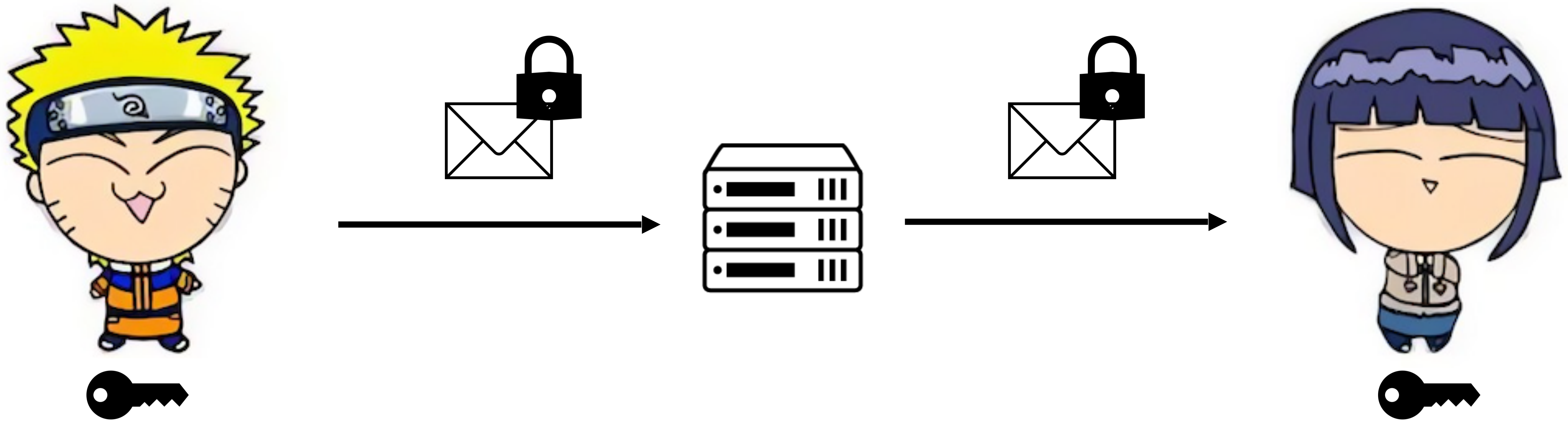
Analyzing Group Chat Encryption in MLS, Session, Signal, and Matrix

Joseph Jaeger and Akshaya Kumar

Eurocrypt 2025

Georgia Tech

E2EE/Secure Messaging



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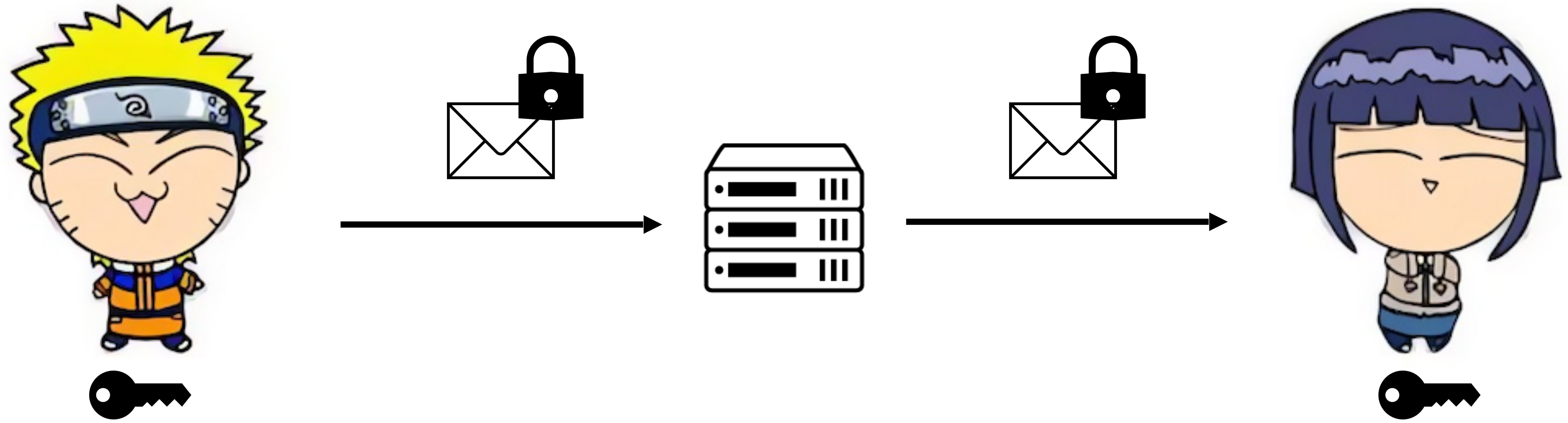

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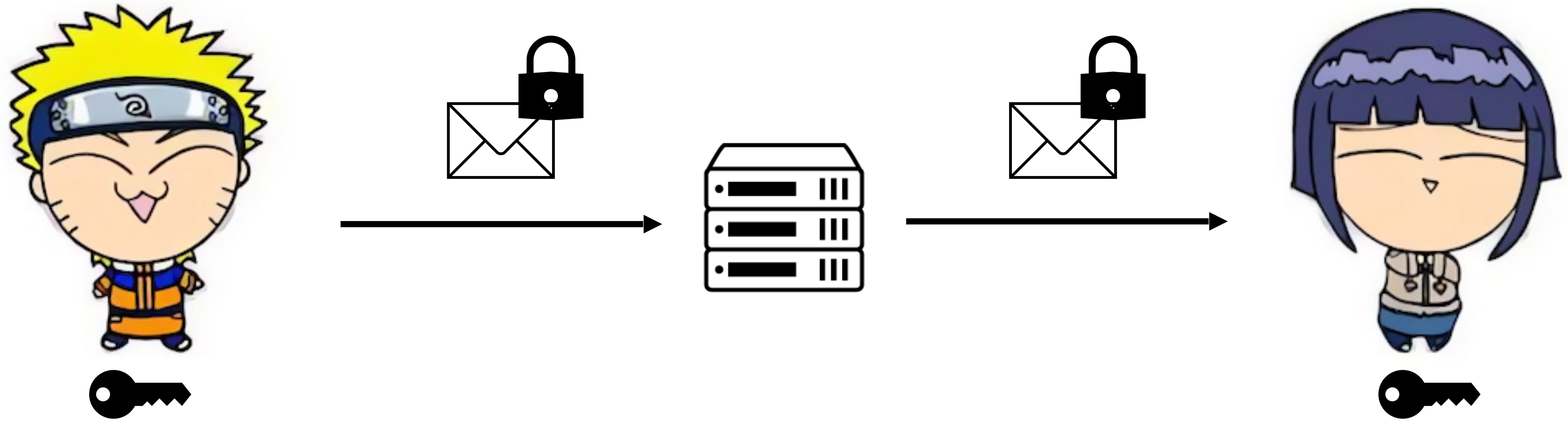
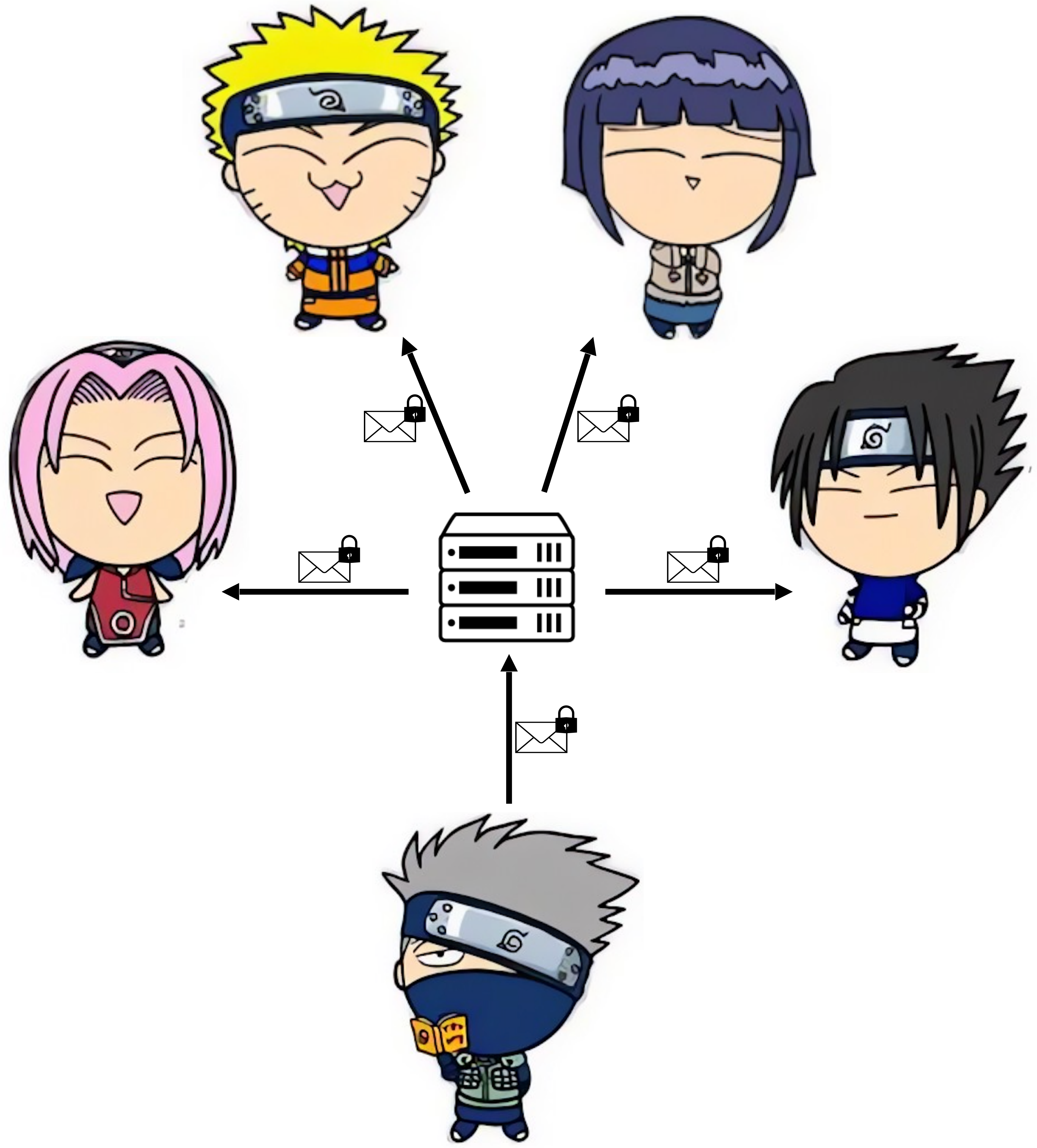


MLS

matrix

Secure Group Messaging



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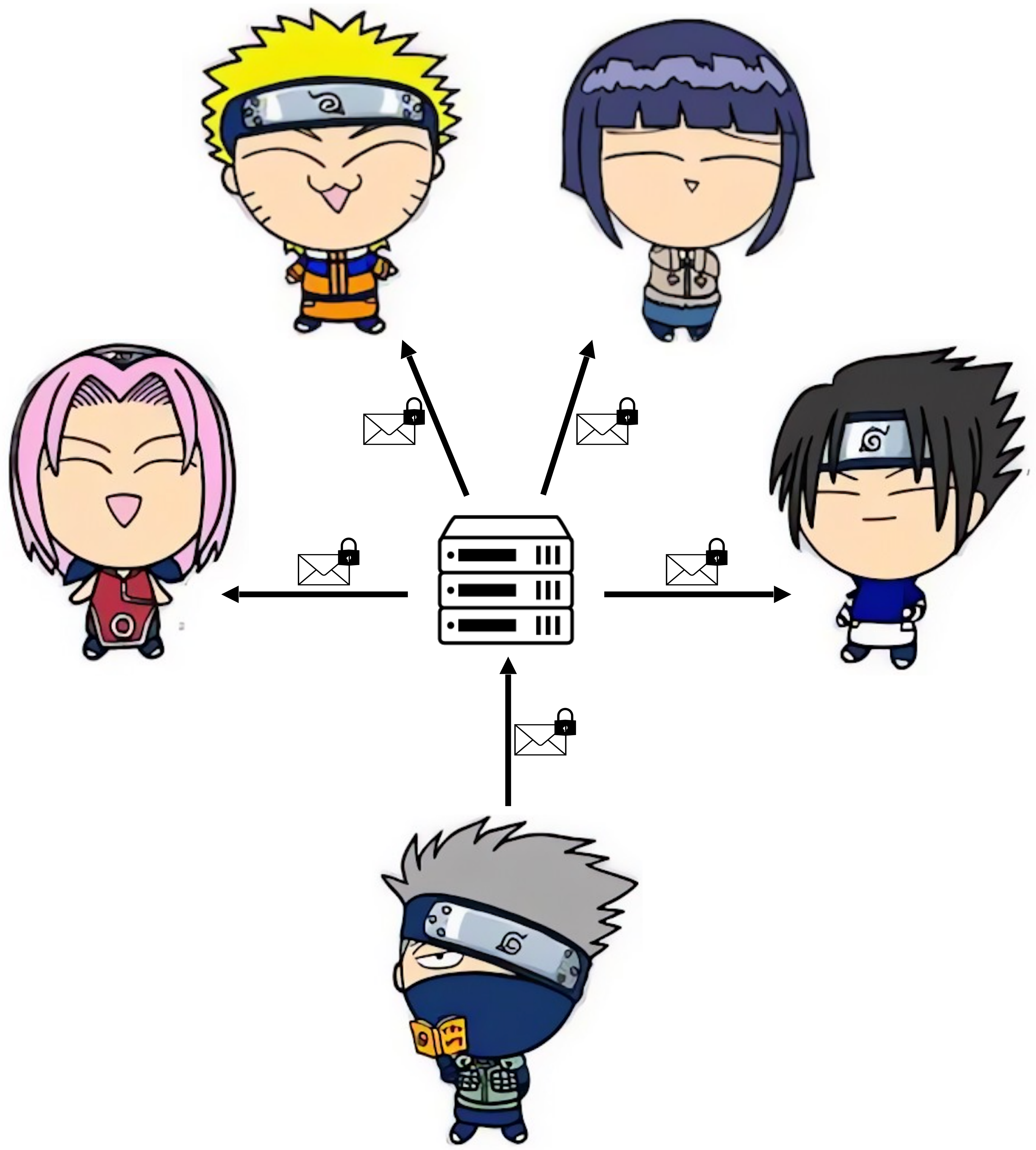

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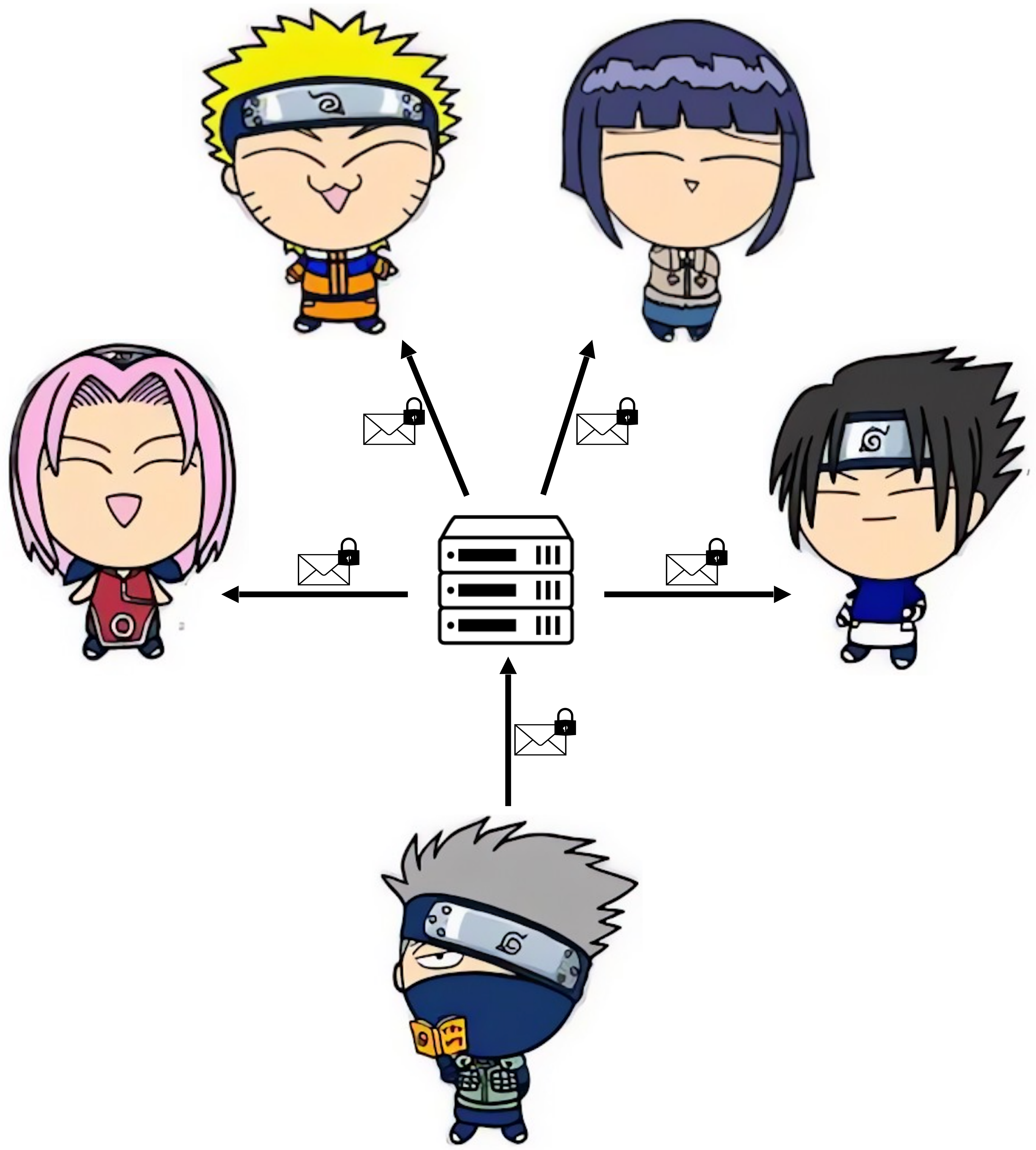

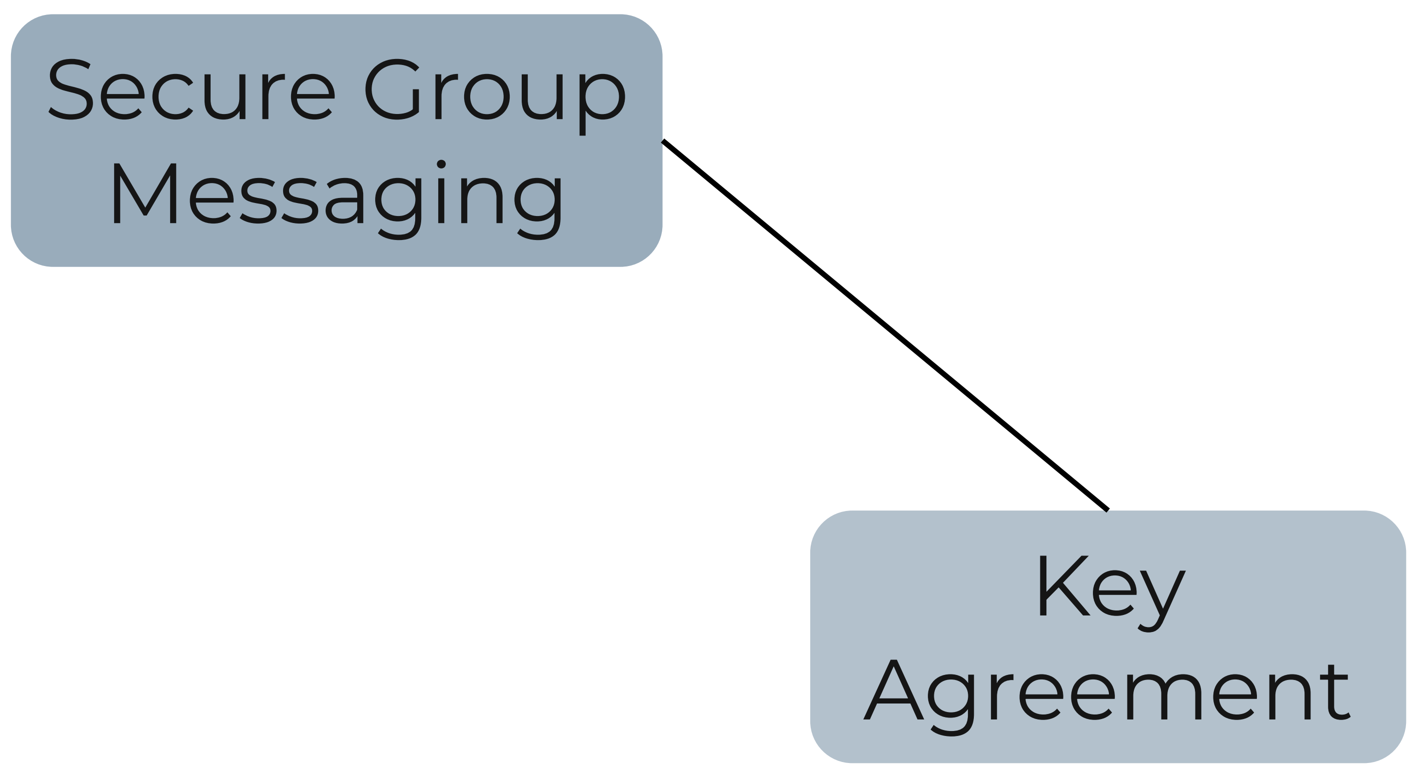

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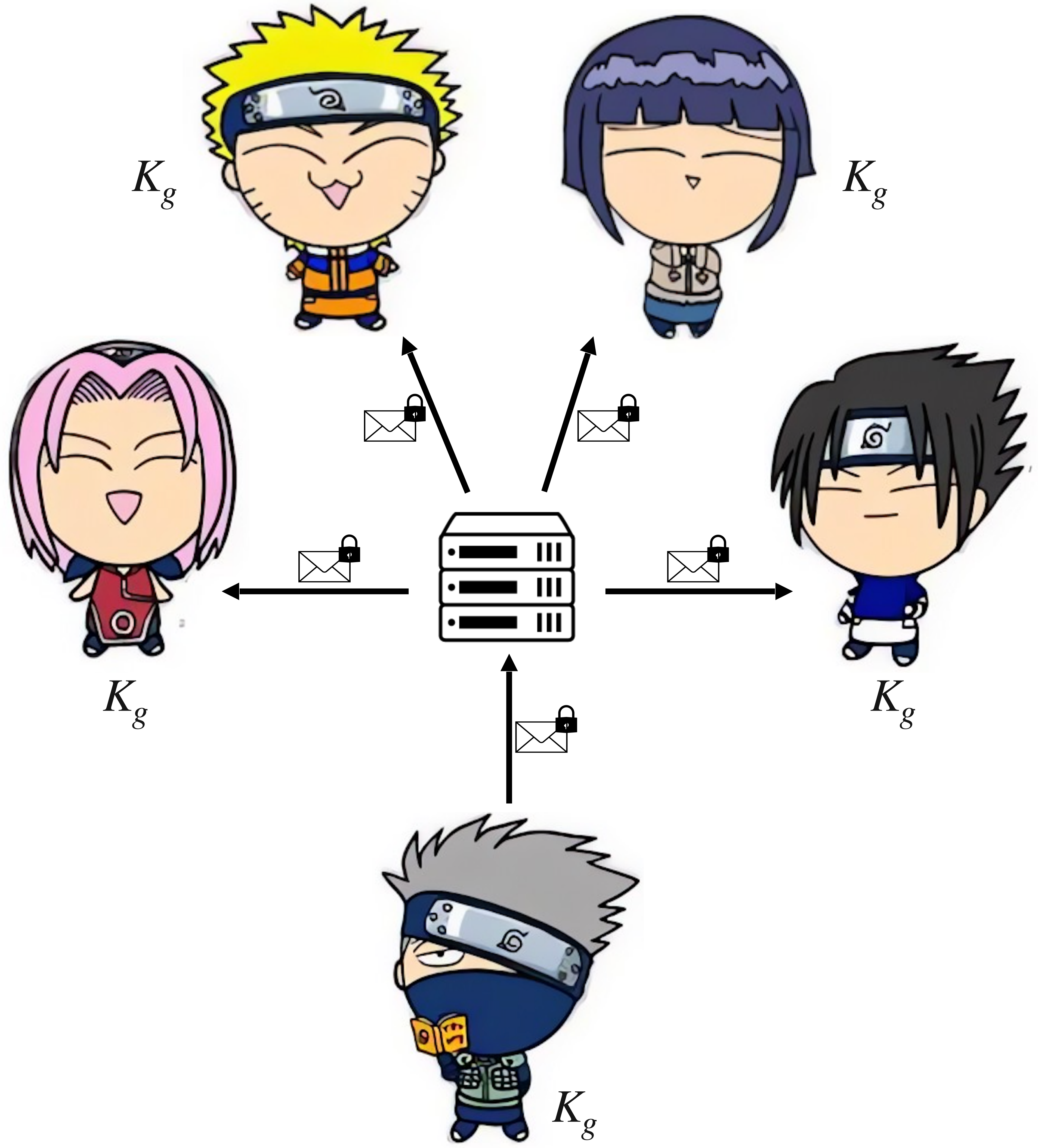

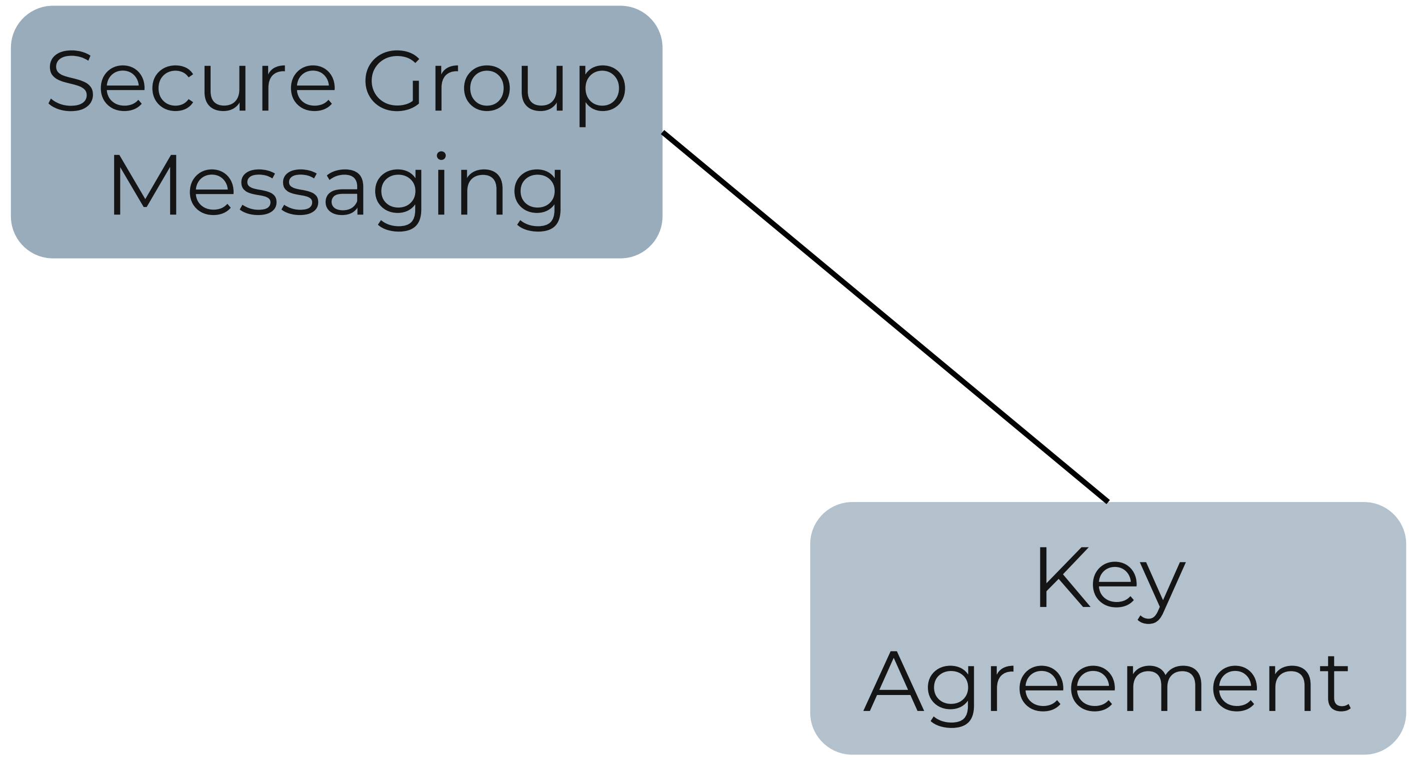

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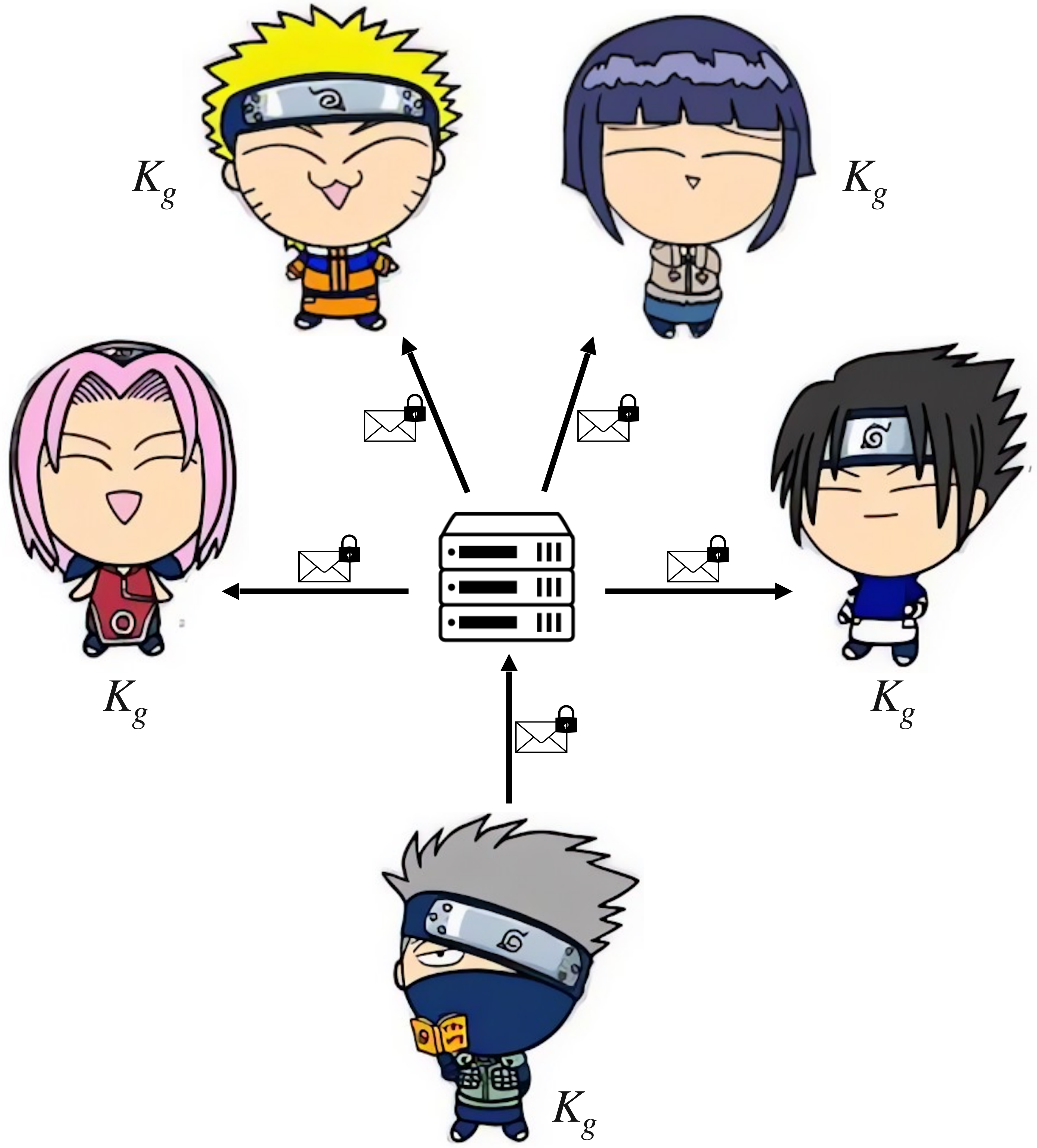

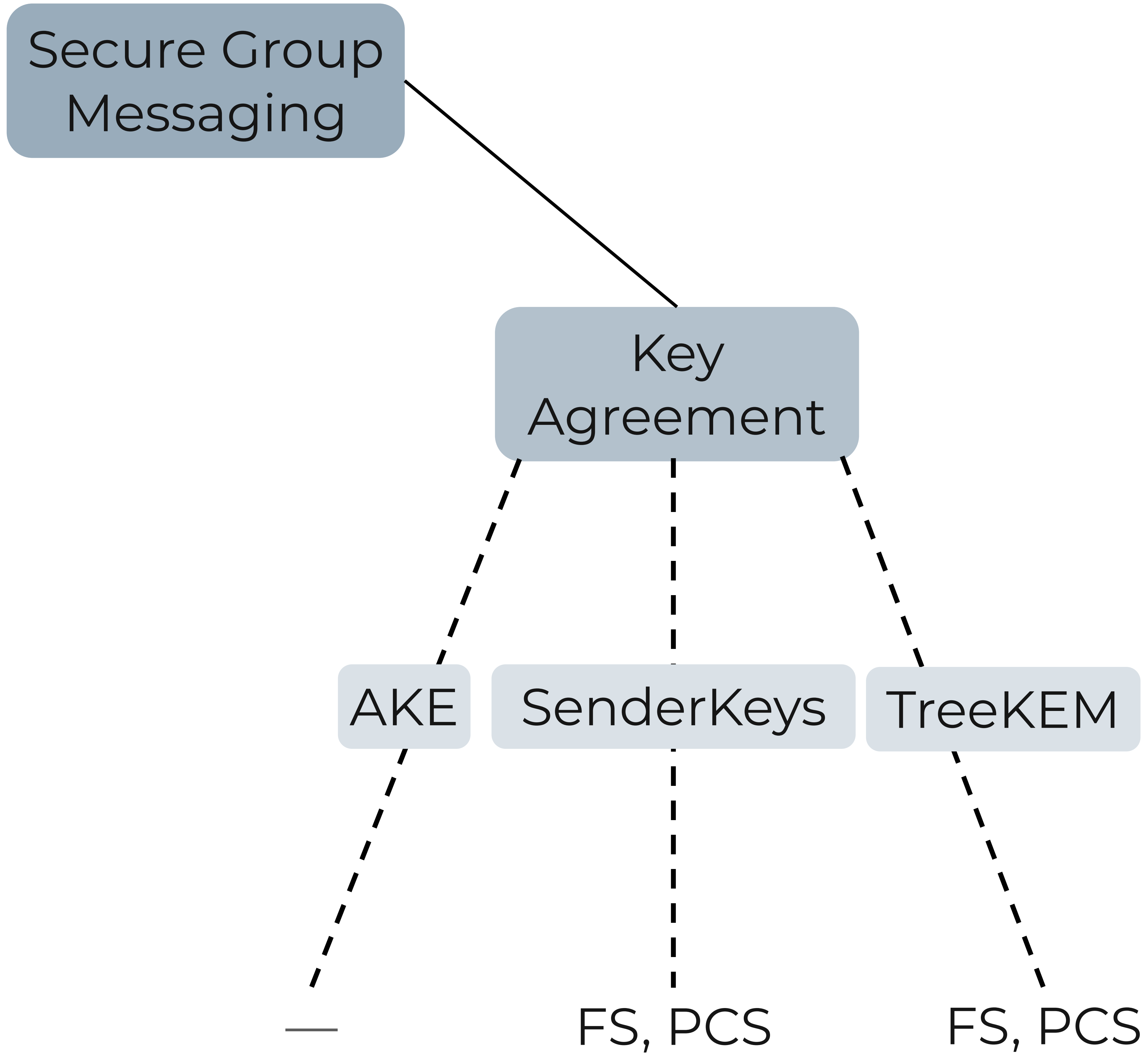

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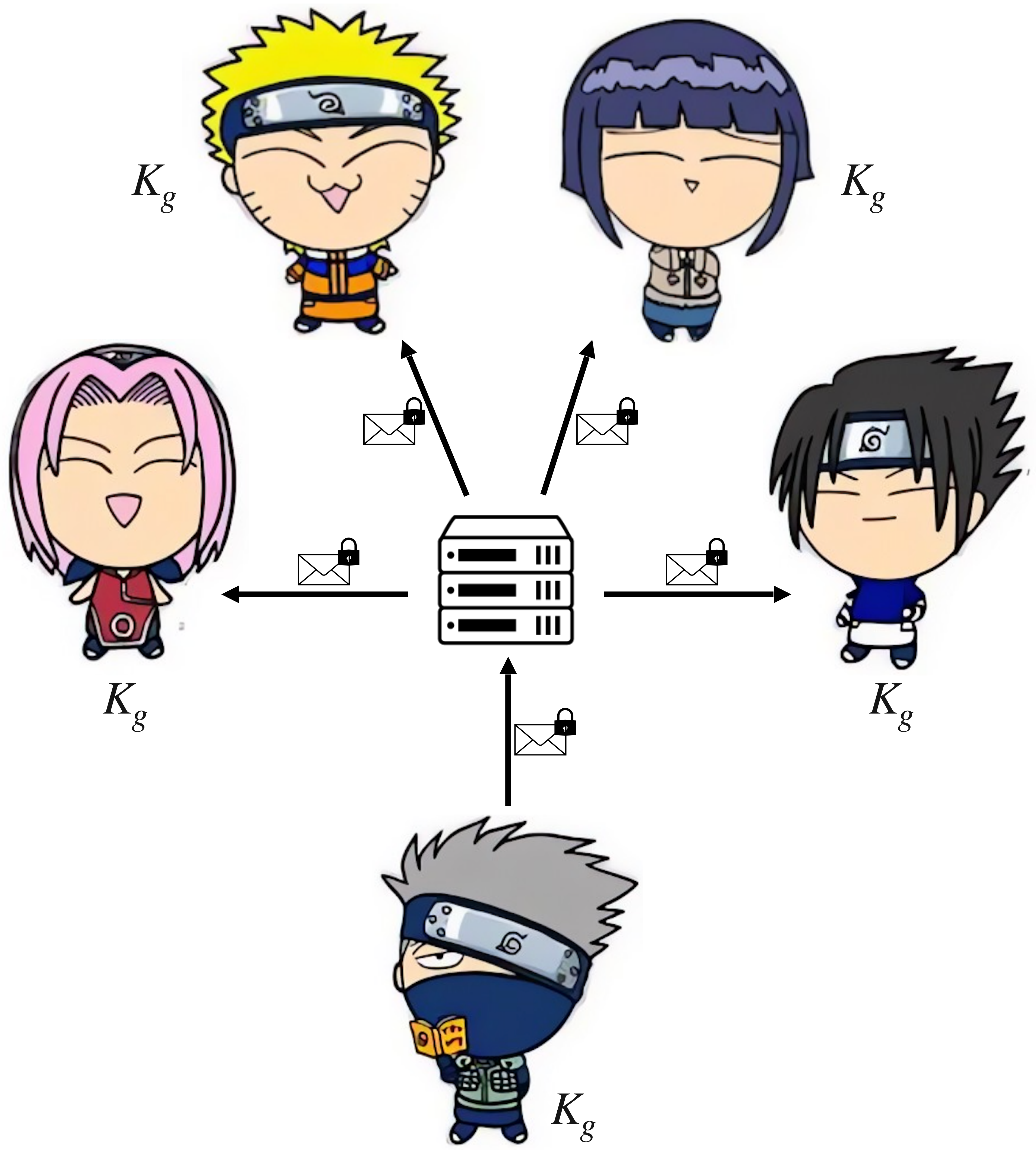
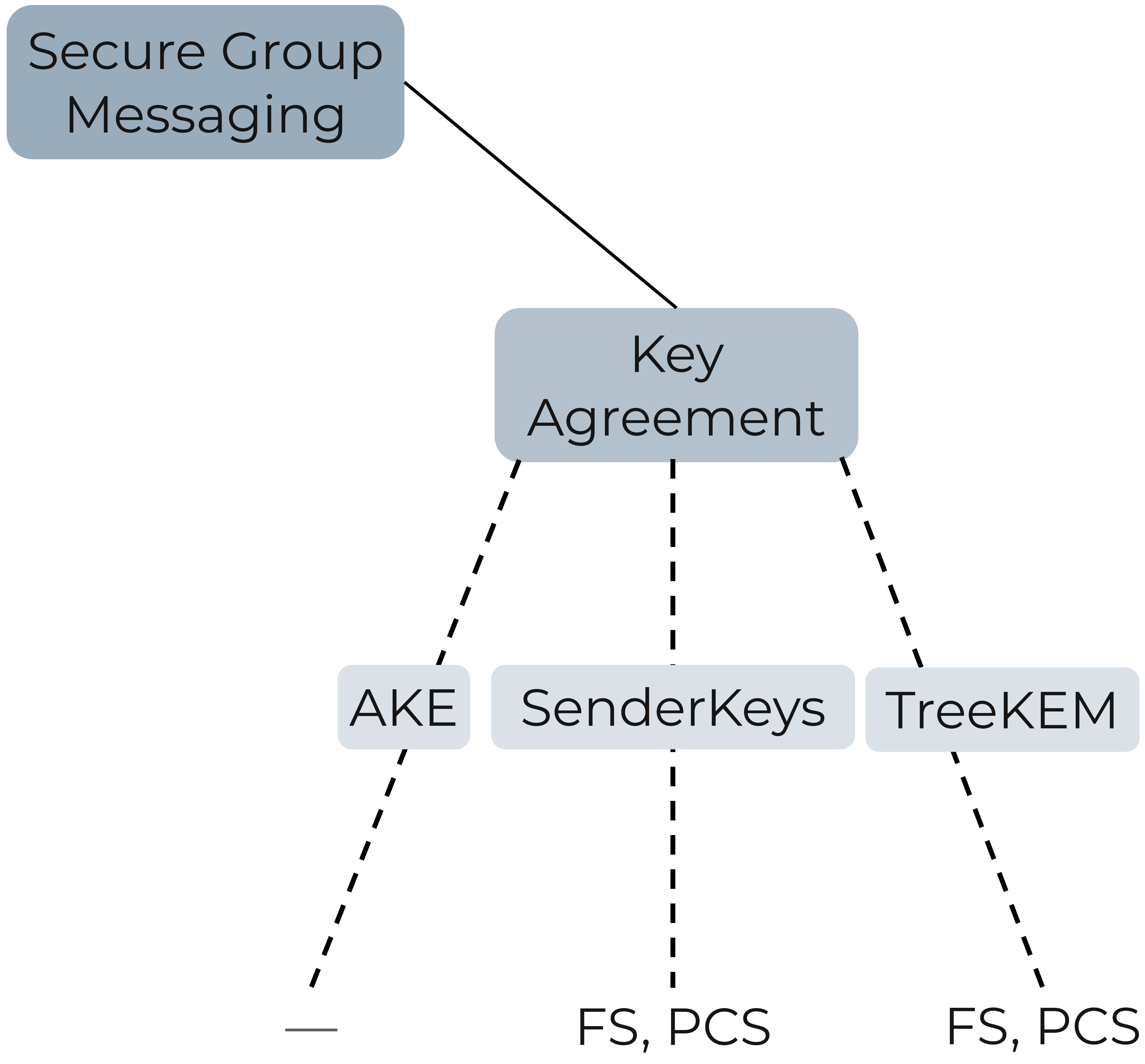
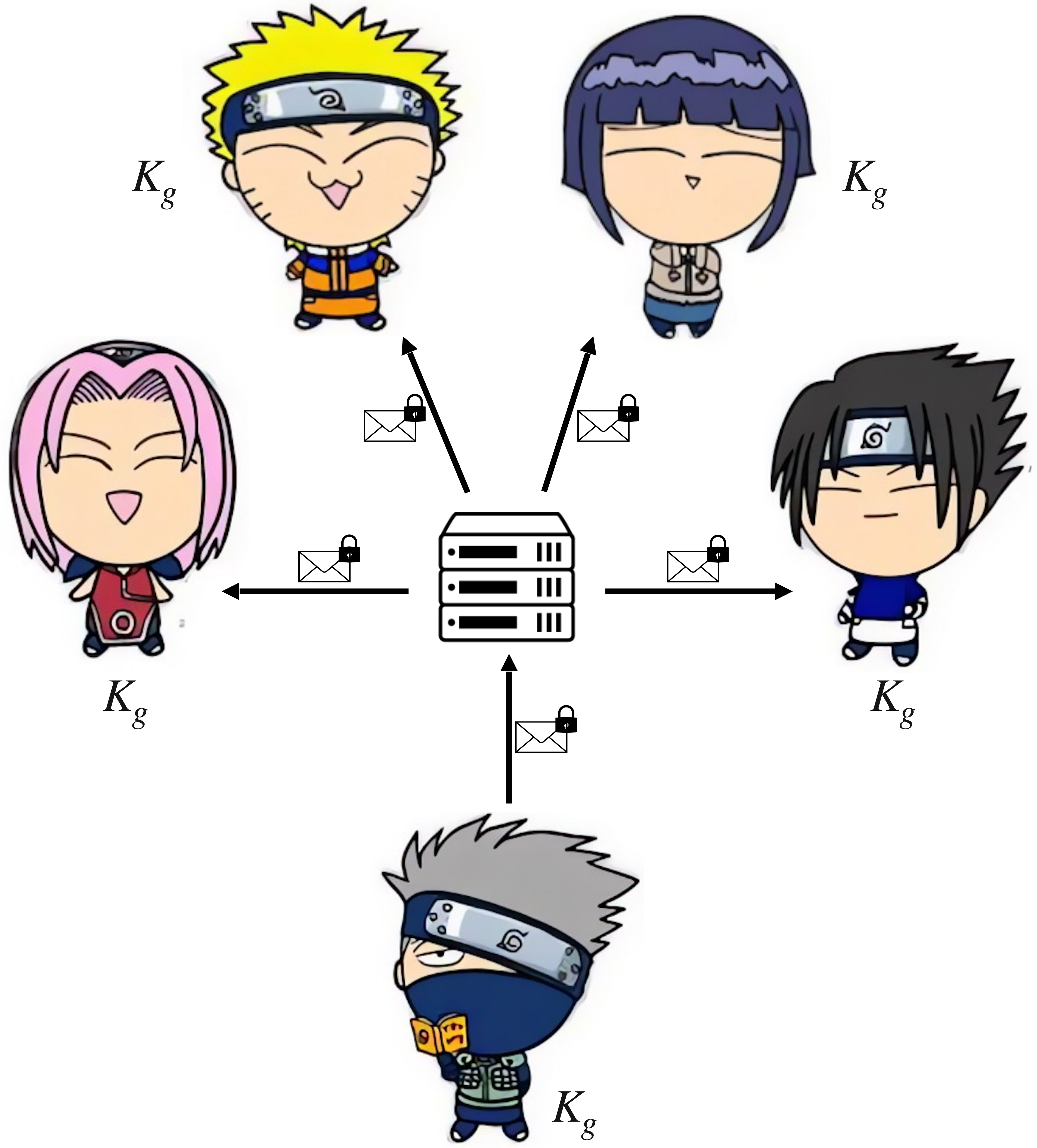
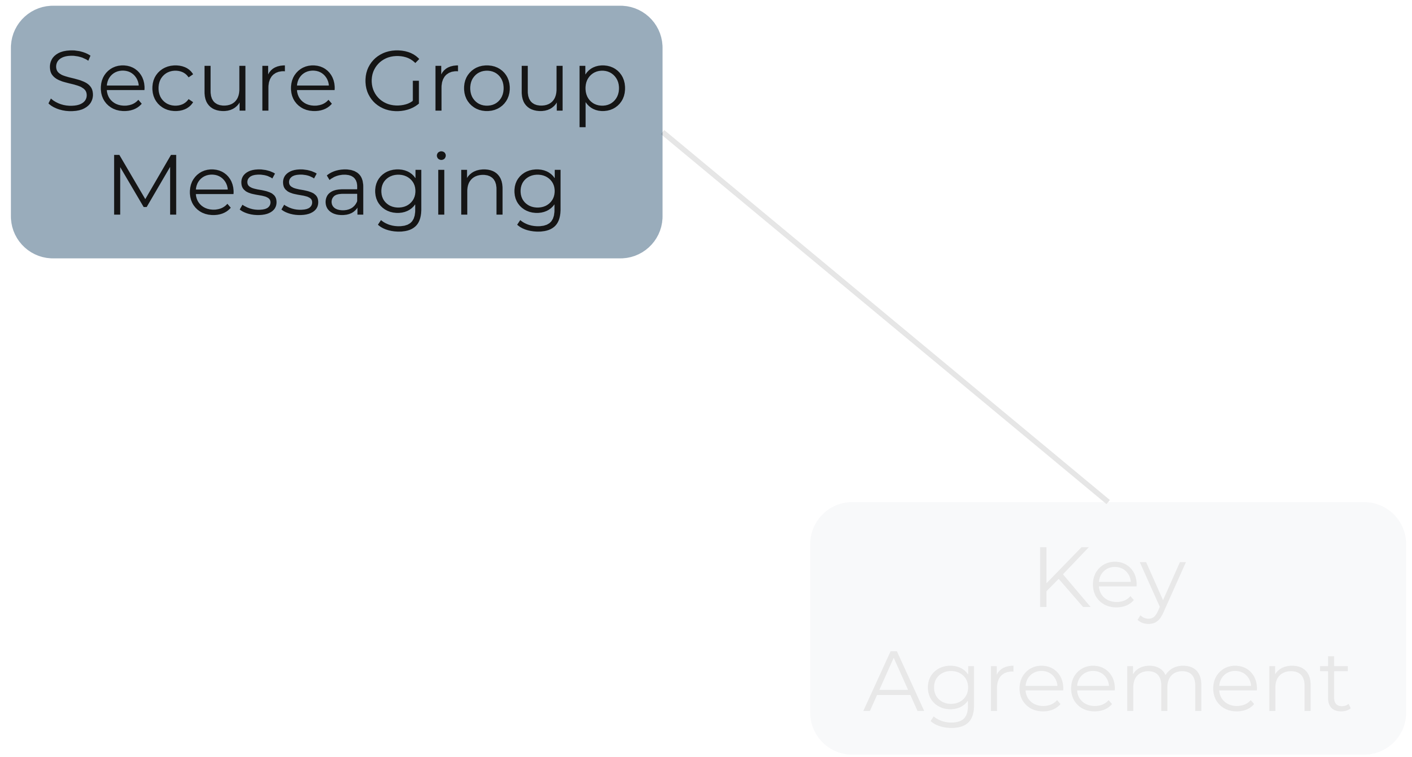




[BBR18, ACDT20, ACJM20, KPPW+21, ACDT21, HKPPW21, AHKM22, ACPP23, AWT23, BCG23, CLM23, ...]

Secure Group Messaging





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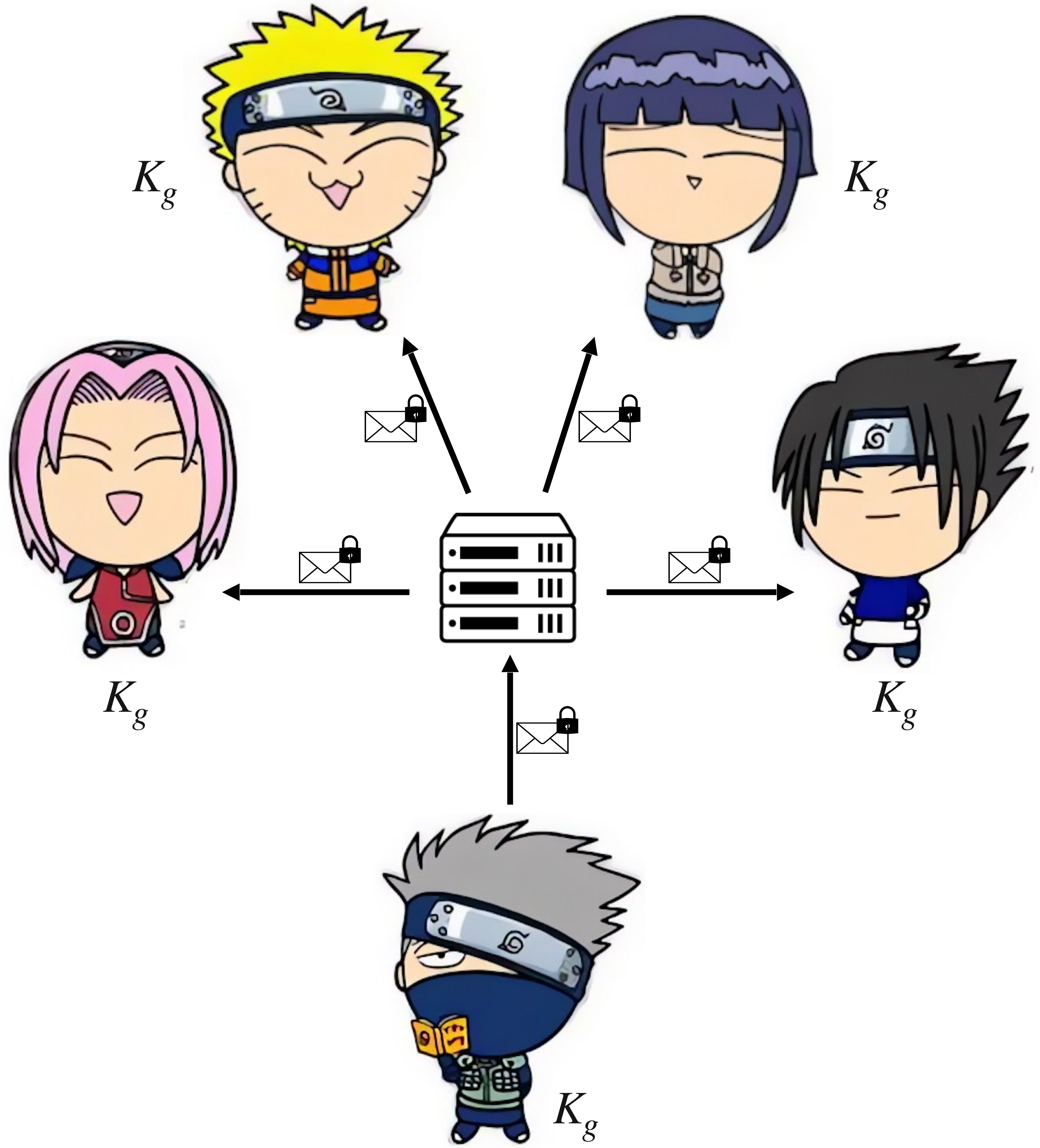

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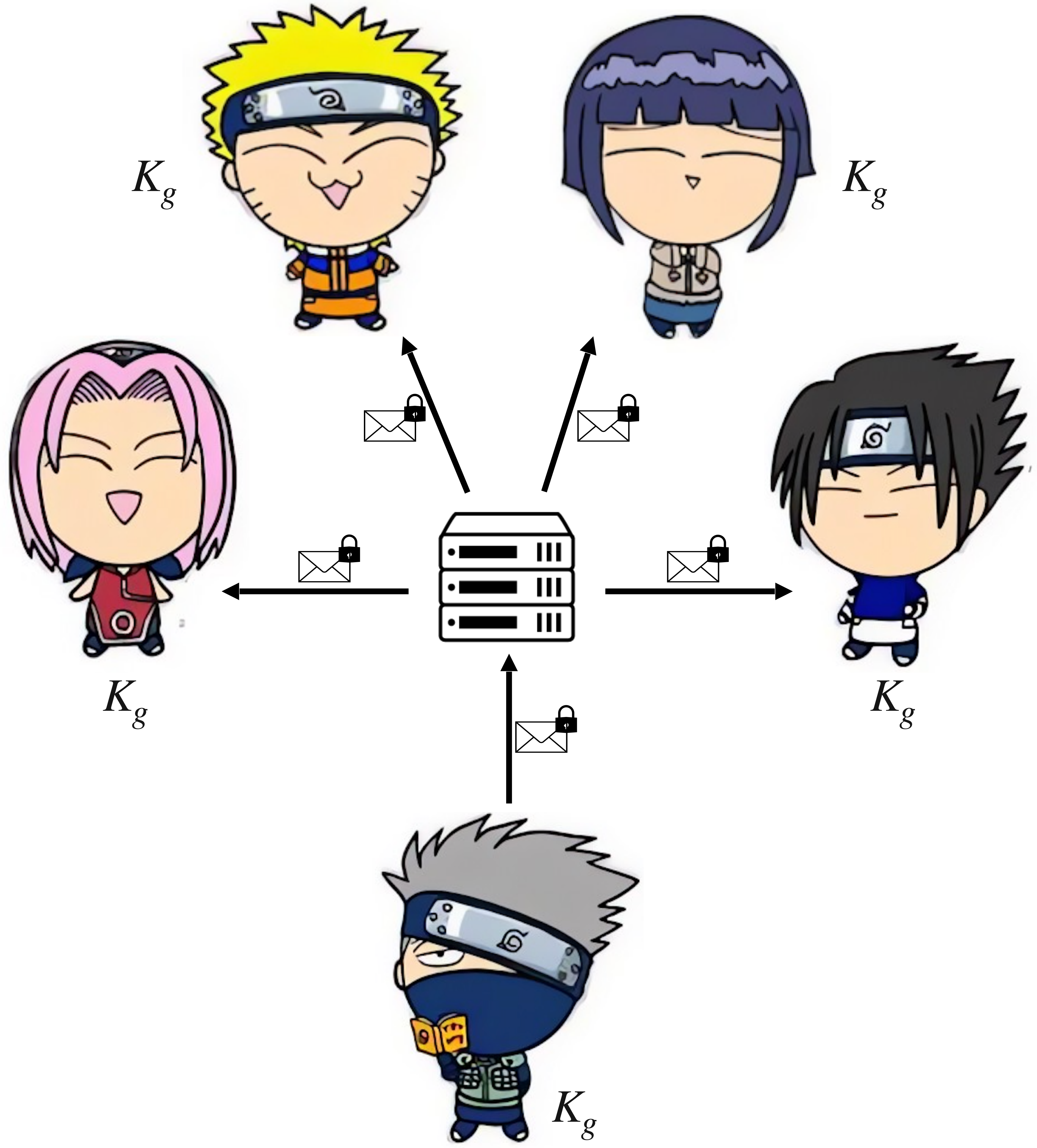

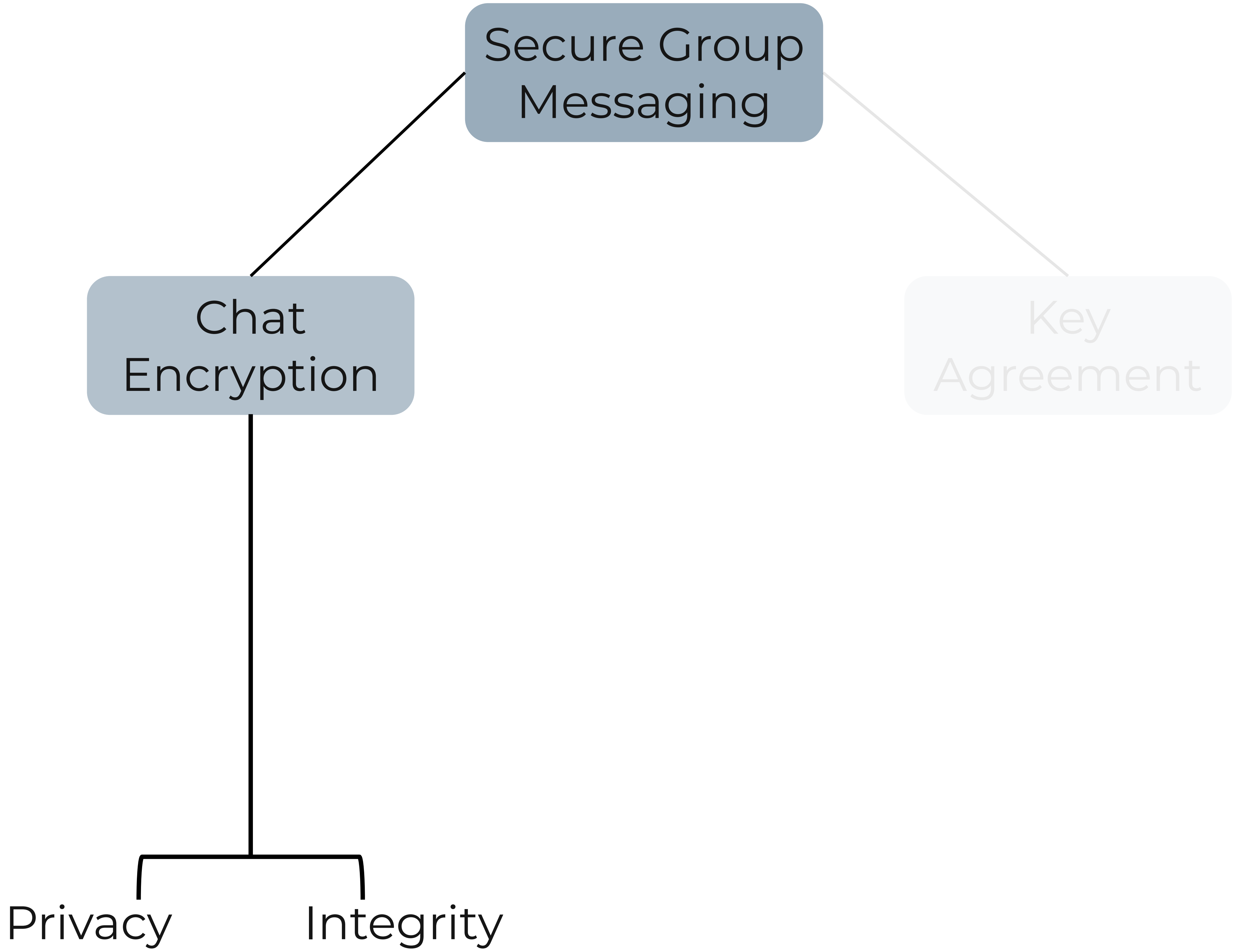

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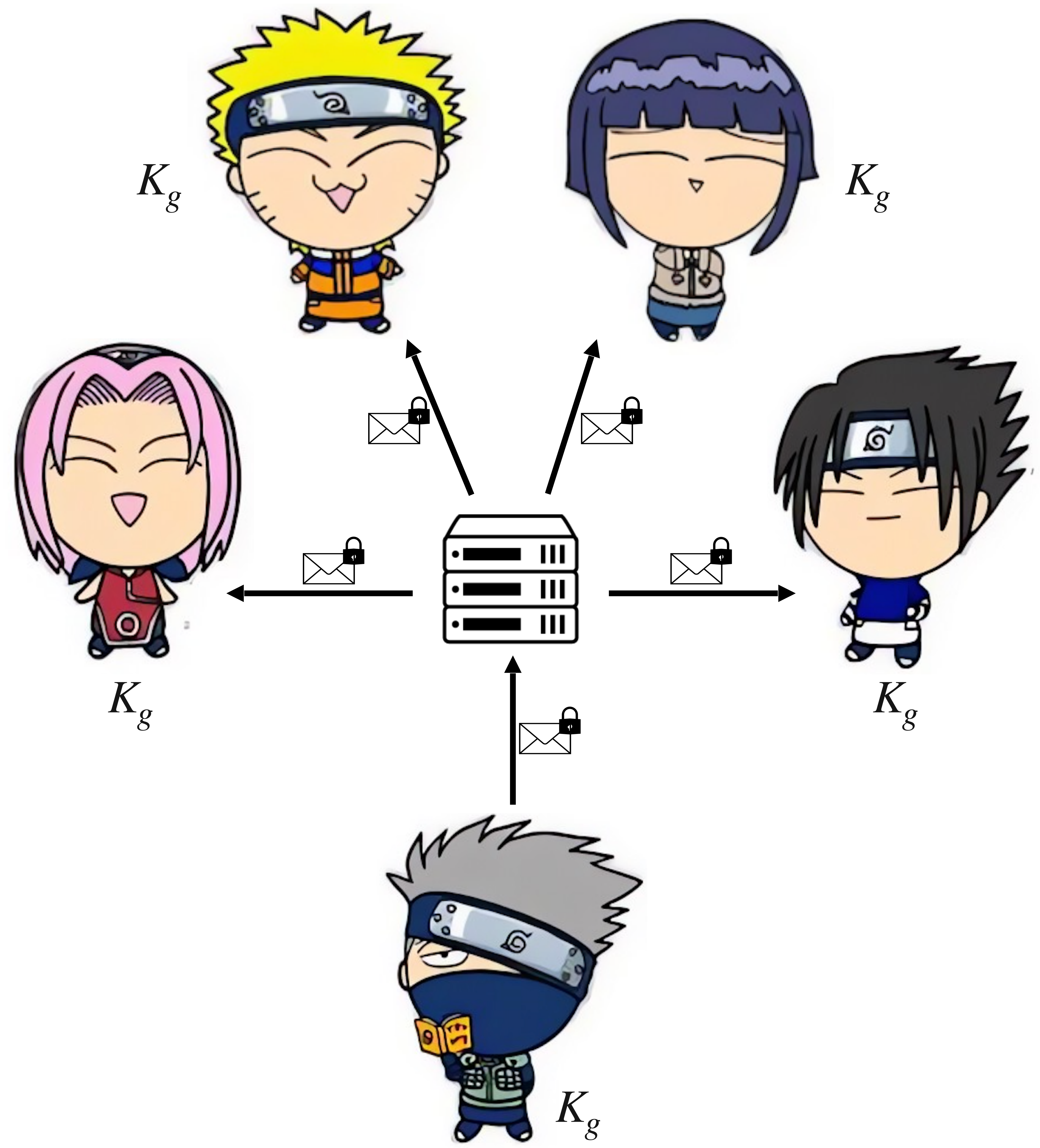

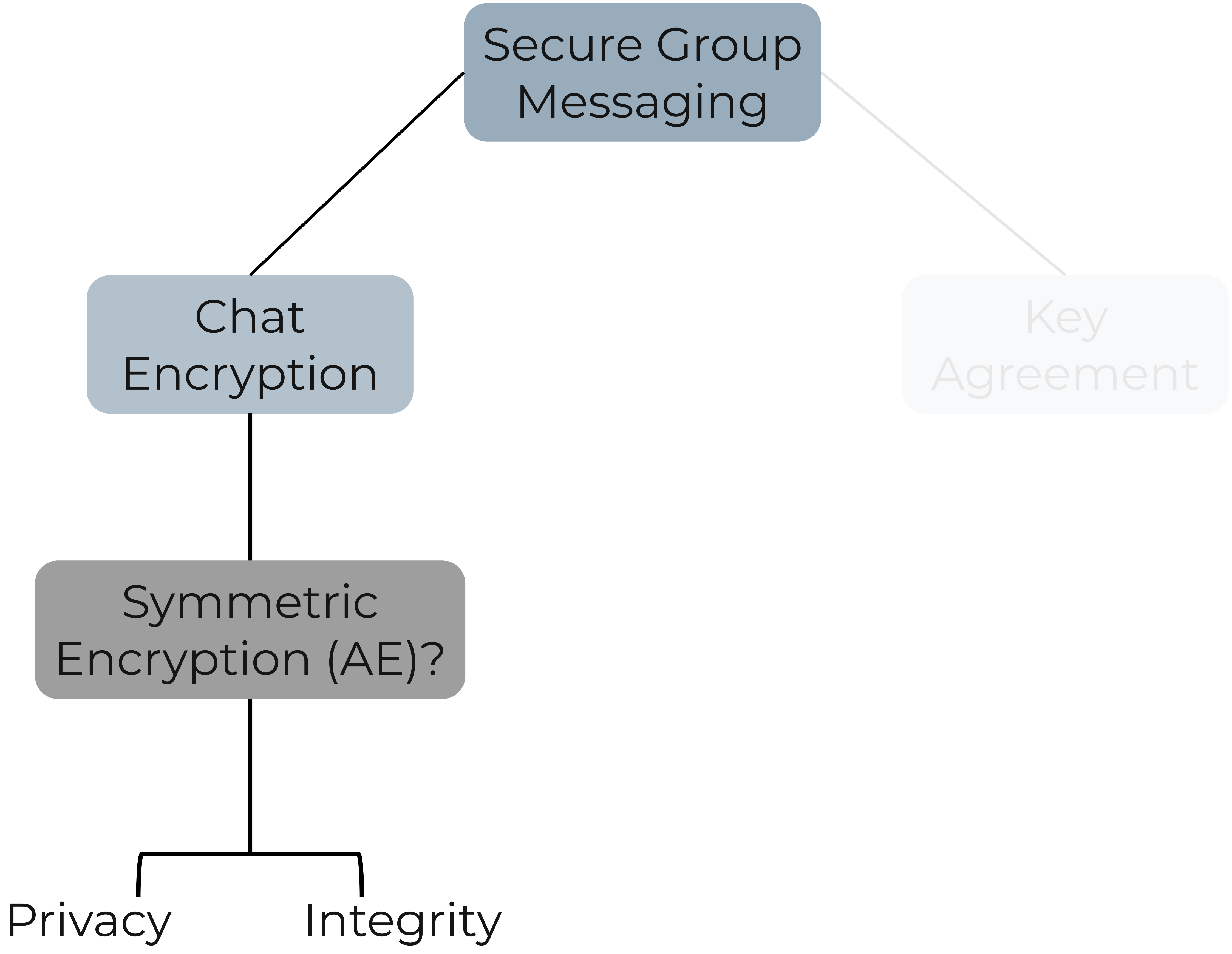

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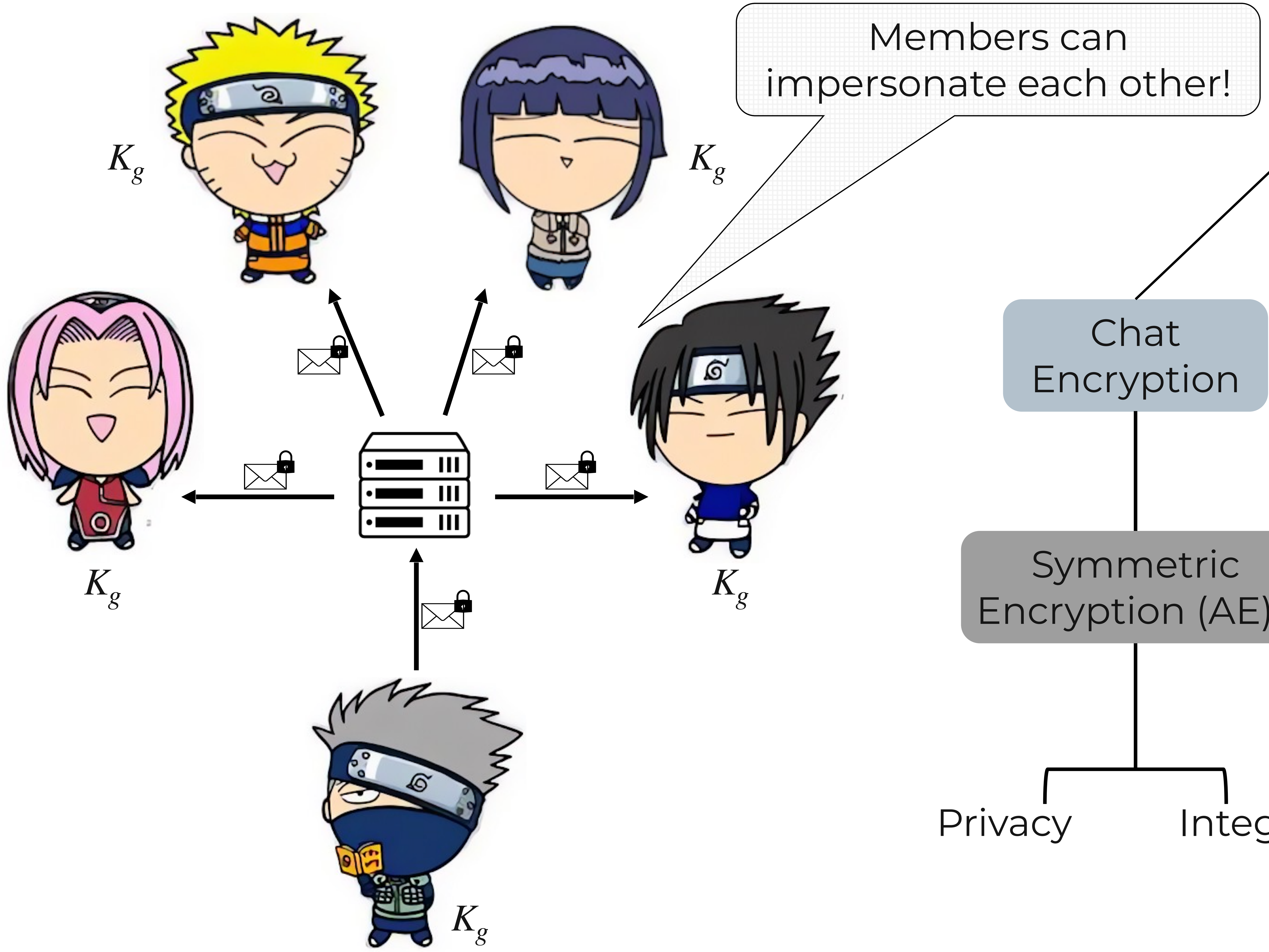

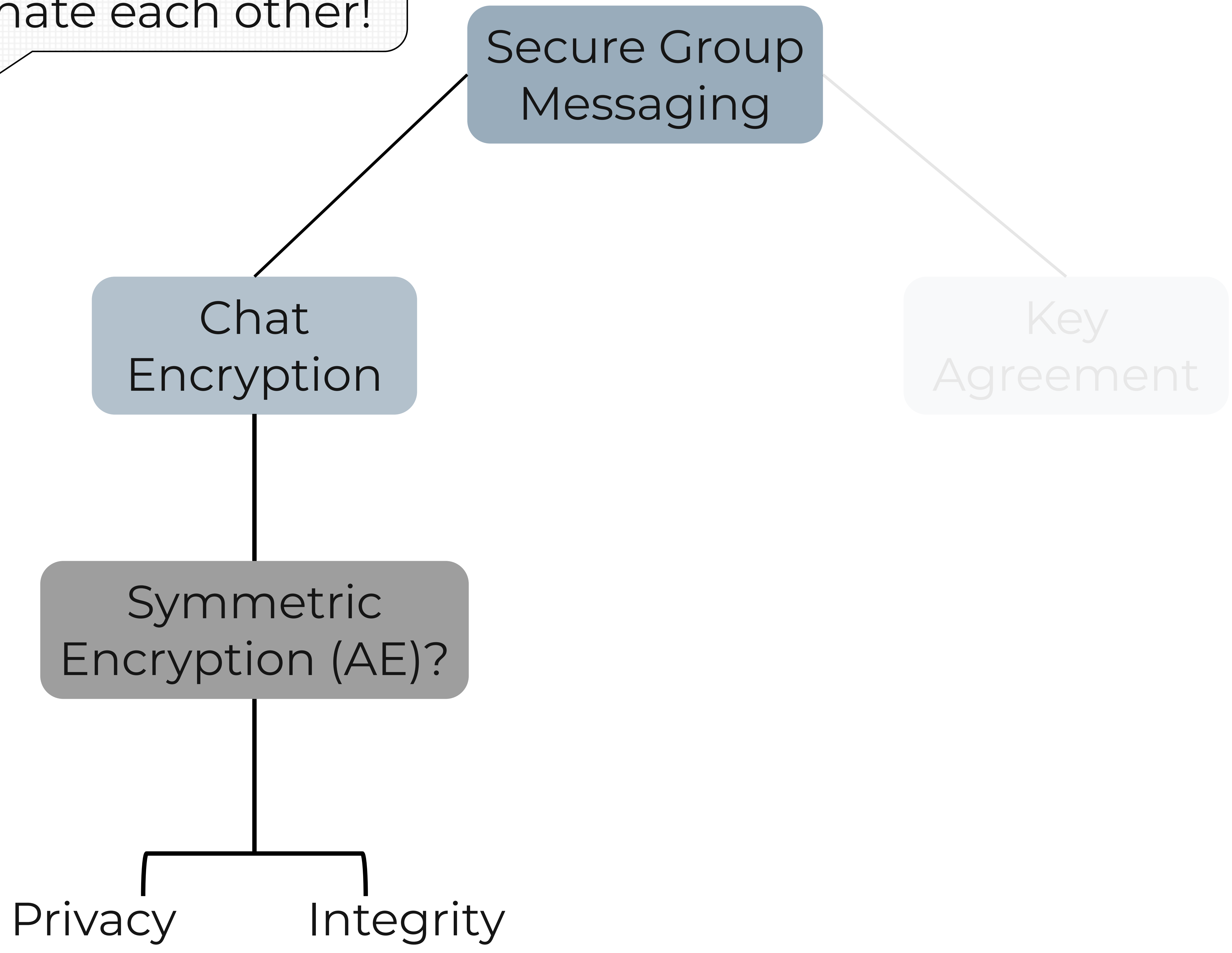

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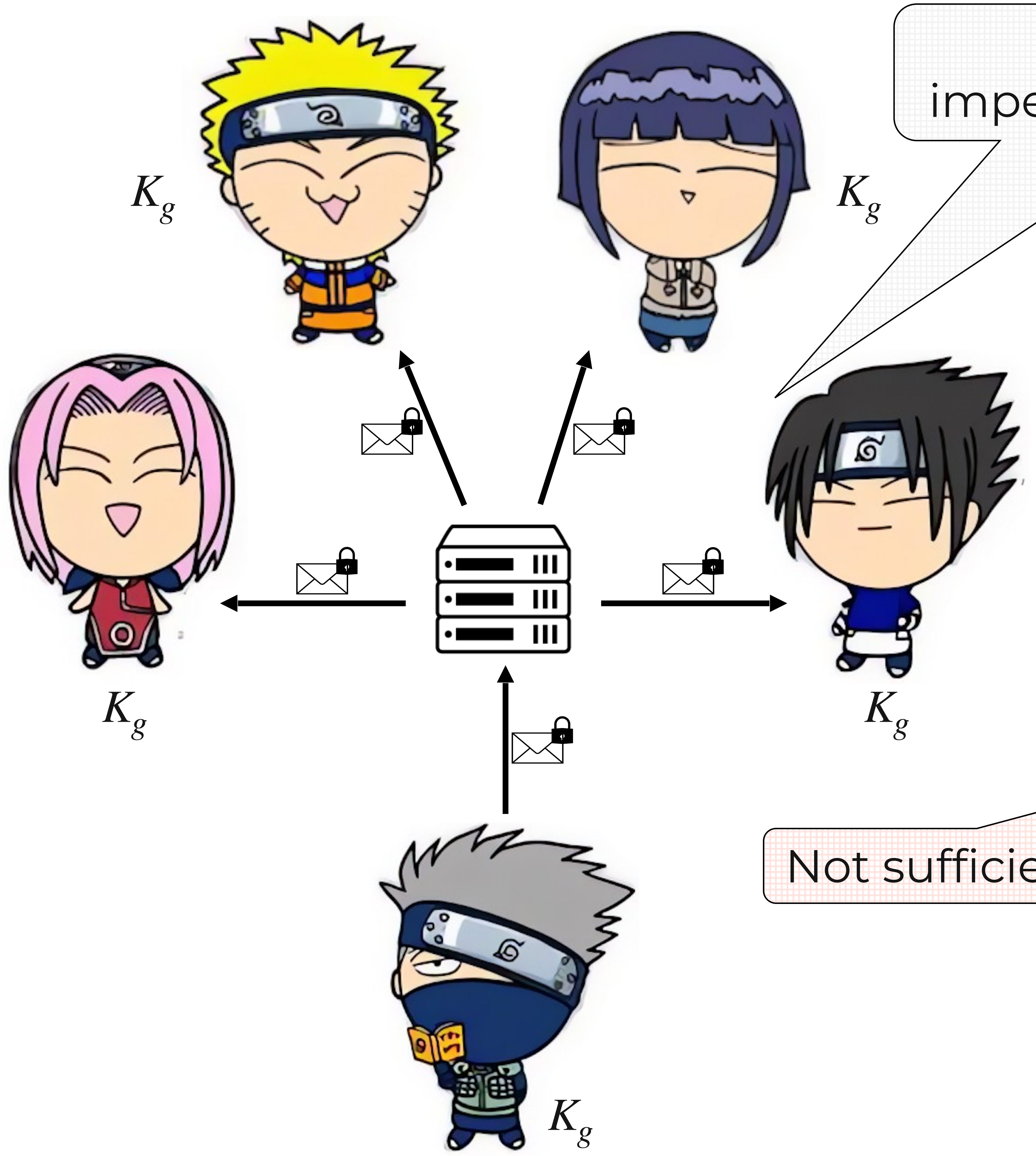
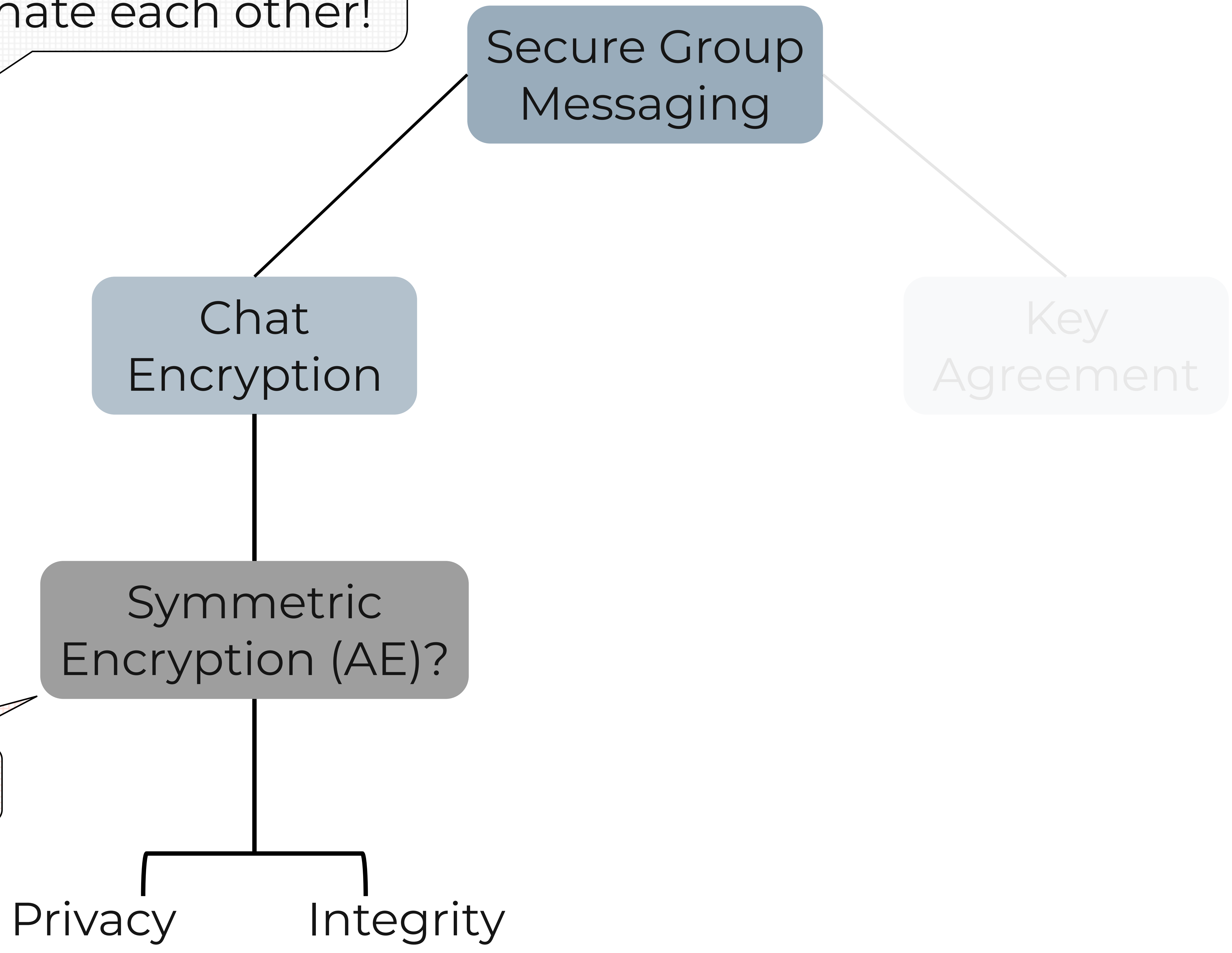


Members can impersonate each other!

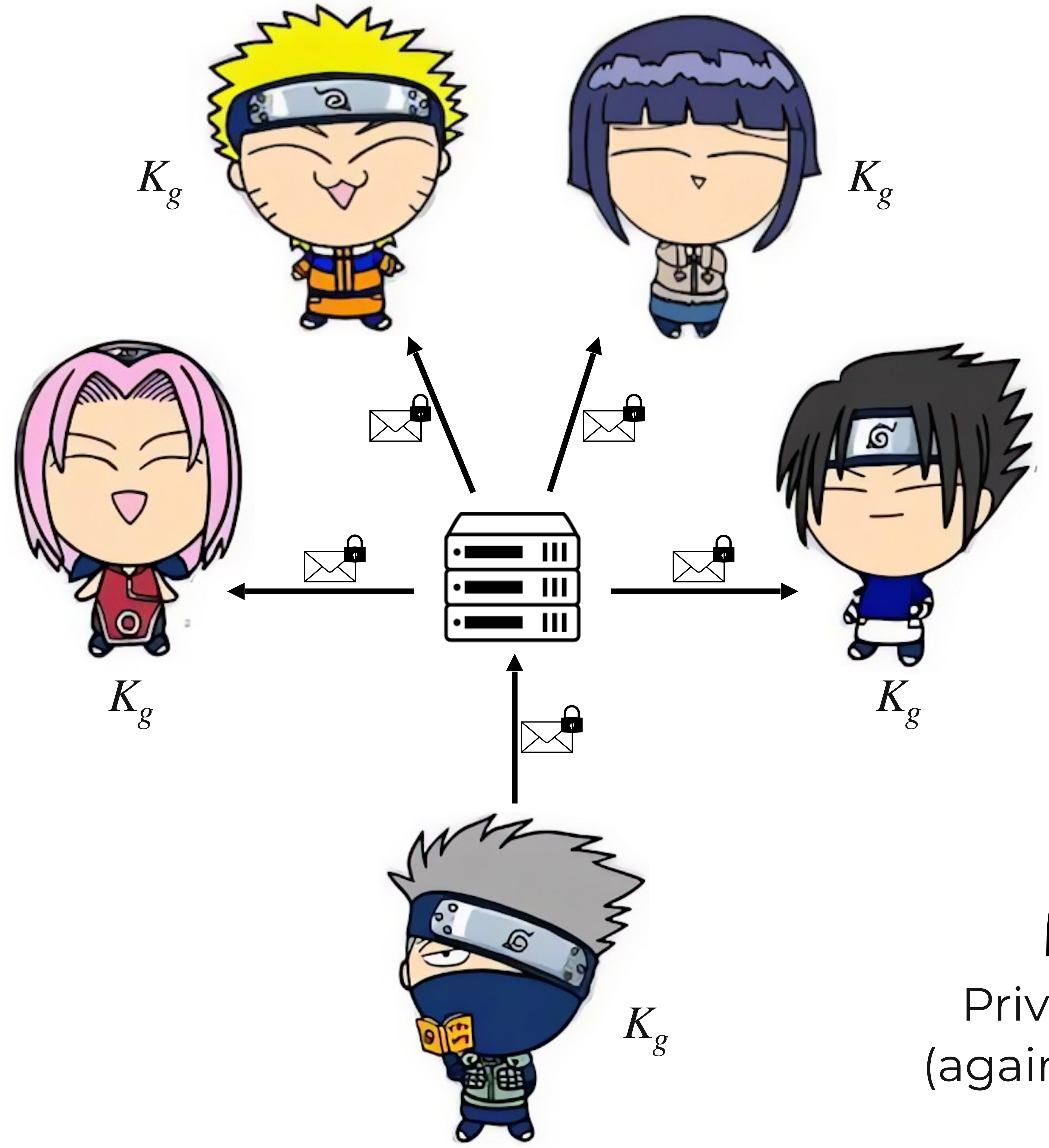
Not sufficient!

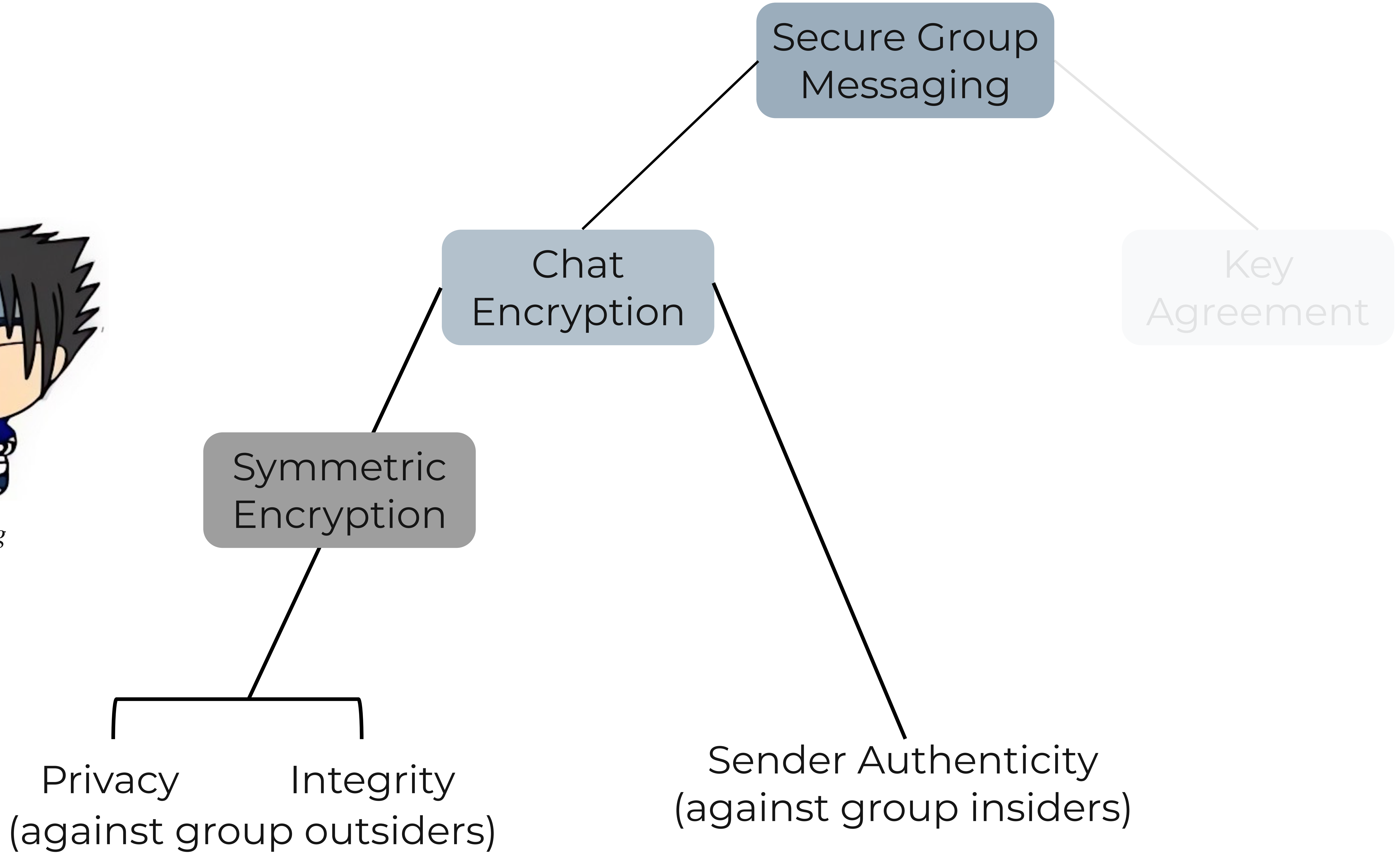


Secure Group Messaging

Need integrity against attackers **in the group** i.e. attackers that know K_g

Secure Group Messaging





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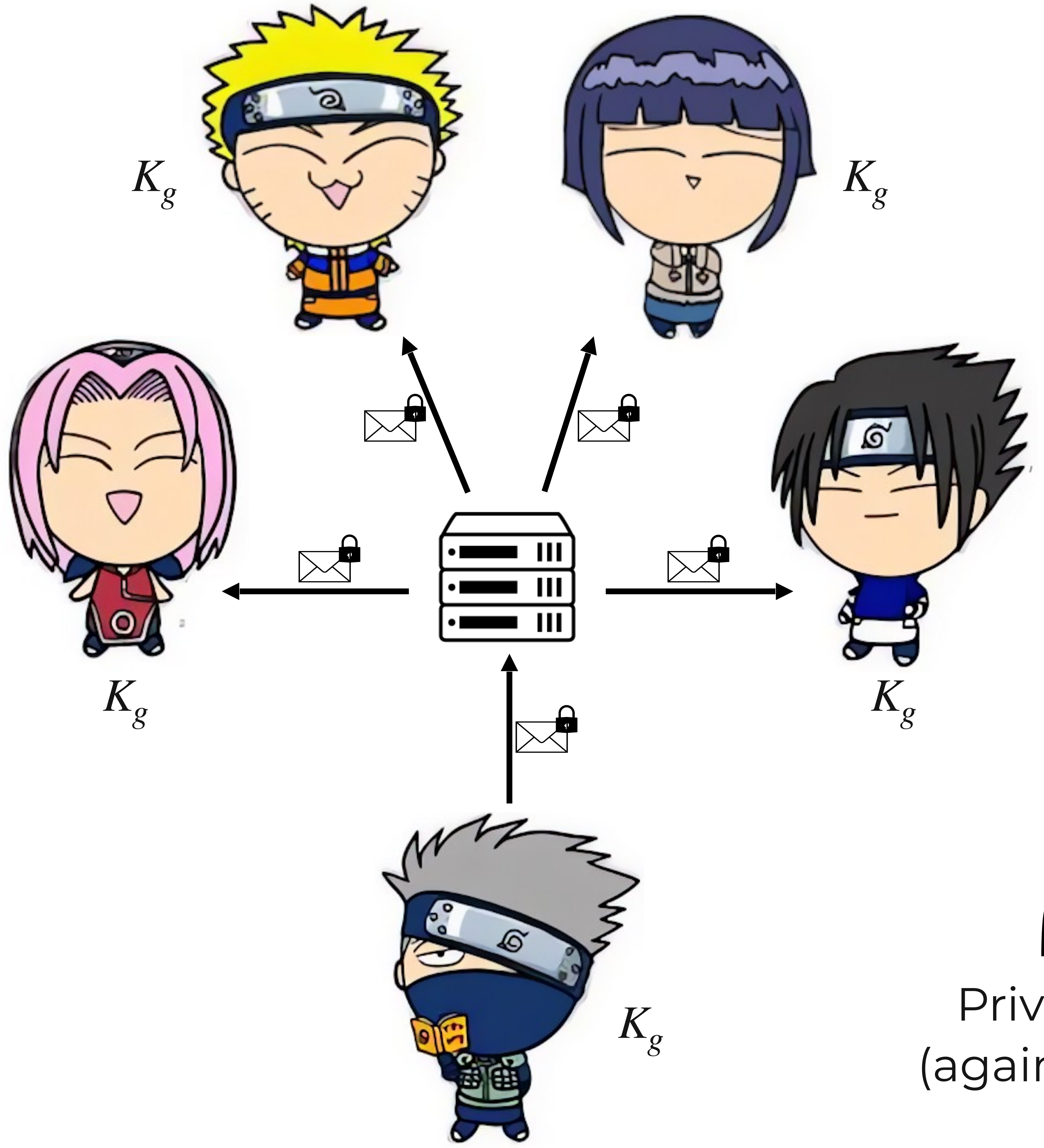

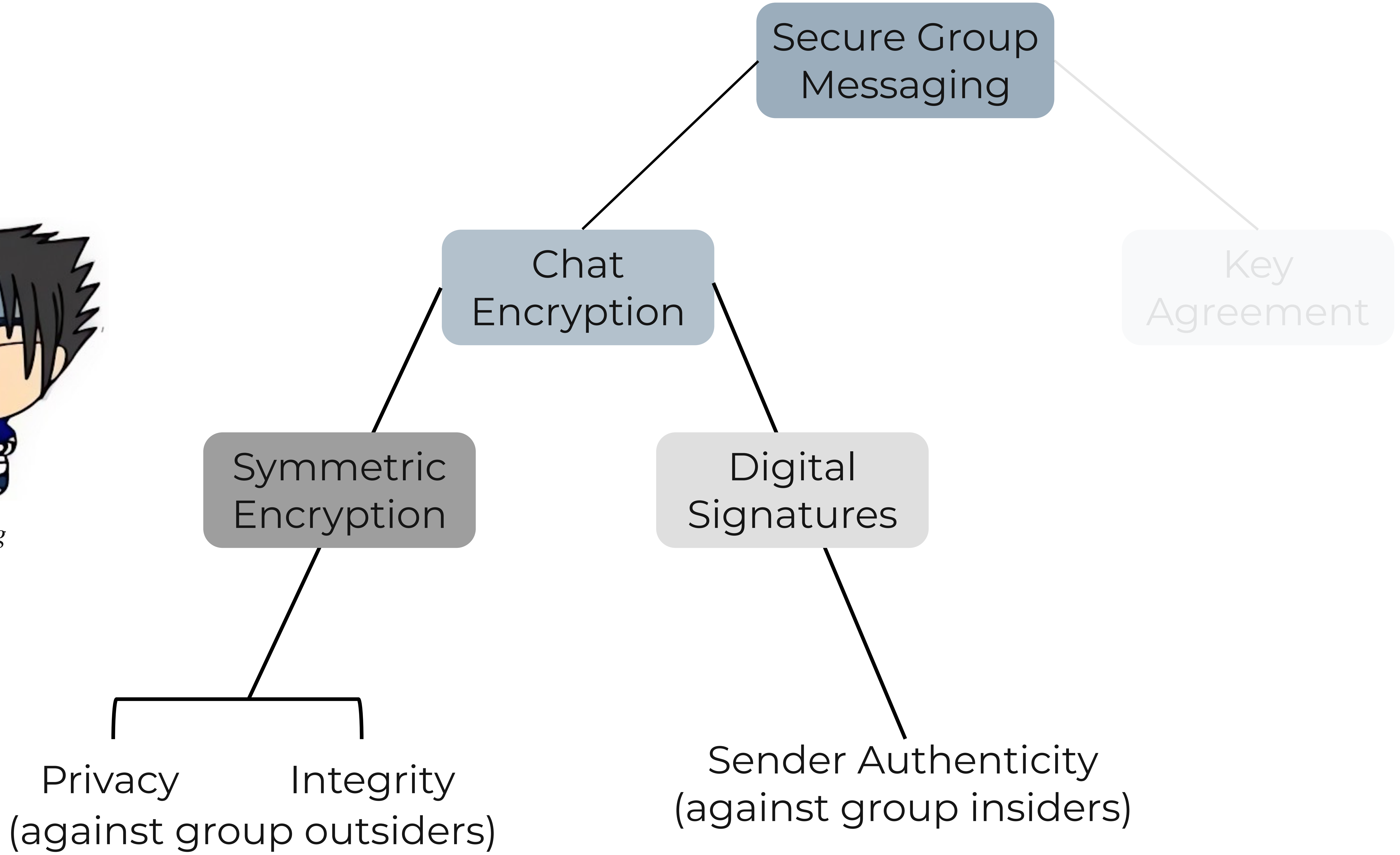

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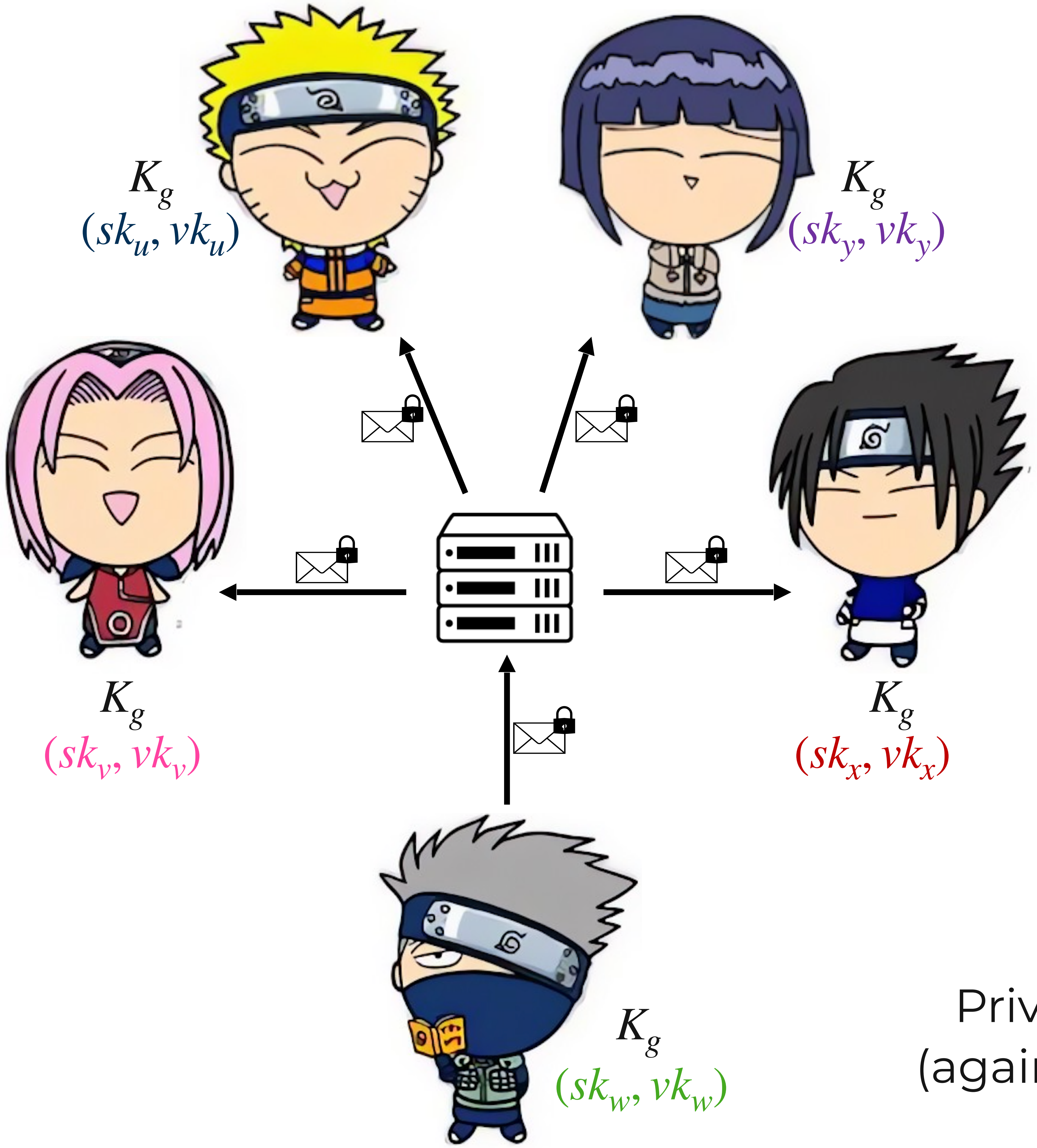

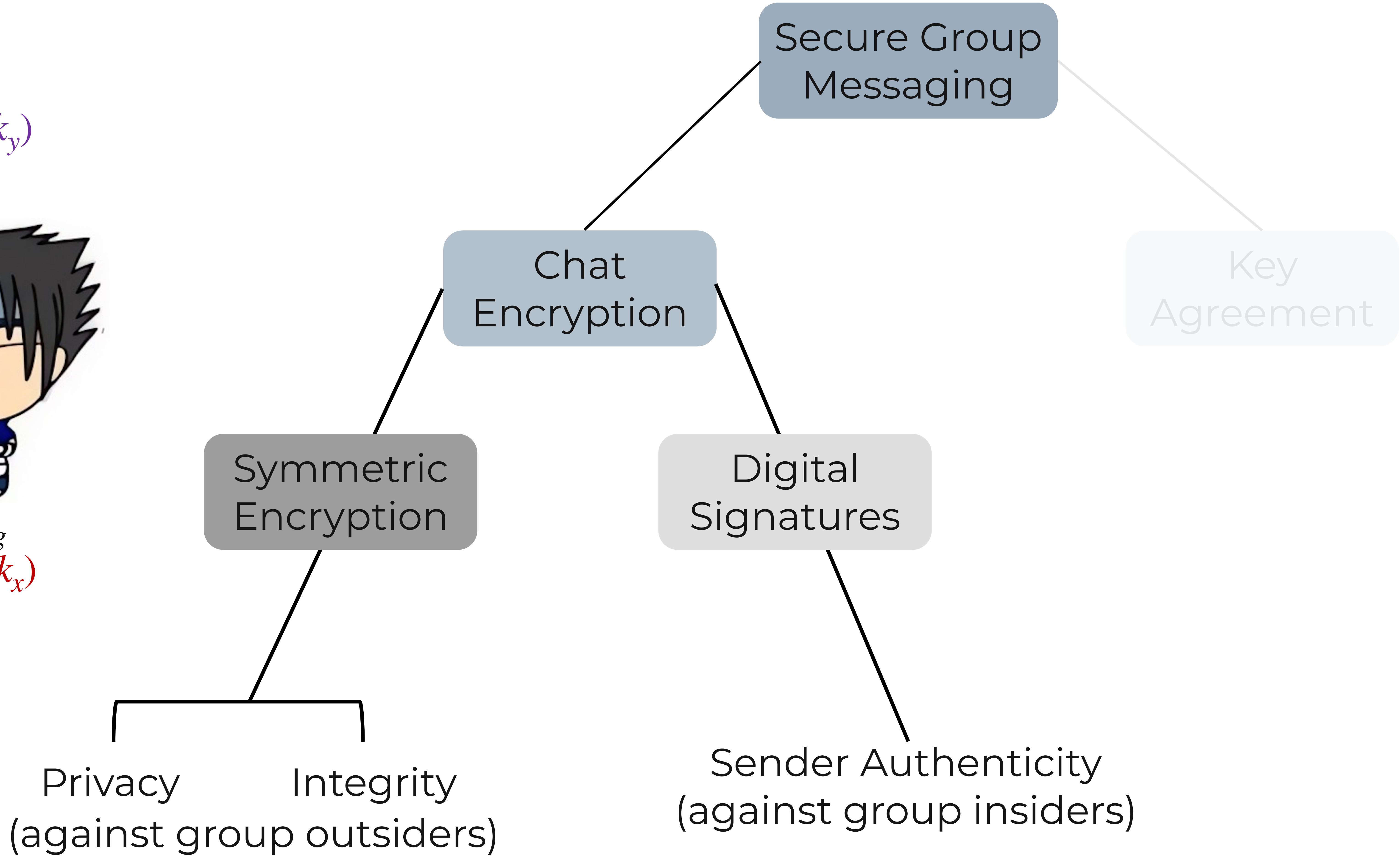

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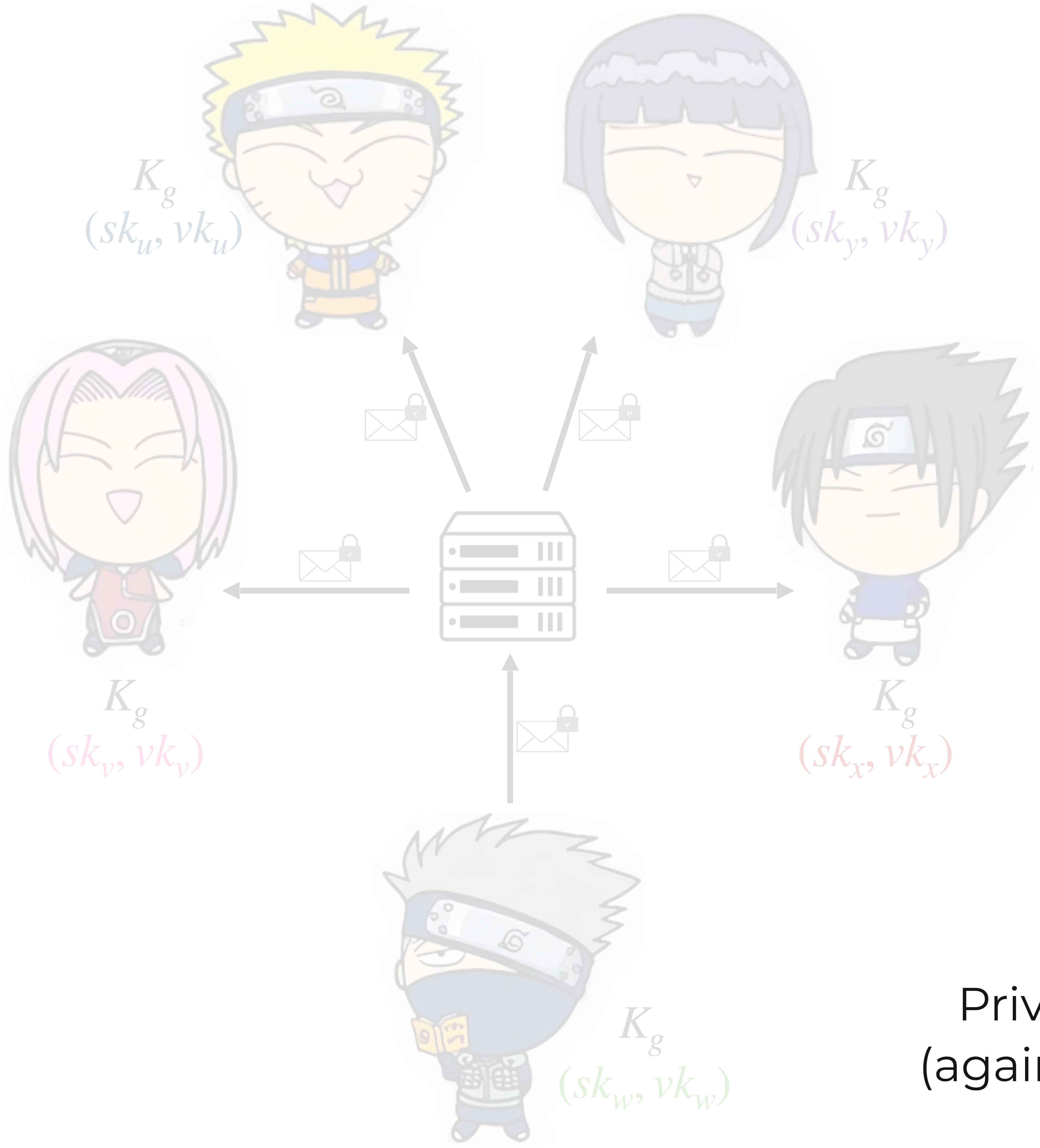

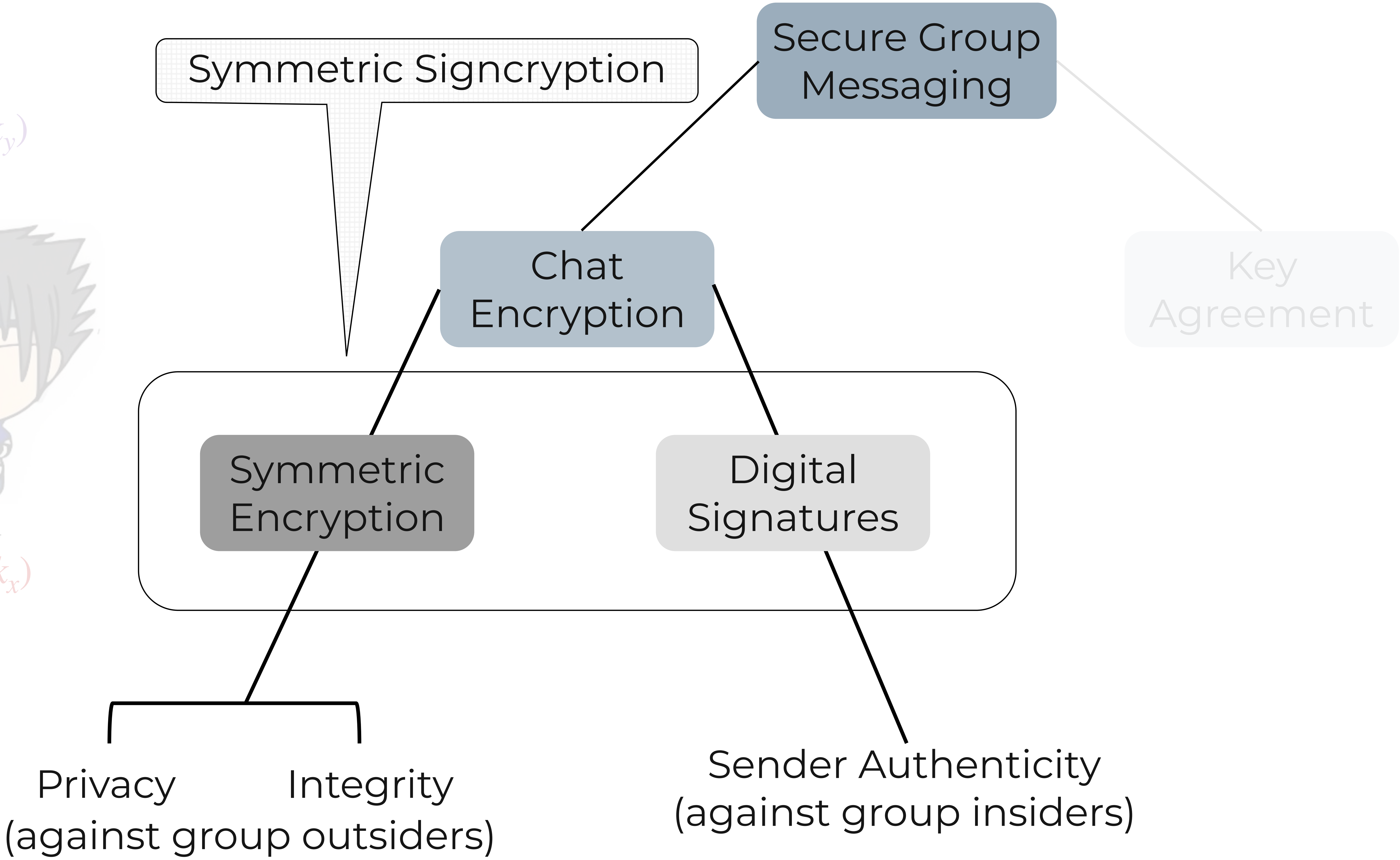

Methodology

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EC24

Symmetric Signcryption and E2EE Group Messaging in Keybase

Joseph Jaeger[1], Akshaya Kumar[1], and Igors Stepanovs[2]

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Symmetric Signcryption Model

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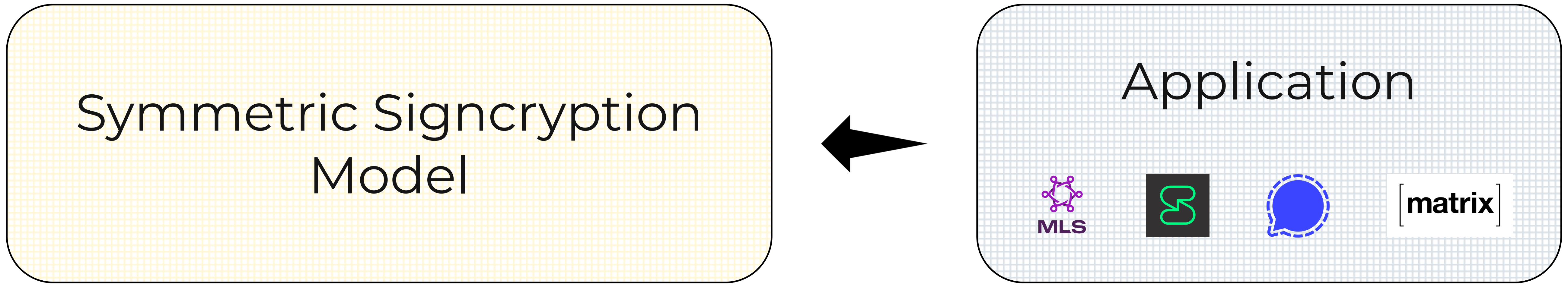

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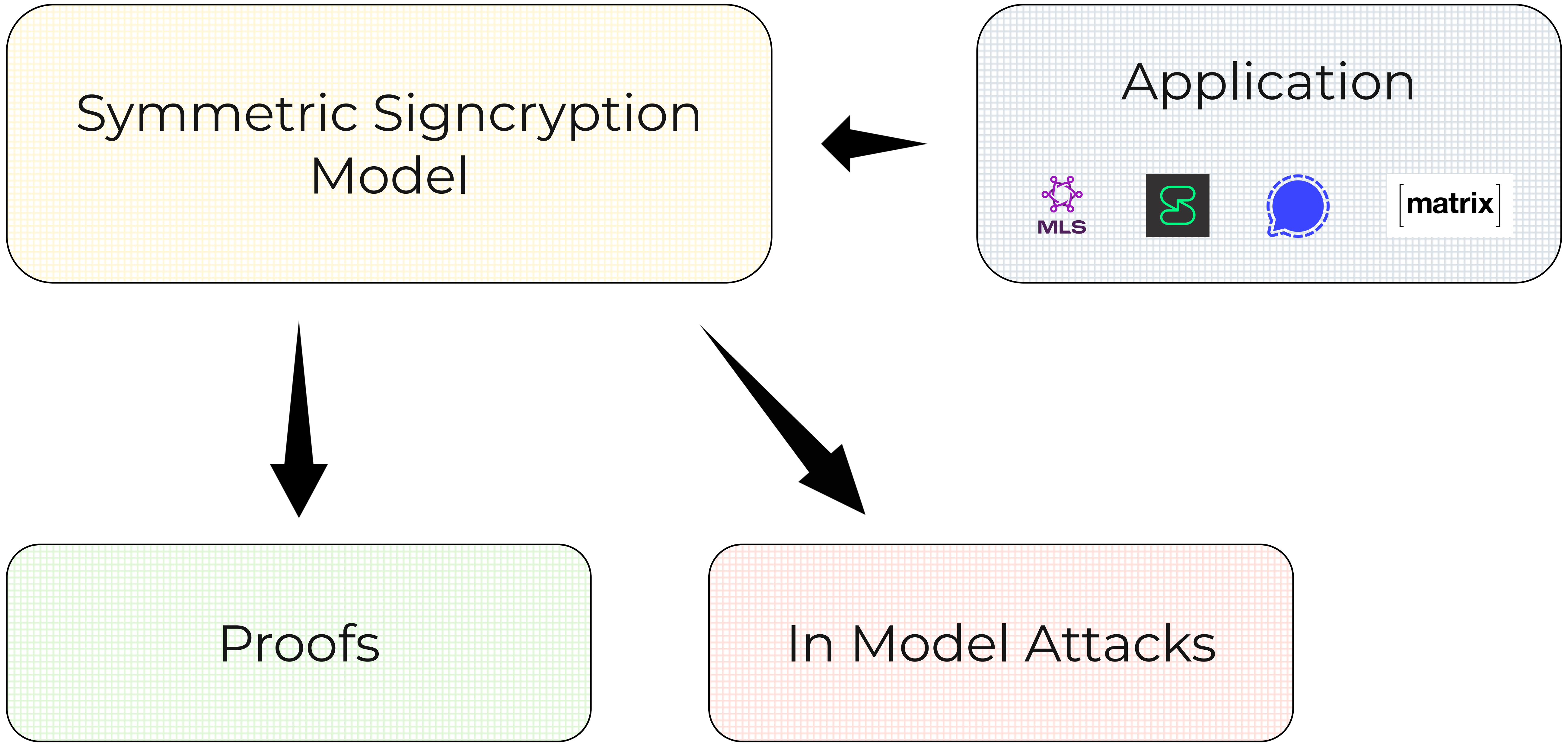

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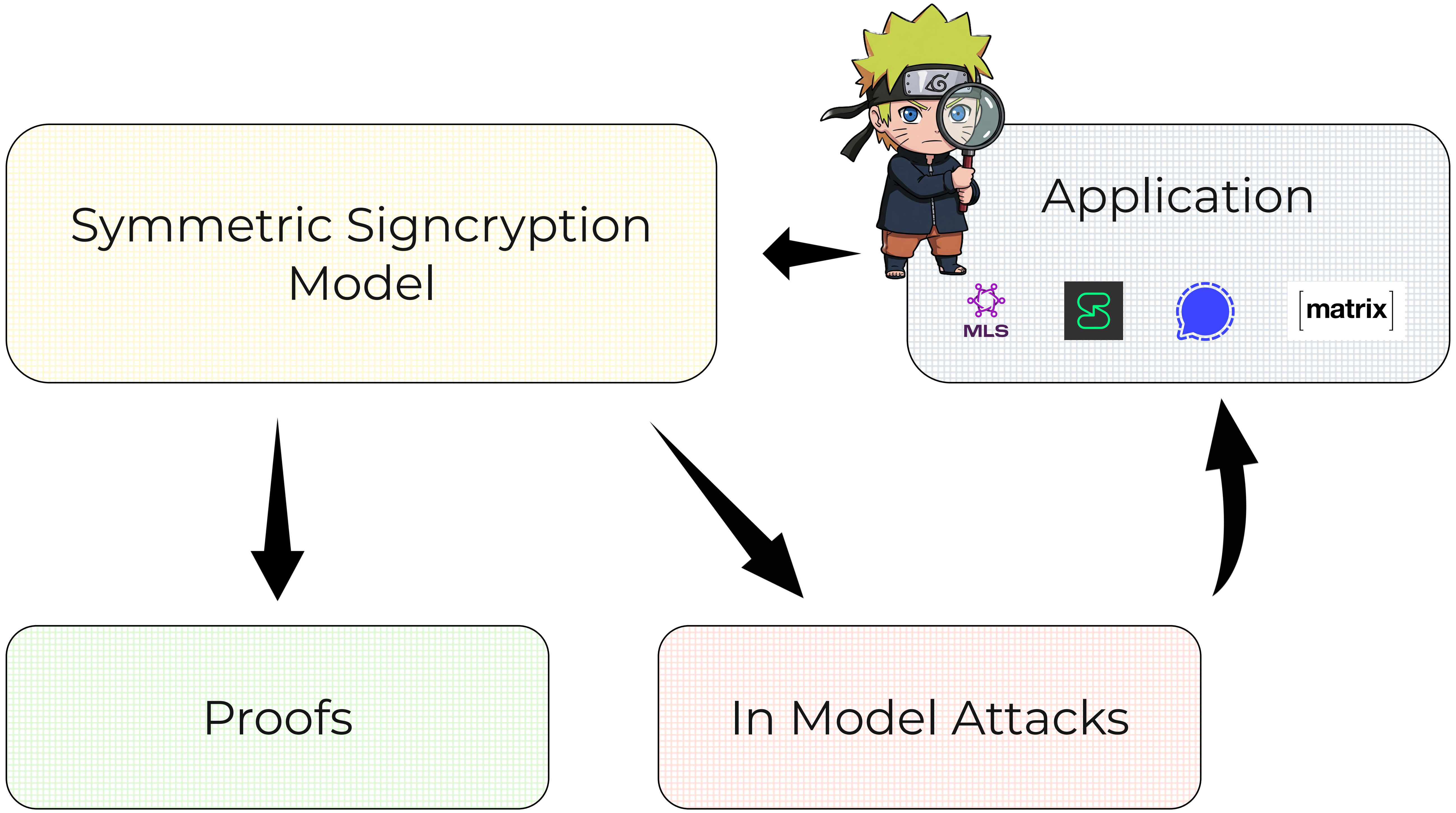
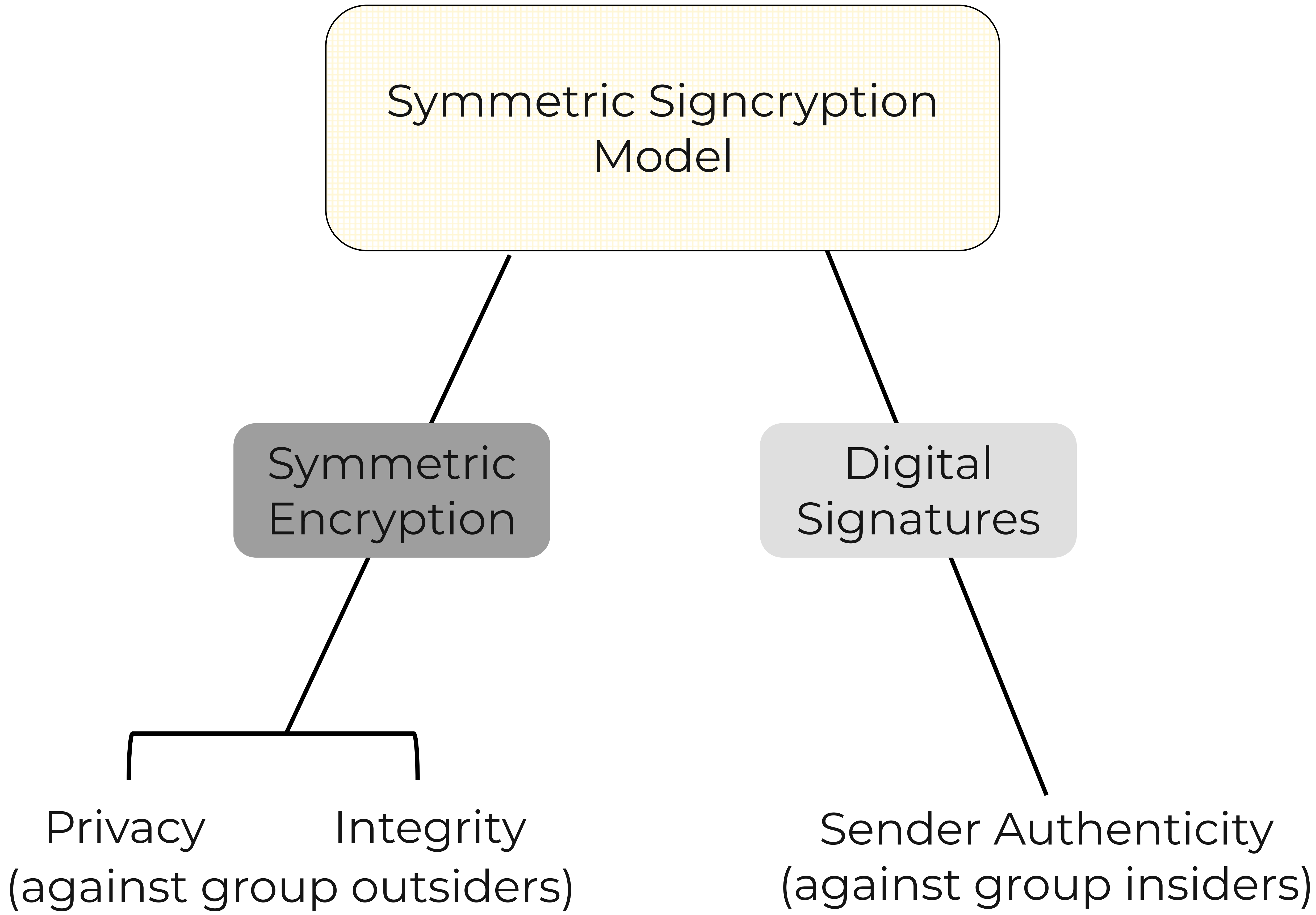


Insider and Outsider Attacks



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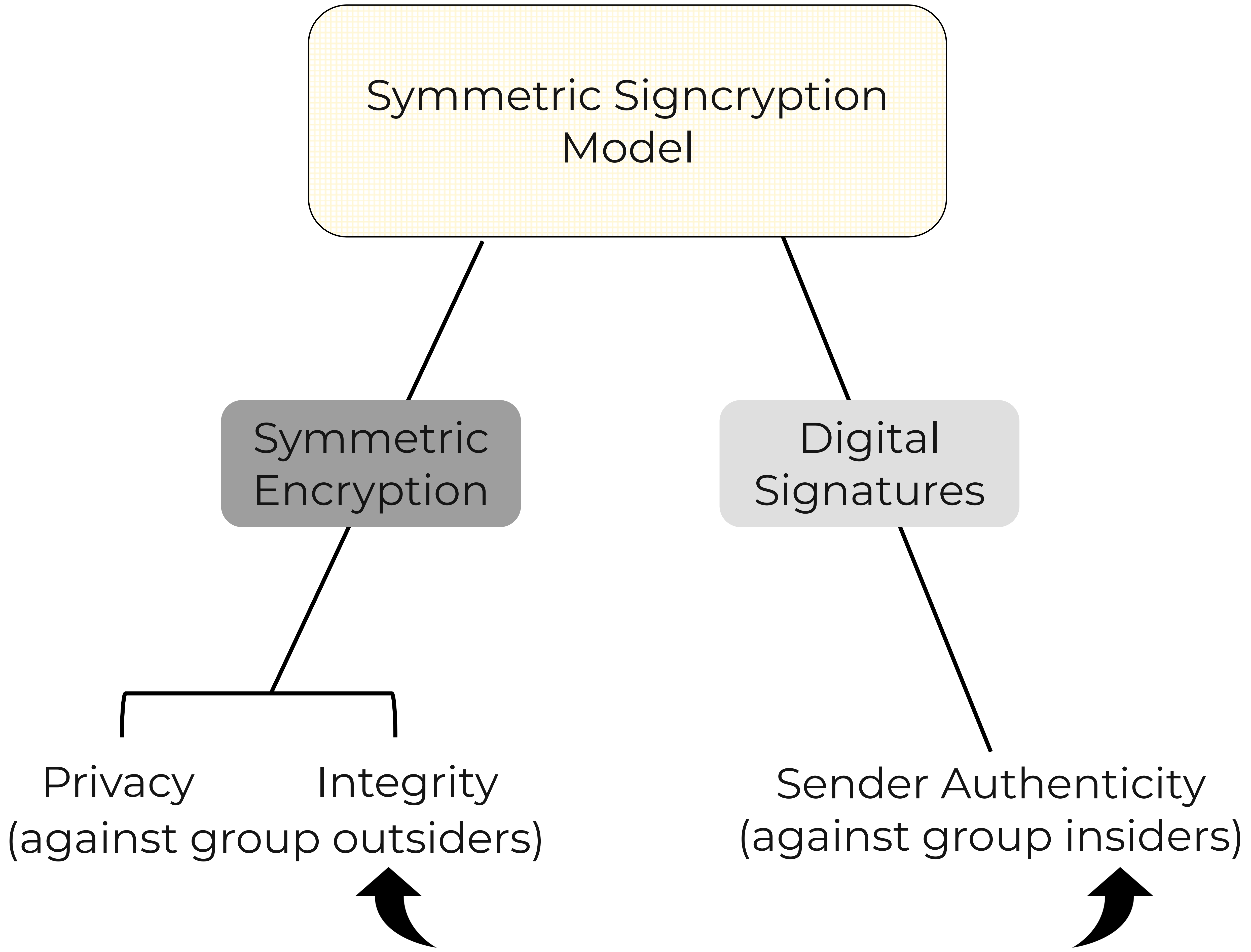
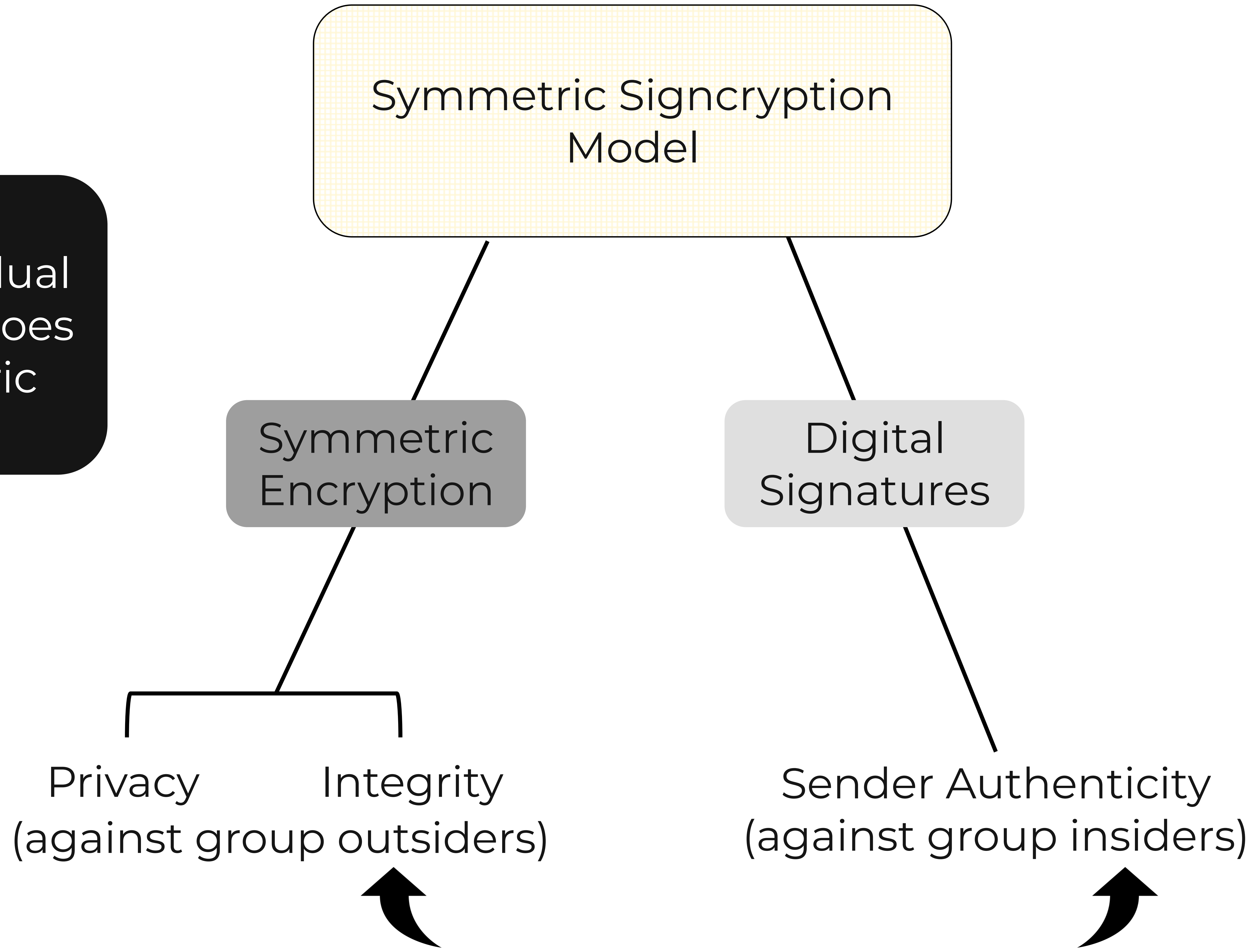


Natural to think about security against insiders and outsiders

Insider and Outsider Attacks

Outsider
May compromise individual users' signing keys but does not know the symmetric group key



Natural to think about security against insiders and outsiders

Insider and Outsider Attacks

Symmetric Signcryption Model

Outsider
May compromise individual users' signing keys but does not know the symmetric group key

Insider
Is part of the group chat and knows the symmetric group key but not the signing key of anyone but themselves

Symmetric Encryption

Digital Signatures

Privacy Integrity
(against group outsiders)

Sender Authenticity
(against group insiders)

Natural to think about security against insiders and outsiders

Insider and Outsider Attacks

Symmetric Signcryption Model

Symmetric Encryption

Privacy Integrity
(against group outsiders)

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__Outsider__
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Interesting attacks

__Insider__
Is part of the group chat and knows the symmetric group key but not the signing key of anyone but themselves

Natural to think about security against insiders and outsiders

Naive Constructions

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Sign-then-Encrypt (StE)

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Encrypt-then-Sign (EtS)

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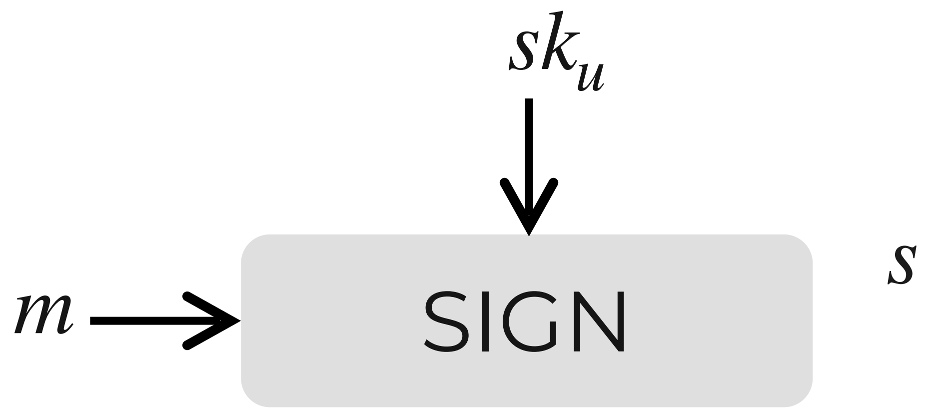
Sign-then-Encrypt (StE)

Encrypt-then-Sign (EtS)



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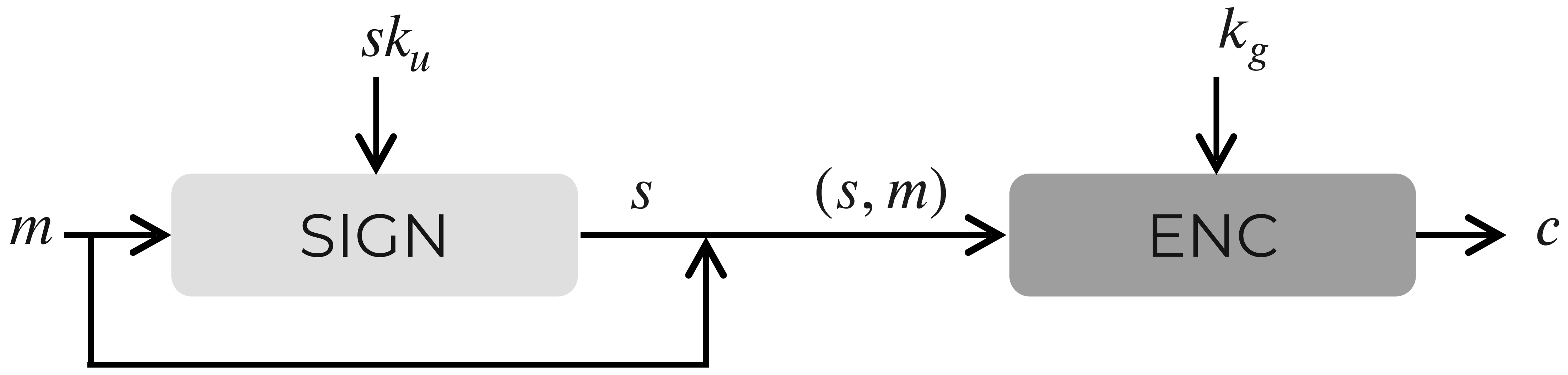

Encrypt-then-Sign (EtS)

Naive Constructions

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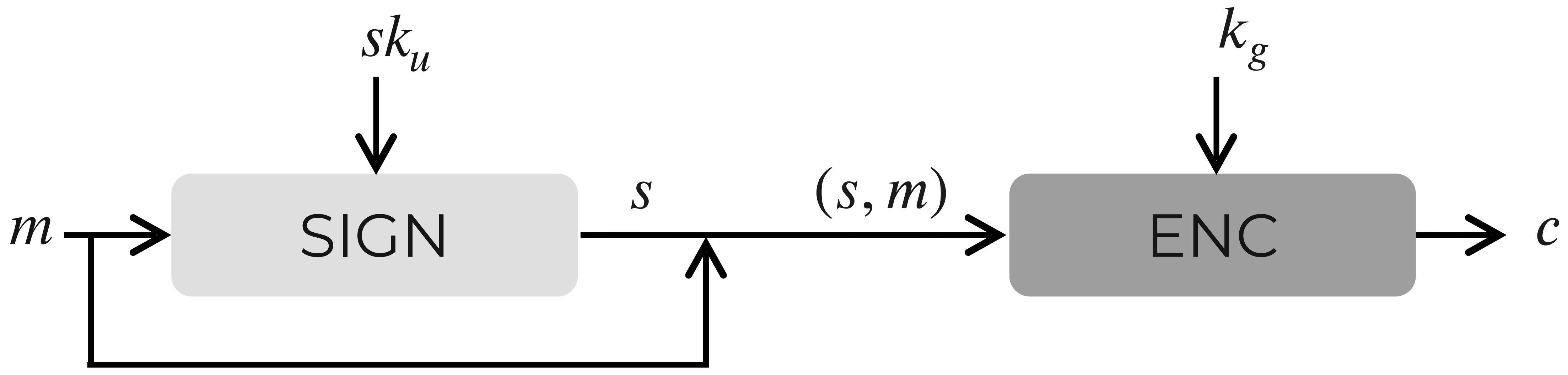

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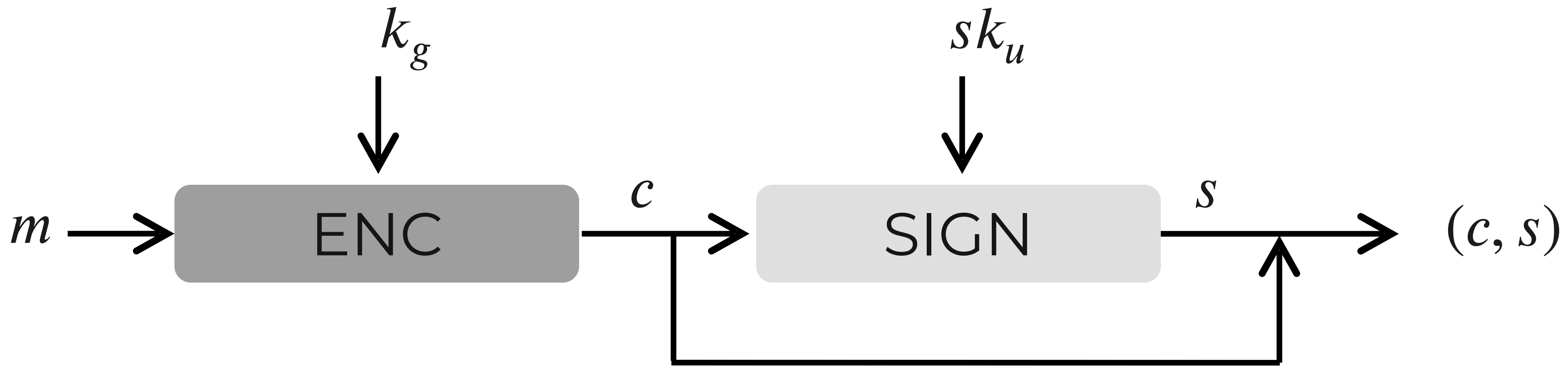

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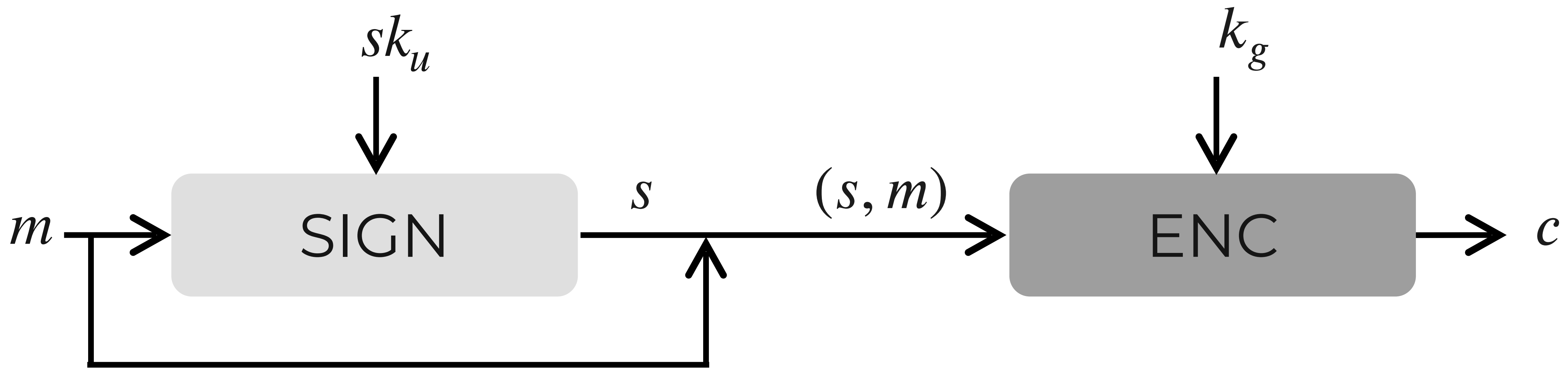

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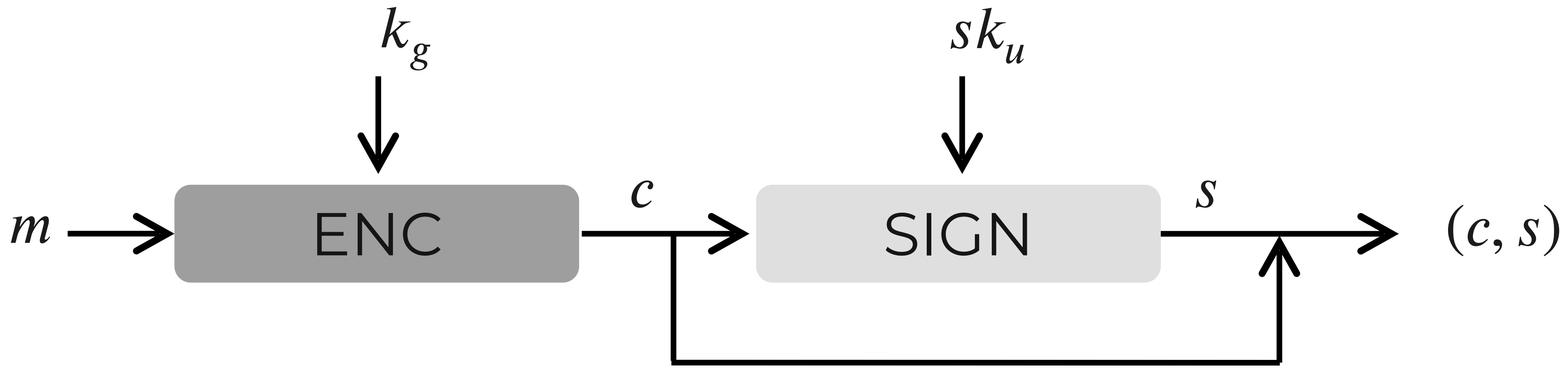

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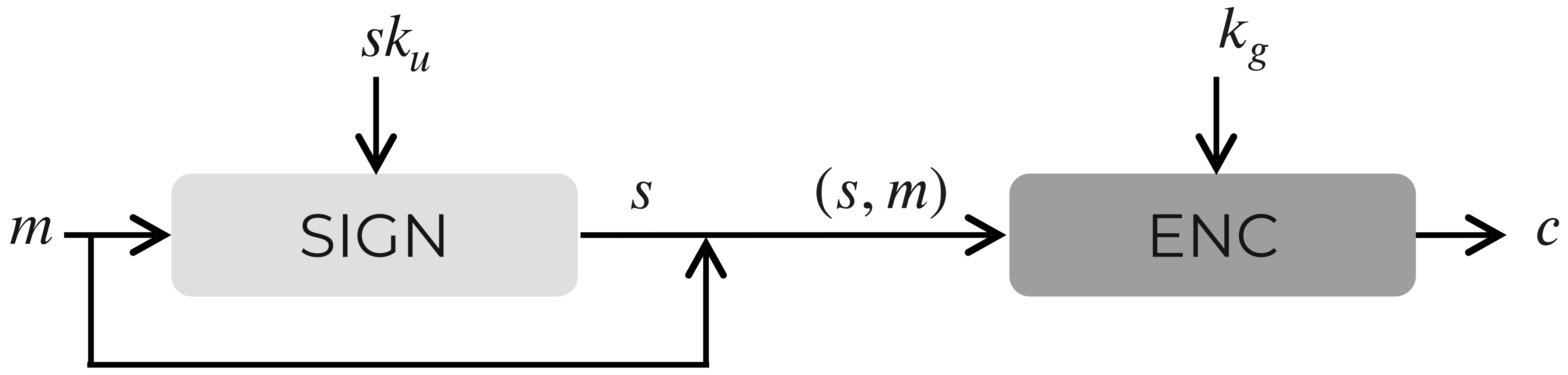

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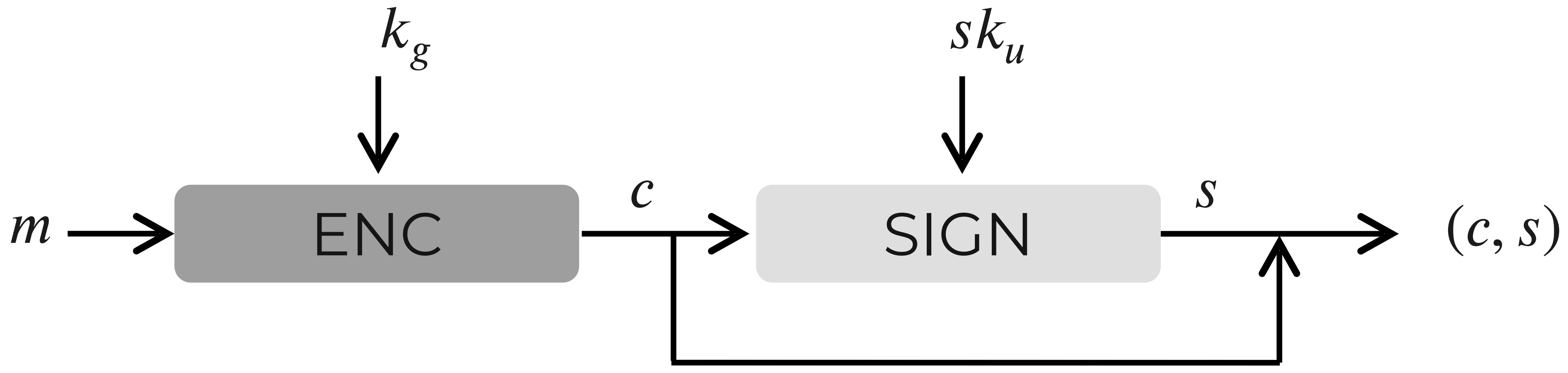

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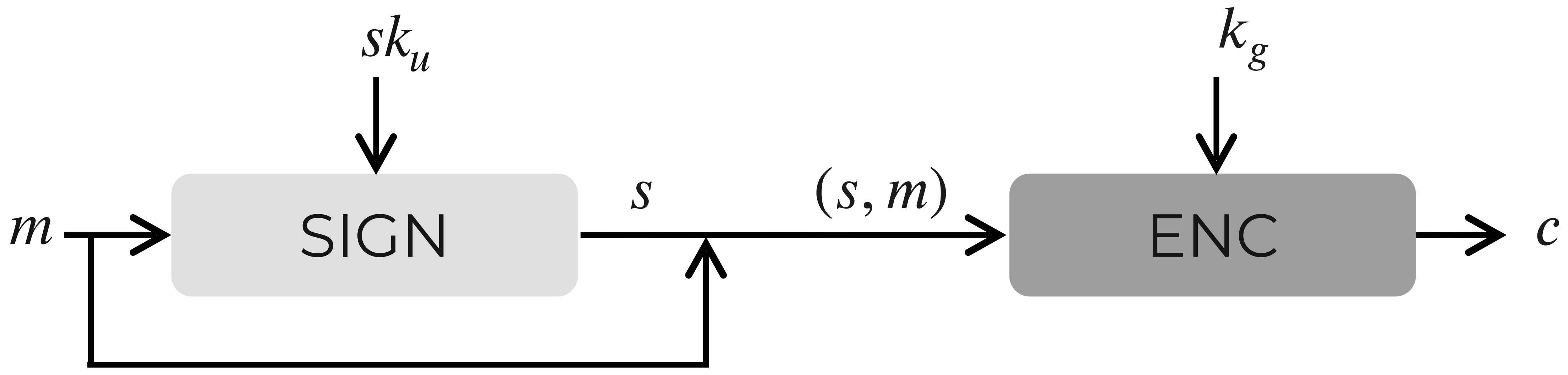


Encrypt-then-Sign (EtS)

MLS

matrix

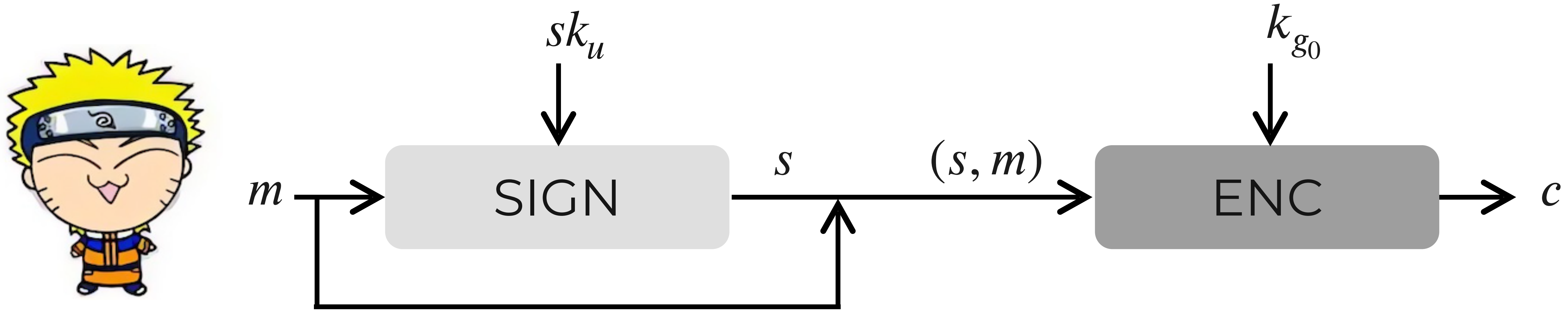
Context-Switching Attacks

Context-Switching Attacks

$\rightarrow group_0$

$\rightarrow group_1$

Context-Switching Attacks



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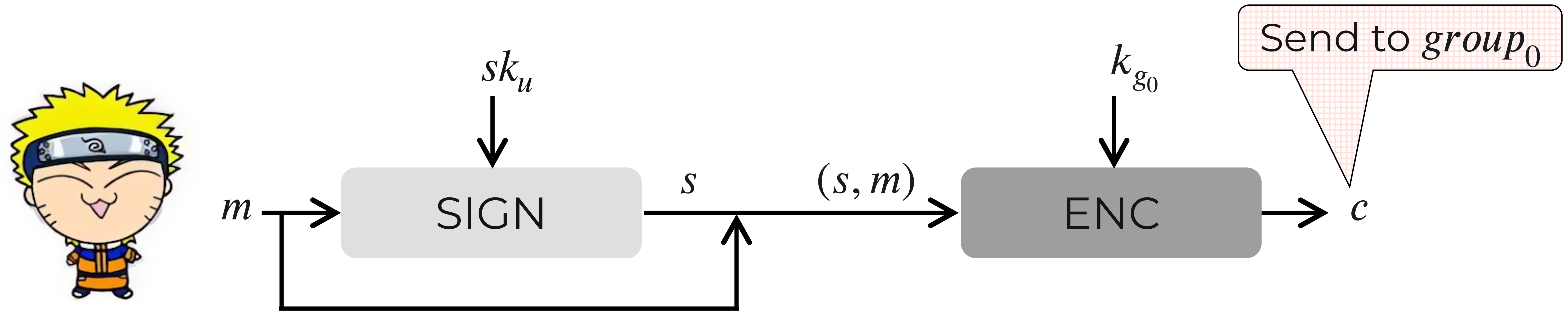

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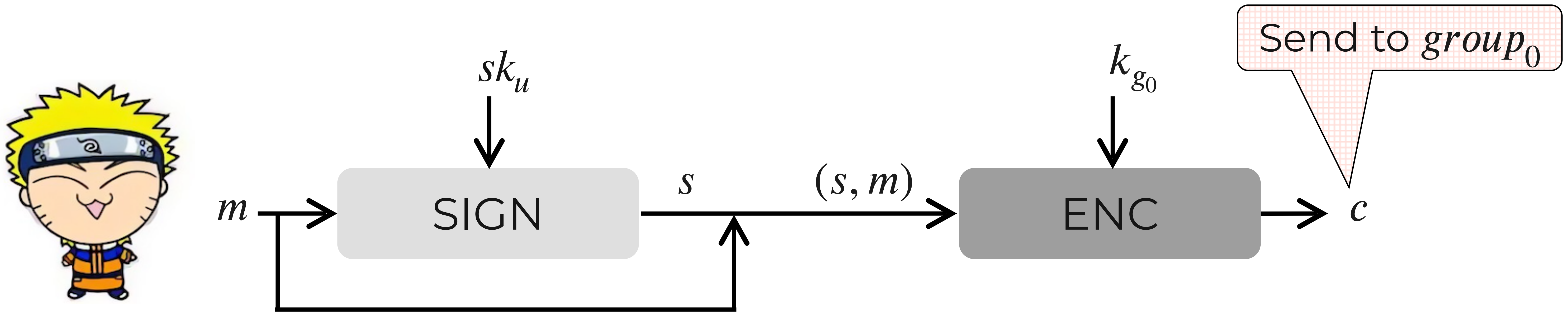

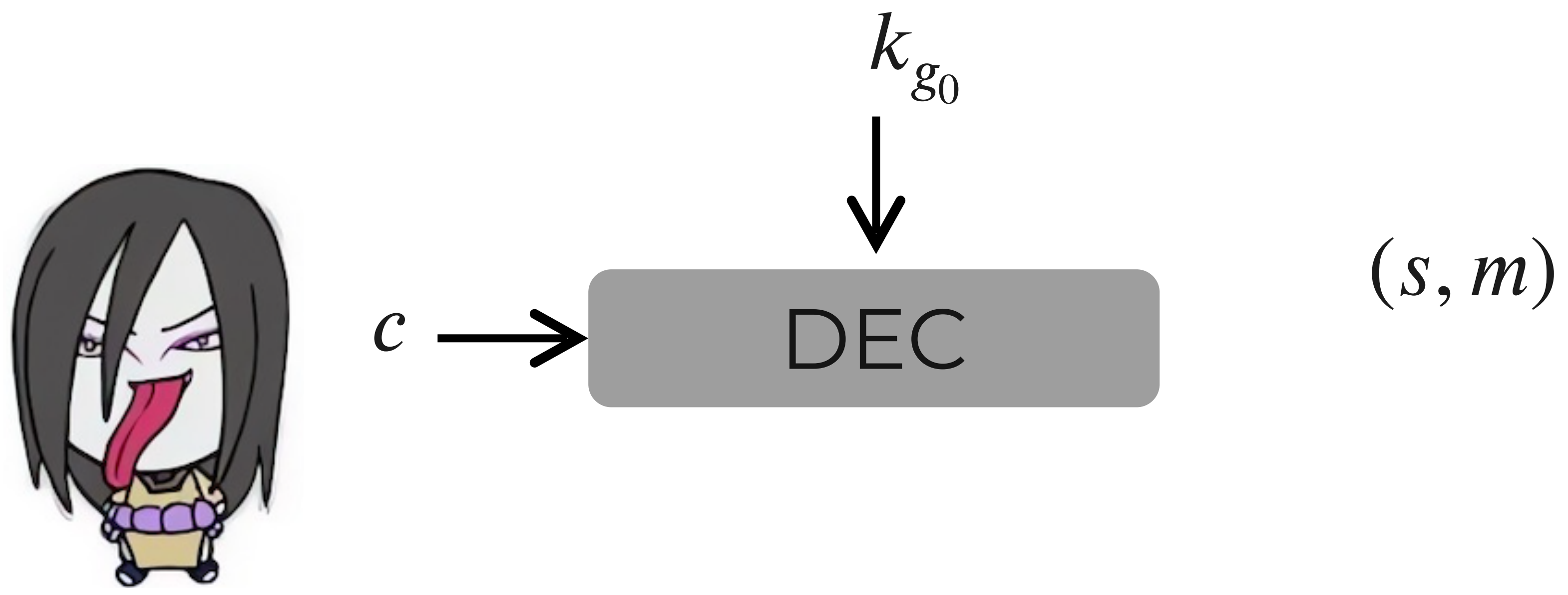

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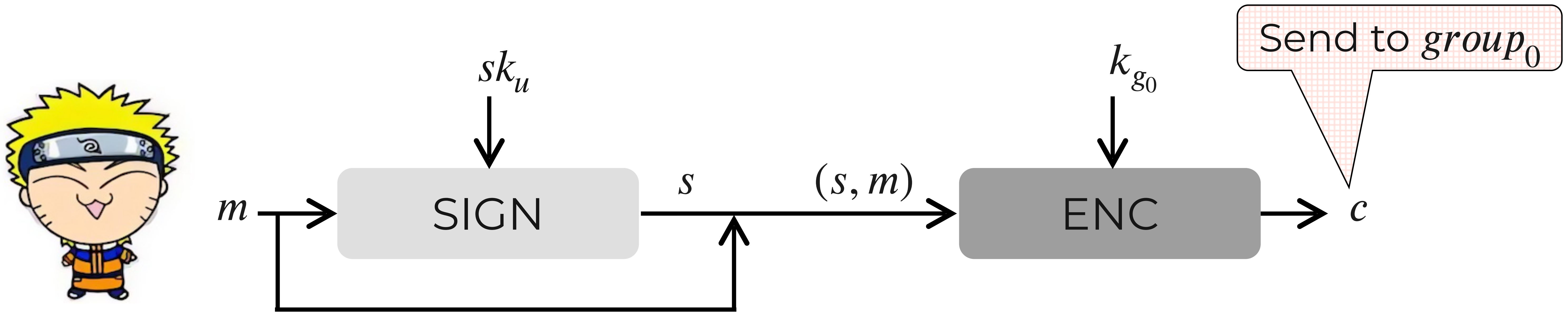

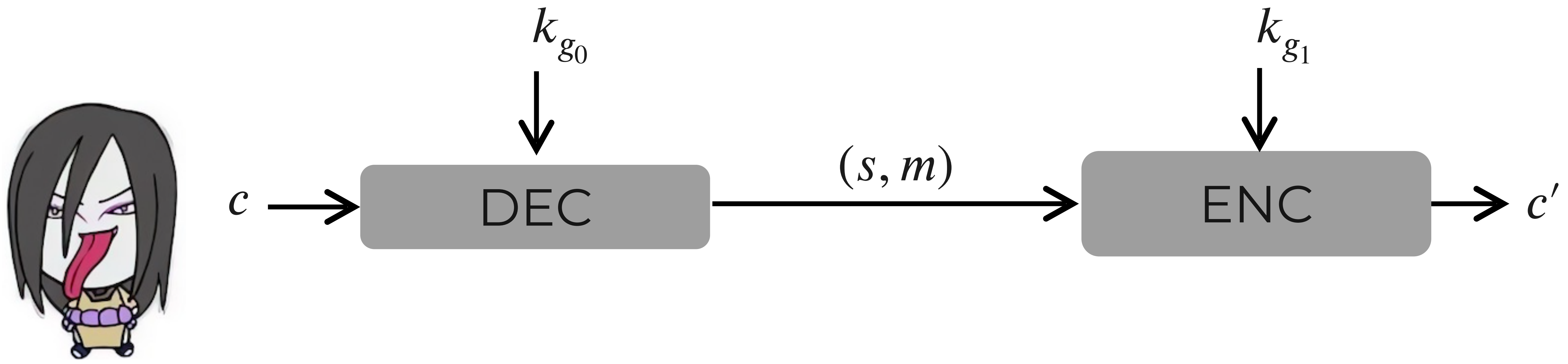

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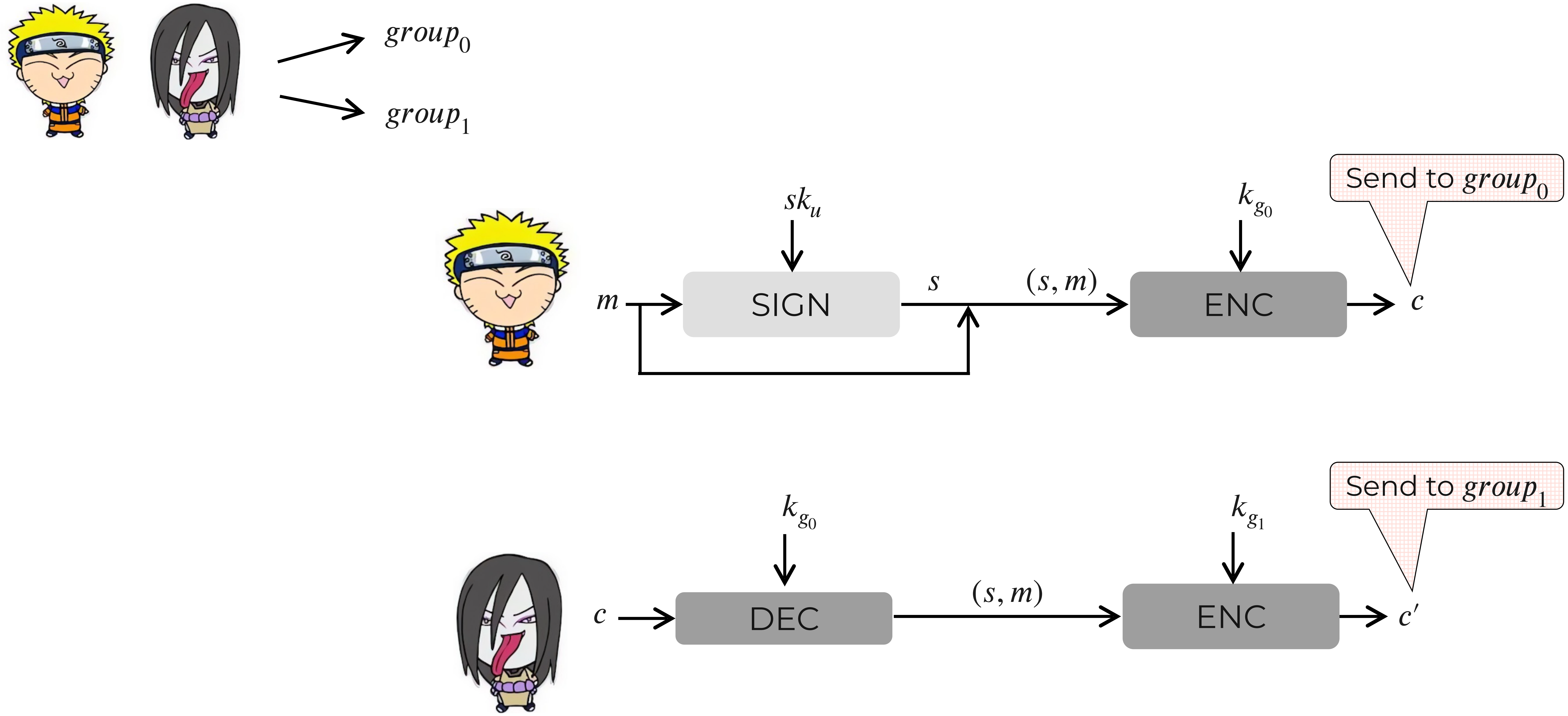

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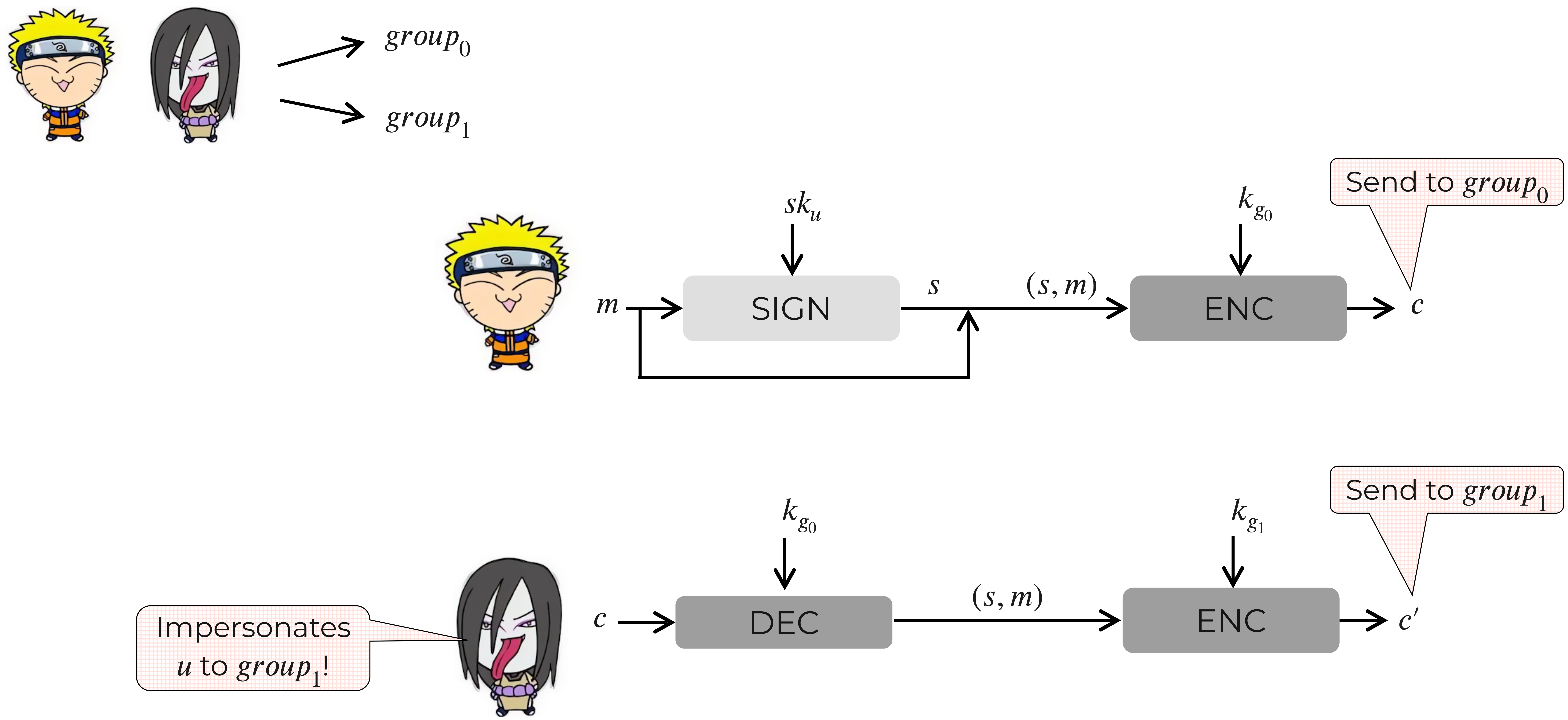

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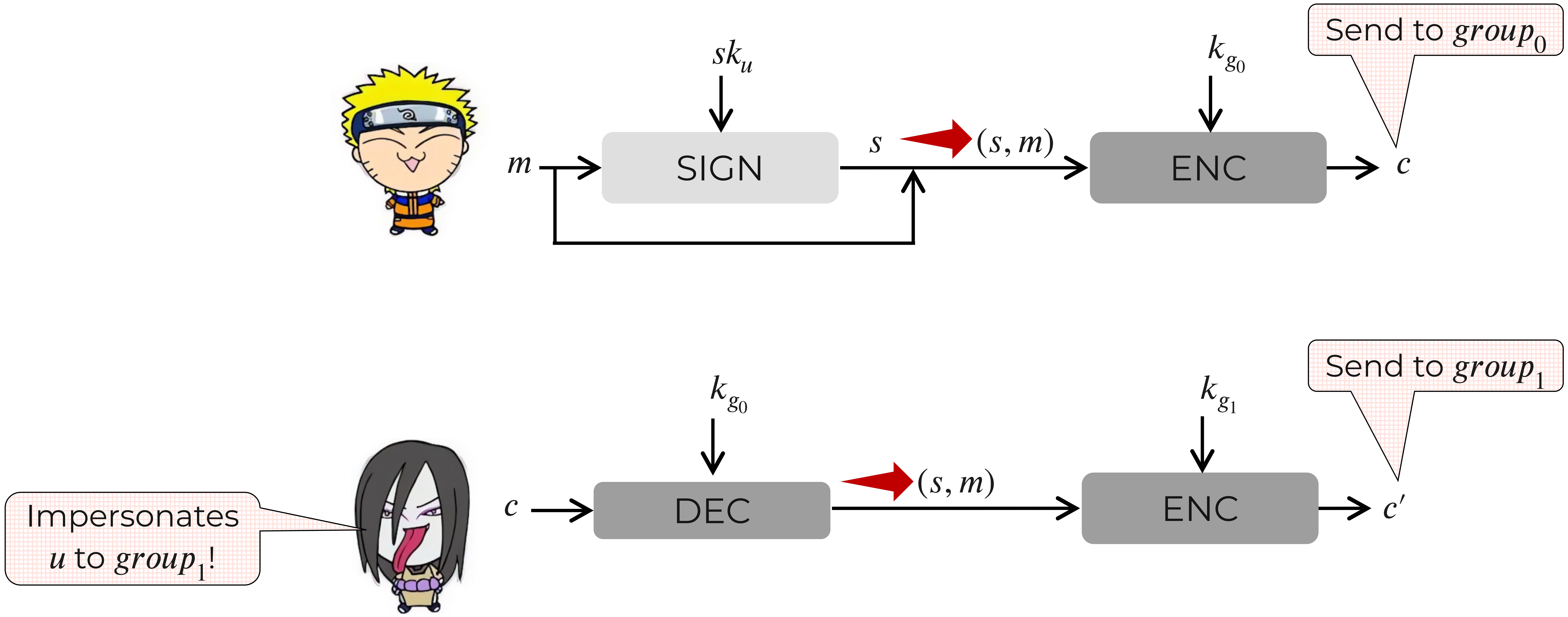

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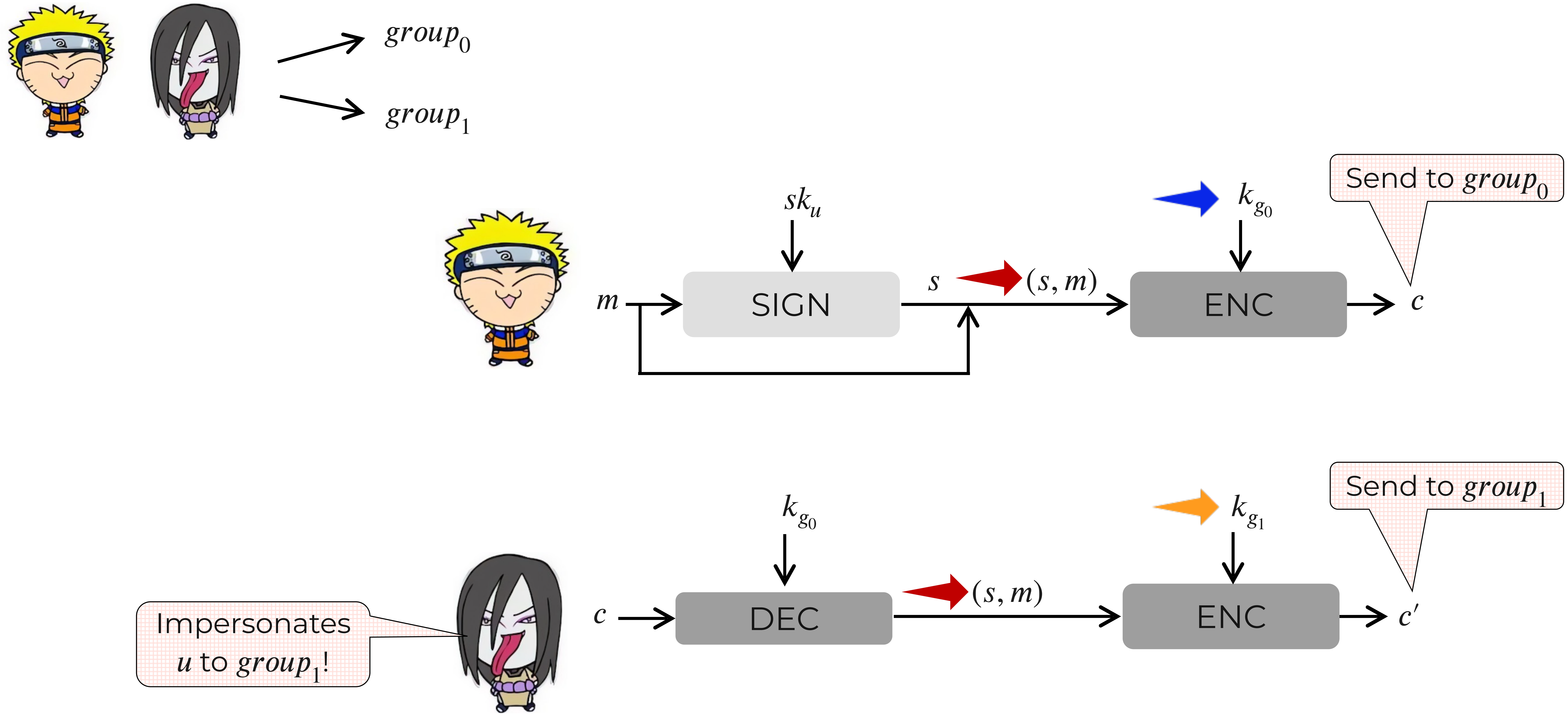

Context Binding

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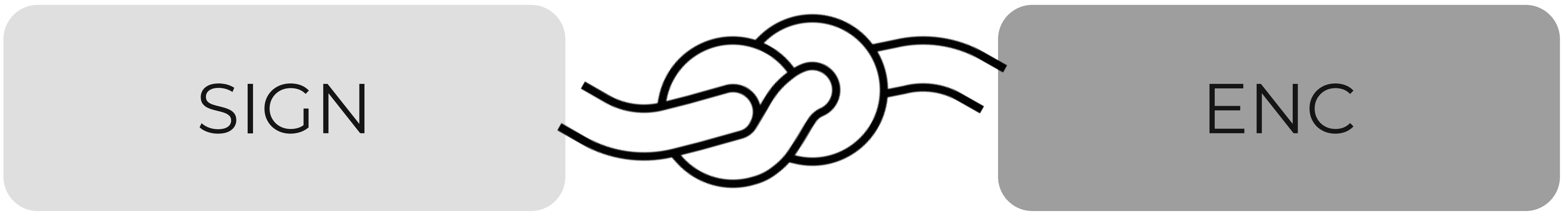
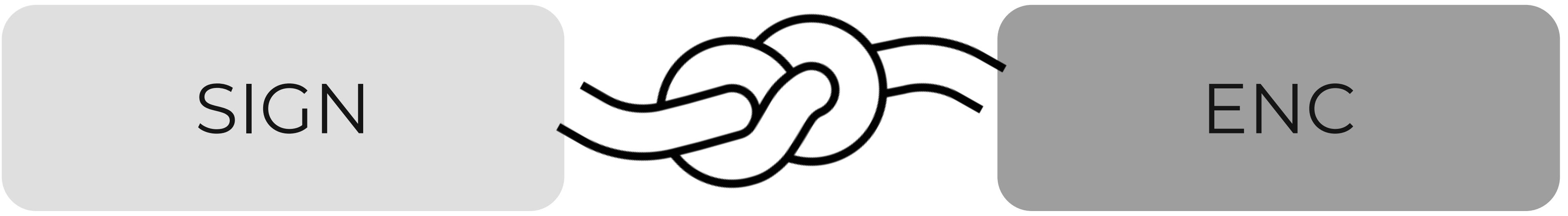


“bind”

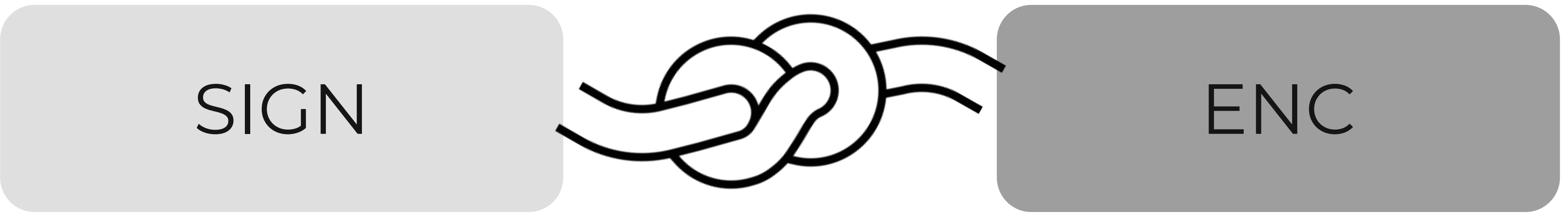
Context Binding



“bind”

SIGN
group_key_id
n
ad

Context Binding



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Value that uniquely identifies the group’s encryption key

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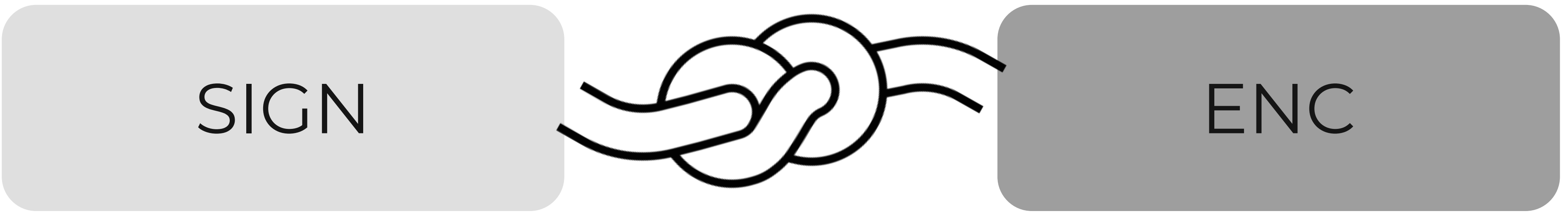


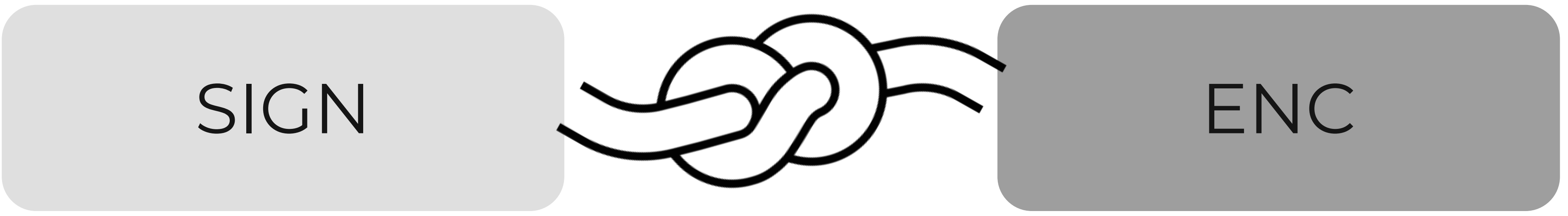
“bind”

Value that uniquely identifies the group’s encryption key

SIGN
group_key_id
n
ad

ENC
sender_id

Context Binding



“bind”

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n
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group_key_id: Value that uniquely identifies the group’s encryption key

ENC
sender_id

sender_id: Value that uniquely identifies the sender’s signing key

Our Analysis: An Overview

Our Analysis: An Overview

MLS

matrix

Our Analysis: An Overview

MLS

matrix

Insider Replay

Insider Re-ordering

Our Analysis: An Overview

MLS

matrix

Insider Replay

Insider Re-ordering

No context binding

Our Analysis: An Overview

MLS

Insider Replay

Insider Re-ordering

No context binding

Insider Replay

Outsider Replay

Outsider Forgery*

matrix

* stolen signing key

Our Analysis: An Overview

MLS

matrix

Insider Replay

Insider Re-ordering

Insider Replay

Outsider Replay

Outsider Forgery*

No context binding

No context binding

* stolen signing key

Our Analysis: An Overview

Insider Replay
Insider Re-ordering

Insider Replay
Outsider Replay
Outsider Forgery*

Outsider Forgery†

No context binding

No context binding

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Our Analysis: An Overview

MLS

Insider Replay
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No context binding

Insider Replay
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No context binding

Outsider Forgery†

Unauthenticated Symmetric Encryption

matrix

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Our Analysis: An Overview

MLS	Session	Signal	matrix
Insider Replay Insider Re-ordering	Insider Replay Outsider Replay Outsider Forgery*	Outsider Forgery†	In-model Insider Replay
No context binding	No context binding	Unauthenticated Symmetric Encryption	No context binding

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Our Analysis: An Overview

Insider Replay
Insider Re-ordering

No context binding

Insider Replay
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Case Study I: MLS

MLS

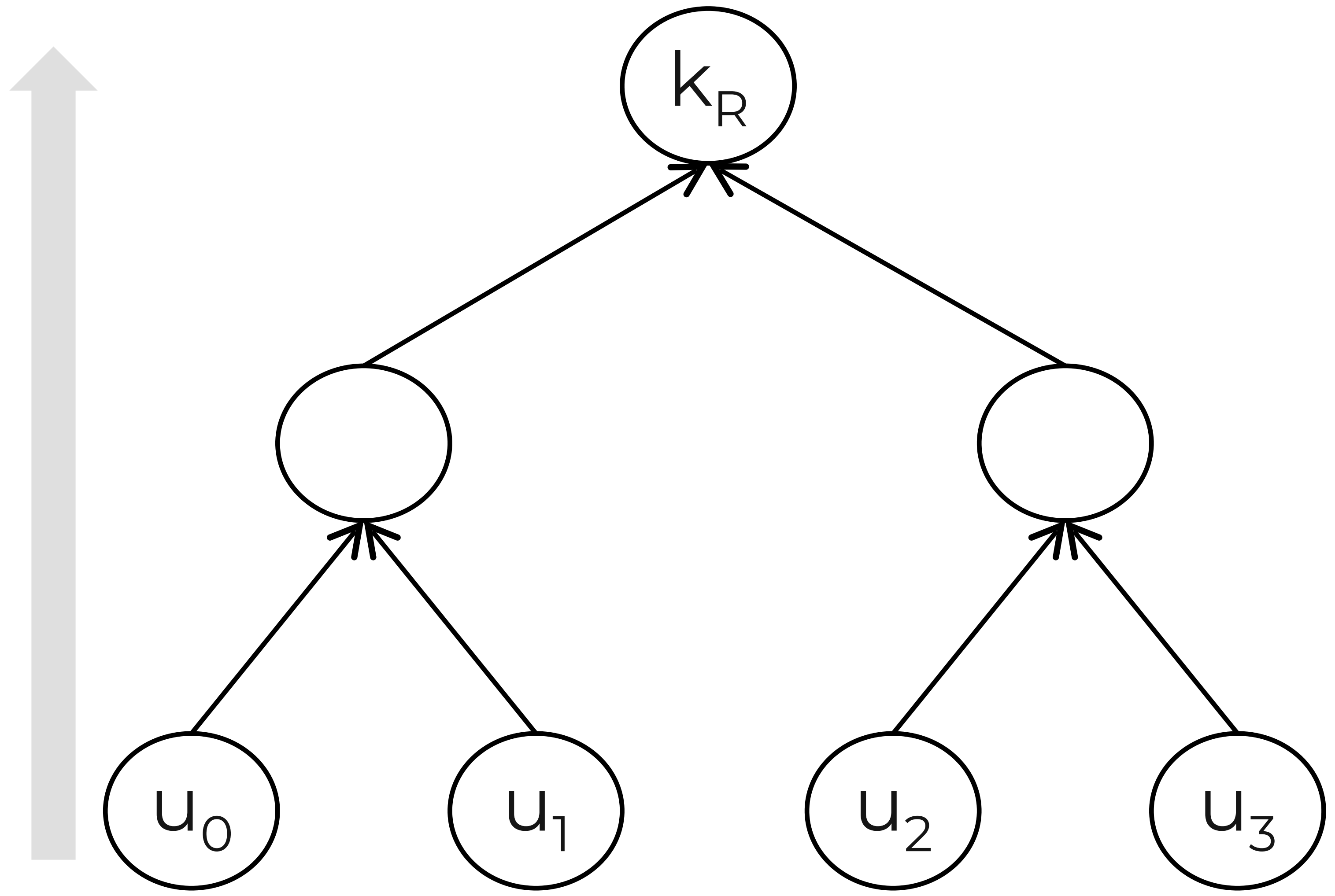
Encryption Key Derivation in MLS

Encryption Key Derivation in MLS

Ratchet tree

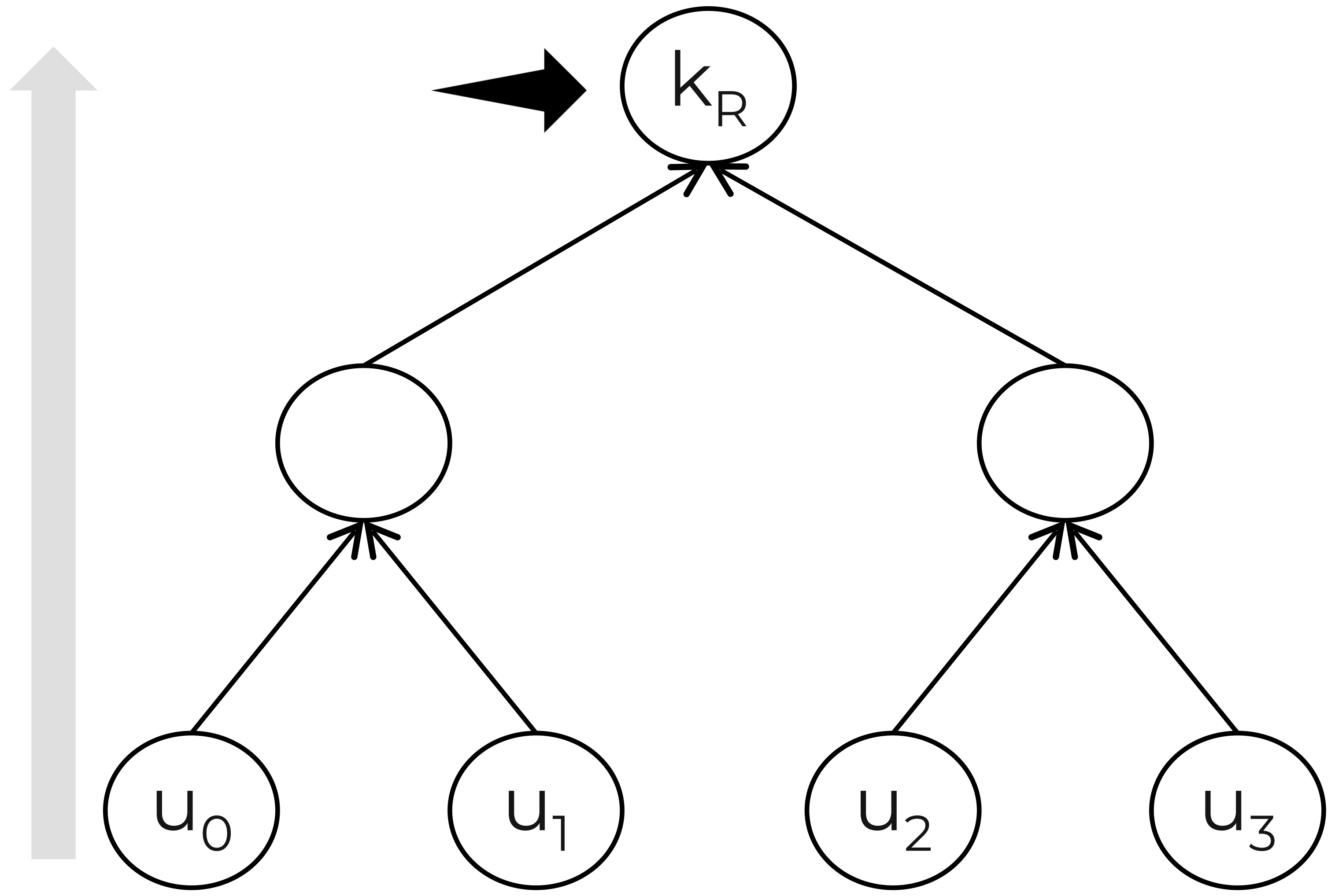
Encryption Key Derivation in MLS

Ratchet tree



Encryption Key Derivation in MLS

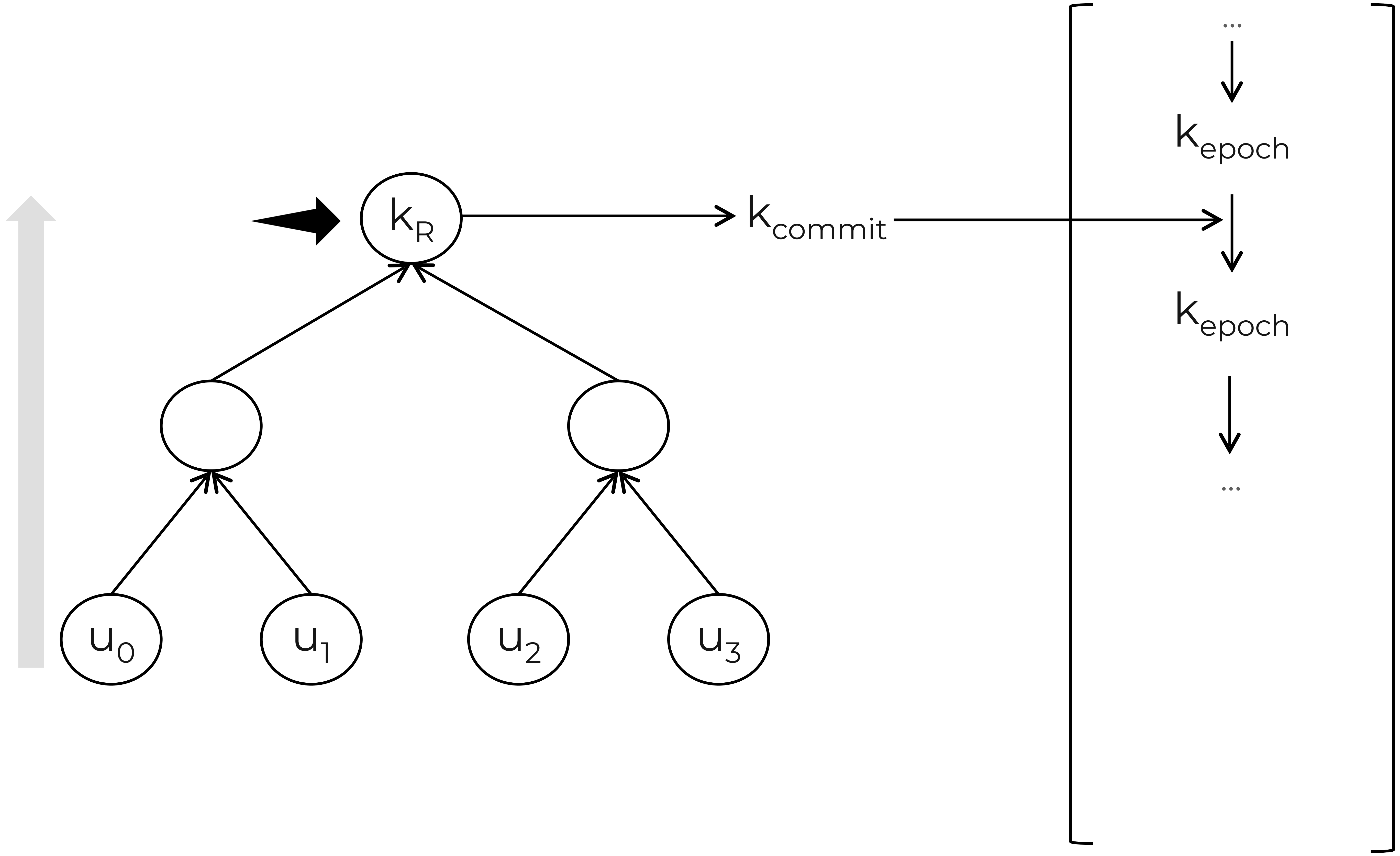
Ratchet tree



Encryption Key Derivation in MLS

Ratchet tree

Key schedule



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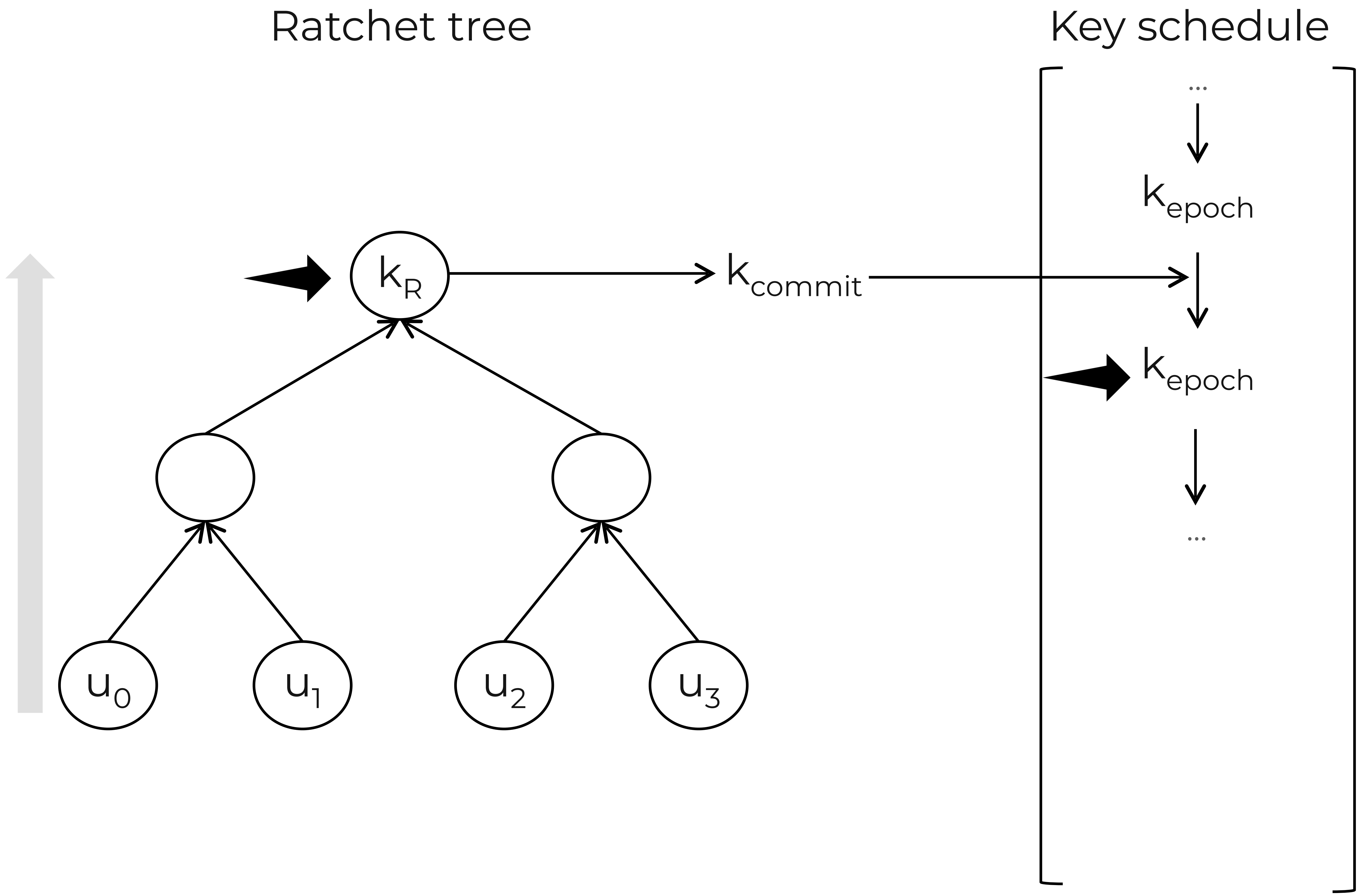

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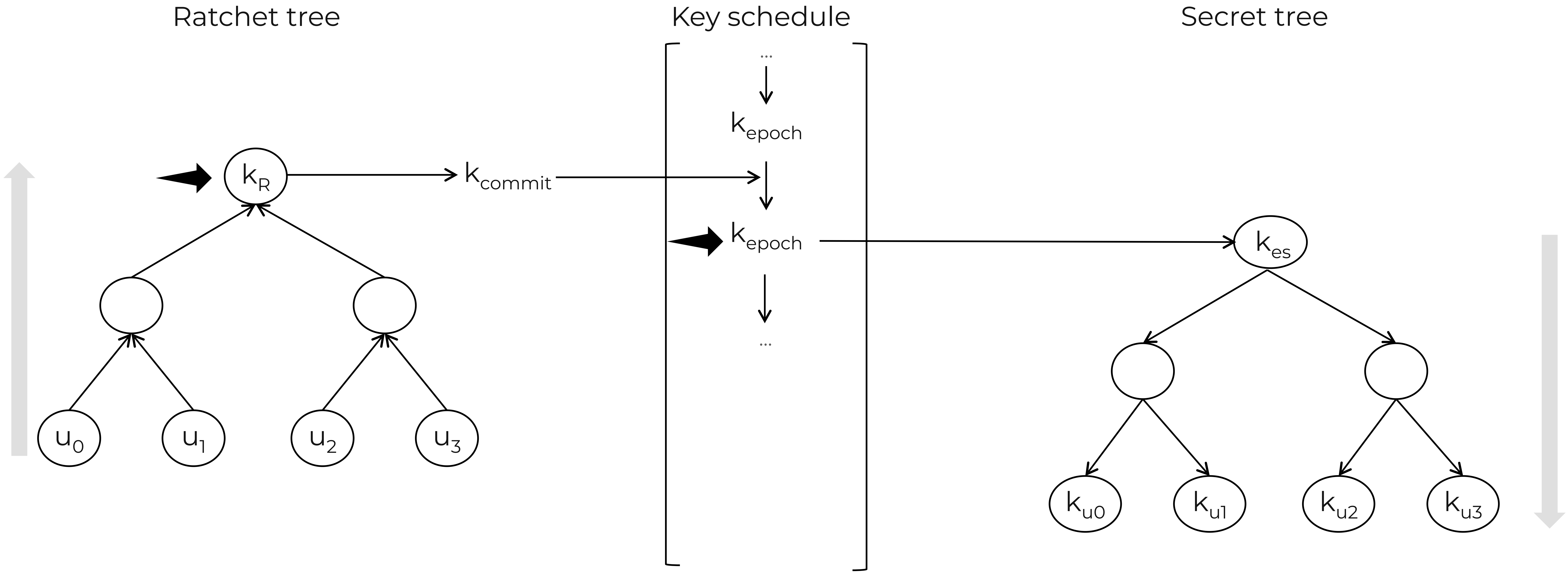

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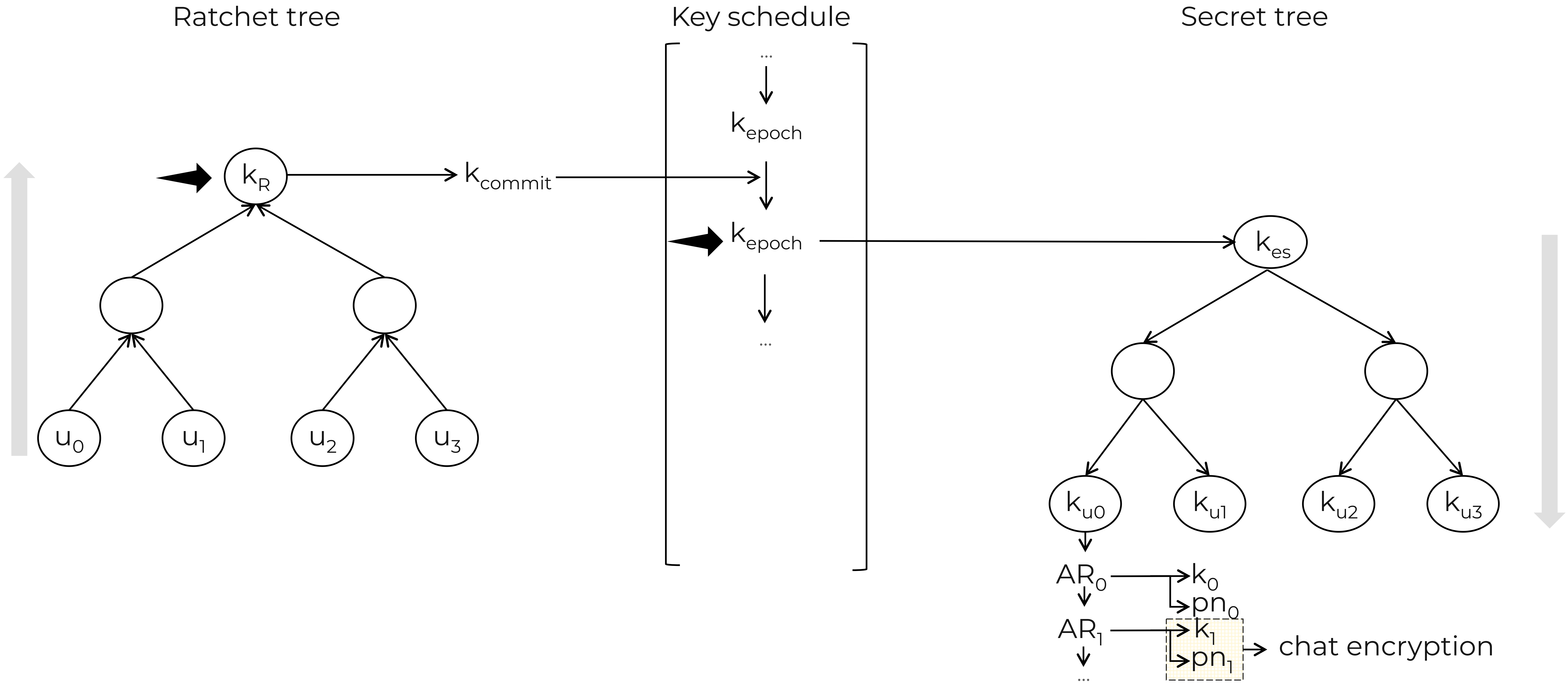

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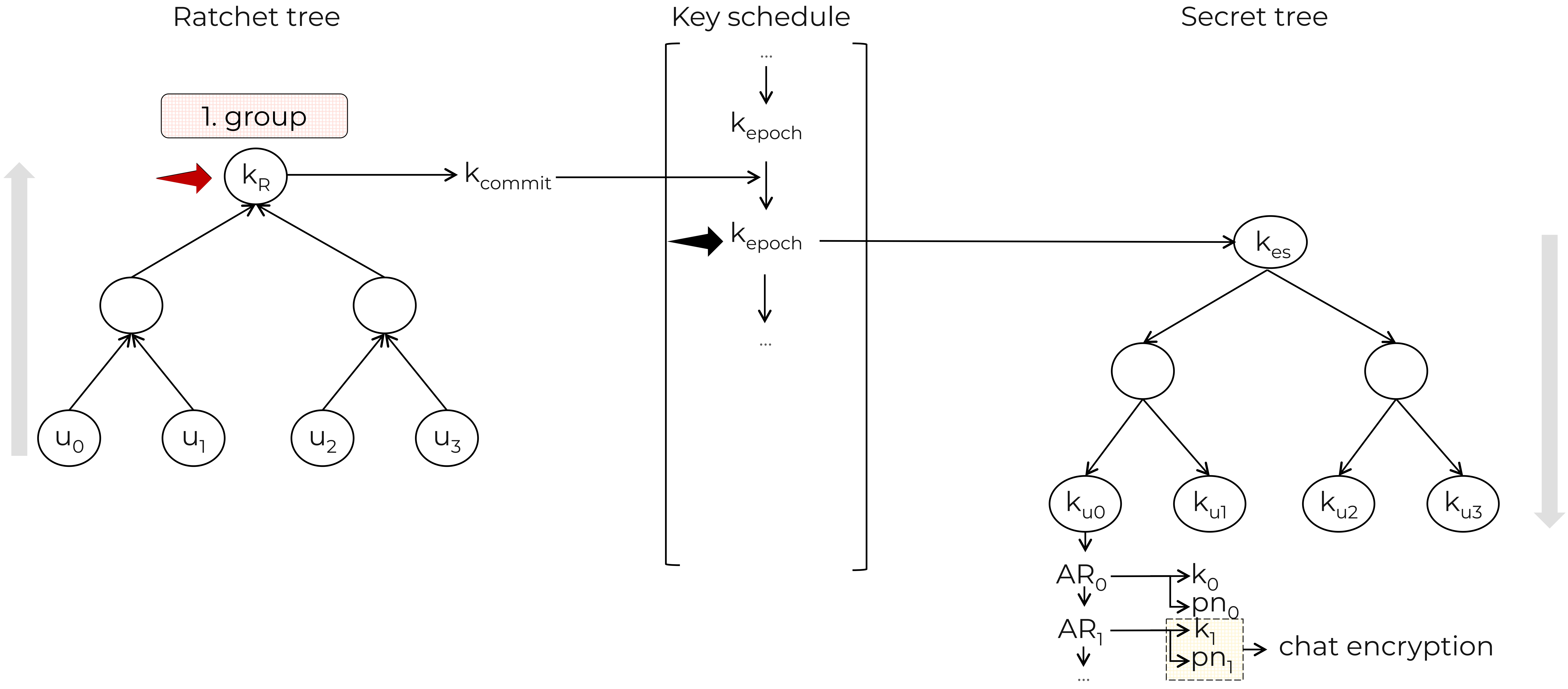

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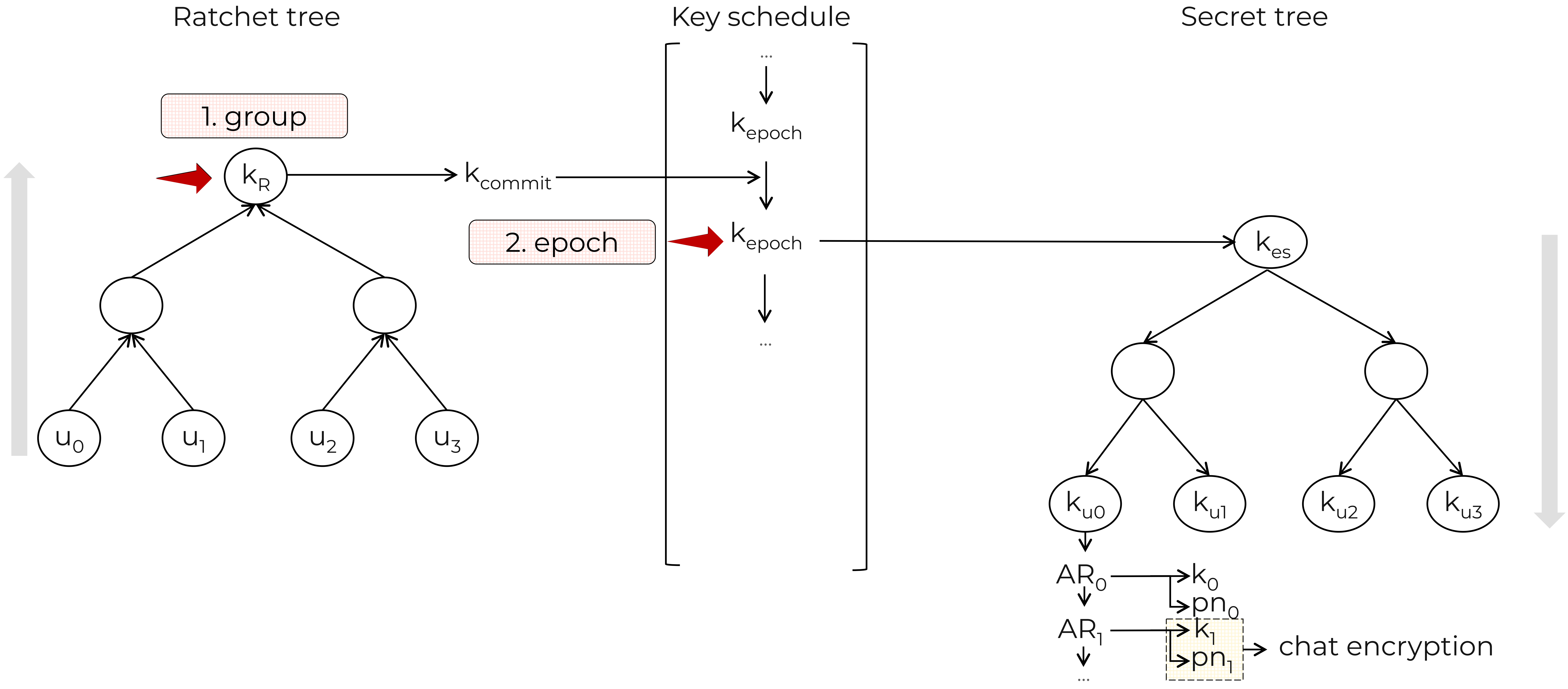

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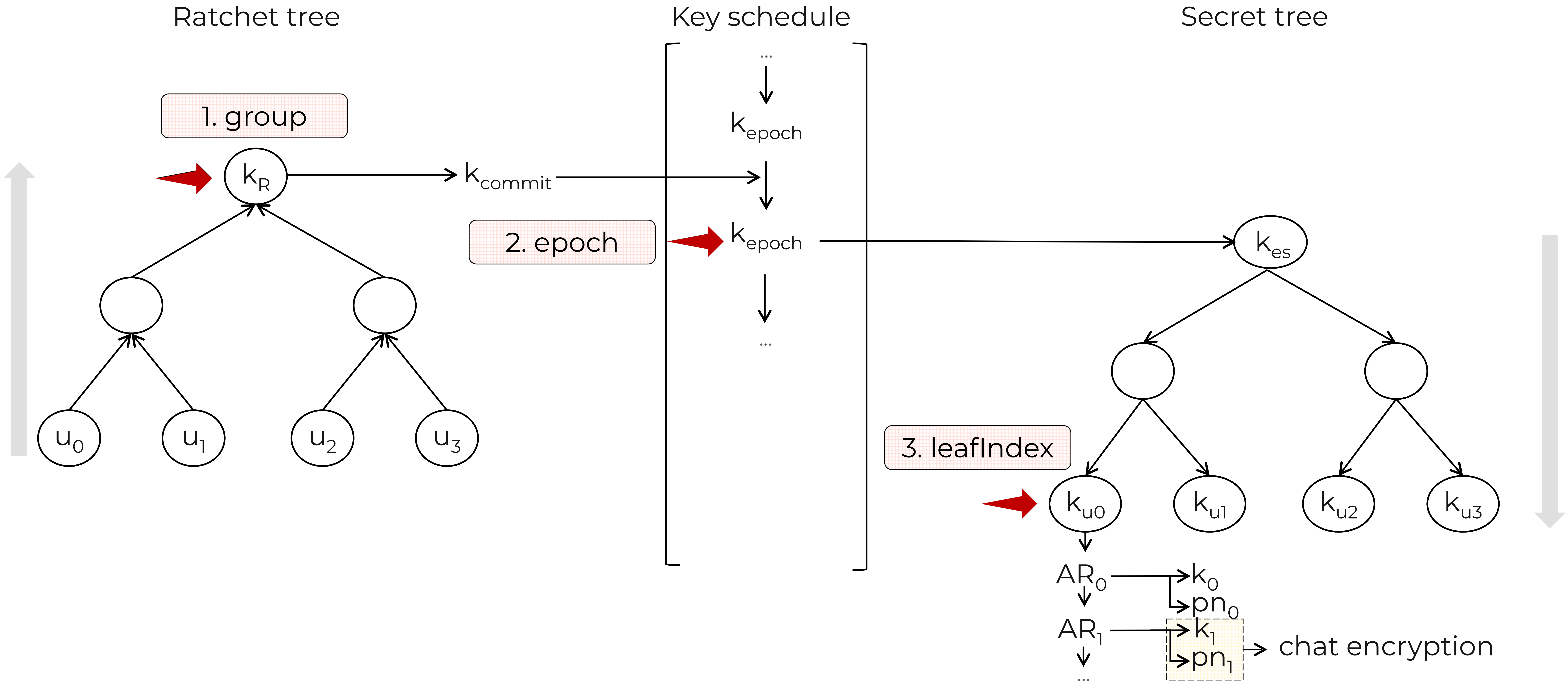

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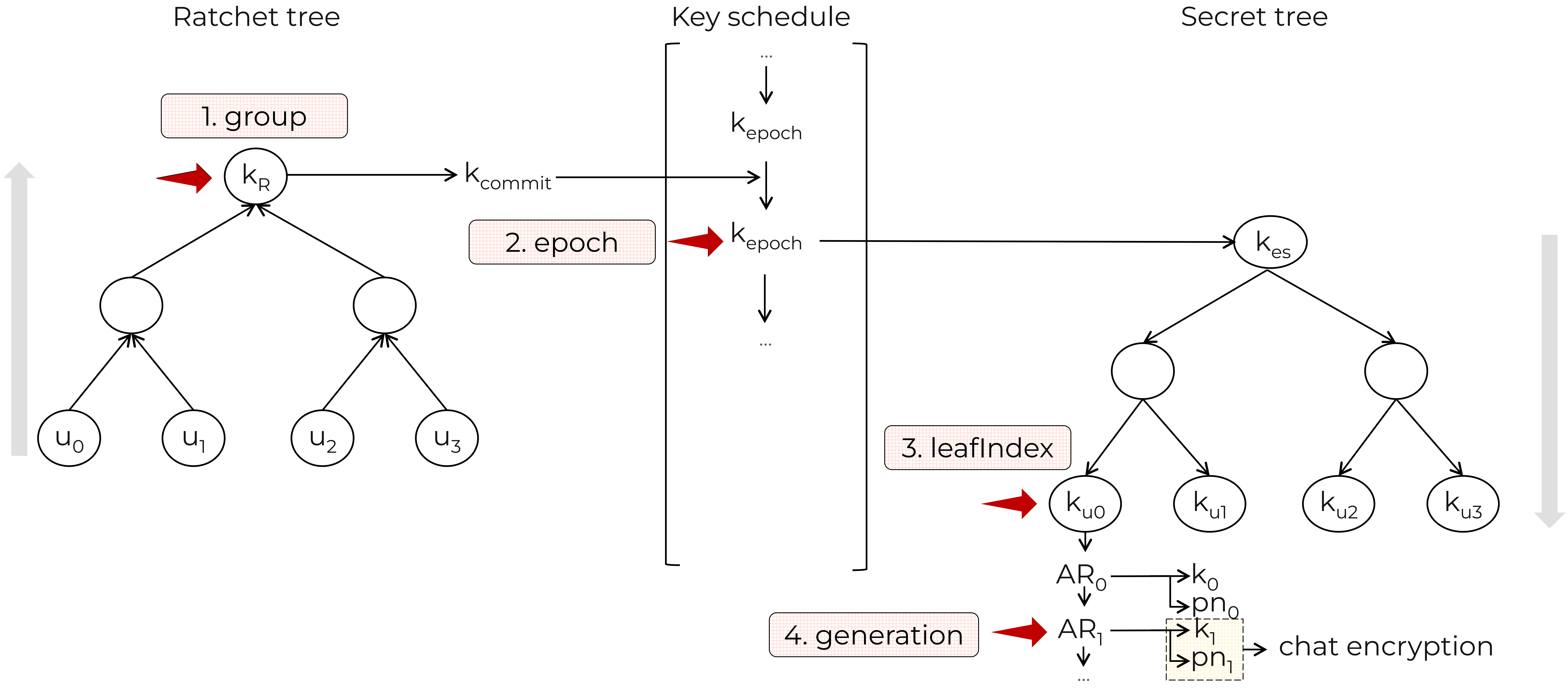

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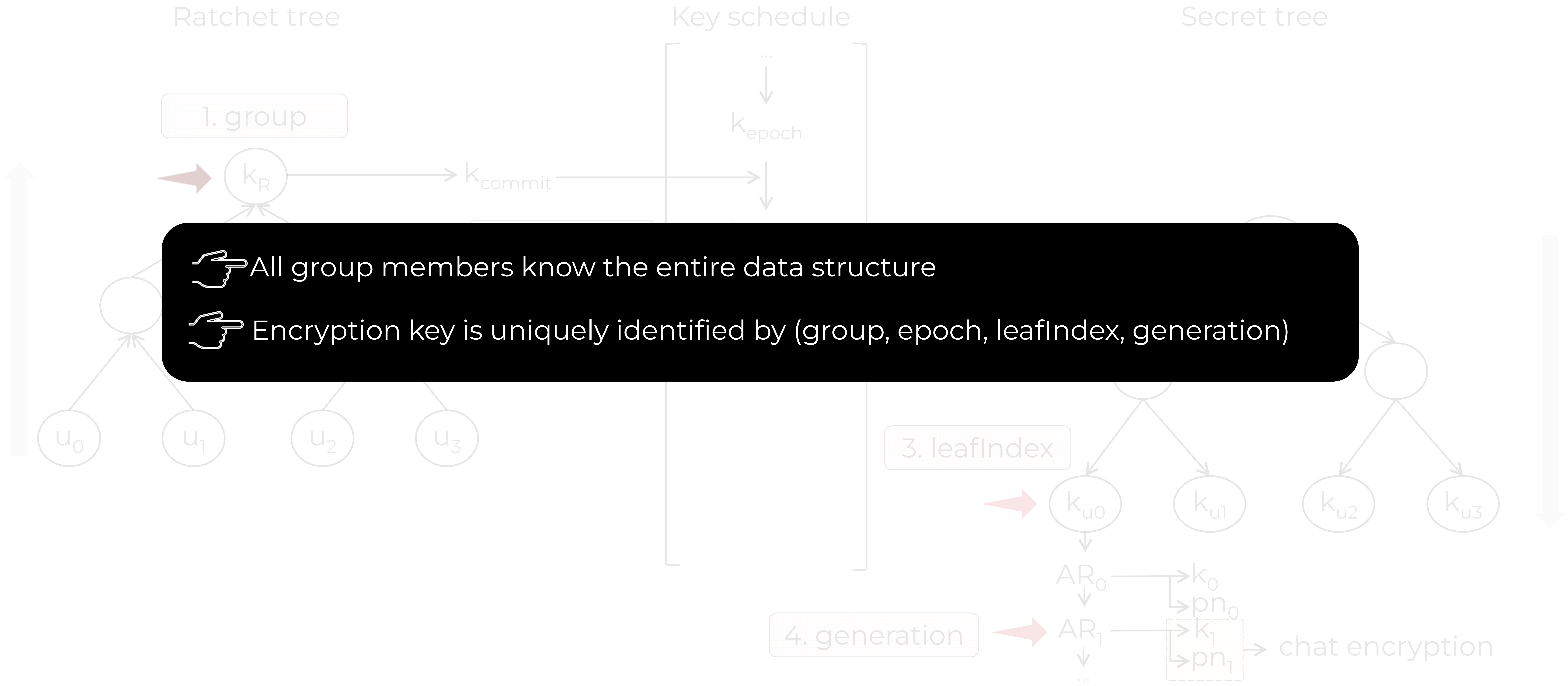

- All group members know the entire data structure
- Encryption key is uniquely identified by (group, epoch, leafIndex, generation)

Chat Encryption in MLS

Chat Encryption in MLS

Chat encryption in MLS composes a digital signature scheme and a nonce-based encryption scheme in a Sign-then-Encrypt fashion

MLS-Sign-then-Encrypt

u: user_id
g: key_id

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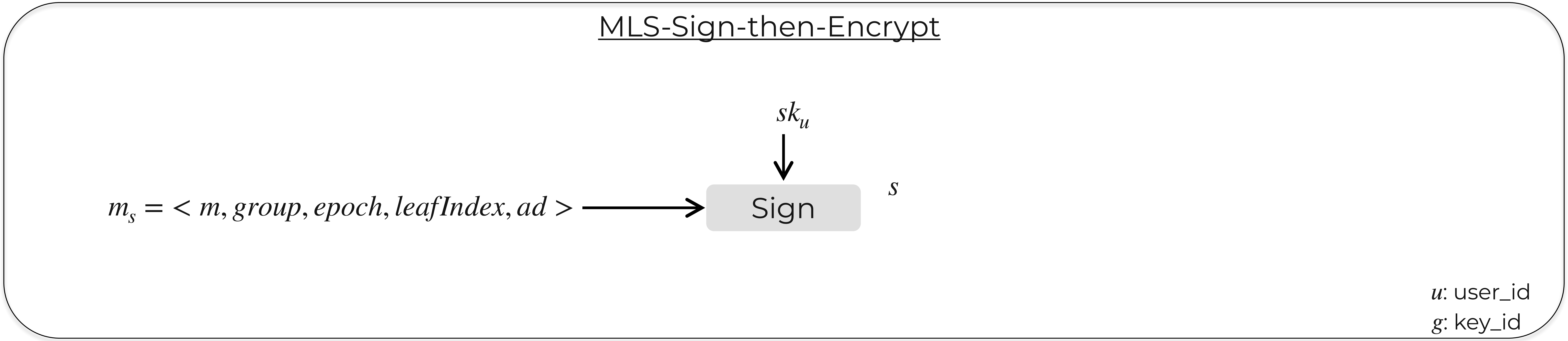

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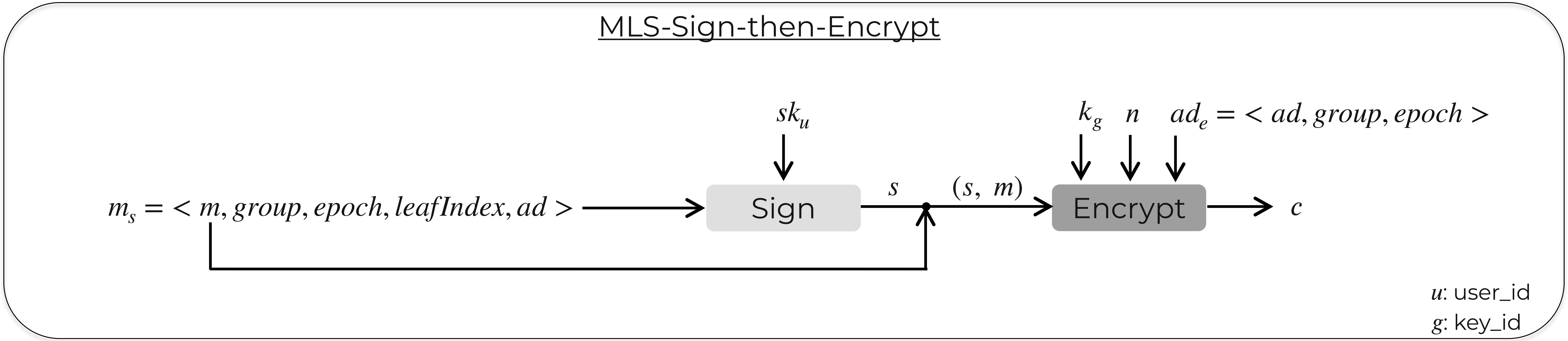

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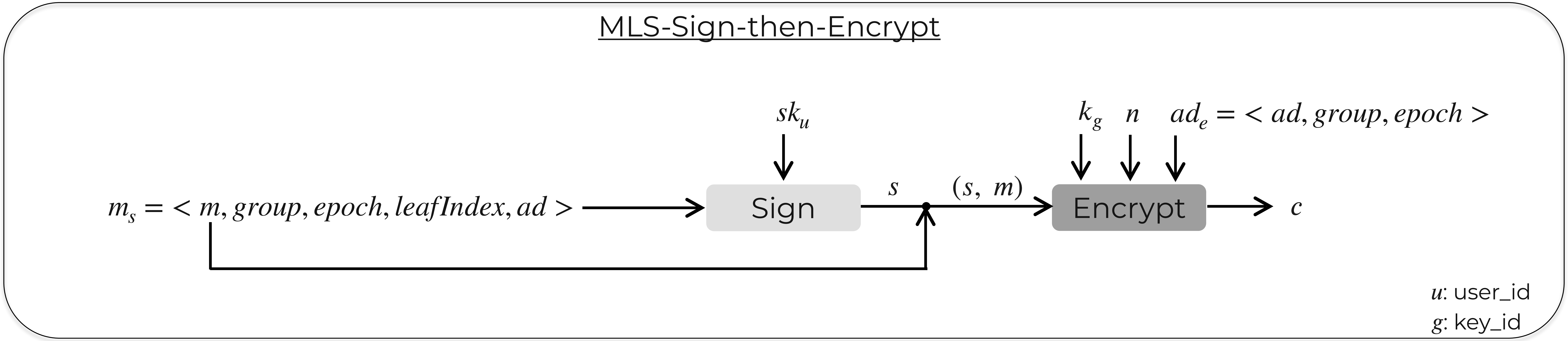

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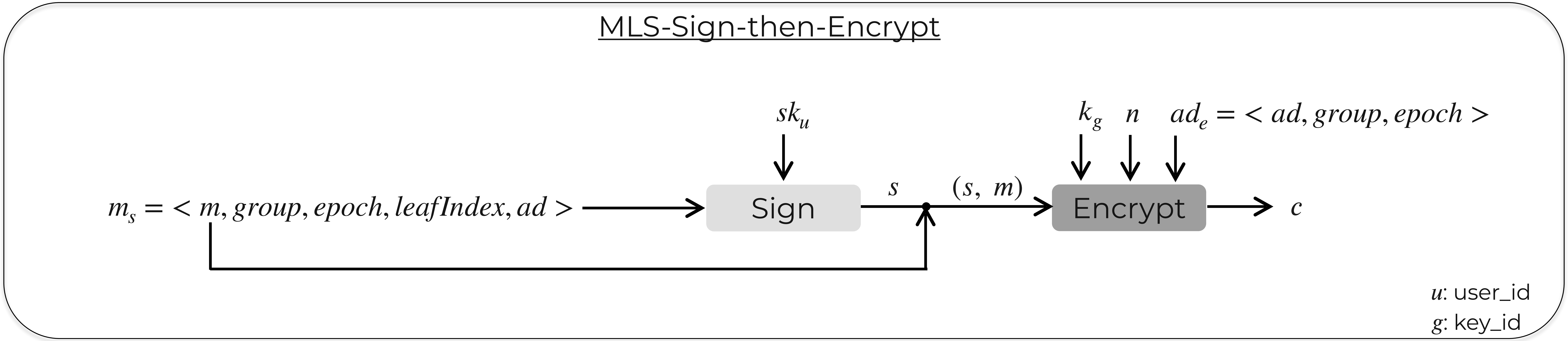

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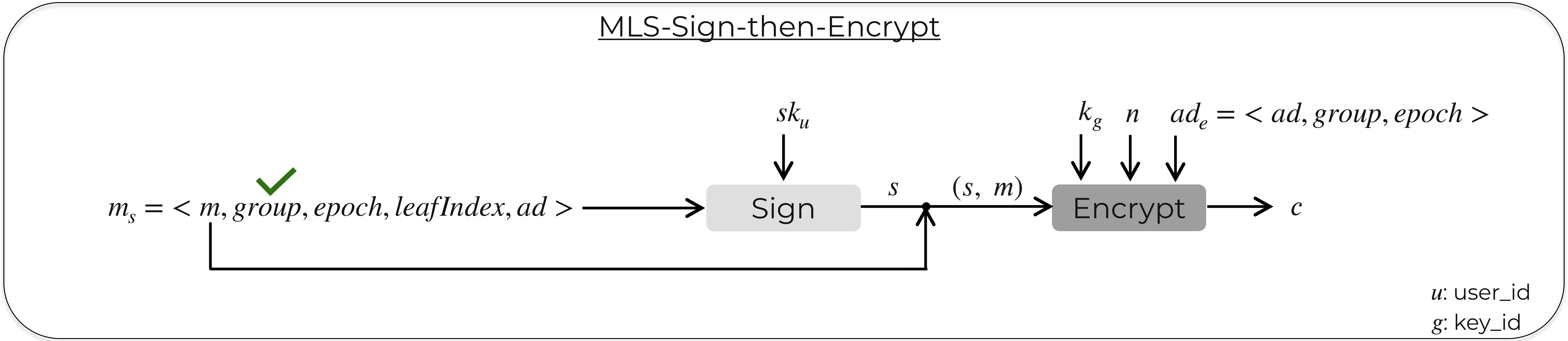

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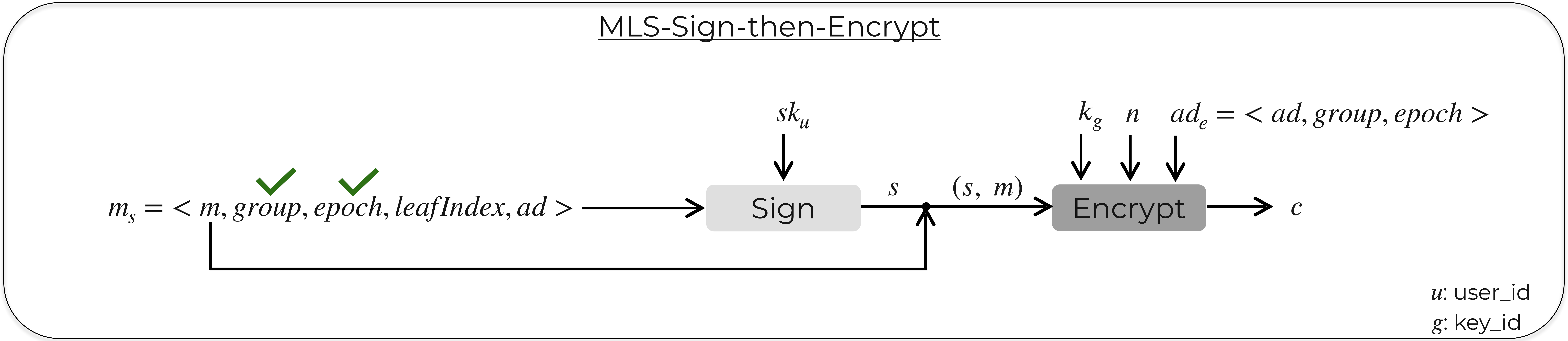

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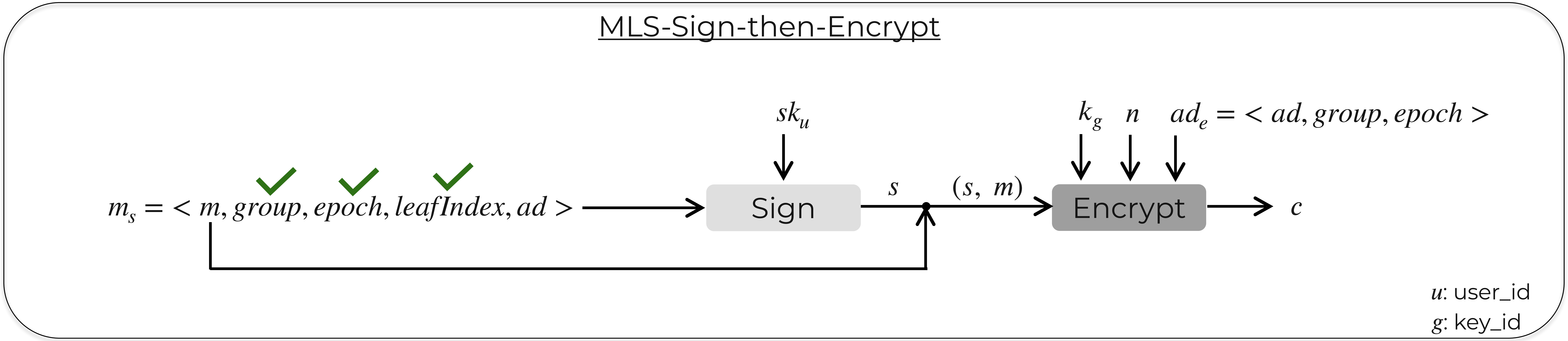

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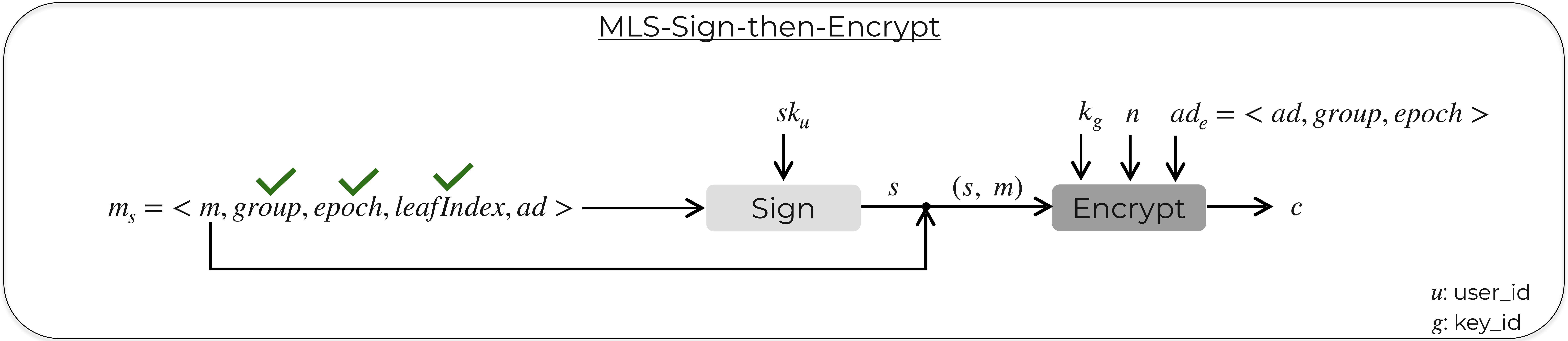

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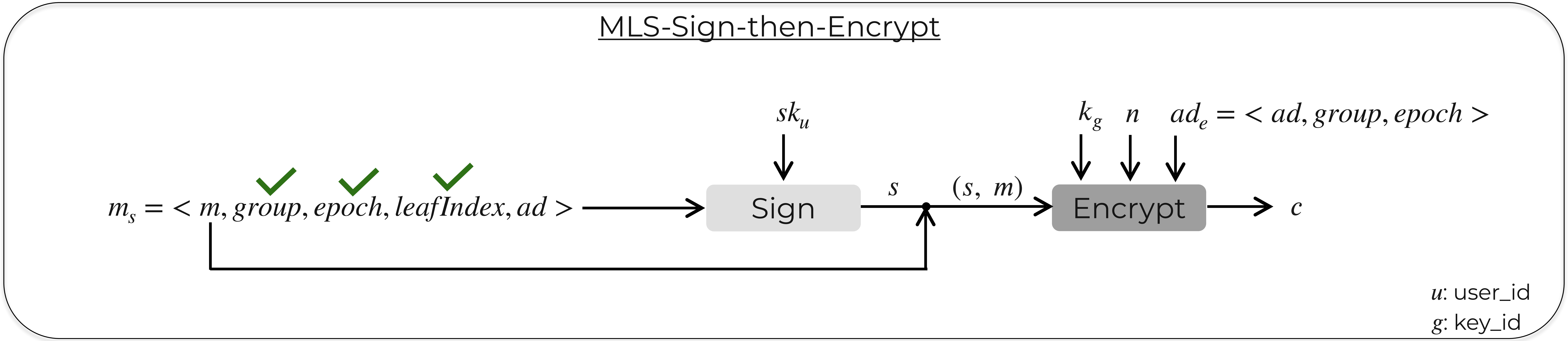

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SIGN
group_key_id

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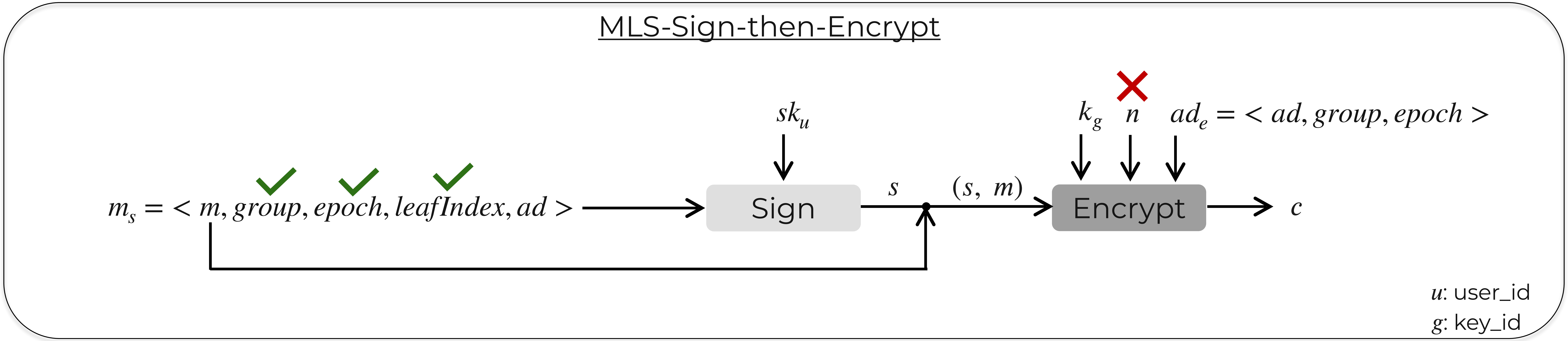

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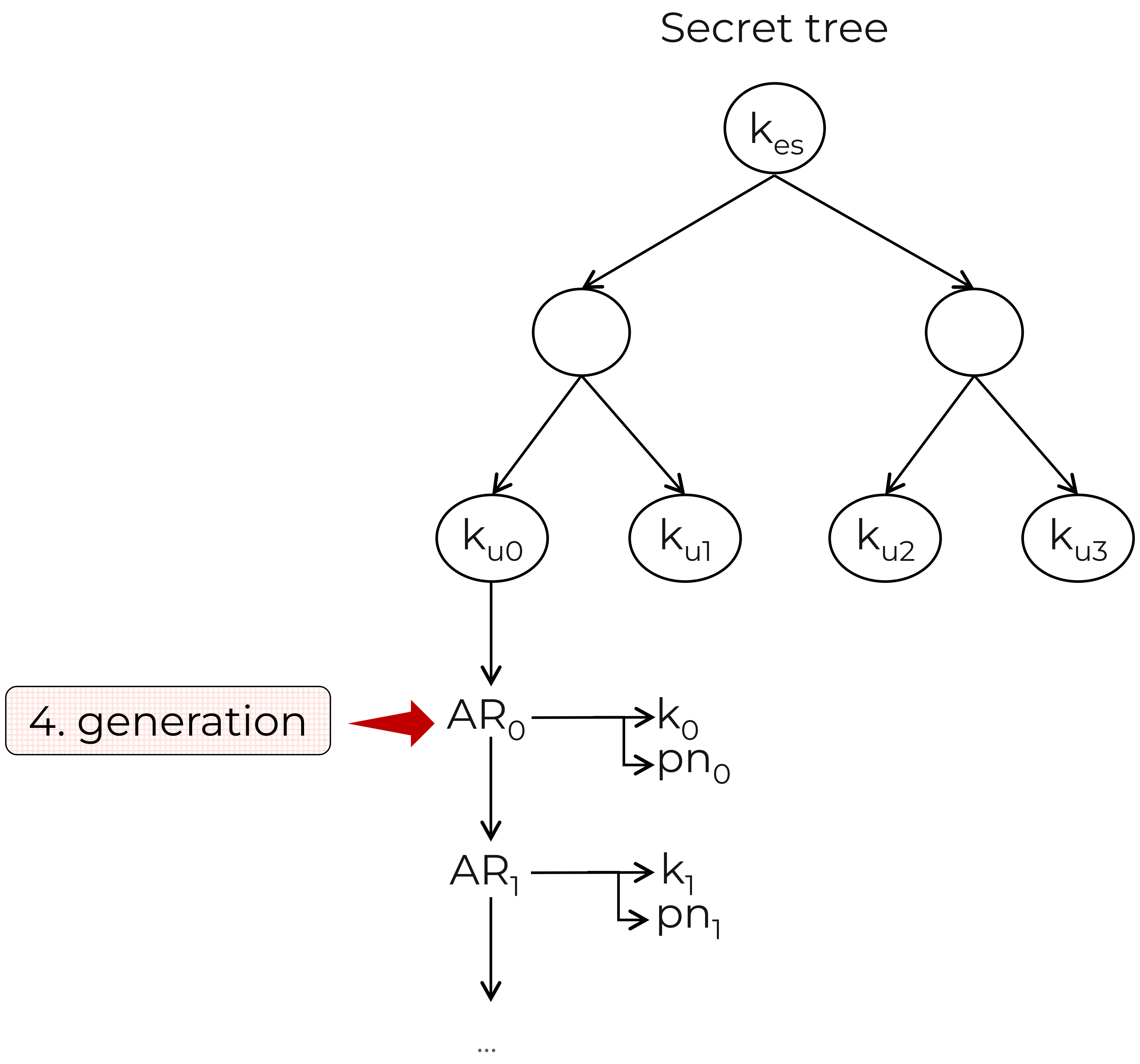

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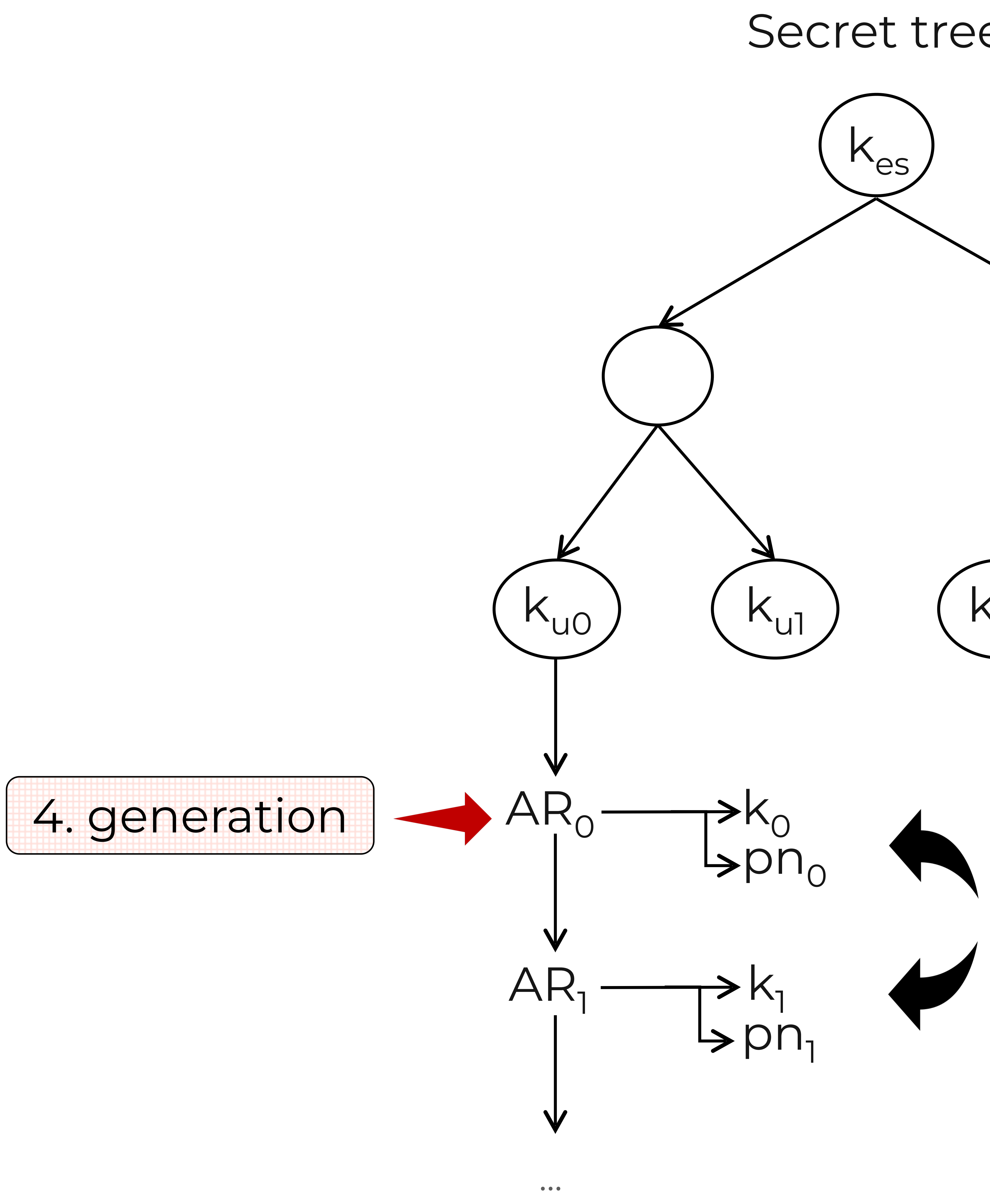

malicious insider can hop between generations!

1. Insider Replay Attack

SIGN
group_key_id ❌

Insider Replay Attack

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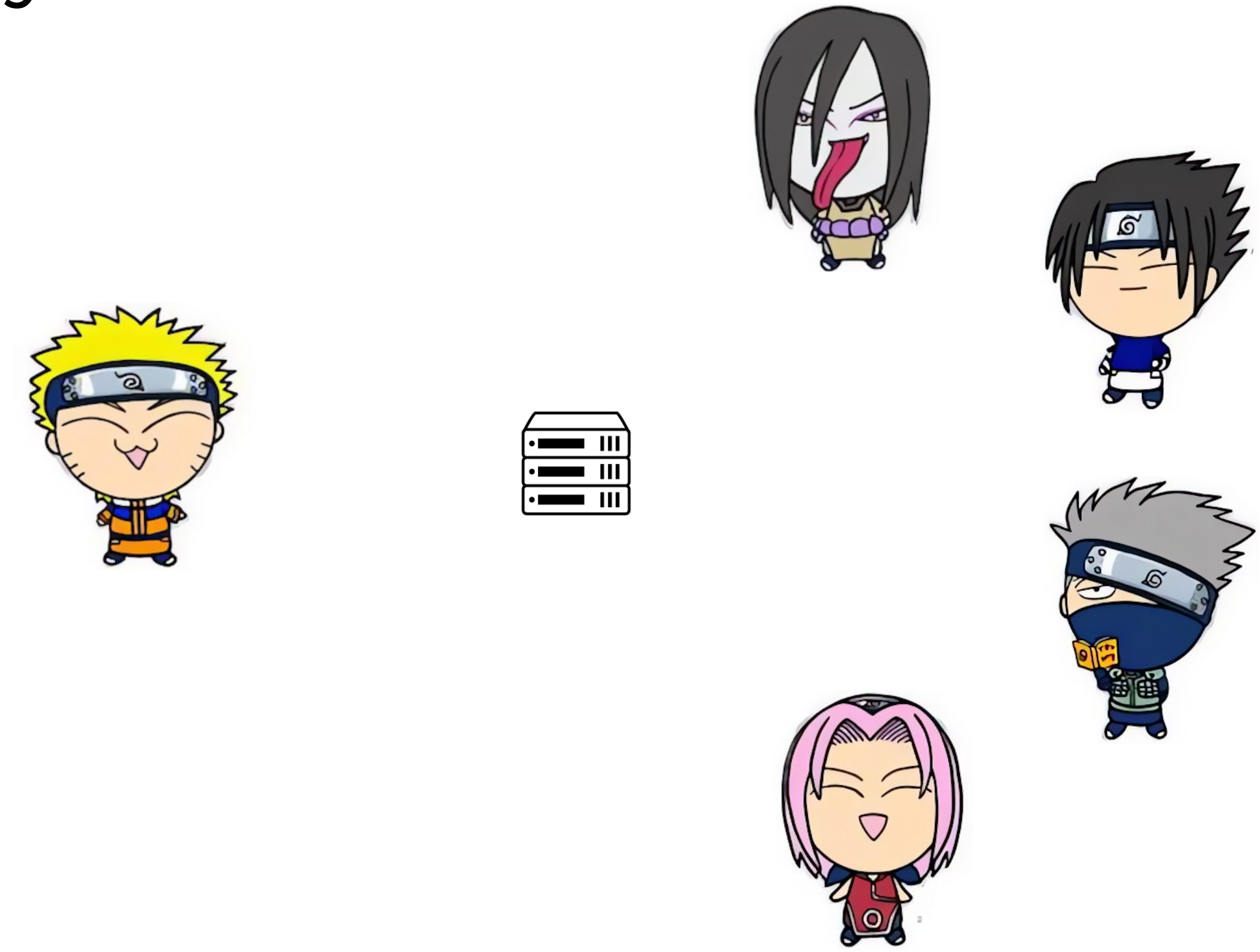

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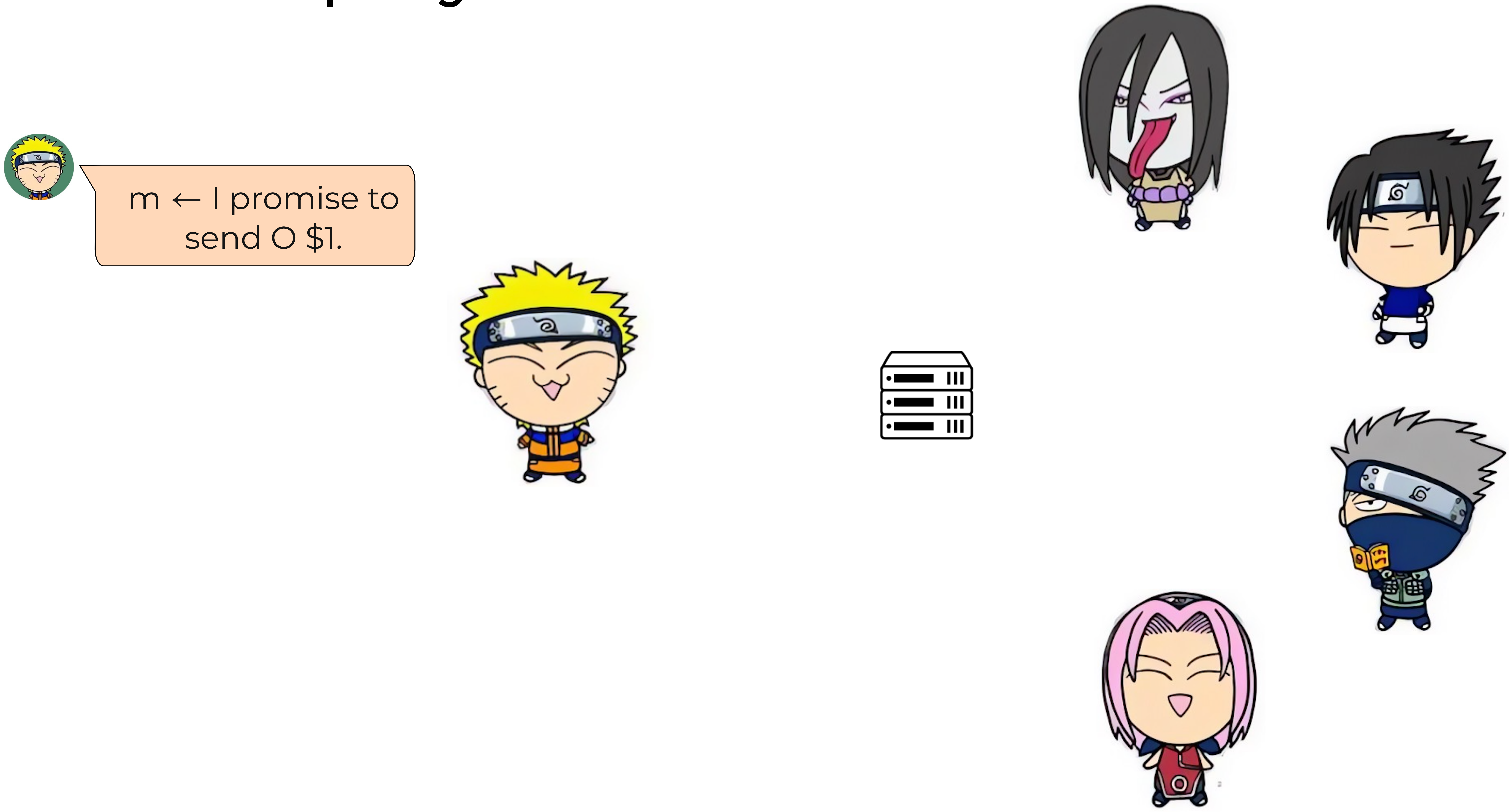

Insider Replay Attack

m ← I promise to send O $1.

MLS-Sign-then-Encrypt

$s \leftarrow \text{Sign}(sk_u,\ m_s)$

$c \leftarrow \text{Enc}(k_{g_0},\ n,\ s||m,\ ad_e)$

u : user_id
g_0 : key_id

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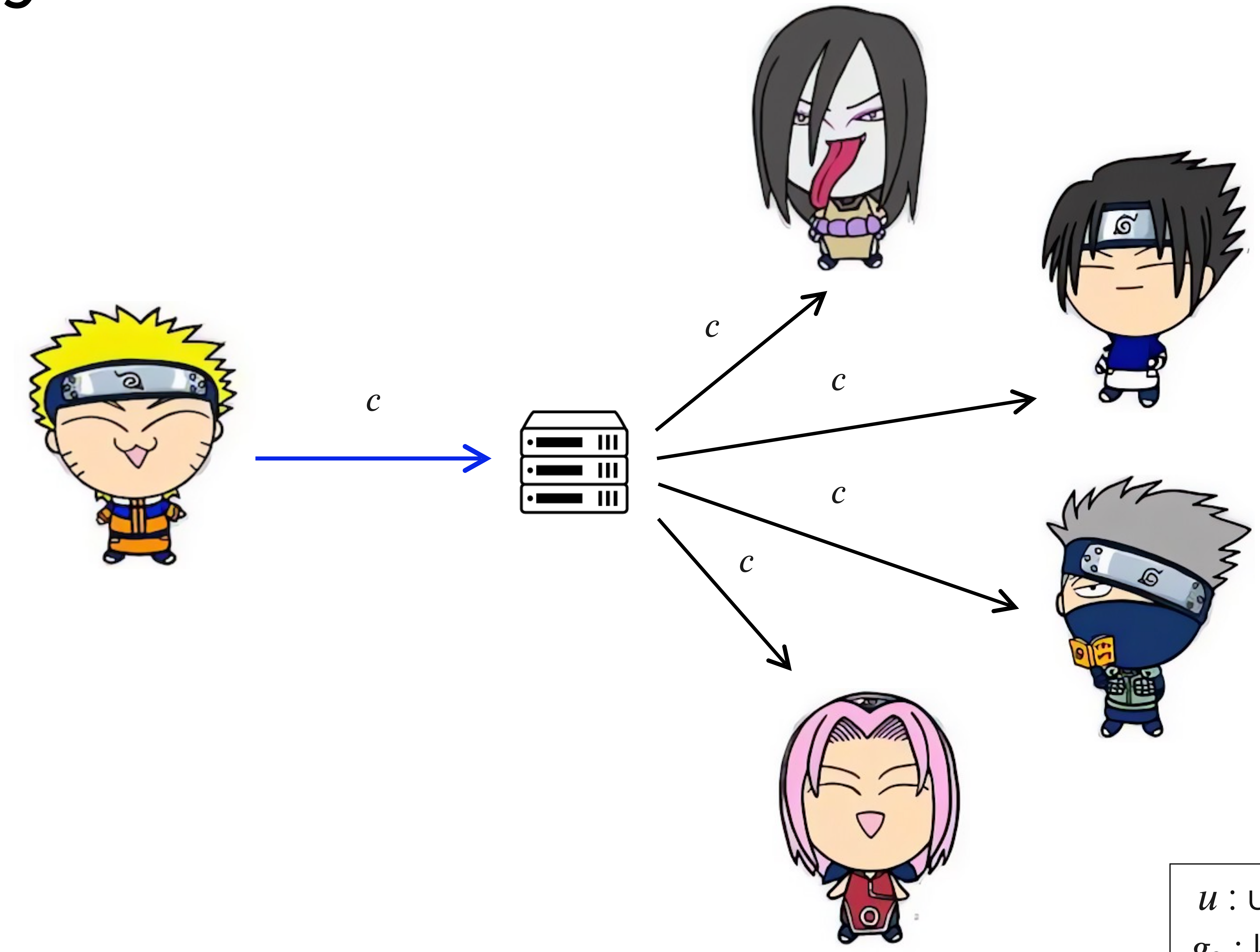

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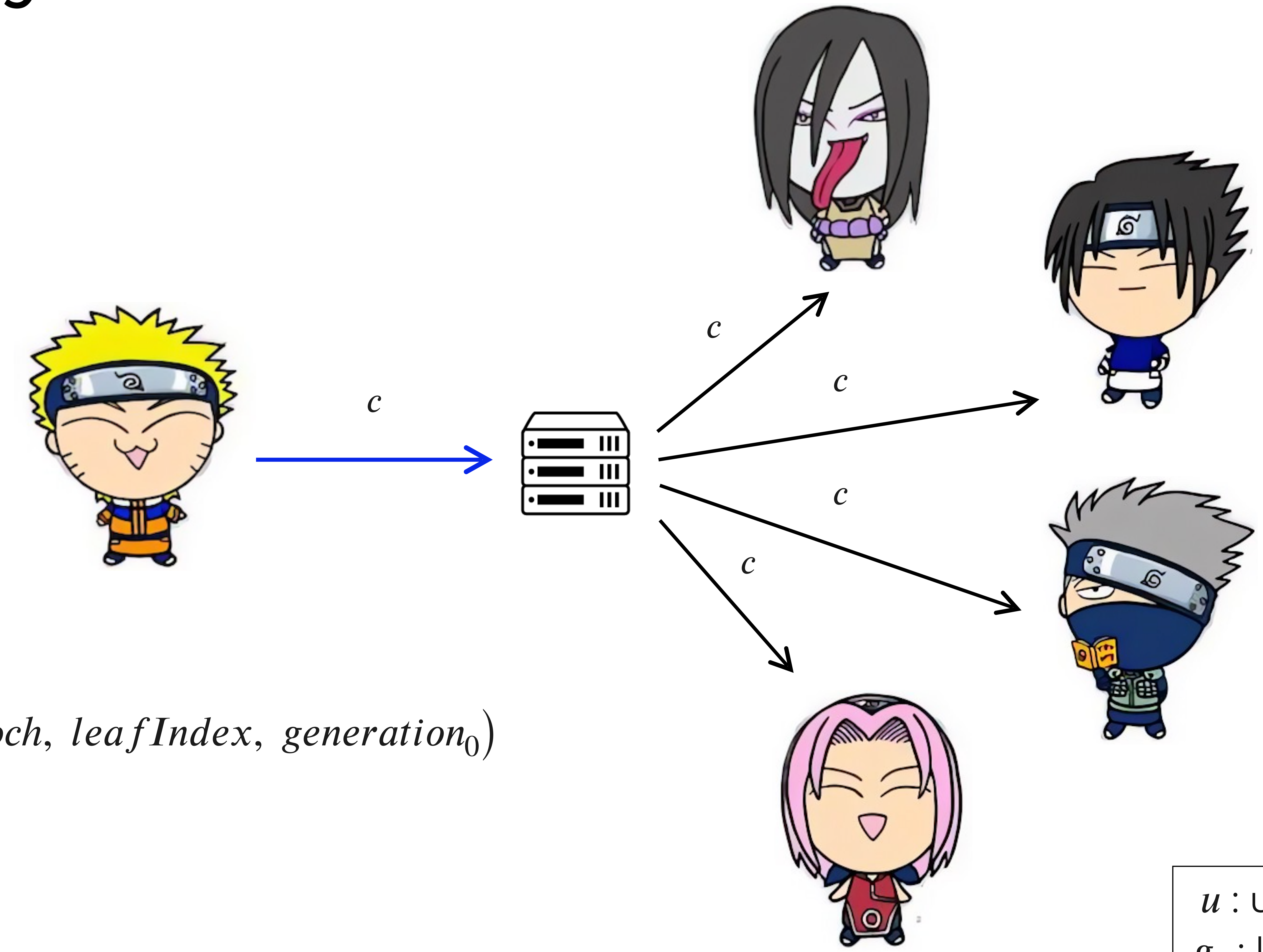

Let key identifier $g_0 = \left(group,\ epoch,\ leafIndex,\ generation_0\right)$

u : user_id
g_0 : key_id

Insider Replay Attack

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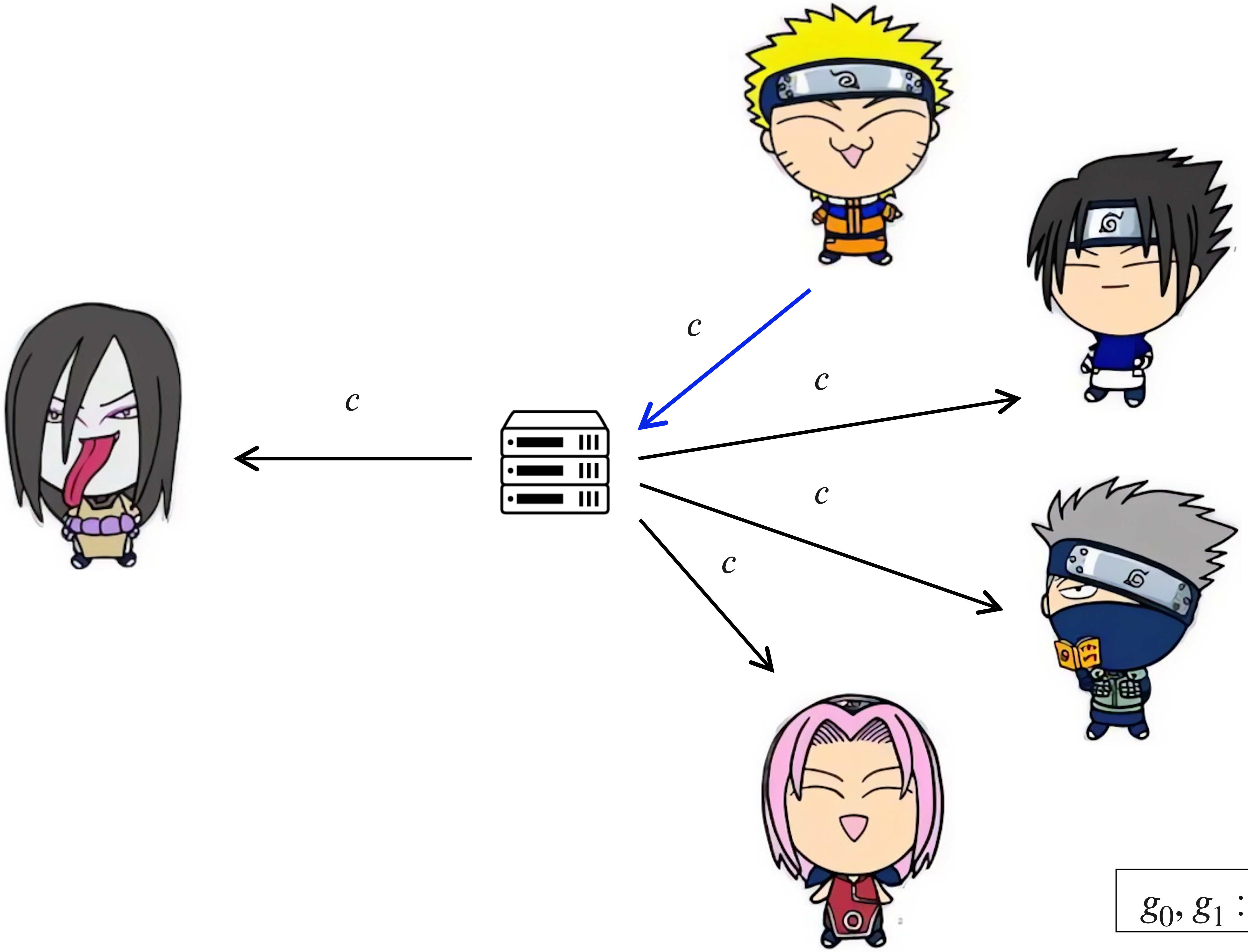
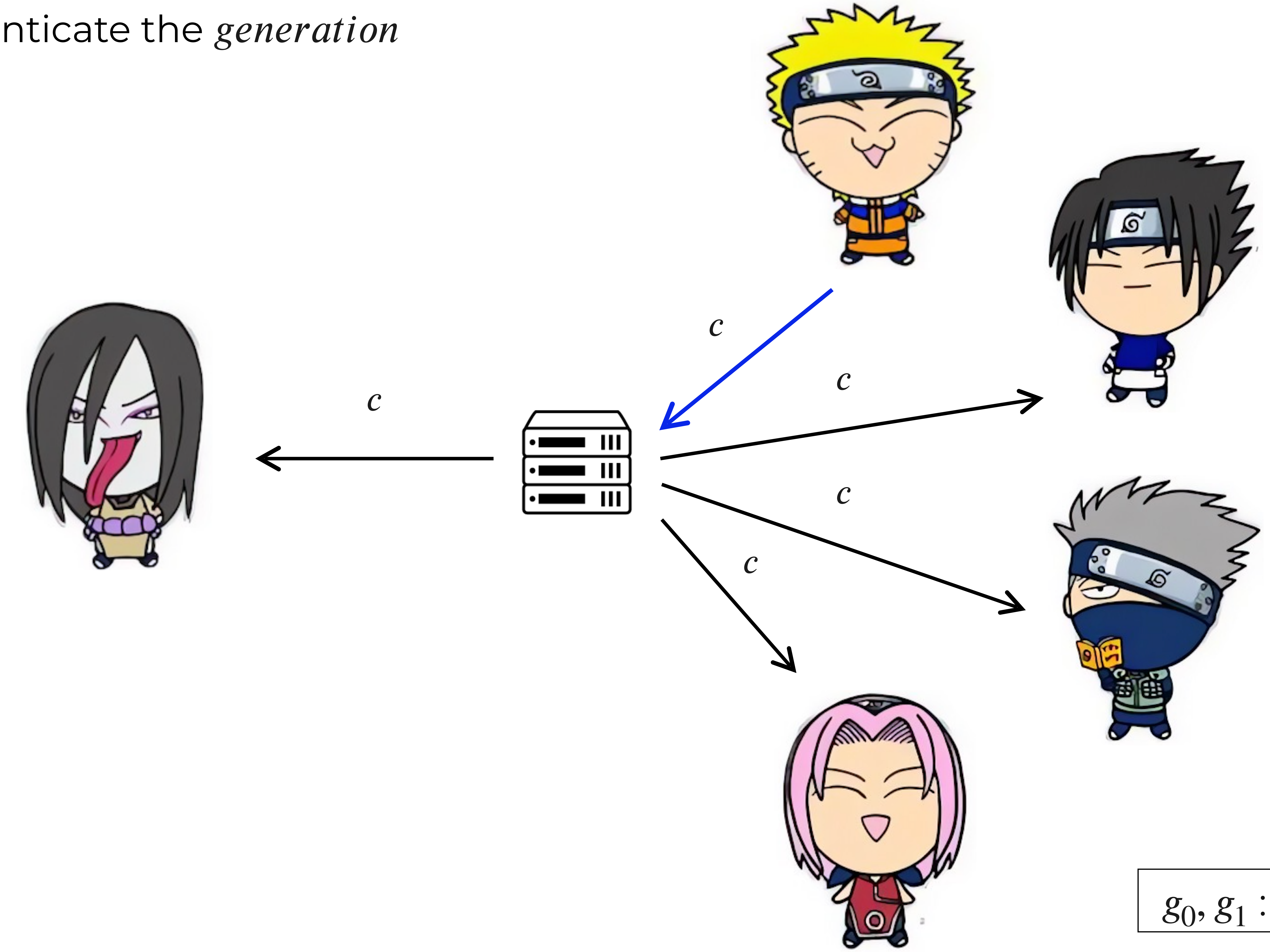


g_0, g_1 : key_id

Insider Replay Attack

Recall: signature s does not authenticate the *generation*



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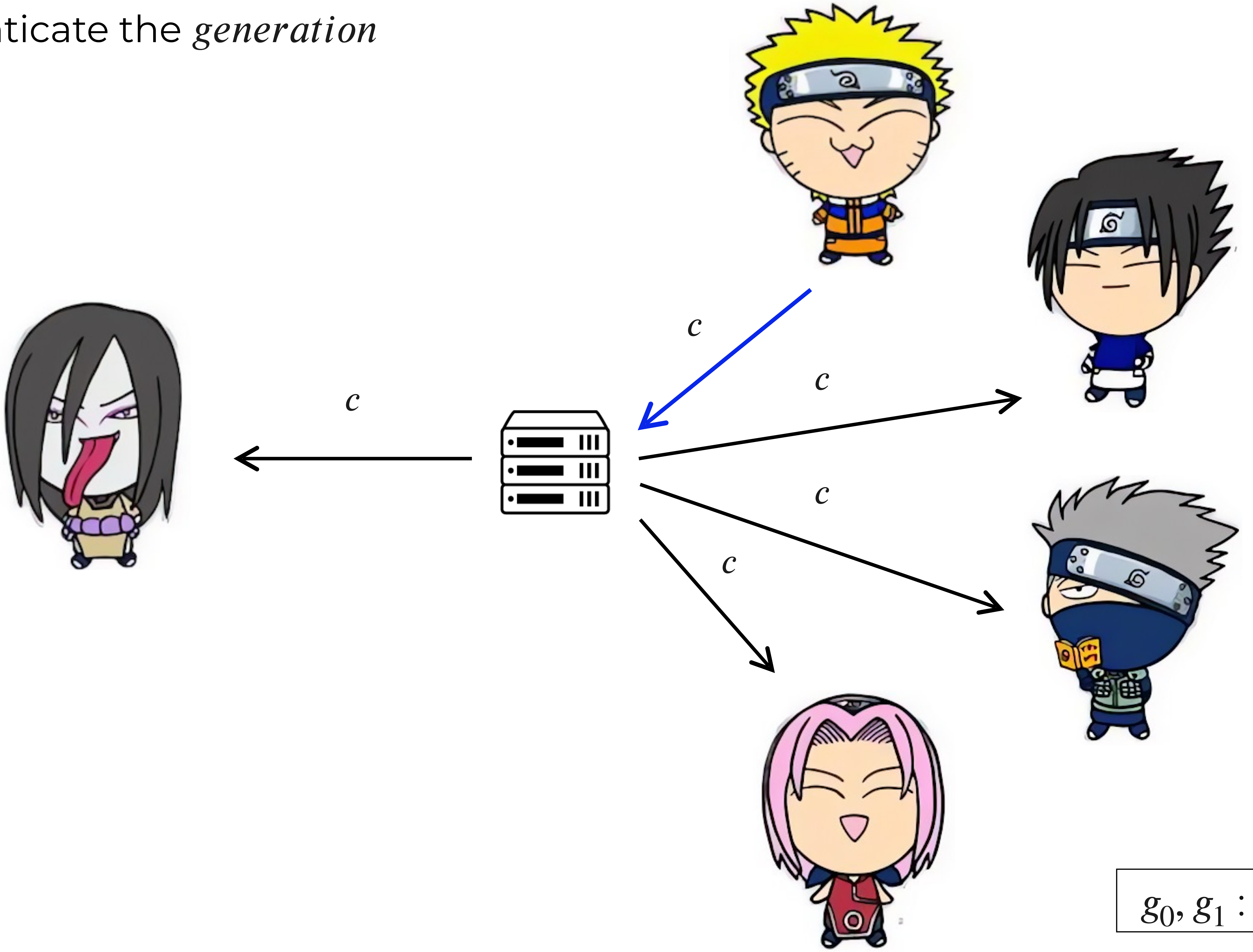
<u>Decrypt-then-Re-Encrypt</u>

$s||m \leftarrow \text{Dec}(k_{g_0}, n, c, ad_e)$

$c' \leftarrow \text{Enc}(k_{g_1}, n, s||m, ad_e)$



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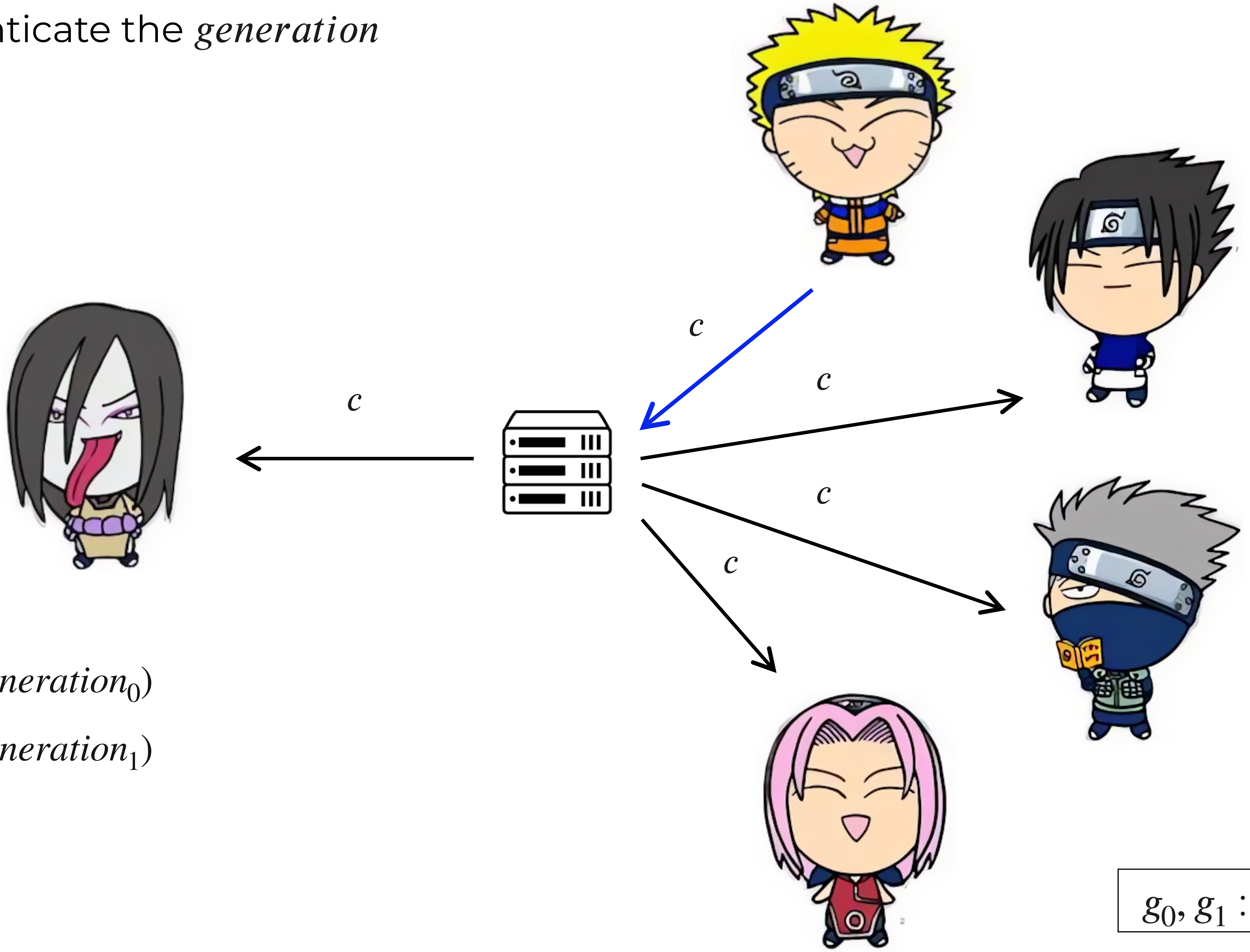

$g_0 = (group, epoch, leafIndex, generation_0)$

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$(generation_1 > generation_0)$

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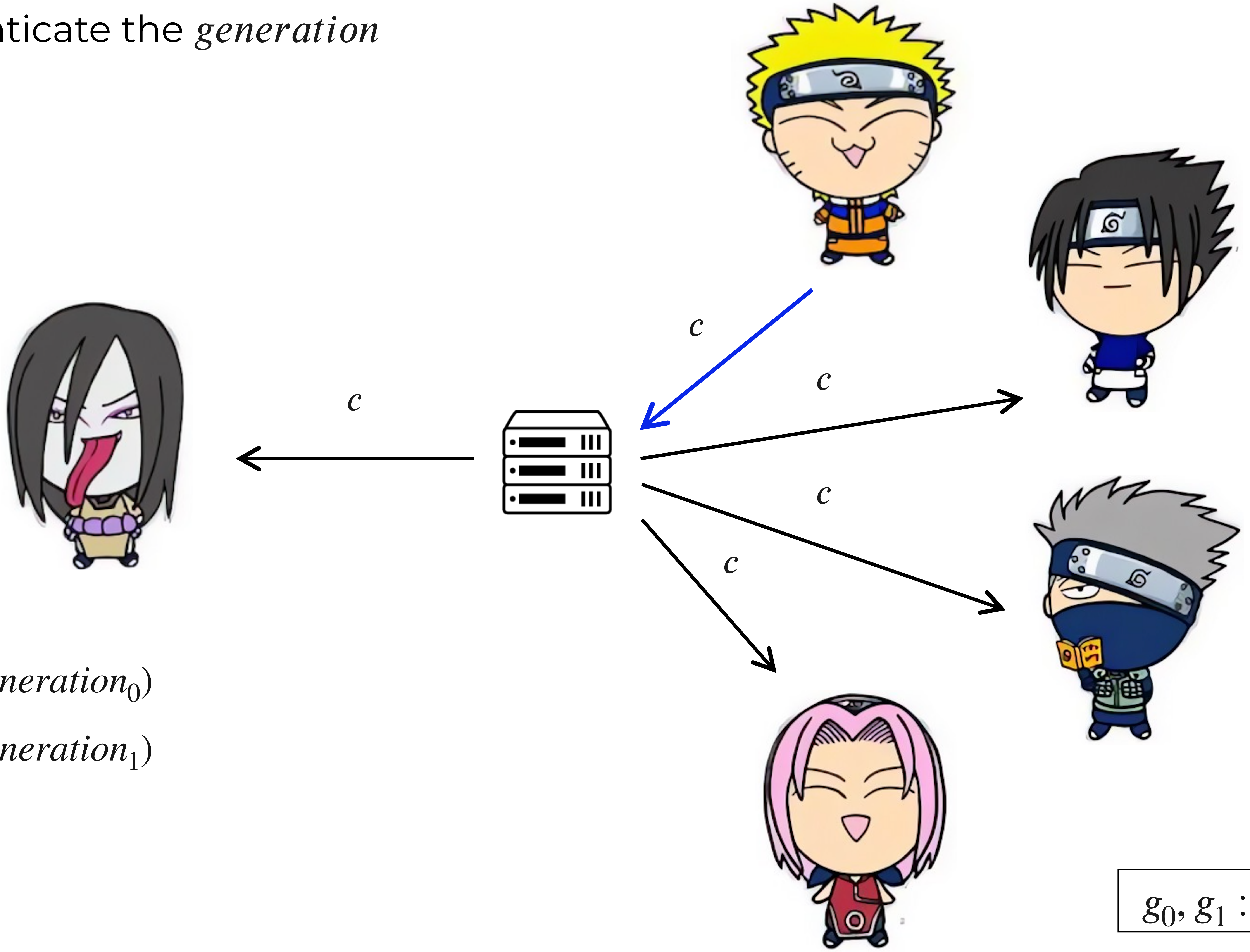
Save for later



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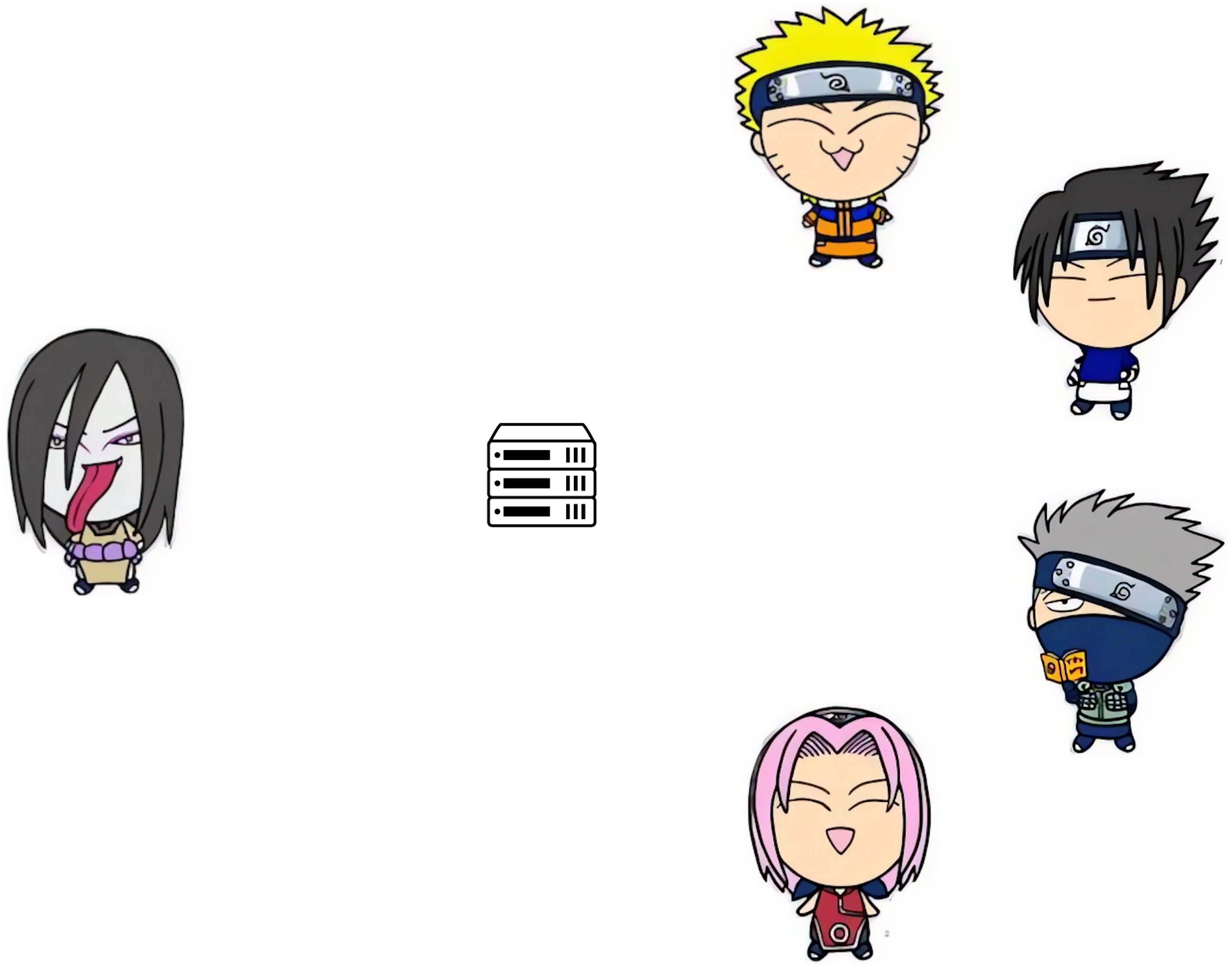

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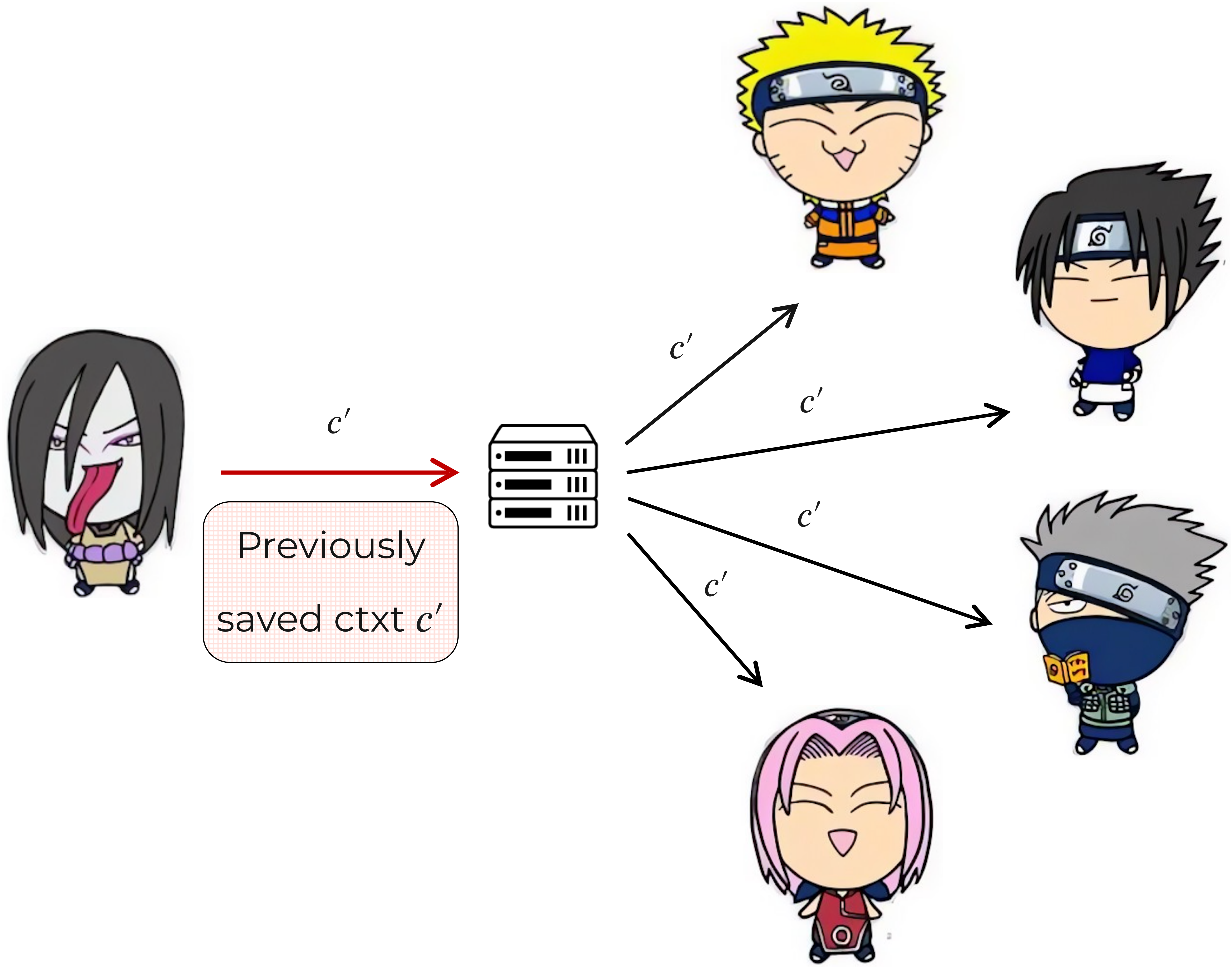

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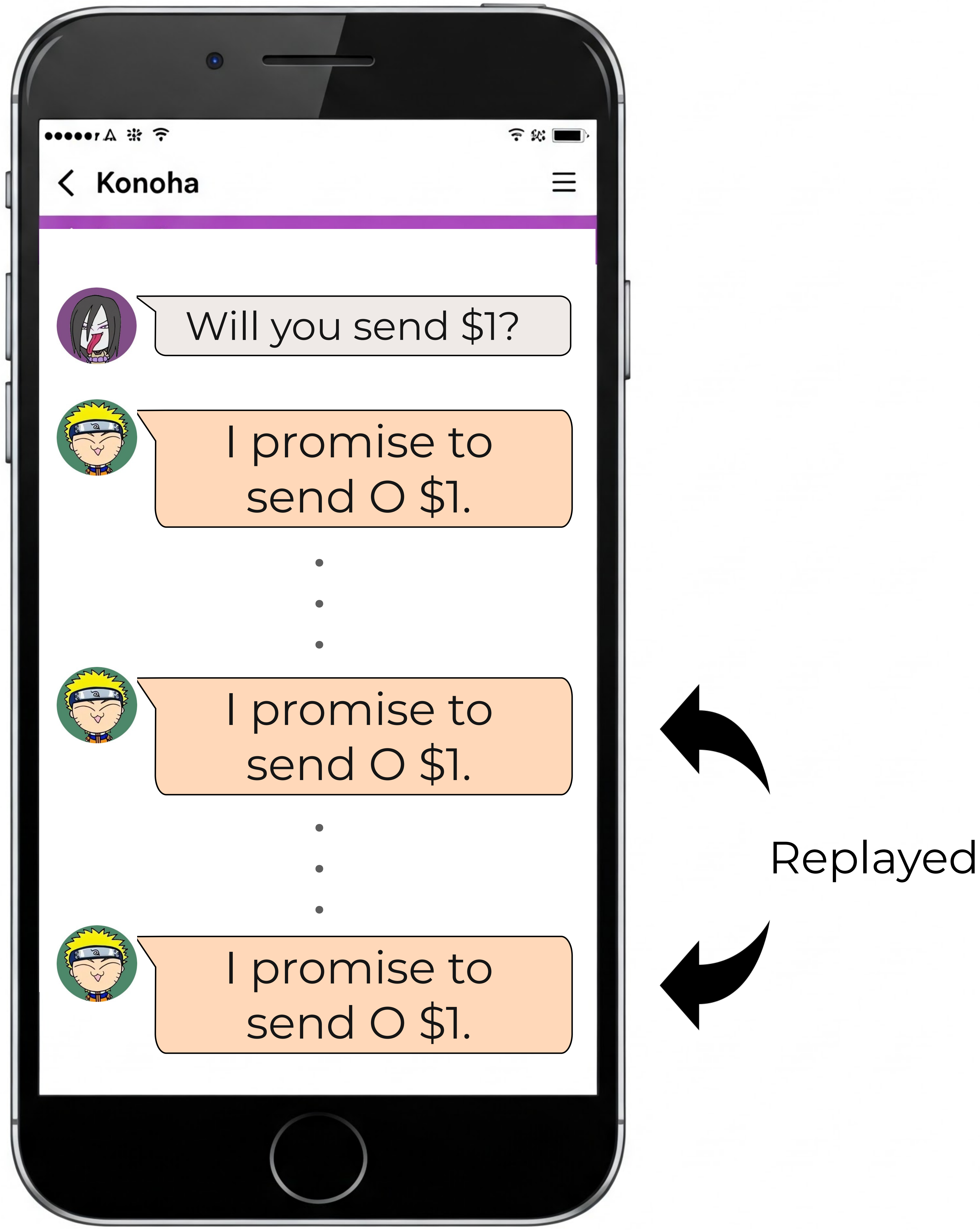

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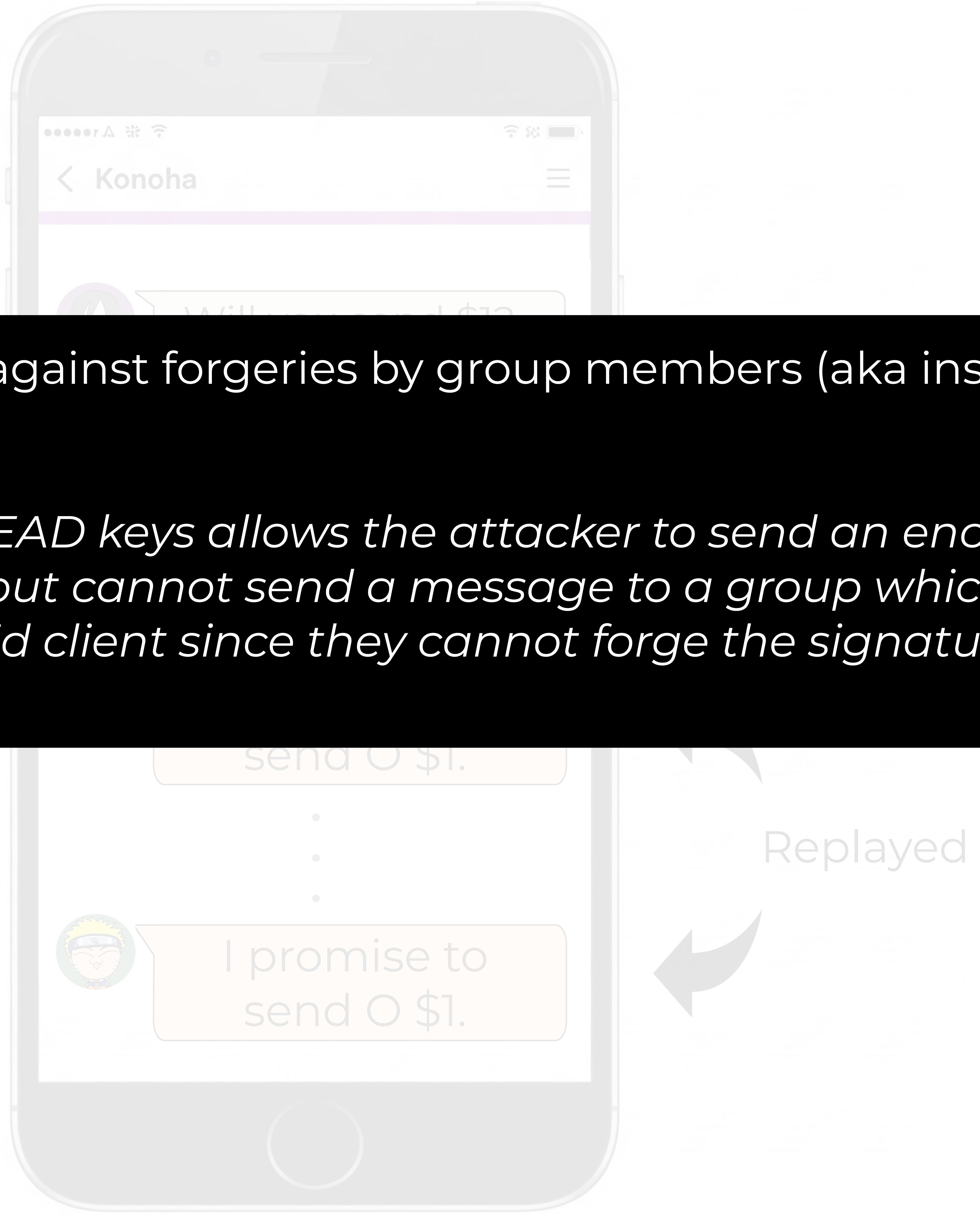

MLS aims to protect against forgeries by group members (aka insiders)

"[Knowledge] of the AEAD keys allows the attacker to send an encrypted message using that key, but cannot send a message to a group which appears to be from any valid client since they cannot forge the signature."

Mitigation and Disclosure

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Attack results from lack of binding between signature and generation; mitigation is to bind them

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Mitigation and Disclosure

Attack results from lack of binding between signature and generation; mitigation is to bind them

No Protection against Replay by Insiders

MLS does not protect against one group member replaying a PrivateMessage sent by another group member within the same epoch that the message was originally sent. Similarly, MLS does not protect against the replay (by a group member or otherwise) of a PublicMessage within the same epoch that the message was originally sent. Applications for whom replay is an important risk should apply mitigations at the application layer, as discussed below.

In addition to the risks discussed in {{symmetric-key-compromise}}, an attacker with access to the Ratchet Secrets for an endpoint can replay PrivateMessage objects sent by other members of the group by taking the signed content of the message and re-encrypting it with a new generation of the original sender's ratchet. If the other members of the group interpret a message with a new generation as a fresh message, then this message will appear fresh. (This is possible because the message signature does not cover the `generation` field of the message.) Messages sent as PublicMessage objects similarly lack replay protections. There is no message counter comparable to the `generation` field in PrivateMessage.

Applications can detect replay by including a unique identifier for the message (e.g., a counter) in either the message payload or the `authenticated_data` field, both of which are included in the signatures for PublicMessage and PrivateMessage.

- Disc

- Turn around time very quick ~couple hours, acknowledgement of findings

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Interlude

Interlude

Session 5C: Messaging and Privacy — CCS '21, November 15–19, 2021, Virtual Event, Republic of Korea

Modular Design of Secure Group Messaging Protocols and the Security of MLS

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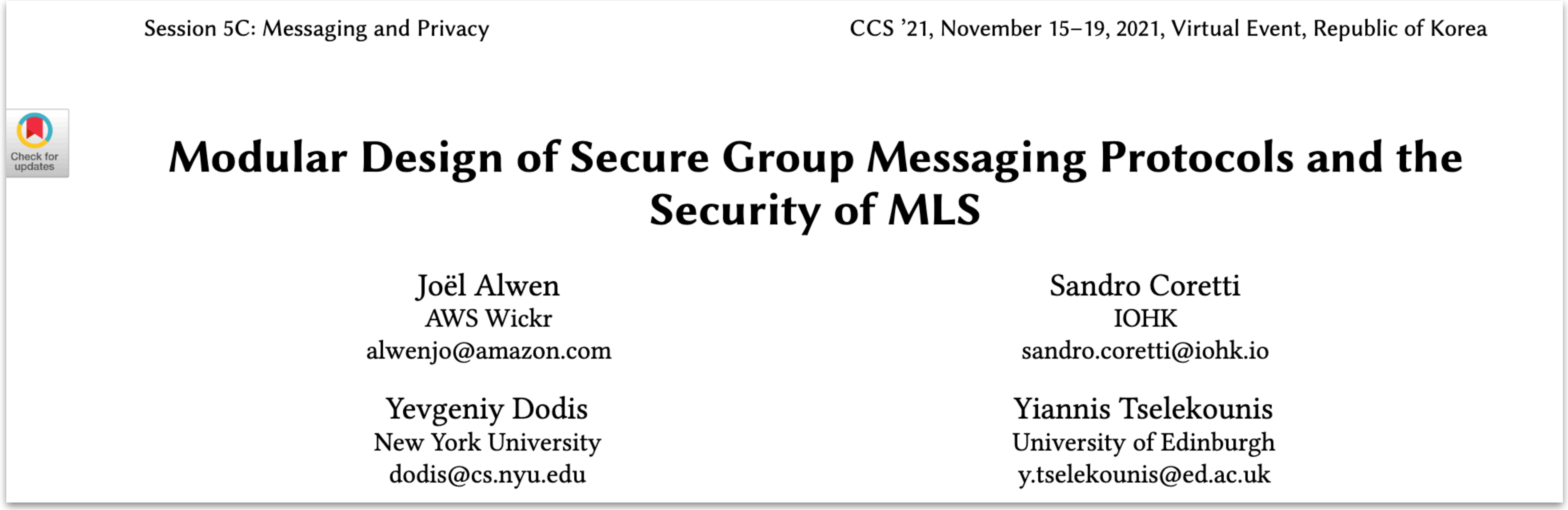
Modular Design of the Messaging Layer Security (MLS) Protocol

Master Thesis

Tijana Klimovic

Interlude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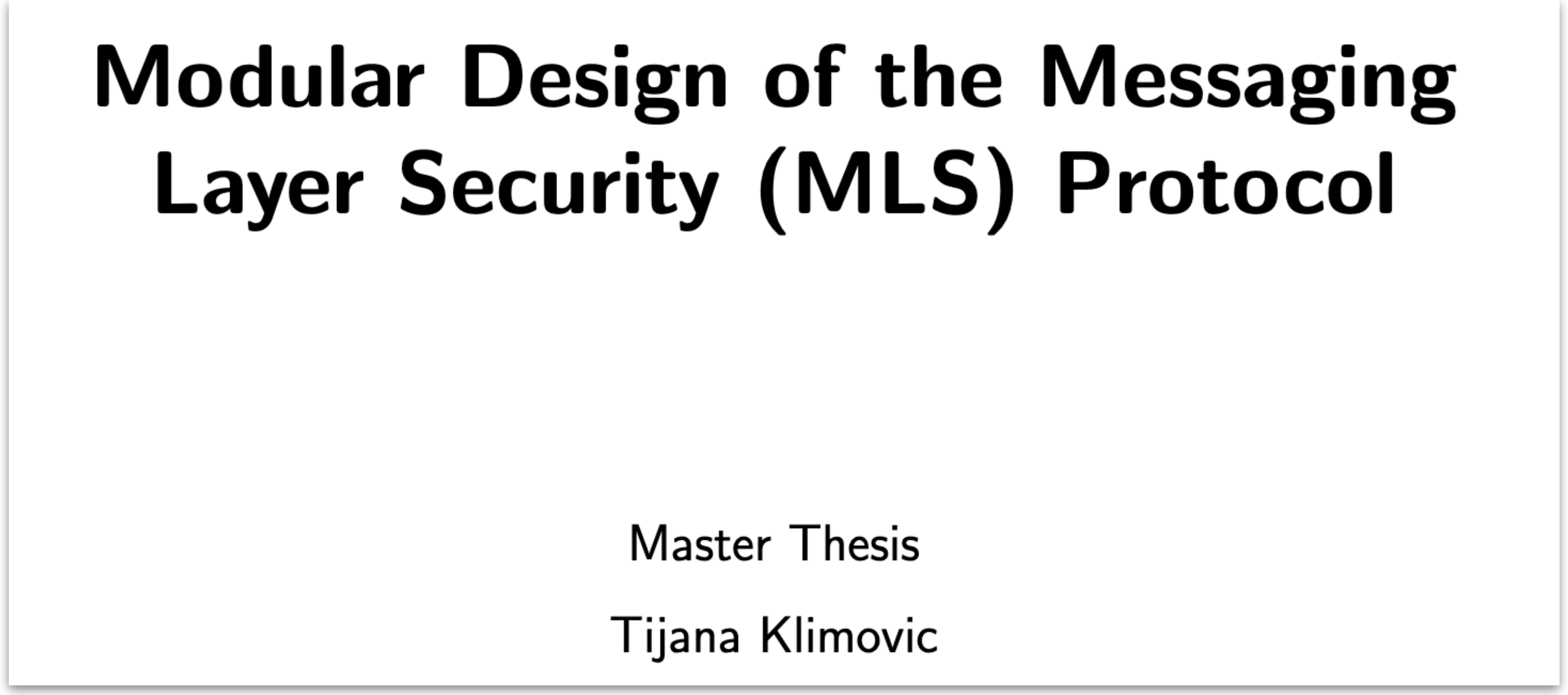
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Master Thesis

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Modeled but did not formally analyze MLS chat encryption

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Check for updates

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Security game defines corruption as learning both symmetric and signing keys

Modular Design of the Messaging Layer Security (MLS) Protocol

Master Thesis

Tijana Klimovic

Modeled but did not formally analyze MLS chat encryption

Interlude

Session 5C: Messaging and Privacy — CCS '21, November 15–19, 2021, Virtual Event, Republic of Korea

Modular Design of Secure Group Messaging Protocols and the Security of MLS

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Signed message generation

```
struct {
    uint8  group[32];
    uint32 epoch;
    uint32 generation;
    uint32 sender;
    opaque content<0..2^32-1>;
} MLSSignatureContent;
```

Version 1

Security game defines corruption as learning both symmetric and signing keys

Interlude

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Check for updates

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    opaque content<0..2^32-1>;
} MLSSignatureContent;
```

Version 1

```
struct {
    opaque group_id<0..255>;
    uint32 epoch;
    uint32 sender;
    ContentType content_type;

    select (MLSPlaintext.content_type) {
        case handshake:
            GroupOperation operation;

        case application:
            opaque application_data<0..2^32-1>;
    }

    opaque signature<0..2^16-1>;
} MLSPlaintext;
```

Version 5

Case Study II: Session

Insider Replay Attack in Session

Insider Replay Attack in Session

MLS Insider Replay $\approx$ Session Insider Replay

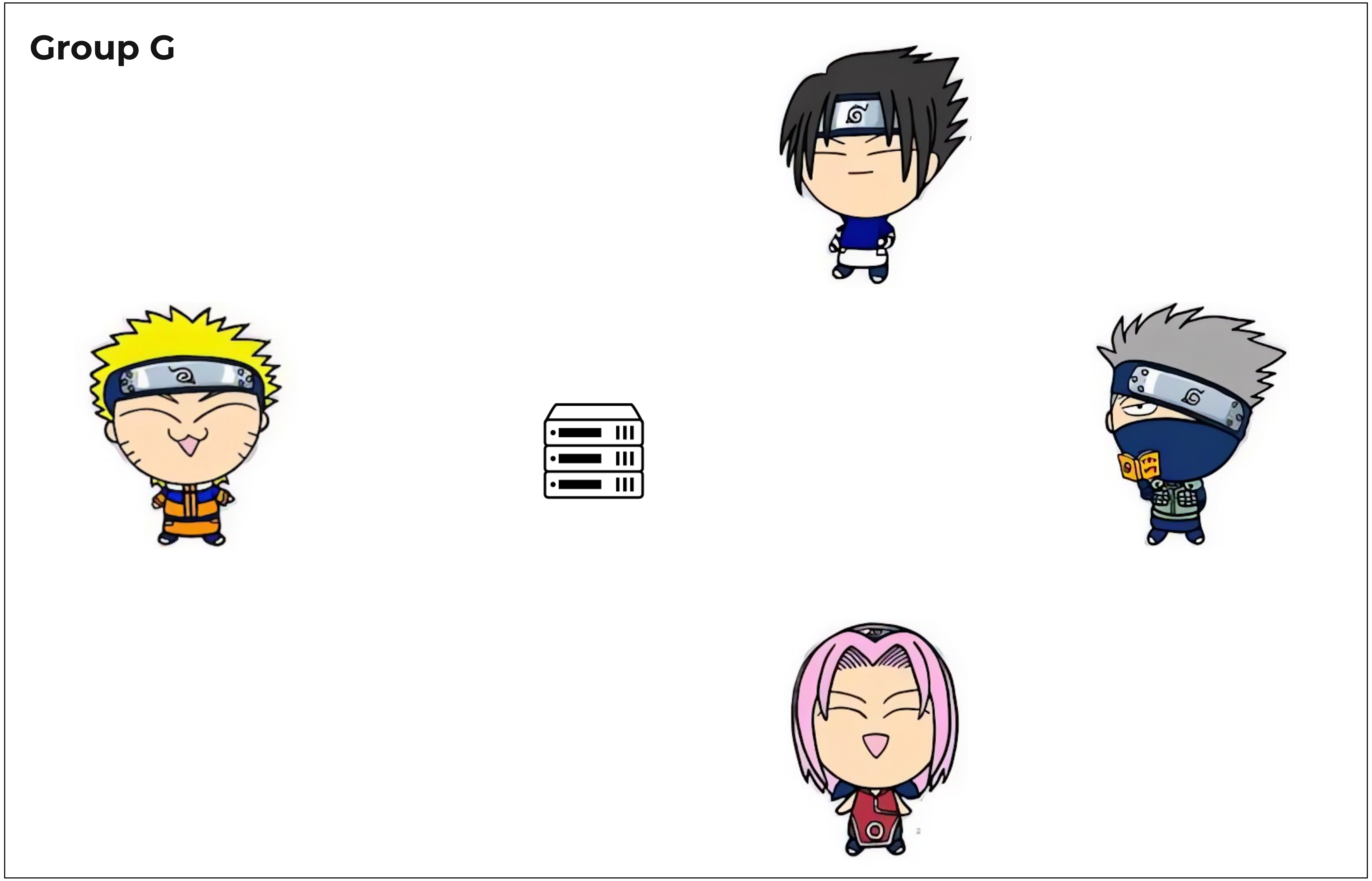
Insider Replay Attack in Session

MLS Insider Replay $\approx$ Session Insider Replay

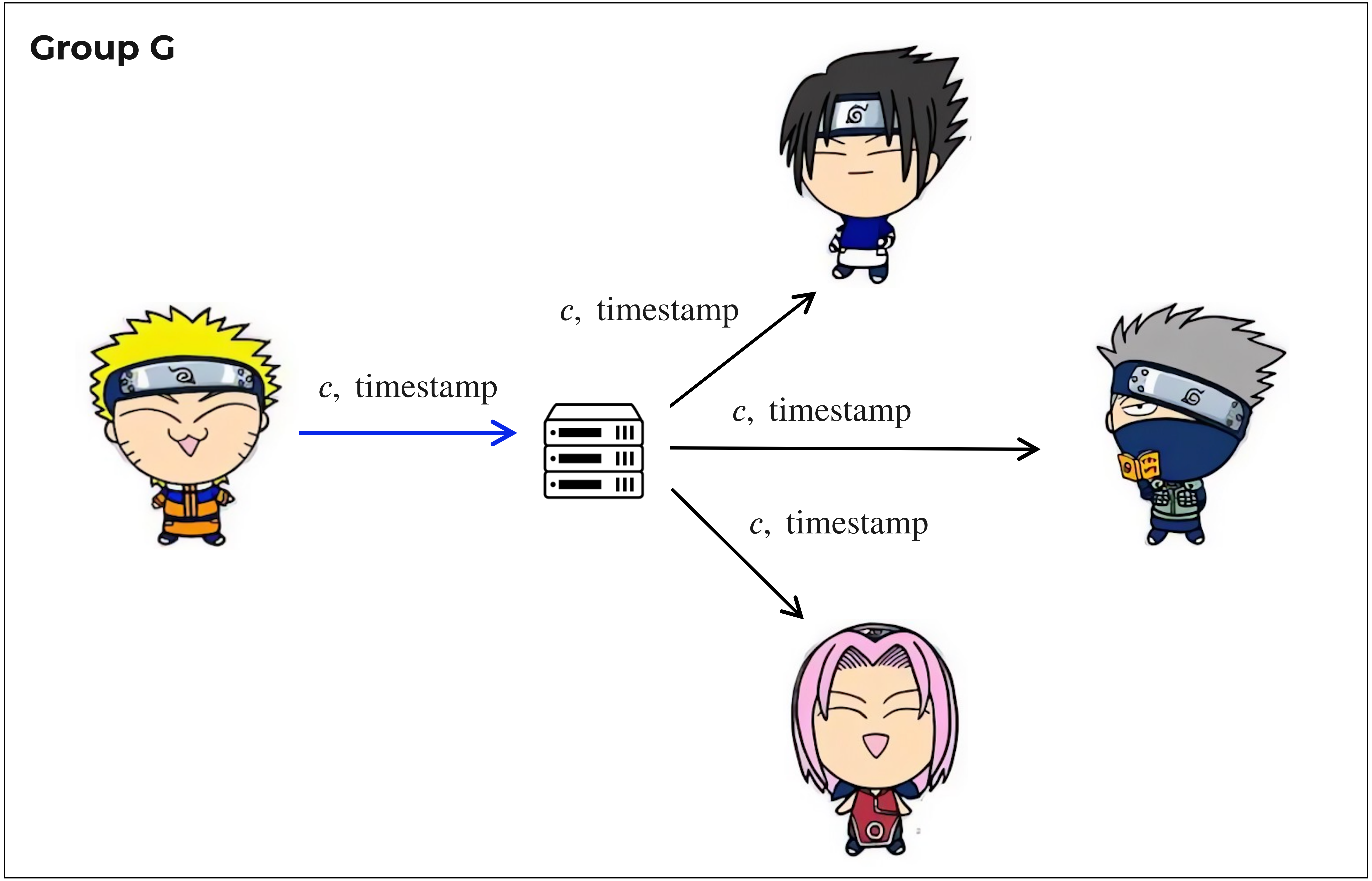
SIGN
group_key_id

Outsider Replay Attack in Session

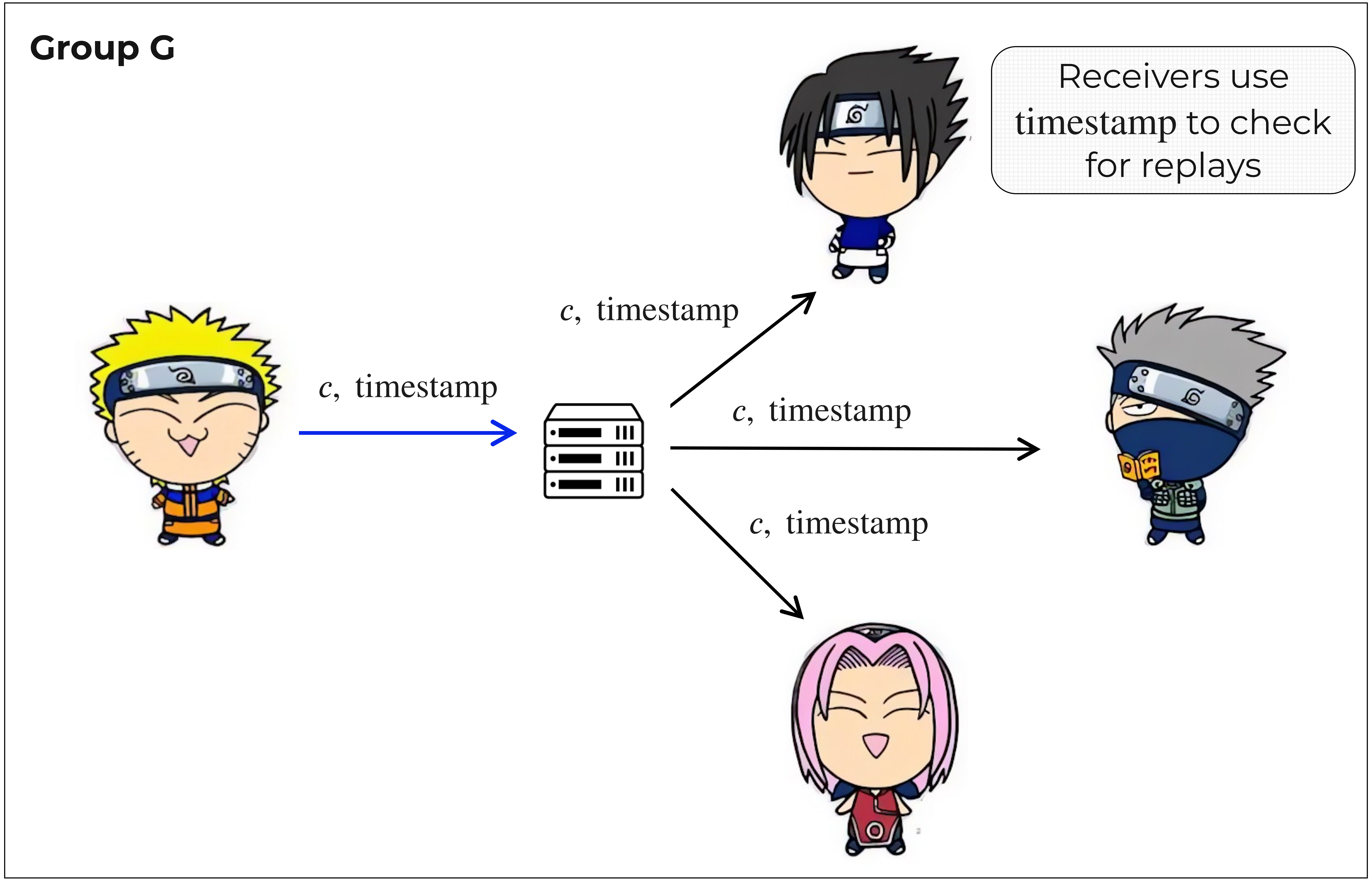
Outsider Replay Attack in Session



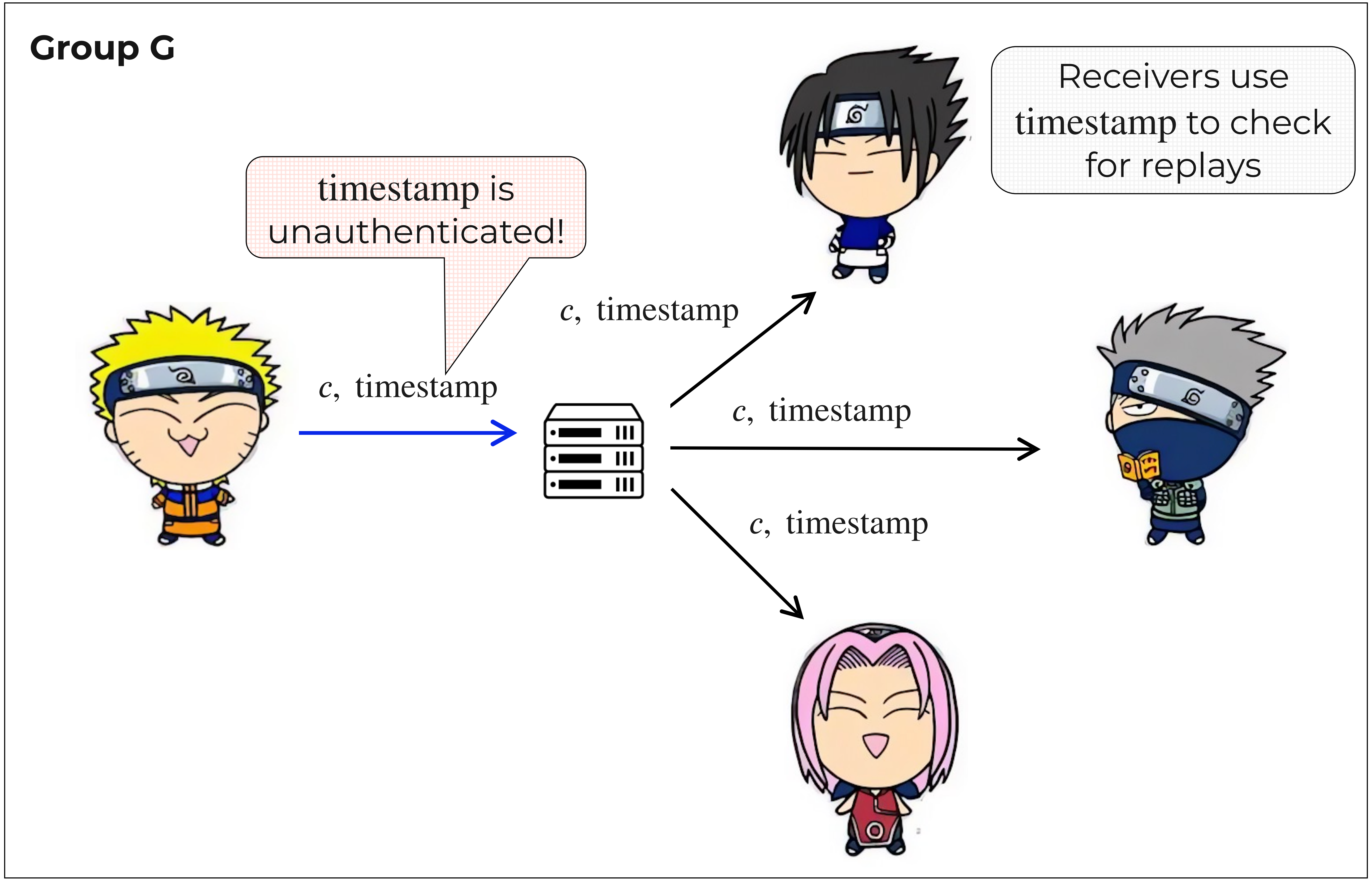
Outsider Replay Attack in Session



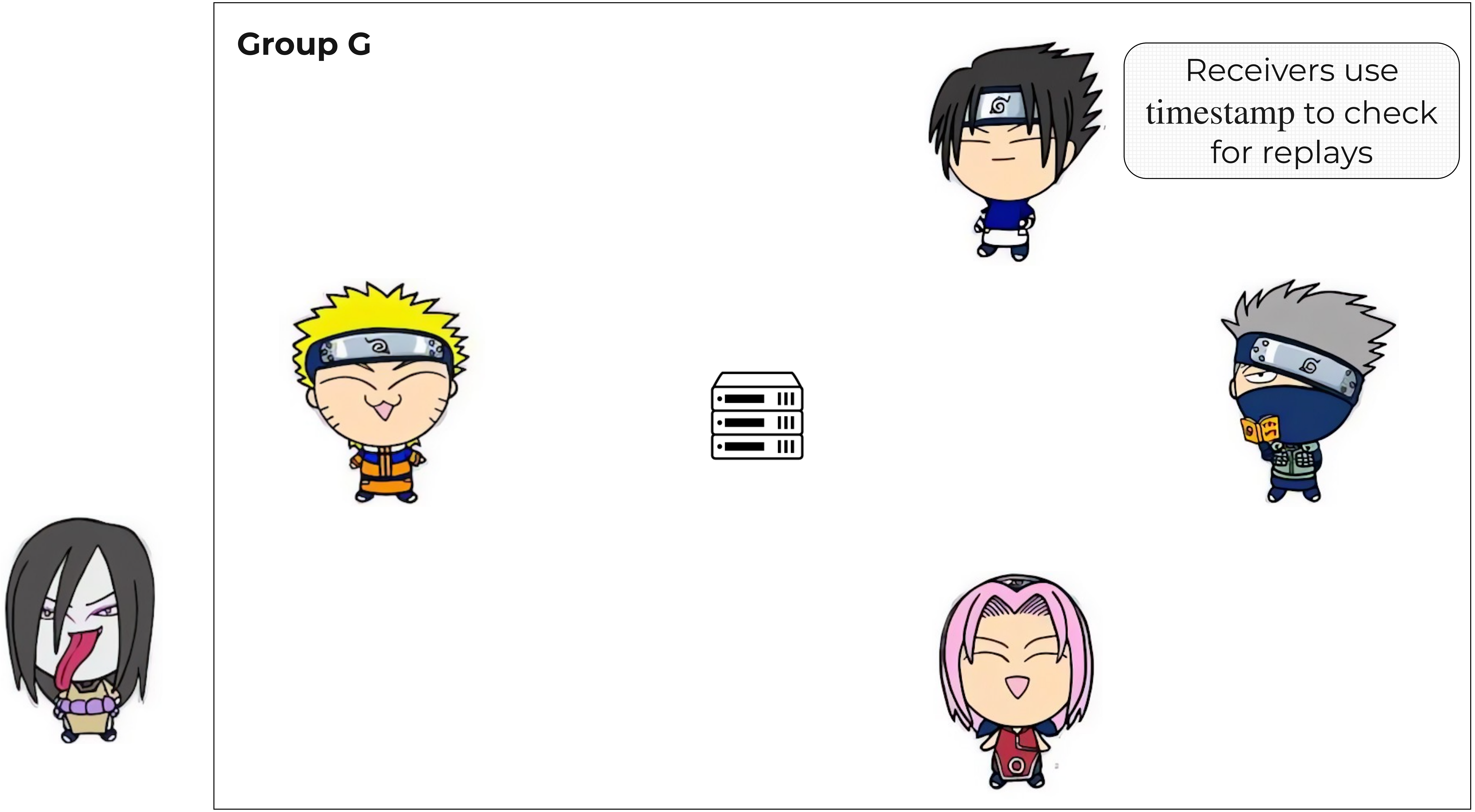
Outsider Replay Attack in Session



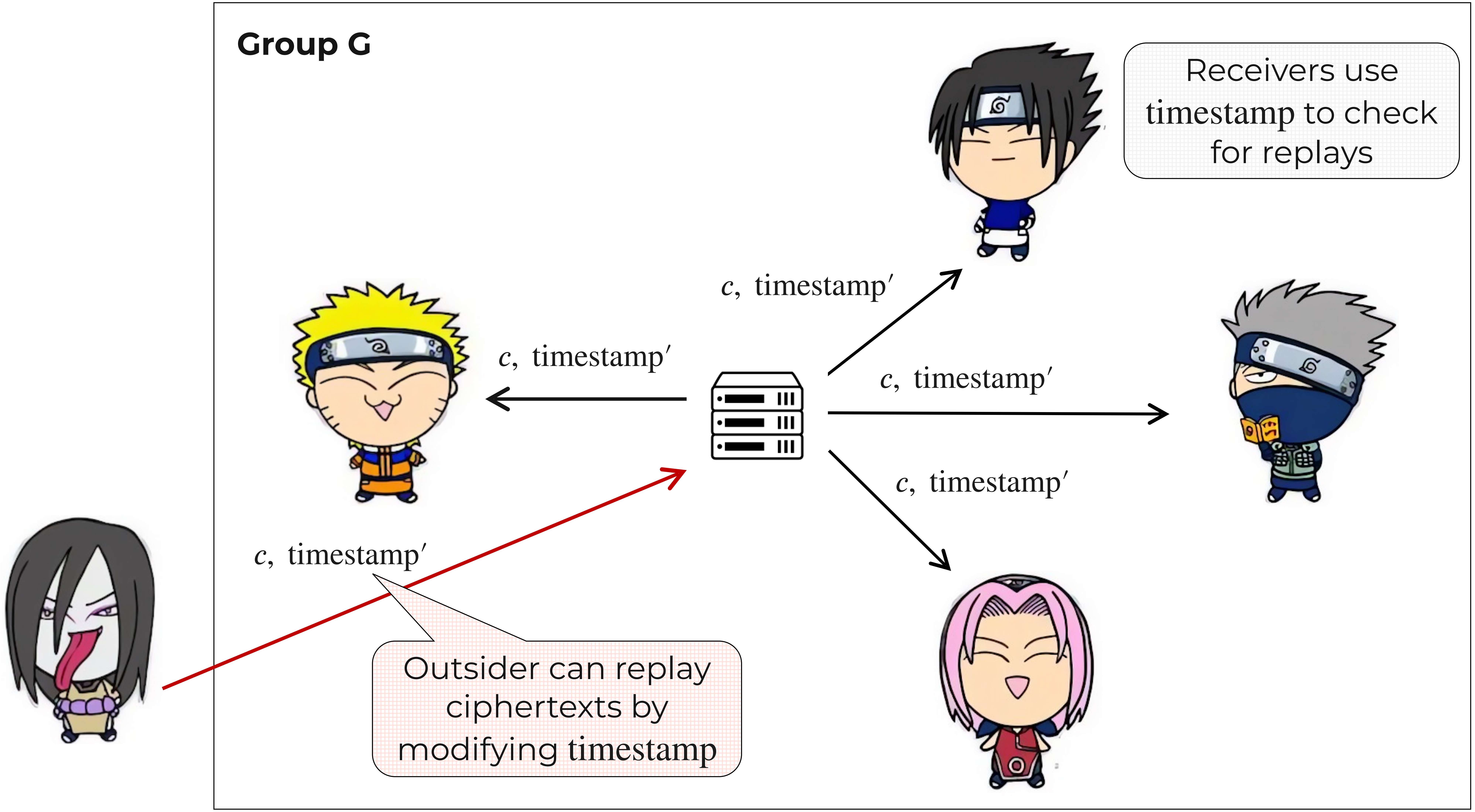
Outsider Replay Attack in Session



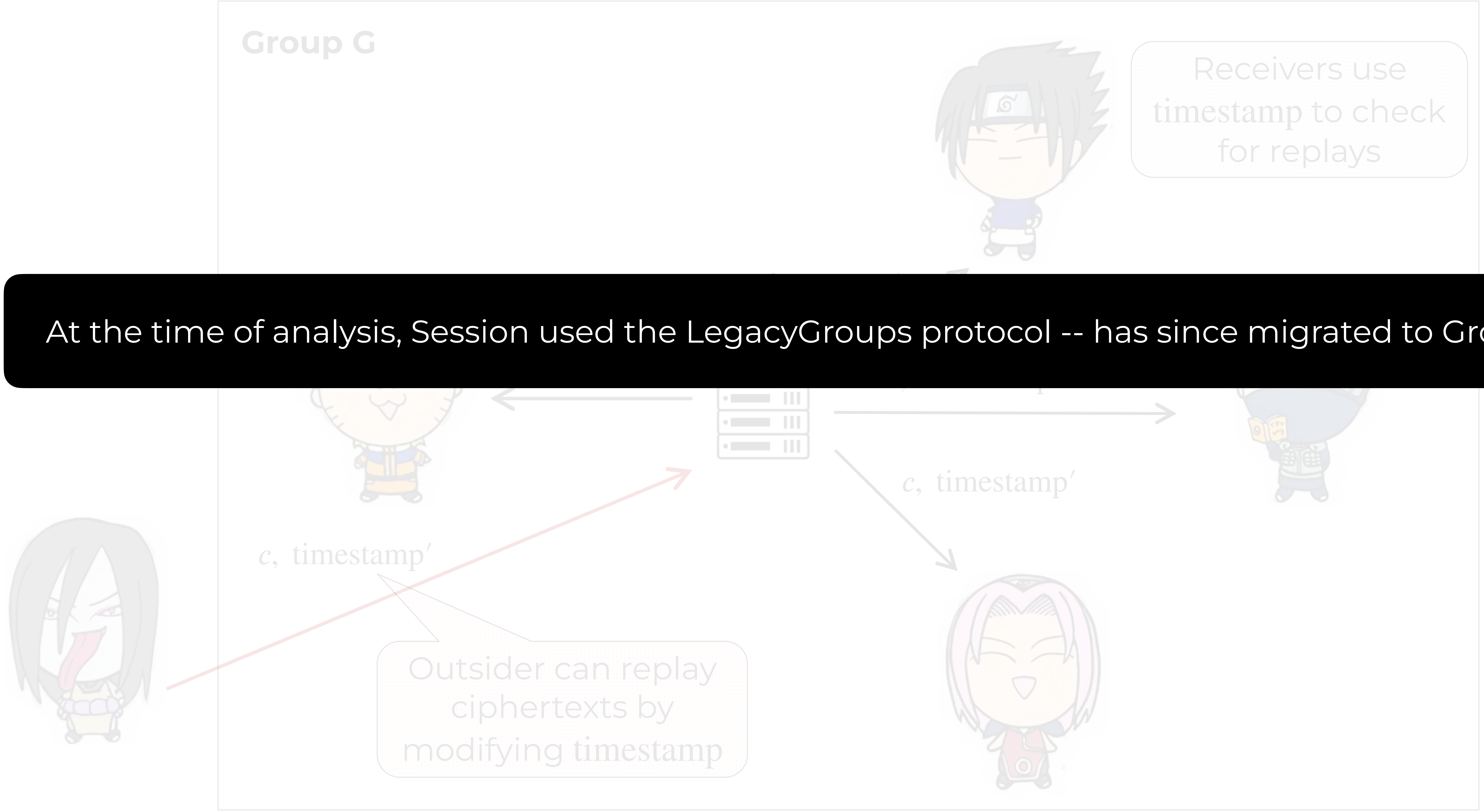
Outsider Replay Attack in Session



Outsider Replay Attack in Session



Outsider Replay Attack in Session



At the time of analysis, Session used the LegacyGroups protocol -- has since migrated to GroupsV2

Takeaways

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- Message and sender authenticity are important in group messaging settings (sometimes even more than privacy)

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Details in the paper! eprint.iacr.org/2025/554