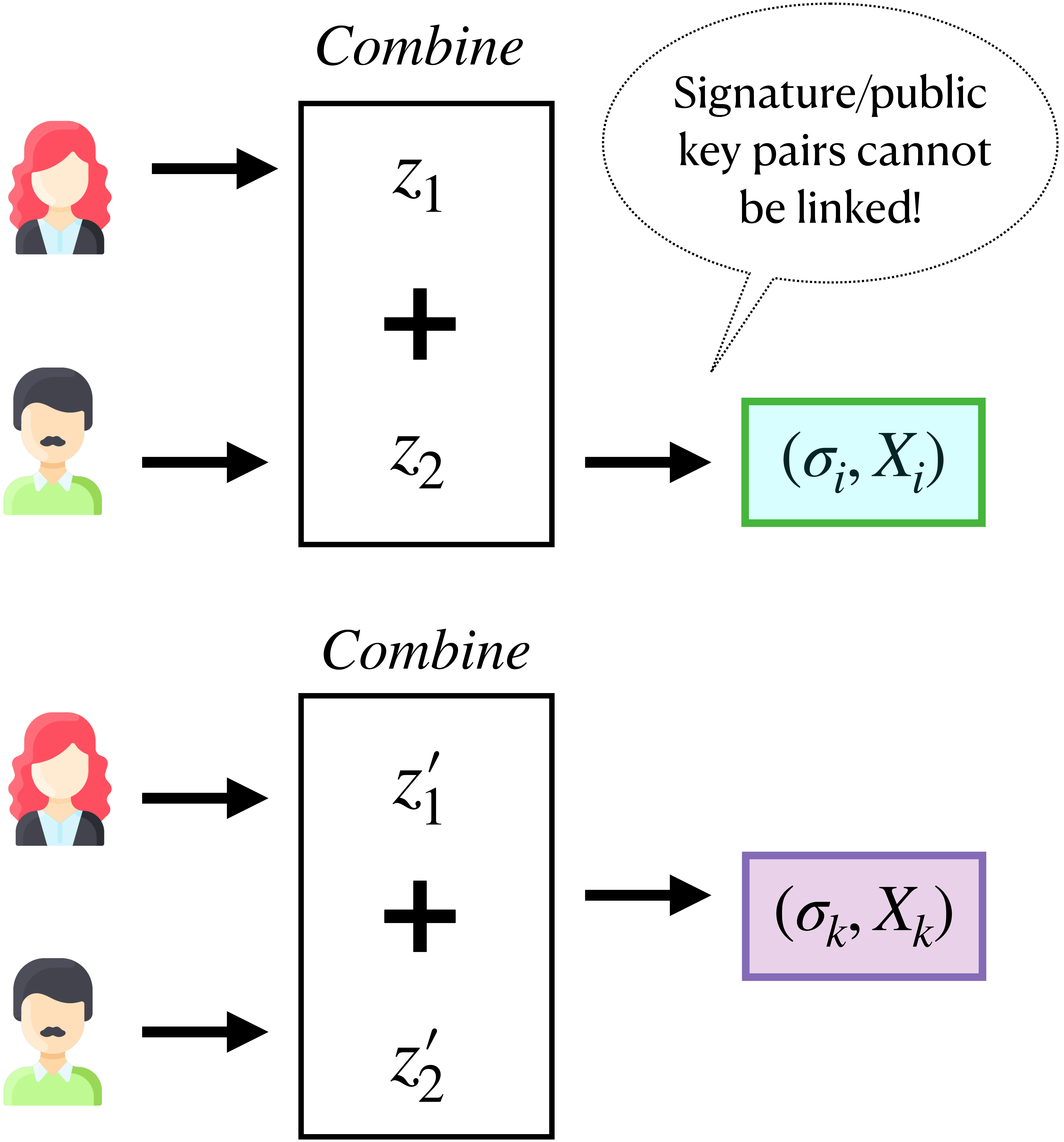


What's Next: Unlinkable FROST

- This is an ongoing effort, we have a candidate scheme



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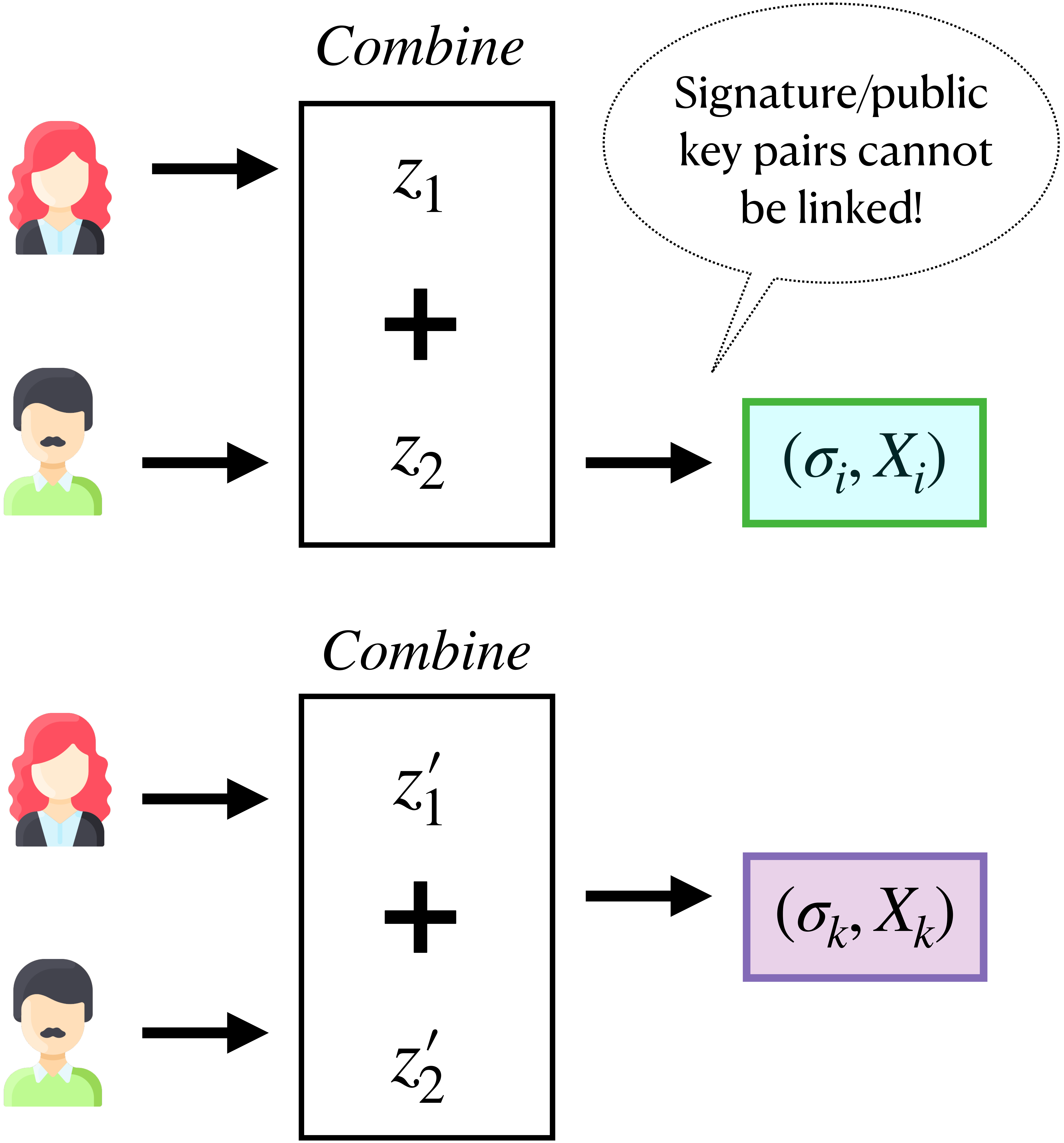

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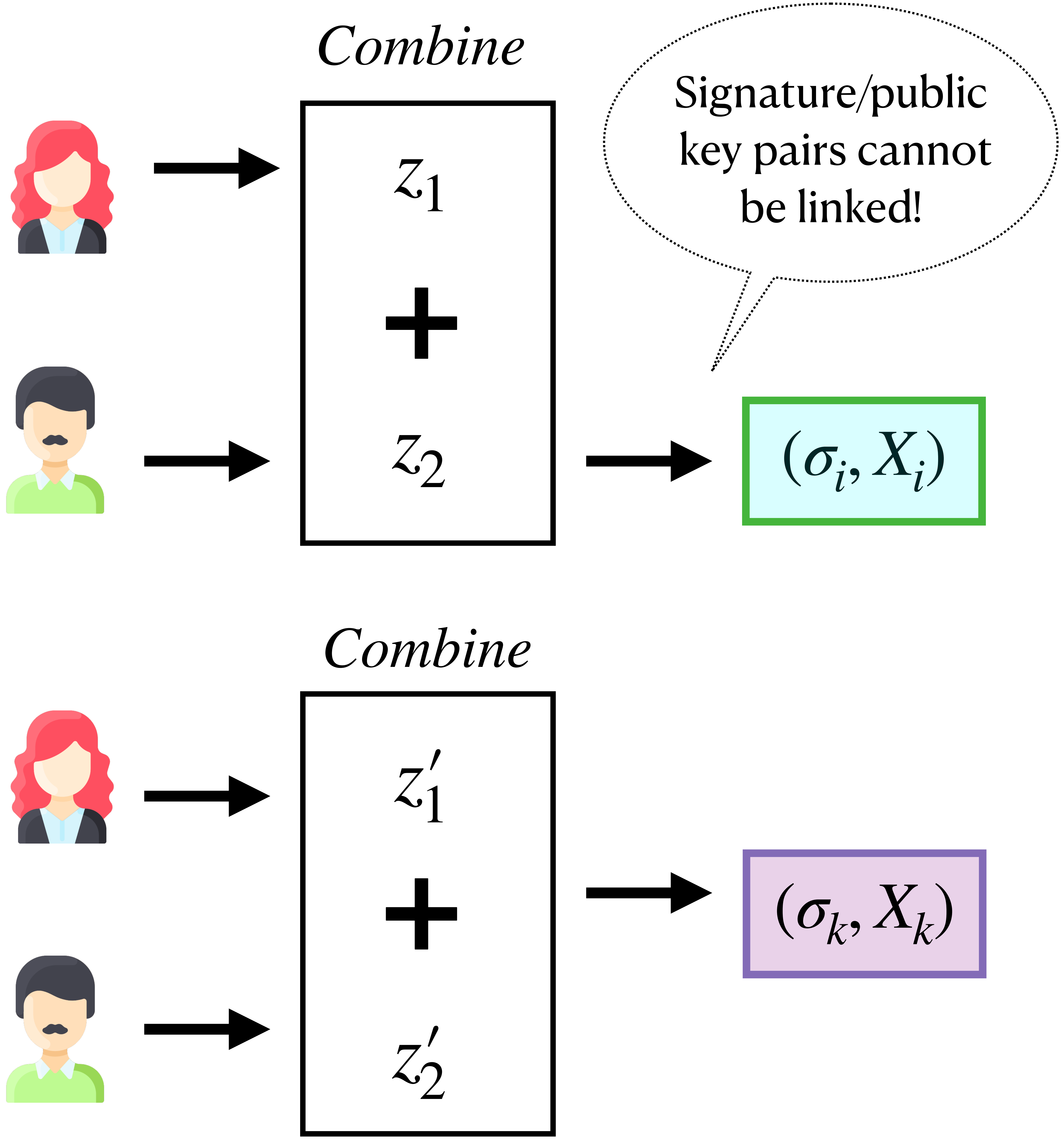
- If you are interested in this work or have use cases, come talk to me!



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Thank you! ❄