

RSA[®]Conference2020

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HUMAN
ELEMENT

SESSION ID: CRYPT-R07

Post-Quantum Crypto: Traceable Ring Signatures with Post- quantum Security



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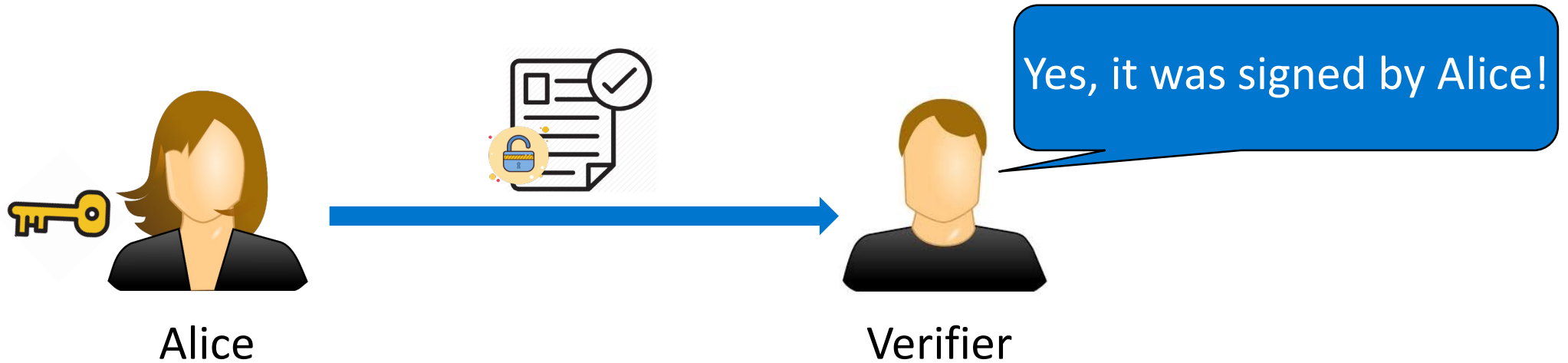
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Background and Motivations

Background: Digital Signatures

Alice can use her secret key to sign any message



- Correctness: Anyone can verify that the message was signed by Alice
- Security: Anyone without Alice's secret key cannot forge a valid signature
- Privacy Concern: Digital signature **cannot provide privacy protection** for signers.

Background: Privacy Demands from Real-World



- A ballot should not reveal the identity of the voter

E-voting



E-cash

- Transactions should not be traced



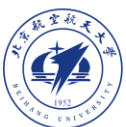
- The message should not reveal the identity of the TPM

Trusted Platform Module



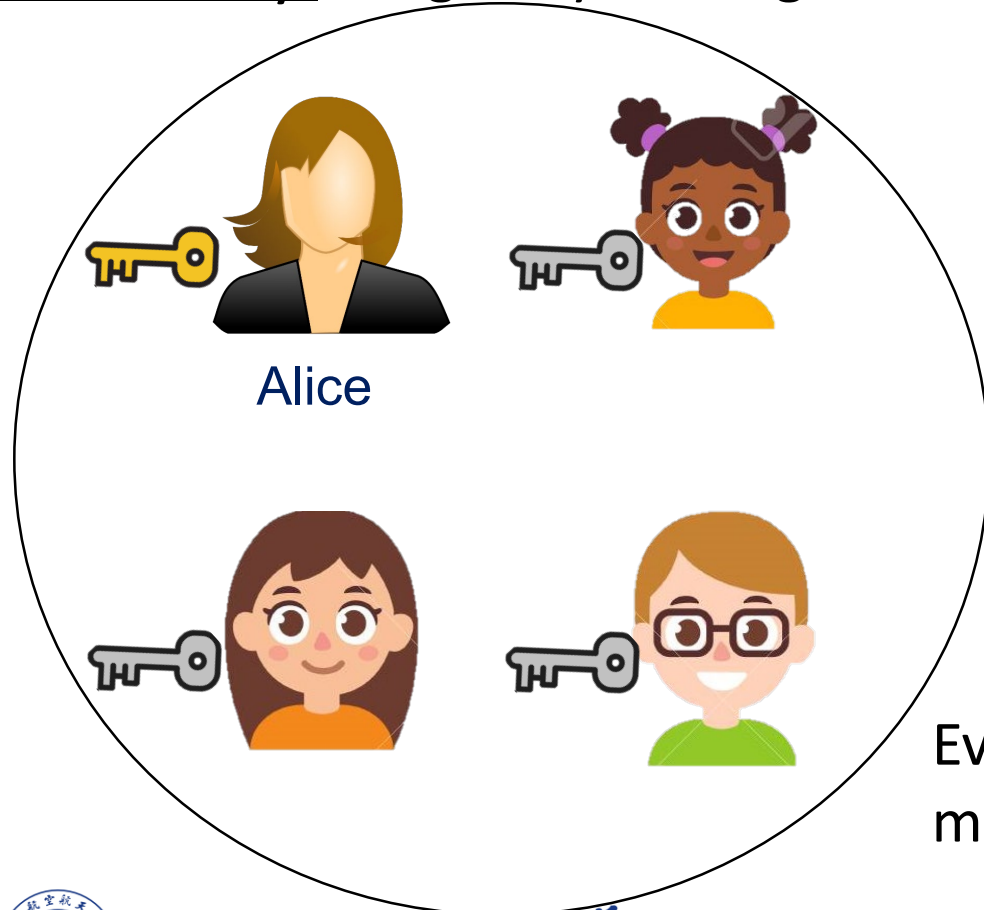
Vehicle Network

- A broadcast message should not reveal the speed or position of a vehicle

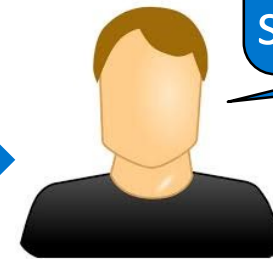


Background: Ring Signatures

Ring signature [RST01] allows a ring member to use her/his secret key to sign any message on behalf of this ring



Drawback:
Uncountable Anonymity



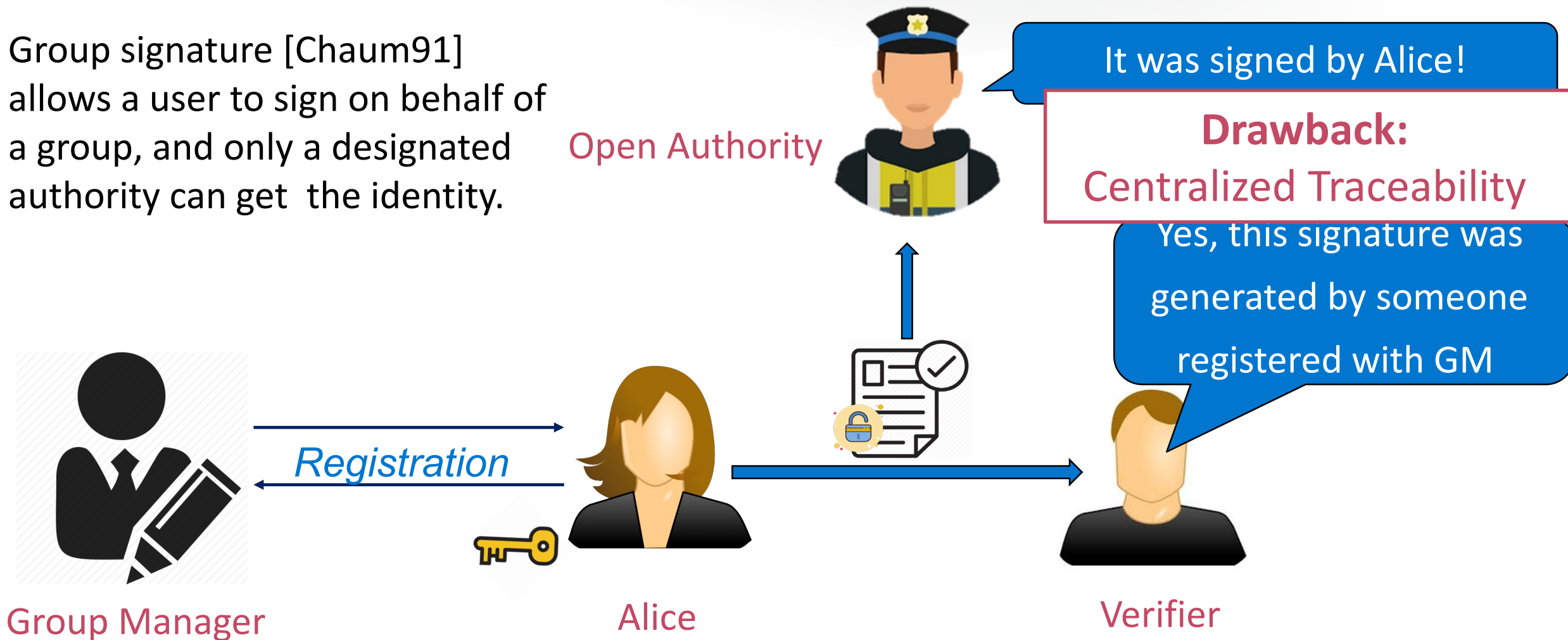
Verifier

Yes, it was signed by
someone in this ring!

Everyone can verify this message was signed by a ring member, but cannot infer anything about the real signer

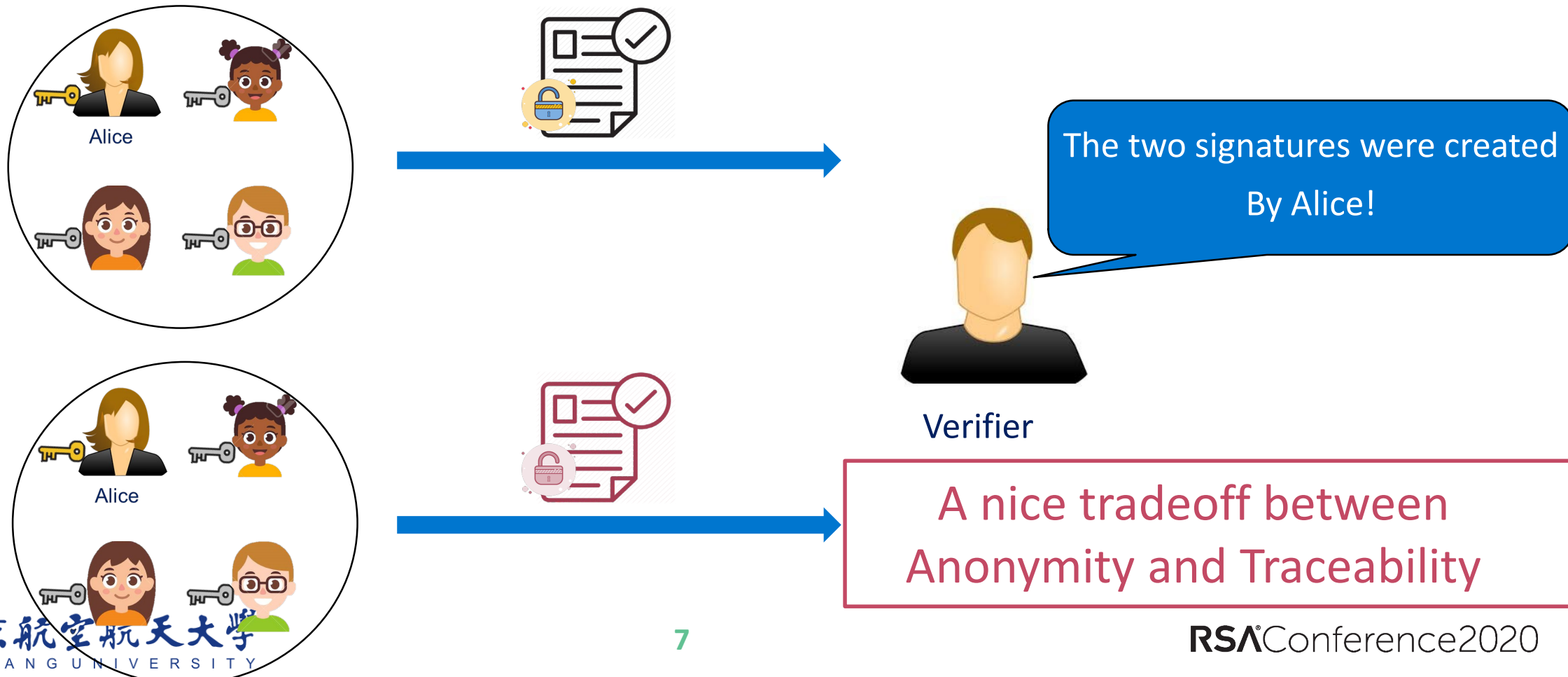
Background: Group Signatures

Group signature [Chaum91] allows a user to sign on behalf of a group, and only a designated authority can get the identity.



Background: Traceable Ring Signatures

In ring signature [LWW04], every two signatures w.r.t the same ring, generated by the same signer for different messages, can be publicly traced to the singer



Background: Application of Traceable Ring Signatures



E-voting

- Dishonest voters who vote for two candidates will be identified



Offline E-cash

- Dishonest users who perform double-spending attacks will be identified



Background: Post-quantum Cryptography

Digital Signature, Group Signature,
Ring Signature, Traceable Ring Signatures...

PKE, PE



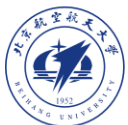
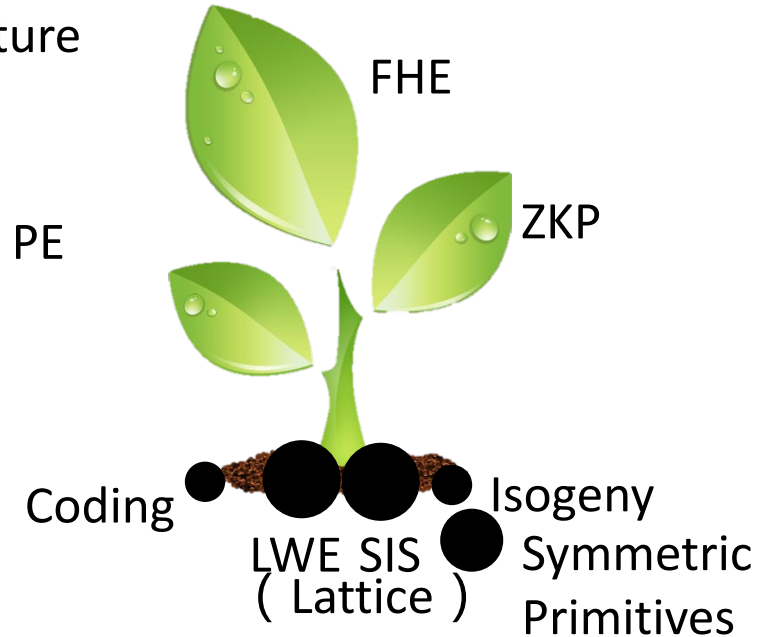
ZKP

Factoring Discrete Log Pairing

[Shor94]: Algorithms for quantum computation: discrete logarithms and factoring

Digital Signature,
Group Signature,
Ring Signature

PKE、PE

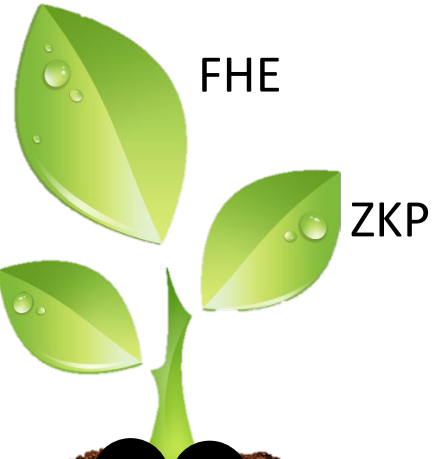


Motivations

Digital Signature,
Group Signature,
Ring Signature

Traceable Ring Signature

PKE、PE



ZKP

Coding

LWE SIS
(Lattice)

Isogeny
Symmetric
Primitives



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Building Blocks

Building Blocks: Pseudorandom Function

- $F: K \times X \rightarrow Y$ is a family of pseudorandom functions, if for $k \leftarrow K, f \leftarrow \mathcal{F}[X:Y]$

$$F(k, \cdot) \approx f(\cdot)$$

- Additional Property ---Uniqueness

For $x \in X, k_1 \neq k_2$, we have

$$\Pr[F(k_1, x) \neq F(k_2, x)] \in \text{negl}(\lambda)$$

Building Blocks: Pseudorandom Function

Additional Property --- Intersection-free Range

- The range Y is a vector space of rational numbers
- For every two distinct elements y_1, y_2 , and any polynomial $N(\cdot)$,

$$\Pr[\exists i \leq N(\lambda), y_1 + i\delta_1 = y_2 + i\delta_2 : \delta_1, \delta_2 \leftarrow \mathcal{Y}] \in \text{negl}(\lambda)$$

Building Blocks: Pseudorandom Function- Example

Example: PRF in Fujisaki and Suzuki's construction [FS07]

$$F(k, x) = H(x)^k \in G$$

G is a DDH group, and H is a random oracle.

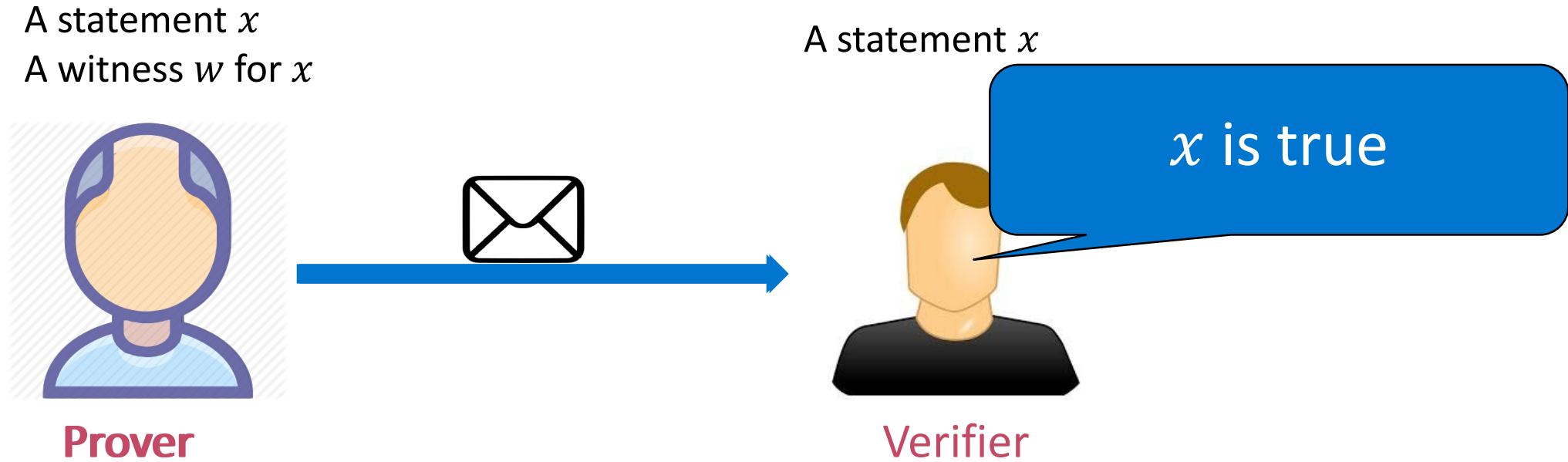
Uniqueness: every $k_1 \neq k_2, H(x)^{k_1} \neq H(x)^{k_2}$

Intersection-free range:

G is a vector space of rational numbers

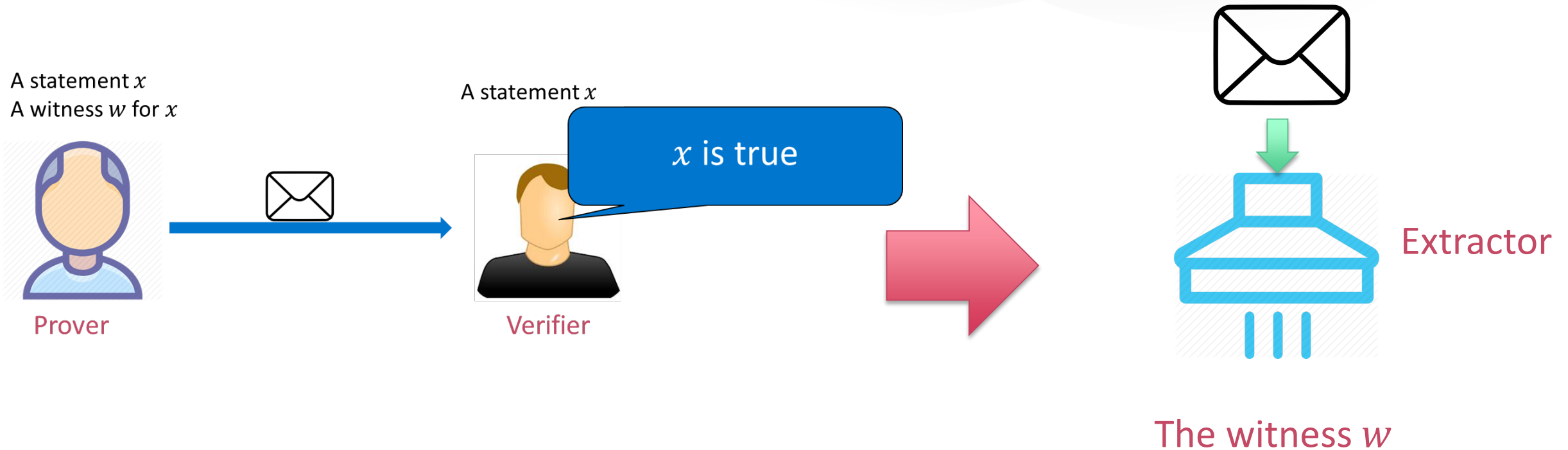
$$\begin{aligned} & \Pr[\exists i \leq N(\lambda), y_1 \cdot \delta_1^i = y_2 \cdot \delta_2^i : \delta_1, \delta_2 \leftarrow \mathbb{G}] \\ & \leq \Pr[\exists i \leq N(\lambda), y_1/y_2 = \delta^i : \delta \leftarrow \mathbb{G}] \leq \frac{N(\lambda)}{q(\lambda)} \in \text{negl}(\lambda). \end{aligned}$$

Building Blocks: Non-interactive Zero-knowledge Proof of Knowledge



- Completeness: an honestly generated proof for a true statement will always be accepted

Building Blocks: Non-interactive Zero-knowledge Proof of Knowledge



- Proof of knowledge: a witness can be extracted from a valid proof by an extractor

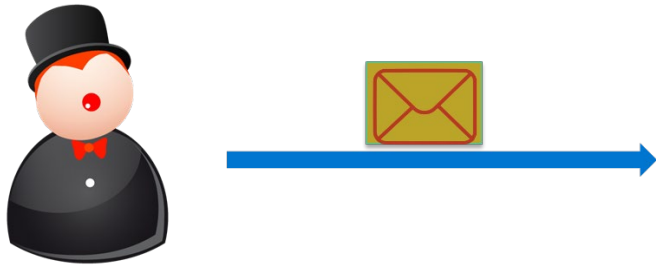
Building Blocks: Non-interactive Zero-knowledge Proof of Knowledge

A statement x
A witness w for x

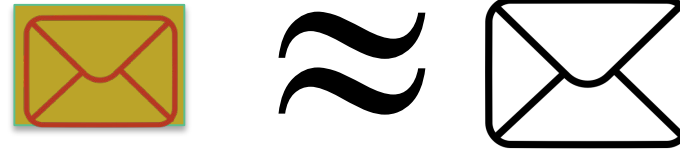


Prover

A statement x



Simulator



- Zero-knowledge : a valid proof can be simulated without the witness

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General Framework of Traceable Ring Signatures

Framework of Unique Ring Signature [FZ12]

- Key Generation:

Choose a key of PRF as the secret key, and take the commitment of it as the public key.

- Sign: a signature consists of a label and a proof

Label: $l = F(sk, (R, m))$, R is a set of public keys, m is the message

Proof: prove l is correctly generated by some sk whose public key is in R

- Link:

If the two signatures have the same label, they will be linked

Our Framework: Design Principle

- Ring

pk1

pk2

pk3

pk4

pk5

- Signature 1

L 1

L 2

L 3

L 4

L 5

Using sk3

Proof: At least one label is honestly generated

- Signature 2

L 1

L 2

L 3

L 4

L 5

Using sk3

Proof: At least one label is honestly generated

- L3 in two signatures are identical,
- We know they are created by someone **whose pk is pk3**

A Possible Attack

- Ring

pk1

pk2

pk3

pk4

pk5

- Signature 1

L 1

L 2

L 3

L 4

L 5

Using sk3

Proof: At least one label is honestly generated

- Signature 2

L 1

L 2

L 3

L 4

L 5

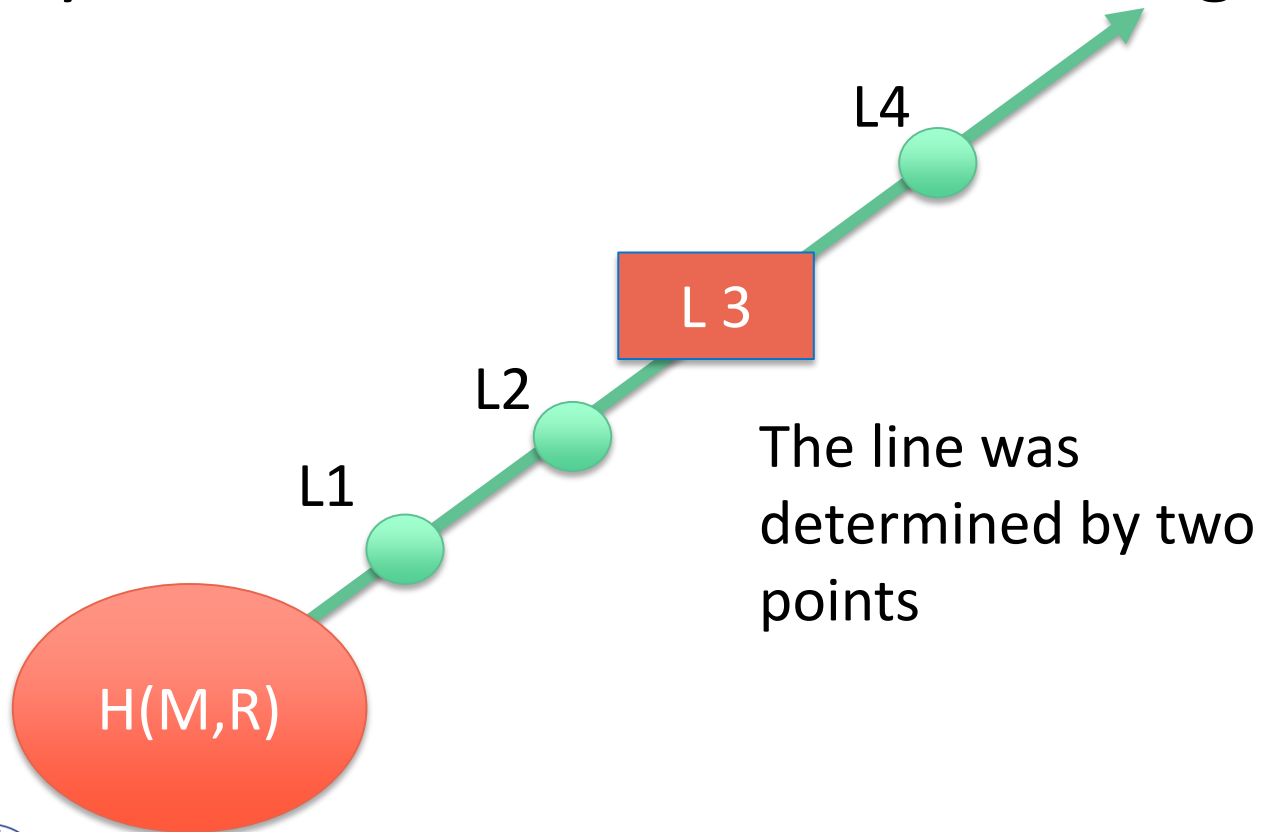
Using sk4

Proof: At least one label is honestly generated

- Signature 2 contains a label L2 that was borrowed from Signature 1
- The two signatures **will be wrongly traced to PK2!**

Our Framework: More Details

- To prevent malicious users from framing honest users, we need to ensure that other labels are uniquely determined by the honest label and the message.



$$\delta = \frac{L3 - H(M, R)}{3}$$

$$L_i = H(M, R) + i\delta$$

L3 is an evaluation of PRF.
We need to perform ADD
and Scalar Multiplication
Operations on L3.

Our Framework: Security analysis

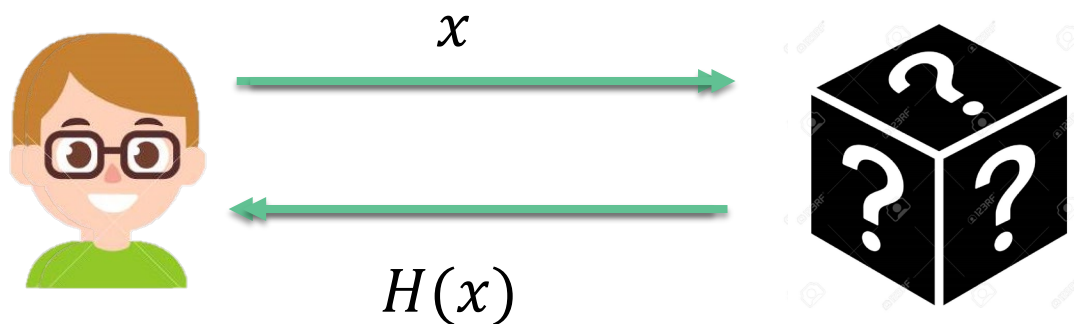
- Tag-Linkability: the total number of unlinked signatures with one tag cannot exceed the total number of ring members
- From the simulation-extractability of the NIZK proof system, and the uniqueness of PRF.
- Anonymity: when a signature is signed by either of two signers, an attacker cannot infer anything as to by whom this signature is signed
- From the zero knowledgeness of the NIZK proof system, and the pseudorandomness of the PRF.
- Exculpability : an honest signer cannot be accused of being dishonest by breaking the rule, even if every ring member except him is corrupted.
- From the simulation-extractability of the NIZK proof system, and the pseudorandomness of PRF.

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Efficient Traceable Ring Signatures in Quantum Random Oracle Model

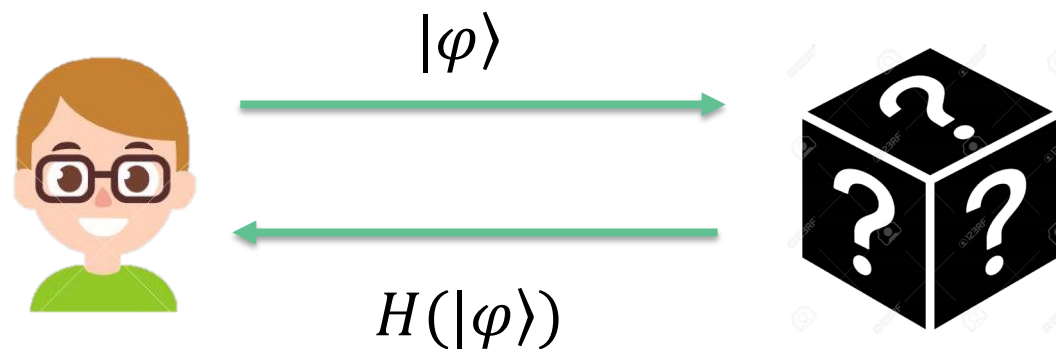
What is the Quantum Random Oracle Model

To get the output of a hash function H

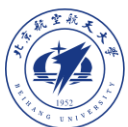


Random Oracle Model

Superposition queries are allowed



Quantum Random Oracle Model



An Efficient PRF in QROM

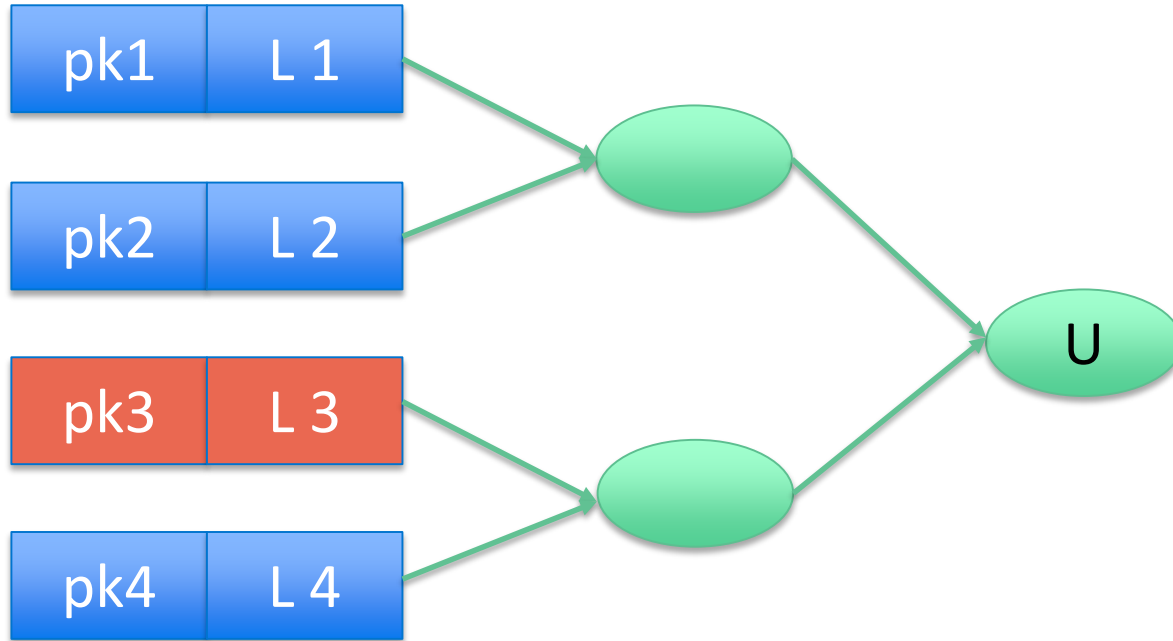
$$F^H : \mathbb{Z}_q^n \times \{0, 1\}^* \rightarrow \mathbb{Z}_p^m \text{ with } F^H(T, \mathbf{s}) = \lfloor H(T) \cdot \mathbf{s} \rfloor_p$$

- H is modeled as a quantum random oracle
- The pseudorandomness can be reduced from LWE assumption

We prove the pseudorandomness in QROM, by using Zhandry's programming technique [Zhandry 12]



A Sigma Protocol for Our Construction



Merkle Tree-based
Accumulator

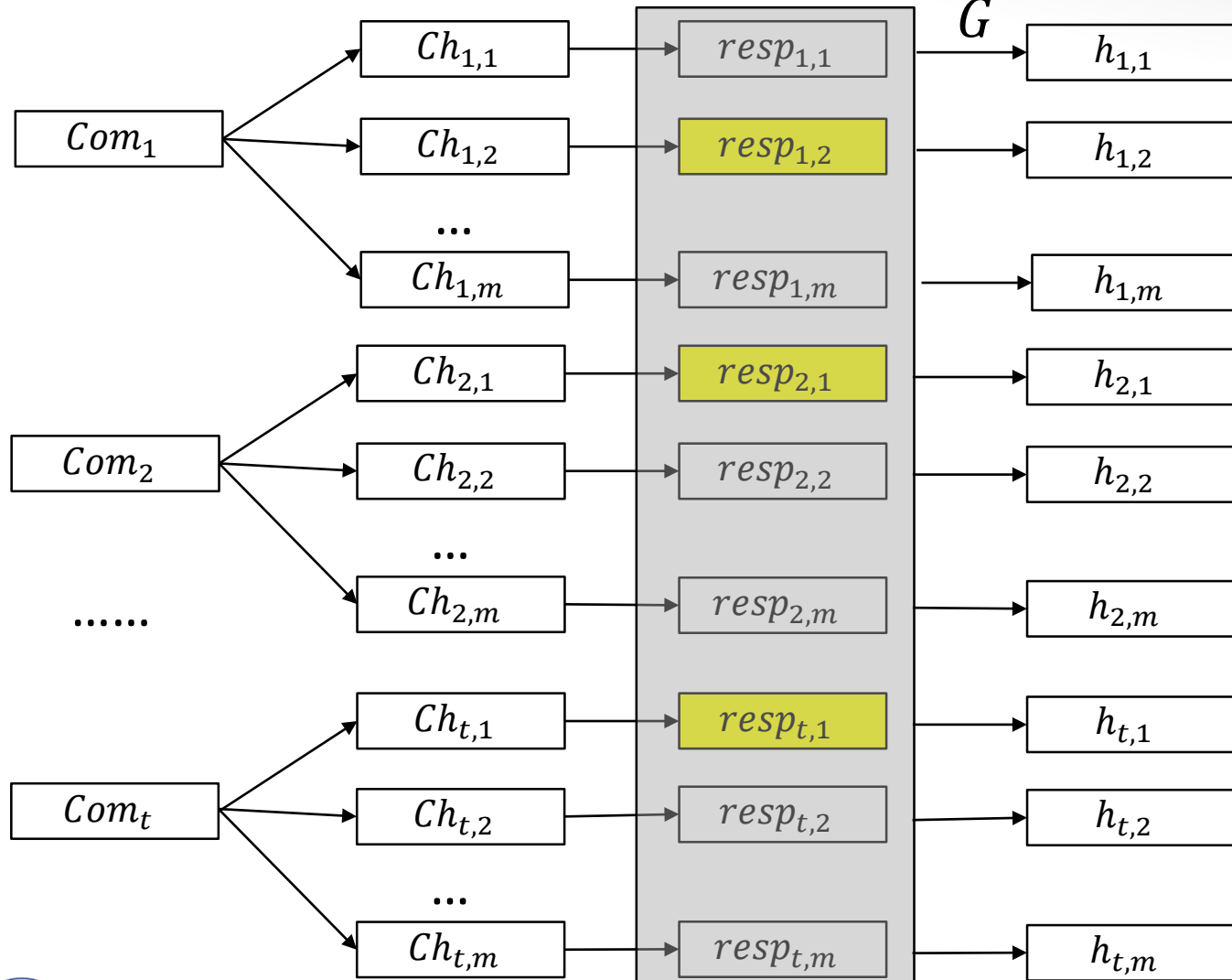
We design a Stern-like
protocol to prove :


- There is an honestly
generated node that was
accumulated to U



Obtain a secure NIZKPoK in QROM: Unruh Transform

Hash all of them to get the selection what to open



 Hidden by a random function

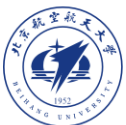
Idea

- Make the random function invertible (for extractor)
- All needed information to extract the witness is already contained in the proof.



Apply What You Have Learned Today

- In this paper, we give a general framework of traceable ring signatures from PRF and NIZKPoK
- We also provide a concrete construction by instantiating our framework with lattice-based components, and prove its security in the quantum random oracle model
- You can obtain your traceable ring signatures by instantiating our framework with other possible components
- You may improve our framework in efficiency or security





Thanks for your listening