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Applied Cryptography
Spring Semester 2023

Lectures 33 and 34
Transport Layer Security

Felix Günther

Applied Cryptography Group

https://appliedcrypto.ethz.ch/

Overview of this lecture

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Part I Introduction to TLS

- The Transport Layer Security (TLS) protocol: history, design, and flaws.
- Why TLS 1.3 and what does it change?

Part II TLS 1.3 Design & Security Analyses

- TLS 1.3: the technical details
- Understanding the security of TLS 1.3: some research bits

Part I

Introduction to TLS

Transport Layer Security (TLS)

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TLS allows client/server applications to communicate over the Internet in a way that is designed to prevent eavesdropping, tampering, and message forgery.

TLS 1.3 [RFC 8446]

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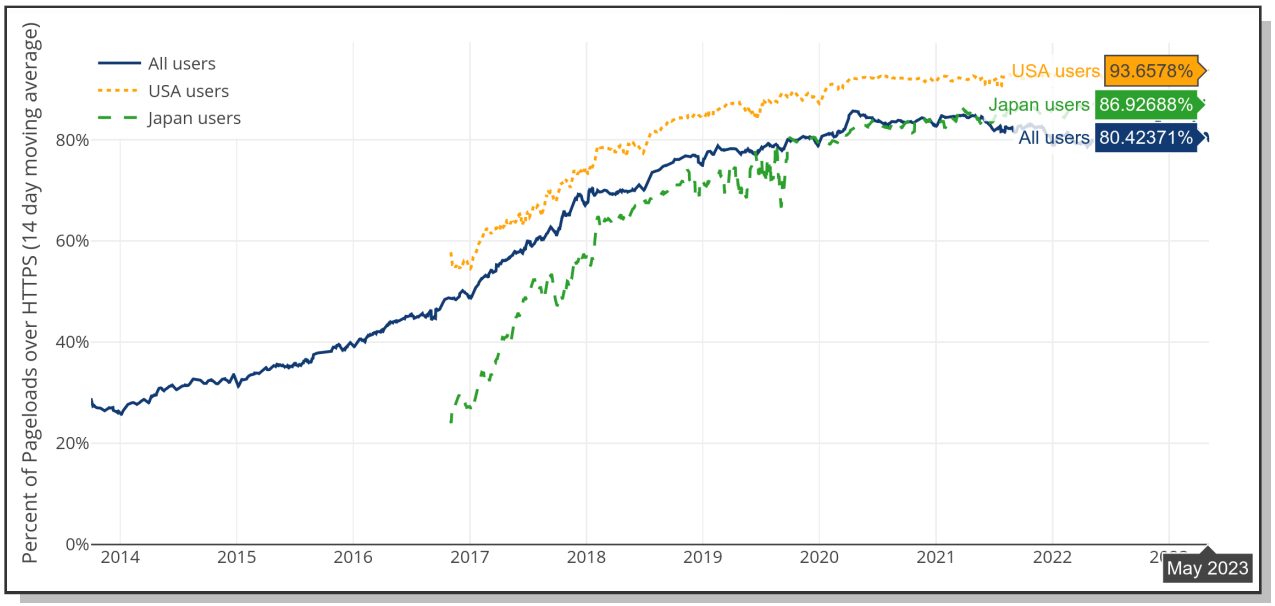
HTTPS page loads

- 80–93% Firefox (May 23)
  (Telemetry)



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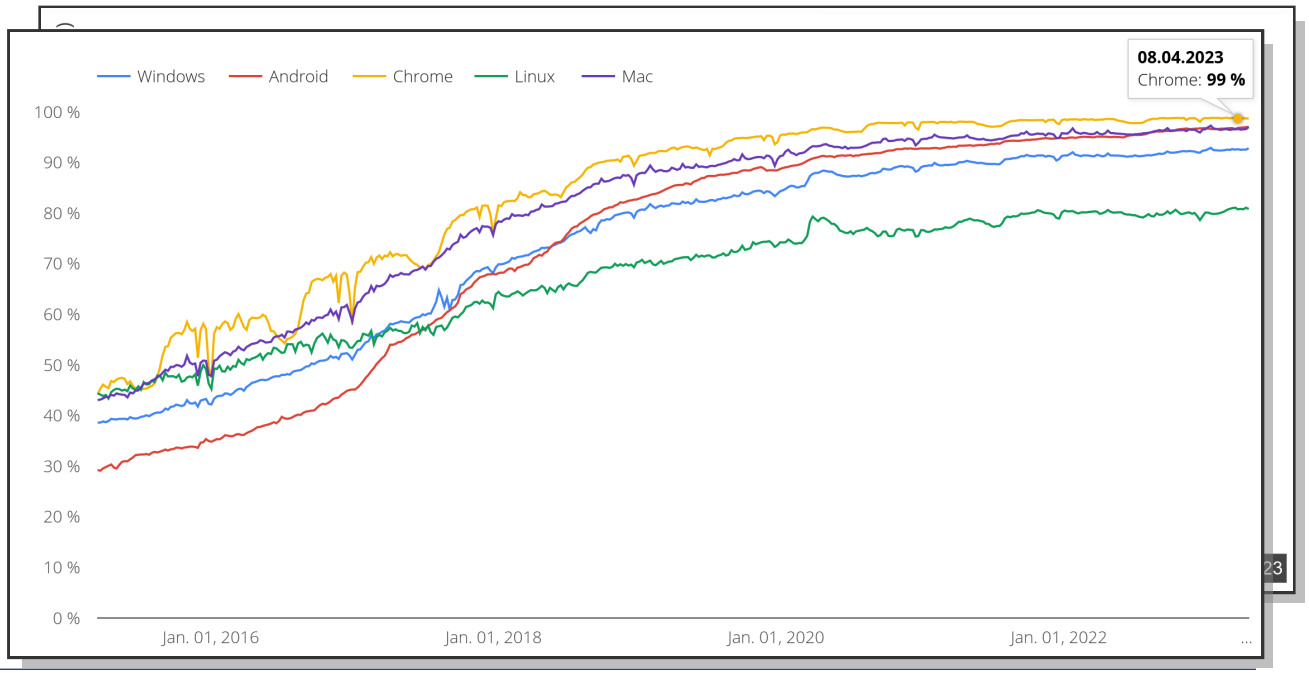

Transport Layer Security (TLS)

The SSL/TLS history . . .

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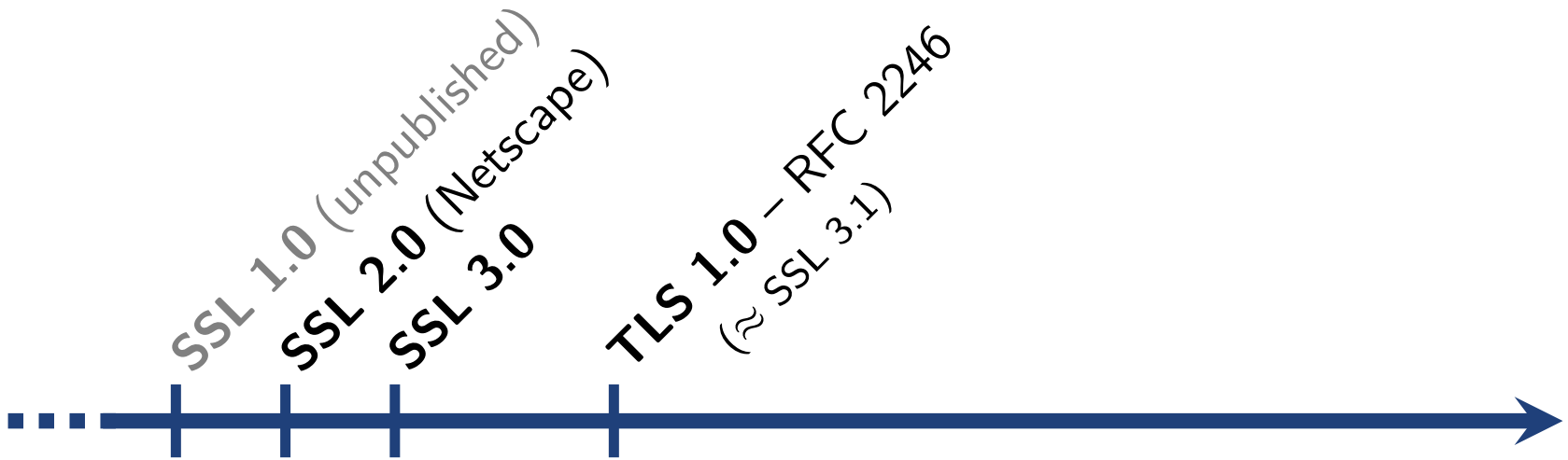

adopted by IETF TLS working group
main editor: Eric Rescorla

Transport Layer Security (TLS)

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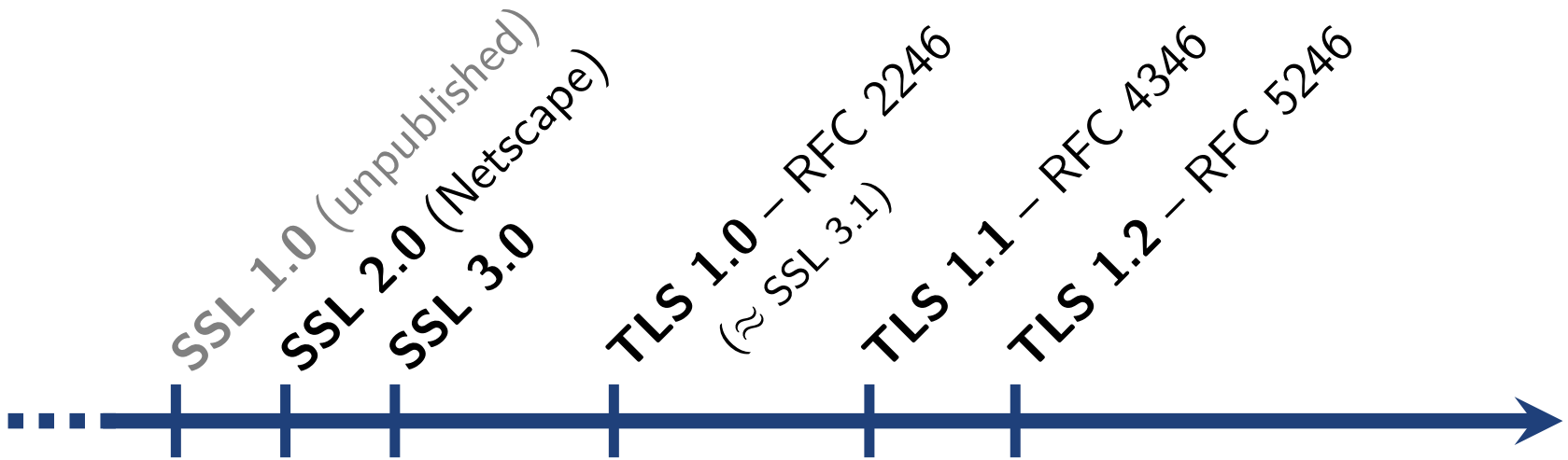

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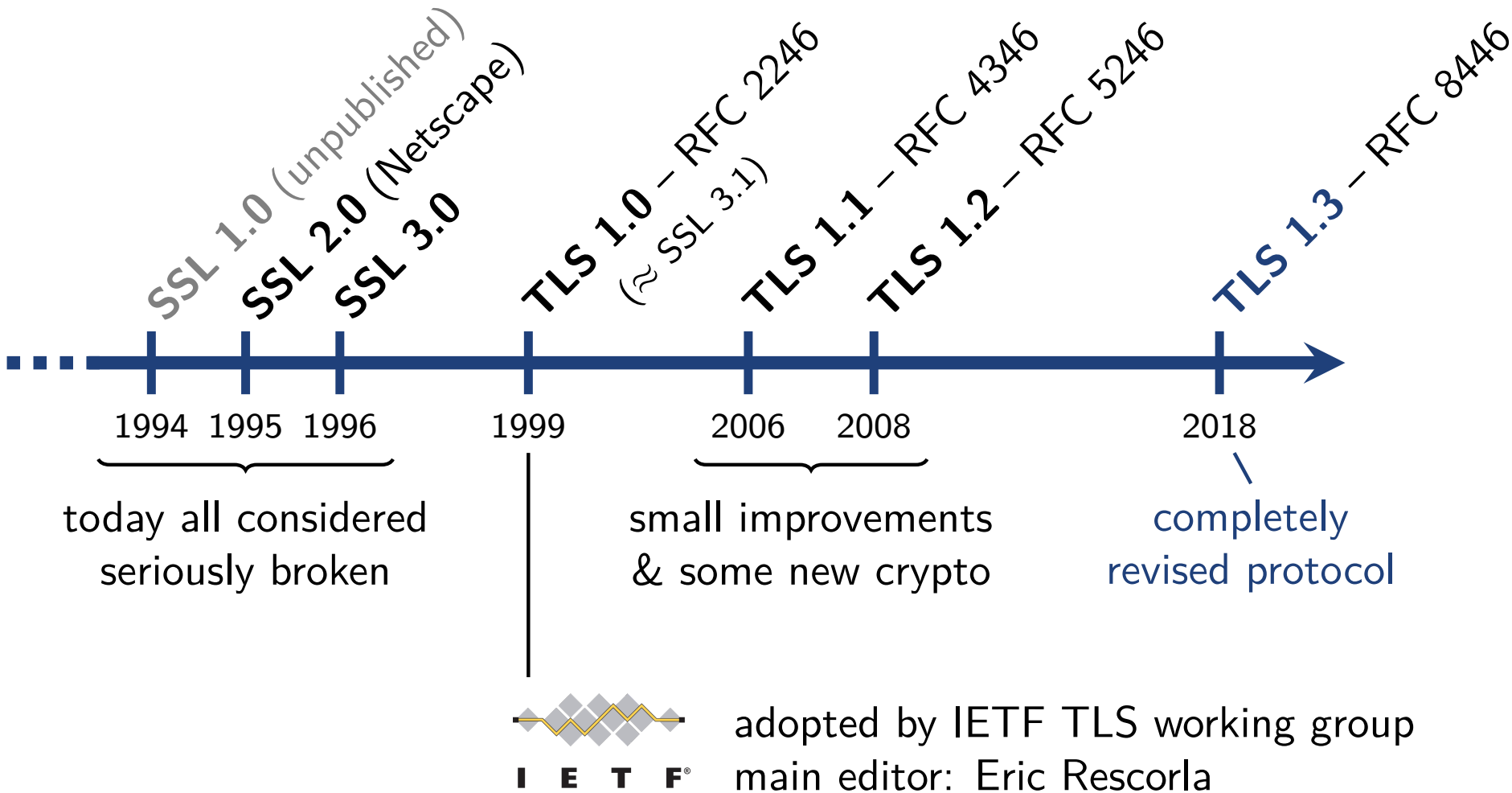

The TLS Protocol

High-level Goals

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"The primary goal of TLS is to provide a **secure channel between two peers**"

TLS 1.3 [RFC 8446]

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- **Authentication**
  - **server** side of the channel is **always authenticated**
  - **client** side is **optionally authenticated**
  - via **asymmetric crypto** (e.g., signatures) or a symmetric **pre-shared key**

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  - **data** sent over the channel is **only visible to the endpoints**
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- **Integrity**
  - **data** sent over the channel **cannot be modified** without detection
- security in the face of **attacker who has complete control of the network**
- only requirement from underlying transport: reliable, in-order data stream

Transport Layer Security (TLS)

Main Components (overly simplified)

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Client

Server

Transport Layer Security (TLS)

Main Components (overly simplified)

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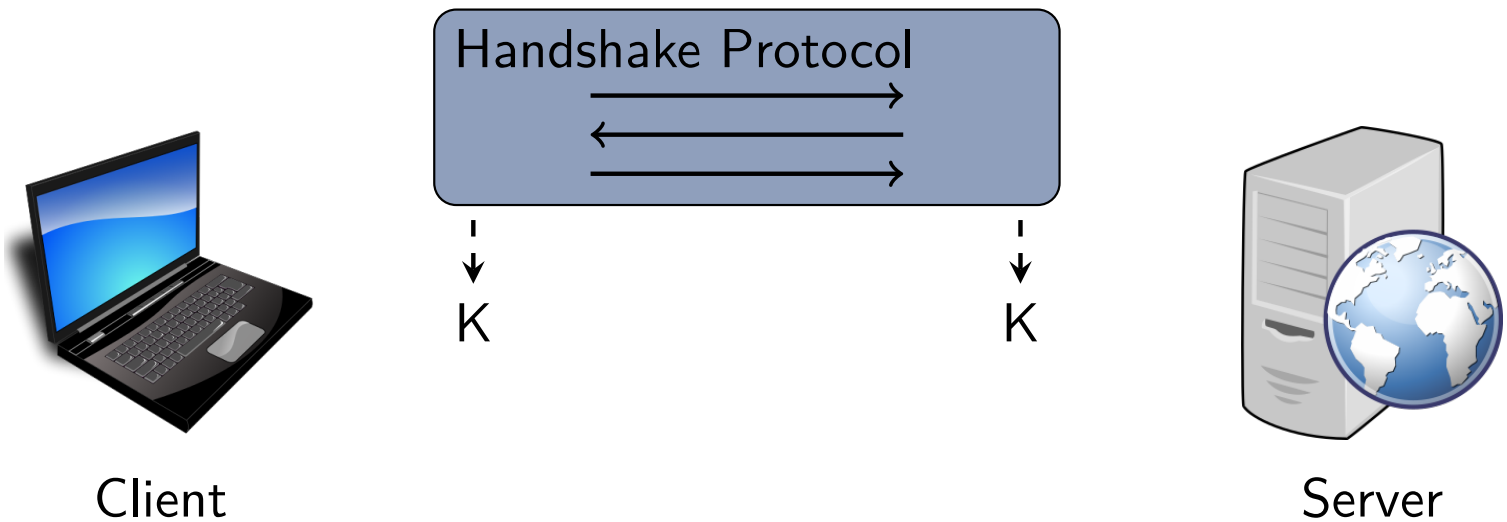
Handshake Protocol:

- negotiate security parameters ("cipher suite")
- authenticate peers
- establish key material for data protection



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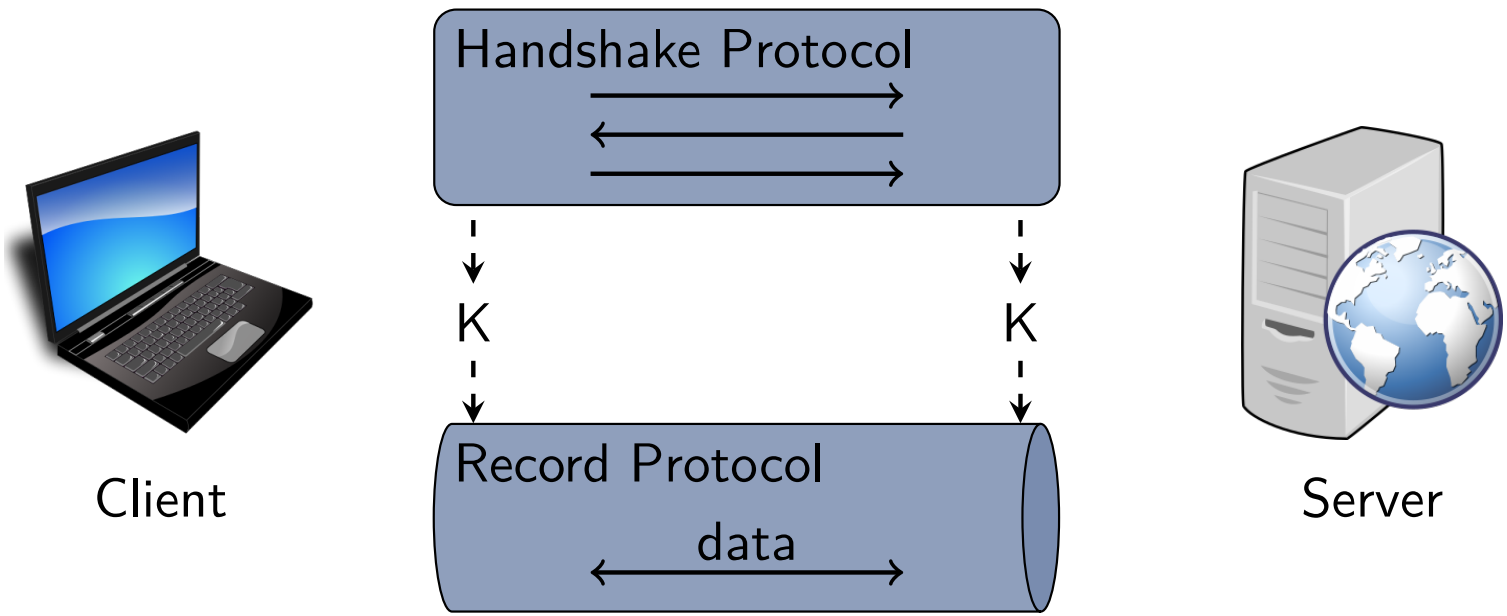

Record Protocol:

- protect data using key material from handshake
- ensuring confidentiality and integrity

The TLS Protocol

Architecture within Network Stack

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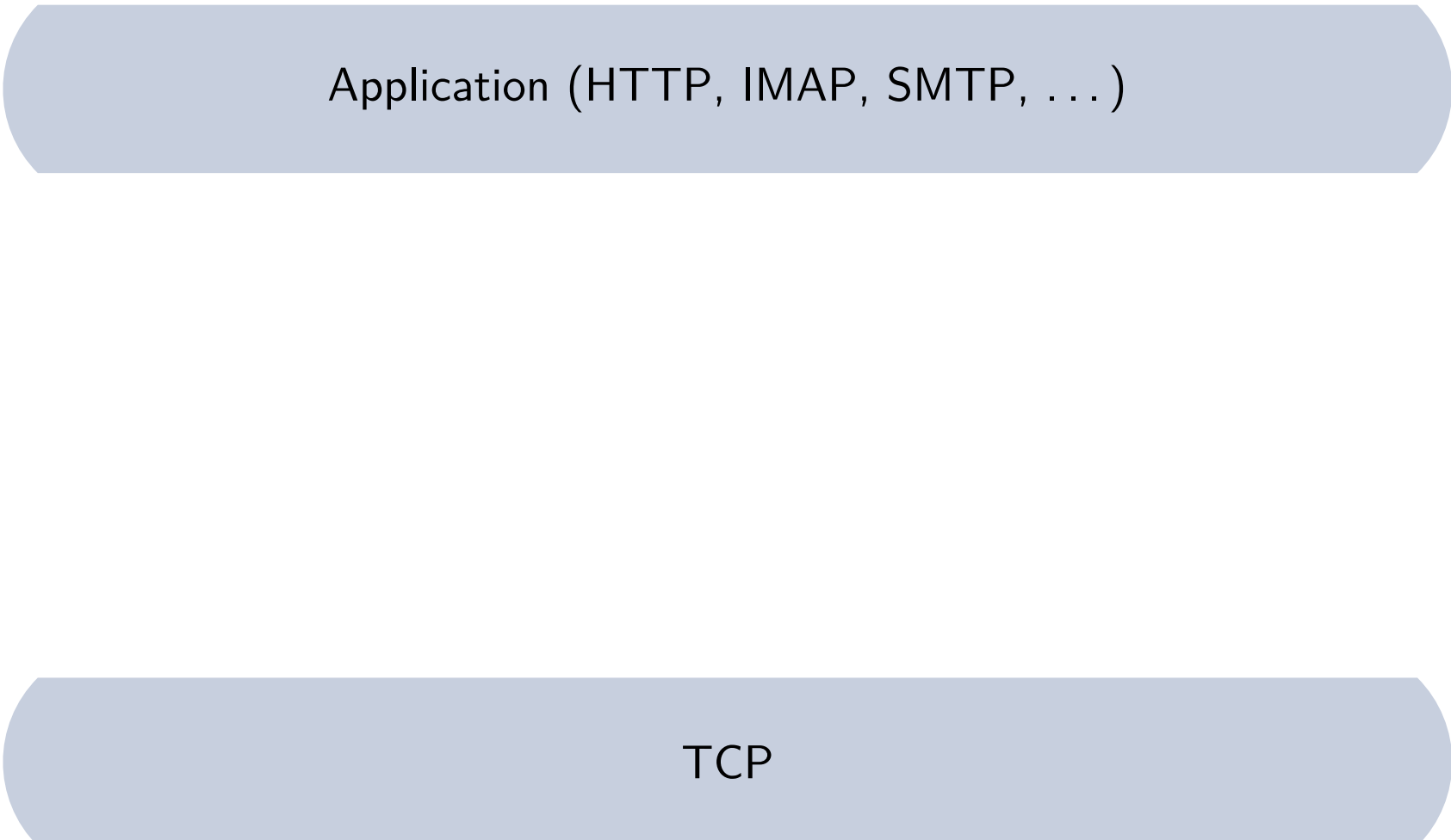

The TLS Protocol

Architecture within Network Stack

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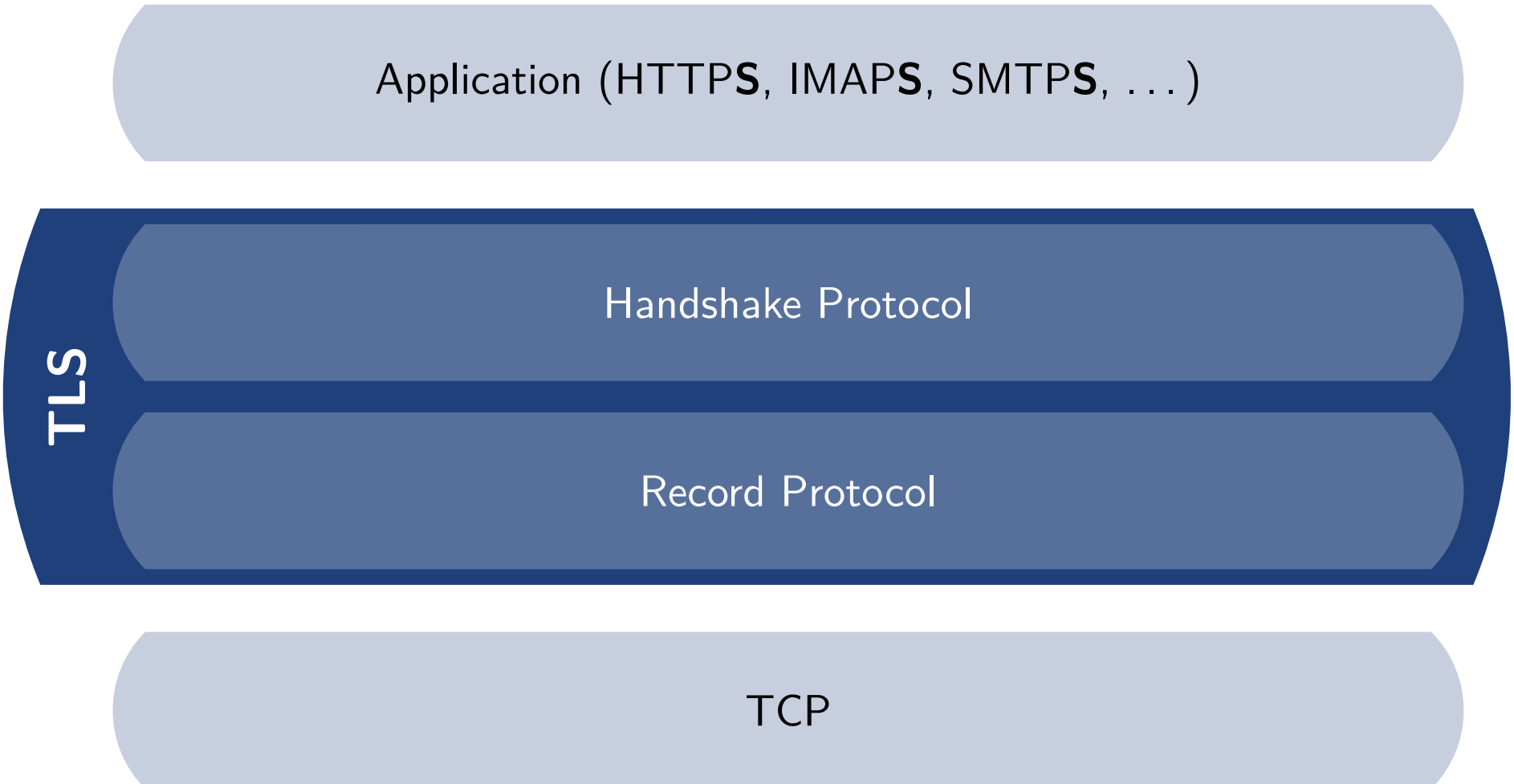

The TLS Protocol

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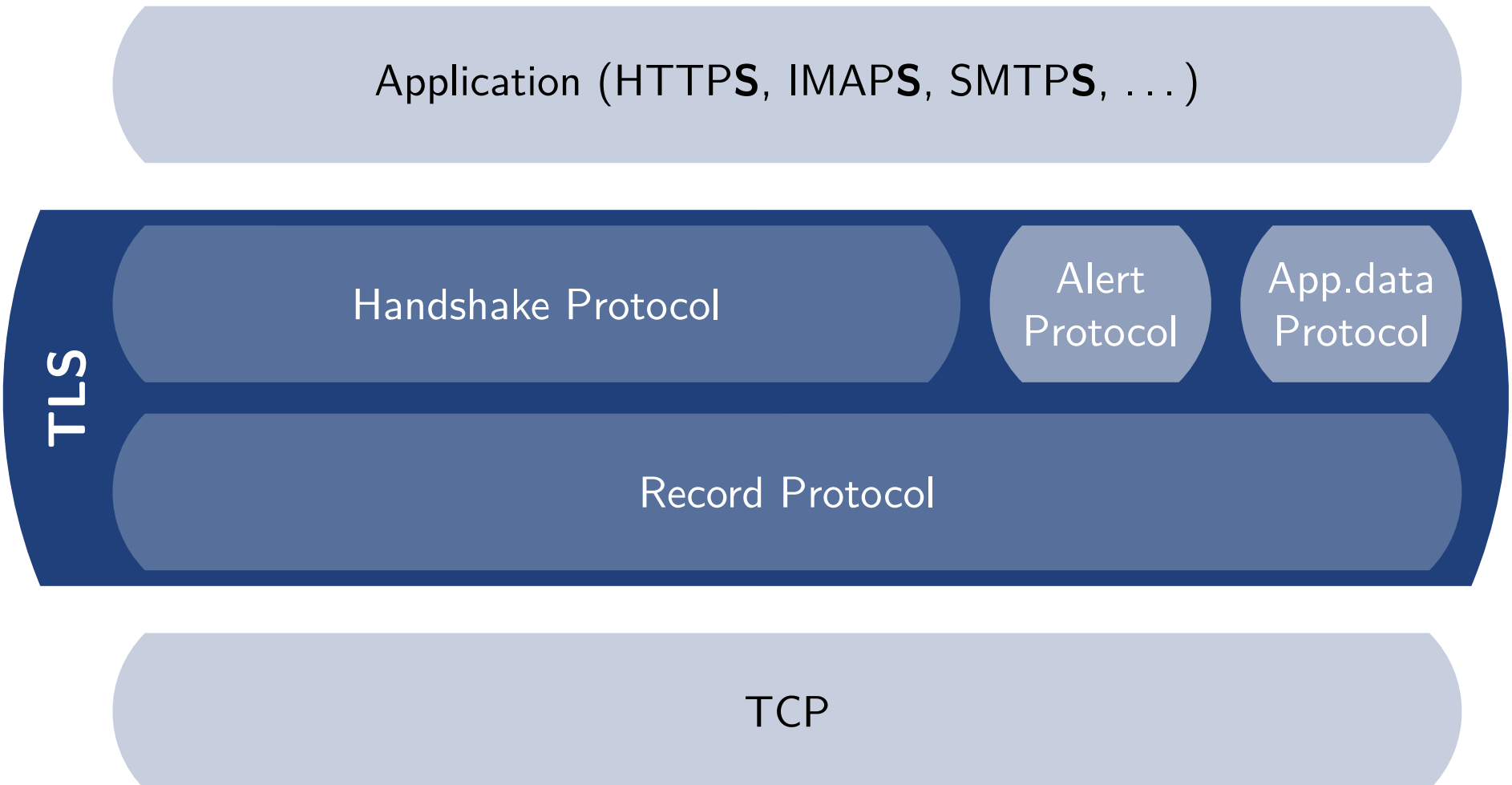

The TLS Protocol

Cryptographic Components

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- TLS is a **"self-negotiating"** protocol
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- format (up to TLS 1.2): `TLS_KEX_AUT_WITH_CIP_MAC`

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Key Exchange

`RSA` `DHE` `ECDHE` `PSK` ...

The TLS Protocol

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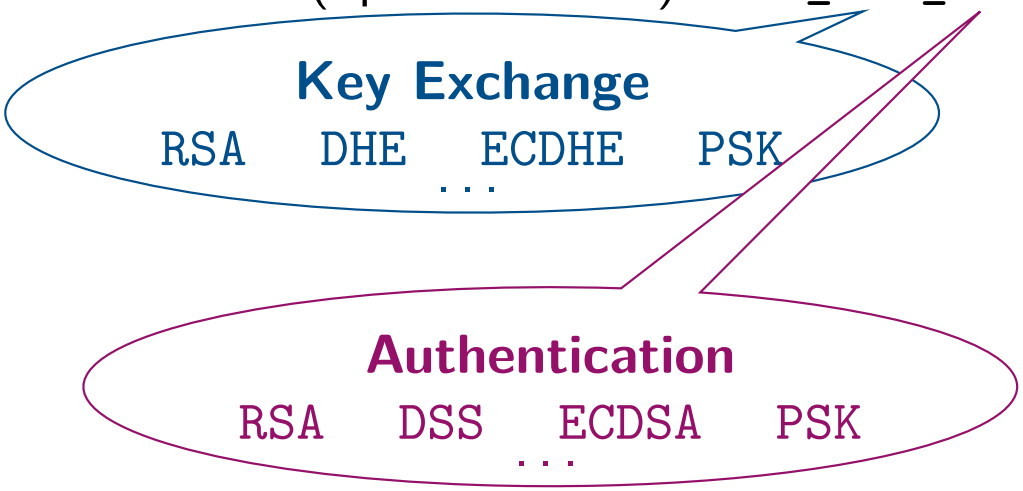

The TLS Protocol

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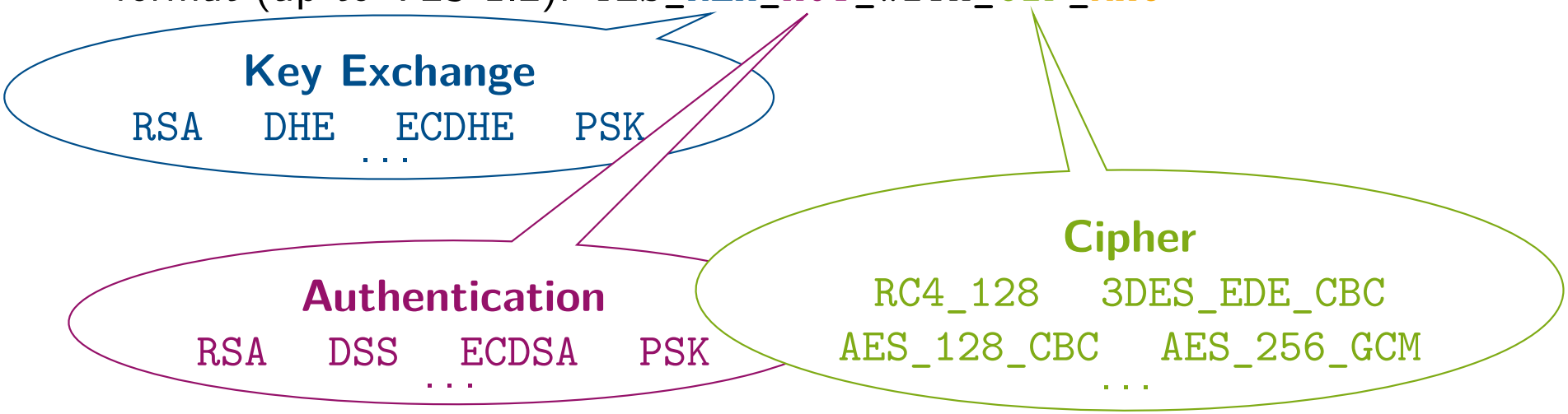

The TLS Protocol

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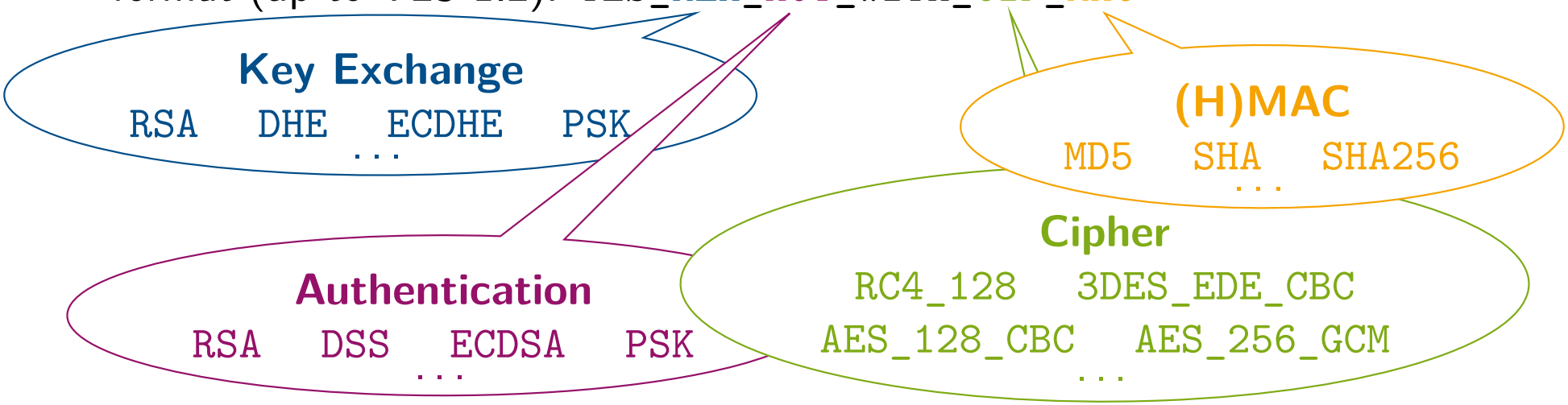

The TLS Protocol

TLS 1.2 Handshake Protocol Structure

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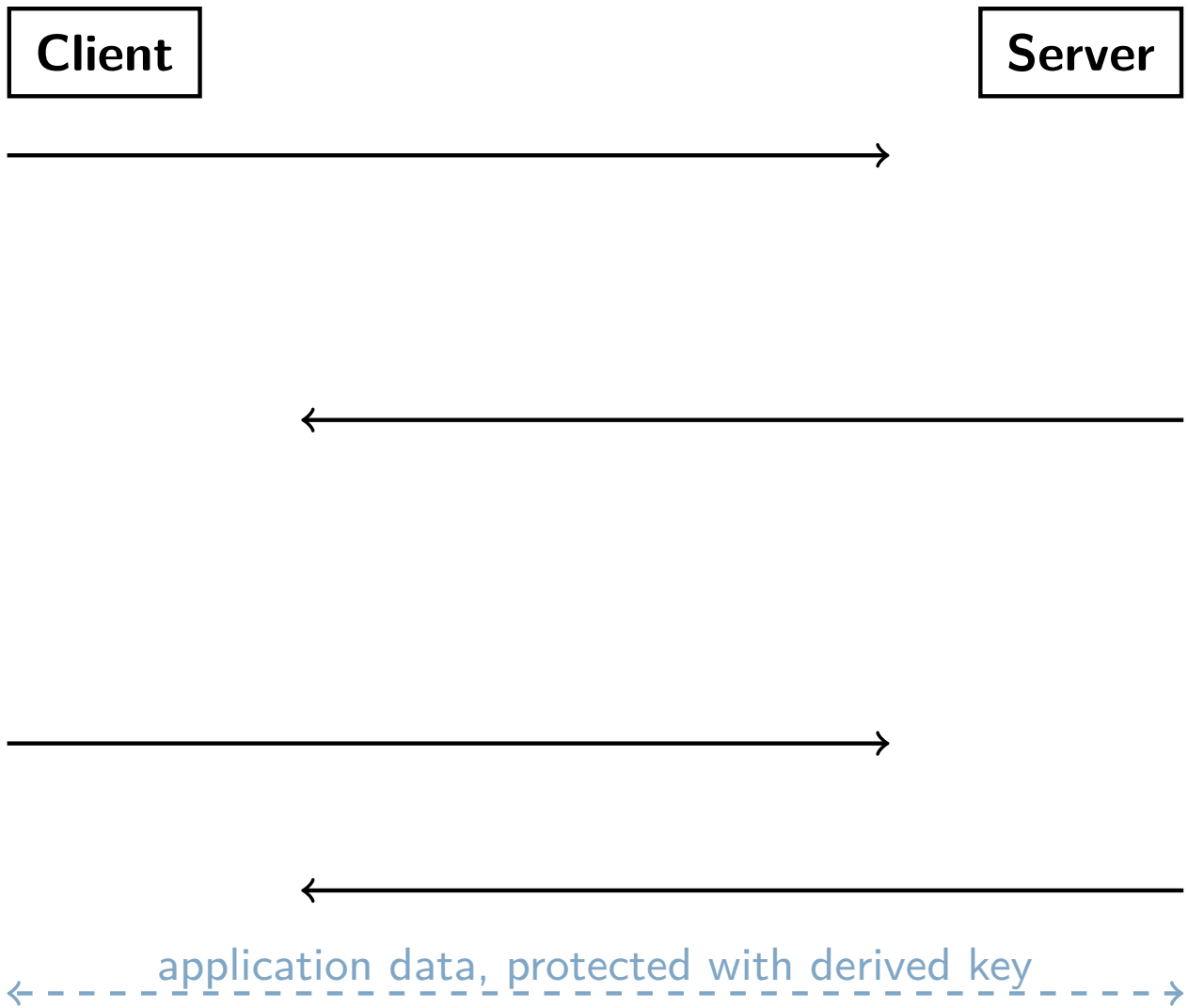

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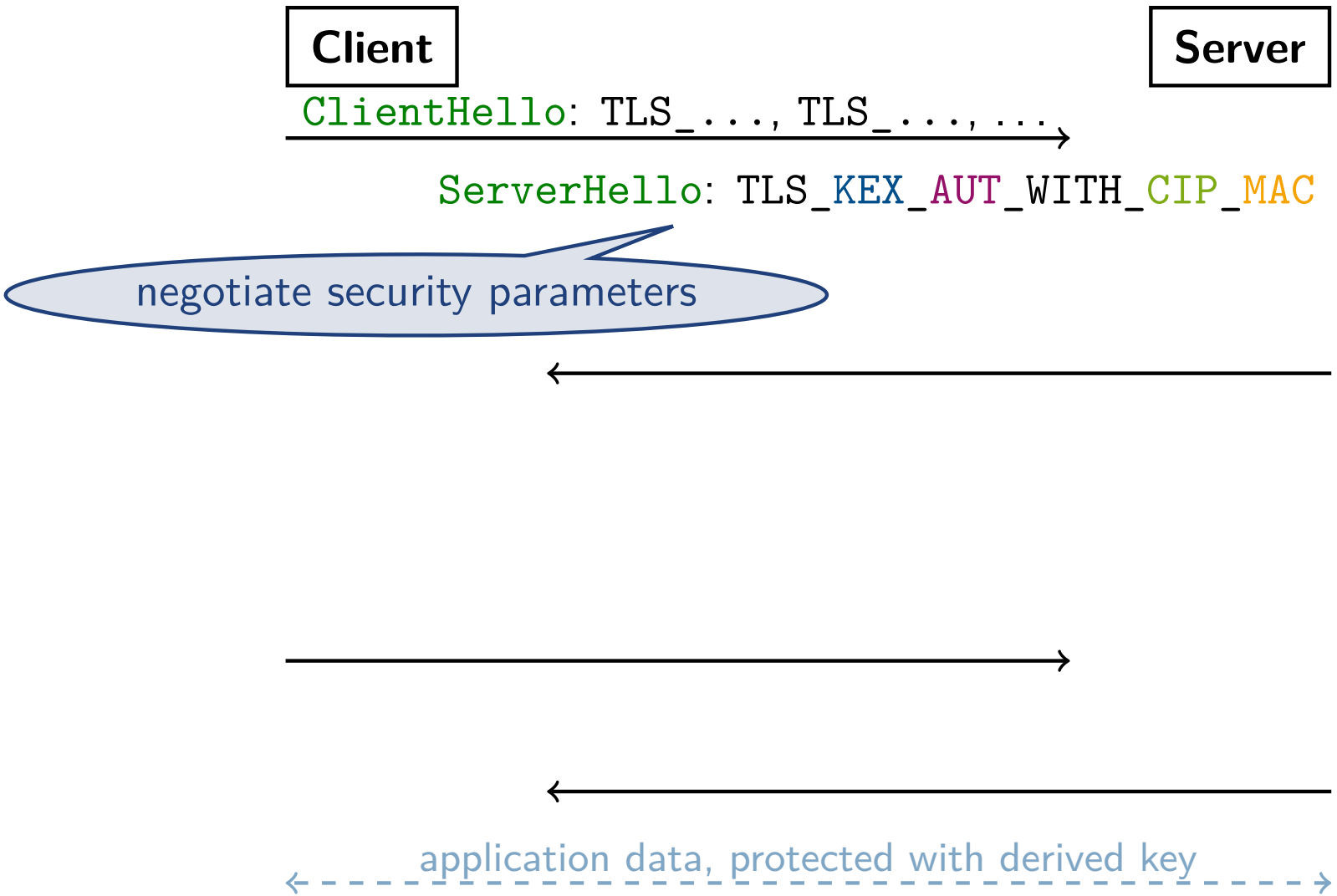

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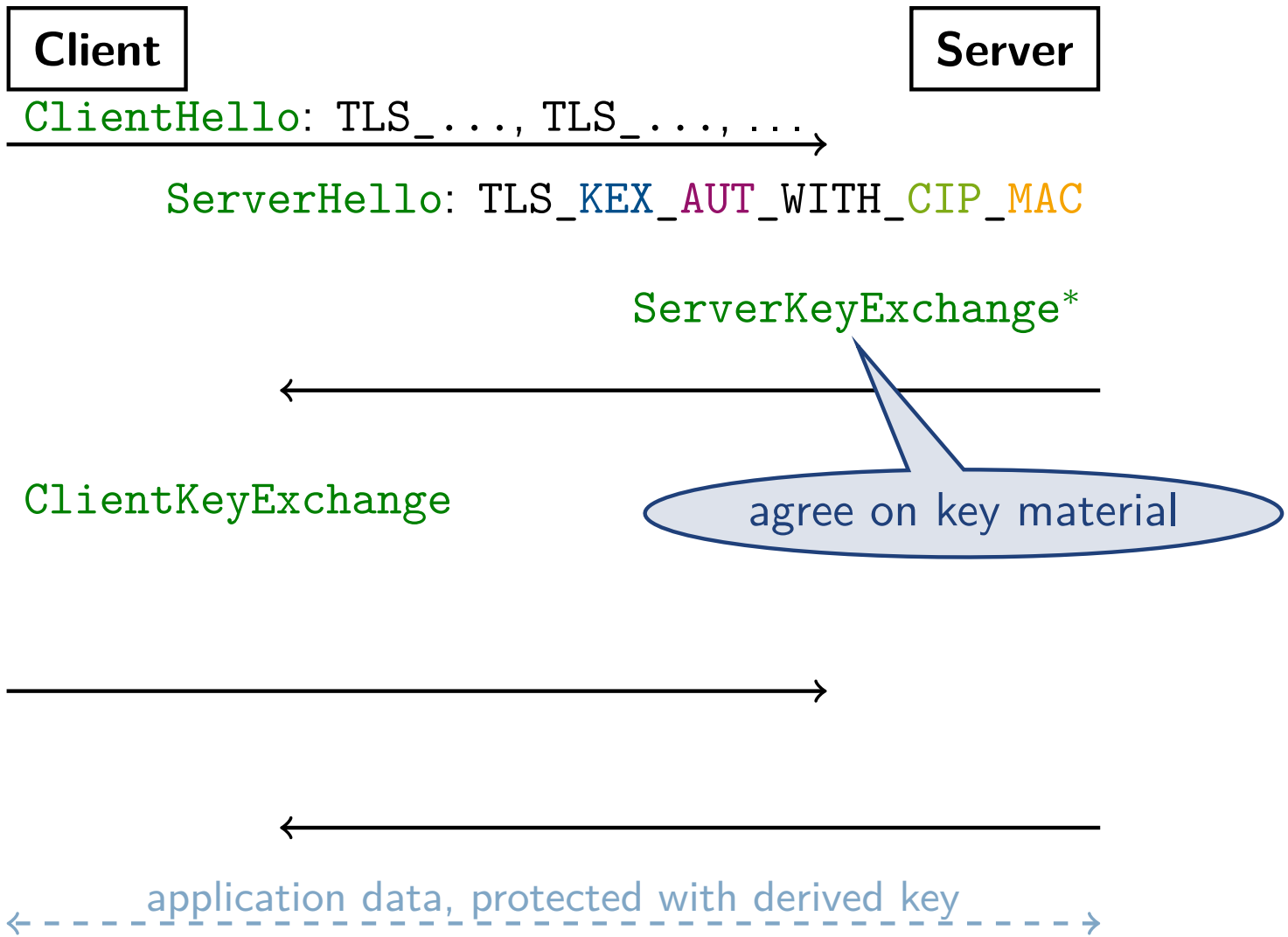

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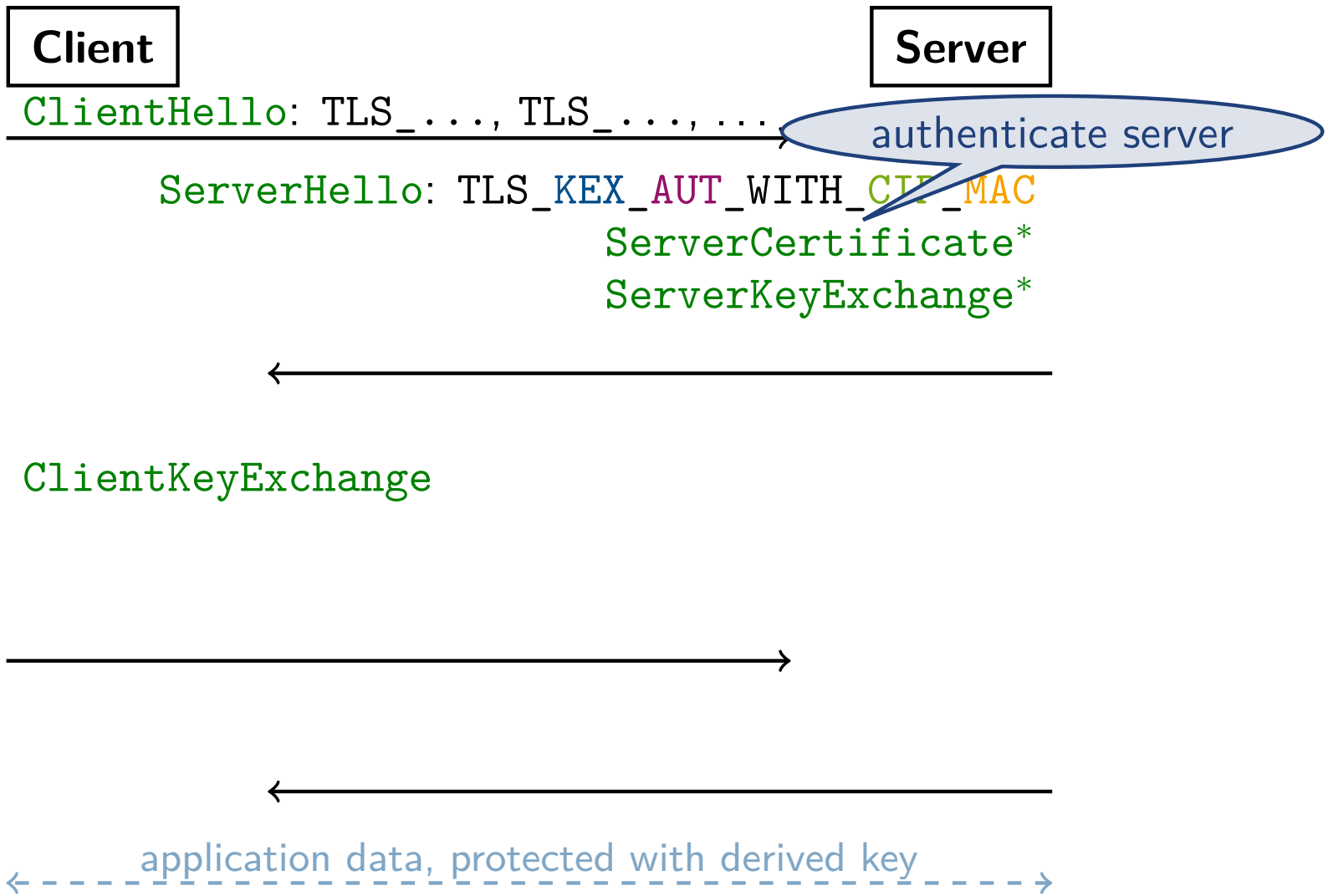

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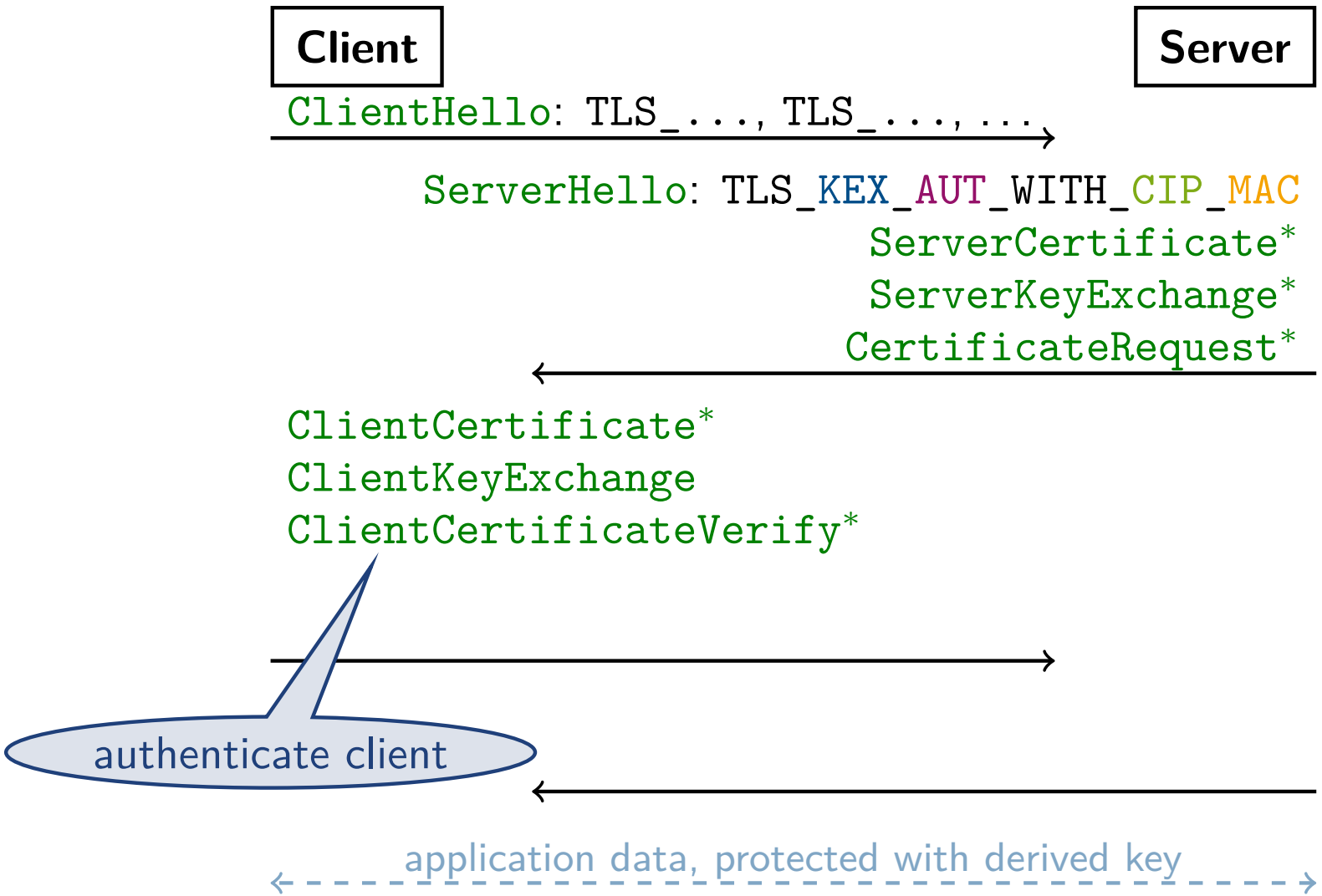

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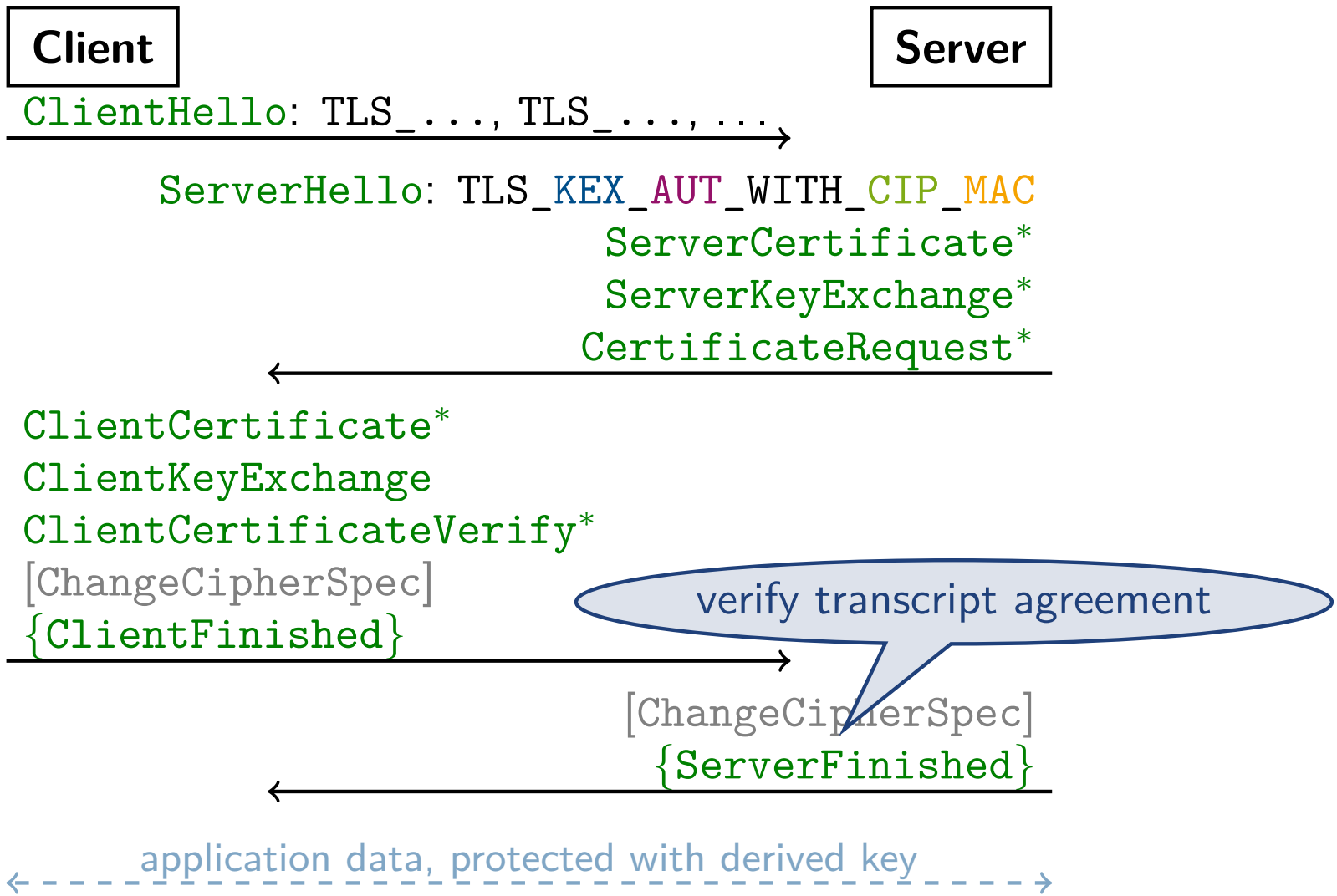

The TLS Protocol

TLS 1.2 Example: TLS_RSA_WITH_AES_128_CBC_SHA — Handshake

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(simplified)

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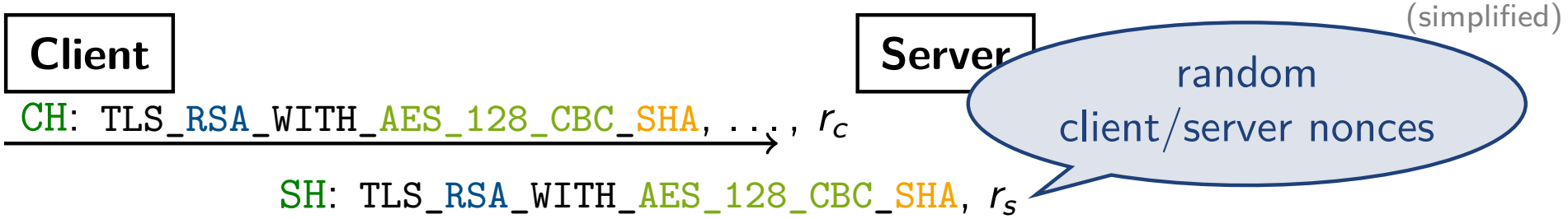

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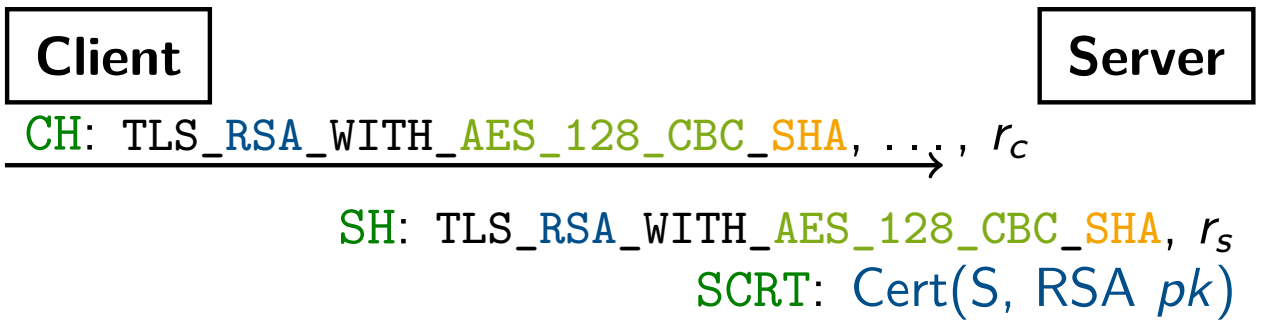

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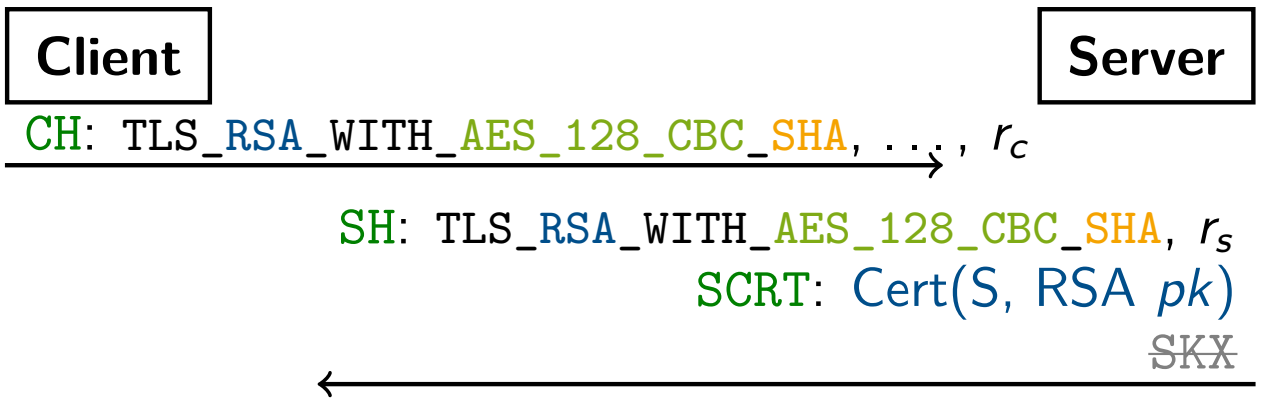

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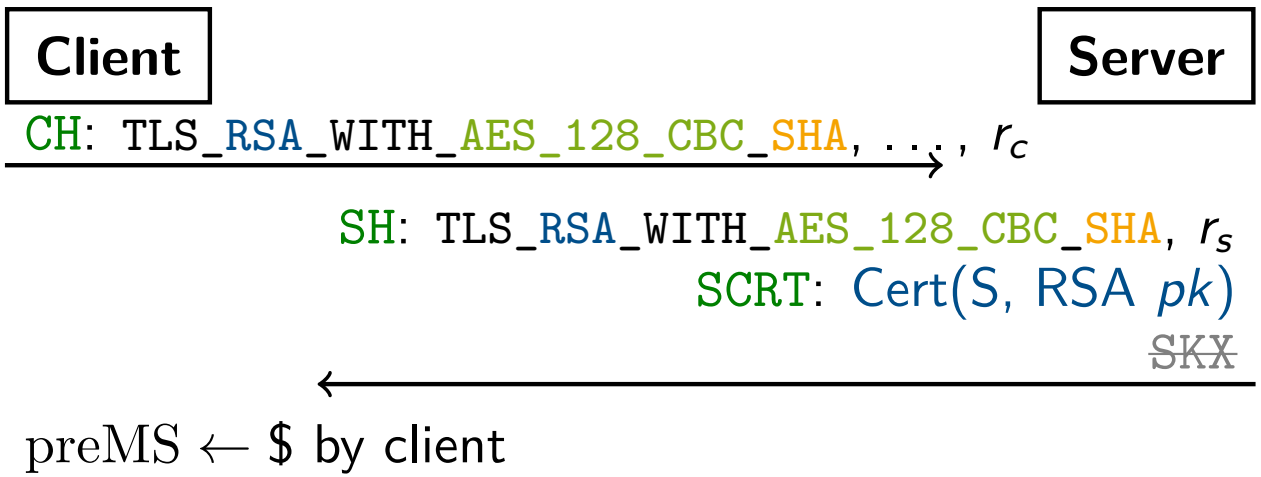

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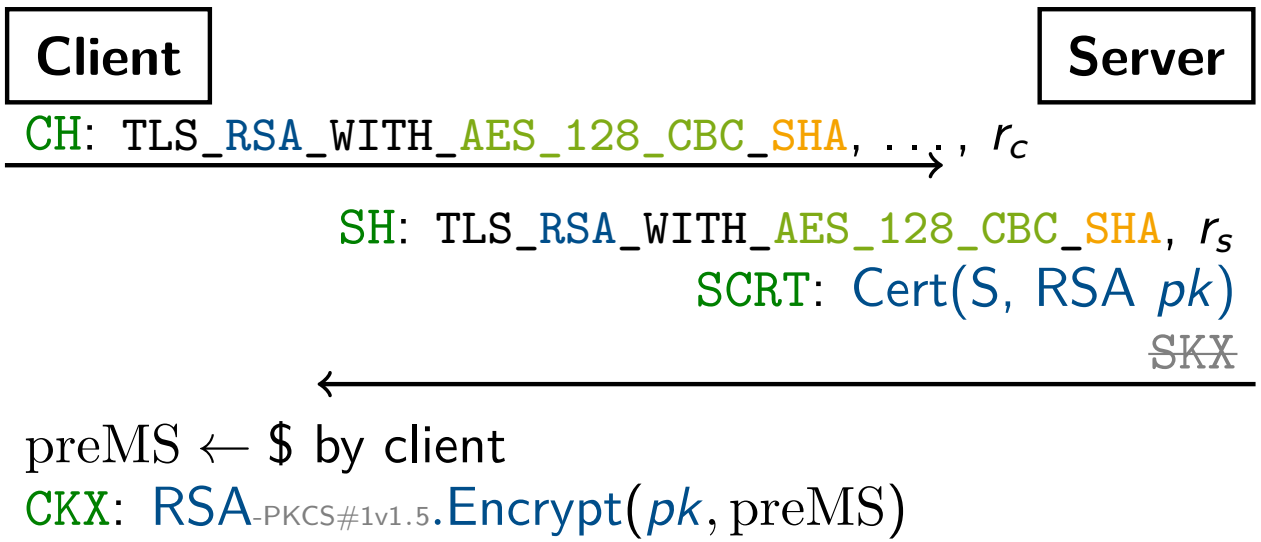

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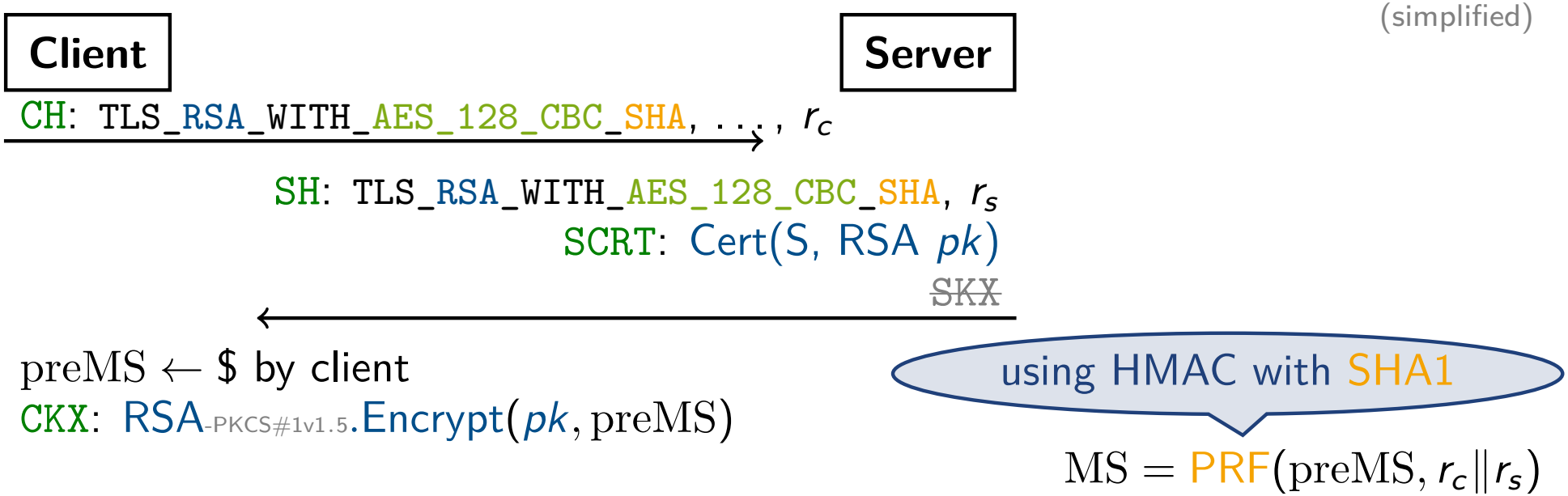

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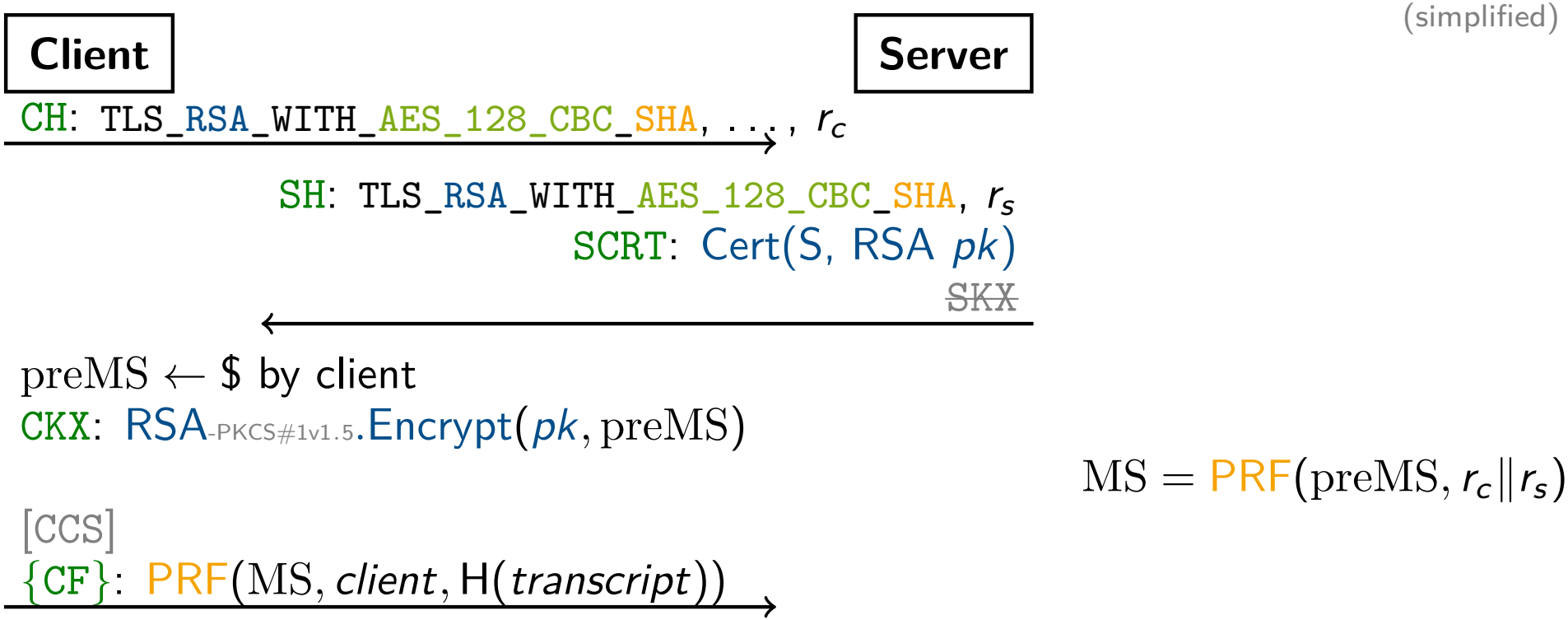

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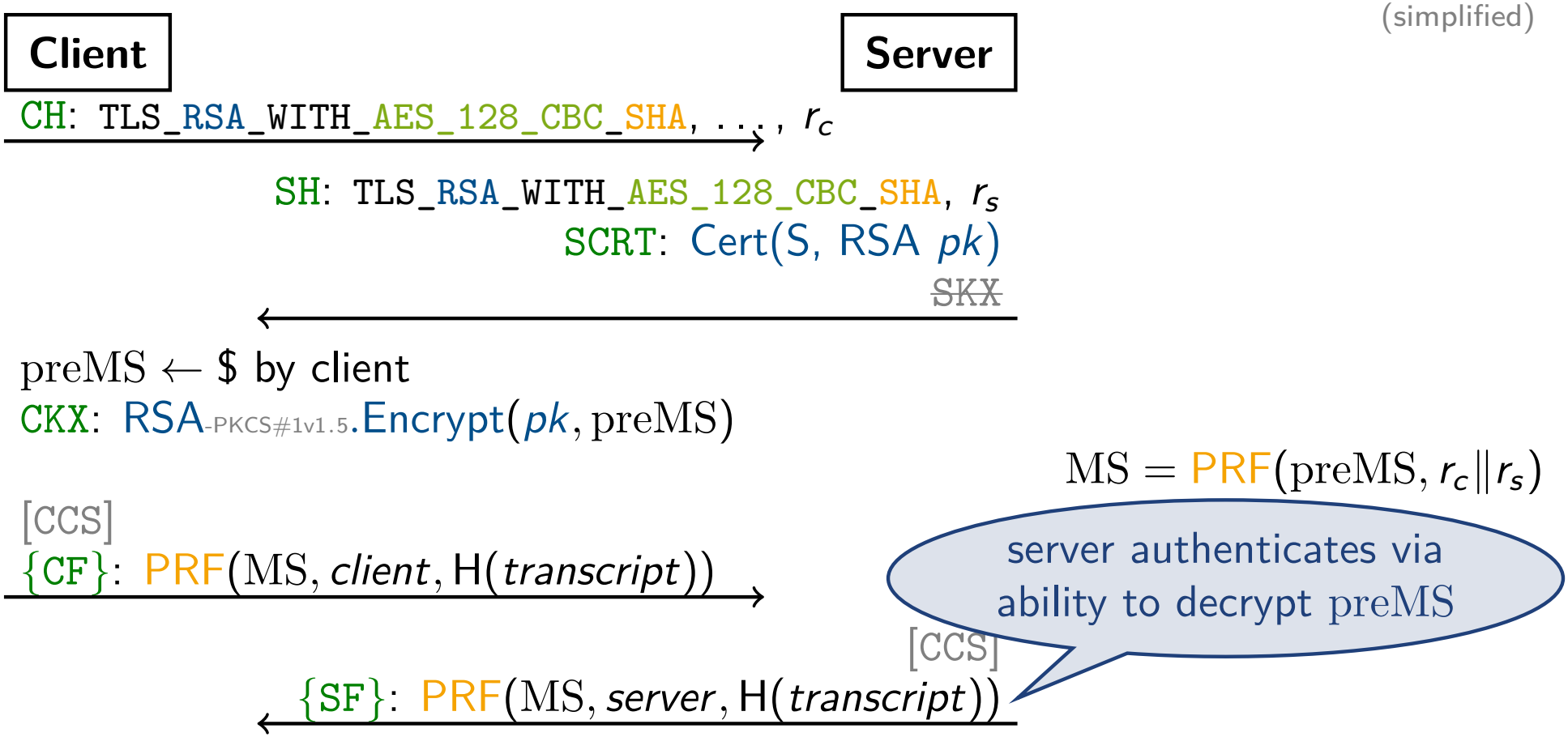

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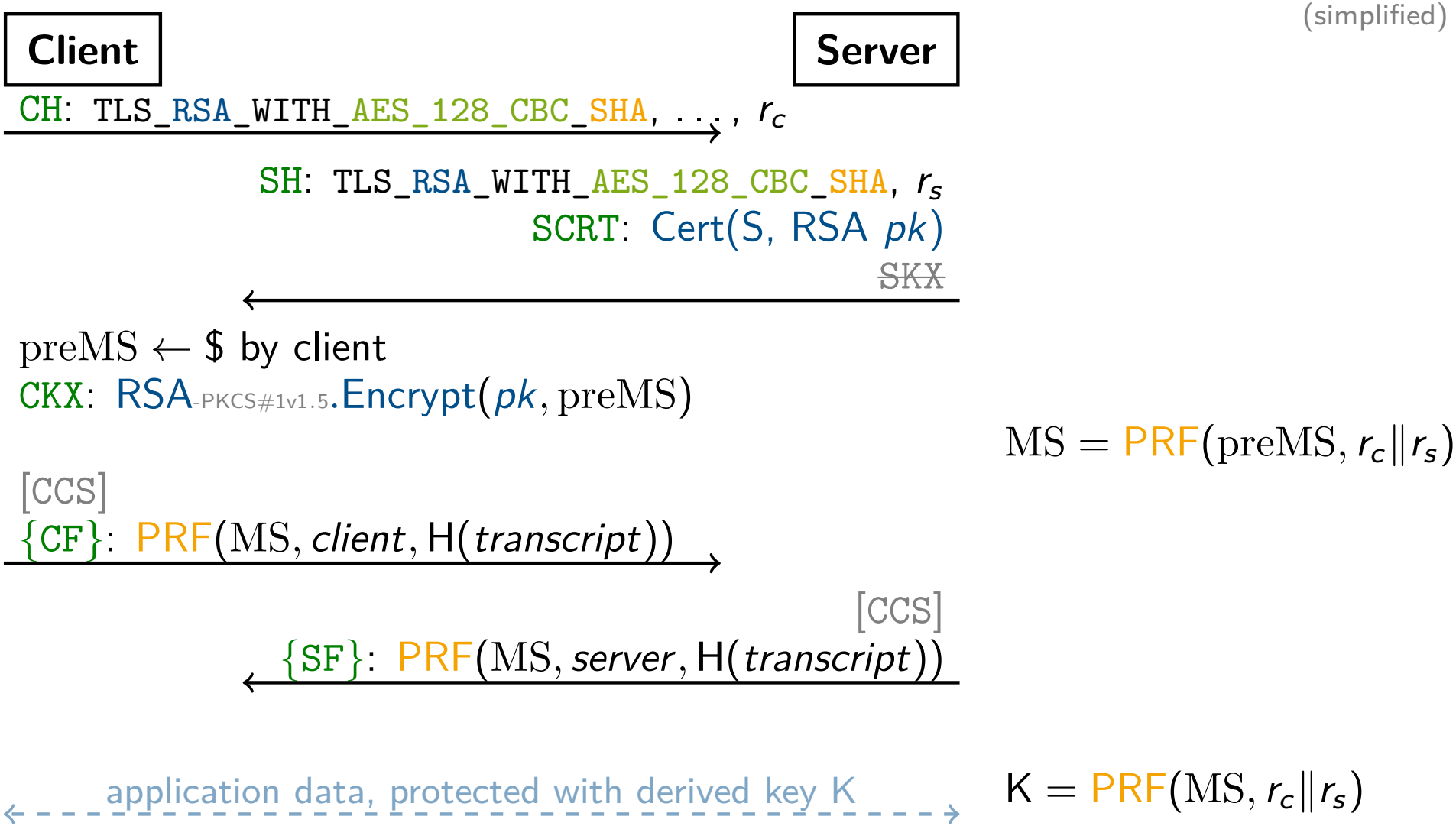

The TLS Protocol

TLS 1.2 Example: TLS_DHE_RSA_WITH_AES_256_GCM_SHA384 — Handshake

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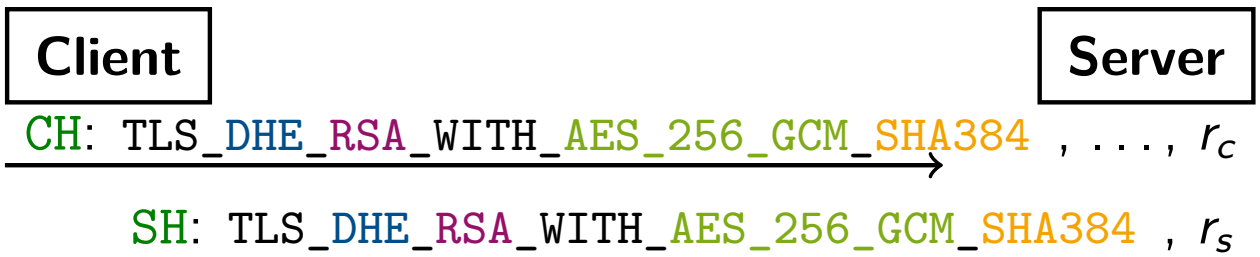

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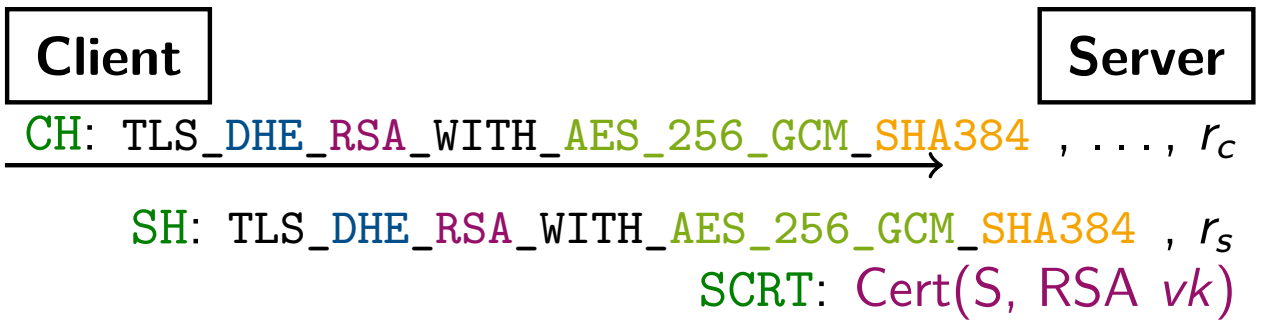

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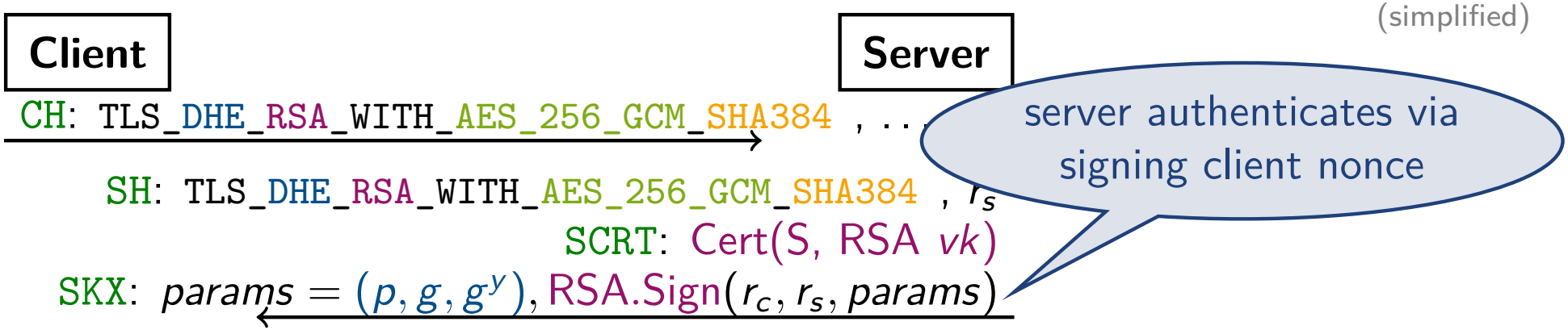

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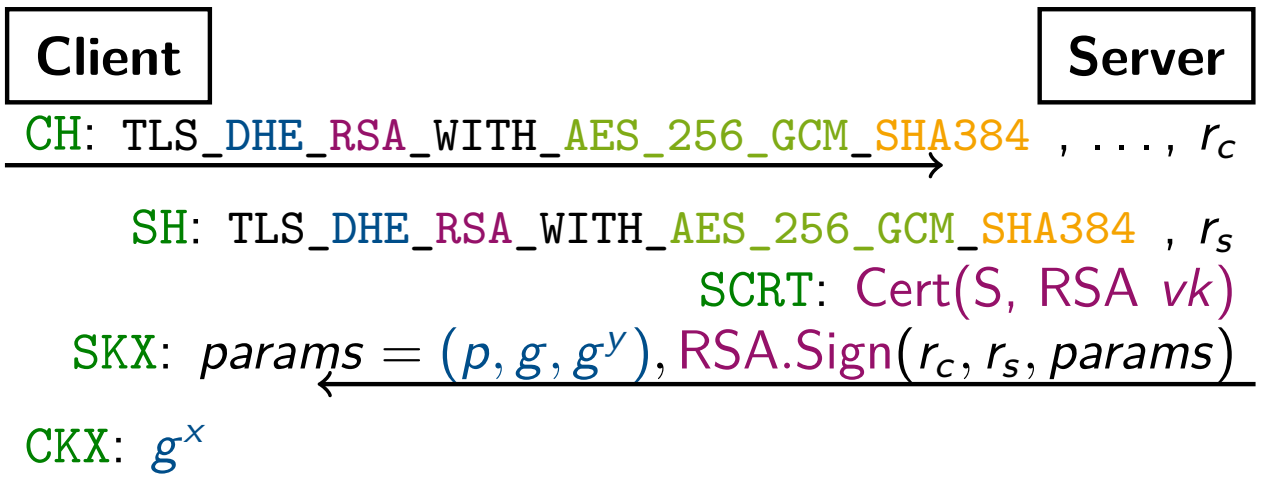

The TLS Protocol

TLS 1.2 Example: TLS_DHE_RSA_WITH_AES_256_GCM_SHA384 — Handshake

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(simplified)

Client		Server
CH: TLS_DHE_RSA_WITH_AES_256_GCM_SHA384 , ..., r_c	$\longrightarrow$	
		SH: TLS_DHE_RSA_WITH_AES_256_GCM_SHA384 , r_s
		SCRT: Cert(S, RSA vk)
	$\longleftarrow$	SKX: $params = (p, g, g^y)$, RSA.Sign$(r_c, r_s, params)$
CKX: g^x		

$\text{preMS} = g^{xy}$

$\text{MS} = \text{PRF}(\text{preMS}, r_c \| r_s)$

The TLS Protocol

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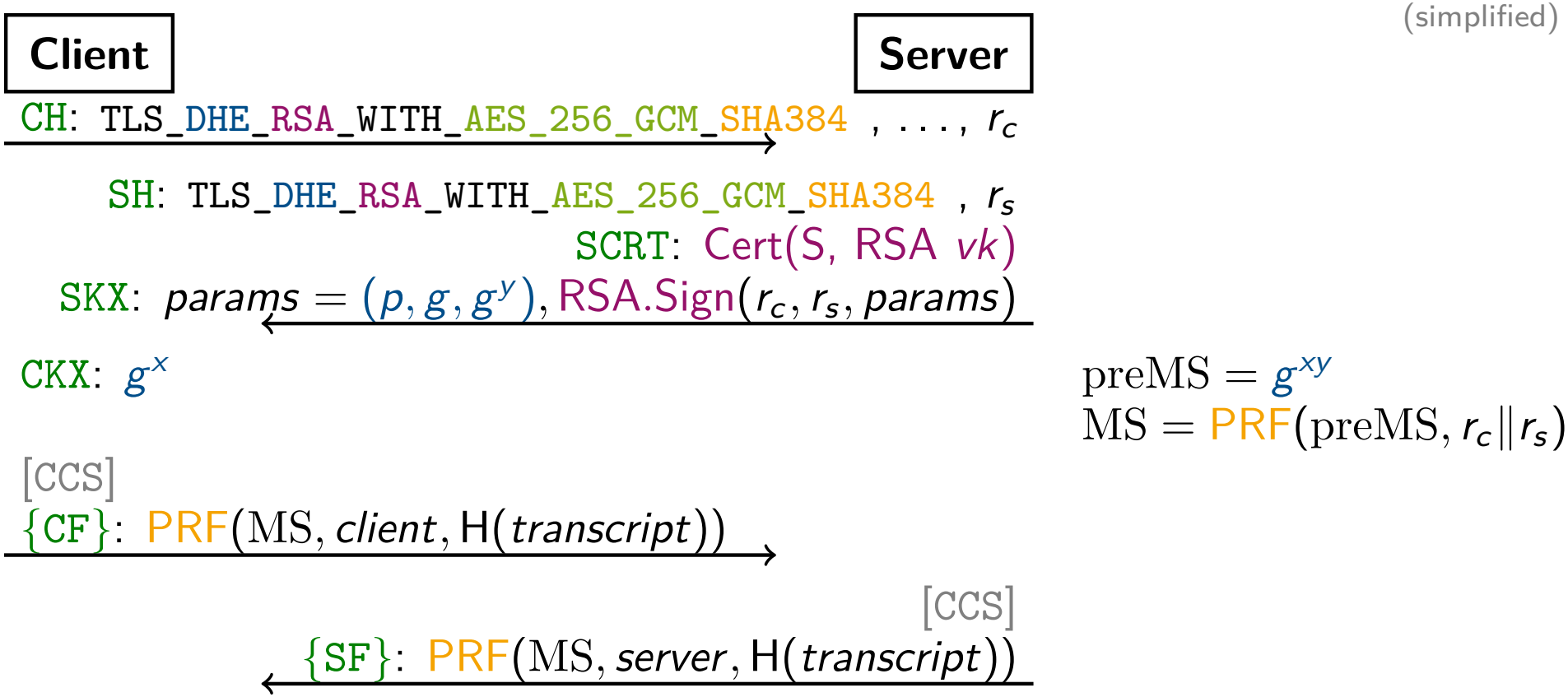
(simplified)



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CKX: g^x	→	
		$\text{preMS} = g^{xy}$
		$\text{MS} = \text{PRF}(\text{preMS}, r_c \| r_s)$
[CCS]		
{CF}: PRF(MS, *client*, H(*transcript*))	→	
	←	[CCS]
	←	{SF}: PRF(MS, *server*, H(*transcript*))
		$\text{K} = \text{PRF}(\text{MS}, r_c \| r_s)$

The TLS Protocol

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(simplified)

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[CCS]		
{CF}: PRF(MS, *client*, H(*transcript*))	→	
	←	[CCS]
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		$\text{K} = \text{PRF}(\text{MS}, r_c \| r_s)$
application data, protected with derived key K	↔	

The TLS Protocol

TLS 1.2 Record Protocol Structure

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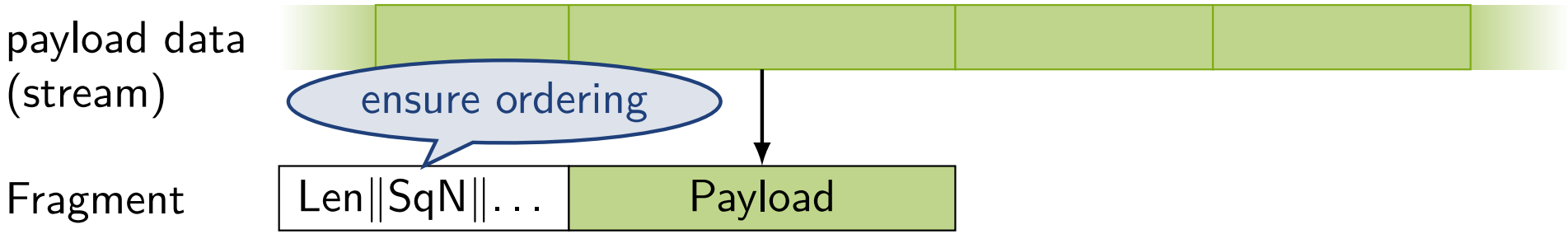
payload data (stream)

The TLS Protocol

TLS 1.2 Record Protocol Structure



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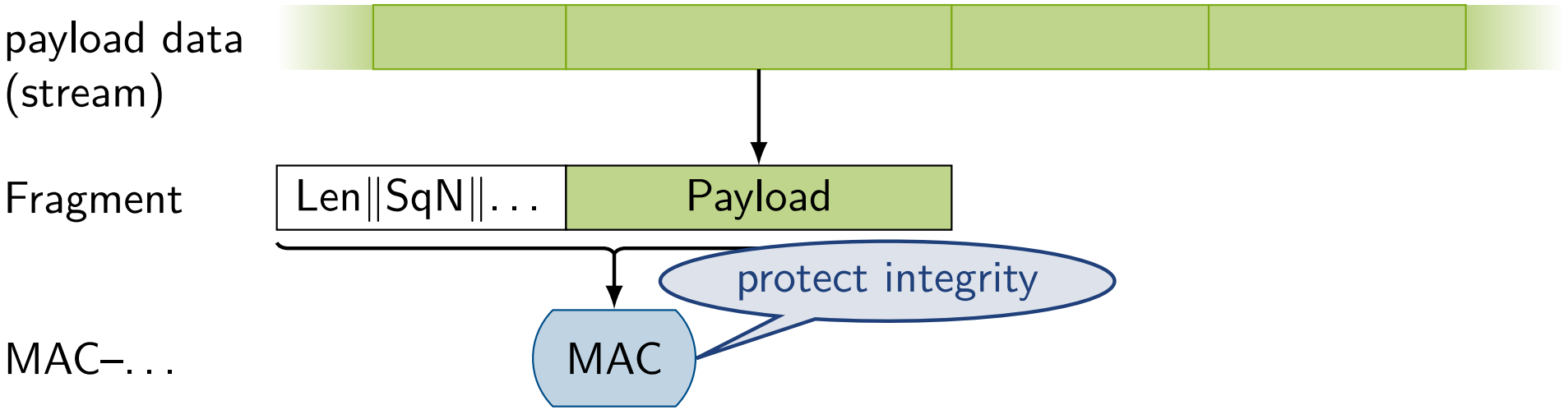
ETH zürich



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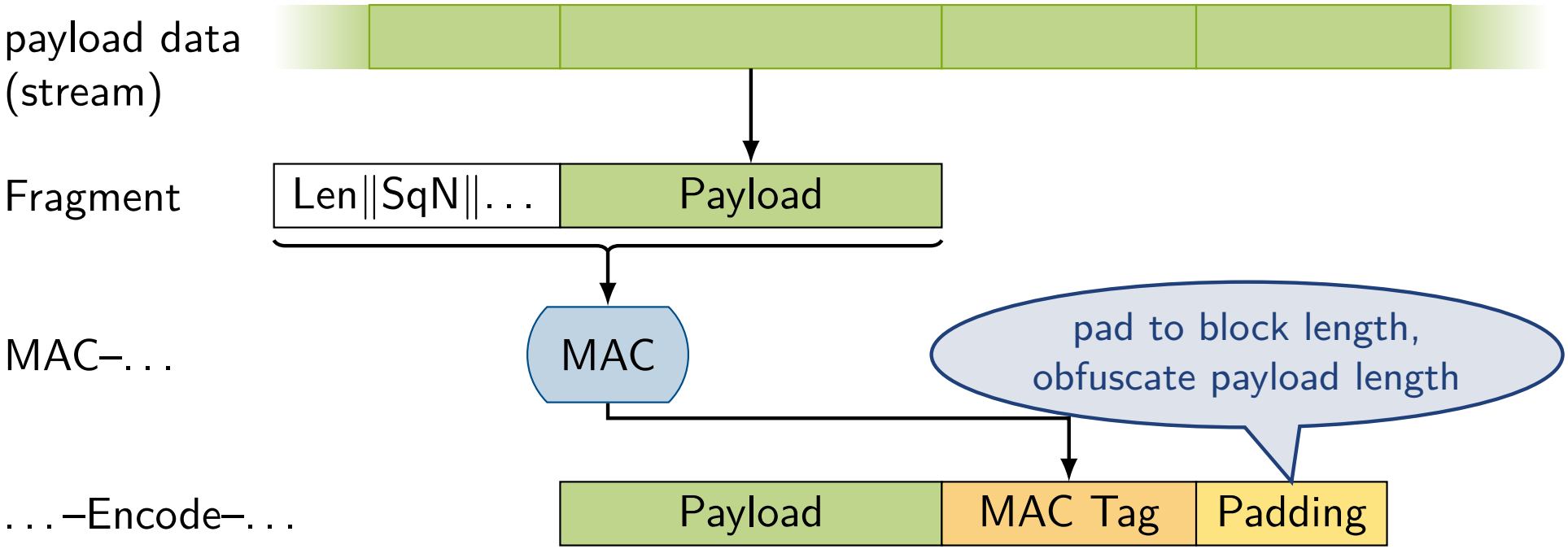

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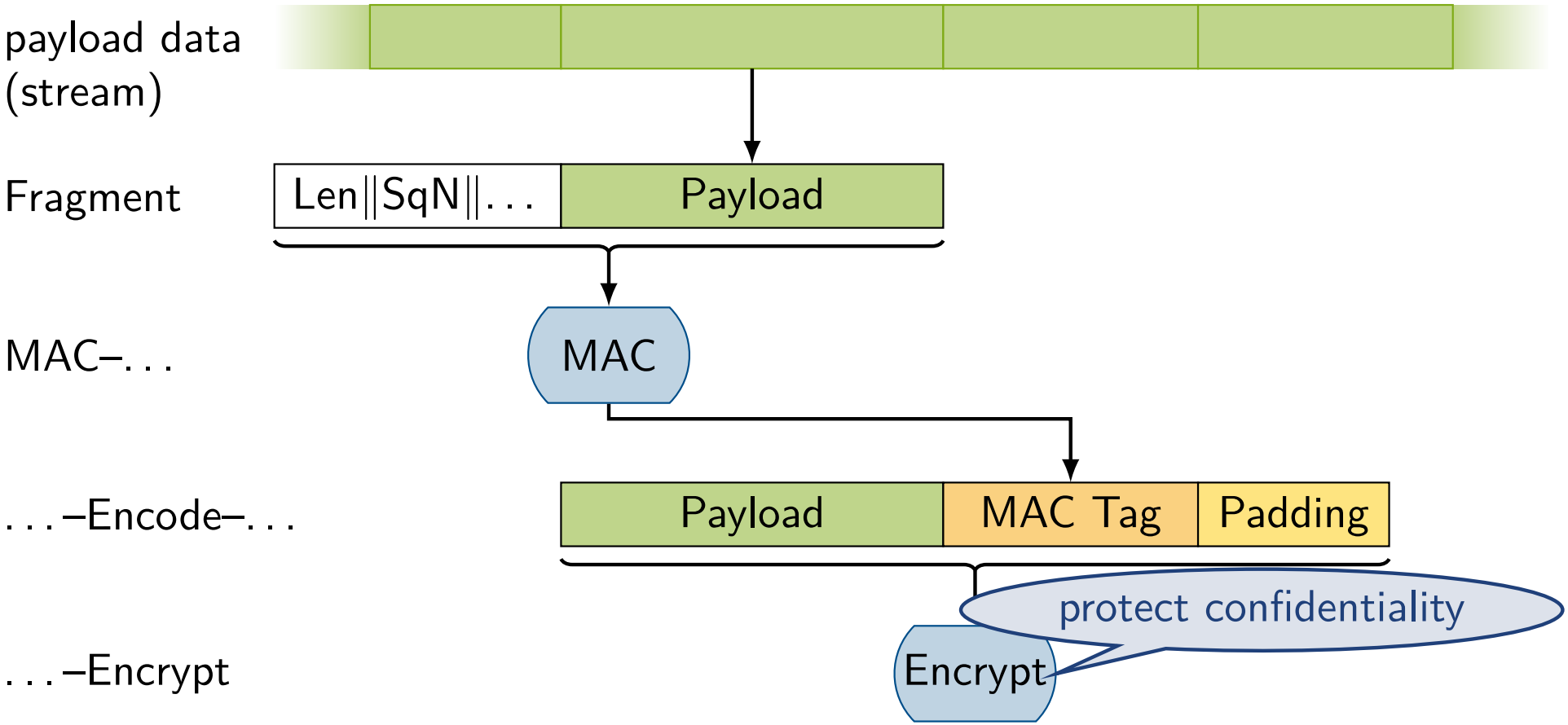

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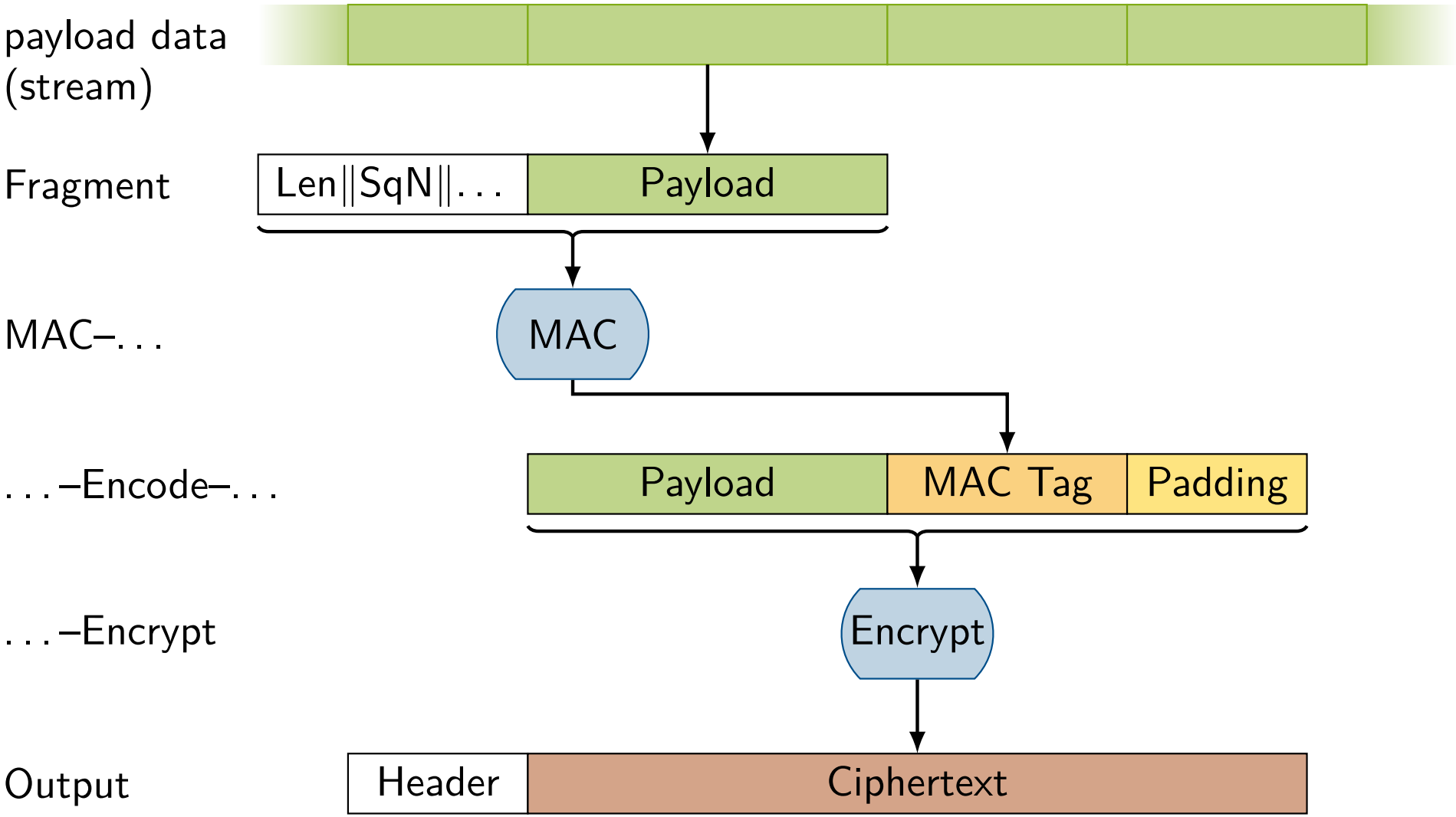

The TLS Protocol

TLS 1.2 Example: TLS_RSA_WITH_AES_128_CBC_SHA — Record Protocol

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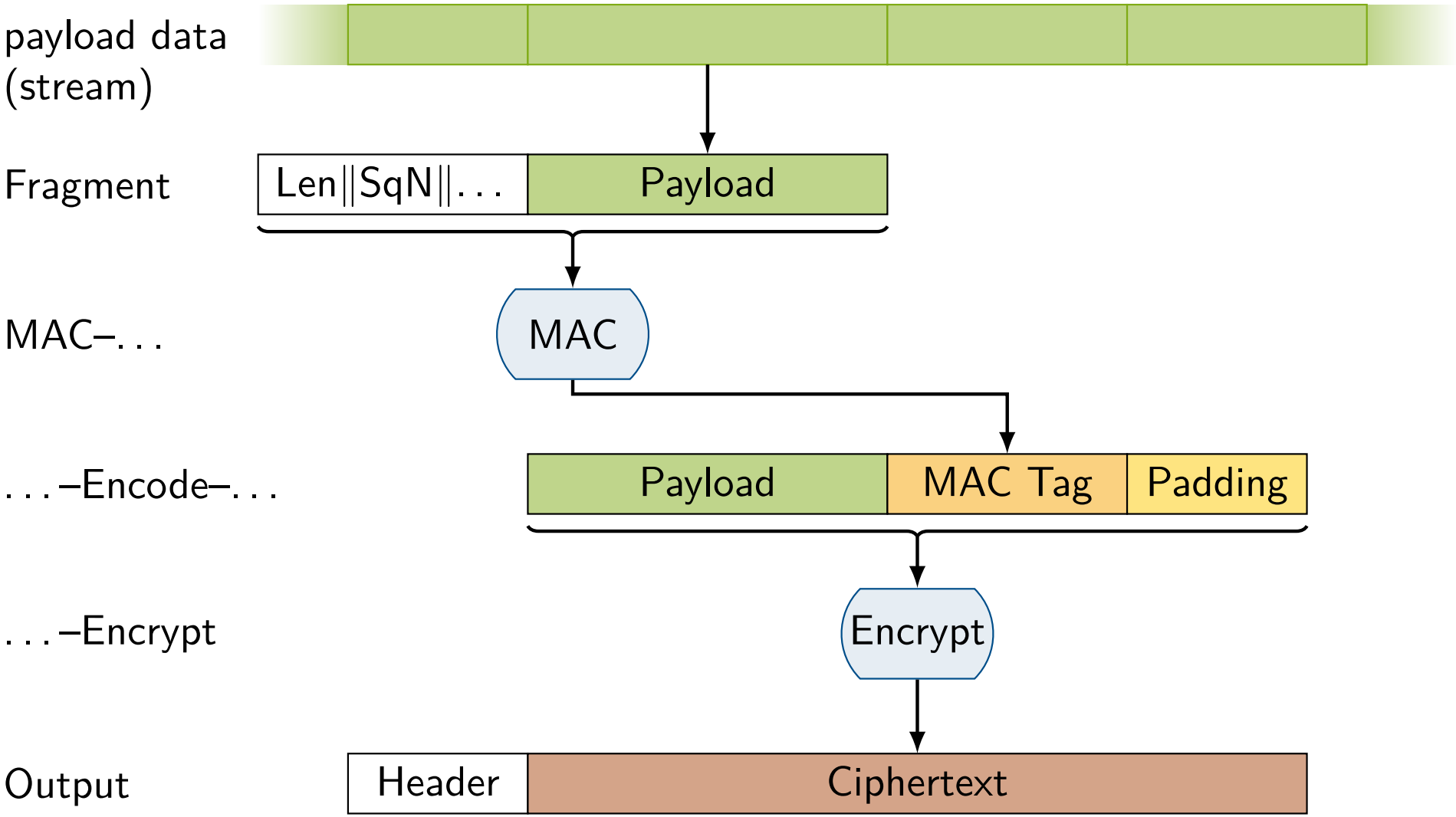

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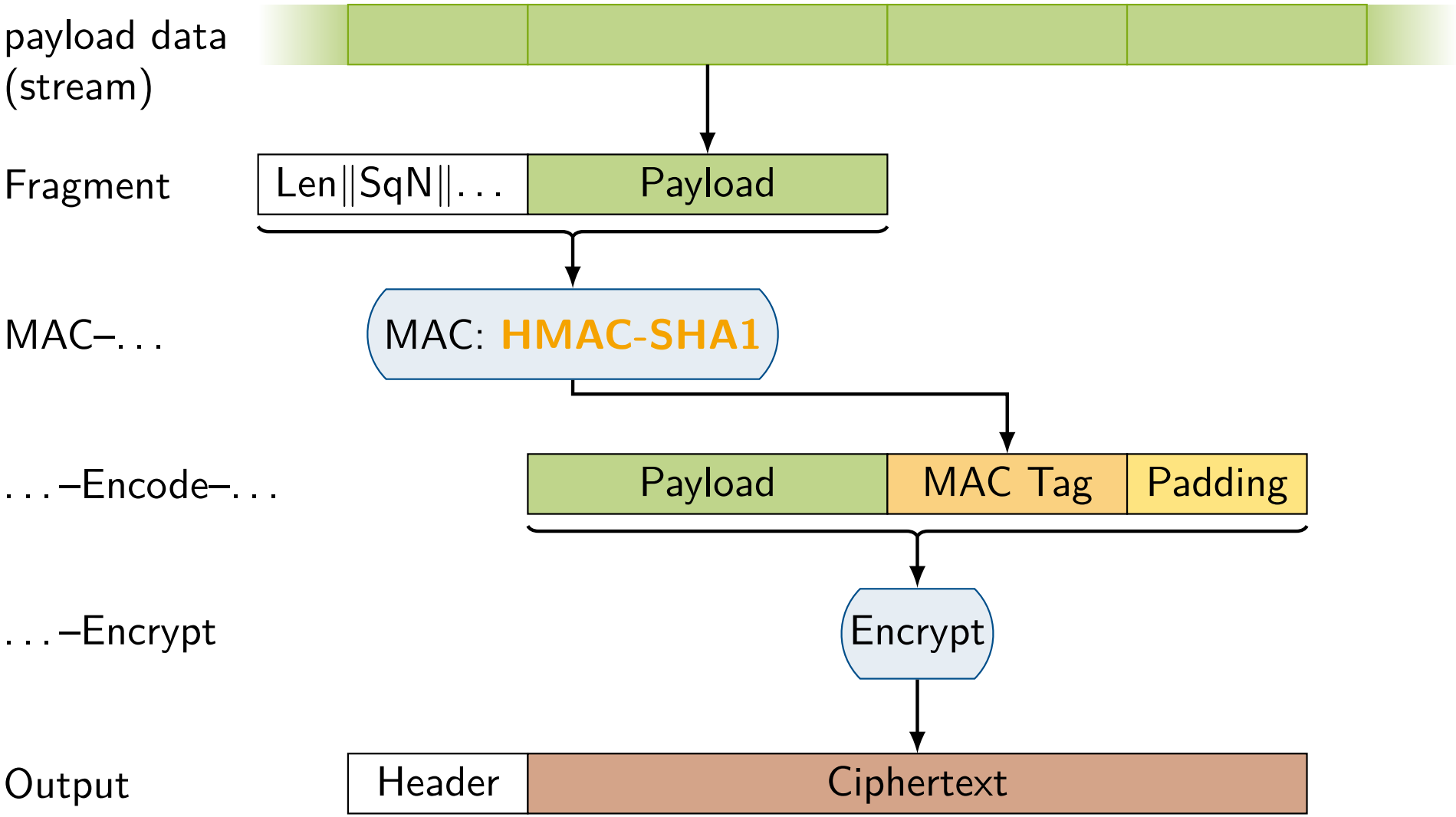

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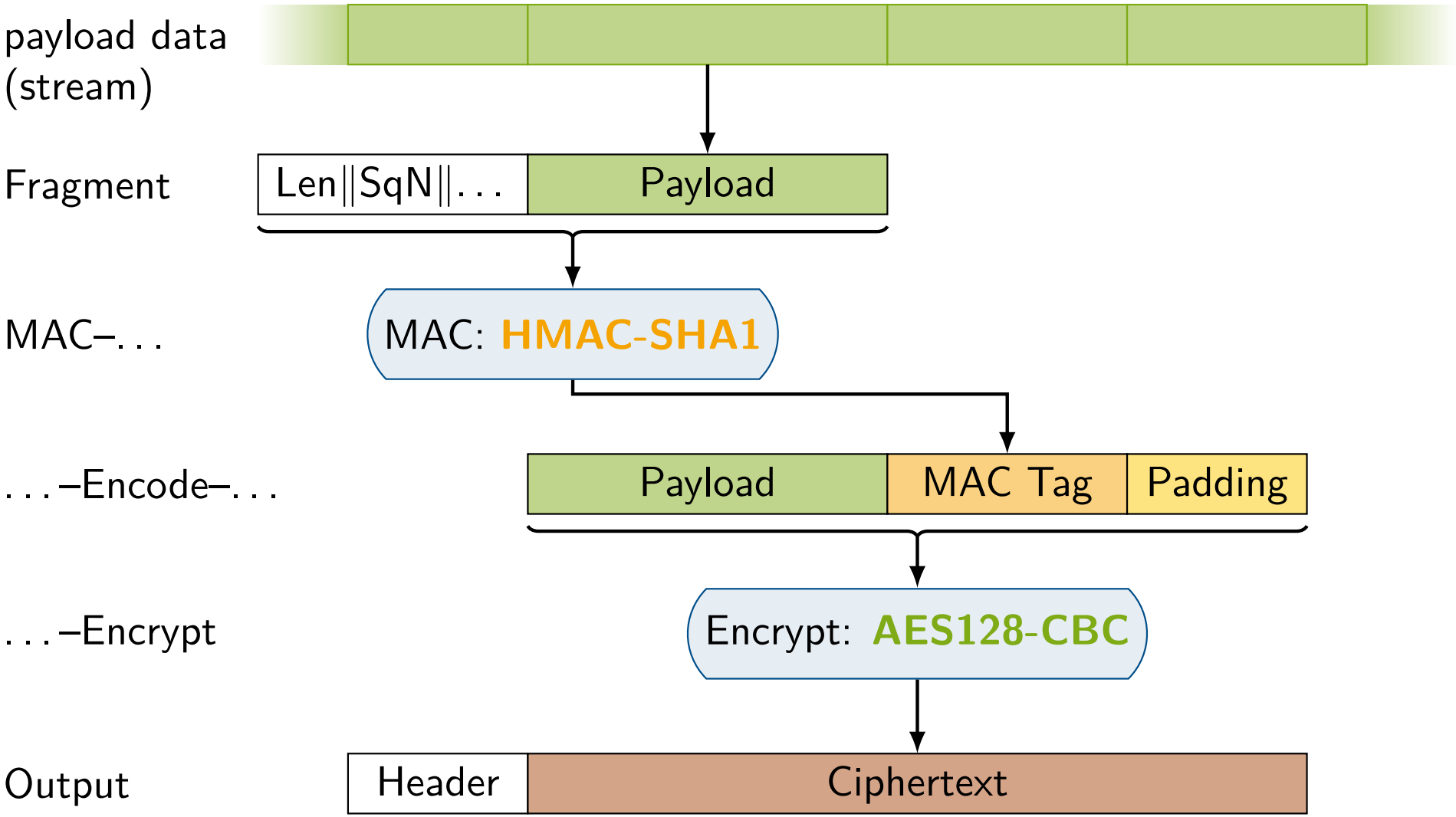
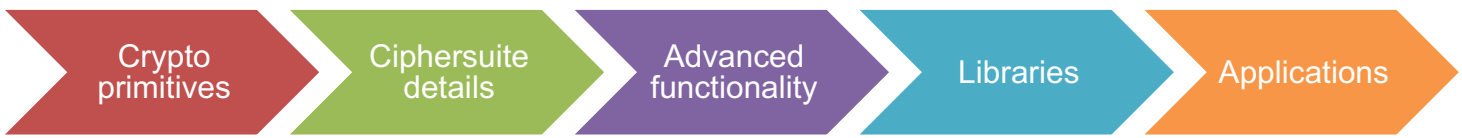


Components of TLS

Slides by Douglas Stebila



- RSA, DSA, ECDSA
- Diffie–Hellman, ECDH
- HMAC
- MD5, SHA1, SHA-2
- DES, 3DES, RC4, AES
- Export grade

- Data structures
- Key derivation
- Encryption modes, IVs
- Padding

- Alerts & errors
- Certification / revocation
- Negotiation
- Renegotiation
- Session resumption
- Key reuse
- Compression
- State machine

- OpenSSL
- LibreSSL, BoringSSL
- NSS
- GnuTLS
- SChannel
- Java JSSE
- Everest / miTLS
- s2n

- Web browsers: Chrome, Firefox, IE/Edge, Safari
- Web servers: Apache, IIS, nginx, node, …
- Application SDKs
- Certificates
- Protocols
  - HTTP, IMAP, ..

https://www.douglas.stebila.ca/research/presentations/tls-attacks/

The TLS Protocol

A complex protocol with many subtly interacting sub-components
"What could possibly go wrong?"

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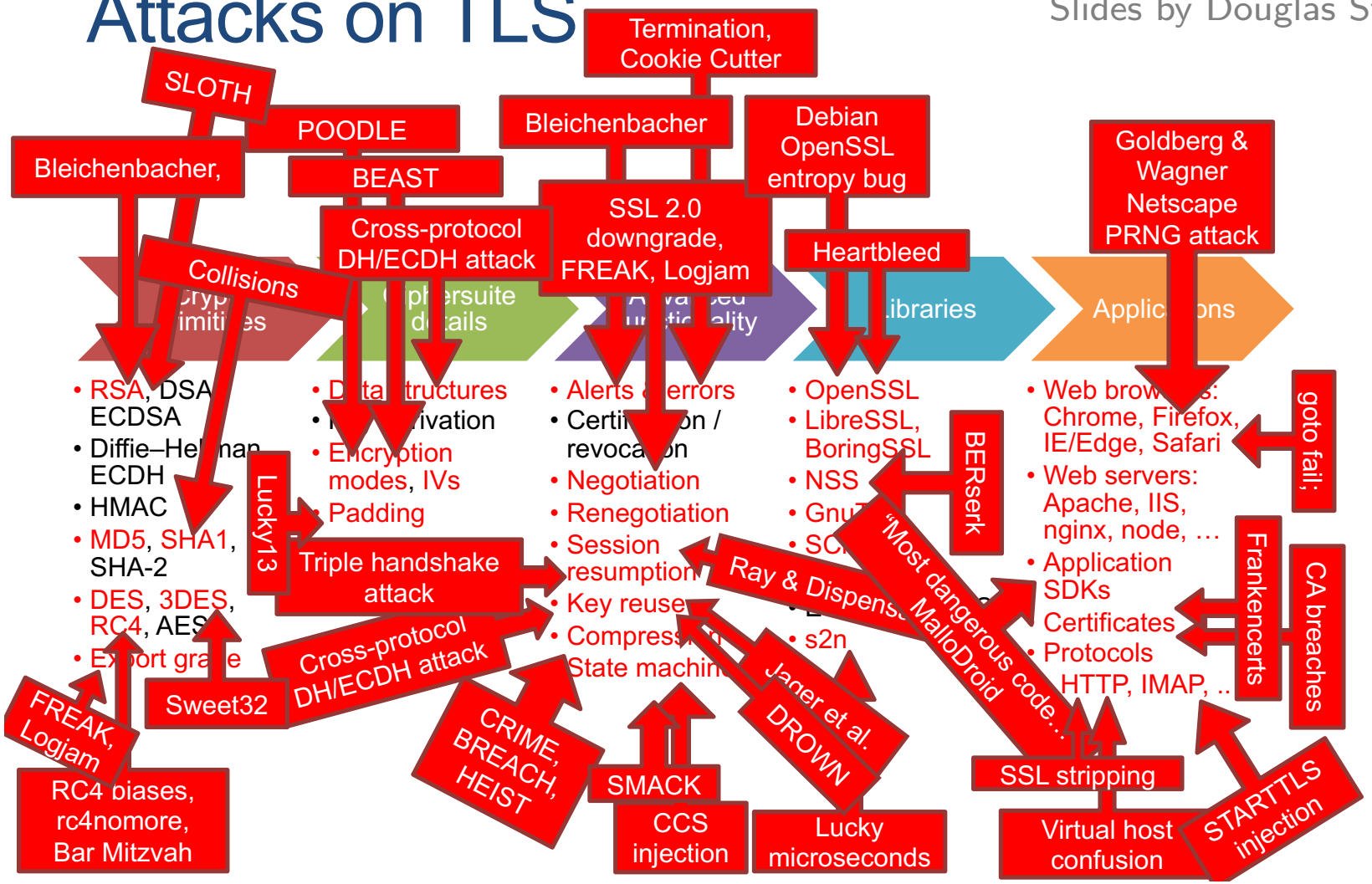
Attacks on TLS

Slides by Douglas Stebila



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TLS Security Issues

@Core Crypto: PKCS#1v1.5 and Bleichenbacher
— see PKE Lectures

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- core issue: RSA PKCS#1v1.5 is **not CCA-secure**

- **RSA key transport**
  - client selects secret random pre-master secret preMS
  - encrypts with the server's public key:

$$\mathsf{RSA}_{\text{-PKCS\#1v1.5}}.\mathsf{Encrypt}(pk, \mathrm{preMS}) = (00\|02\|padding\|00\|\mathrm{preMS})^e \mod N$$

  - server decrypts, checks padding, computes key from preMS
  - RFC doesn't specify exact process, but signals decryption error

- decryption error signal can be transformed into a **decryption oracle** [Ble98]

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- instead of switch to CCA-secure RSA-OAEP, TLS tried hiding error signal
- but Bleichenbacher-style attacks came back repeatedly
- to make things worse: re-use of RSA keys across different SSL/TLS versions
  - downgrade TLS version & attack there – e.g., DROWN attack [Avi+16]

TLS Security Issues

@Core Crypto: MAC-Encode-Encrypt and Lucky13 — see AEAD Lectures, Extra Slides

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- core issue: (good) MAC –then– (good) Encrypt $\neq$ **CCA-secure** AE [BN00]
- **MAC–then–AES-CBC Decryption**
  - decrypt ciphertext to obtain Payload $\|$ MAC Tag $\|$ Padding
  - remove padding — what if padding is incorrect?
  - check MAC
- A padding oracle
  - in a modified ciphertext, either the padding check fails...
  - ... or the MAC check fails
  - if the two are distinguishable: padding oracle
  - can lift a padding oracle to a **decryption oracle** [Vau02] (conditions apply)

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- instead of switch to CCA-secure Enc-then-MAC, TLS tried hiding error signal
  - "compute MAC w/ zero padding"
  - "leaves a [non-exploitable] small timing channel"
  - **Lucky13** [AP13]: HMAC timing difference still big enough
  - really need constant time—which is extremely difficult!

TLS Security Issues

@Protocol Design: Weak DH Negotiation and Logjam

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- core issue: weak algorithms make strong ones fail through **downgrades**

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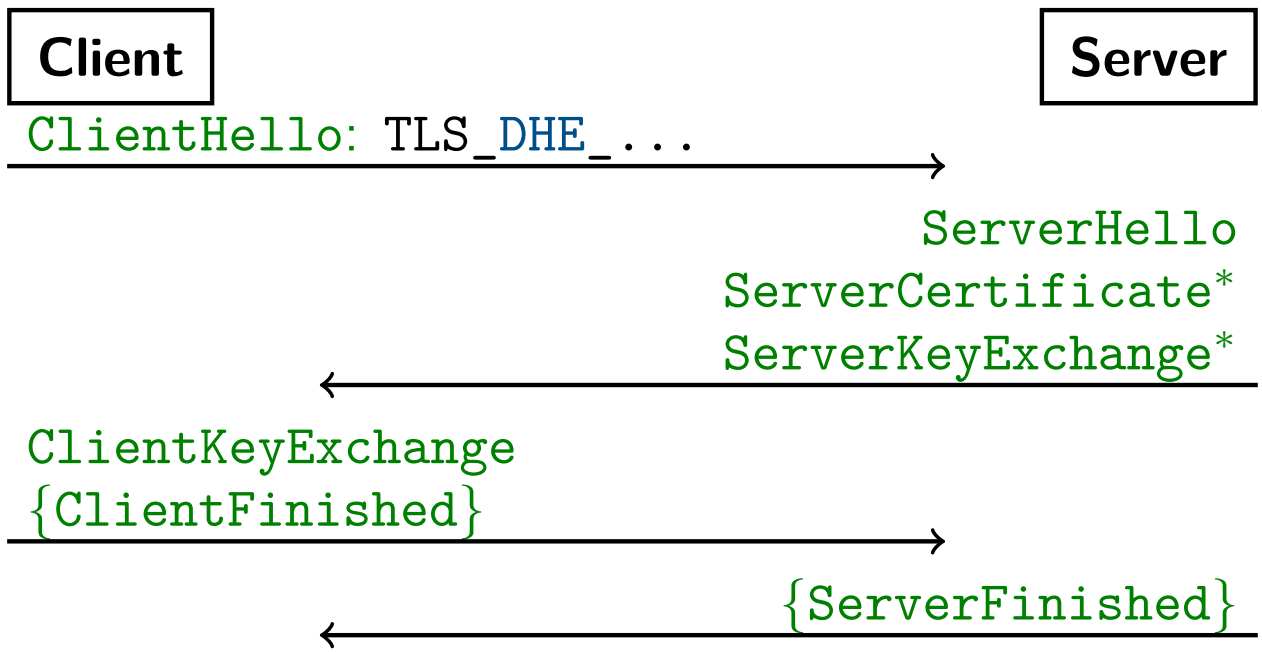

drawings by *Giorgia Azzurra Marson*

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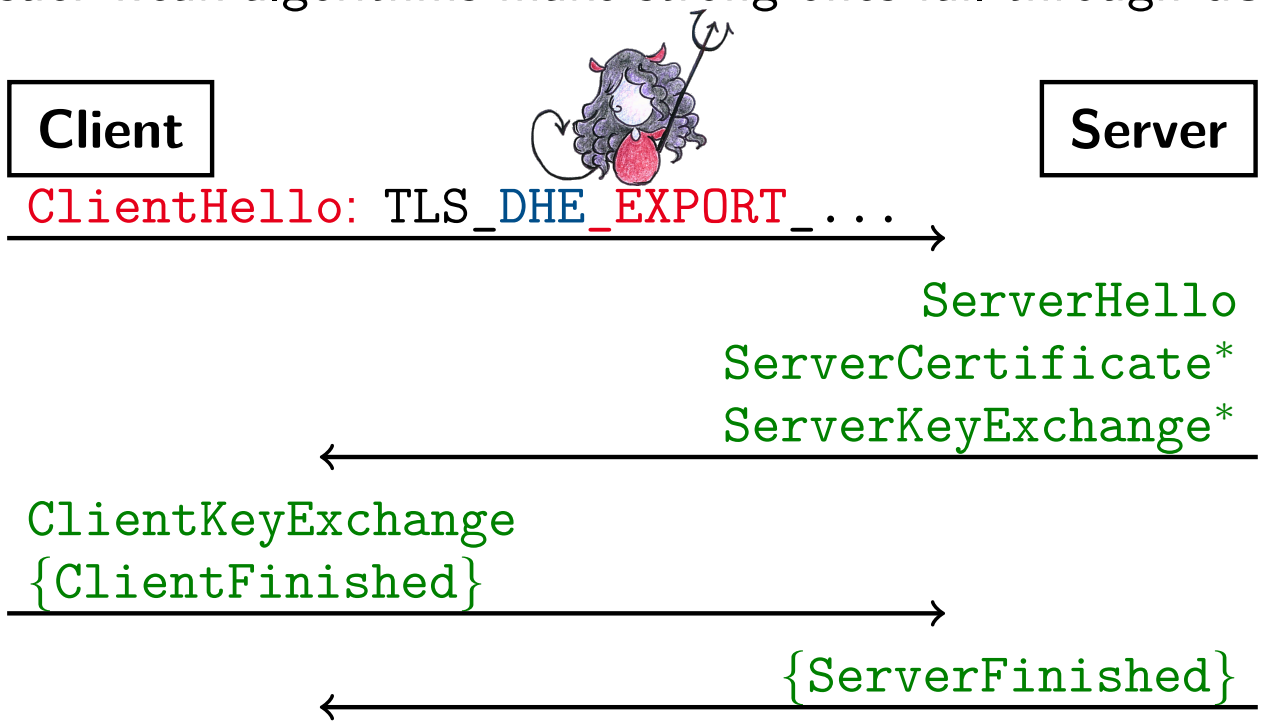

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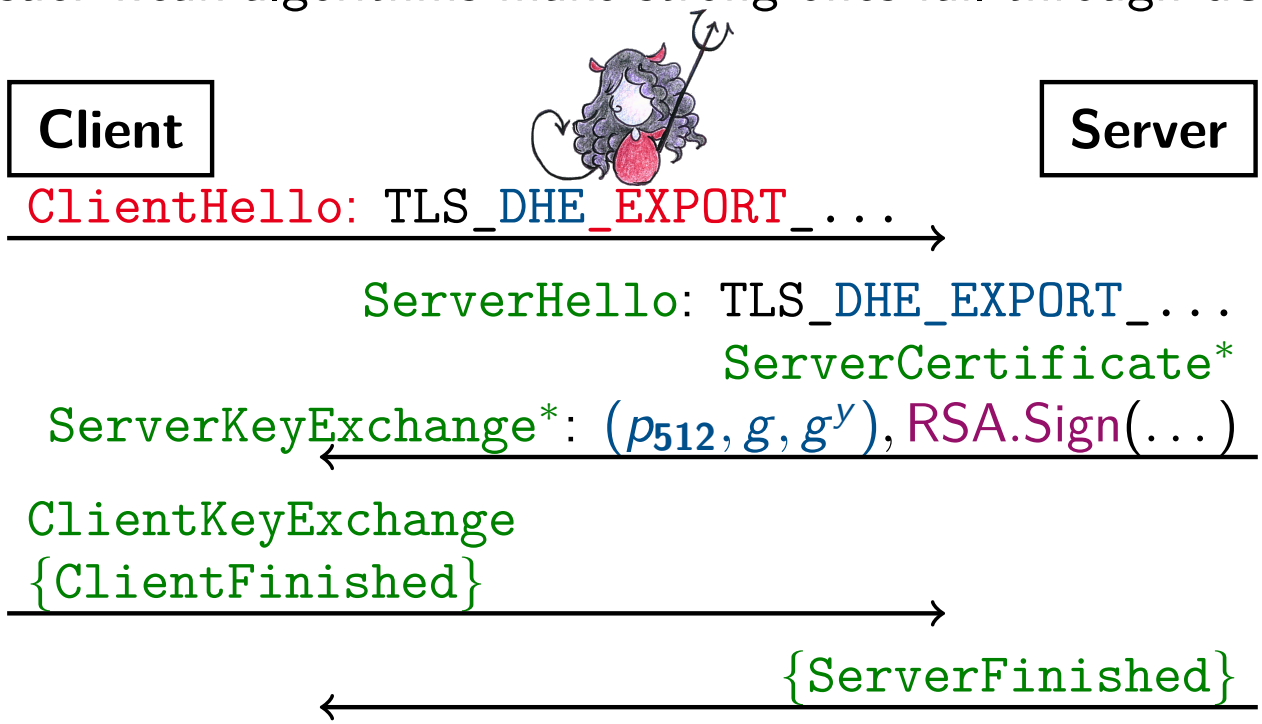

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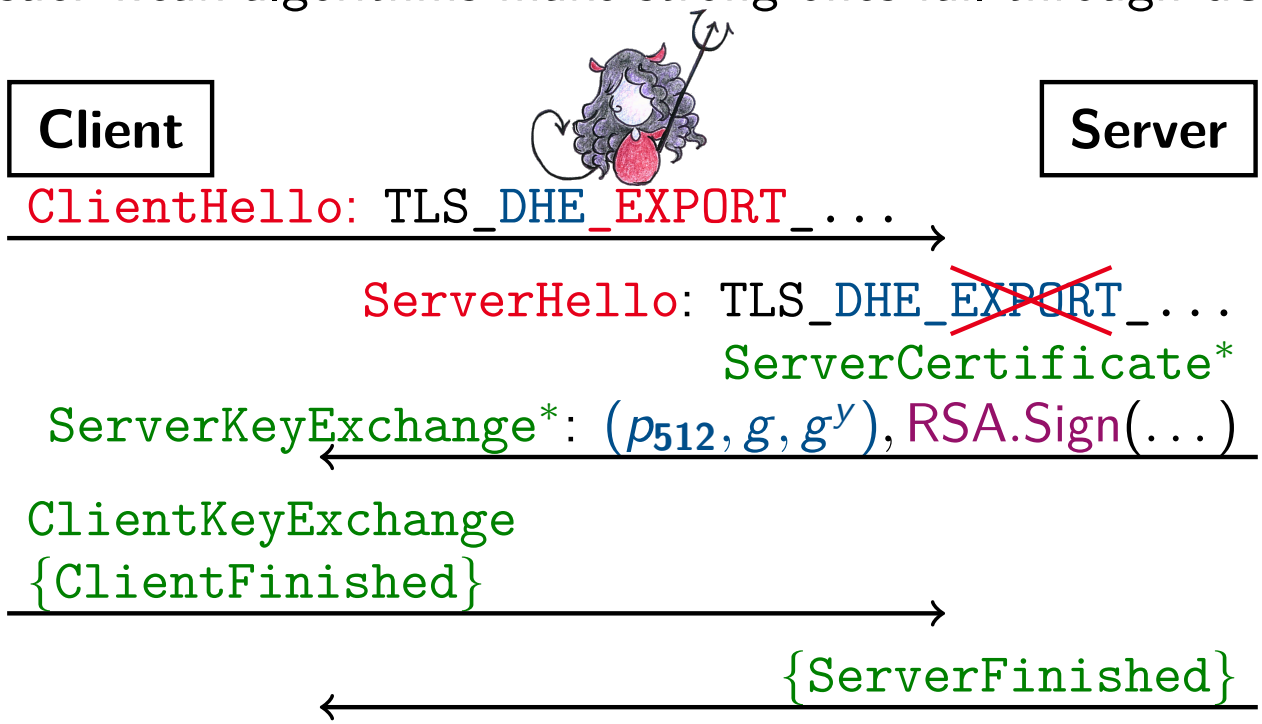

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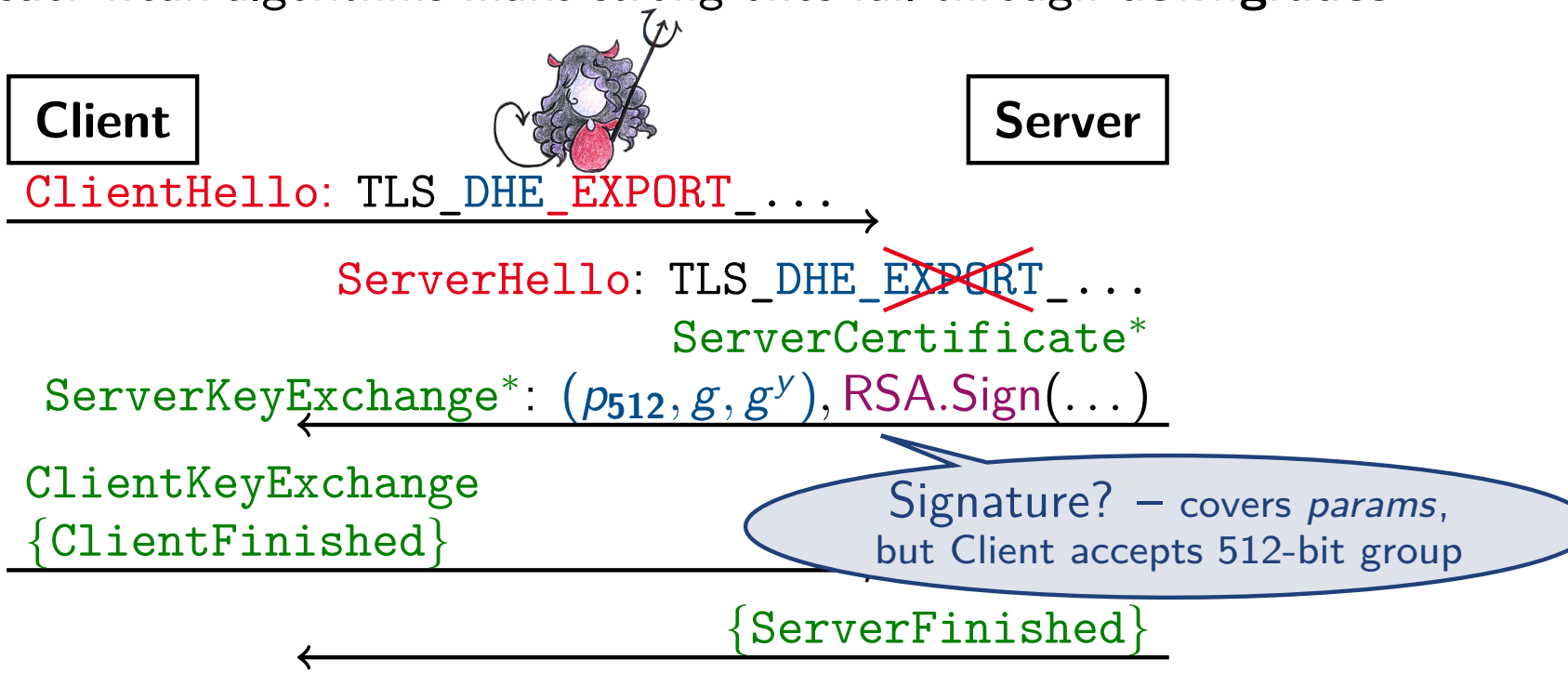

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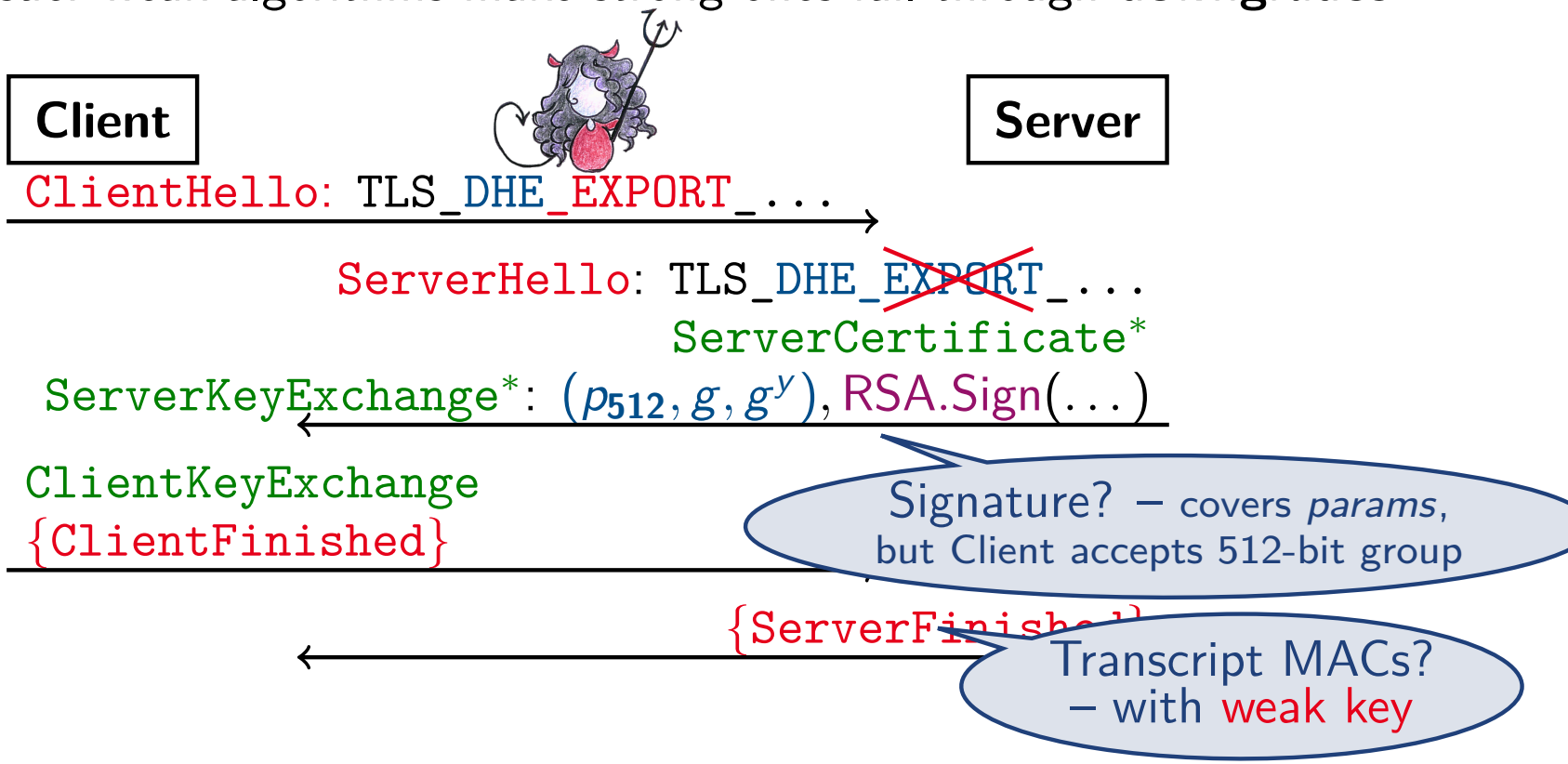

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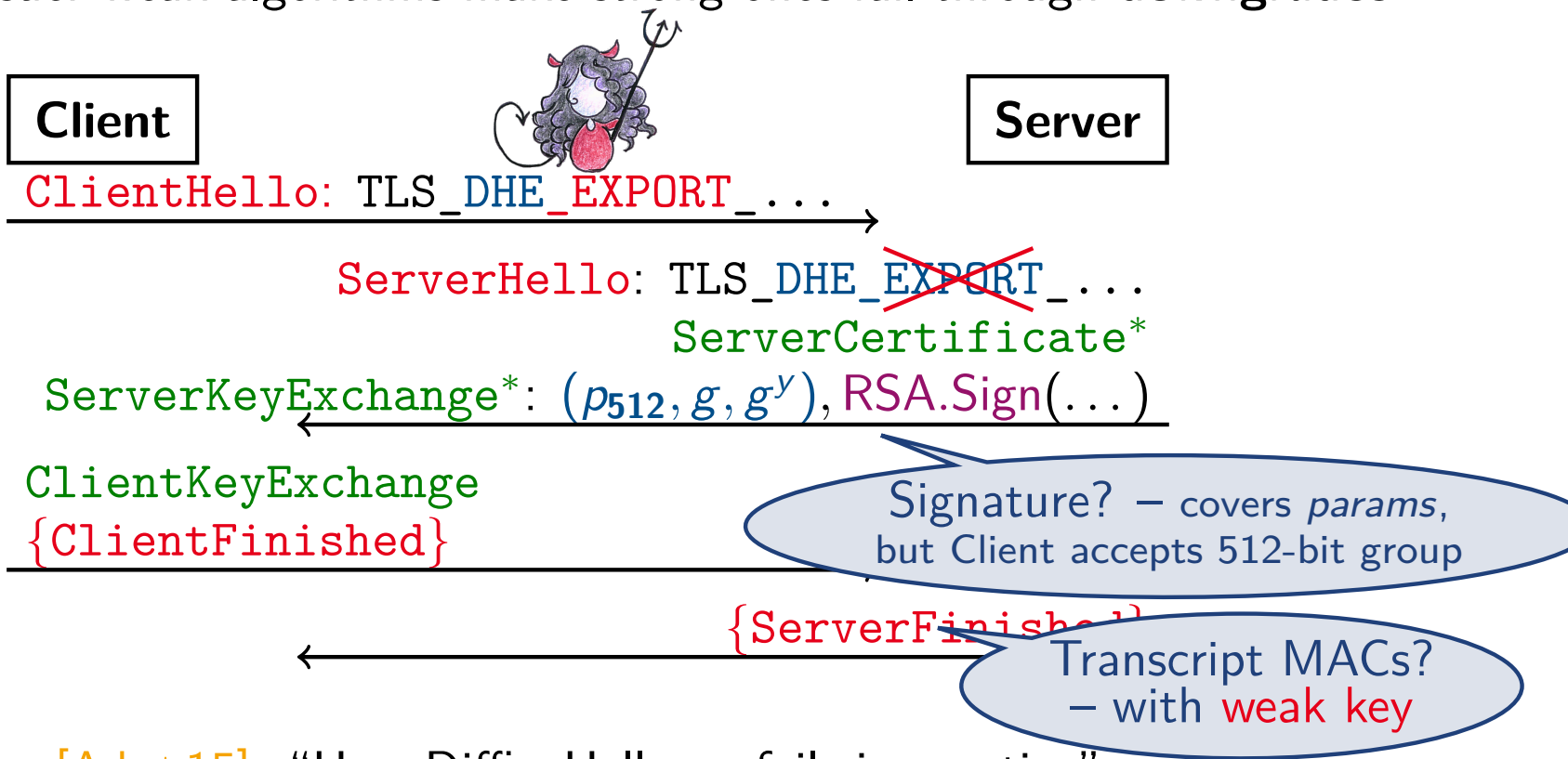

- **Logjam** [Adr+15]: "How Diffie–Hellman fails in practice"
  - server impersonation through (also) supporting weak DH groups

drawings by *Giorgia Azzurra Marson*

TLS Security Issues

@Implementation: Buffers and Heartbleed

ETH zürich

- core issue: **buffer over-read** in OpenSSL

TLS Security Issues

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  - client sends "ping back those 4 bytes: `00 01 02 03`"
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TLS Security Issues

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- **Heartbeat** extension (RFC 6520)
  - client sends "ping back those 4 bytes: `00 01 02 03`"
  - server responds "`00 01 02 03`"
- **Heartbleed** attack [Hea]
  - client sends "ping back those **16 Kbytes**: `00 01 02 03`"
  - server responds "`00 01 02 03 ...<memory dump>`"
  - possibly including sensitive data like server private key etc.
- high severity & public attention — and a catchy logo

Transport Layer Security (TLS)

A new chapter: TLS 1.3

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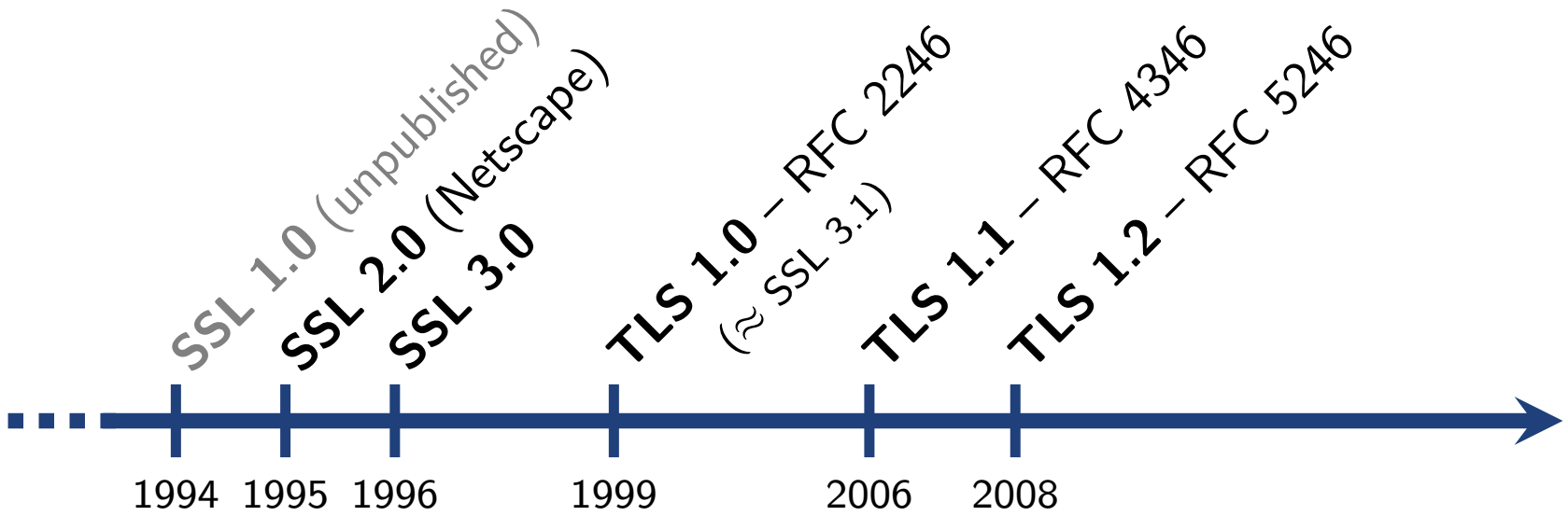

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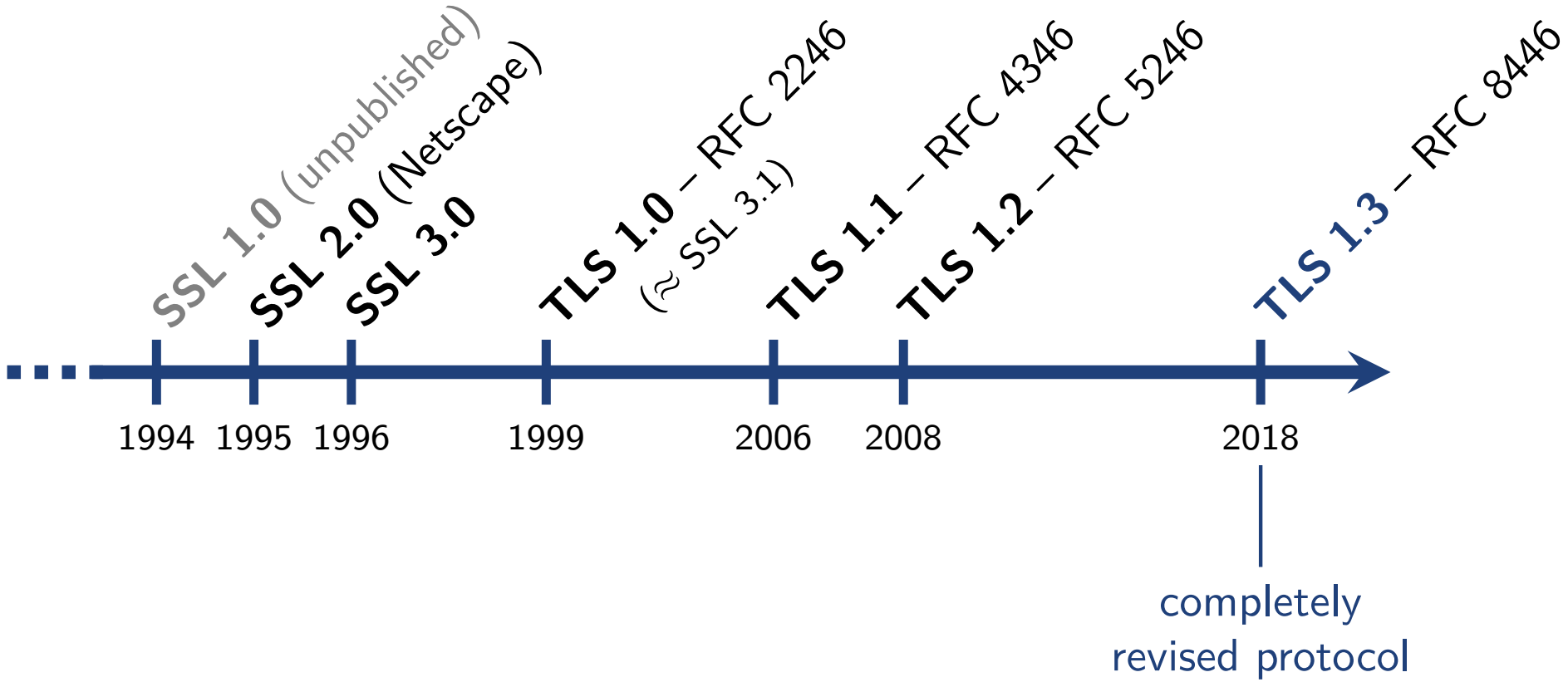

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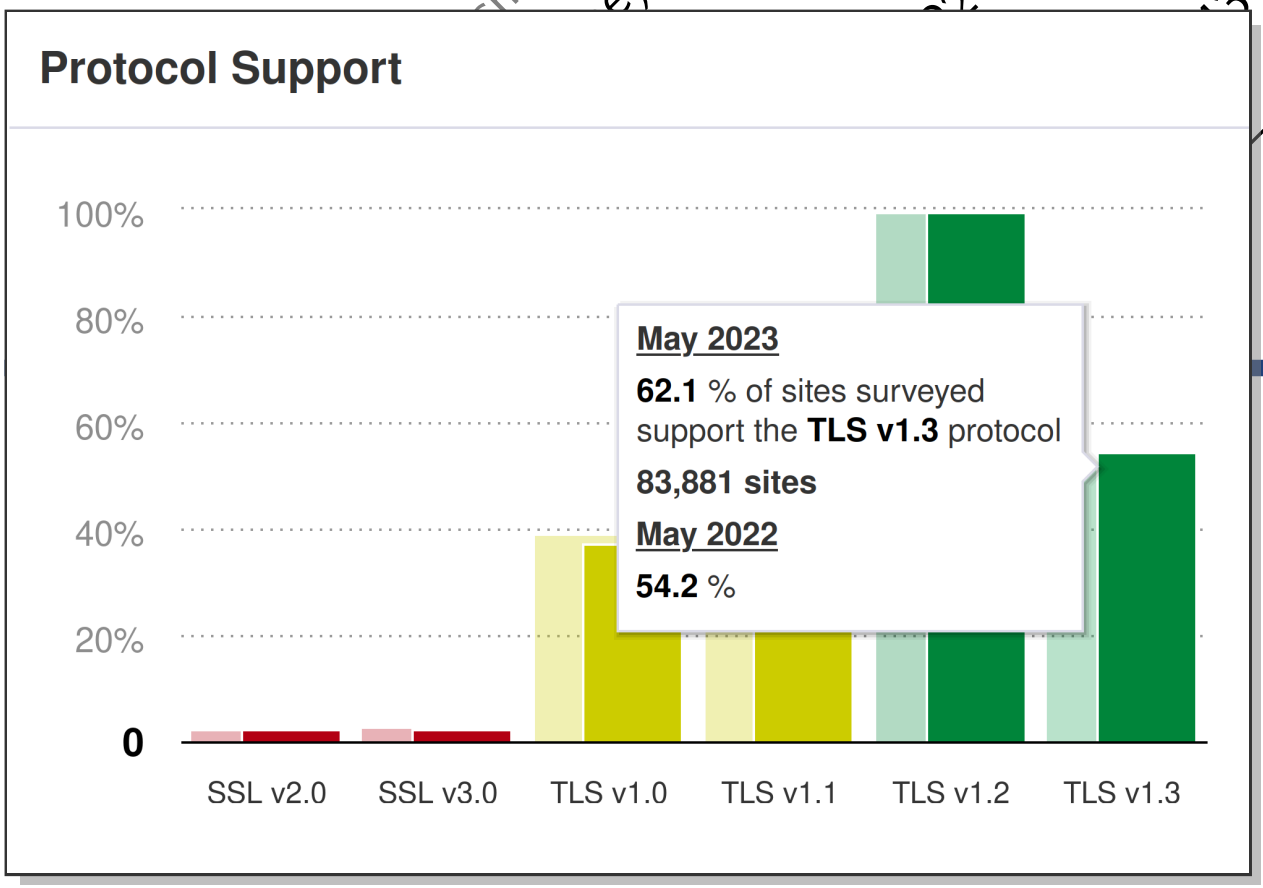

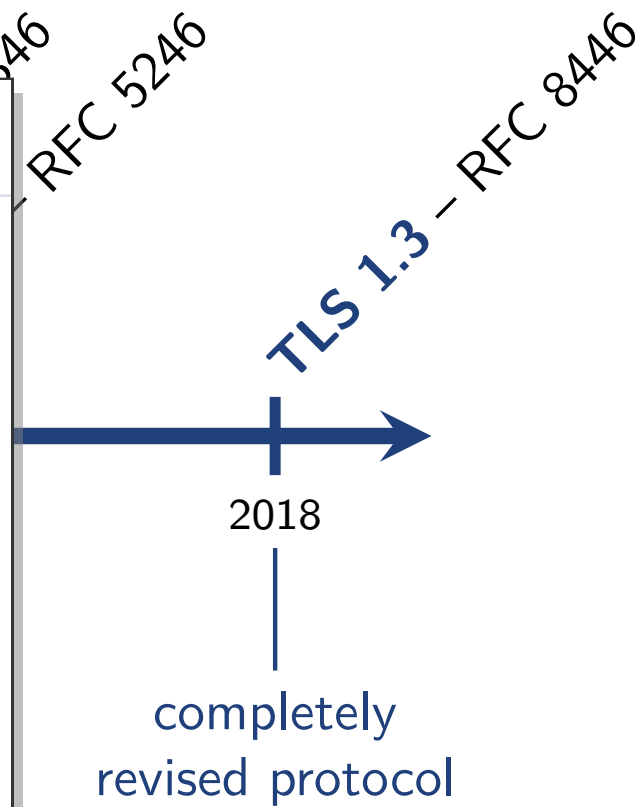

https://www.ssllabs.com/ssl-pulse/, 150K top sites (May 2023)

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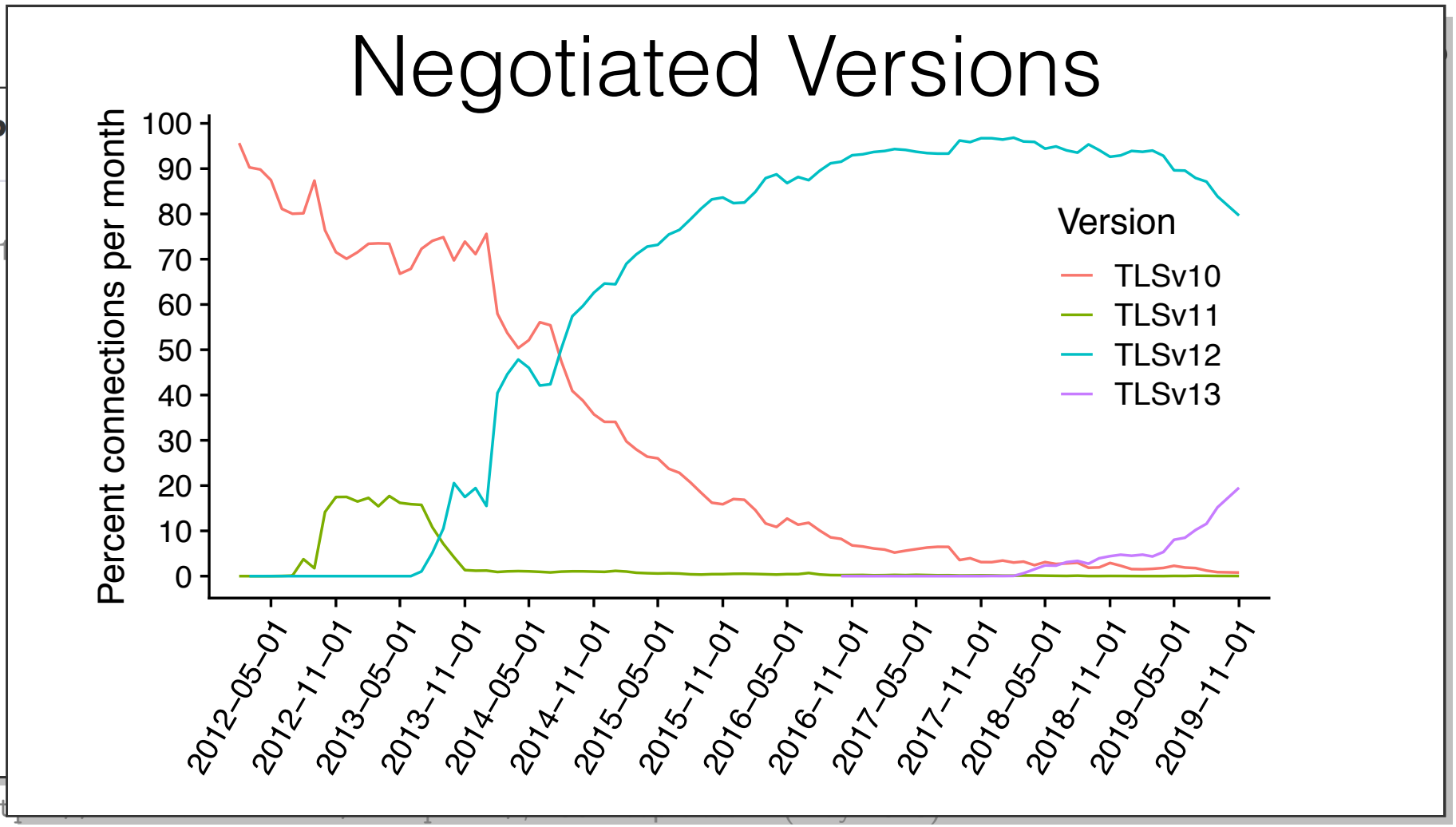

ICSI SSL Notary (Johanna Amann @ RWC 2020)

TLS 1.3

Design Goals

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- **Clean up:** get rid of flawed and unused crypto & features
- **Improve latency:** for main handshake and repeated connections (while maintaining security)
- **Improve privacy:** hide as much of the handshake as possible
- **Continuity:** maintain interoperability with previous versions and support existing important use cases

TLS 1.3

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- **Security Assurance (added later):** have supporting analyses for changes

TLS 1.3

Main changes (from TLS 1.2)

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Clean up

TLS 1.3

Main changes (from TLS 1.2)

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Clean up

- removed **legacy and broken crypto**
  - ciphers: (3)DES, RC4, . . . , MtE (CBC & generally) — only AEAD remains
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quite some resistance from enterprises doing passive inspection

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- **hardened negotiation** of version/cipher suite against downgrades

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Improve latency

TLS 1.3

Main changes (from TLS 1.2)

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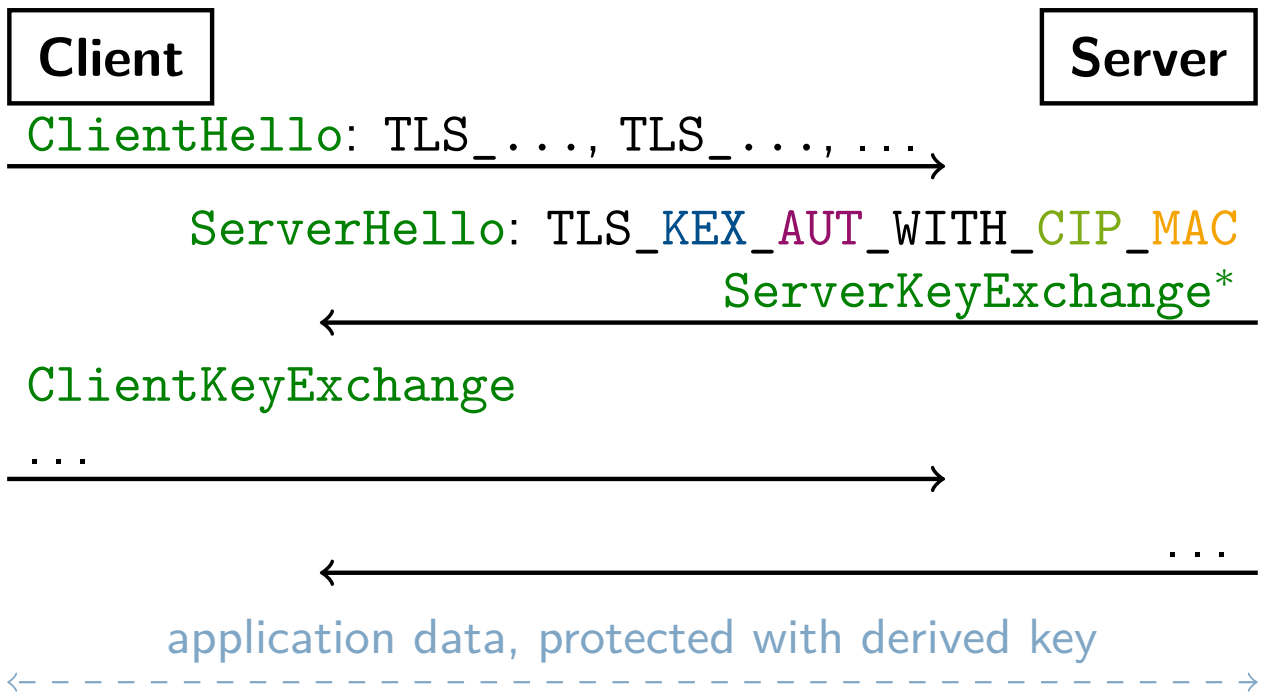
Improve latency

- TLS $\leq$ 1.2 is slow: 2 round trips before client can send data



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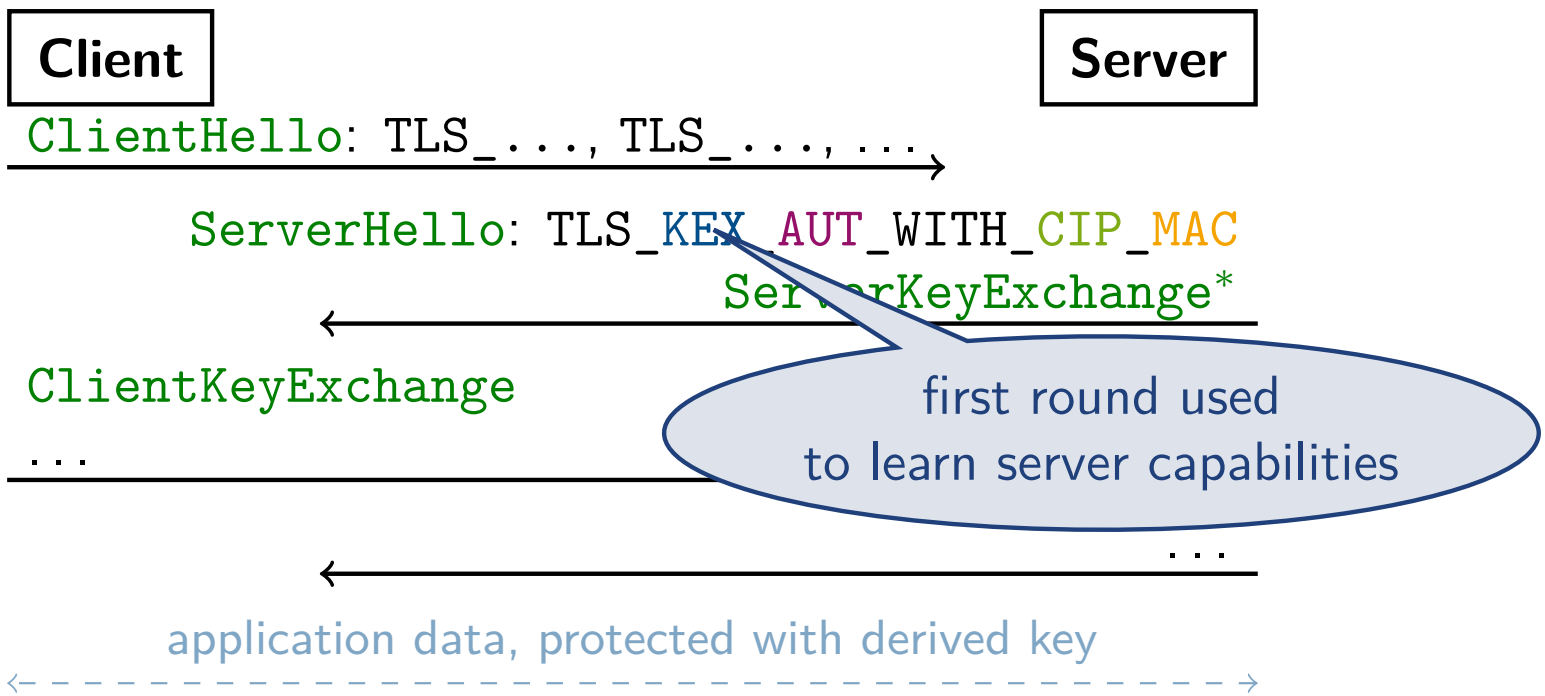

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- TLS 1.3: **full handshake in 1 round trip**
  - feature reduction $\rightarrow$ always do (EC)DHE
  - client speculatively sends several DH shares in supported groups
  - server picks one, replies with its share, and key can be already derived

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  - server picks one, replies with its share, and key can be already derived
- **0-RTT handshake** when resuming previous connection
  - client+server keep shared resumption secret (PSK)
  - client derives a key from that and can immediately encrypt data
  - but: 0-RTT *sacrifices* replay protection (see extra slides)

TLS 1.3

Main changes (from TLS 1.2)

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Improve privacy

TLS 1.3

Main changes (from TLS 1.2)

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Continuity

- e.g.: remove complex renegotiation, but keep features (key update + client auth)
- interoperability (idea): let `ClientHello` look like TLS $<$ 1.3

TLS 1.3

Main changes (from TLS 1.2)

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Contin

- e.g. t auth)
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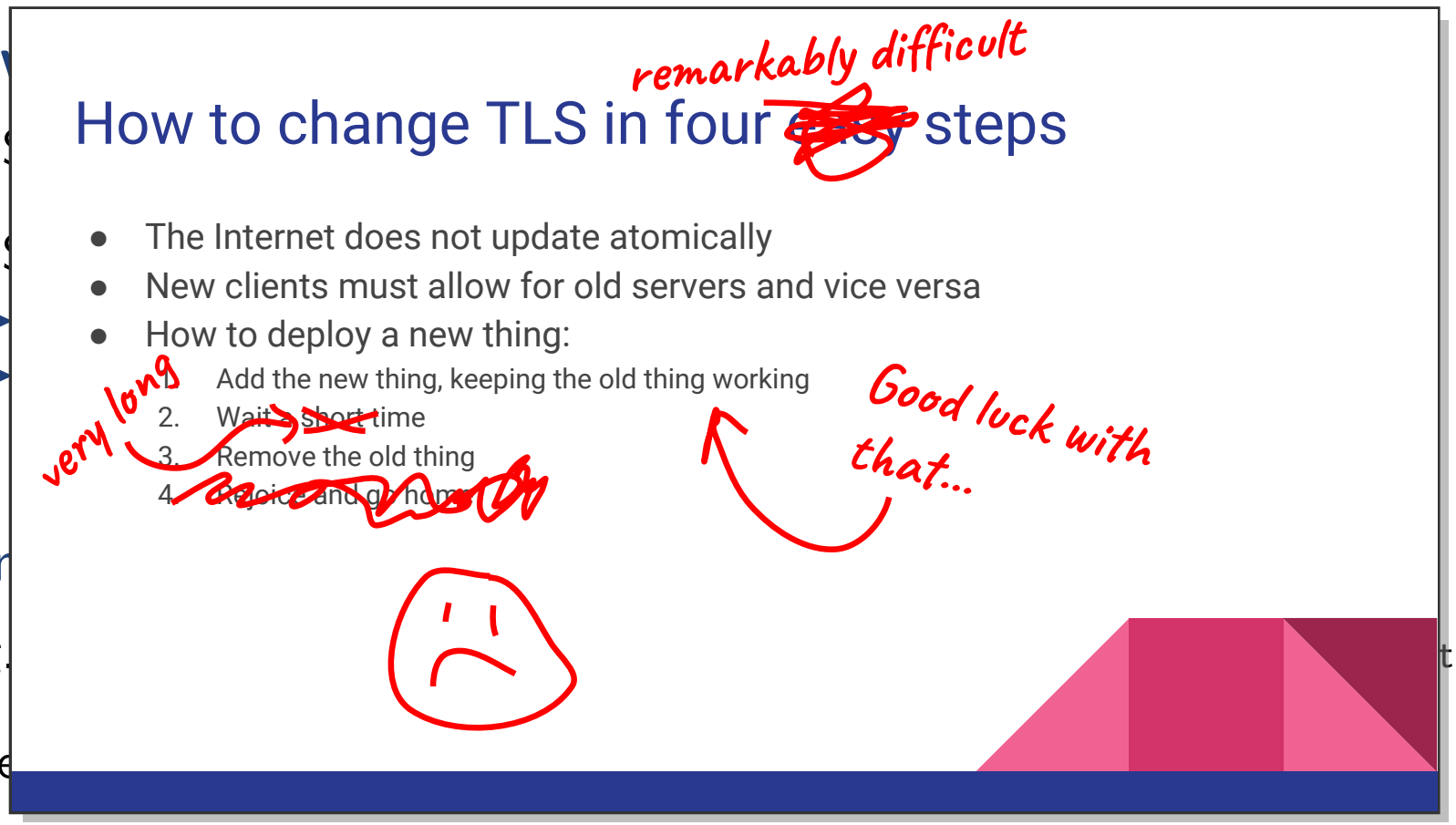

(David Benjamin @ RWC 2018: "TLS Ecosystem Woes: Why your Crypto isn't Real World yet")

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Part II

TLS 1.3
Design & Security Analyses

The Cryptographic Core

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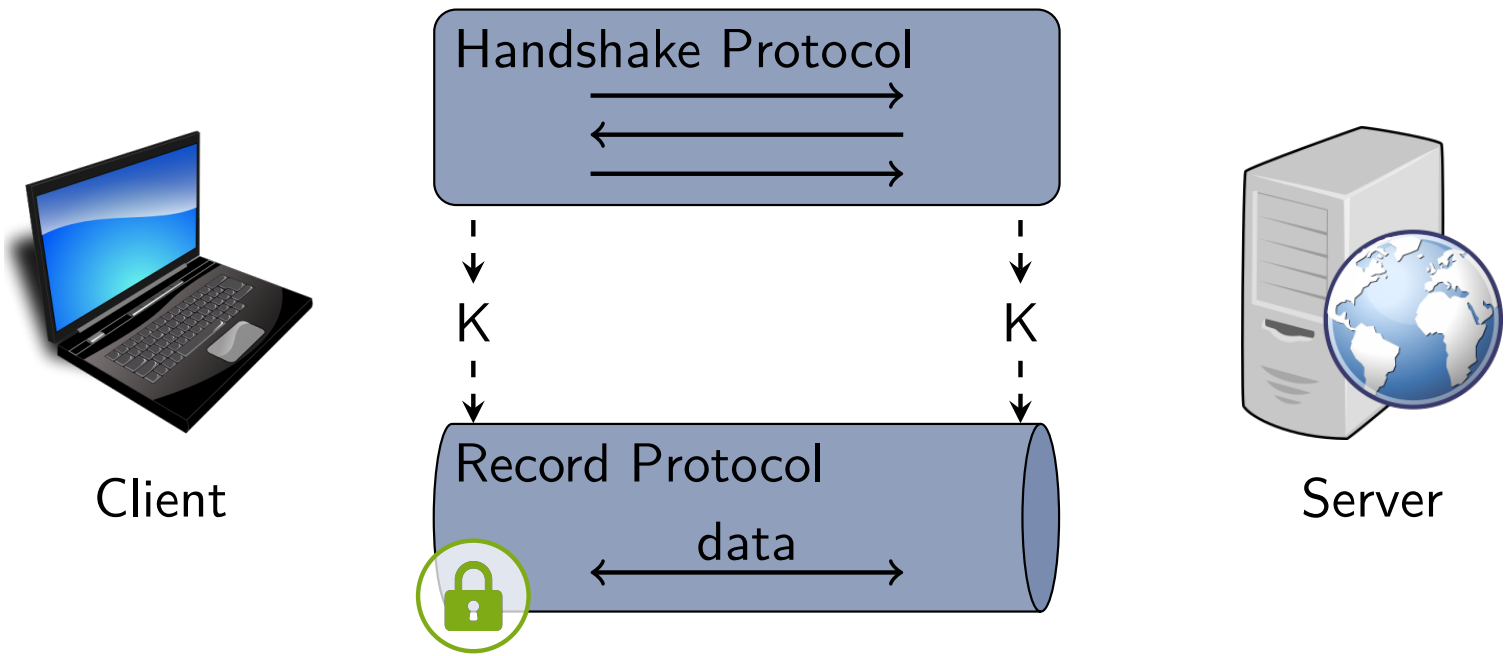

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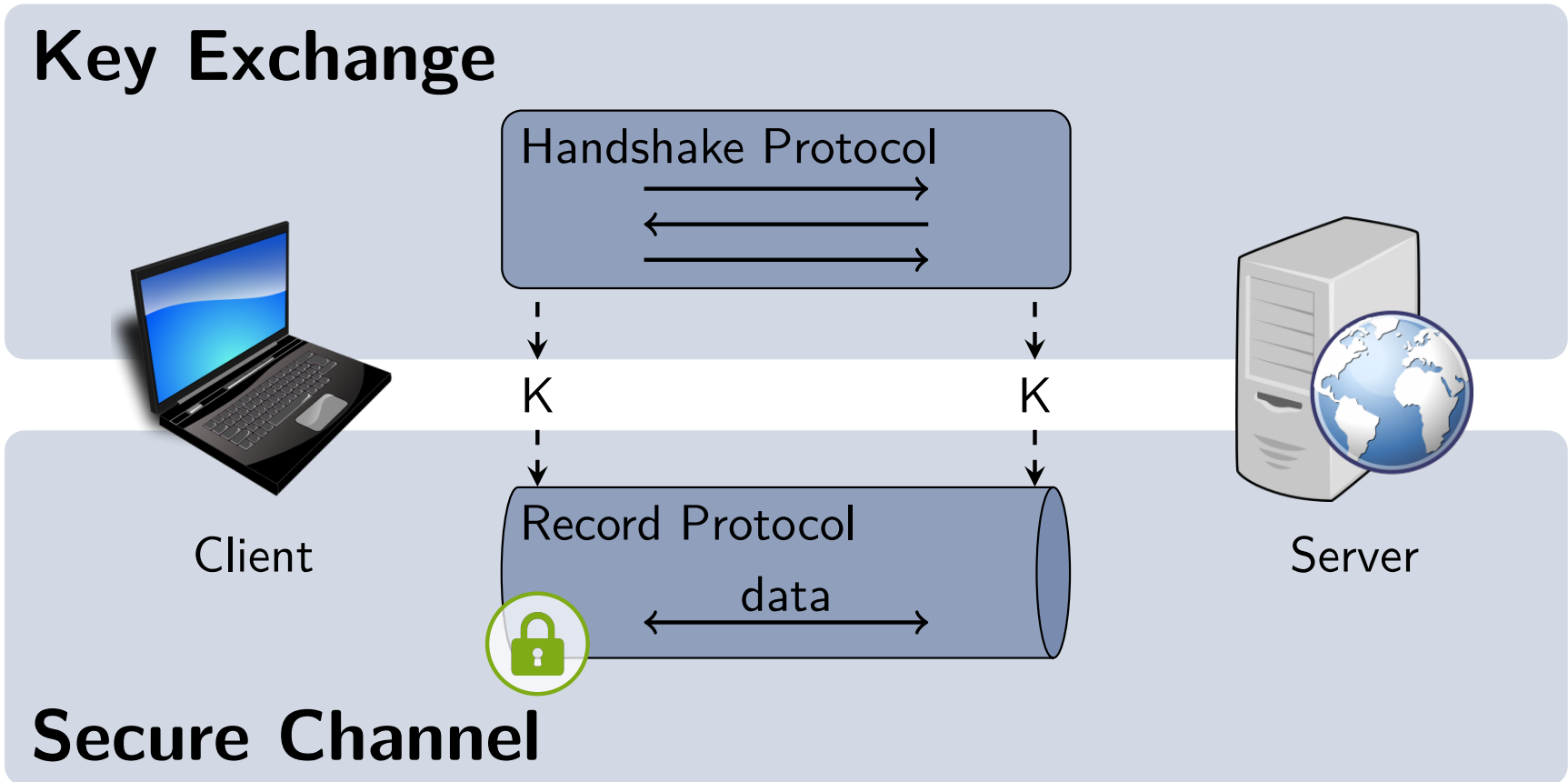
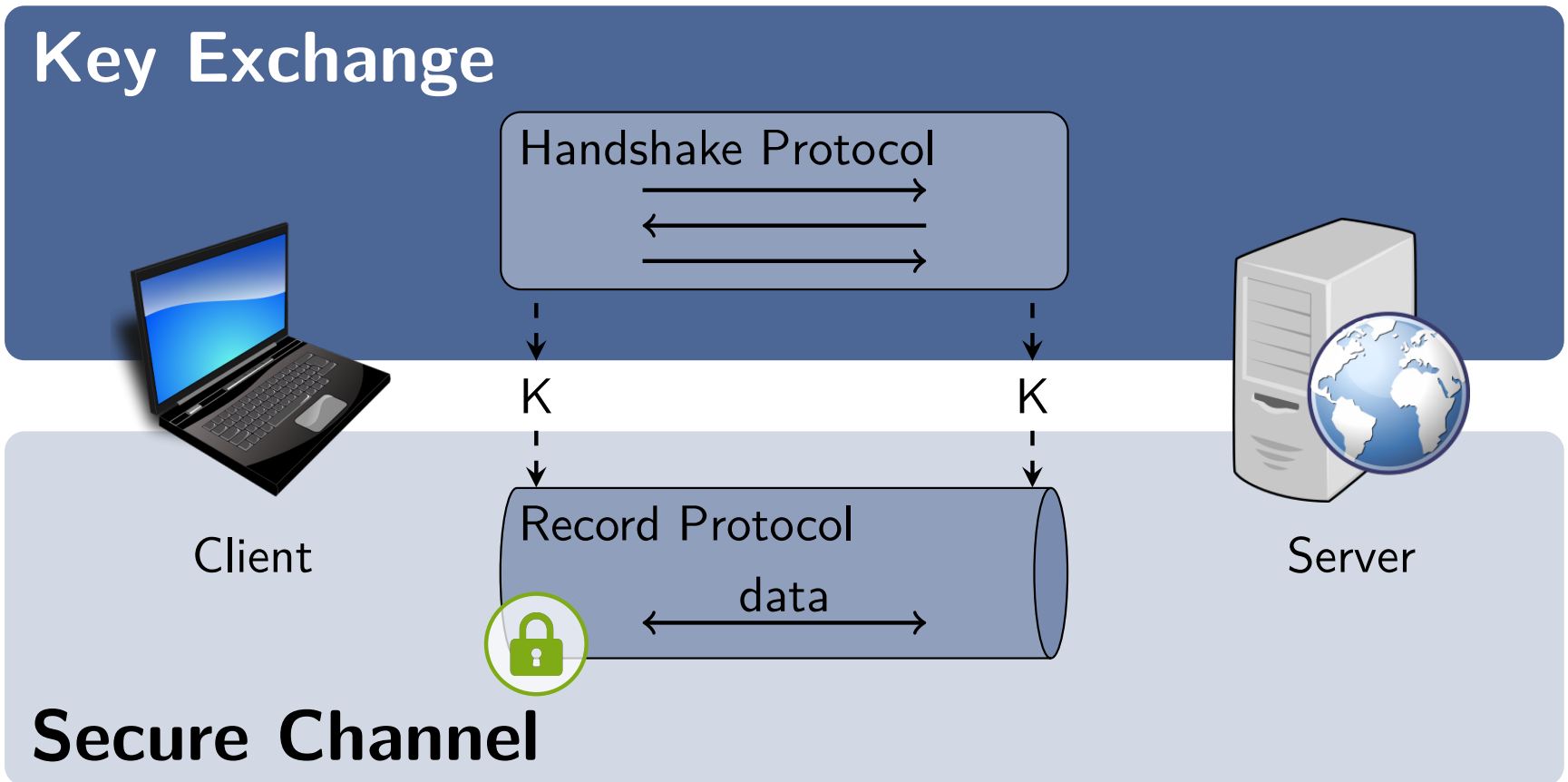
ETH zürich



The Cryptographic Core

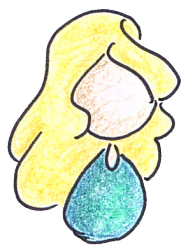
ETH zürich



Key Exchange à la Diffie–Hellman

Diffie, Hellman: New directions in cryptography. 1976 [DH76]
— see PKE Lectures

ETH zürich



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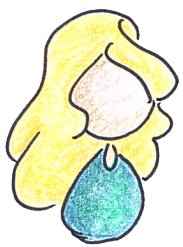
— see PKE Lectures

ETH zürich

knows x



g^x

g^y

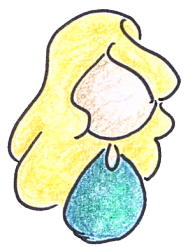
knows y

Key Exchange à la Diffie–Hellman

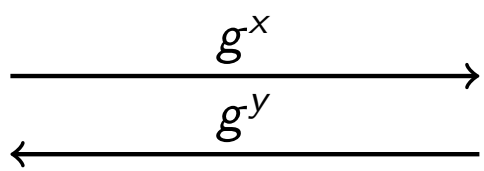
Diffie, Hellman: New directions in cryptography. 1976 [DH76]
— see PKE Lectures

ETH zürich

knows x



knows y



$g^{xy} = (g^y)^x$

$K = \mathrm{KDF}(g^{xy})$

KDF: Key Derivation Function

$g^{xy} = (g^x)^y$

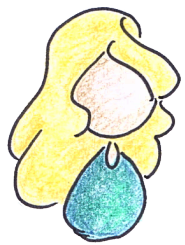
$K = \mathrm{KDF}(g^{xy})$

Key Exchange à la Diffie–Hellman

Diffie, Hellman: New directions in cryptography. 1976 [DH76]
— see PKE Lectures

ETH zürich

knows x



g^x

g^y

knows y

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KDF: Key Derivation Function

$g^{xy} = (g^x)^y$

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- key secrecy: given only g^x and g^y, key K remains secret (indist. from )

Key Exchange à la Diffie–Hellman

Diffie, Hellman: New directions in cryptography. 1976 [DH76]
— see PKE Lectures

ETH zürich

DDH: g^a g^b g^{ab} / g^a g^b g^r ?

knows x knows y

g^x

g^y

$g^{xy} = (g^y)^x$
$K = \mathrm{KDF}(g^{xy})$

KDF: Key Derivation Function

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ETH zürich

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knows x

$g^{xy} = (g^y)^x$

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g^a

g^b

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knows y

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ETH zürich

DDH: g^a g^b g^{ab} / g^a g^b g^r ?

knows x

knows y

g^a

g^b

$g^{xy} = g^?$

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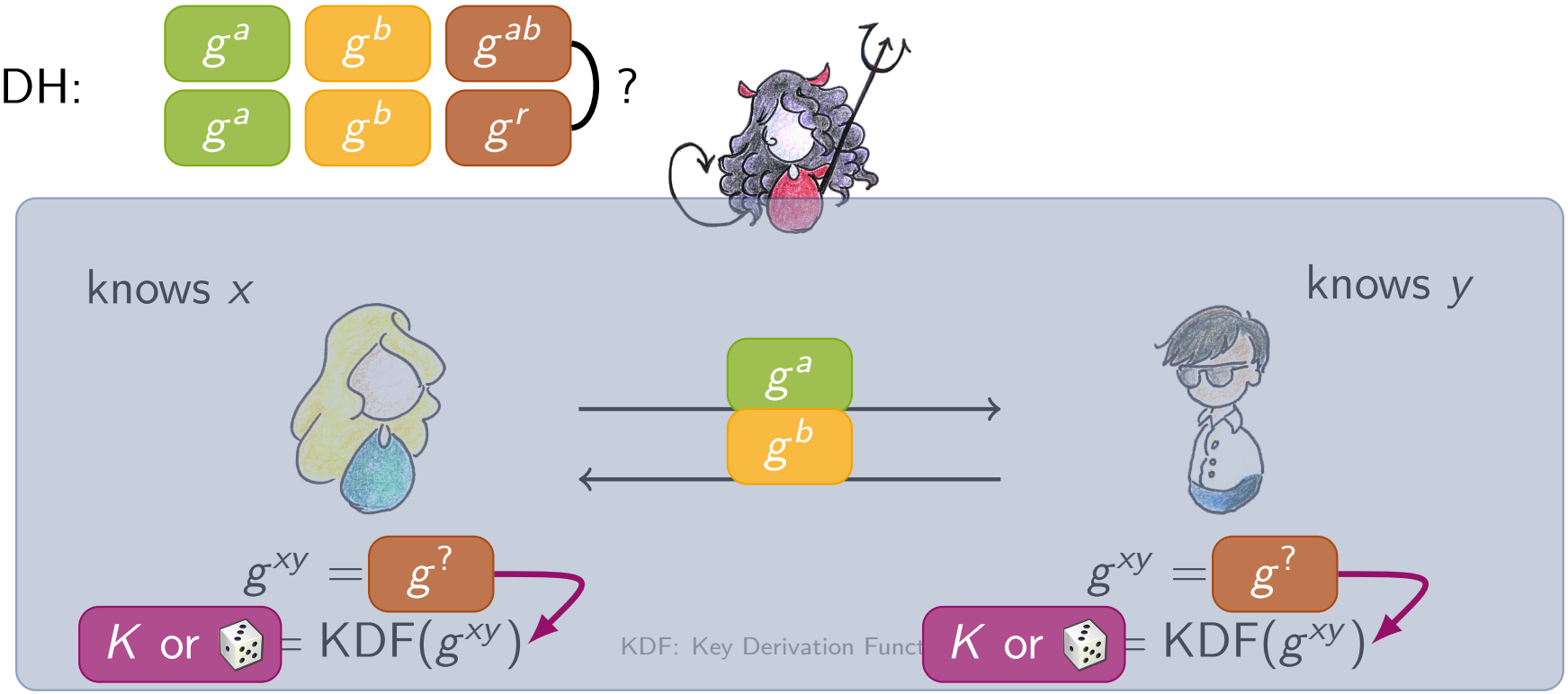
ETH zürich



- key secrecy: given only g^x and g^y, key K remains secret (indist. from)

Key Exchange à la Diffie–Hellman

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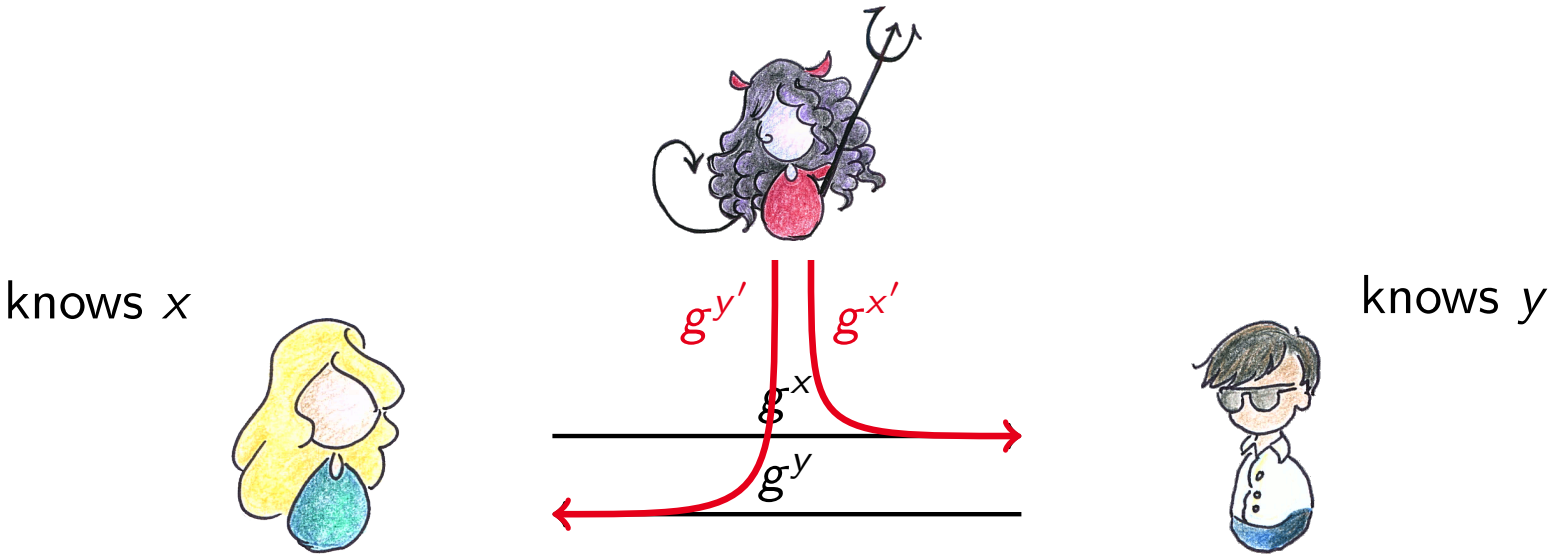
ETH zürich



$g^{xy} = (g^y)^x$
$K = \mathrm{KDF}(g^{xy})$
$K' = \mathrm{KDF}(g^{xy'})$

KDF: Key Derivation Function

$g^{xy} = (g^x)^y$
$K = \mathrm{KDF}(g^{xy})$
$K'' = \mathrm{KDF}(g^{x'y})$

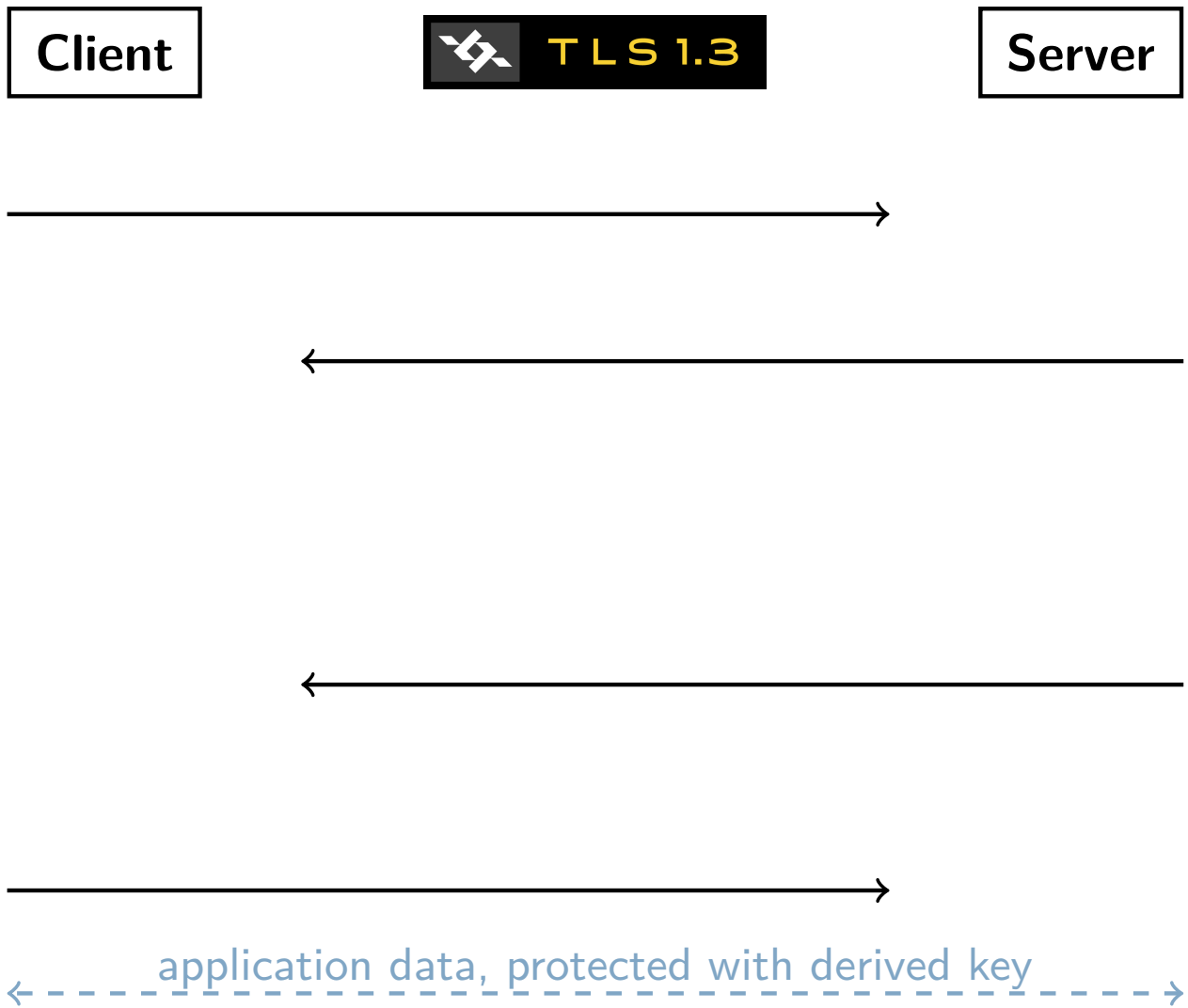
- key secrecy: given only g^x and g^y, key K remains secret (indist. from )
- just one of many building blocks (no security against MitM, . . .)

The TLS 1.3 Handshake

Full (EC)DHE Mode

ETH zürich

(simplified)



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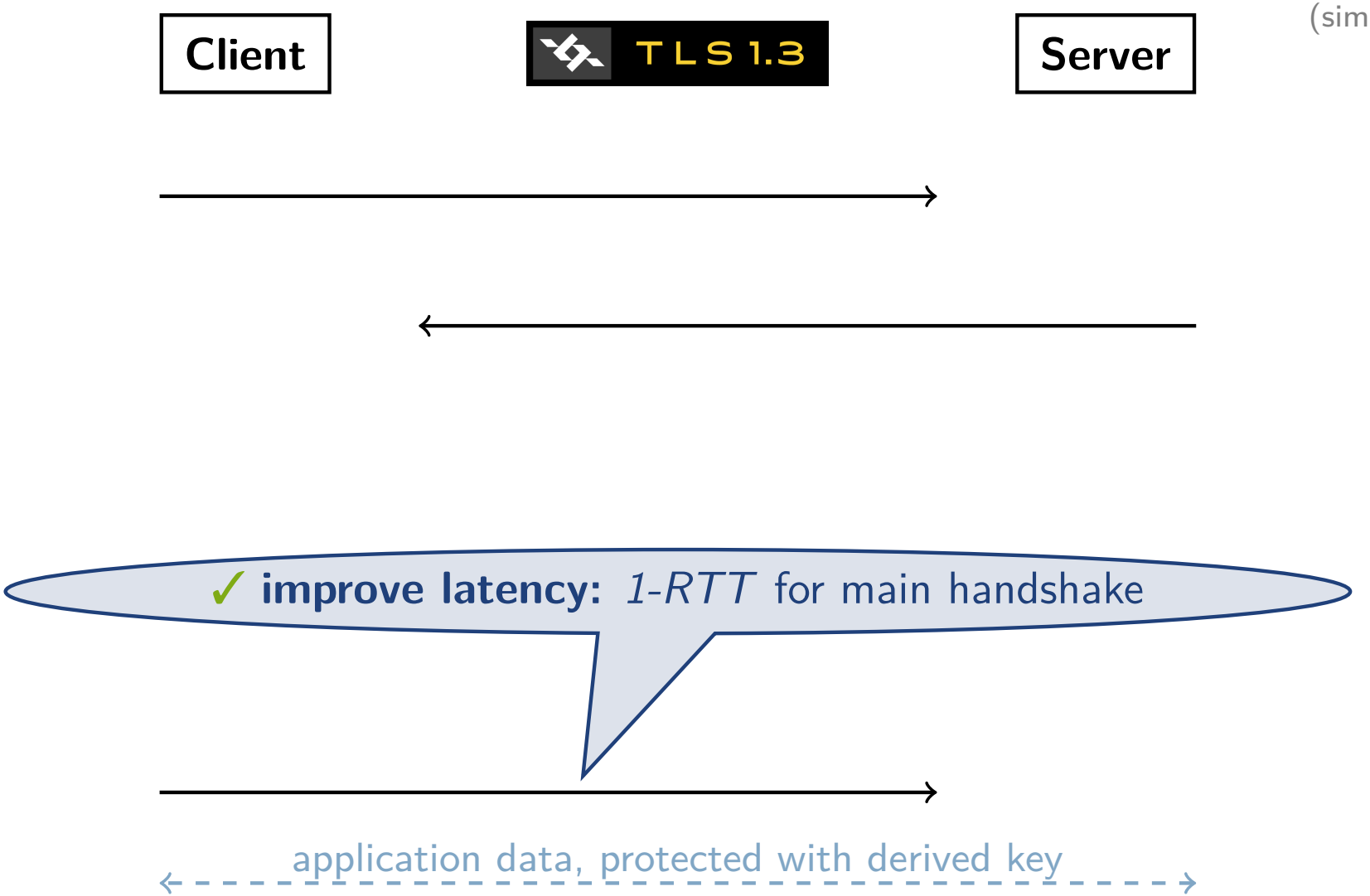
Full (EC)DHE Mode

ETH zürich

(simplified)



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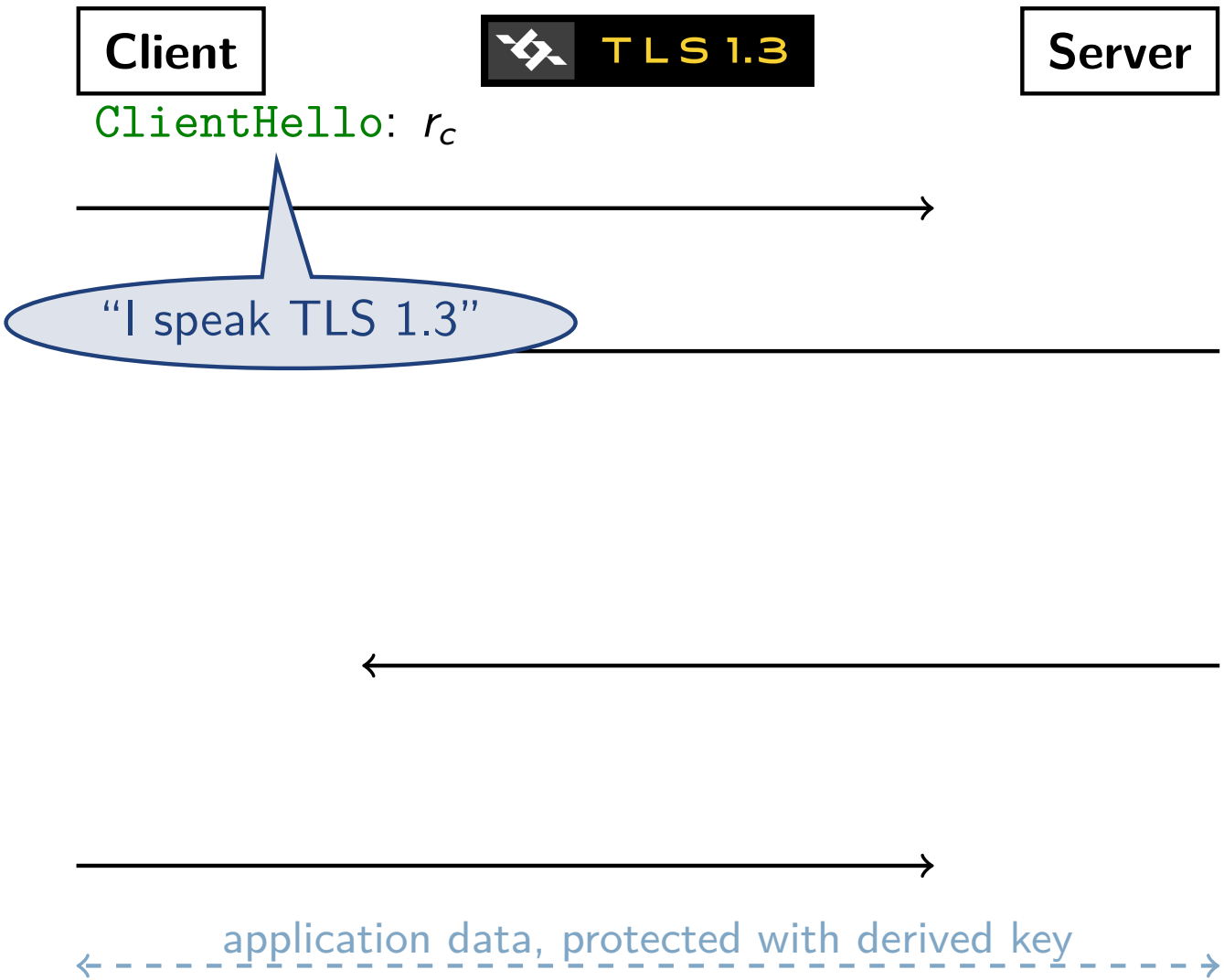
Full (EC)DHE Mode

ETH zürich

(simplified)



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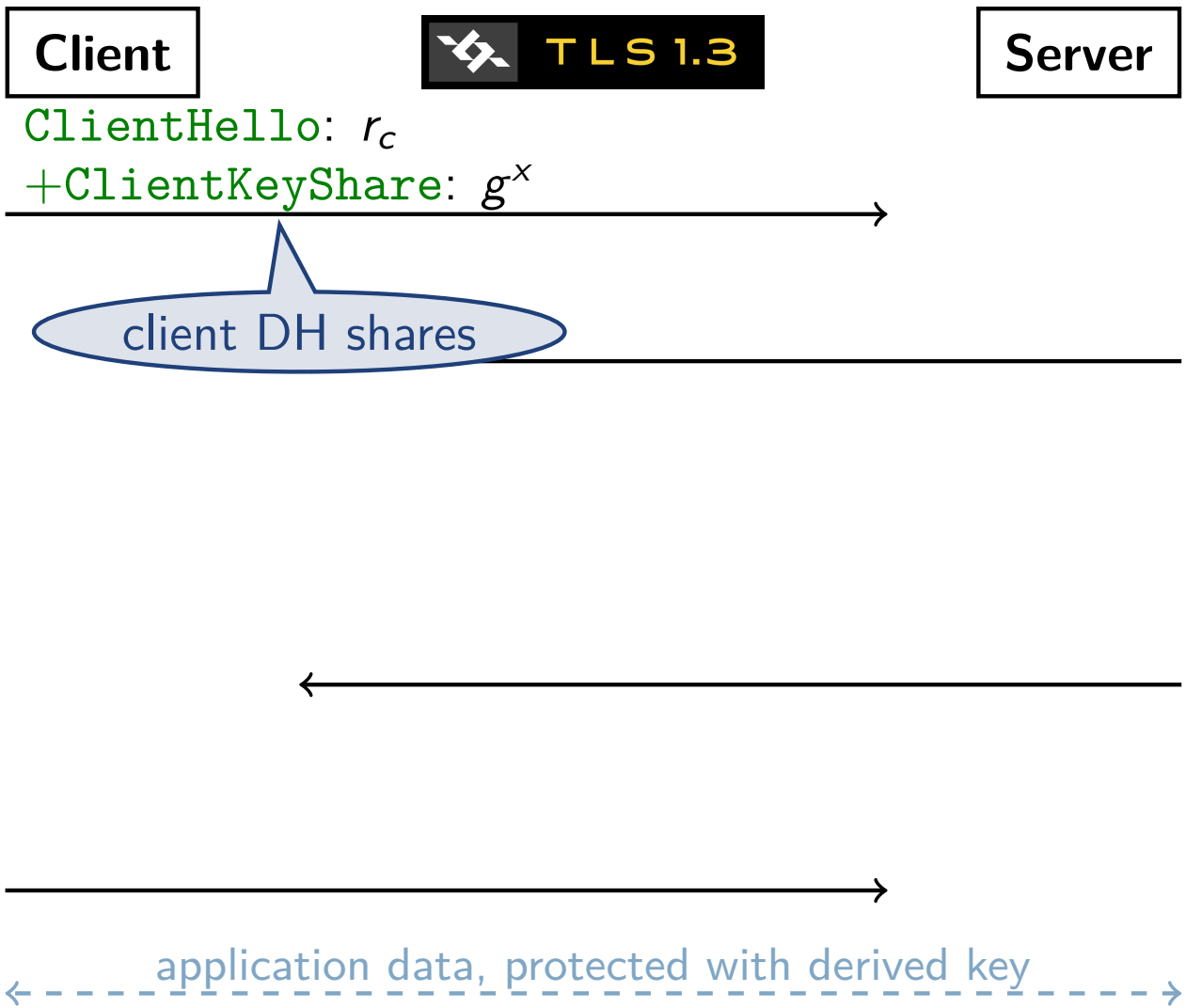
Full (EC)DHE Mode

ETH zürich

(simplified)



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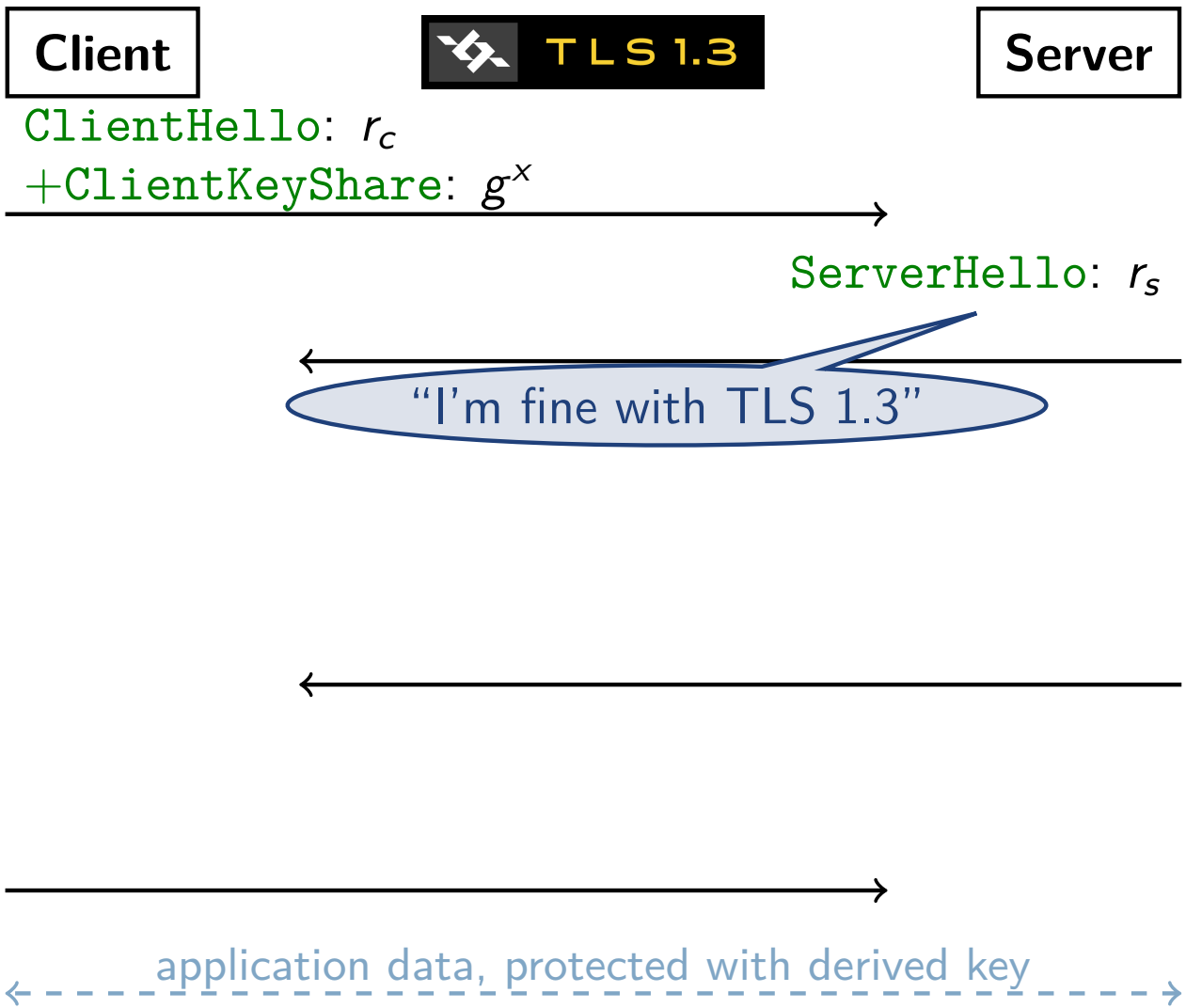
Full (EC)DHE Mode

ETH zürich

(simplified)



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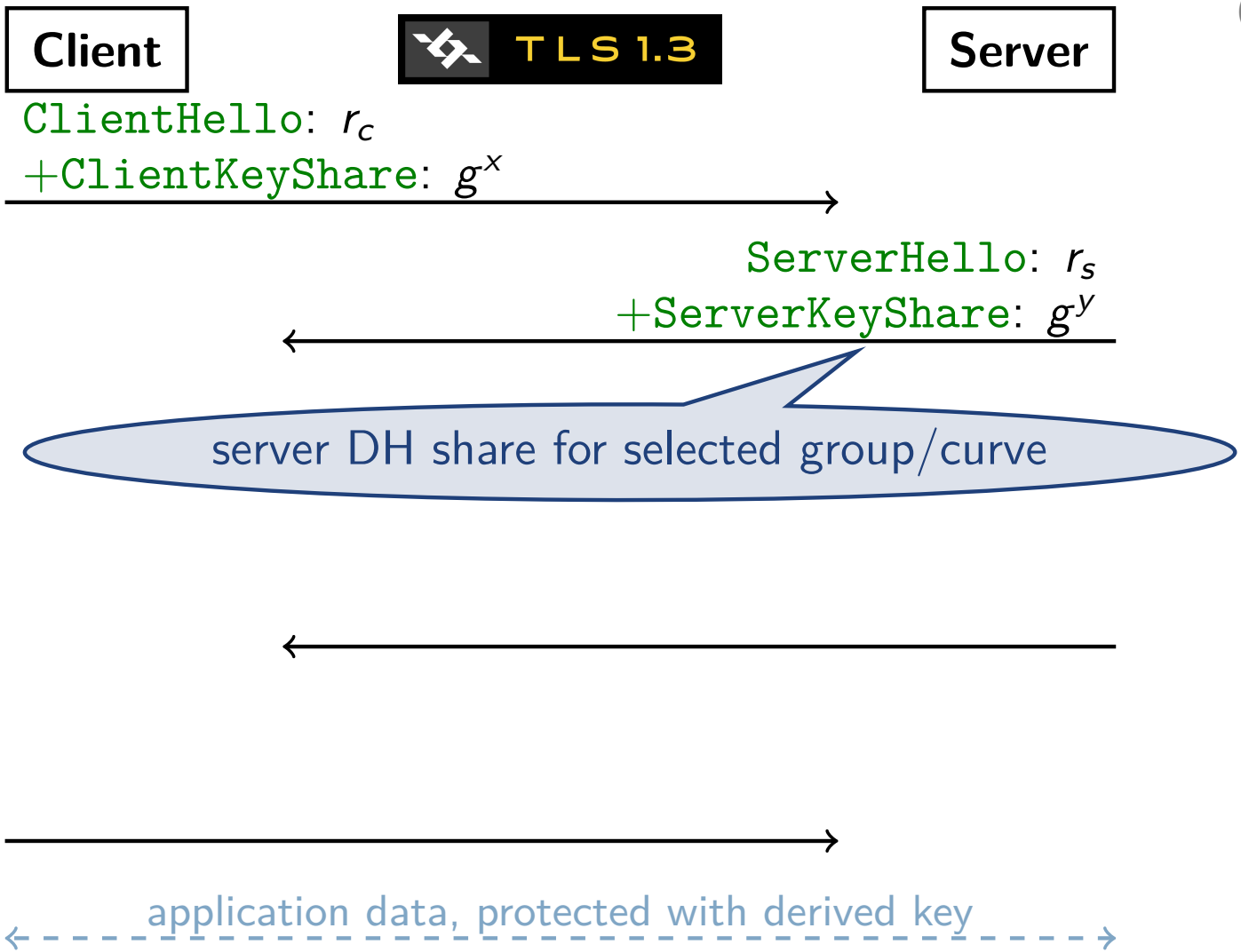
Full (EC)DHE Mode

ETH zürich

(simplified)

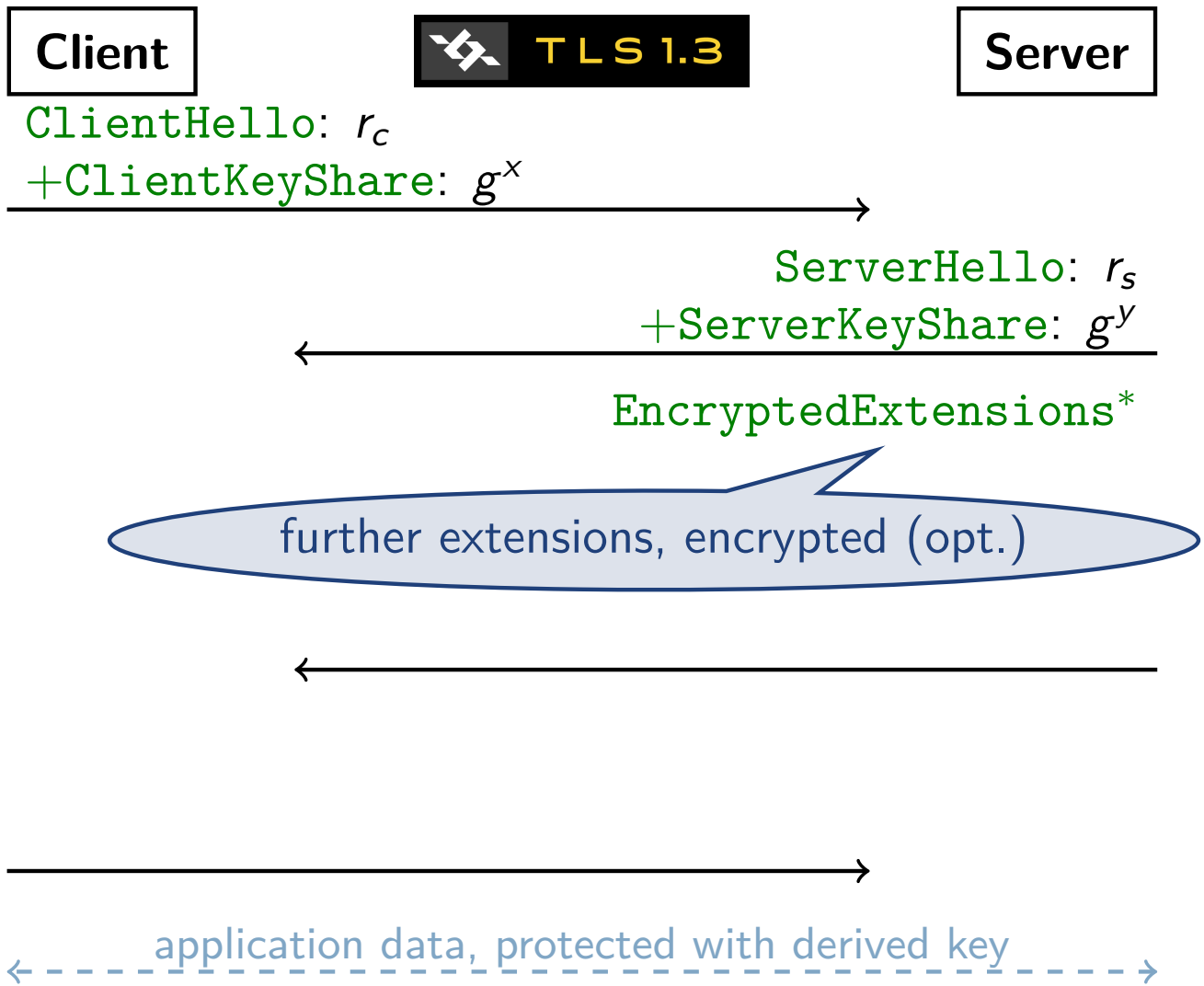


The TLS 1.3 Handshake

Full (EC)DHE Mode

ETH zürich

(simplified)



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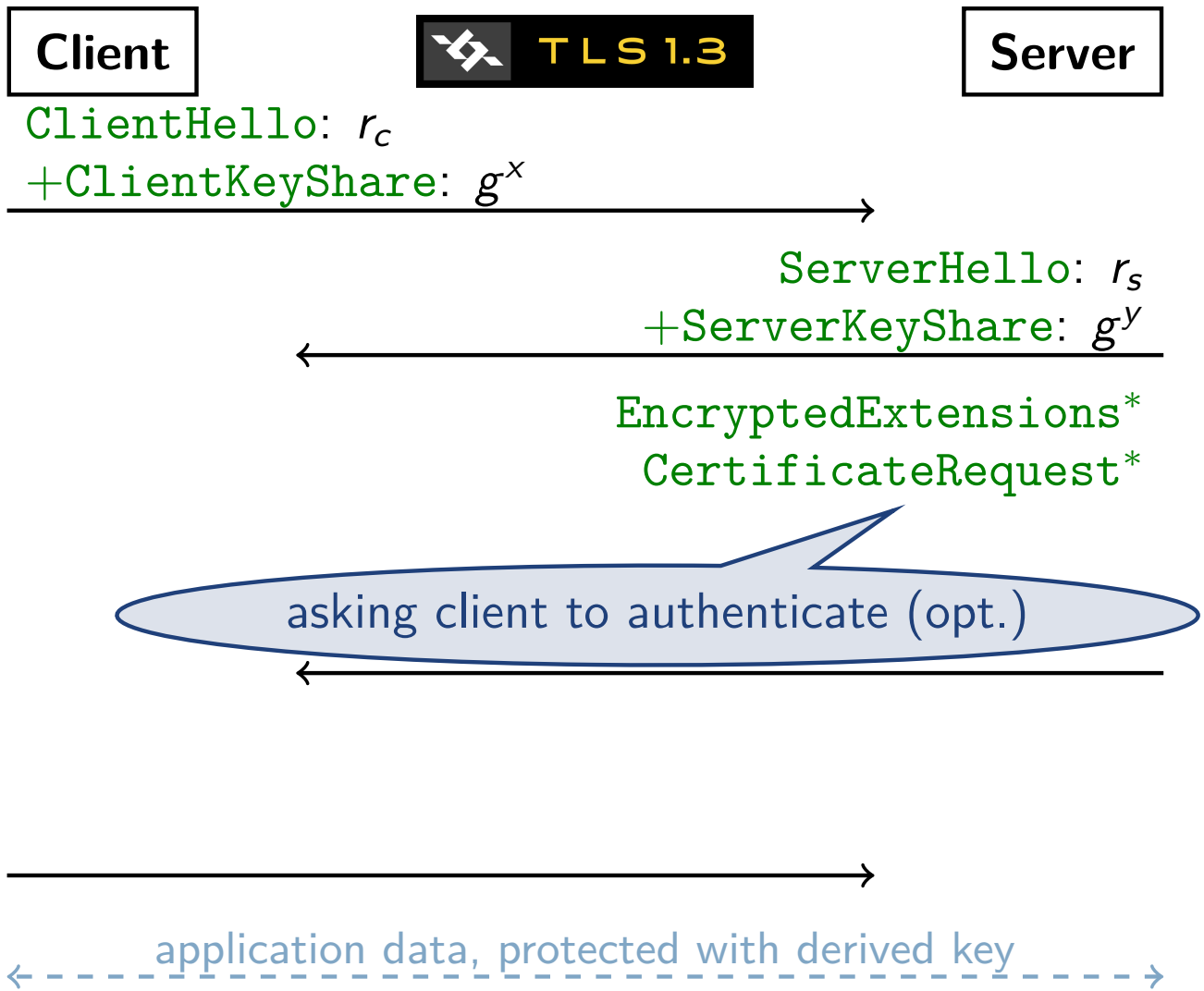
ETH zürich

(simplified)

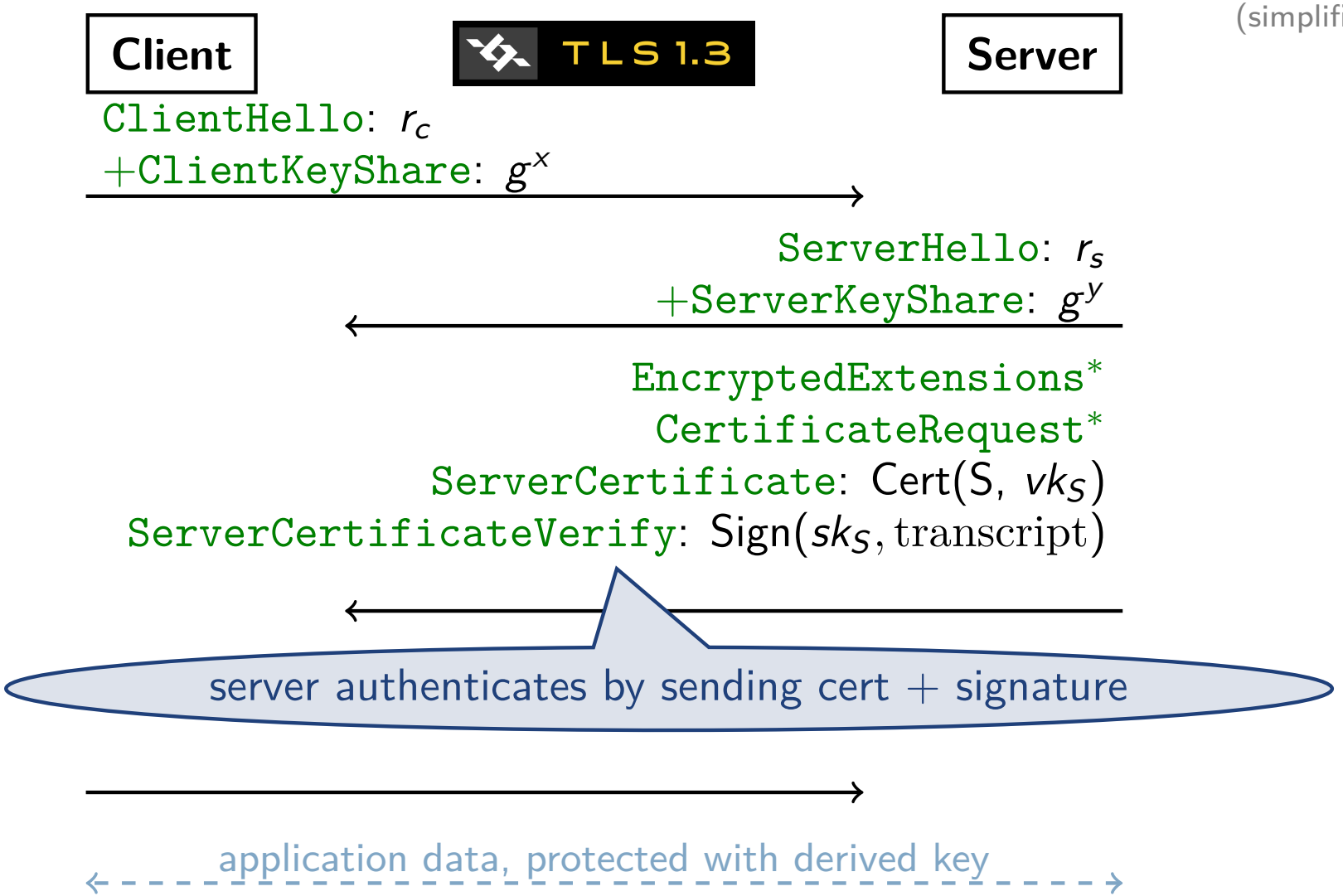


The TLS 1.3 Handshake

Full (EC)DHE Mode

ETH zürich

(simplified)

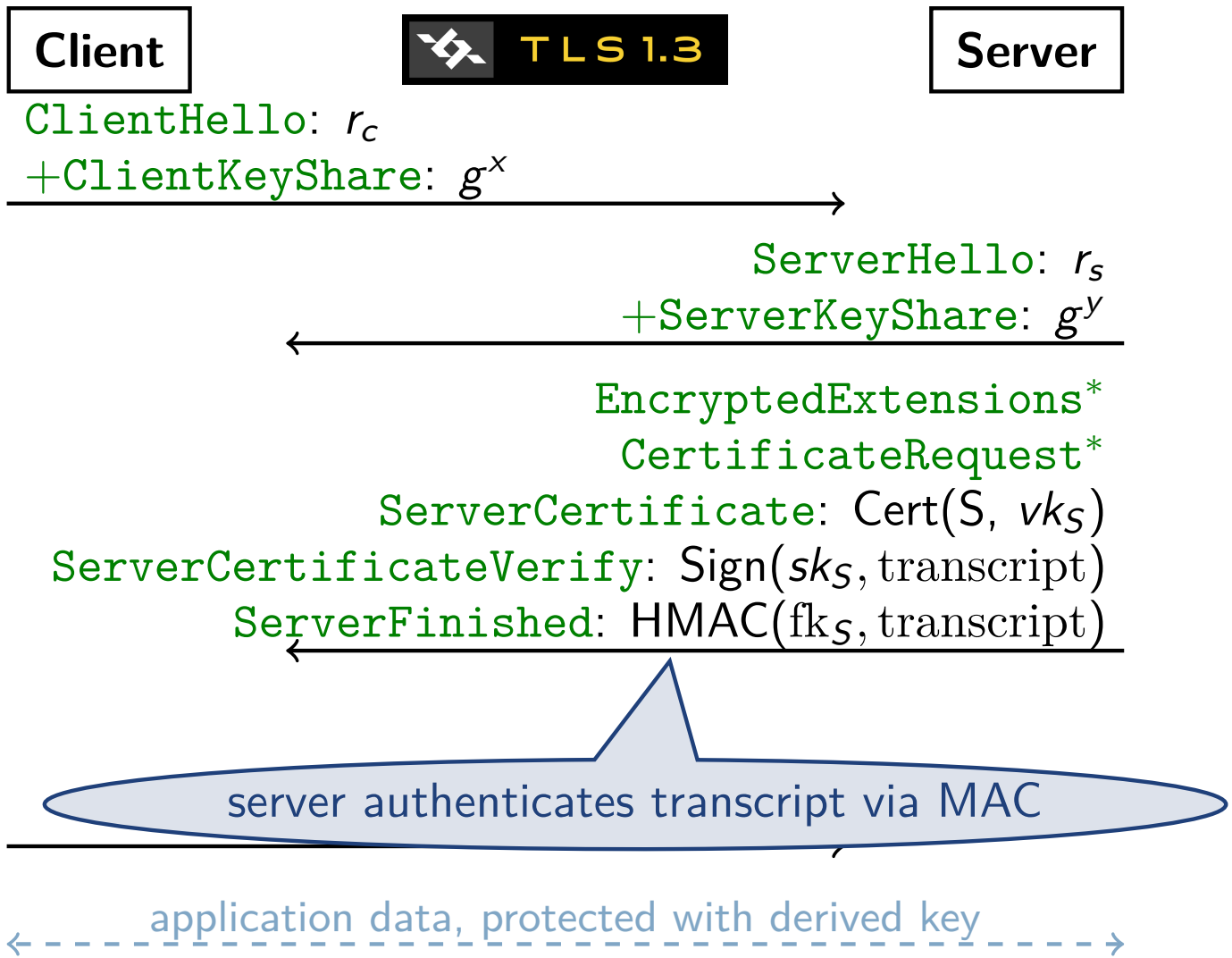


The TLS 1.3 Handshake

Full (EC)DHE Mode

ETH zürich

(simplified)

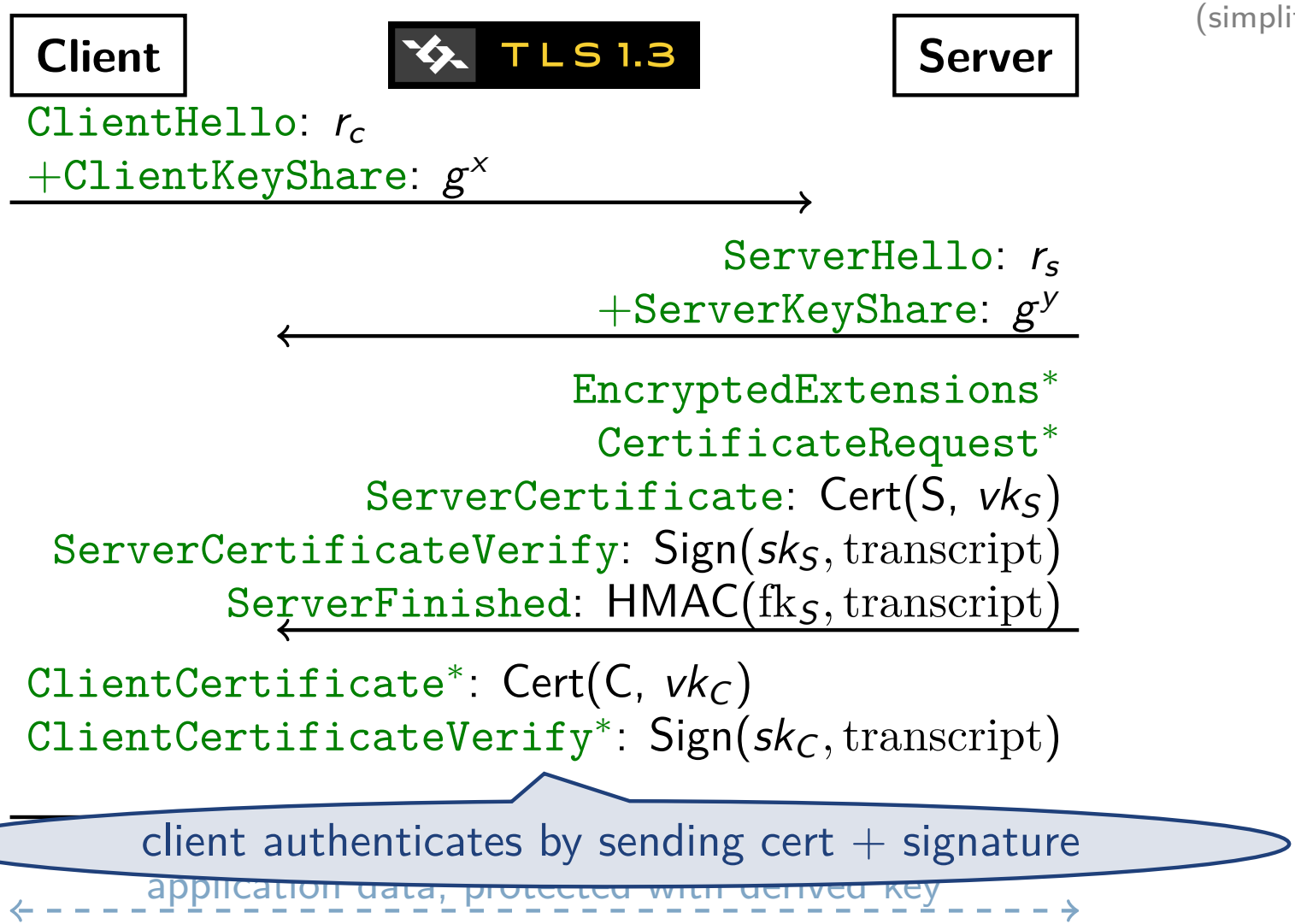


The TLS 1.3 Handshake

Full (EC)DHE Mode

ETH zürich

(simplified)



The TLS 1.3 Handshake

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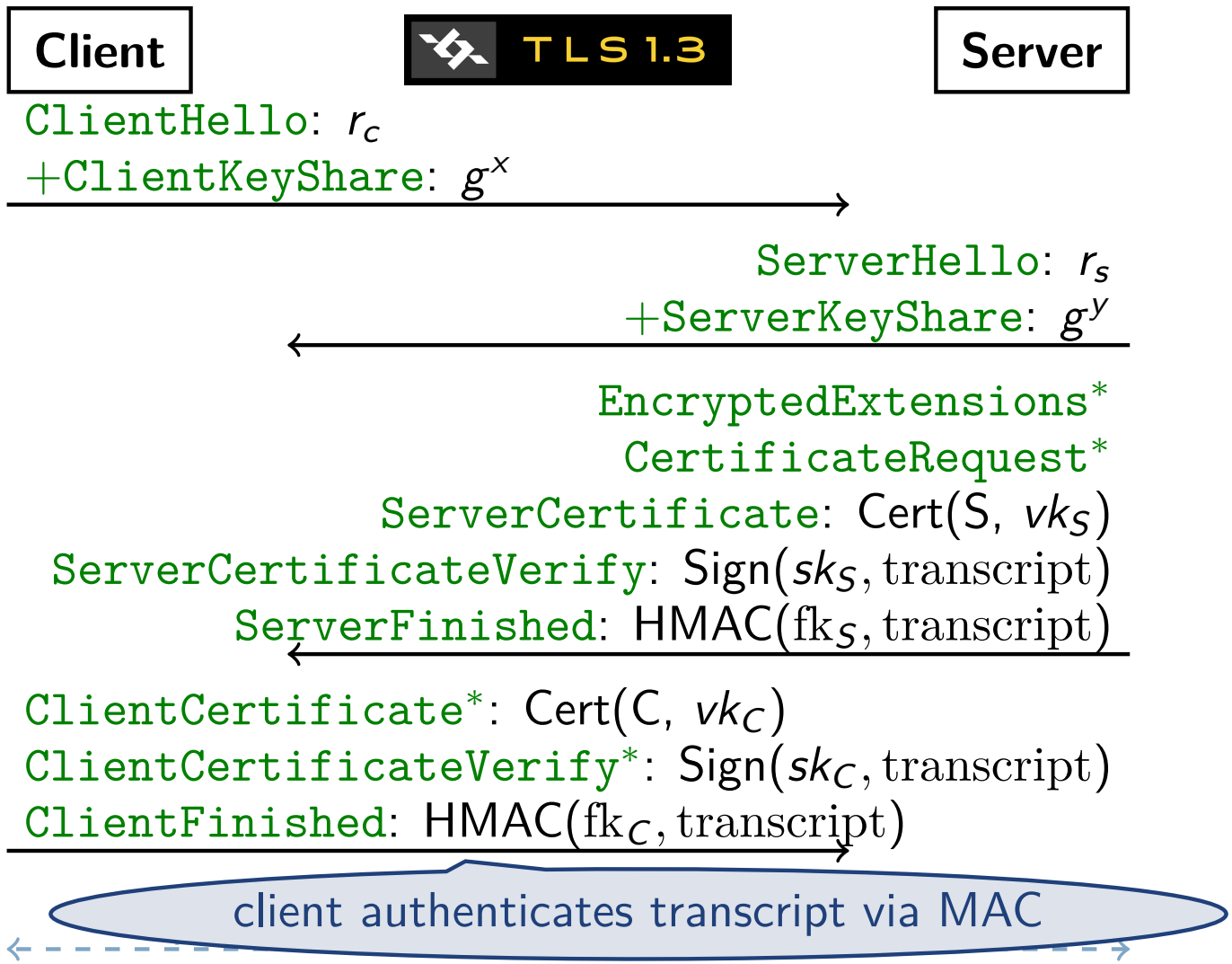
ETH zürich

(simplified)



The TLS 1.3 Handshake

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ETH zürich

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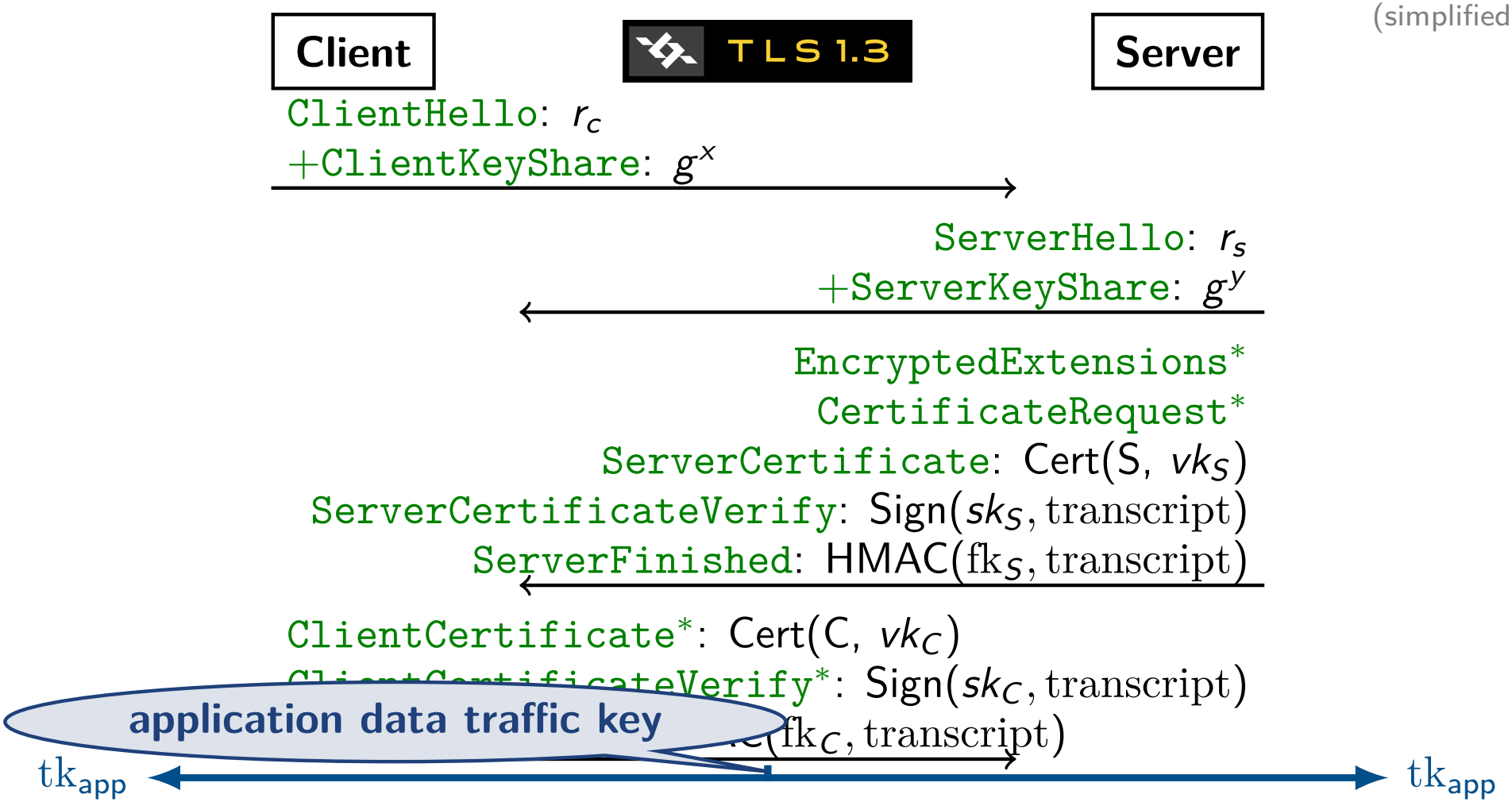

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ETH zürich

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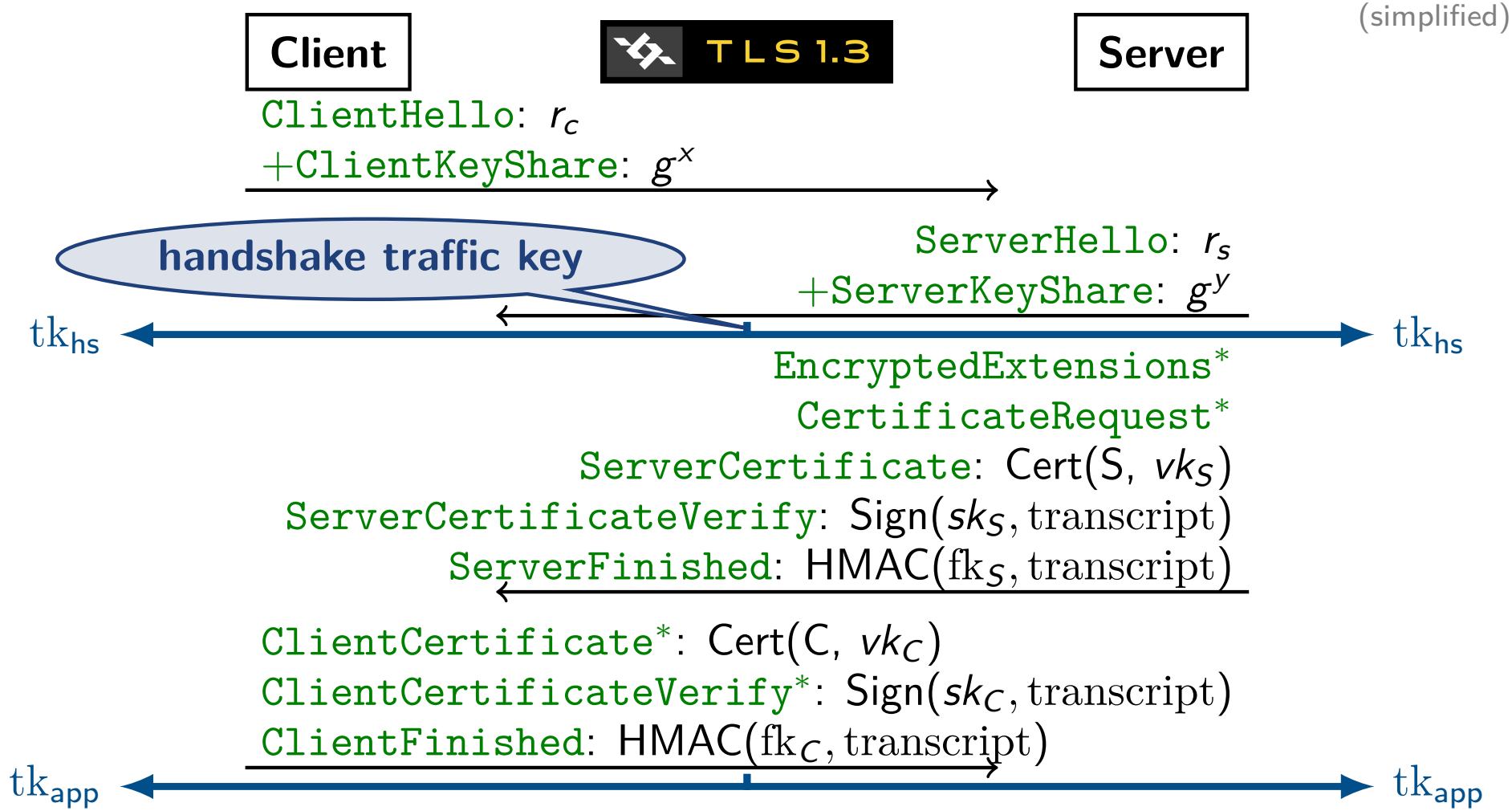

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ETH zürich

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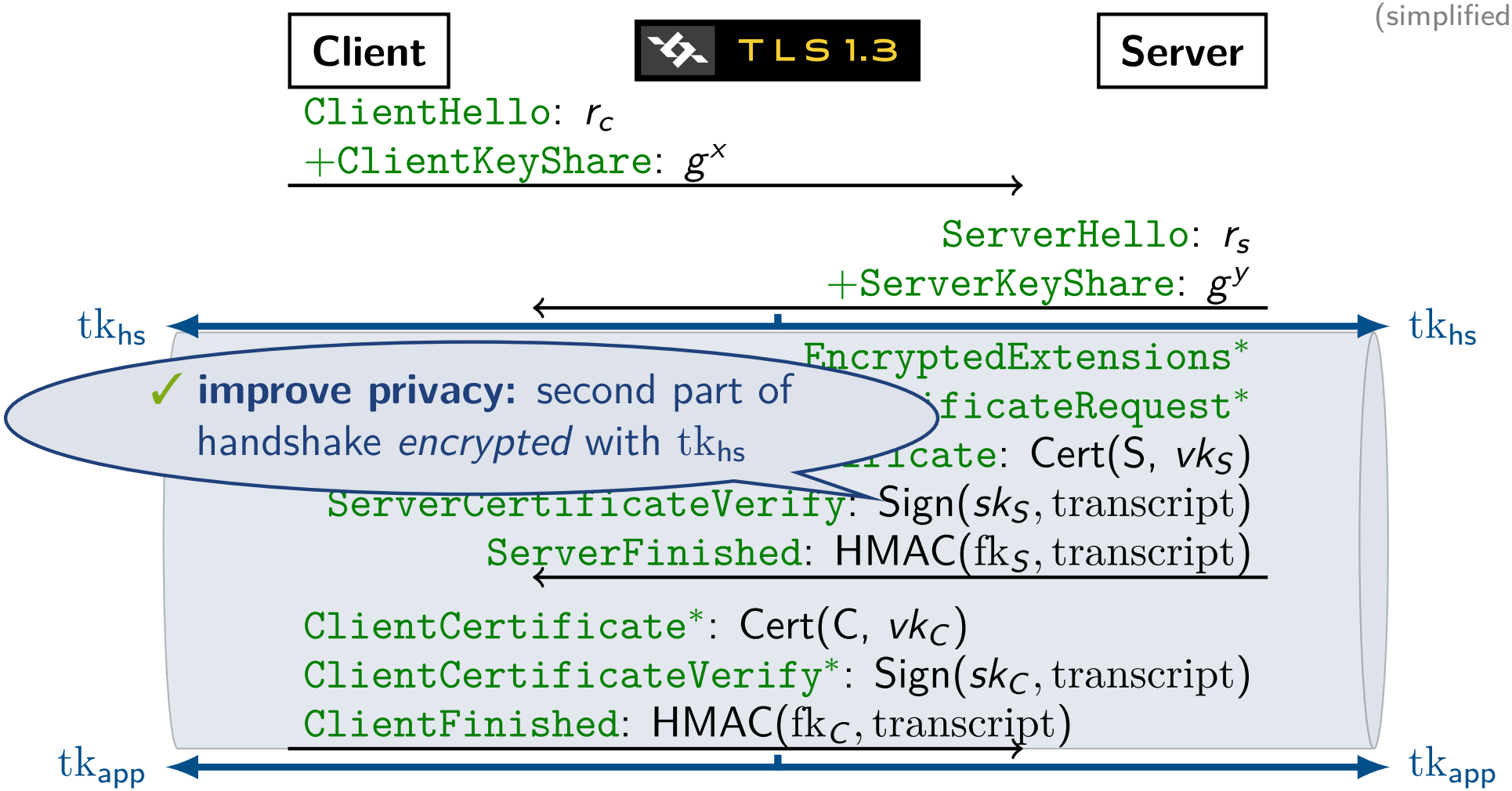

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Full (EC)DHE Mode

ETH zürich

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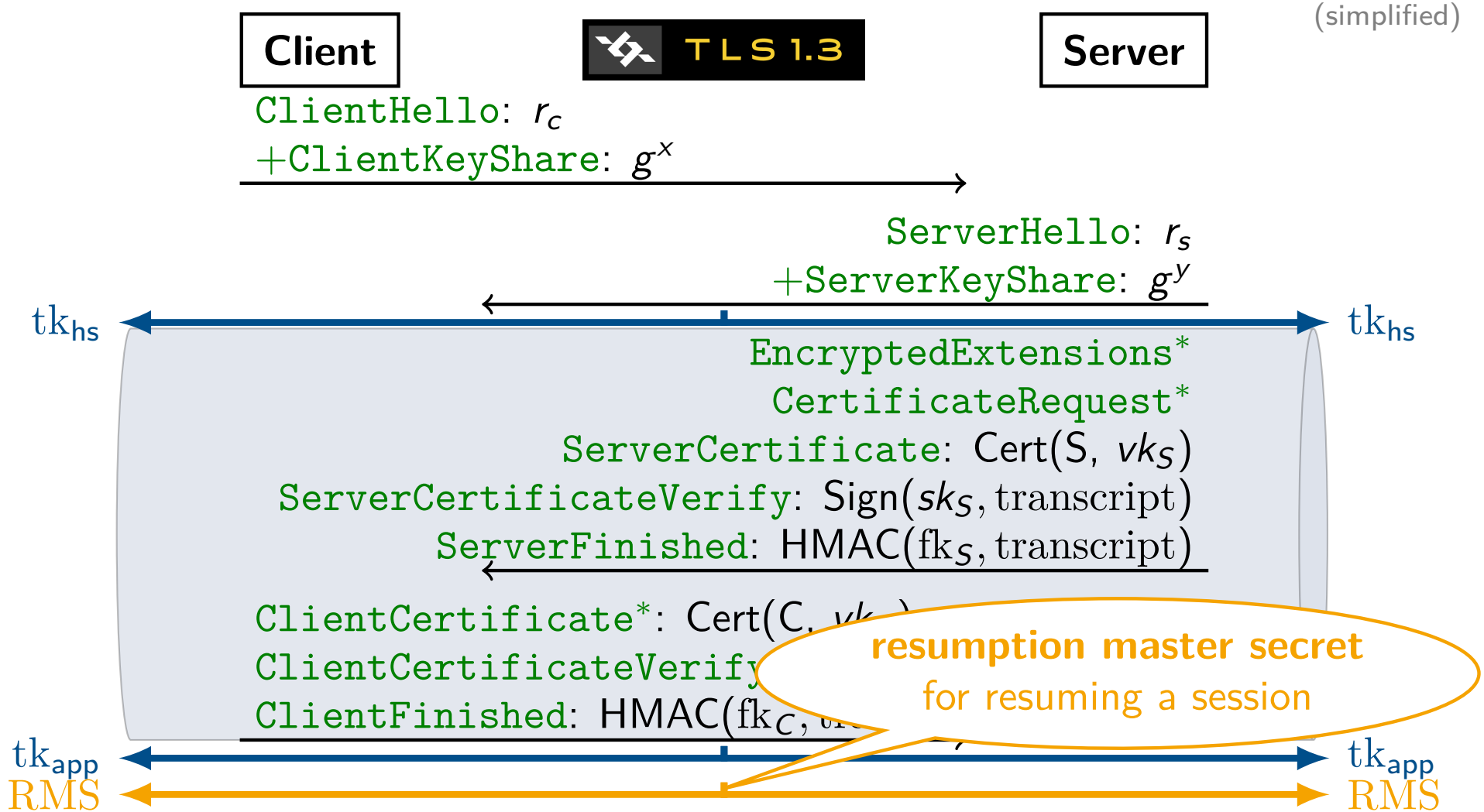

The TLS 1.3 Handshake

Full (EC)DHE Mode

ETH zürich

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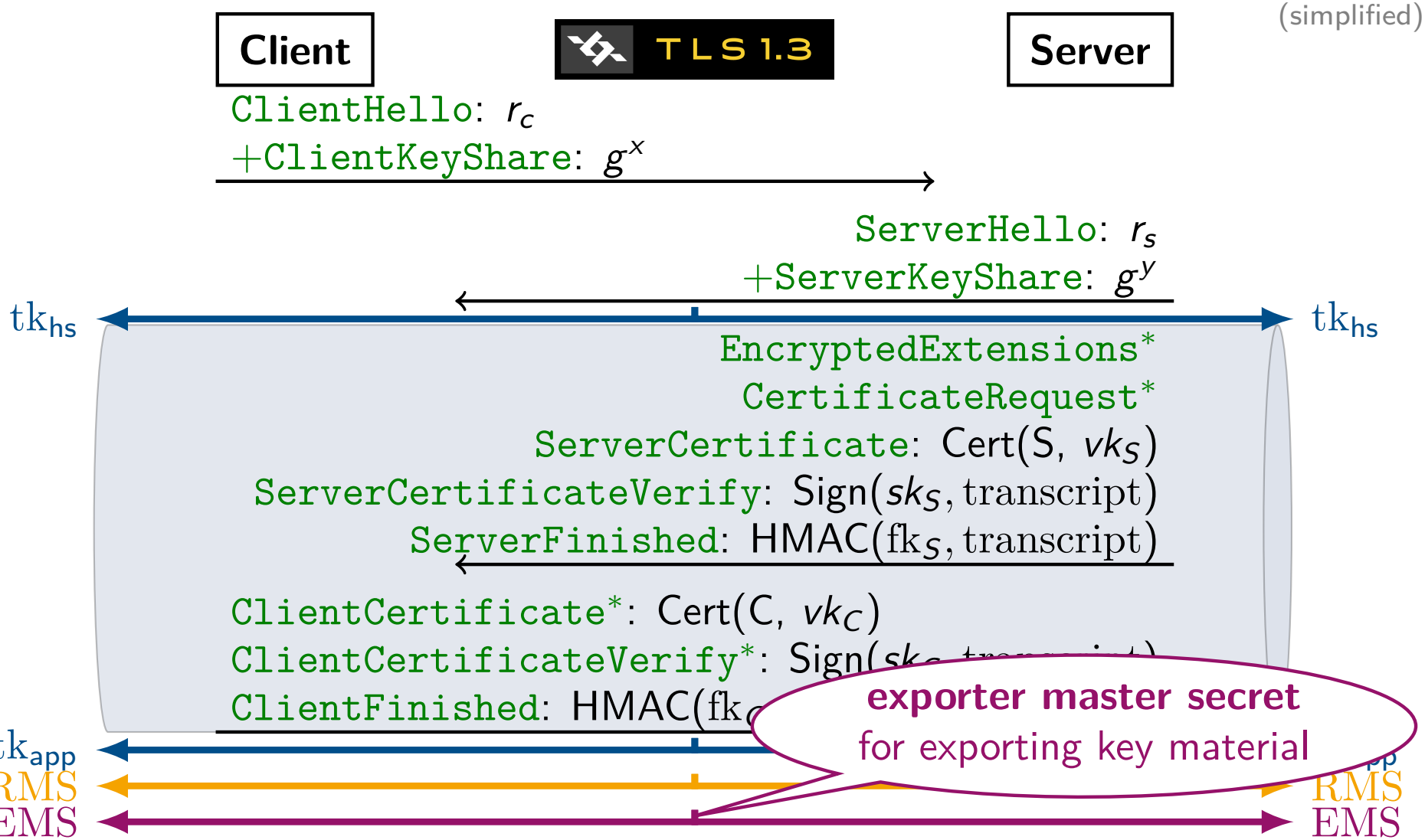

The TLS 1.3 Handshake

Full (EC)DHE Mode

ETH zürich

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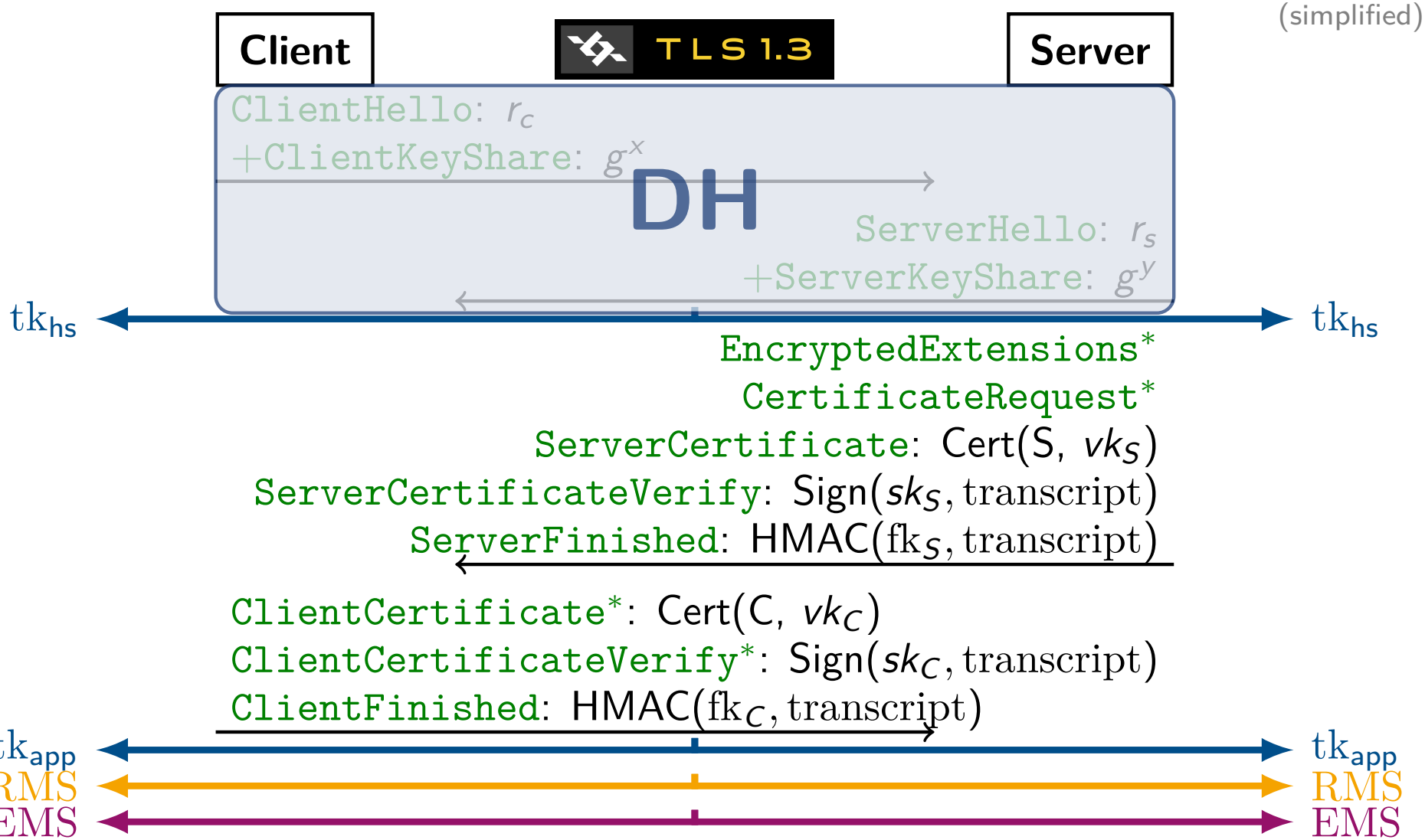
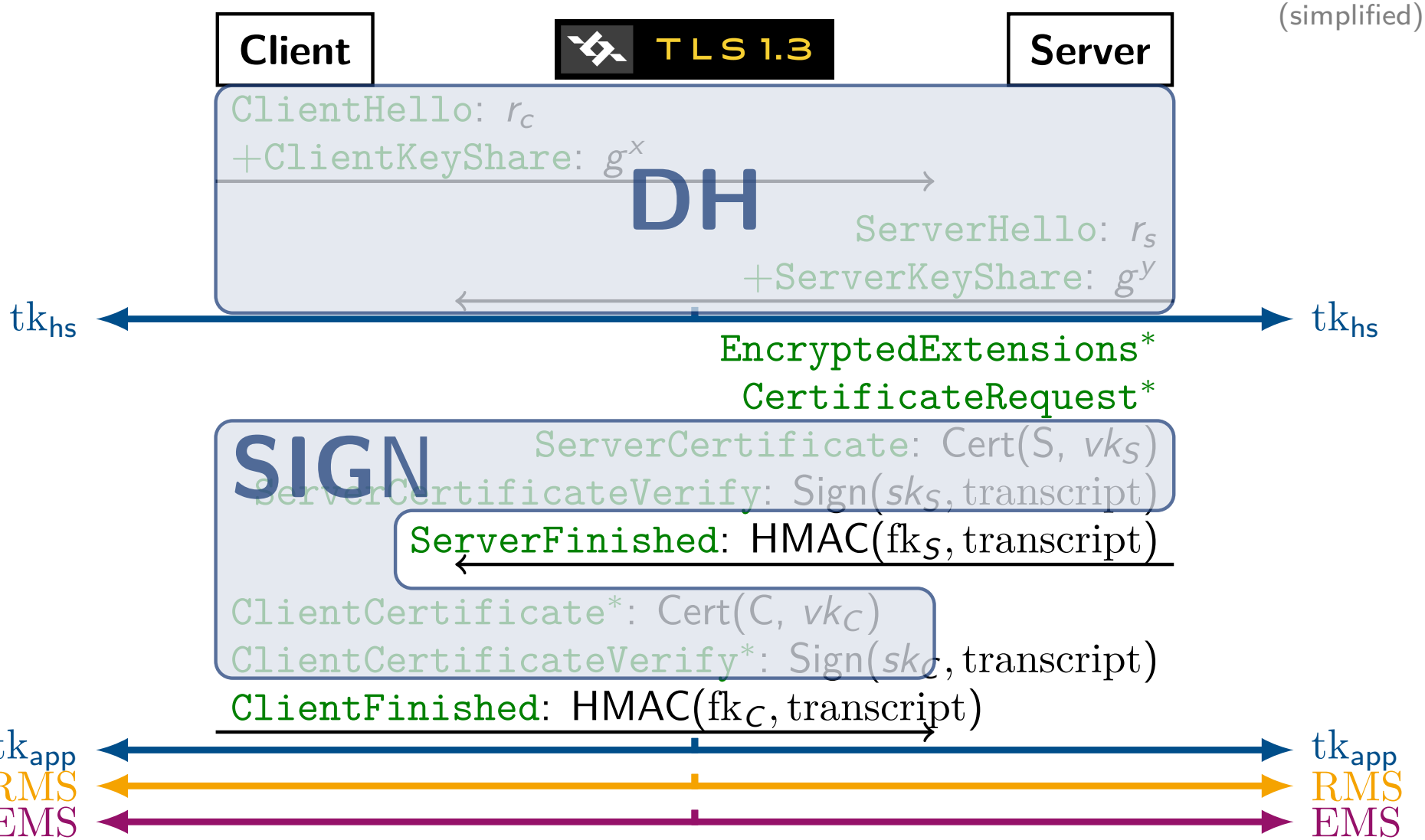


The TLS 1.3 Handshake

Full (EC)DHE Mode

ETH zürich

(simplified)

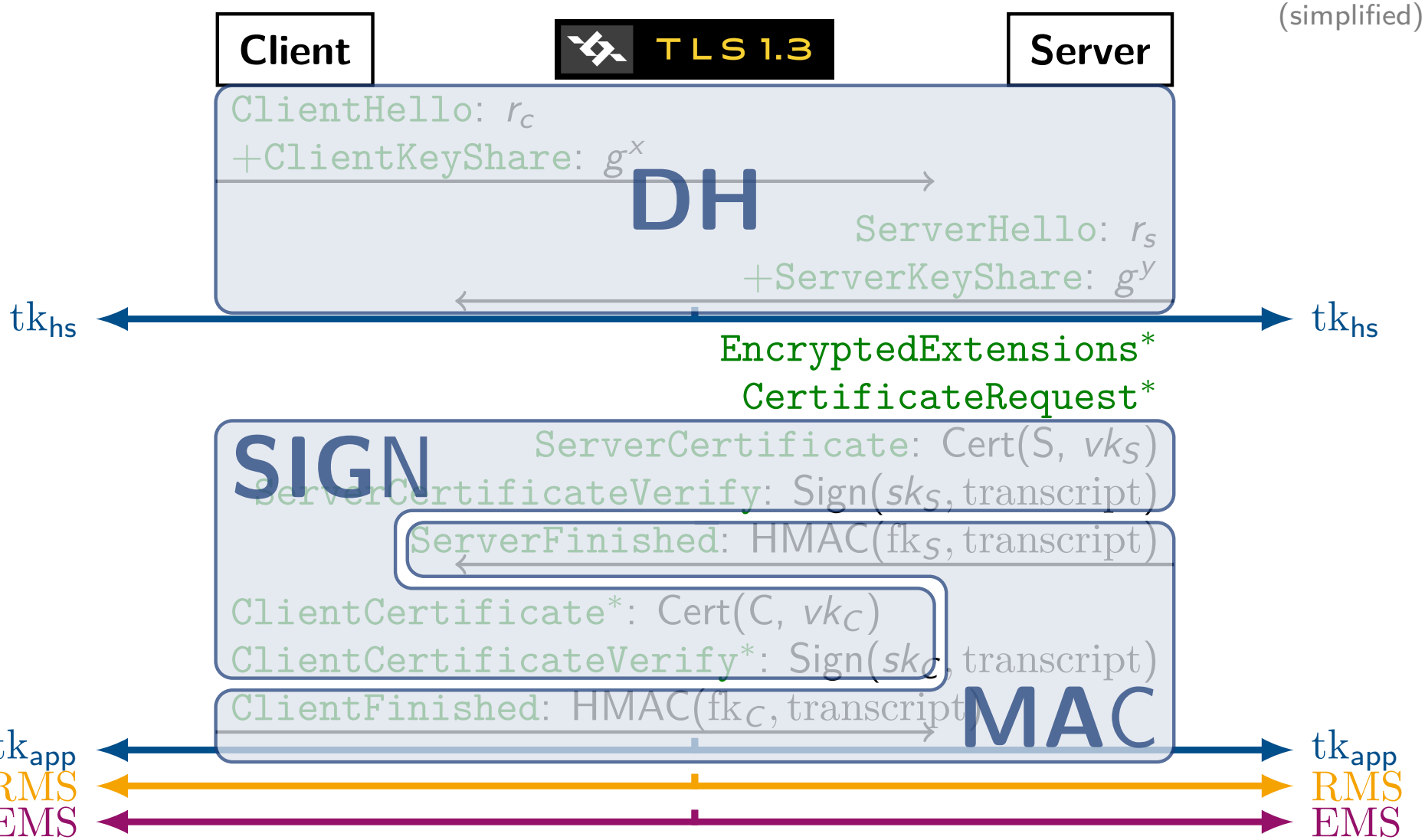


The TLS 1.3 Handshake

Full (EC)DHE Mode ≈ **SIGMA**: (DH w/) **SIG**n-and-**MA**c [Kra03]

ETH zürich

(simplified)

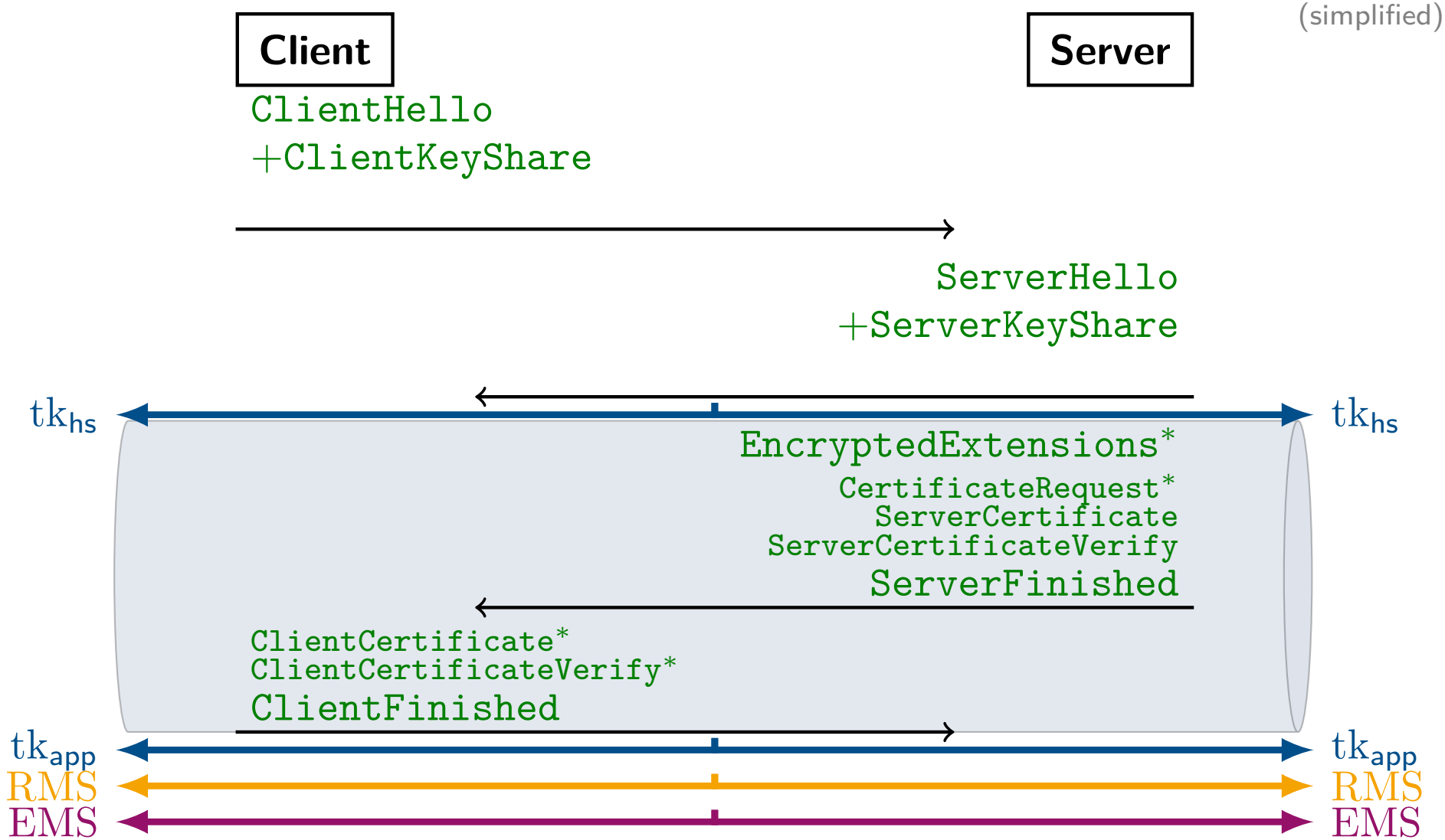


The TLS 1.3 Handshake

PSK / PSK-(EC)DHE Resumption Mode

ETH zürich

(simplified)

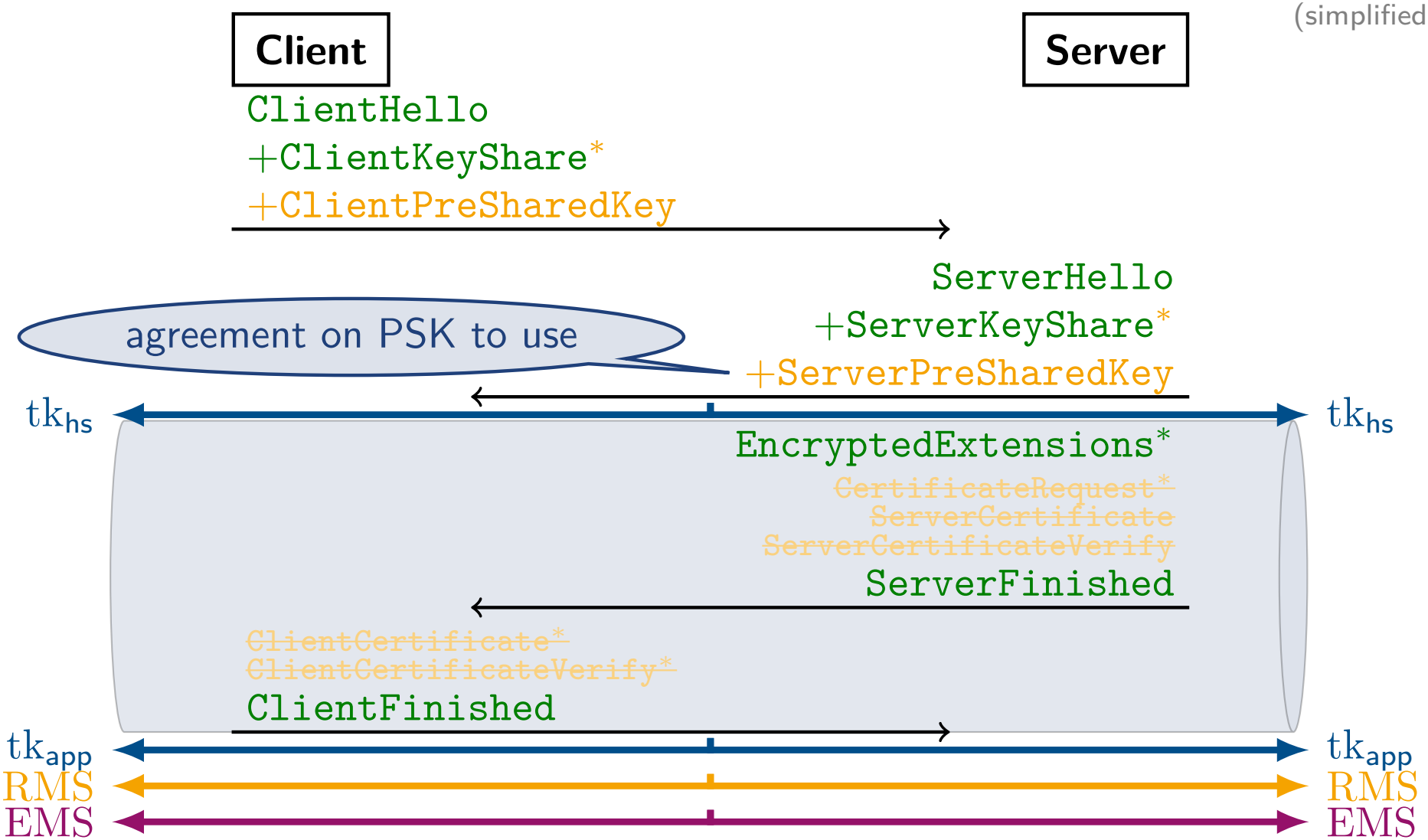


The TLS 1.3 Handshake

PSK / PSK-(EC)DHE Resumption Mode

ETH zürich

(simplified)



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ETH zürich

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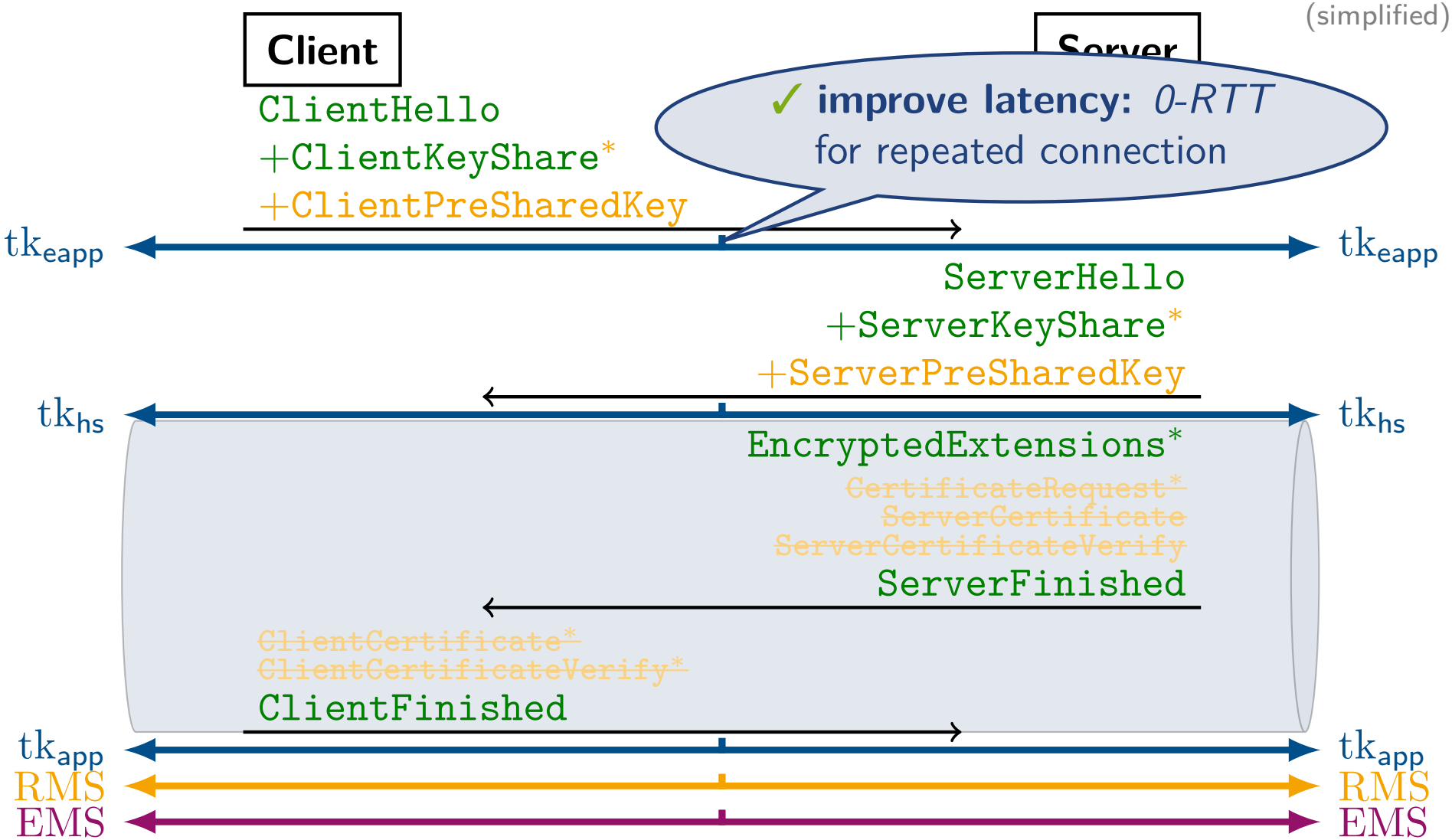


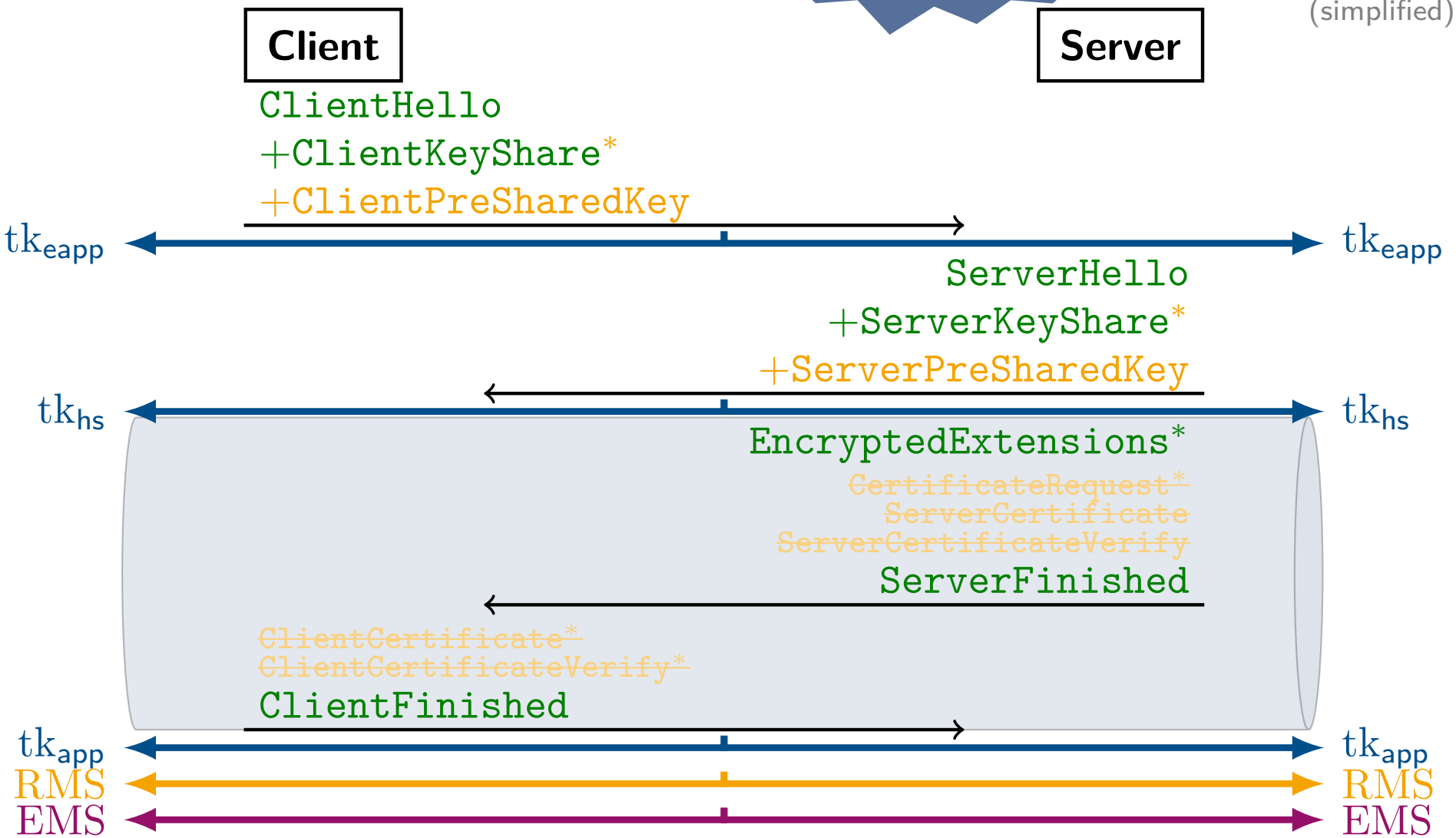
The TLS 1.3 Handshake

PSK / PSK-(EC)DHE Resumption Mode

multi-stage key exchange

ETH zürich

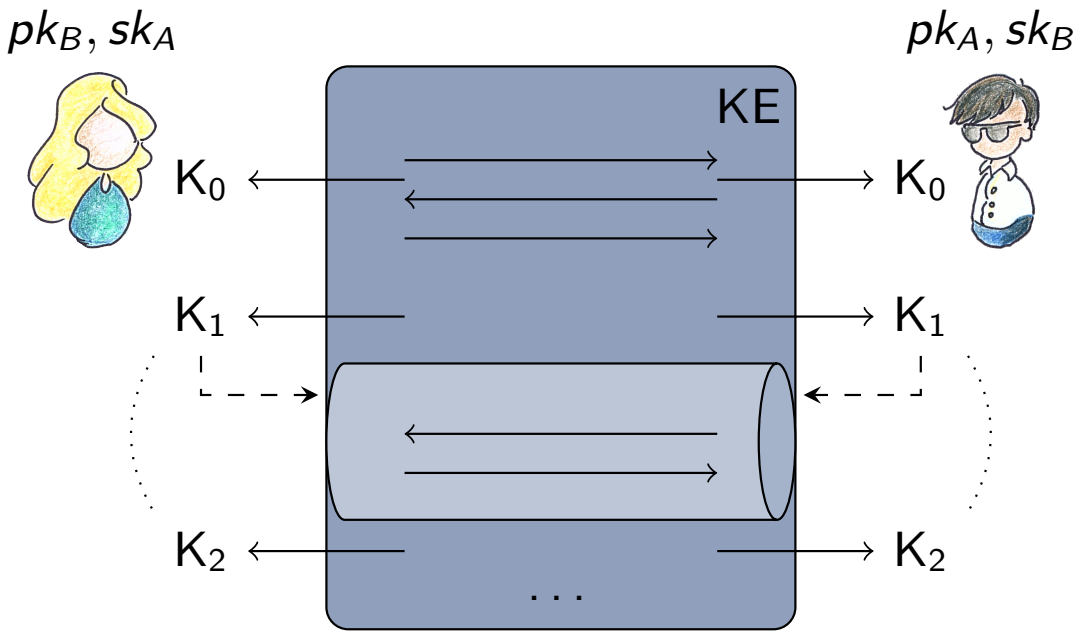
(simplified)



Multi-Stage Key Exchange Security

ETH zürich

(extending [Bellare–Rogaway93])



[FG14], [Dow+15], [Dow+16], [FG17], [Gün18], [Dow+21]

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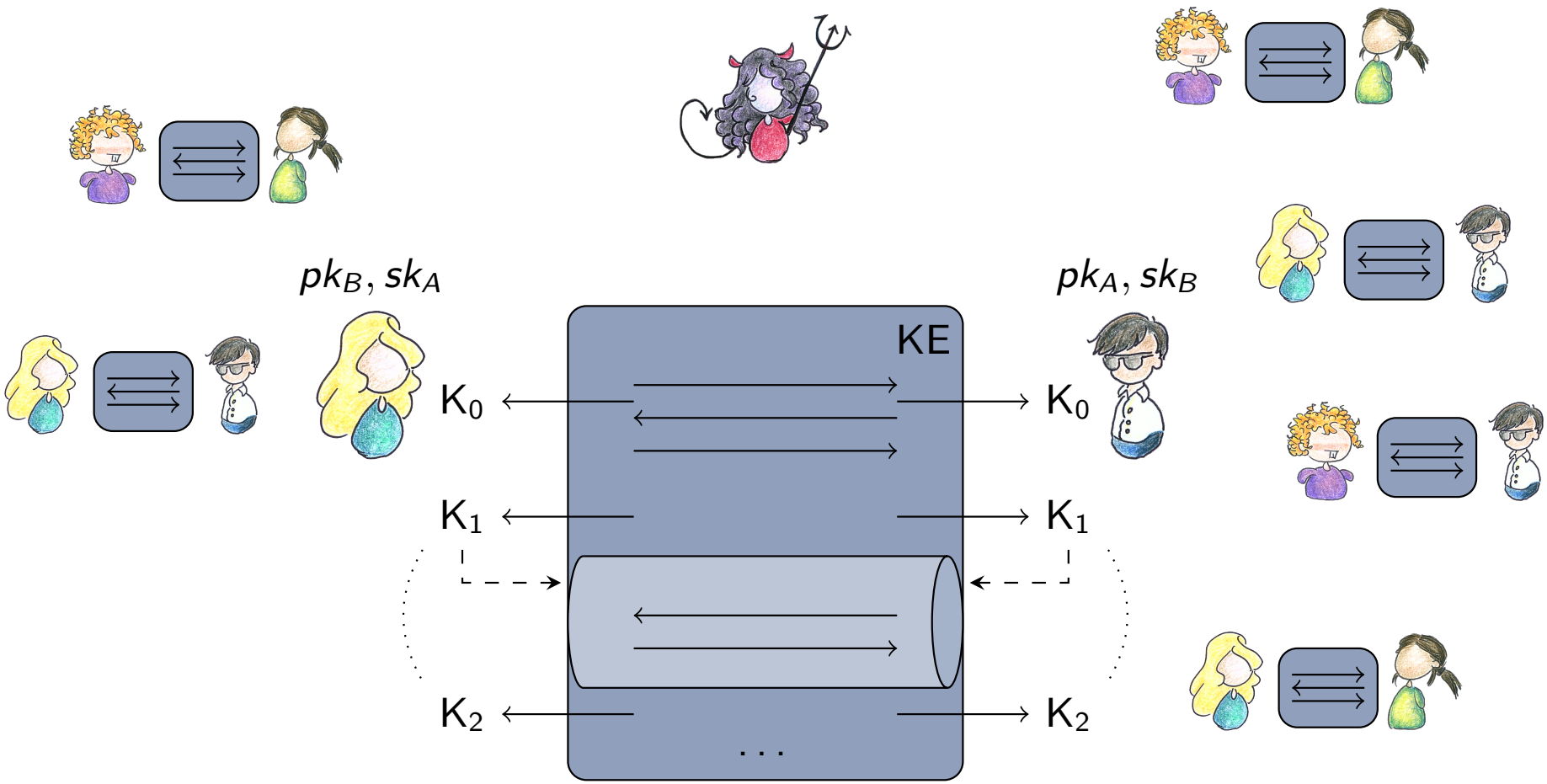

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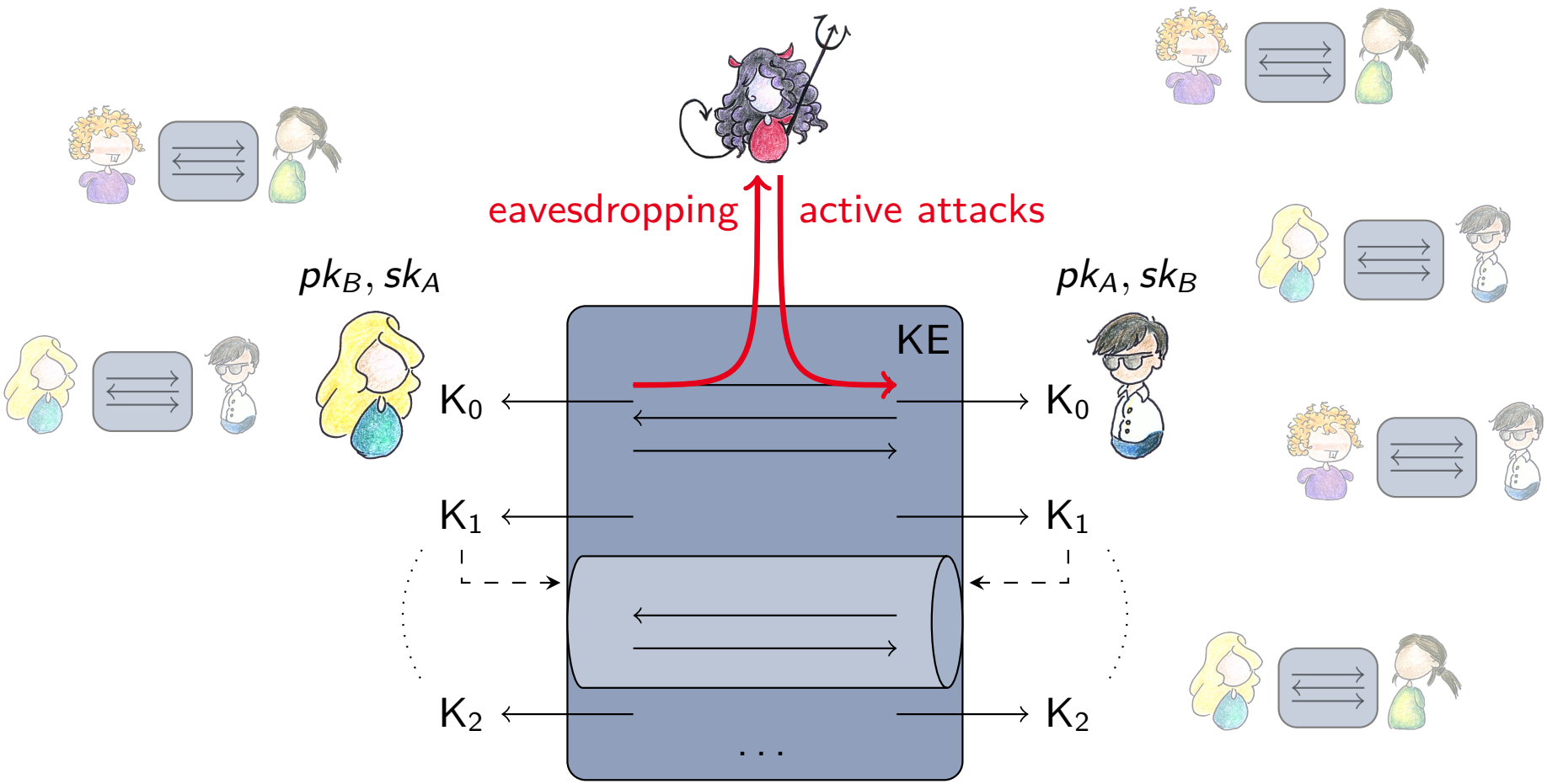

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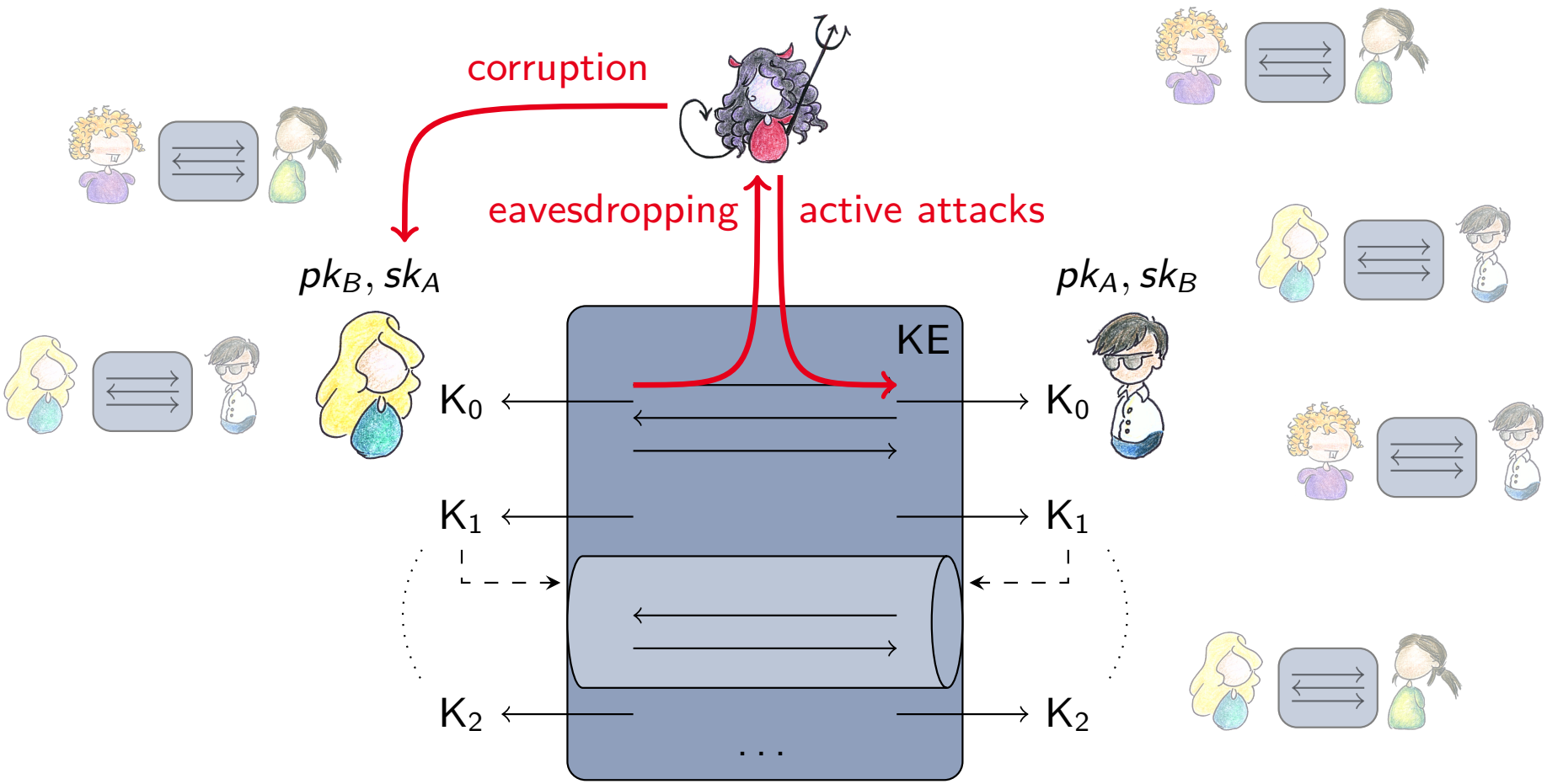

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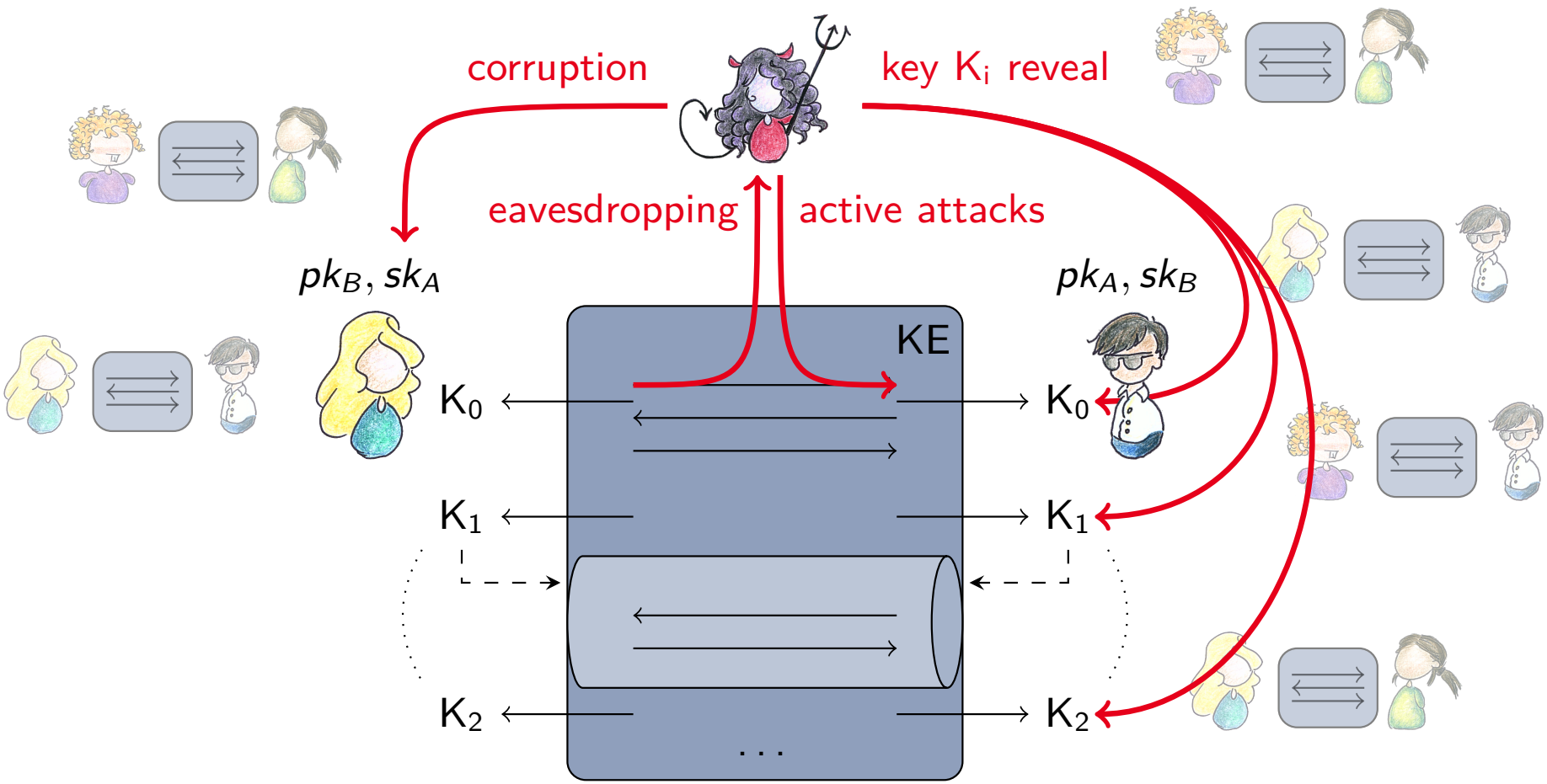

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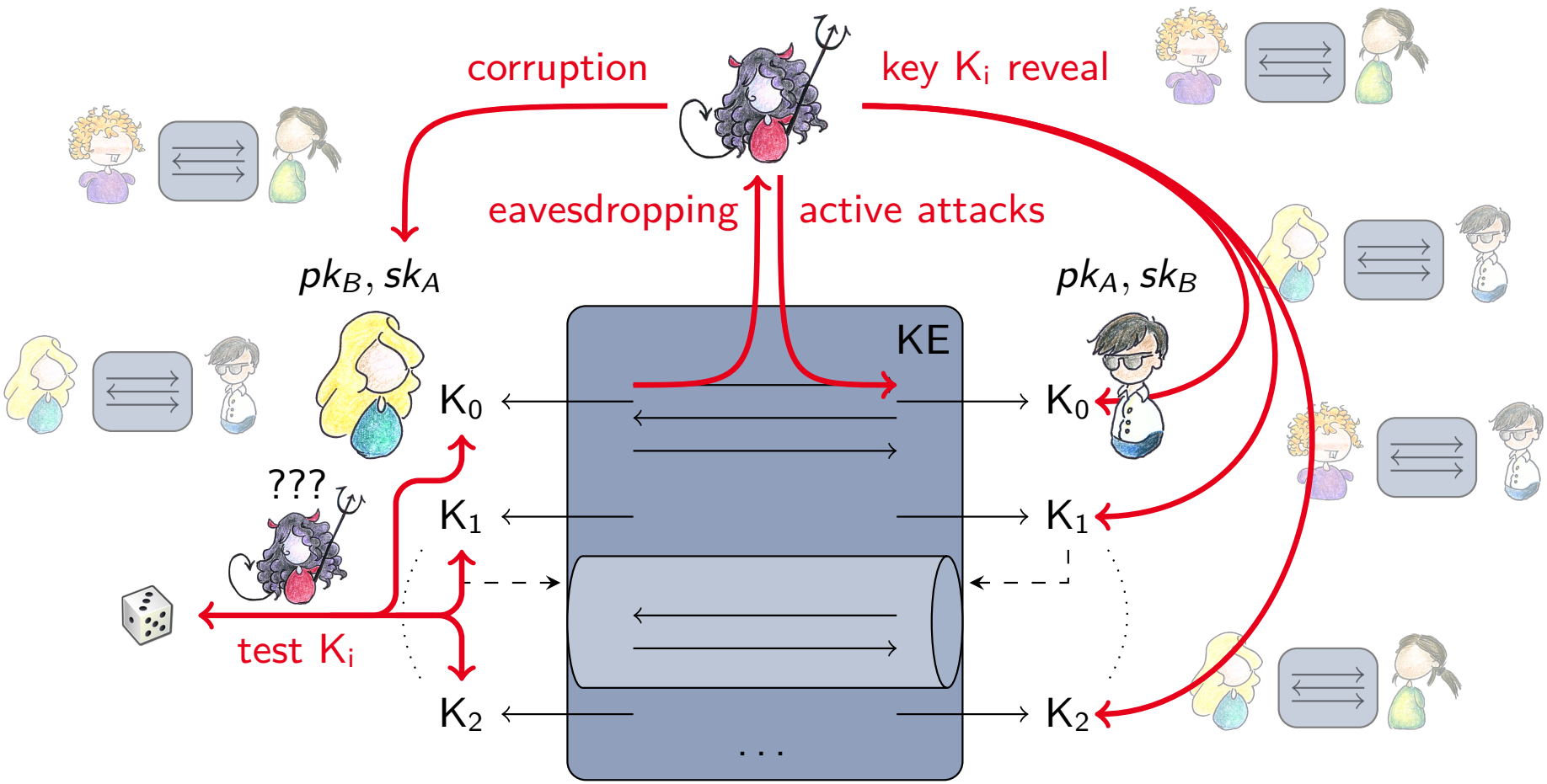

[FG14], [Dow+15], [Dow+16], [FG17], [Gün18], [Dow+21]

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

$$\mathrm{KE}(\mathit{own\ id}, \mathit{peer\ id}, \mathit{sk}_{\mathit{oid}}, \mathit{pk}_{\mathit{pid}}, \mathit{msg\ in}, \dots) \mapsto (\mathit{msg\ out}, \mathit{status}, K, \dots)$$

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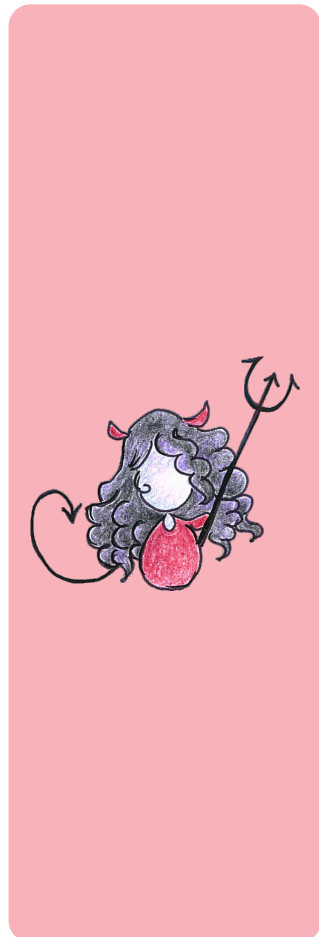

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sk_A

sk_B

sk_C

sk_D

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The communication/security model: a simplified example

ETH zürich

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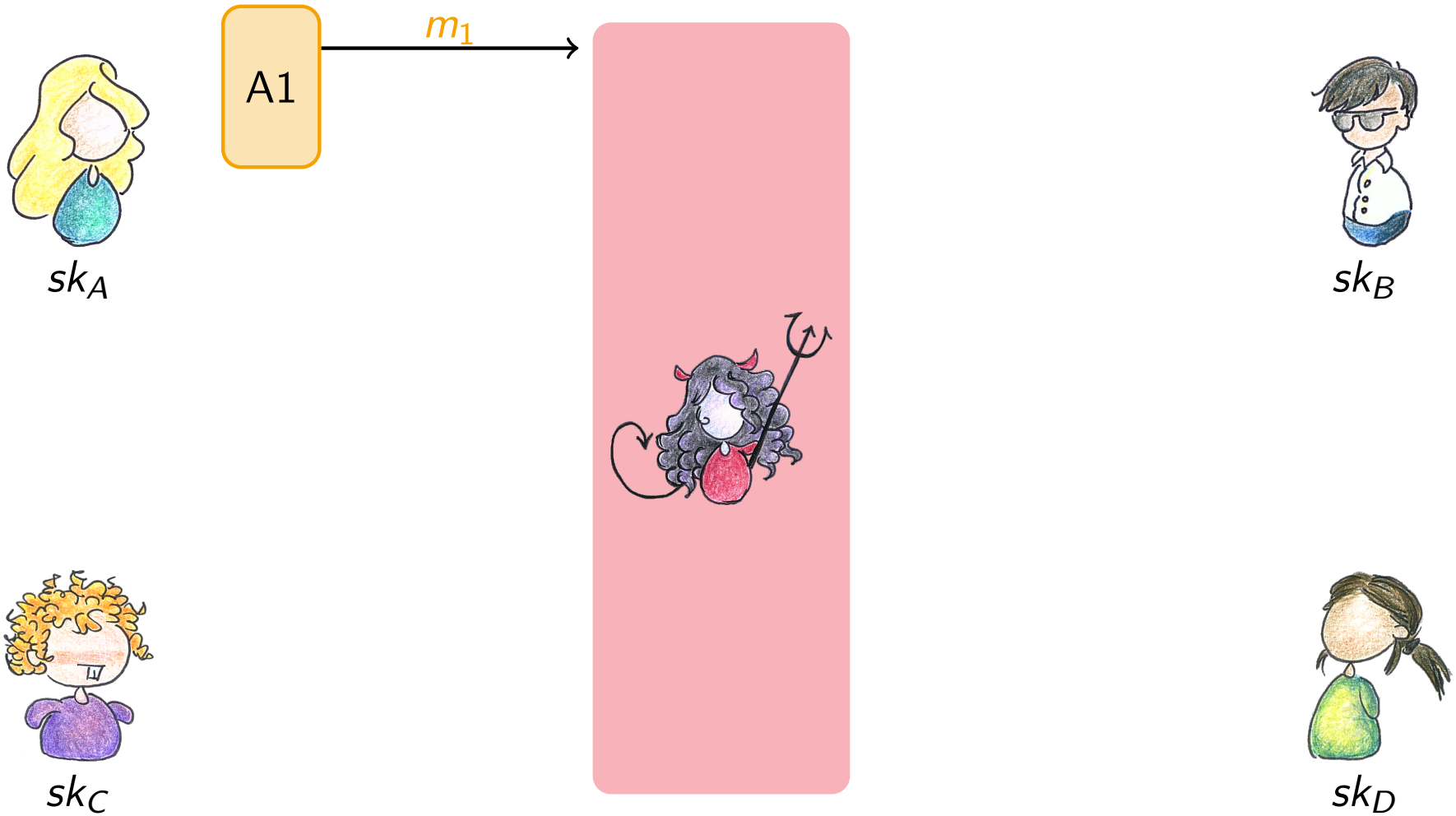

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ETH zürich

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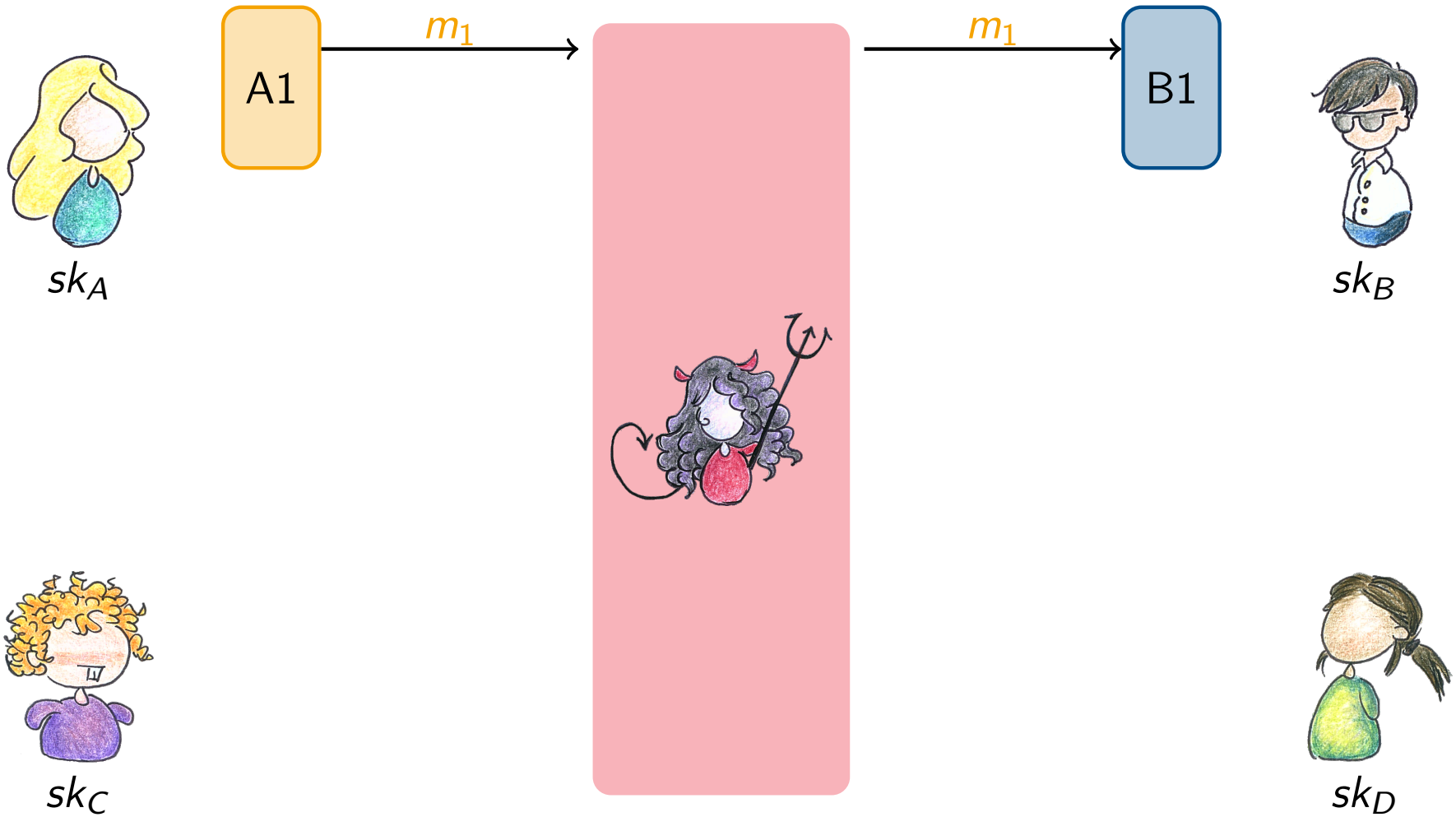
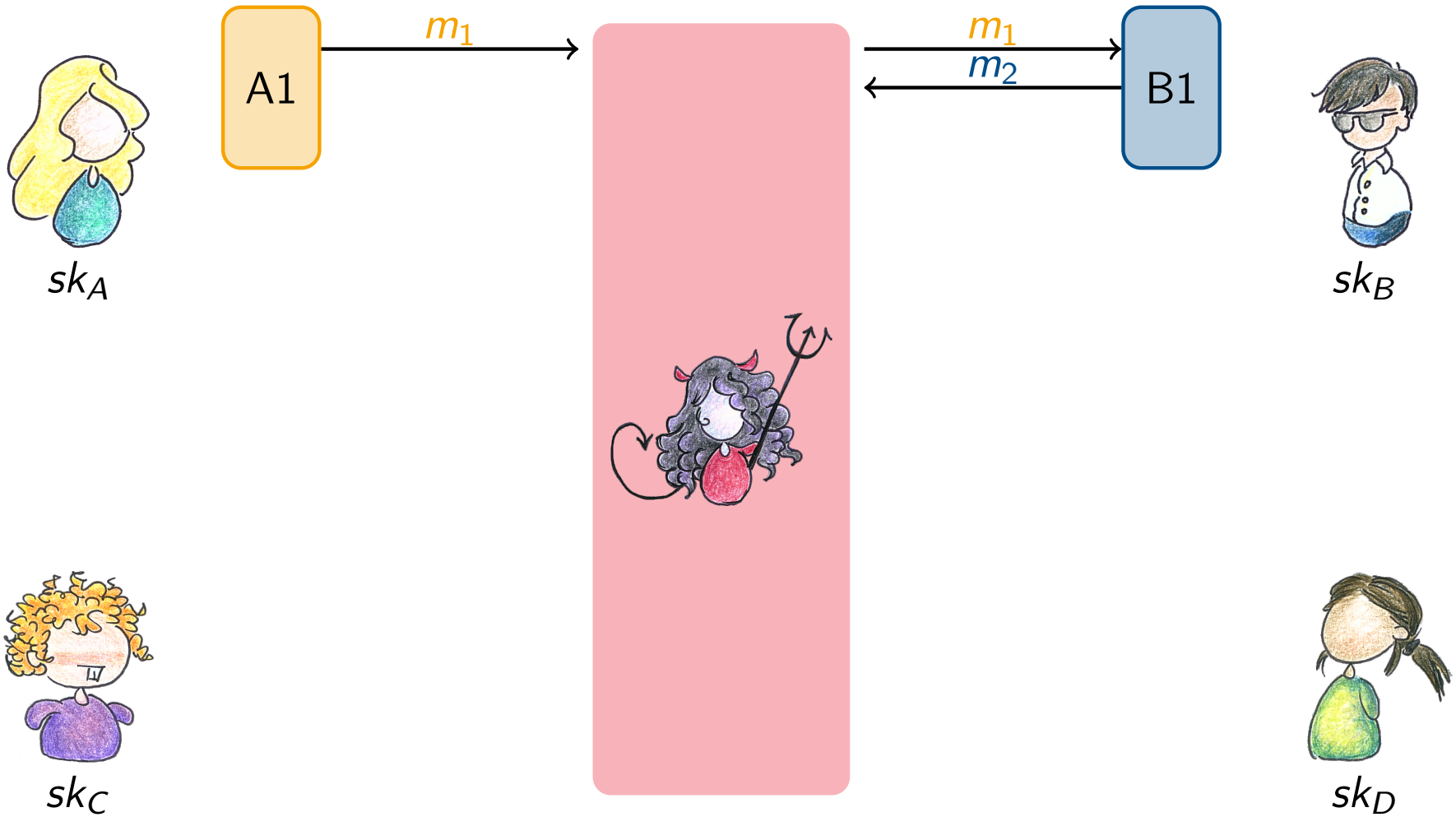


Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

$$\mathrm{KE}(\mathit{own\ id}, \mathit{peer\ id}, \mathit{sk}_{\mathit{oid}}, \mathit{pk}_{\mathit{pid}}, \mathit{msg\ in}, \ldots) \mapsto (\mathit{msg\ out}, \mathit{status}, K, \ldots)$$



Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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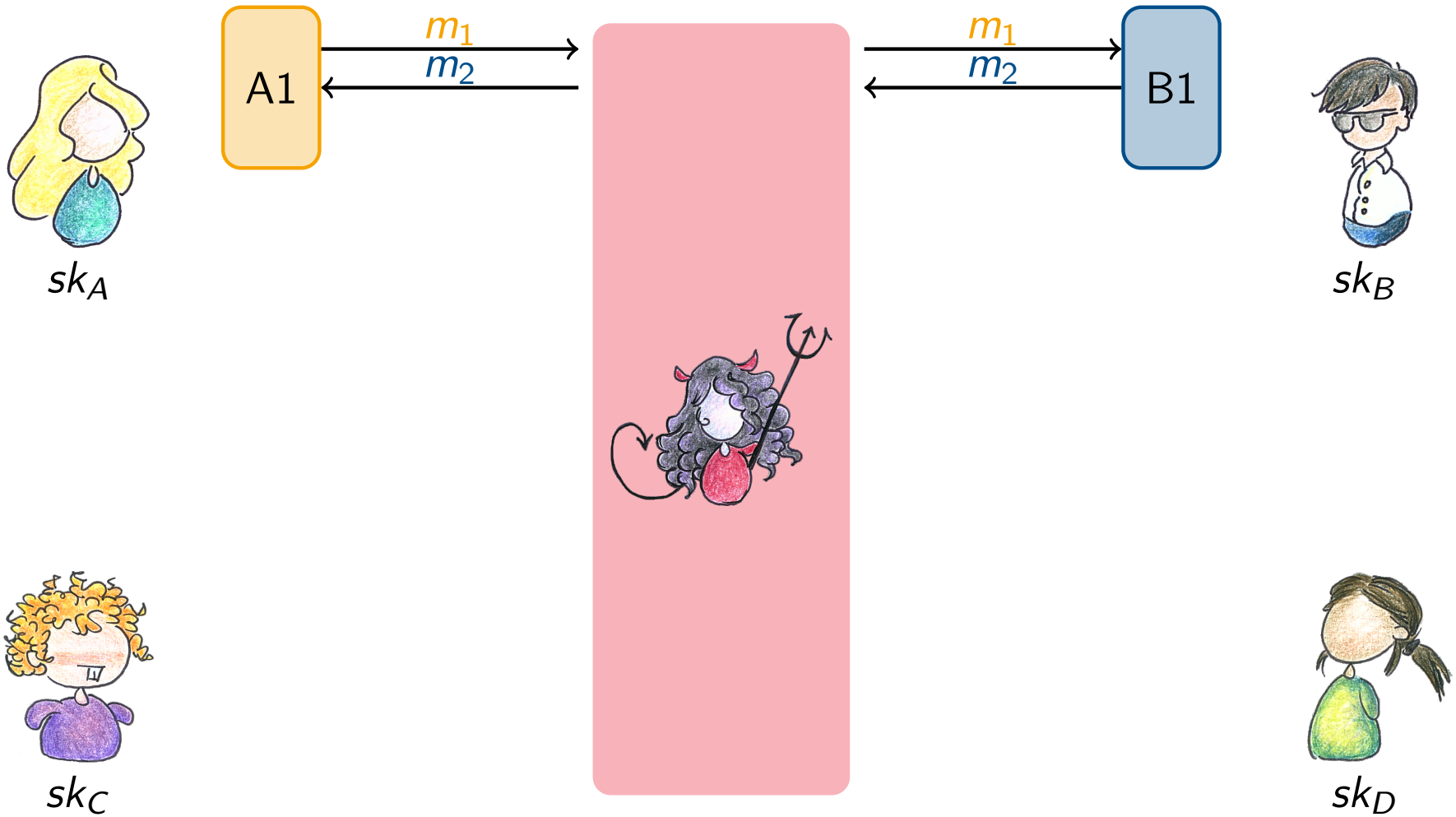

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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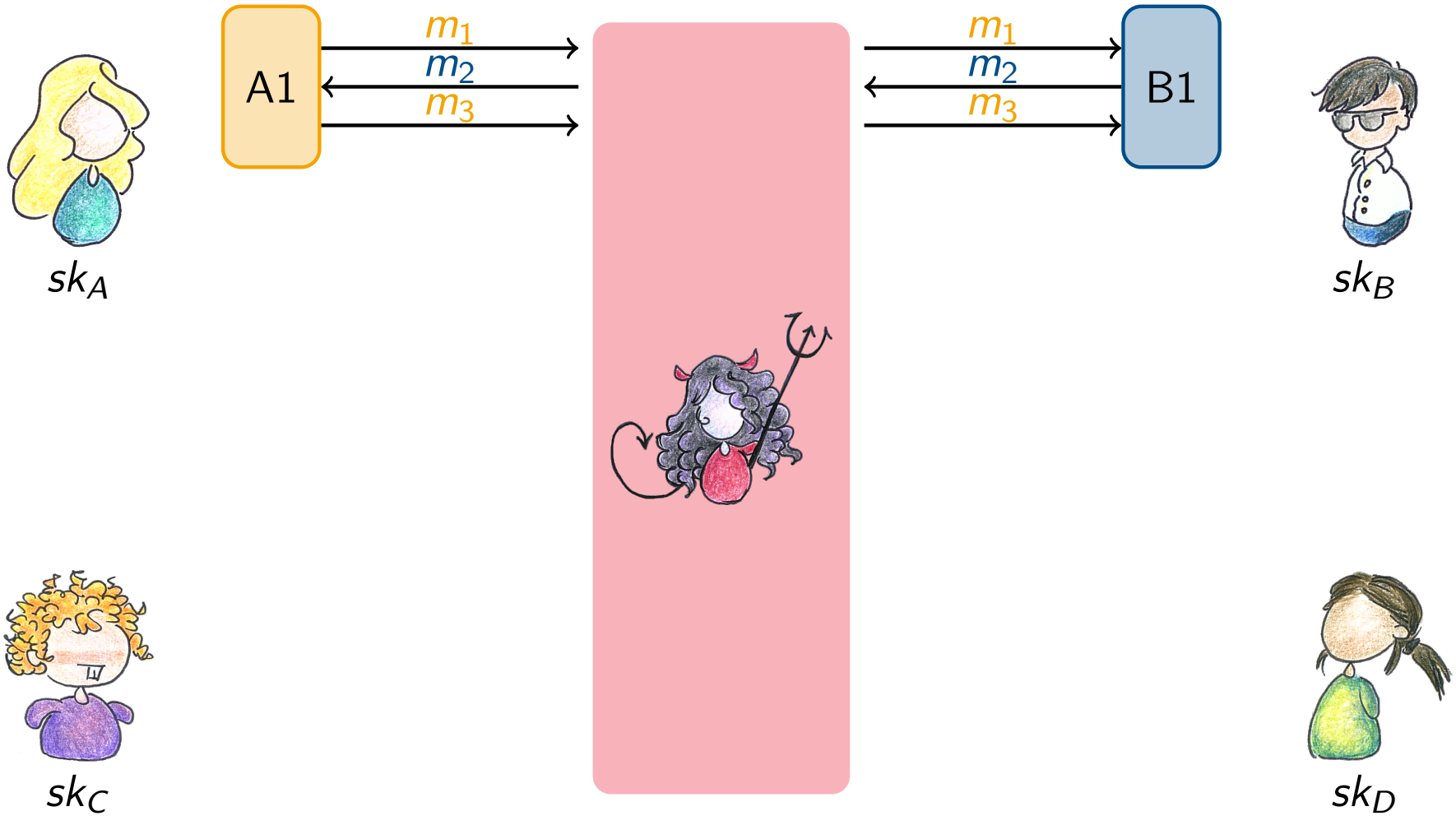

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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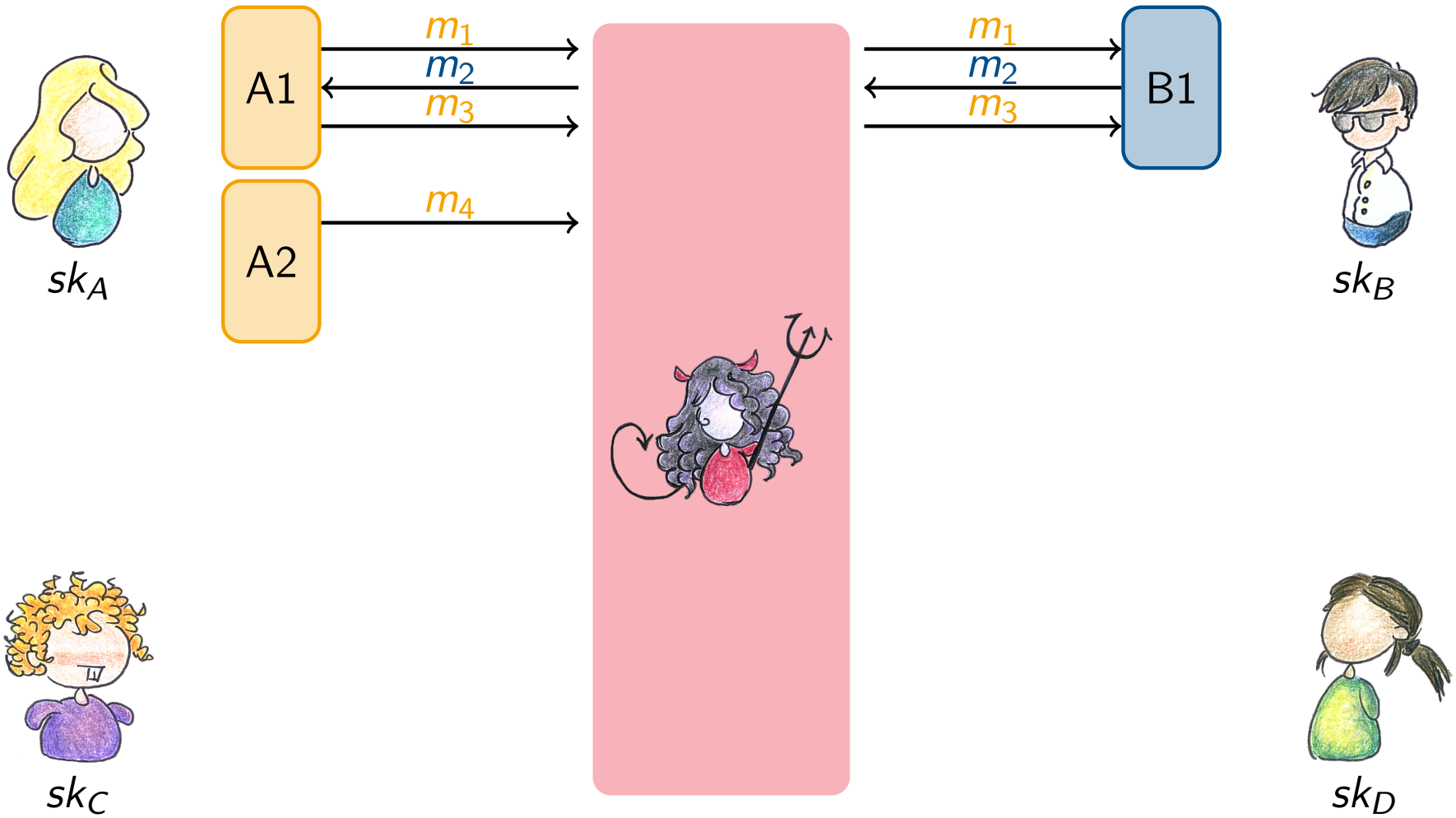

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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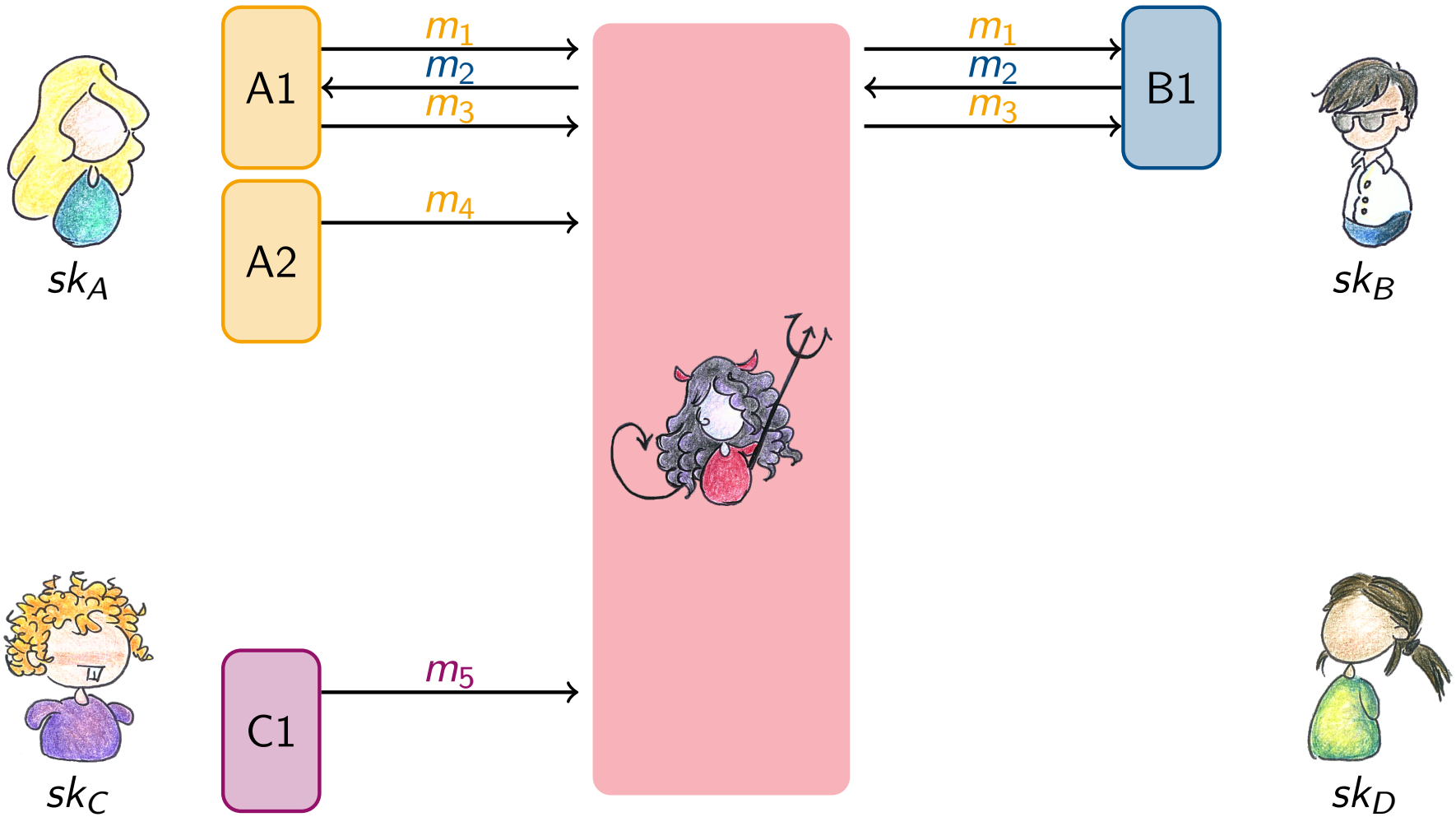

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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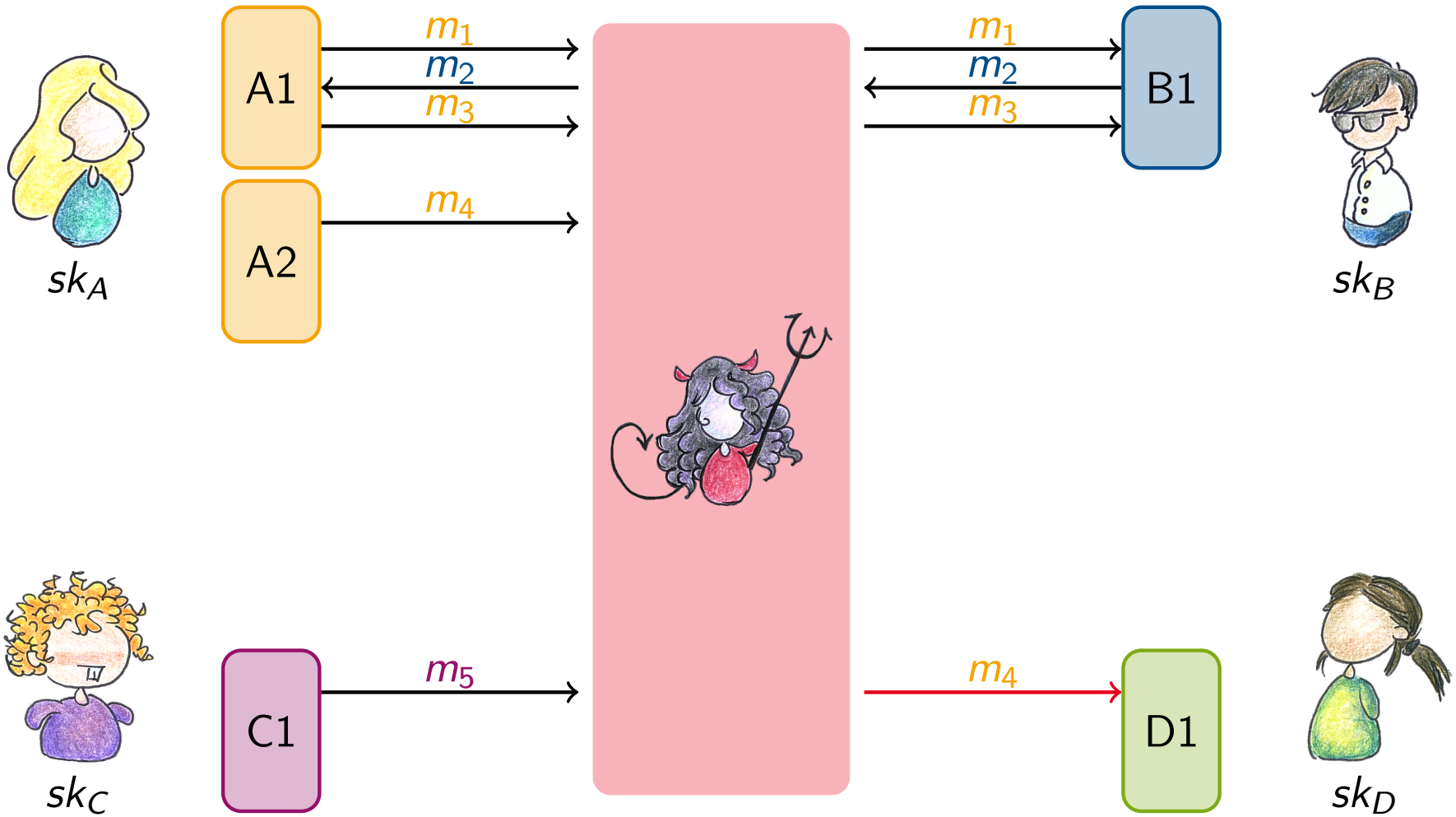

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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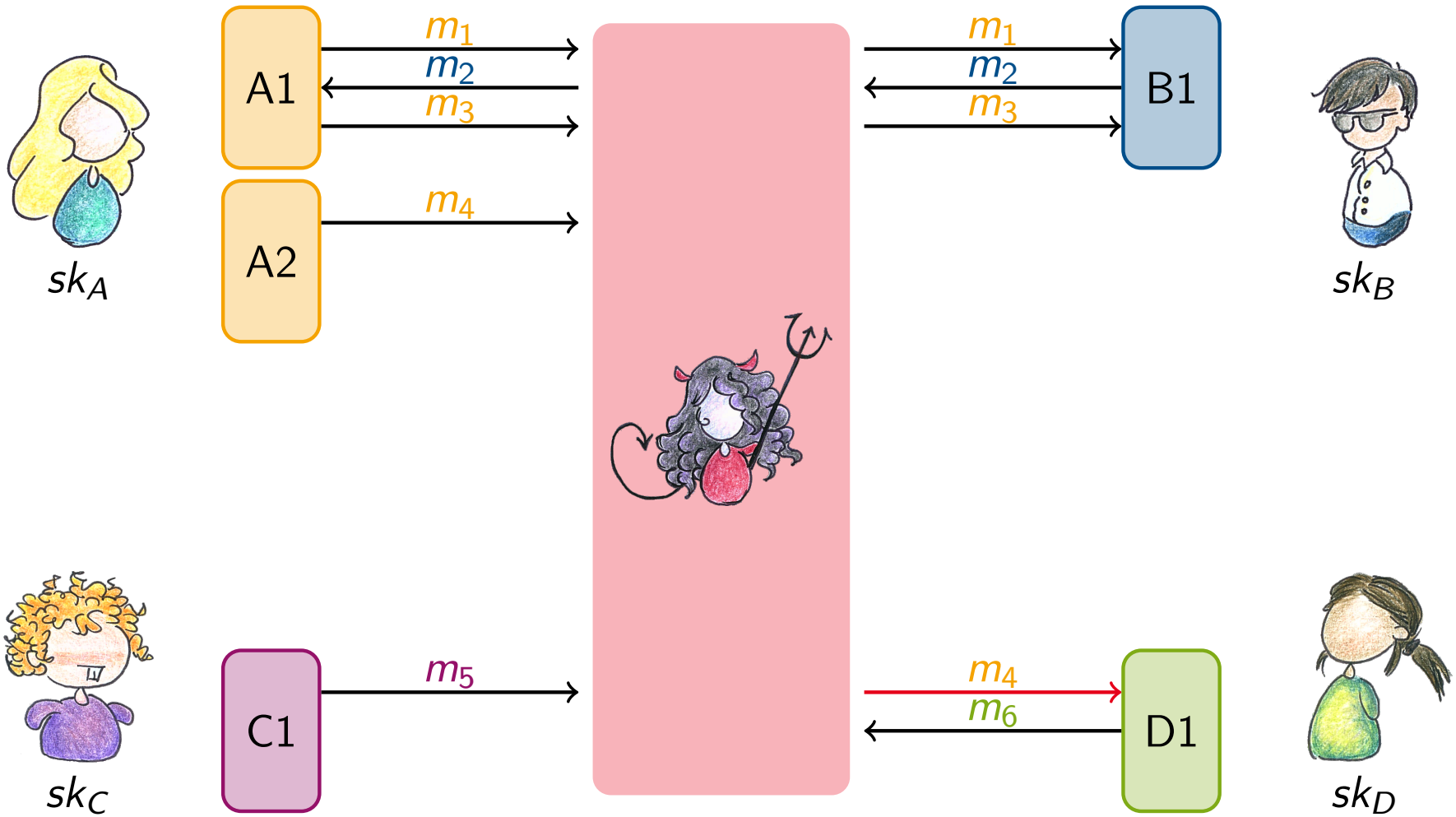

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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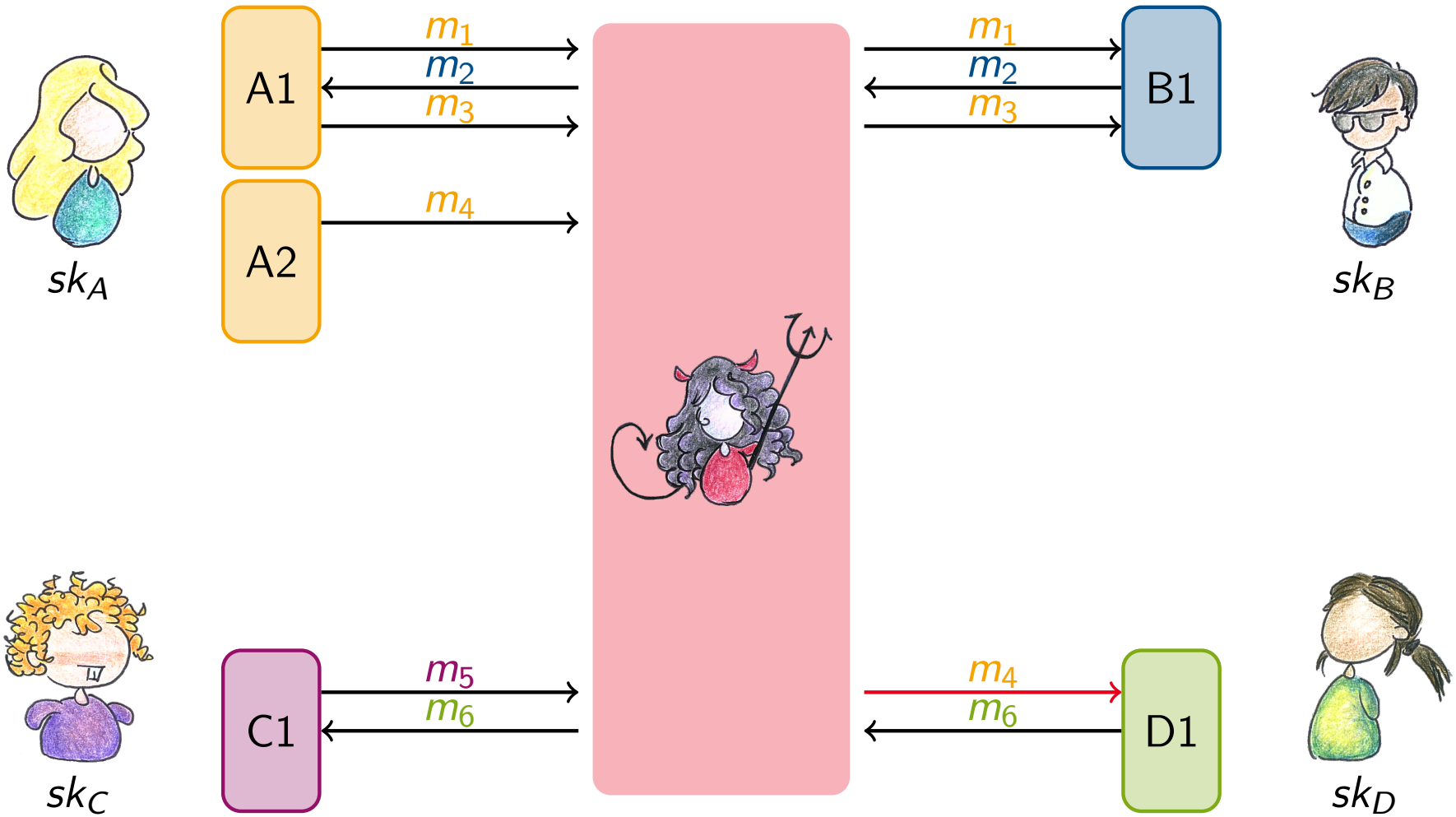

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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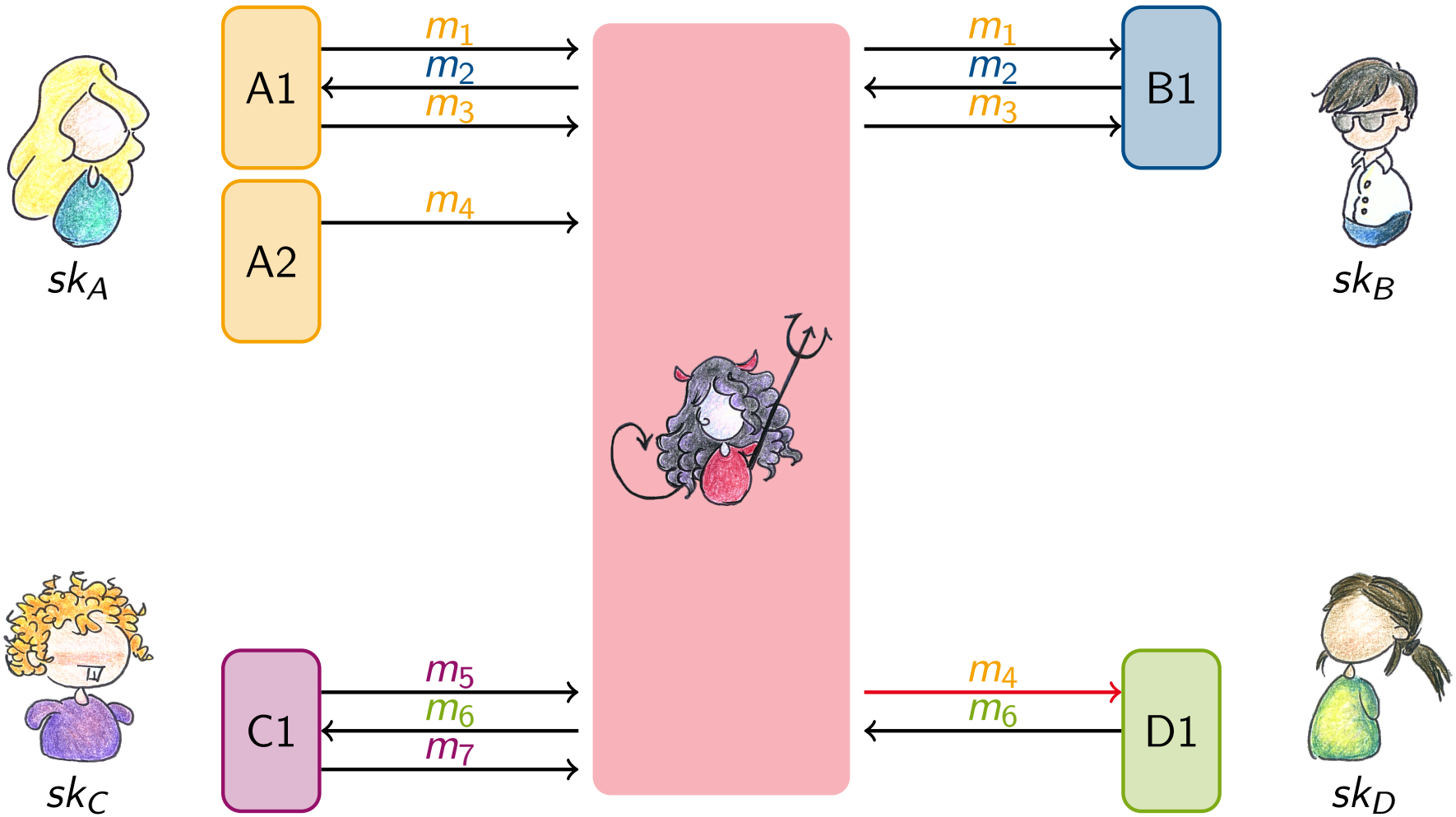

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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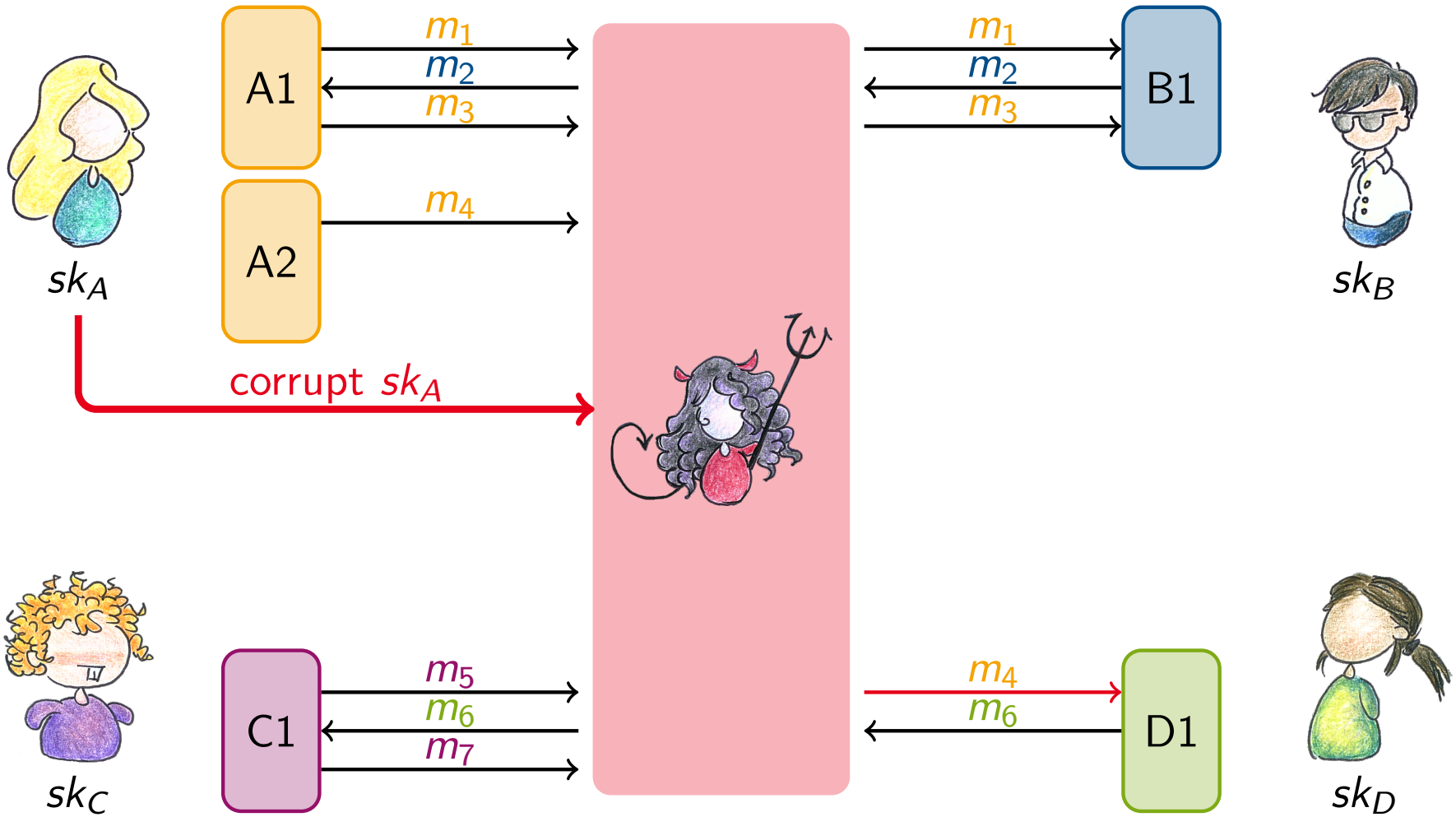
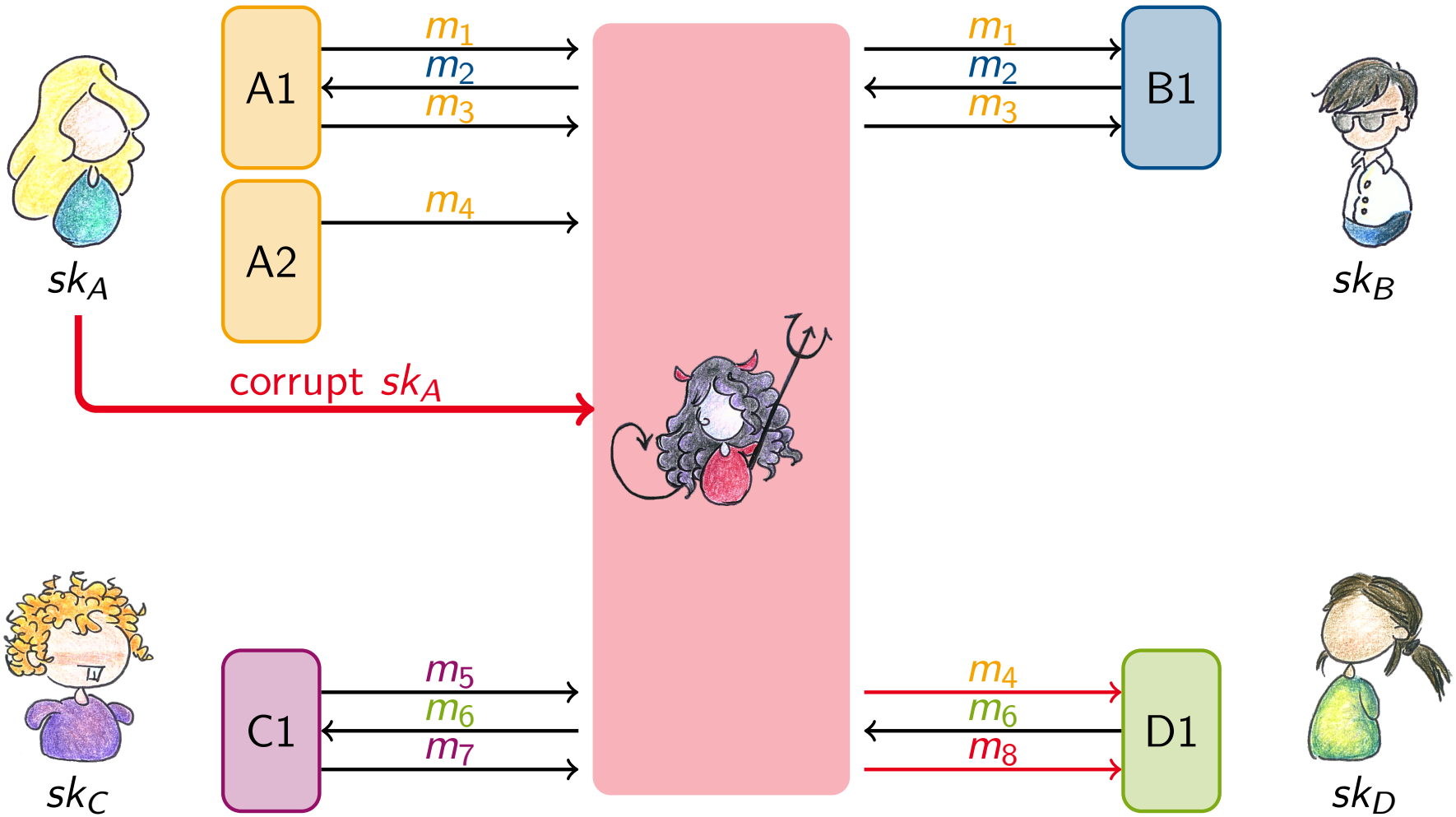


Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

$$\mathrm{KE}(\textit{own id}, \textit{peer id}, sk_{oid}, pk_{pid}, \textit{msg in}, \dots) \mapsto (\textit{msg out}, \textit{status}, K, \dots)$$



Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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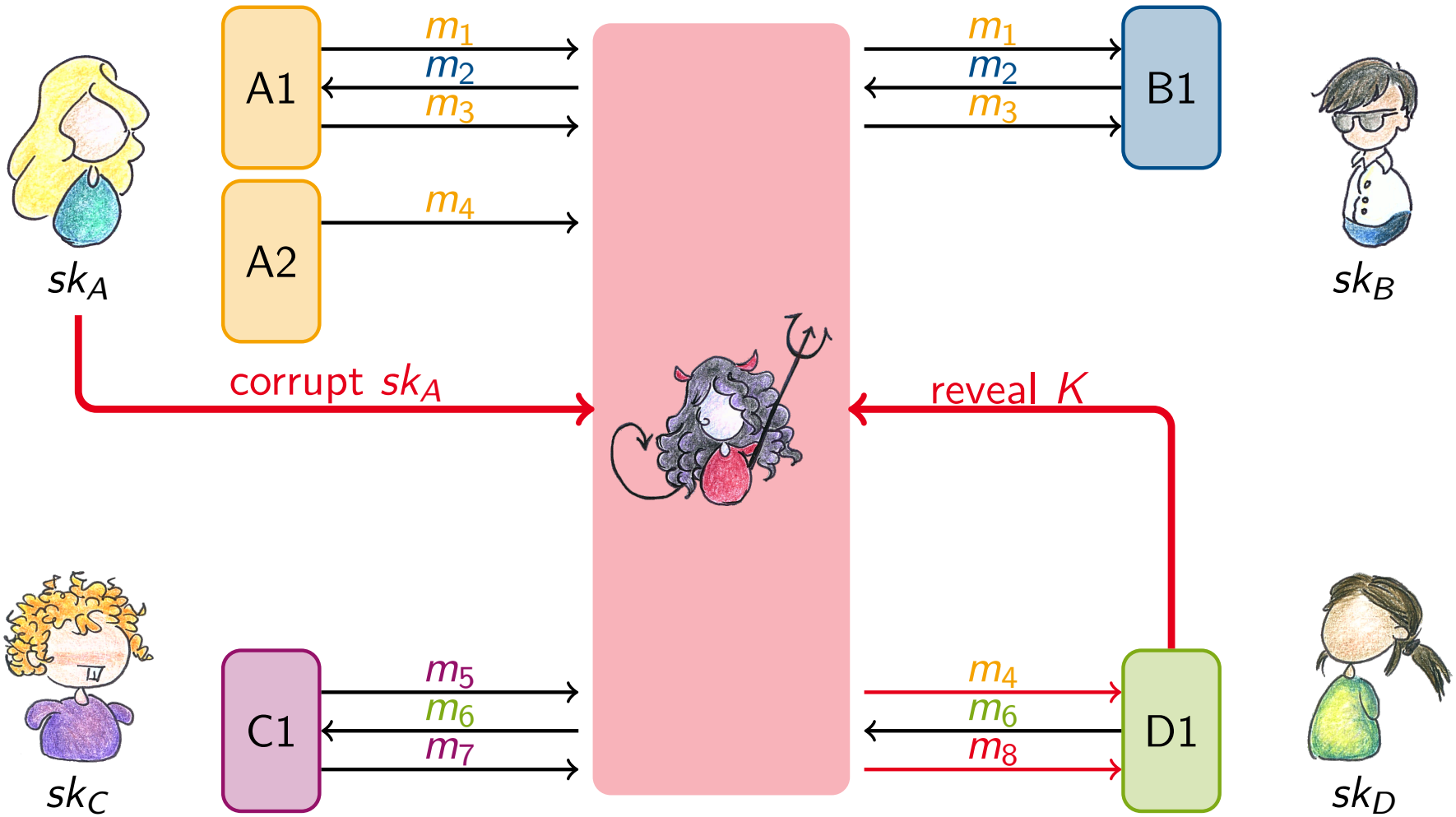

Modeling Key Exchange Security

The communication/security model: a simplified example

ETH zürich

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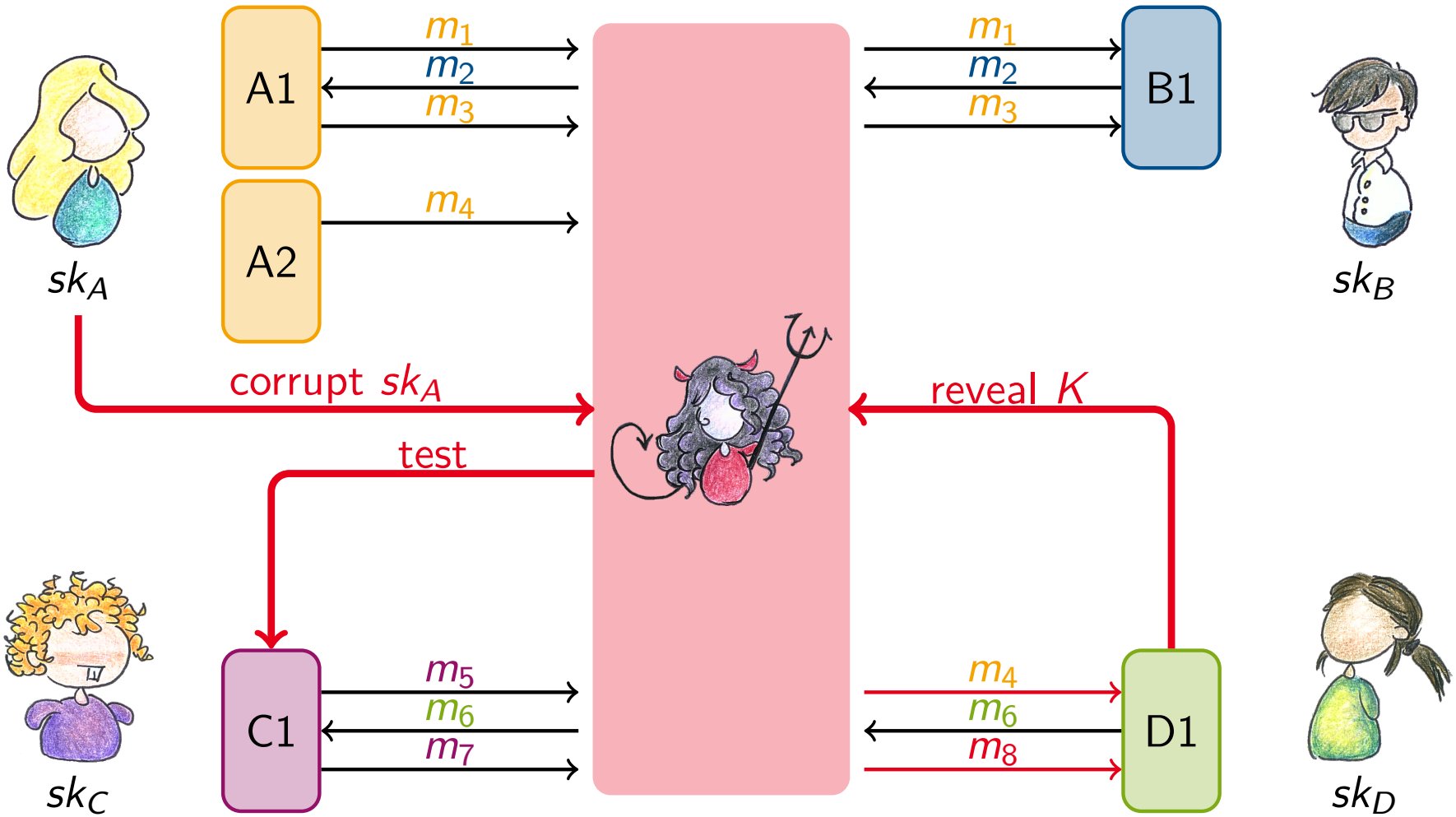


The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

(still simplified)

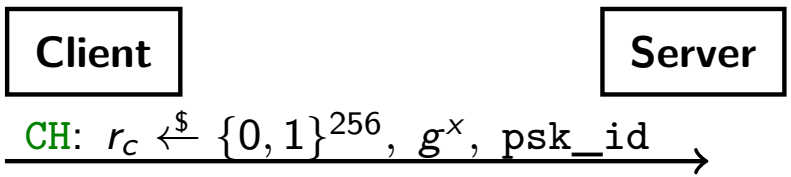
Client **Server**

The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

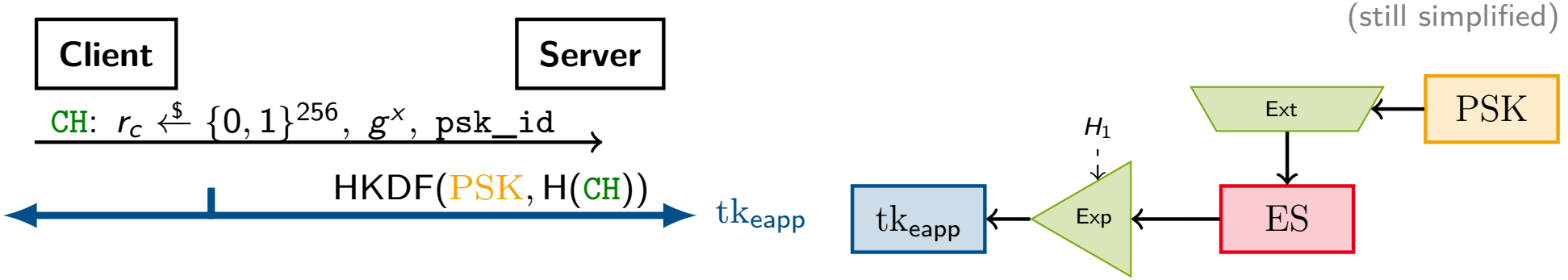
(still simplified)



The TLS 1.3 Handshake

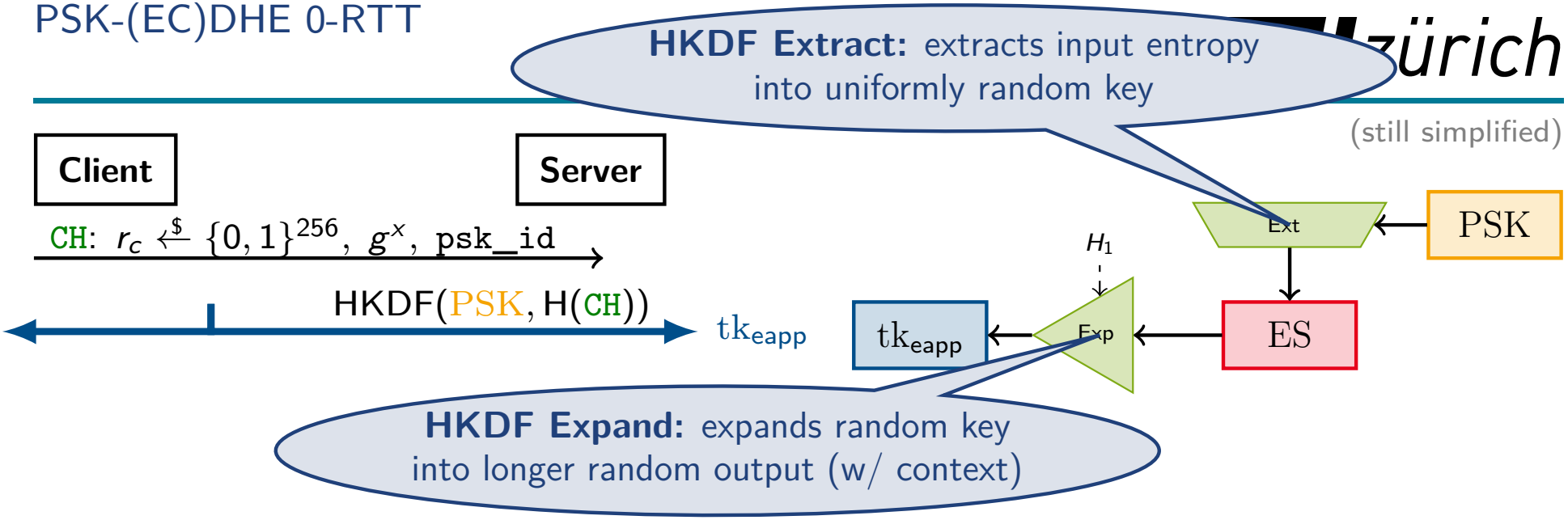
PSK-(EC)DHE 0-RTT

(still simplified)



The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT



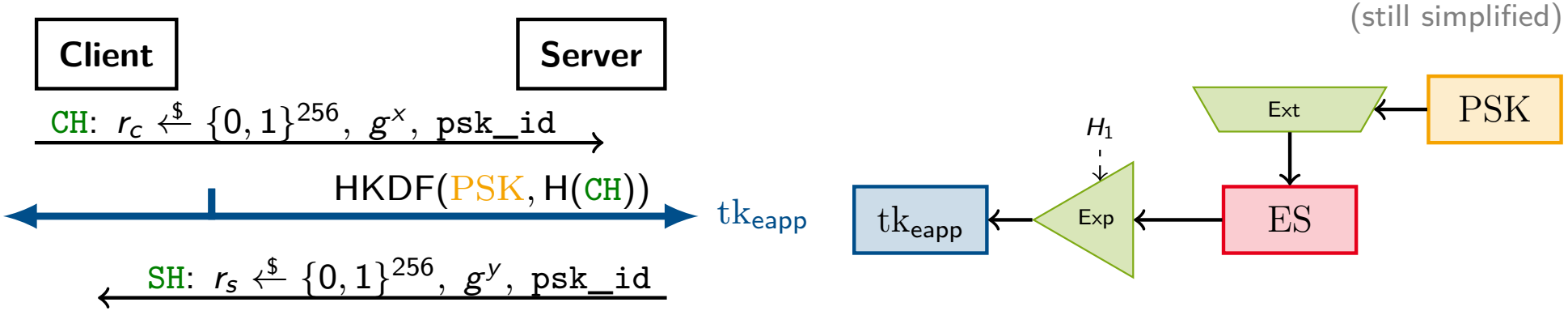
HKDF (recap)

- HKDF.Extract($salt$, $keymaterial$) = HMAC($salt$, $keymaterial$)
- HKDF.Expand(key, $context$, $length$) = $T(1) \| \ldots \| T(N)$
  where $T(0)$ = empty string (zero length)
  $T(i) = \text{HMAC}(key, T(i-1) \| context \| i)$

The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

(still simplified)

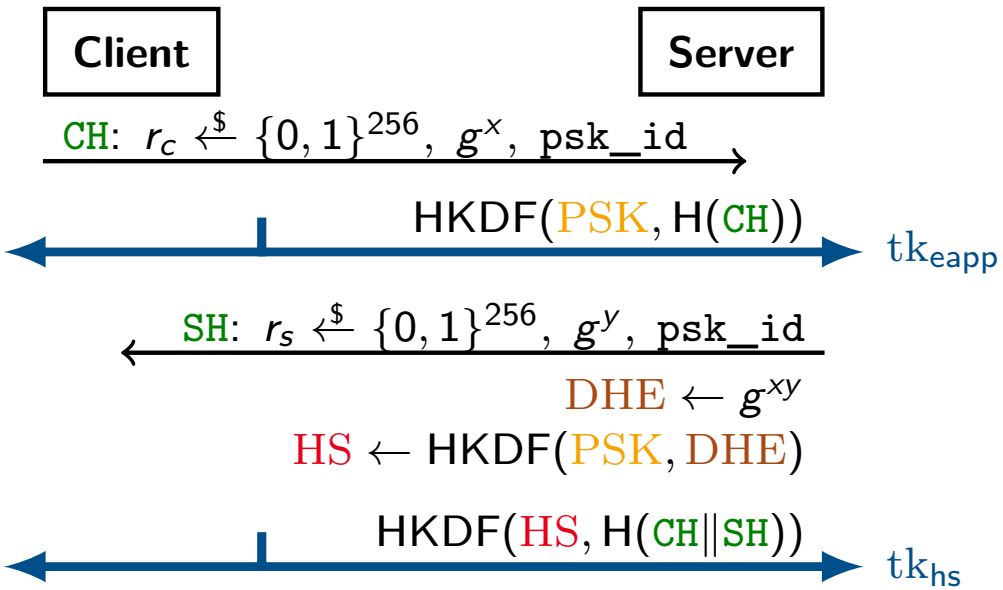


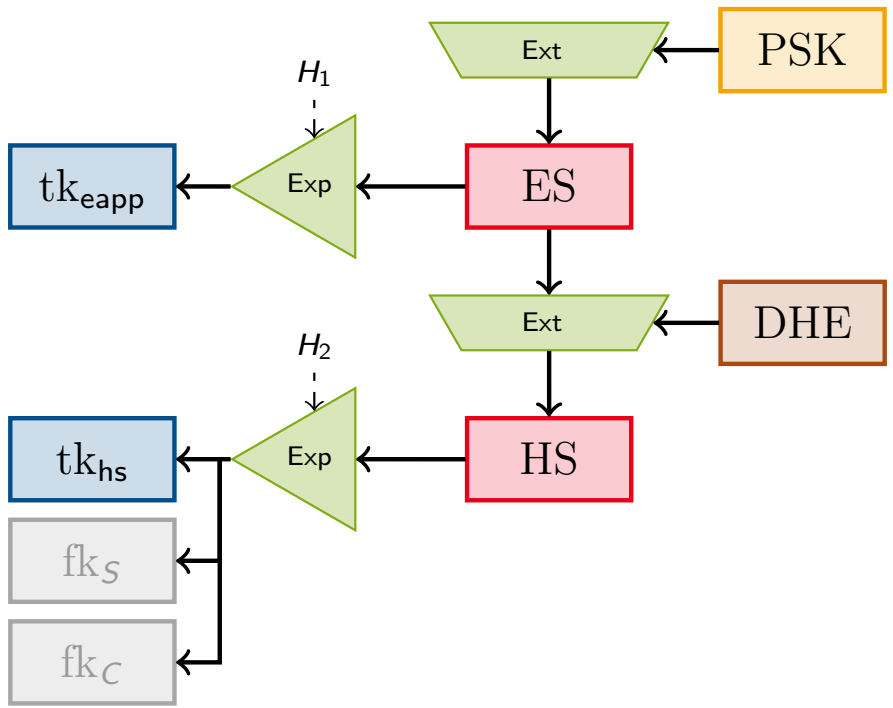
The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

(still simplified)



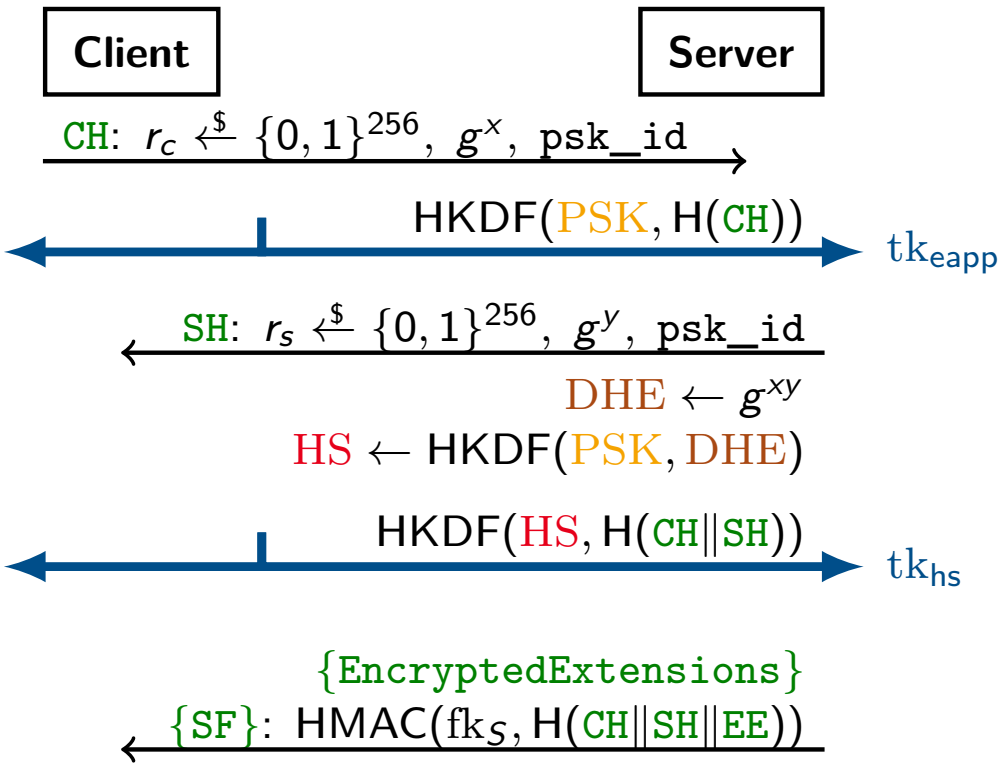


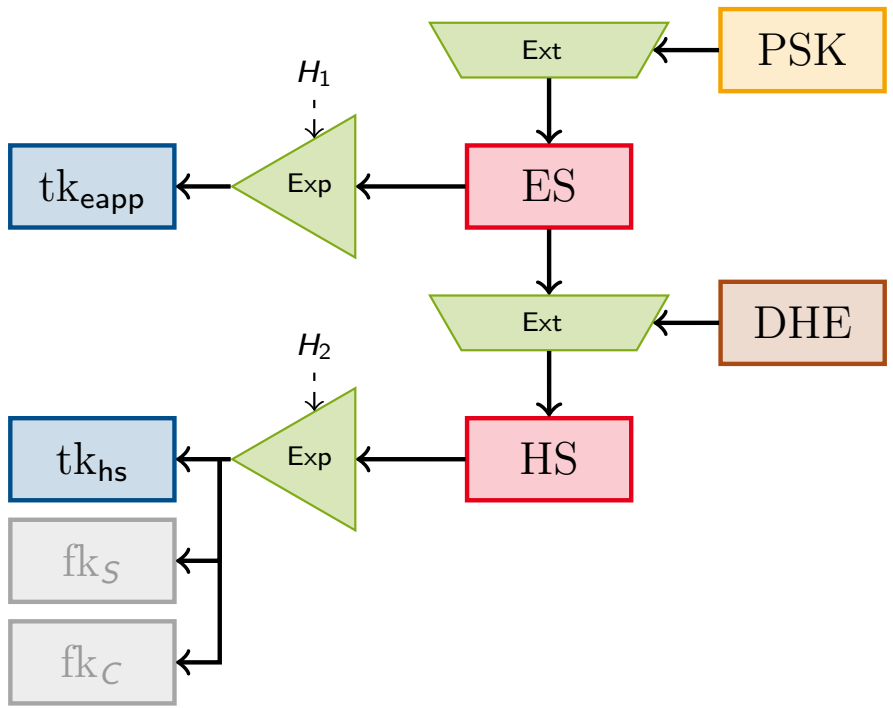
The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

(still simplified)



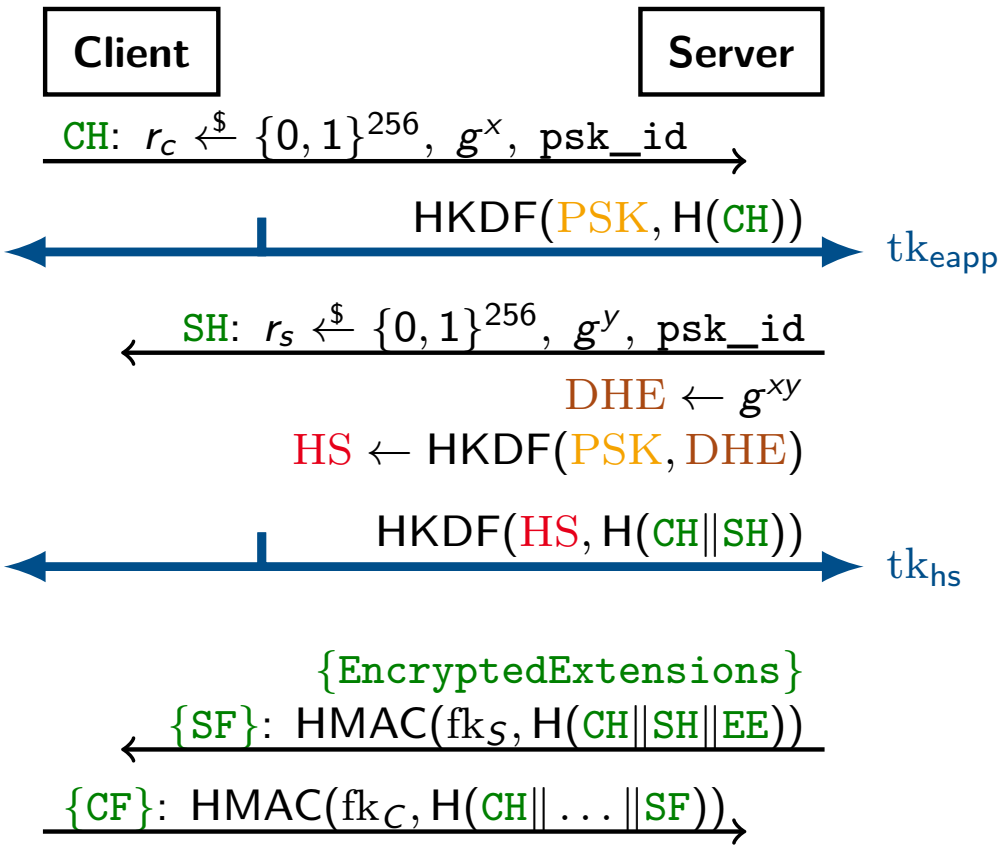


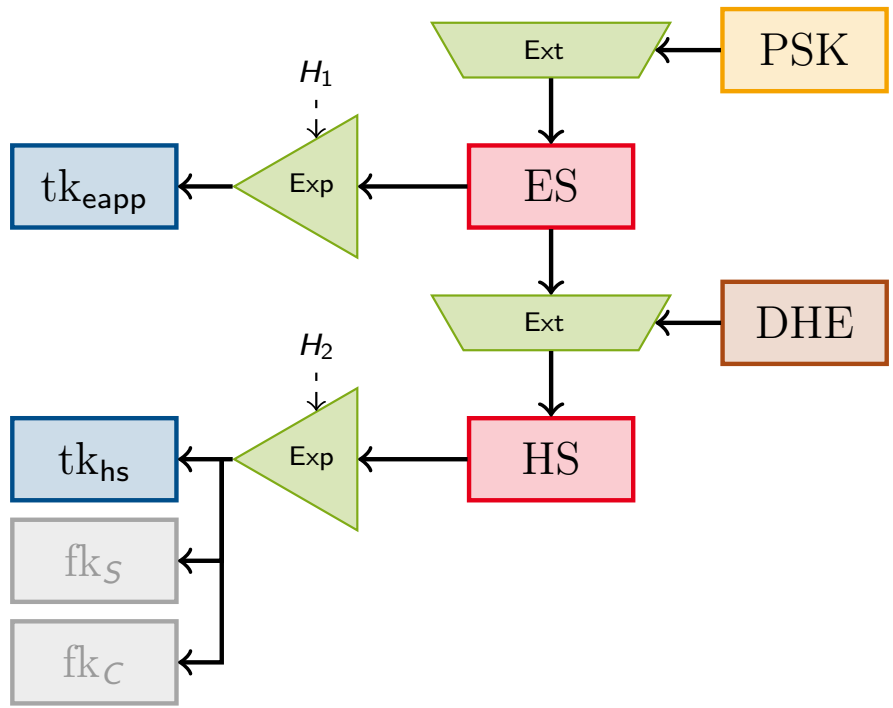
The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

(still simplified)



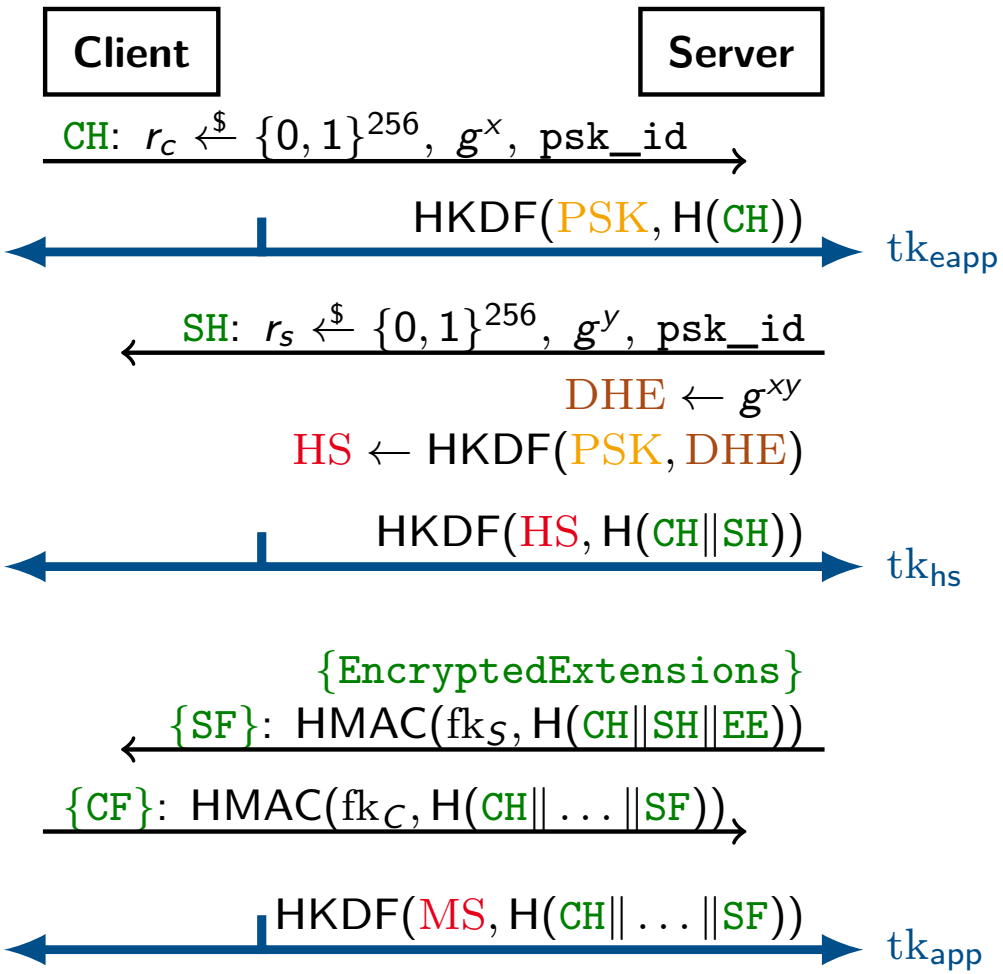


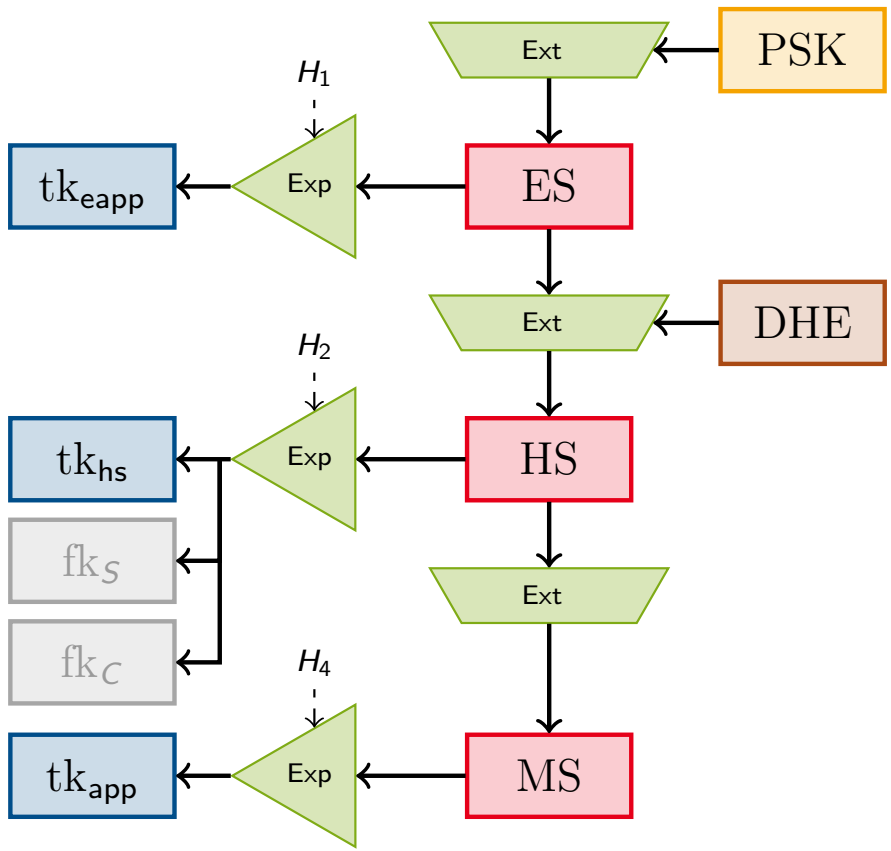
The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

(still simplified)



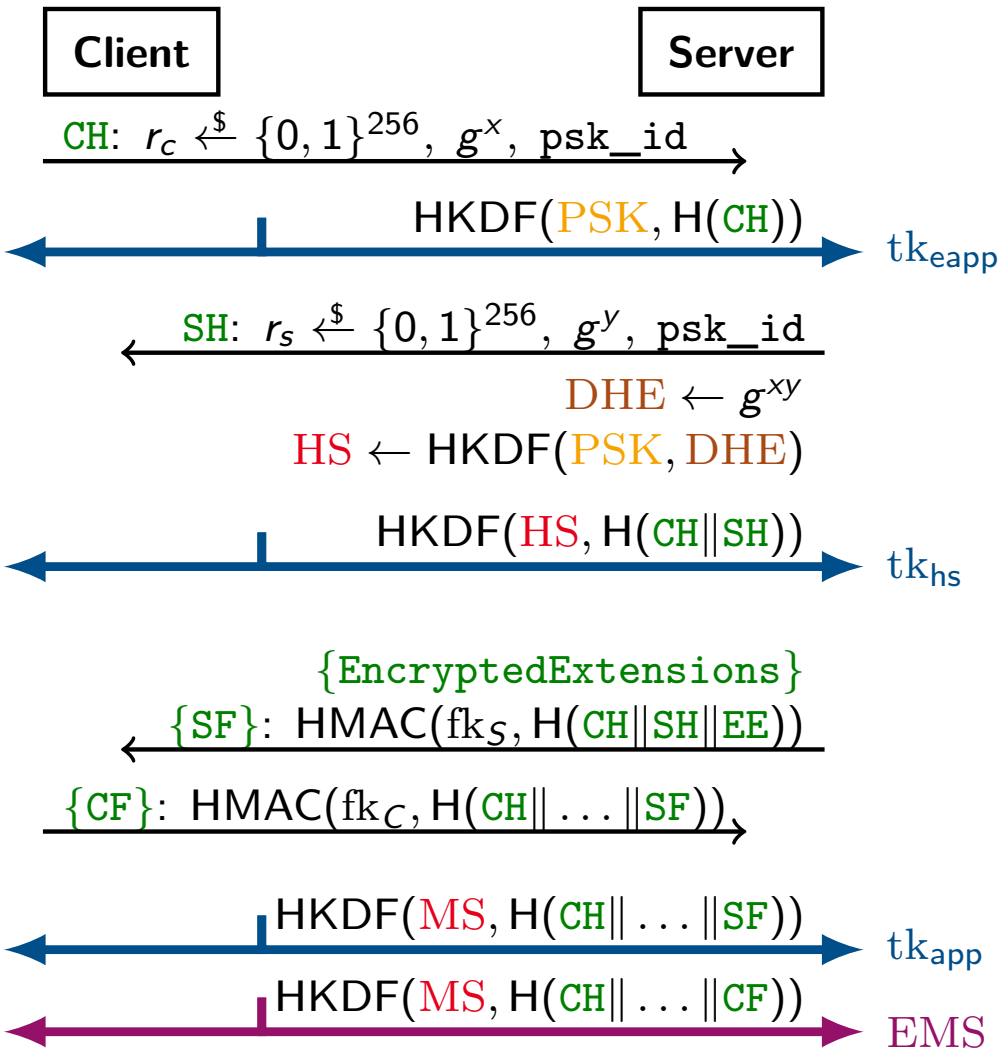


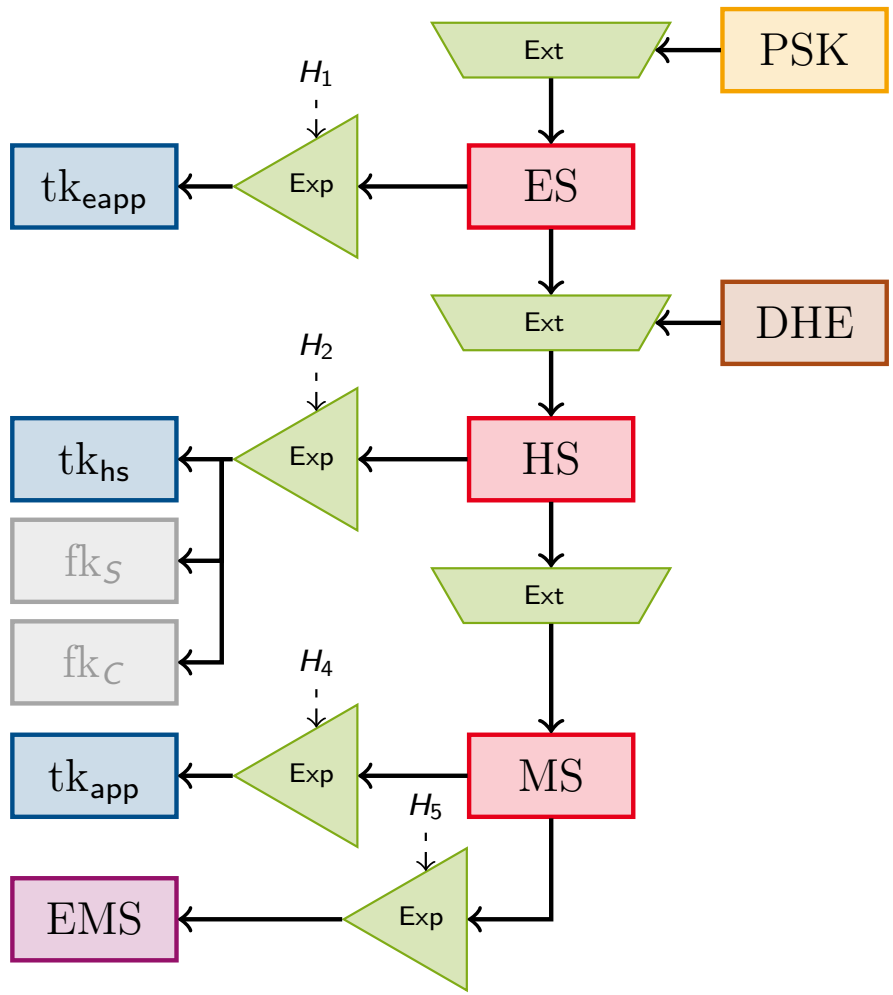
The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

(still simplified)





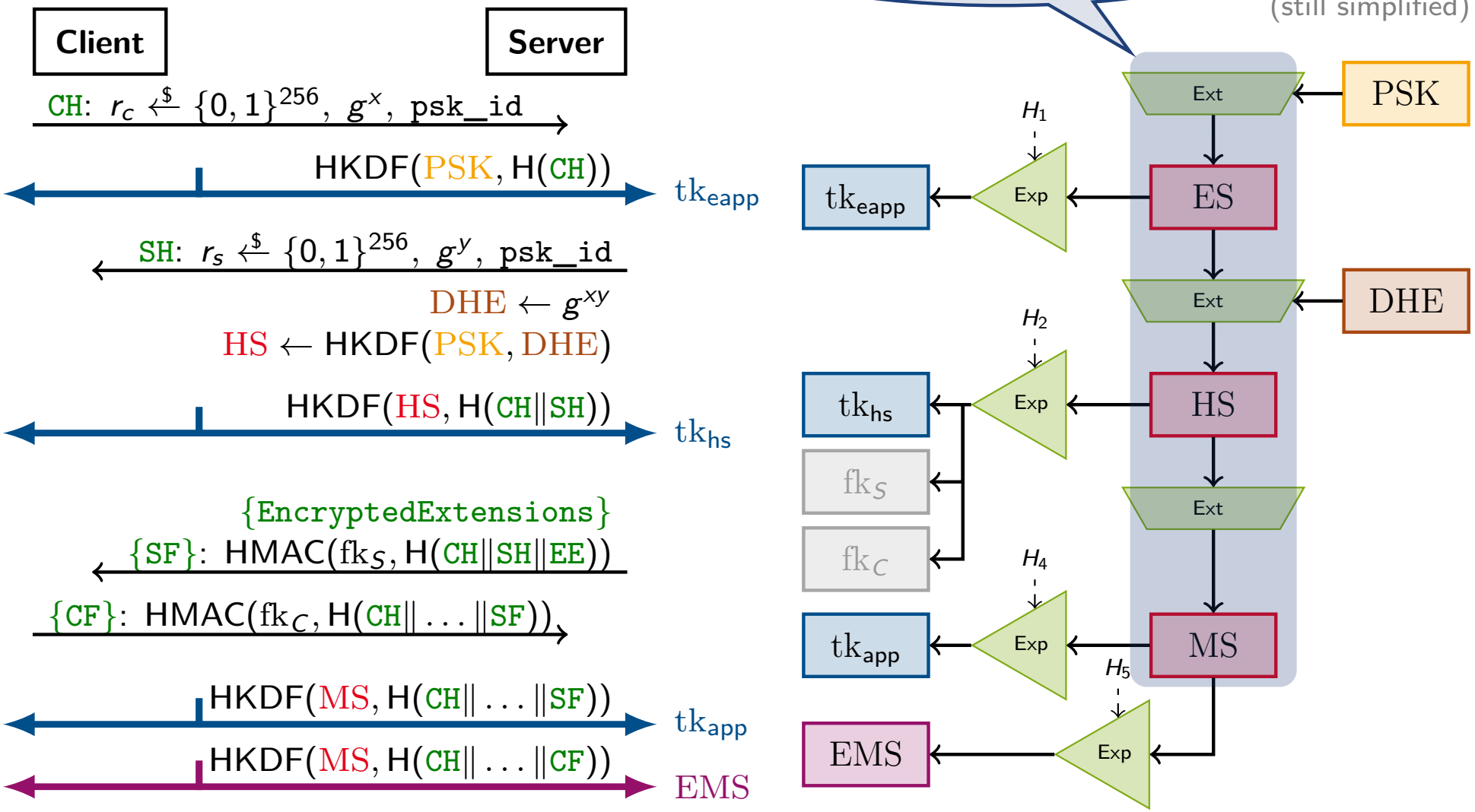
The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

zürich

key schedule: core accumulates secret inputs

(still simplified)

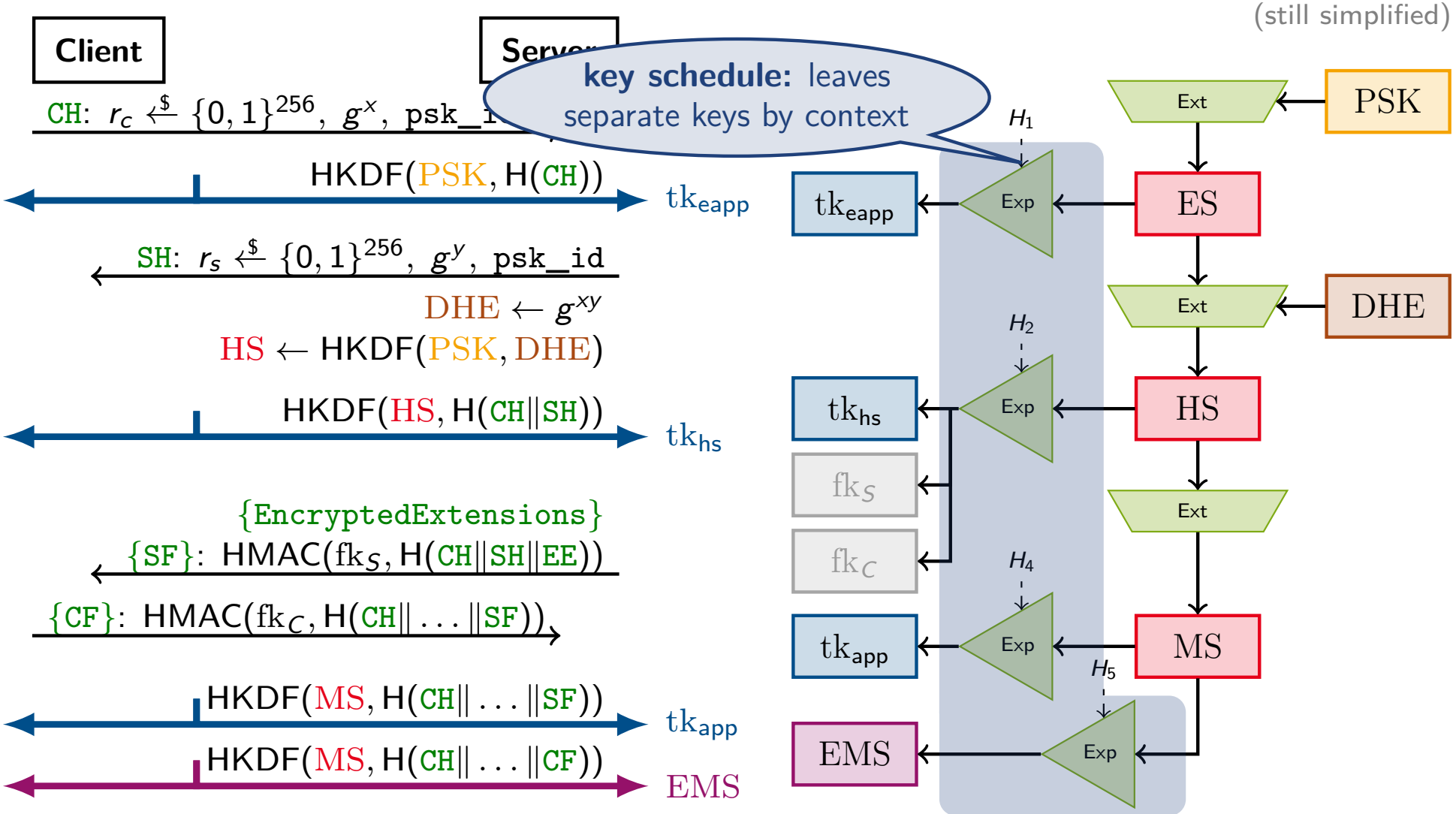


The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

(still simplified)

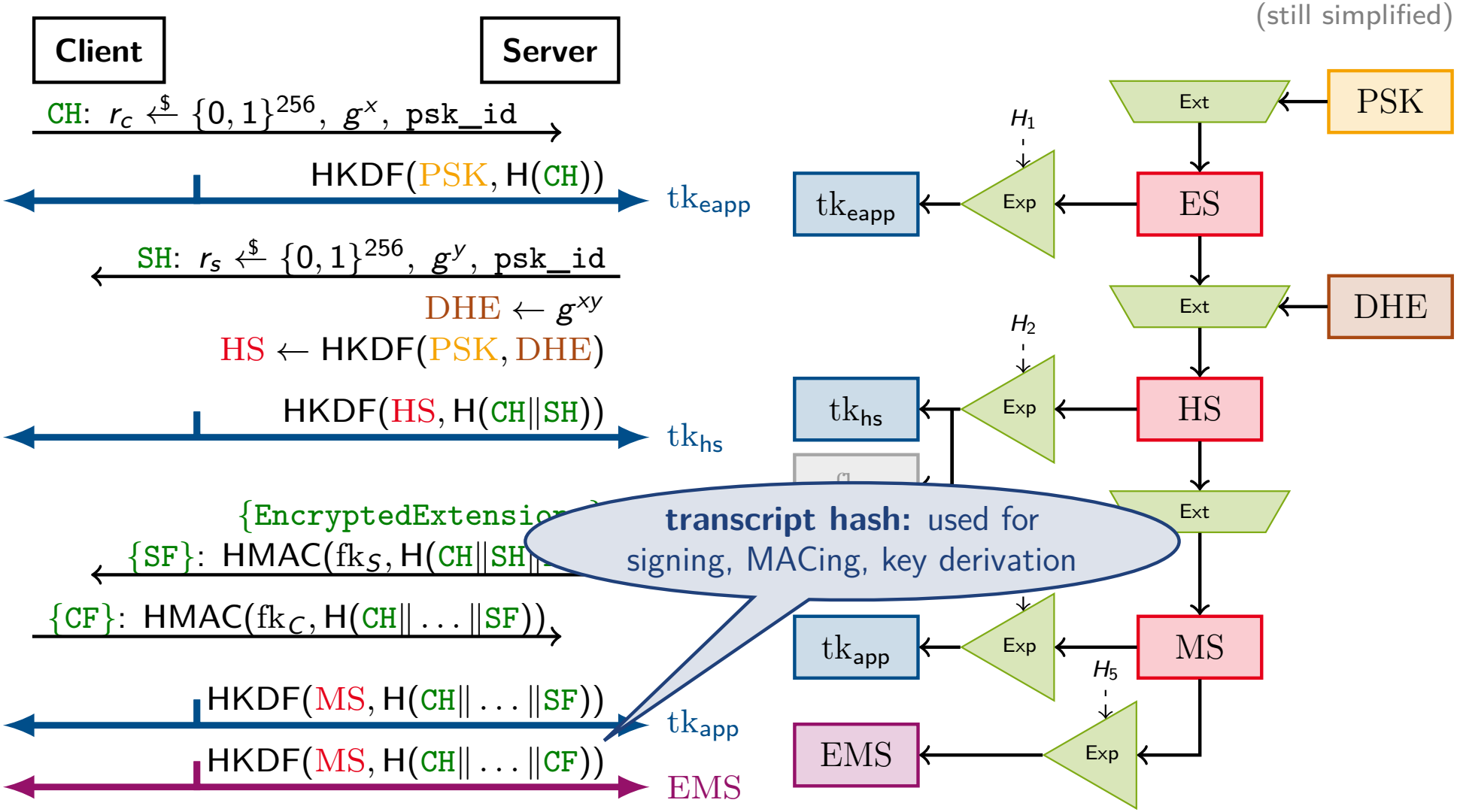


The TLS 1.3 Handshake

PSK-(EC)DHE 0-RTT

ETH zürich

(still simplified)



TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich

Theorem 6.4. *The TLS 1.3 PSK-(EC)DHE 0-RTT handshake is* Multi-Stage*-secure with properties* (M, AUTH, FS, USE, REPLAY).

$$
\begin{aligned}
\mathsf{Adv}^{\text{Multi-Stage},\mathcal{D}}_{\texttt{TLS1.3-PSK-(EC)DHE-0RTT},\mathcal{A}} \leq 8n_s \cdot \Bigg(& \mathsf{Adv}^{\text{COLL}}_{\mathsf{H},\mathcal{B}_1} \\
& + n_p n_s \cdot \Big(\mathsf{Adv}^{\text{dual-PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_2} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_3} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_4} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_5} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_6} + \mathsf{Adv}^{\text{EUF-CMA}}_{\mathsf{HMAC},\mathcal{B}_7} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_8} + \mathsf{Adv}^{\text{EUF-CMA}}_{\mathsf{HMAC},\mathcal{B}_9} \Big) \\
& + n_p n_s \cdot \Big(\mathsf{Adv}^{\text{dual-PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_{10}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{11}} \Big) \\
& + n_s \cdot \Big(\mathsf{Adv}^{\text{dual-snPRF-ODH}}_{\mathsf{HKDF.Extract},\mathbb{G},\mathcal{B}_{12}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{13}} \\
& \qquad + 2\mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{14}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_{15}} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{16}} \Big) \Bigg).
\end{aligned}
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich

The **TLS 1.3 PSK-(EC)DHE 0-RTT** handshake provides

- random-looking secret keys

Theorem 6.4. *The TLS 1.3 PSK-(EC)DHE 0-RTT handshake is* **Multi-Stage-*secure*** *with properties* (M, AUTH, FS, USE, REPLAY).

$$
\begin{aligned}
\mathsf{Adv}^{\text{Multi-Stage},\mathcal{D}}_{\texttt{TLS1.3-PSK-(EC)DHE-0RTT},\mathcal{A}} \leq 8n_s \cdot \Big(& \mathsf{Adv}^{\text{COLL}}_{\mathsf{H},\mathcal{B}_1} \\
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& + n_p n_s \cdot \Big(\mathsf{Adv}^{\text{dual-PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_{10}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{11}} \Big) \\
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& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{16}} \Big) \Big).
\end{aligned}
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich

The **TLS 1.3 PSK-(EC)DHE 0-RTT** handshake provides

- random-looking secret keys
- forward security
  for non–0-RTT keys

Theorem 6.4. *The TLS 1.3 PSK-(EC)DHE 0-RTT handshake is* **Multi-Stage-*secure*** *with properties* (M, AUTH, **FS**, USE, REPLAY).

$$
\begin{aligned}
\mathsf{Adv}^{\text{Multi-Stage},\mathcal{D}}_{\texttt{TLS1.3-PSK-(EC)DHE-0RTT},\mathcal{A}} \leq 8n_s \cdot \Big(& \mathsf{Adv}^{\text{COLL}}_{\mathsf{H},\mathcal{B}_1} \\
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& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_4} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_5} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_6} + \mathsf{Adv}^{\text{EUF-CMA}}_{\mathsf{HMAC},\mathcal{B}_7} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_8} + \mathsf{Adv}^{\text{EUF-CMA}}_{\mathsf{HMAC},\mathcal{B}_9} \Big) \\
& + n_p n_s \cdot \Big(\mathsf{Adv}^{\text{dual-PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_{10}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{11}} \Big) \\
& + n_s \cdot \Big(\mathsf{Adv}^{\text{dual-snPRF-ODH}}_{\mathsf{HKDF.Extract},\mathbb{G},\mathcal{B}_{12}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{13}} \\
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& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{16}} \Big) \Big).
\end{aligned}
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich

The **TLS 1.3 PSK-(EC)DHE 0-RTT** handshake provides

- random-looking secret keys
- forward security
  for non–0-RTT keys
- mutual authentication wrt. PSK

Theorem 6.4. *The TLS 1.3 PSK-(EC)DHE 0-RTT handshake is* **Multi-Stage-*secure*** *with properties* (M, **AUTH**, **FS**, USE, REPLAY).

$$
\begin{aligned}
\mathsf{Adv}^{\text{Multi-Stage},\mathcal{D}}_{\texttt{TLS1.3-PSK-(EC)DHE-0RTT},\mathcal{A}} \leq 8n_s \cdot \Big(& \mathsf{Adv}^{\text{COLL}}_{\mathsf{H},\mathcal{B}_1} \\
& + n_p n_s \cdot \Big(\mathsf{Adv}^{\text{dual-PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_2} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_3} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_4} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_5} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_6} + \mathsf{Adv}^{\text{EUF-CMA}}_{\mathsf{HMAC},\mathcal{B}_7} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_8} + \mathsf{Adv}^{\text{EUF-CMA}}_{\mathsf{HMAC},\mathcal{B}_9} \Big) \\
& + n_p n_s \cdot \Big(\mathsf{Adv}^{\text{dual-PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_{10}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{11}} \Big) \\
& + n_s \cdot \Big(\mathsf{Adv}^{\text{dual-snPRF-ODH}}_{\mathsf{HKDF.Extract},\mathbb{G},\mathcal{B}_{12}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{13}} \\
& \qquad + 2\mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{14}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_{15}} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{16}} \Big) \Big).
\end{aligned}
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich

The **TLS 1.3 PSK-(EC)DHE 0-RTT** handshake provides

- random-looking secret keys
- forward security
  for non–0-RTT keys
- mutual authentication wrt. PSK
- key independence

Theorem 6.4. *The TLS 1.3 PSK-(EC)DHE 0-RTT handshake is* **Multi-Stage-*secure*** *with properties* (M, **AUTH**, **FS**, USE, REPLAY).

$$
\begin{aligned}
\mathsf{Adv}^{\text{Multi-Stage},\mathcal{D}}_{\texttt{TLS1.3-PSK-(EC)DHE-0RTT},\mathcal{A}} \leq 8n_s \cdot \Big(& \mathsf{Adv}^{\text{COLL}}_{\mathsf{H},\mathcal{B}_1} \\
& + n_p n_s \cdot \Big(\mathsf{Adv}^{\text{dual-PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_2} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_3} \\
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\end{aligned}
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[Dow+21]

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TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich

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- key independence
- replayable 0-RTT keys

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\end{aligned}
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich

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assuming . . .

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$$
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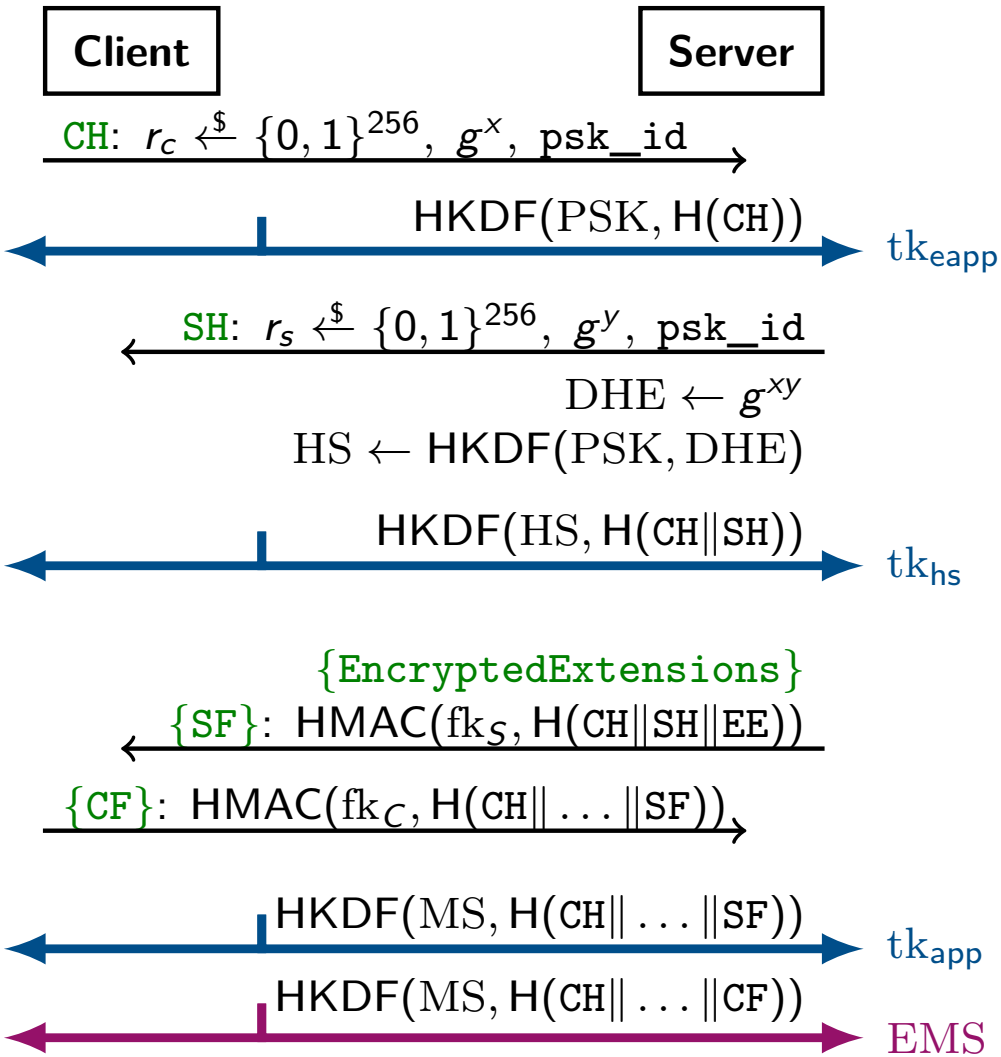
& \qquad + 2\mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{14}} + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Extract},\mathcal{B}_{15}} \\
& \qquad + \mathsf{Adv}^{\text{PRF-sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{16}} \Big) \Big).
\end{aligned}
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich



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$$
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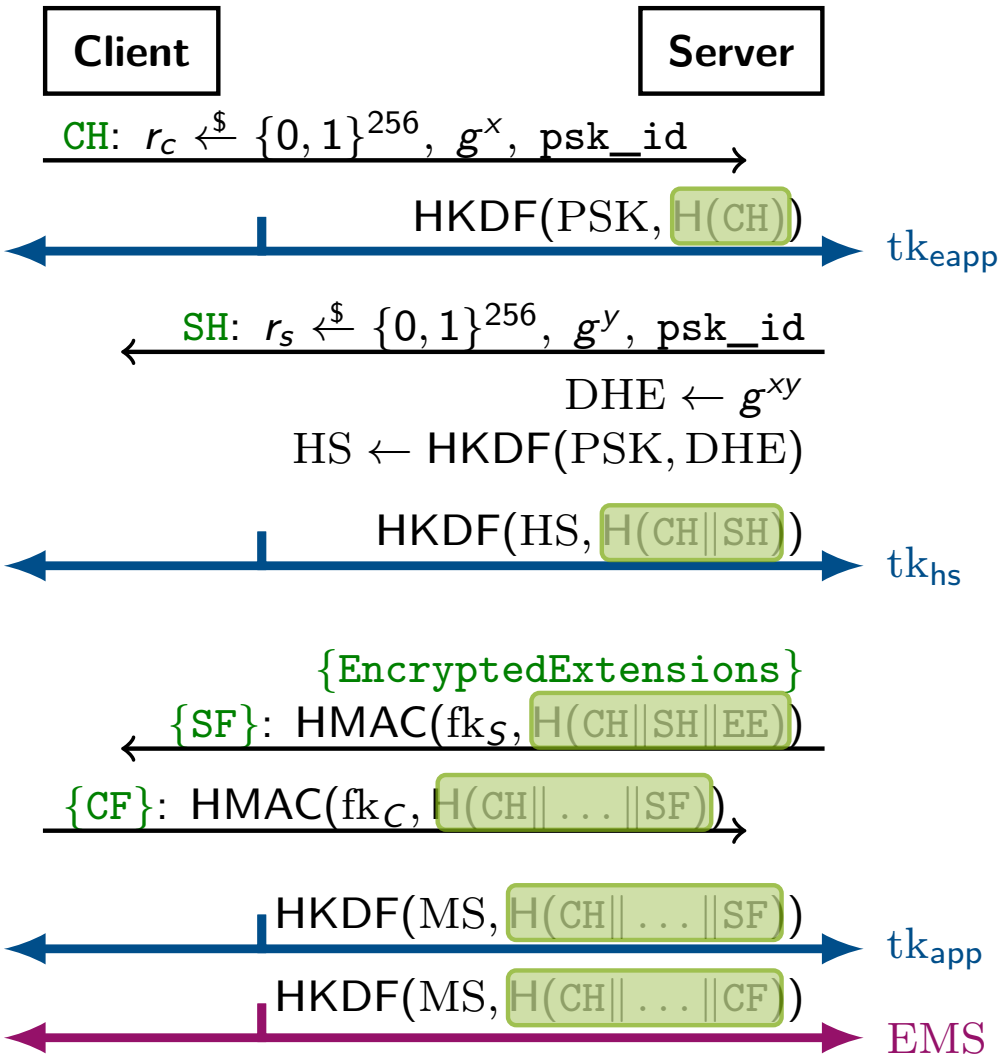
\end{aligned}
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich



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$$
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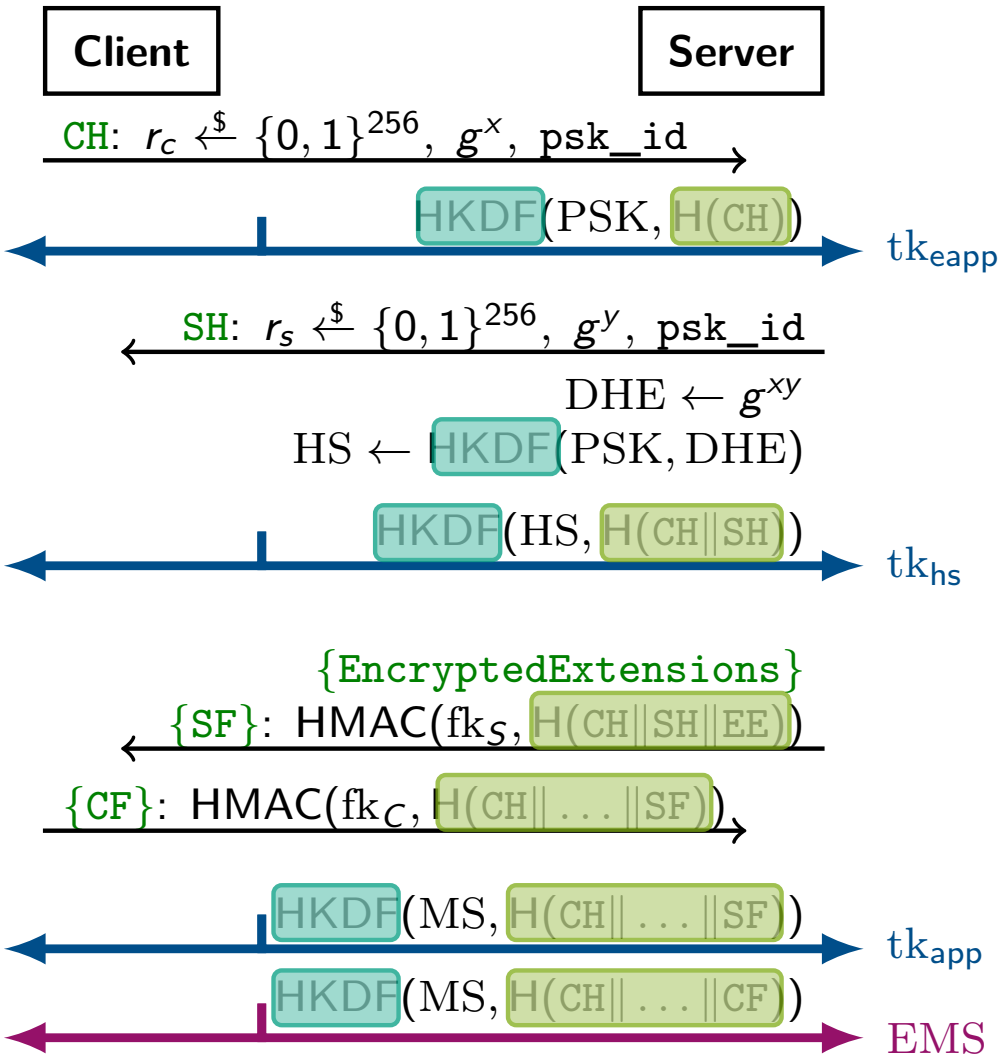
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich



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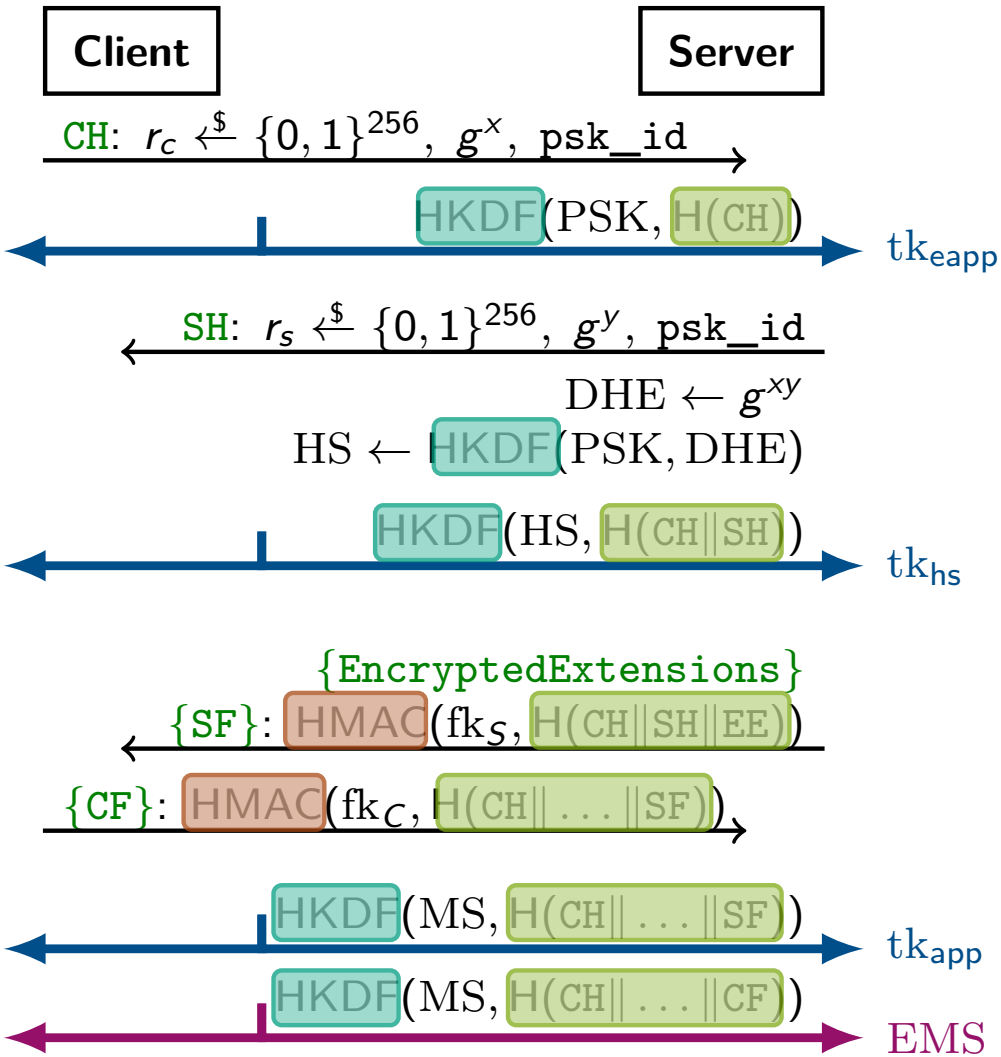
\end{aligned}
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich



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$$
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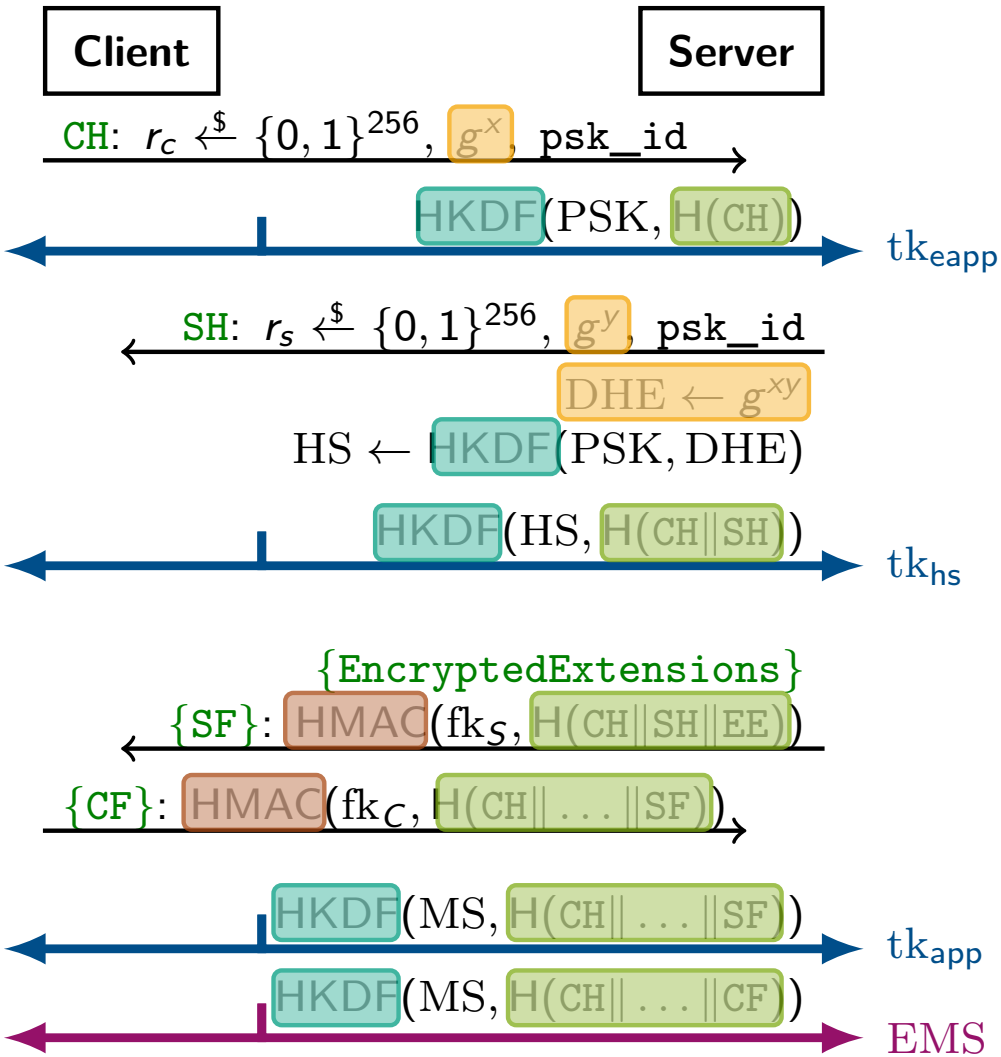
$$

[Dow+21]

TLS 1.3 Handshake Security

TLS 1.3 PSK-(EC)DHE 0-RTT as Multi-Stage Key Exchange

ETH zürich



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$$\begin{aligned}
\mathsf{Adv}^{\text{Multi-Stage},\mathcal{D}}_{\text{TLS1.3-PSK-(EC)DHE-ORTT},\mathcal{A}} \leq\ & 8n_s \cdot \Big(\mathsf{Adv}^{\text{COLL}}_{H,\mathcal{B}_1} \\
& + n_p n_s \cdot \Big(\mathsf{Adv}^{\text{dual-PRF-sec}}_{\text{HKDF.Extract},\mathcal{B}_2} + \mathsf{Adv}^{\text{PRF-sec}}_{\text{HKDF.Expand},\mathcal{B}_3} \\
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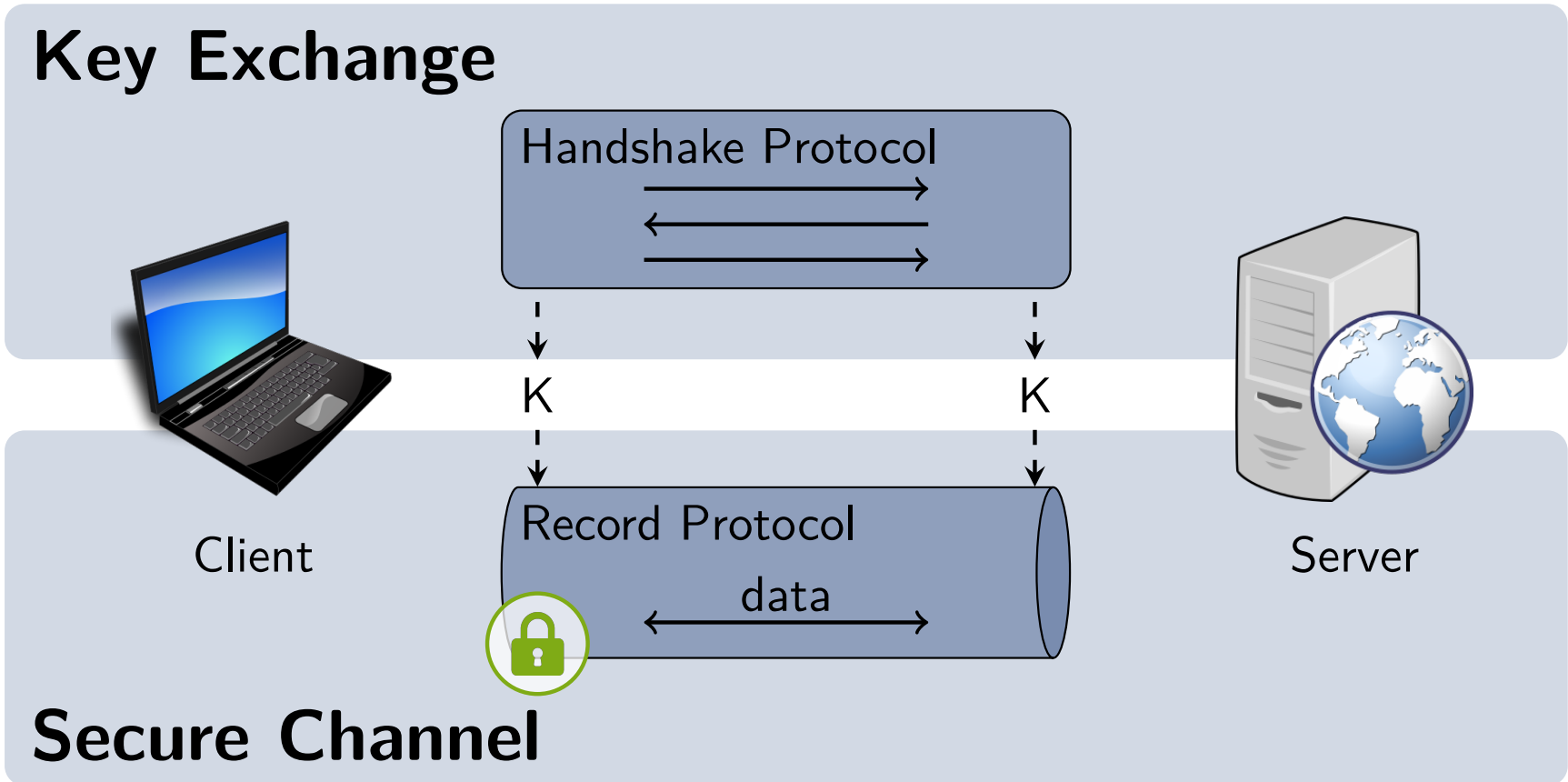
\end{aligned}$$

[Dow+21]

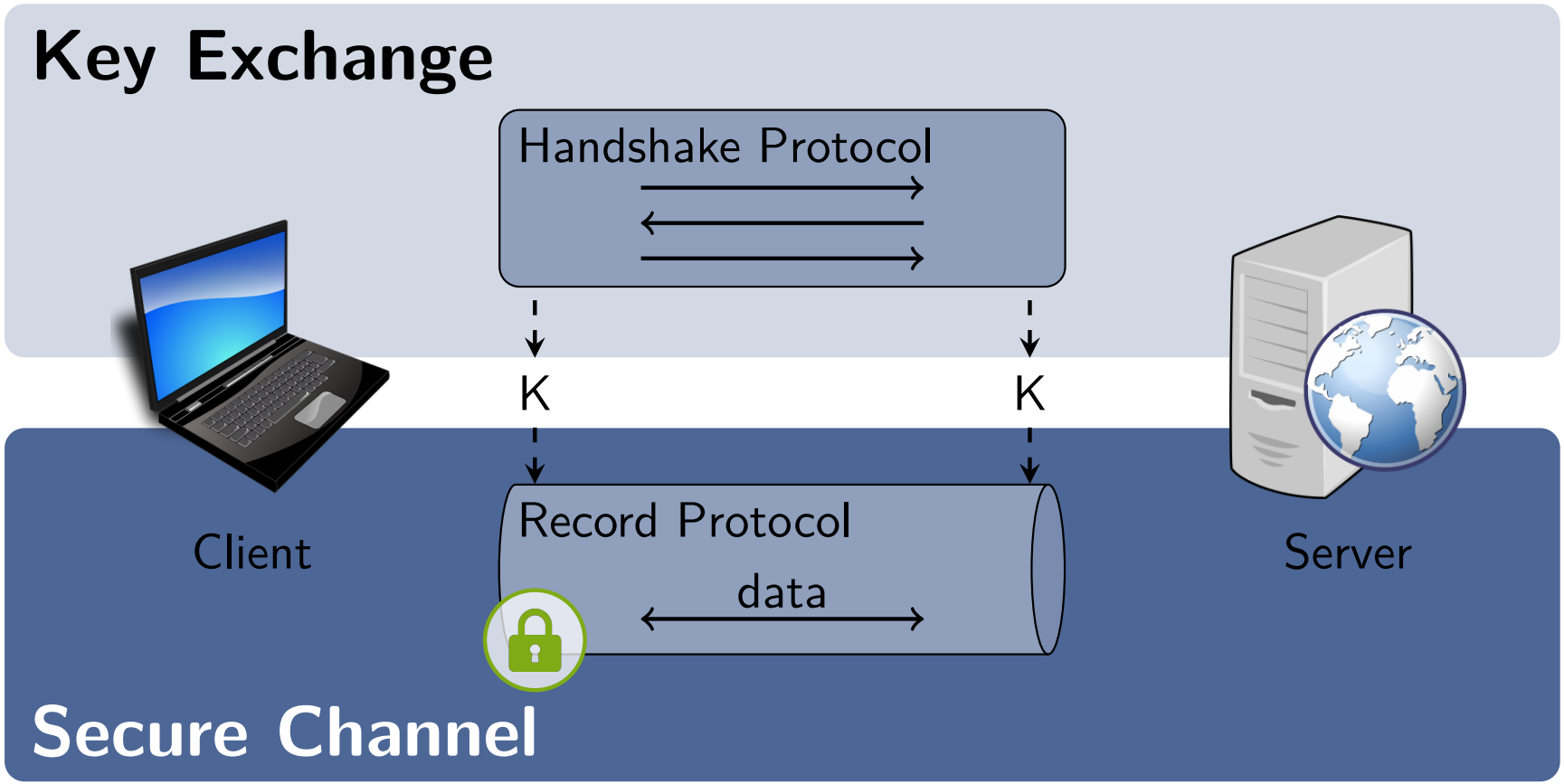
The Cryptographic Core

ETH zürich



The Cryptographic Core

ETH zürich



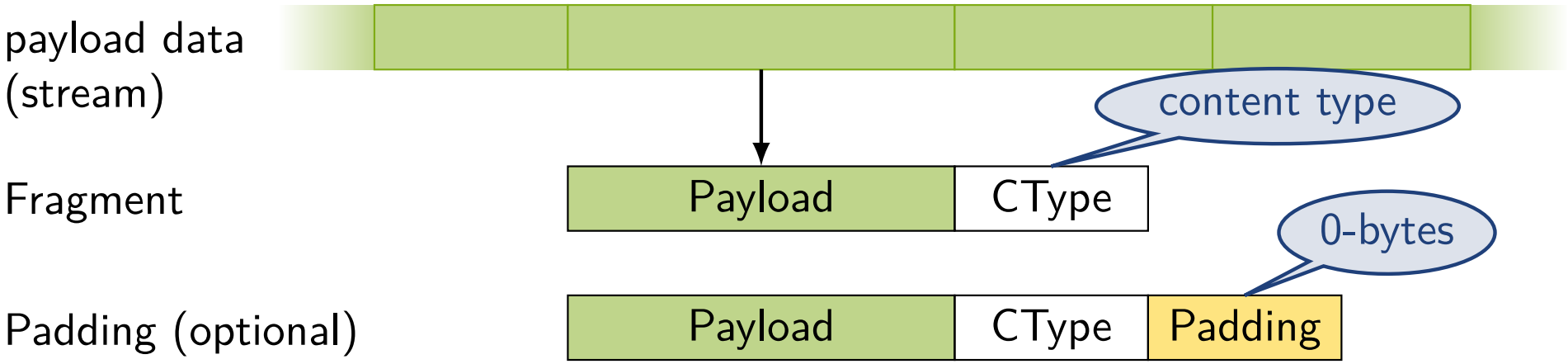
The TLS 1.3 Record Protocol

ETH zürich

payload data
(stream)

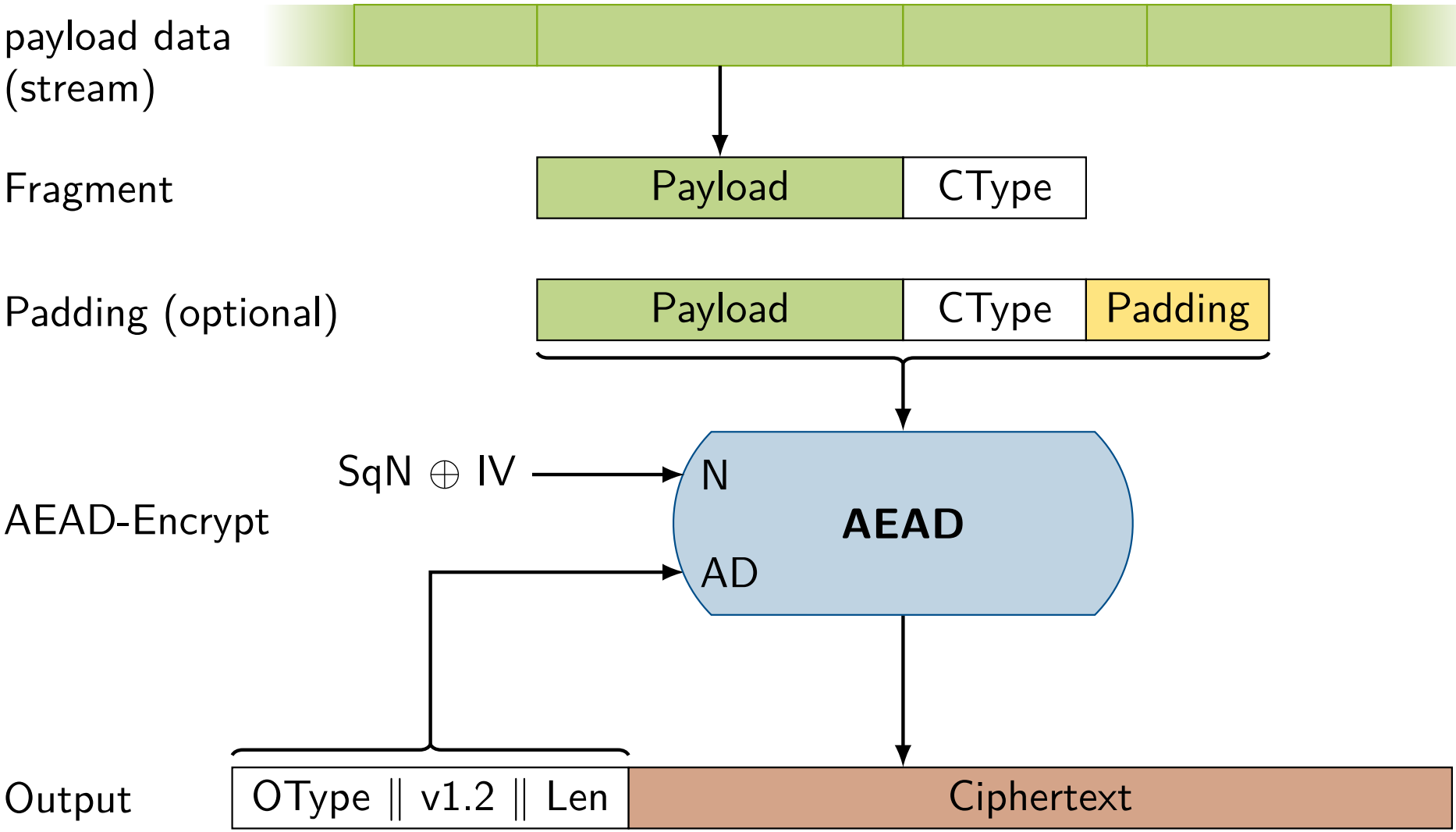
The TLS 1.3 Record Protocol

ETH zürich



The TLS 1.3 Record Protocol

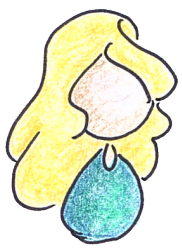
ETH zürich



Channel Security: Stateful Auth. Encryption

Originating from [BKN02]

ETH zürich

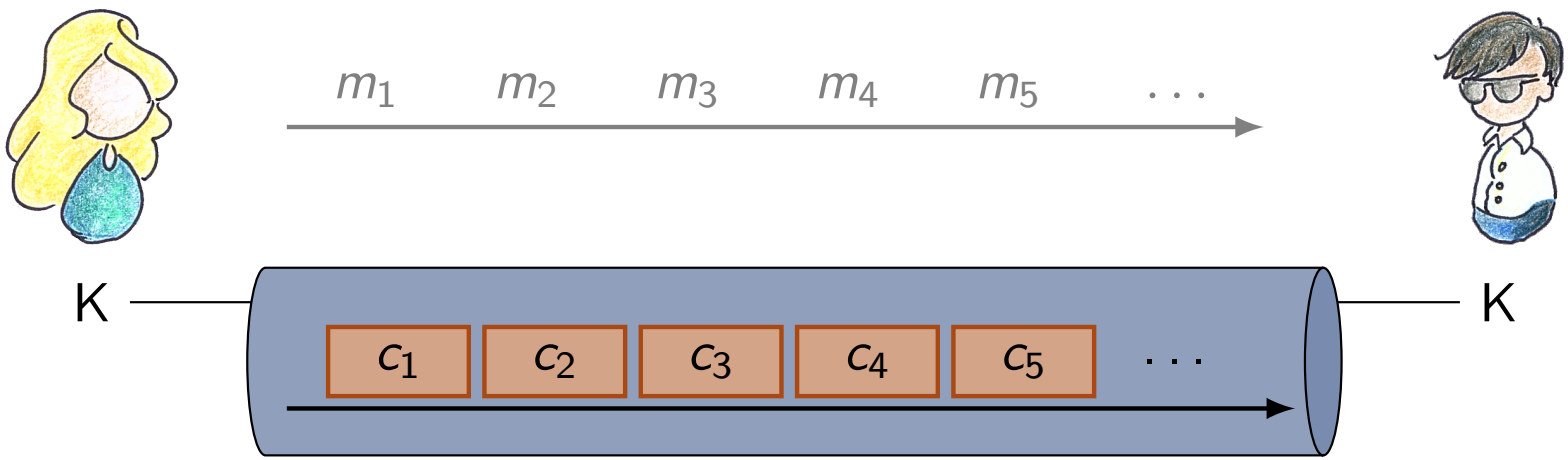


$m_1 \quad m_2 \quad m_3 \quad m_4 \quad m_5 \quad \ldots$

Channel Security: Stateful Auth. Encryption

Originating from [BKN02]

ETH zürich



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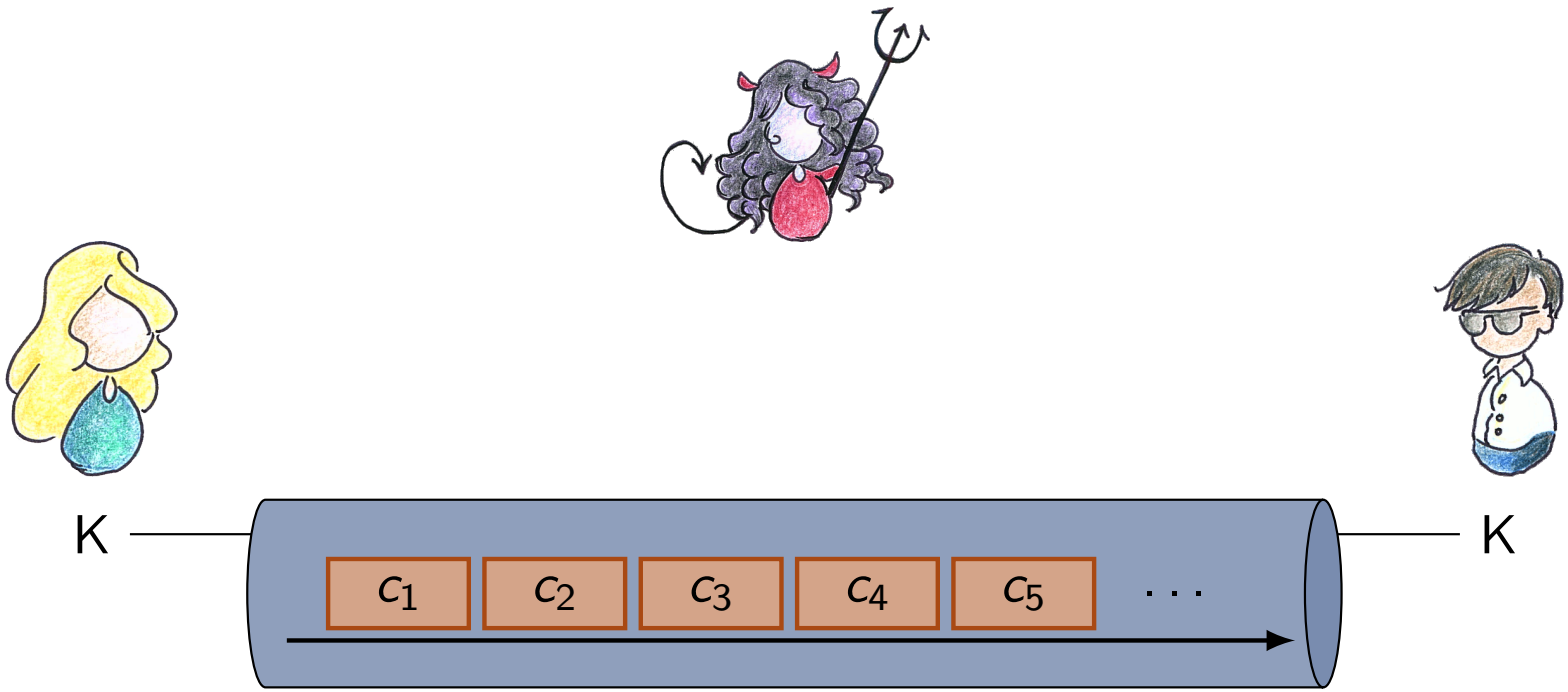

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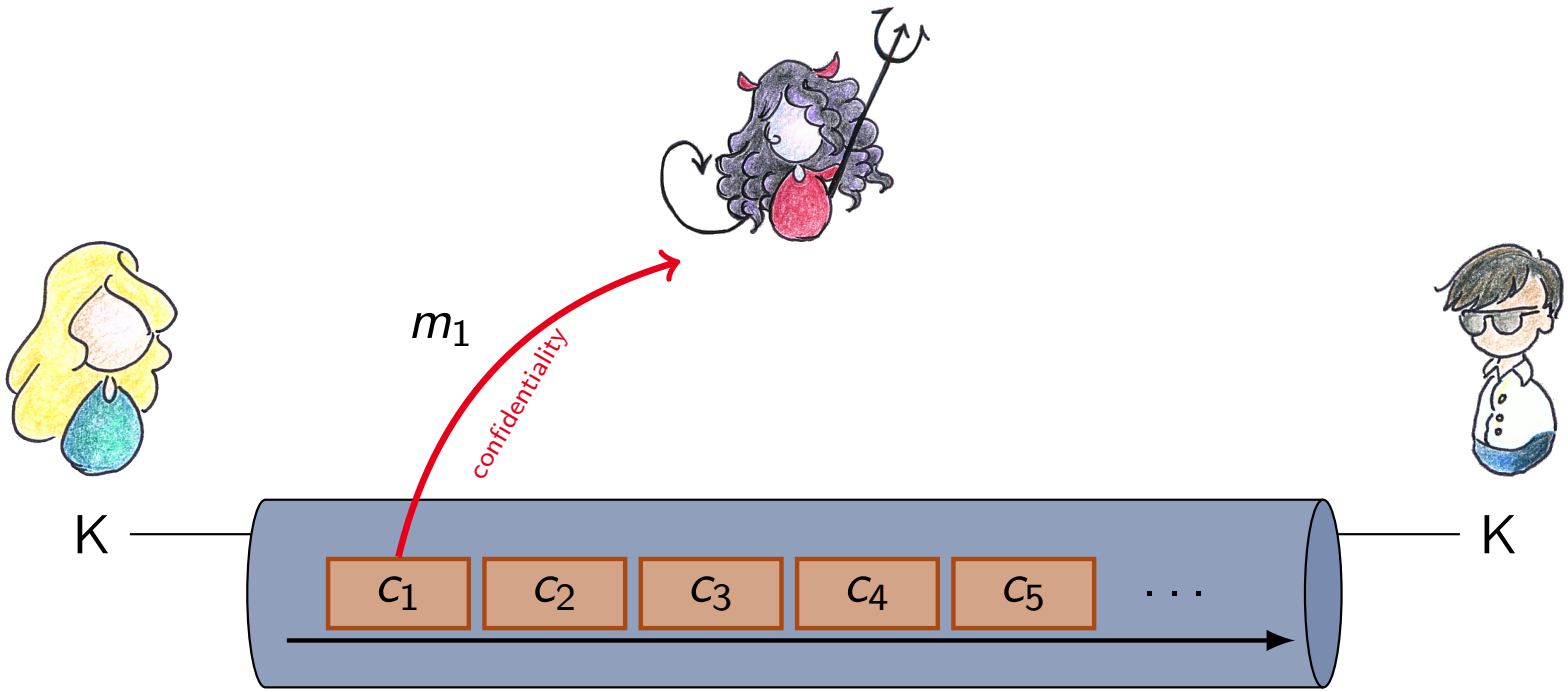


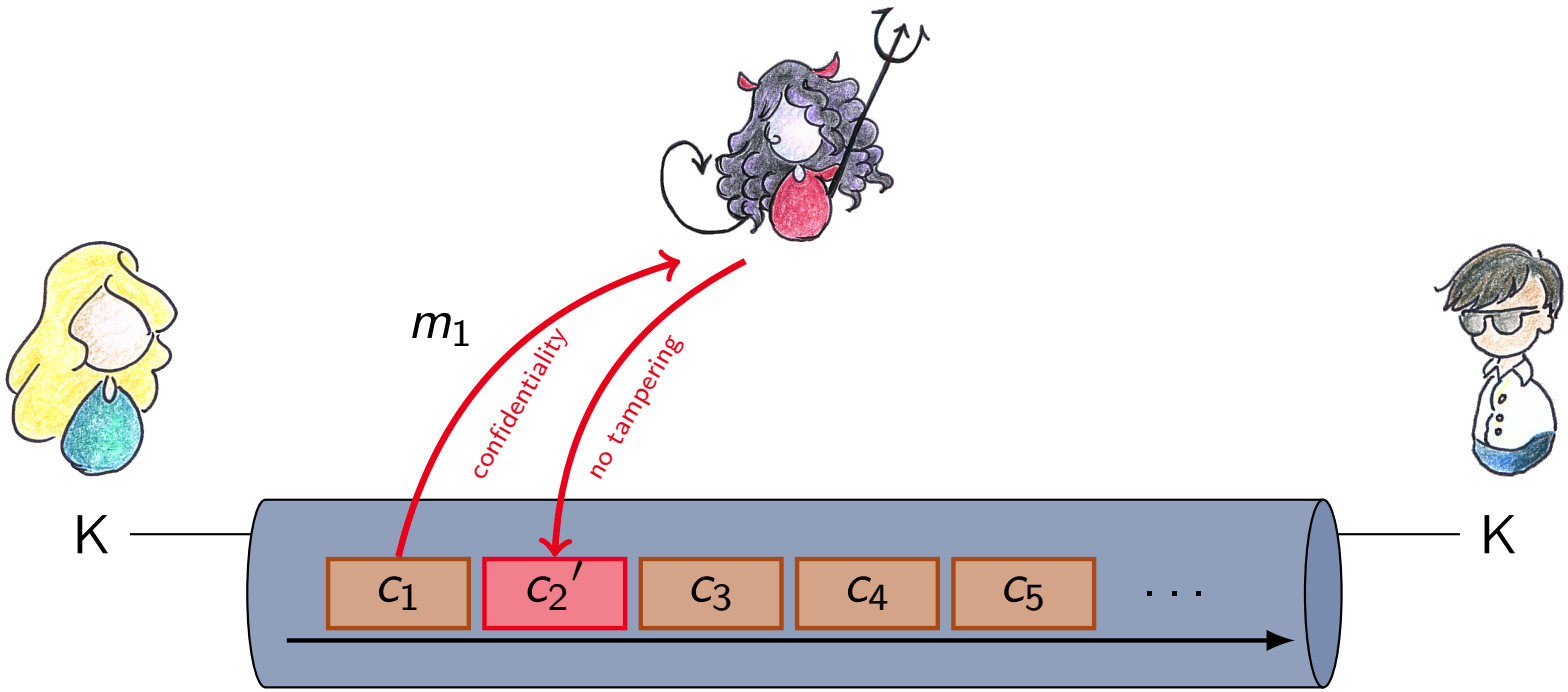
IND-sfCPA (passive confidentiality)

IND-sfCCA (active confidentiality)

Channel Security: Stateful Auth. Encryption

Originating from [BKN02]

ETH zürich



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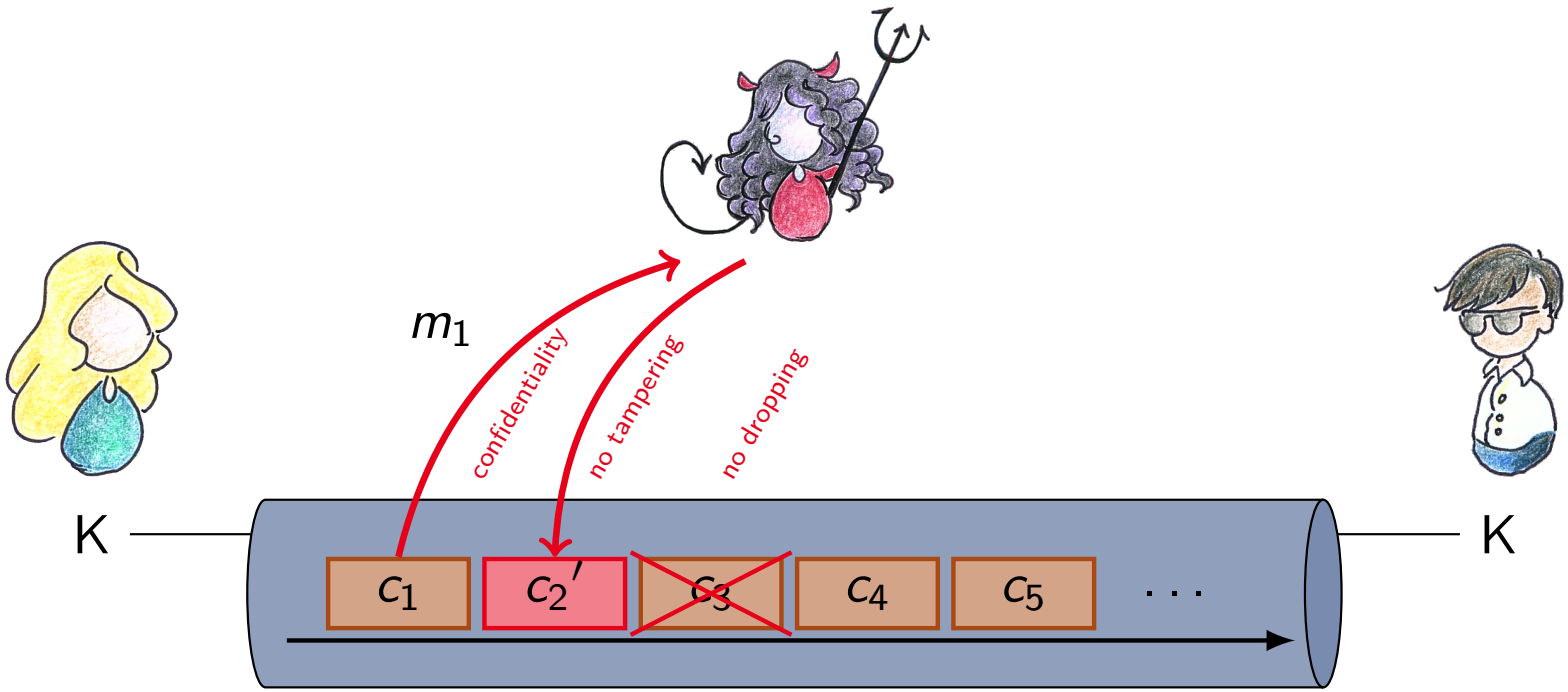
Channel Security: Stateful Auth. Encryption

Originating from [BKN02]

ETH zürich



IND-sfCPA (passive confidentiality)

IND-sfCCA (active confidentiality)

Channel Security: Stateful Auth. Encryption

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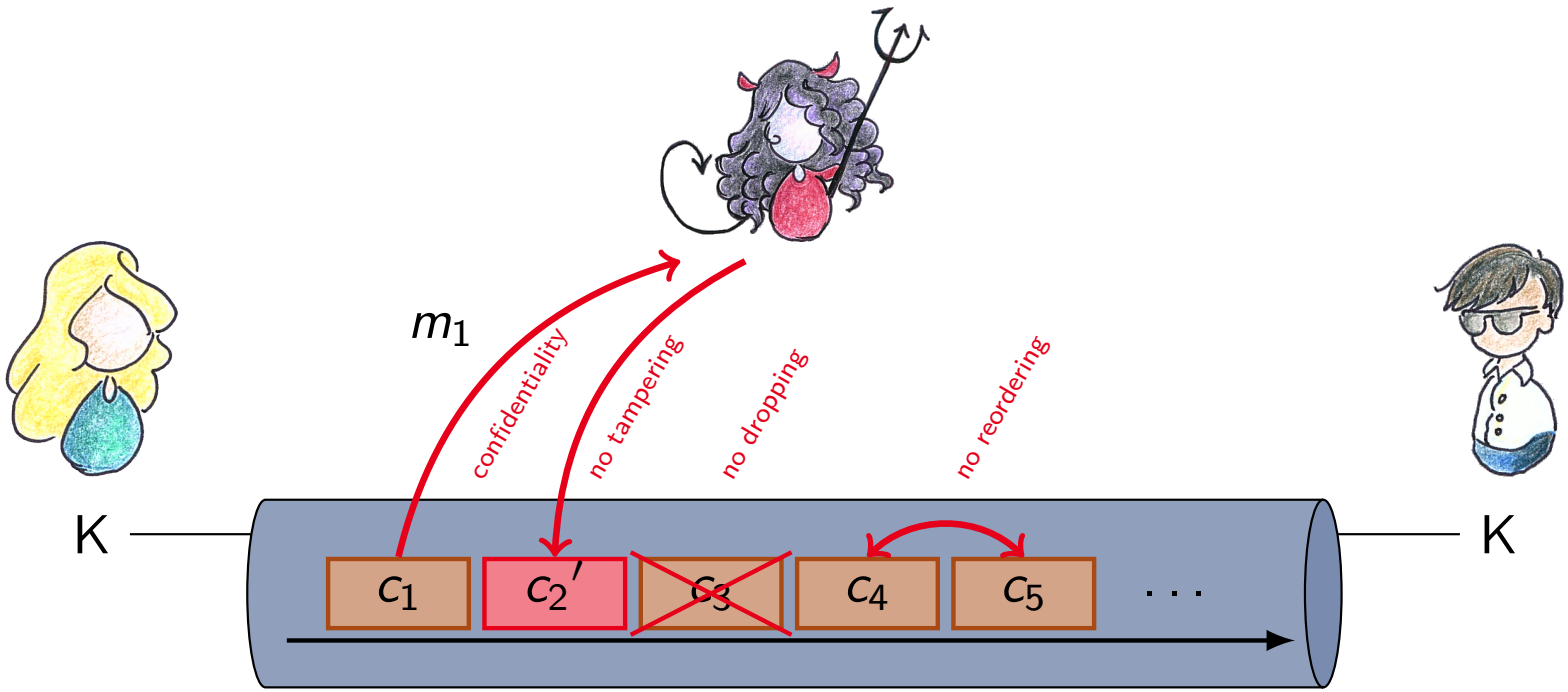

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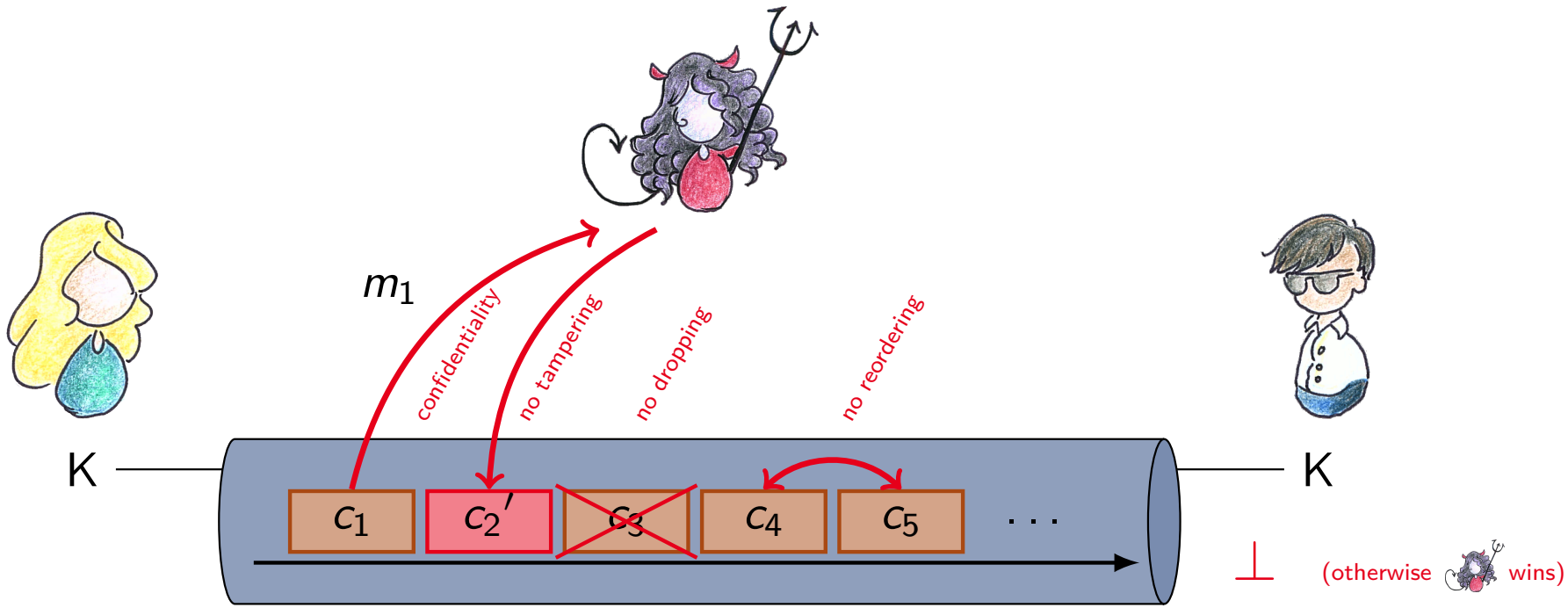

IND-sfCPA (passive confidentiality)

IND-sfCCA (active confidentiality)

INT-sfPTXT (plaintext integrity)

INT-sfCTXT (ciphertext integrity)

TLS 1.3 Record Protocol Security

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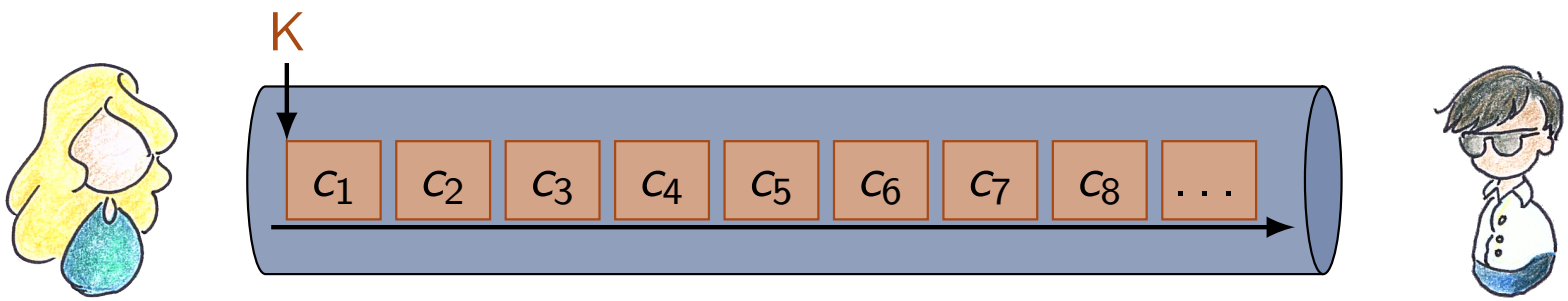
ETH zürich

- classically: 1 key ✓



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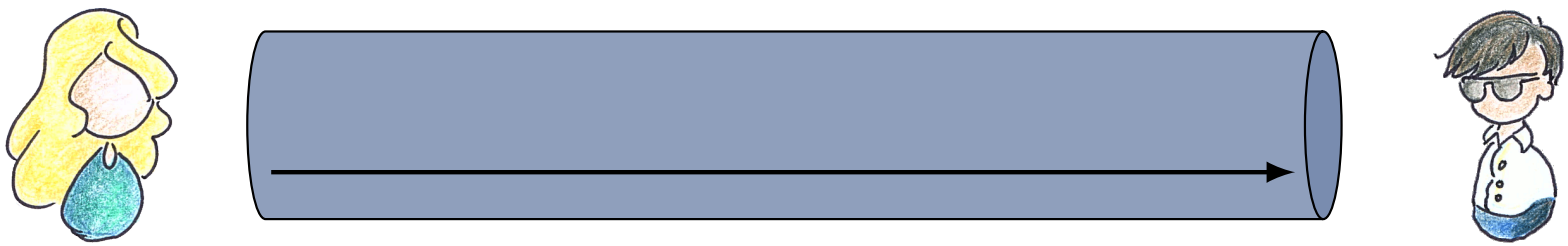

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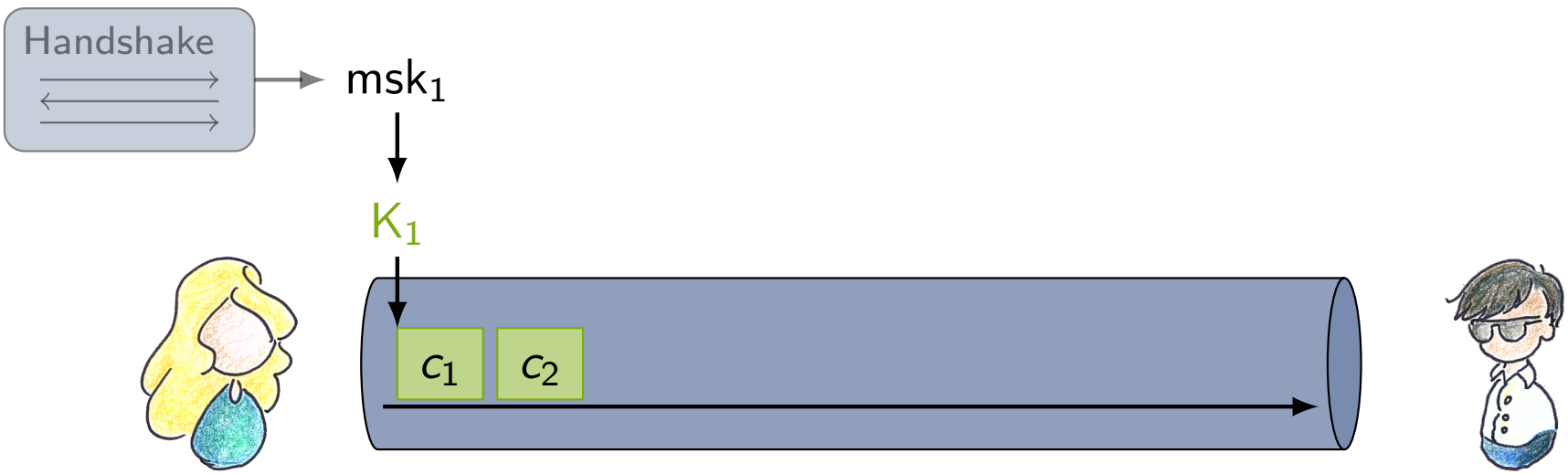

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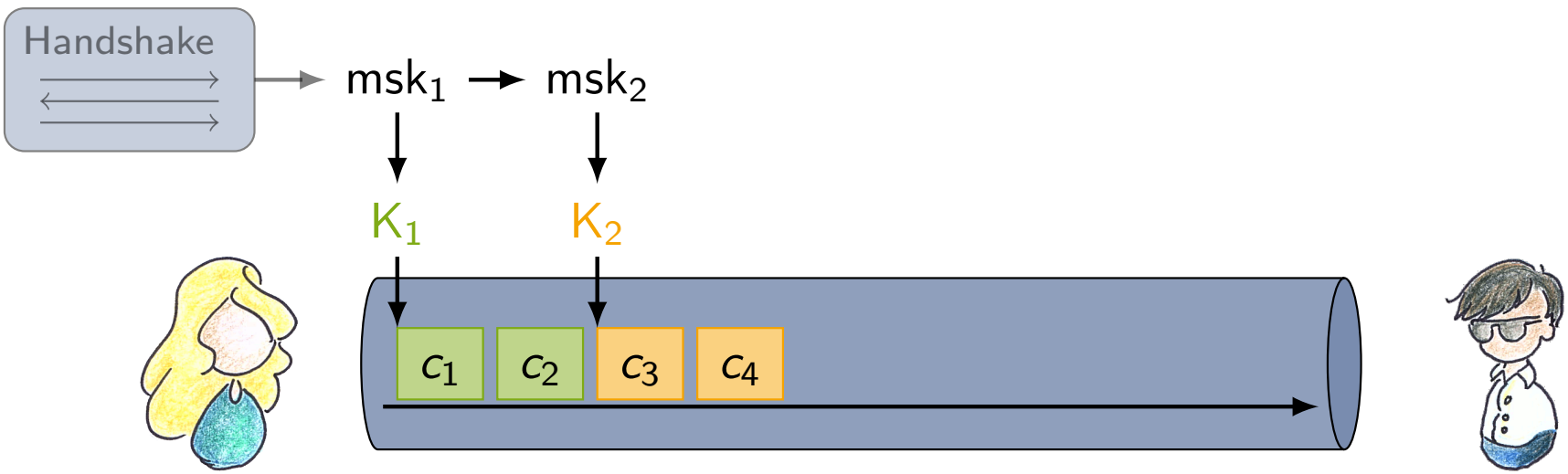

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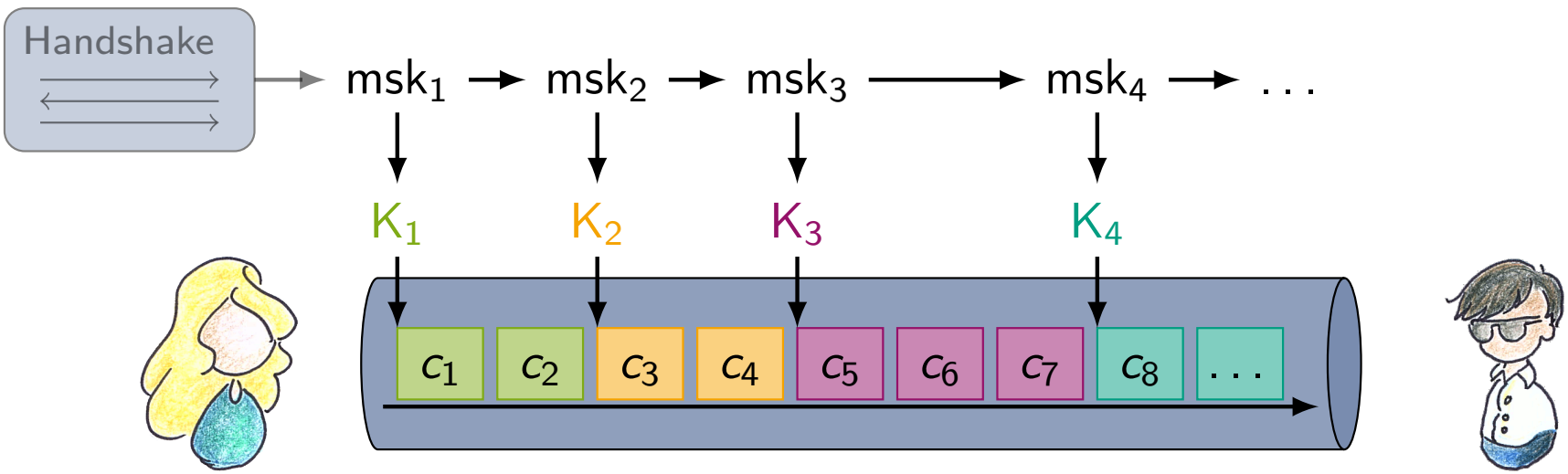

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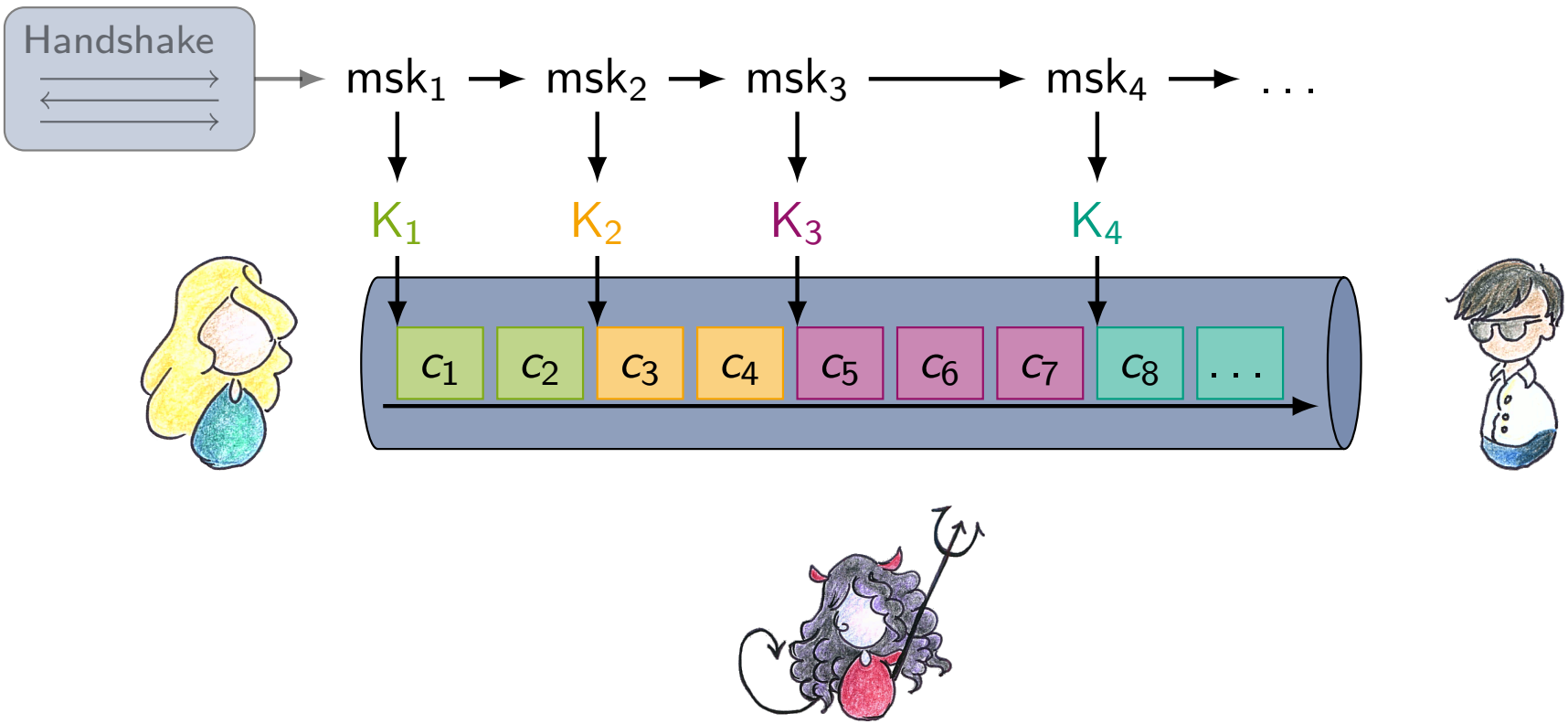

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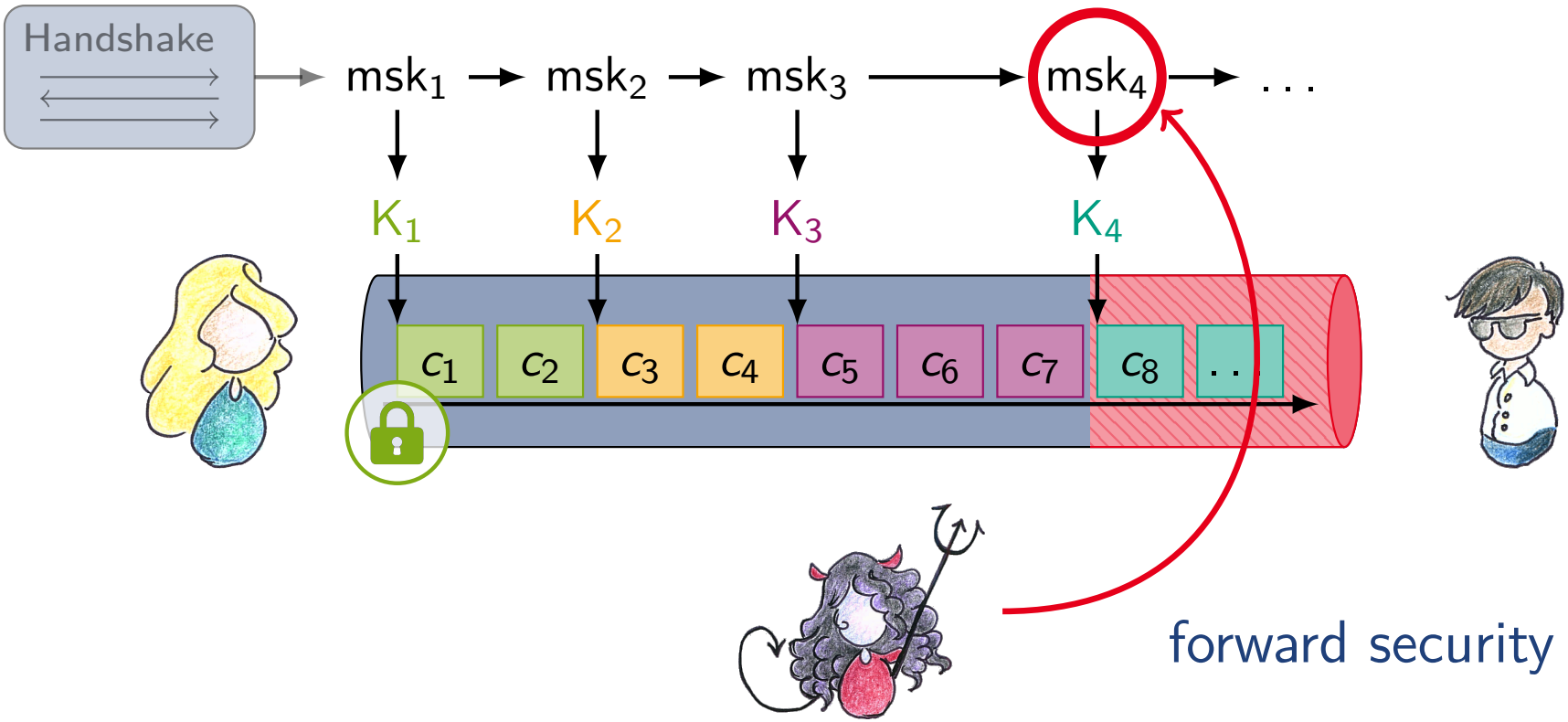

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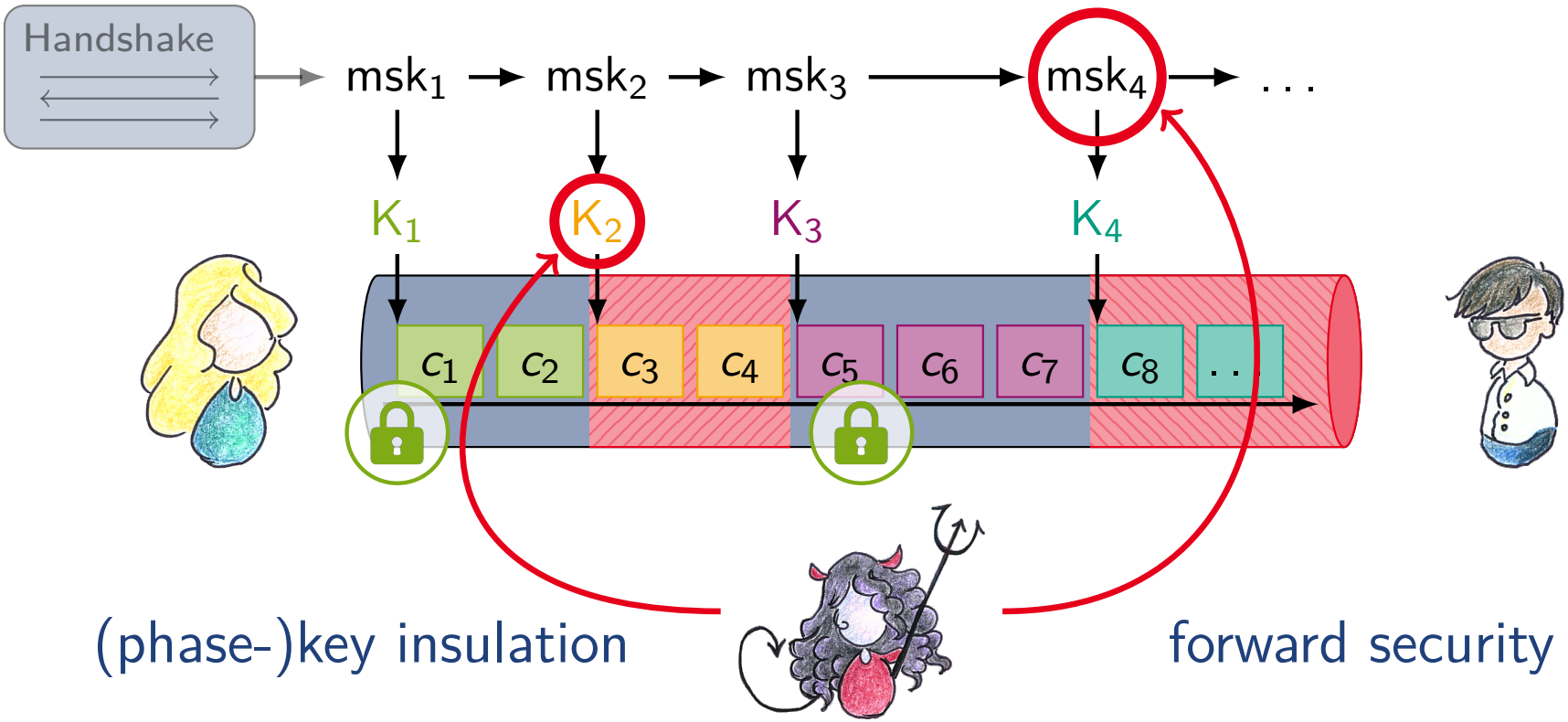

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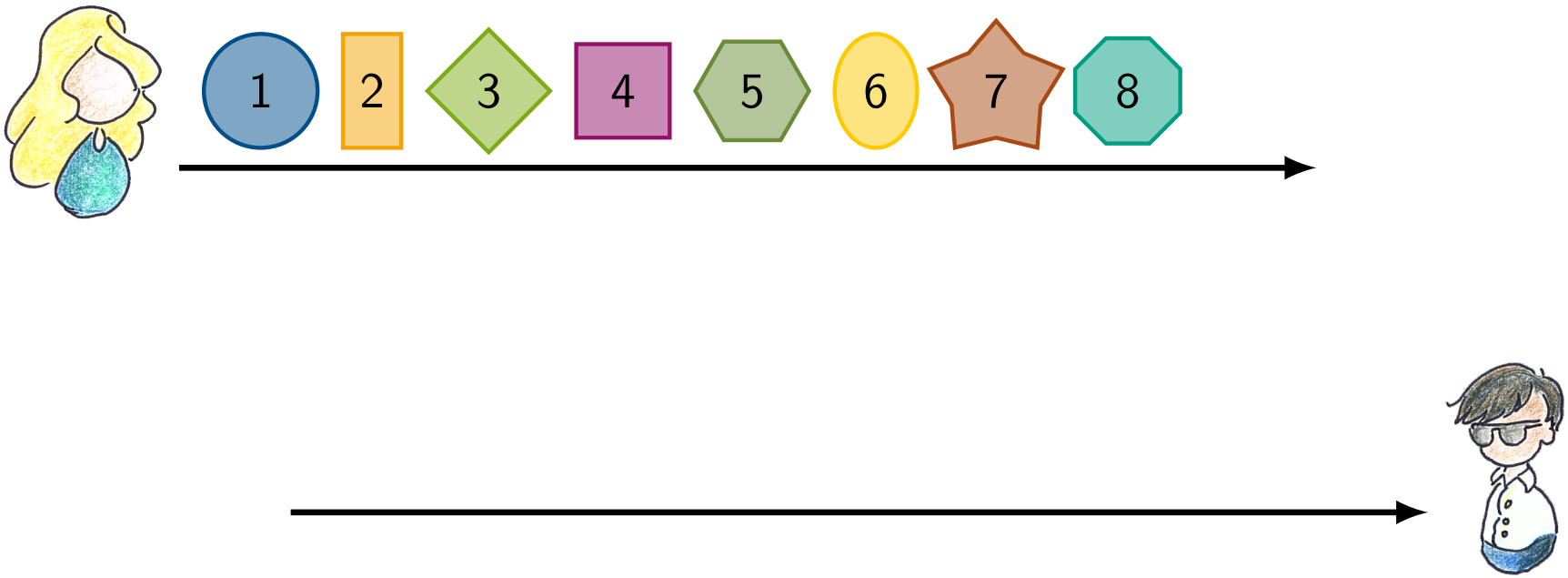

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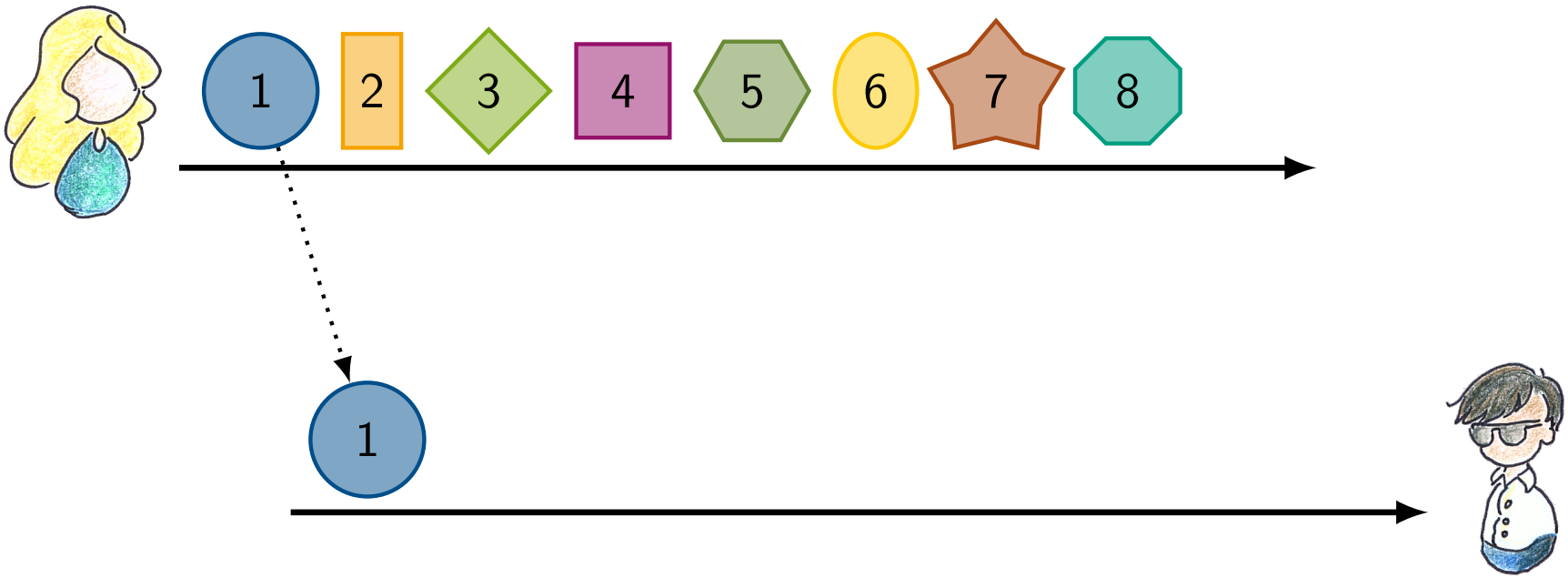

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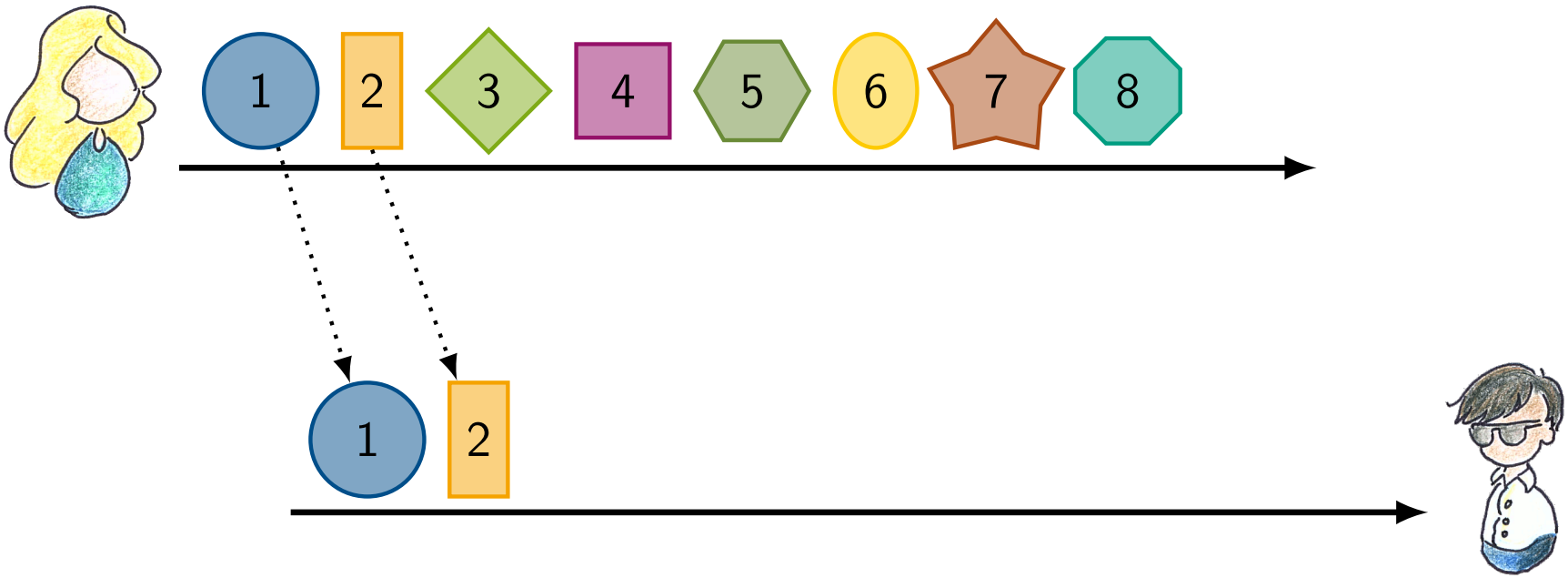

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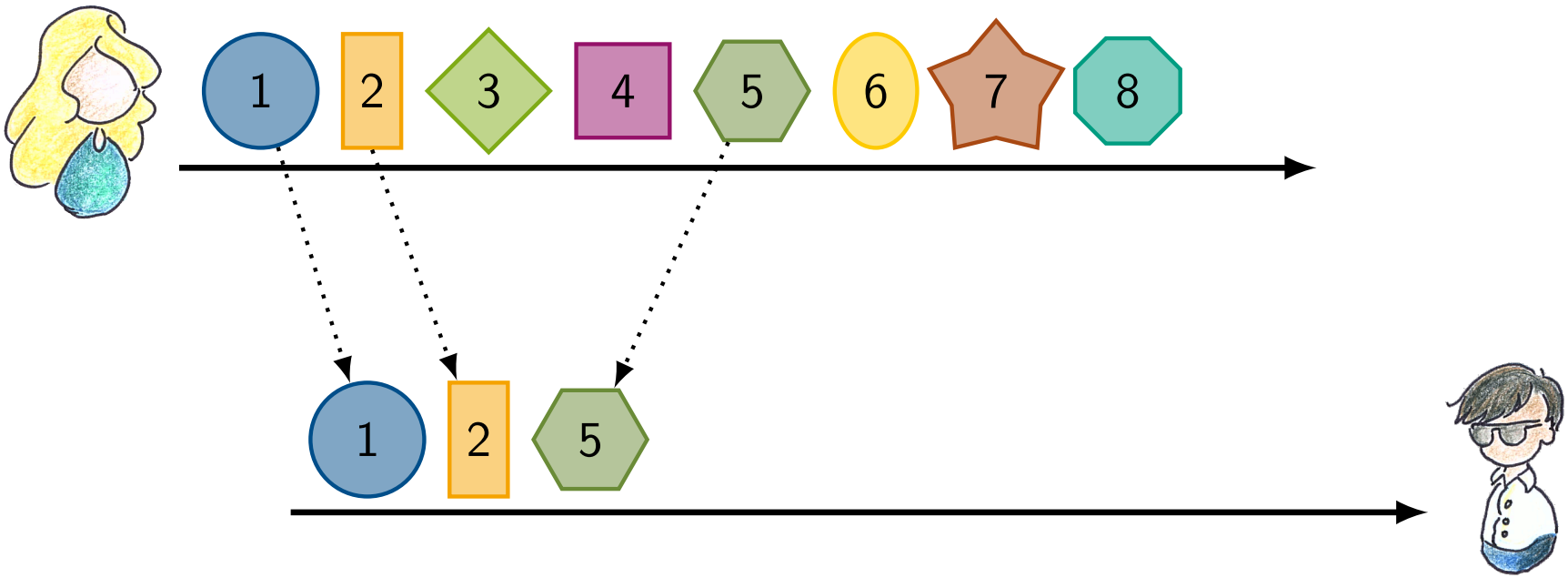

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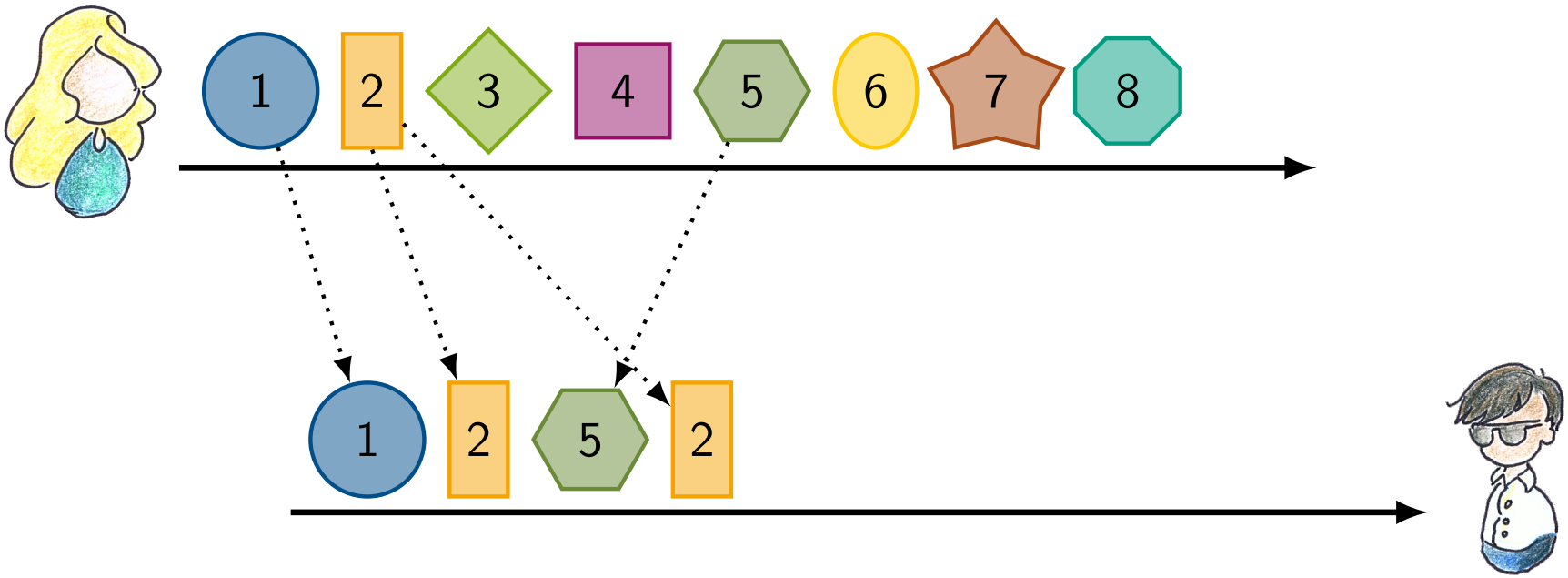

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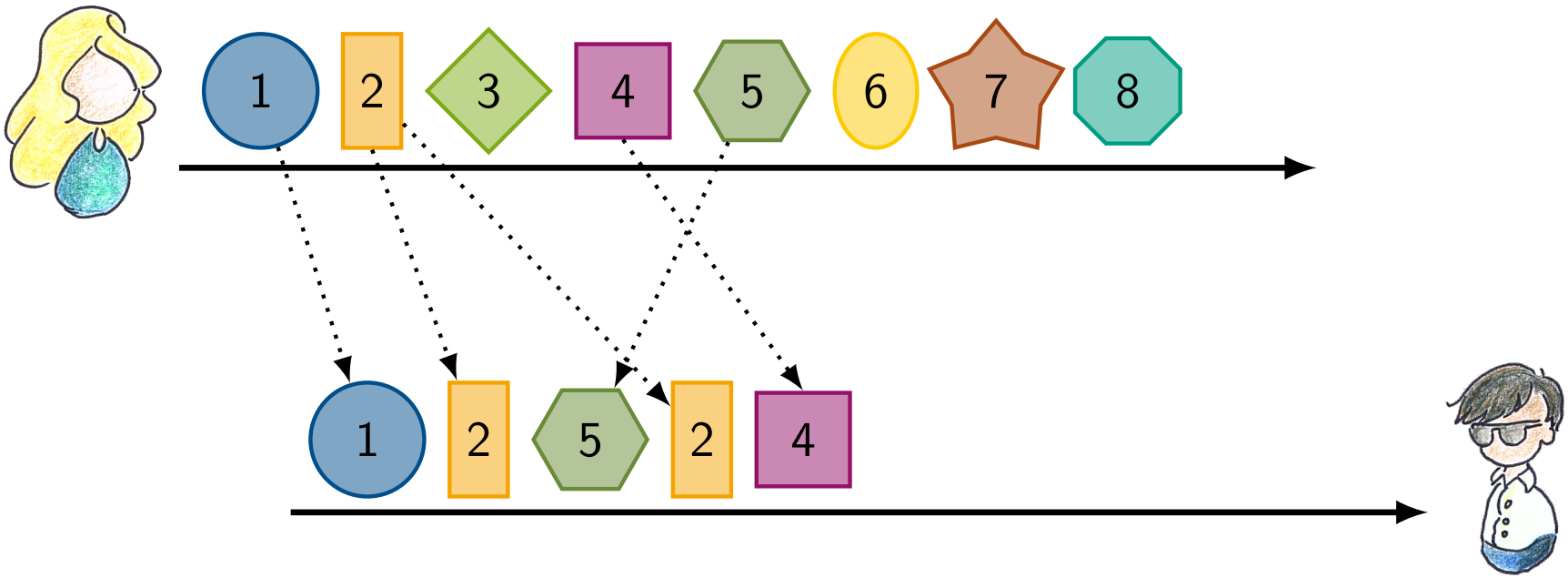

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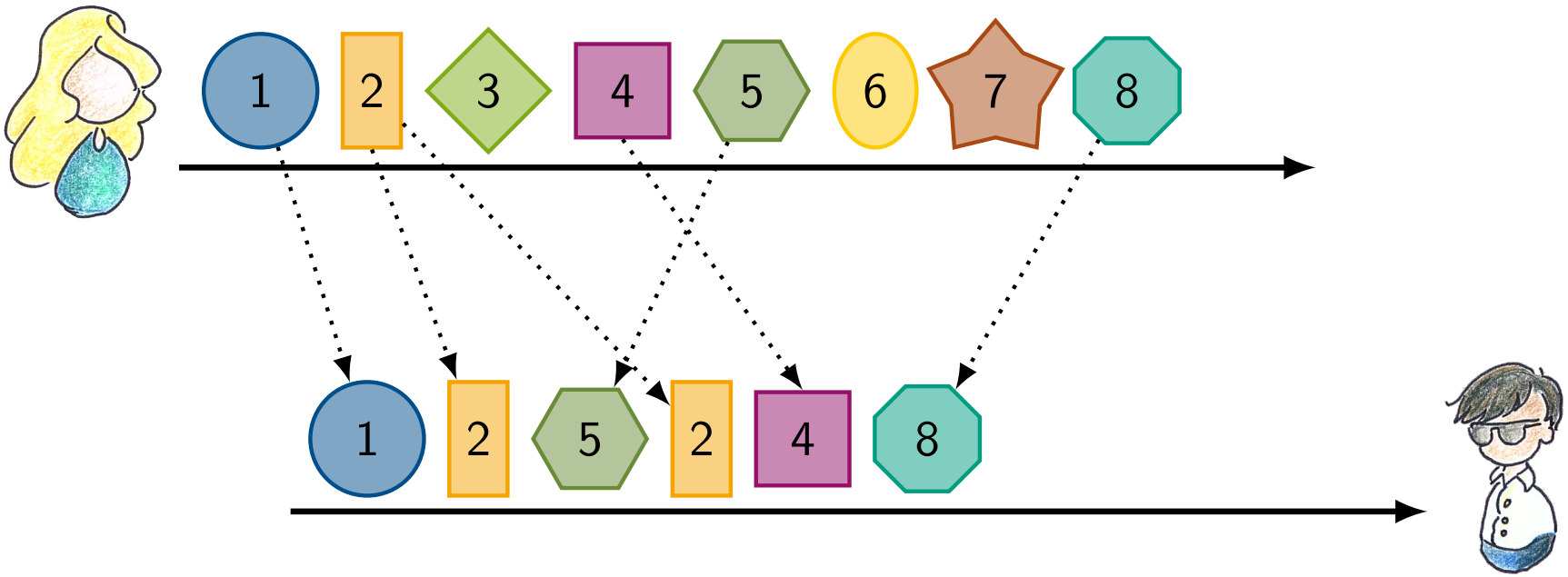

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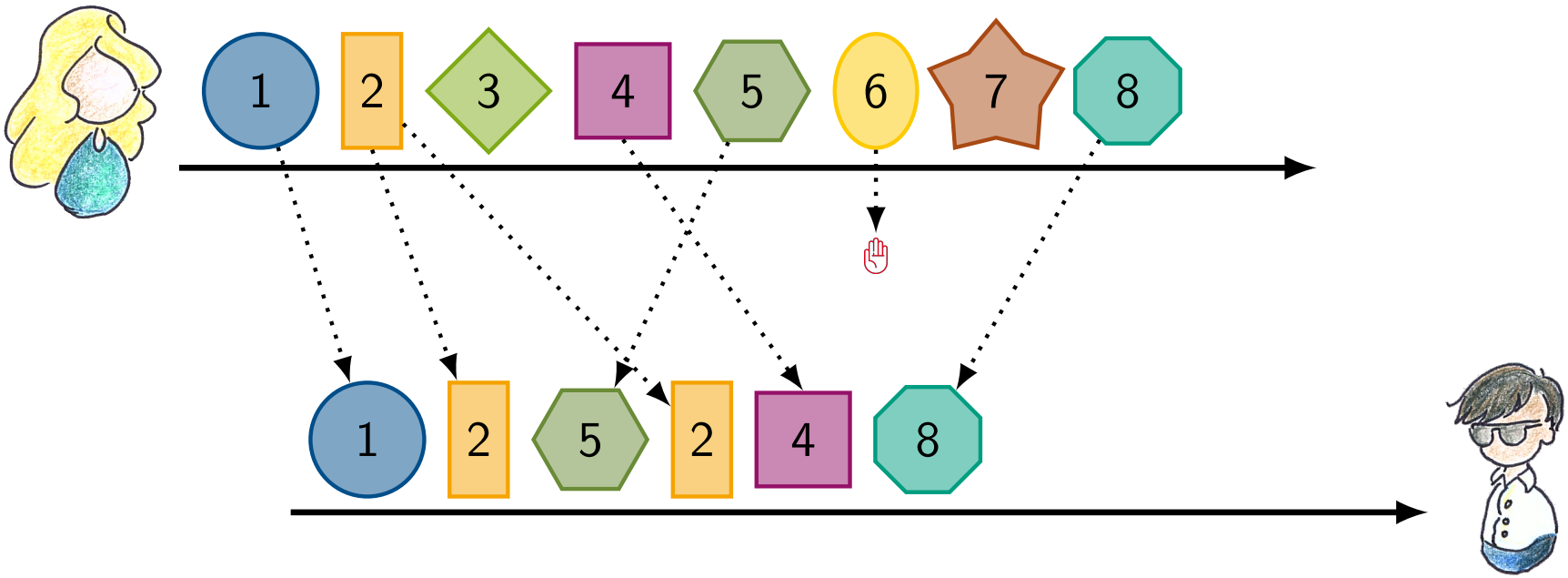

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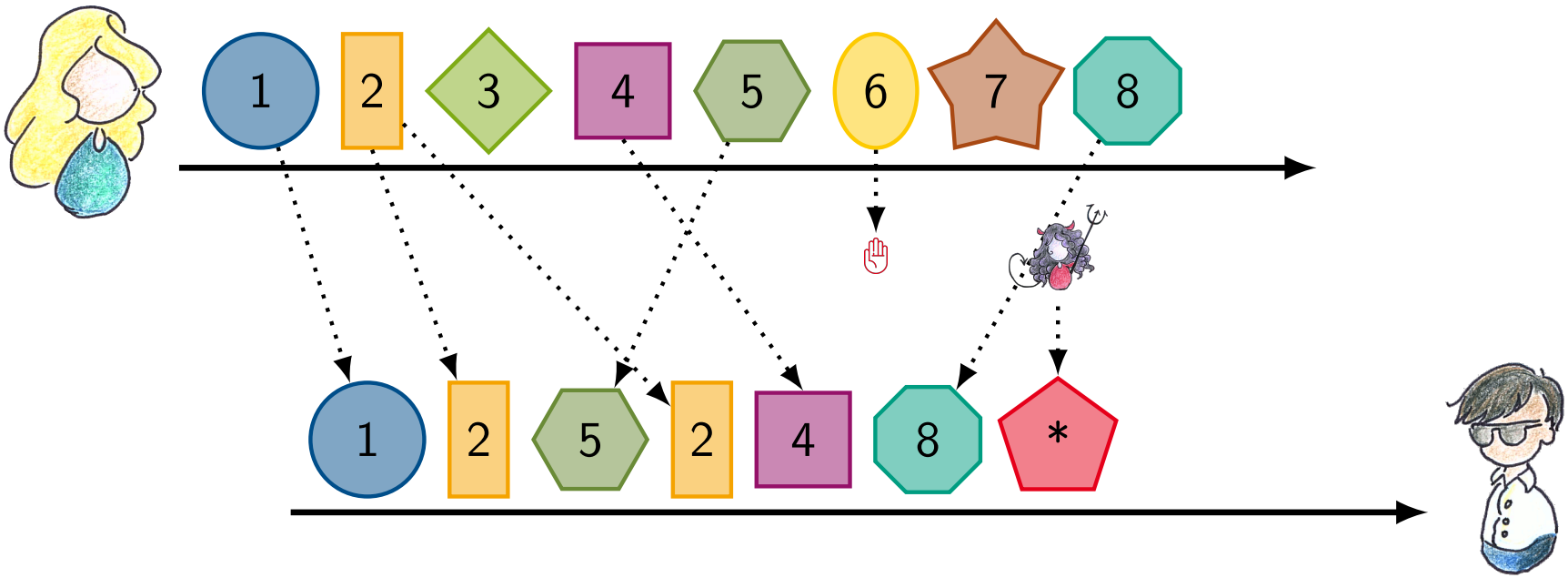

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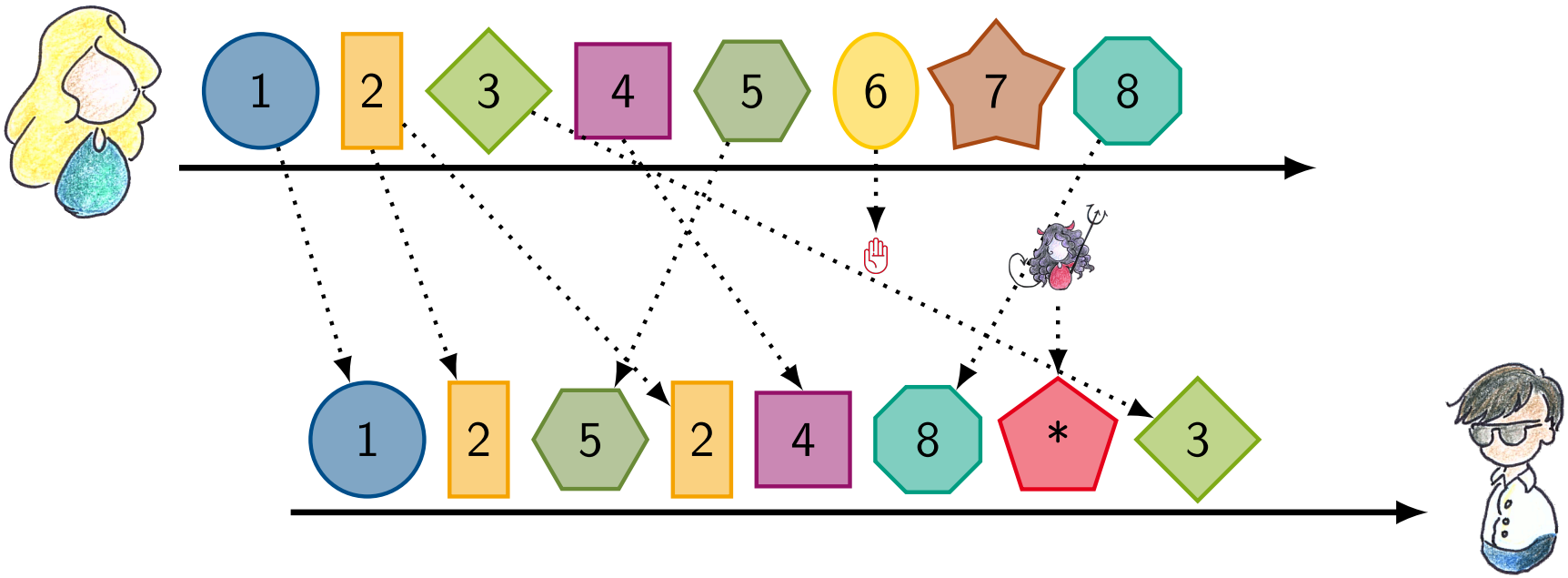

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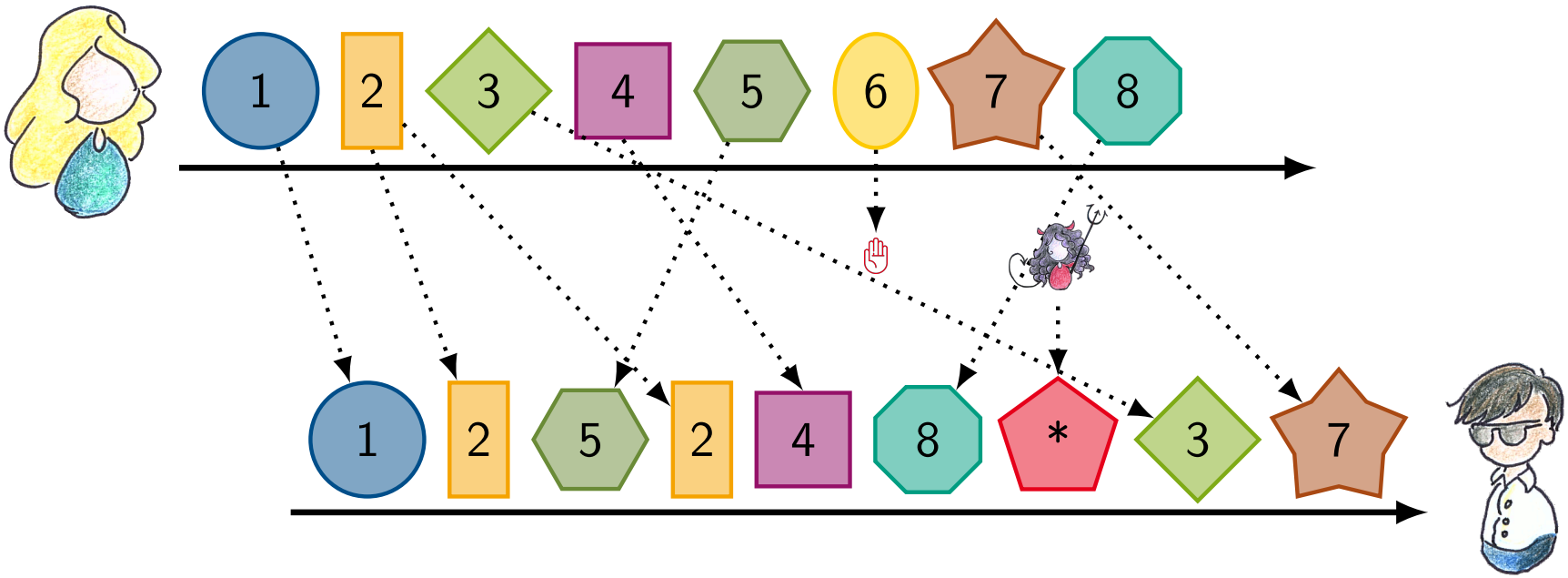

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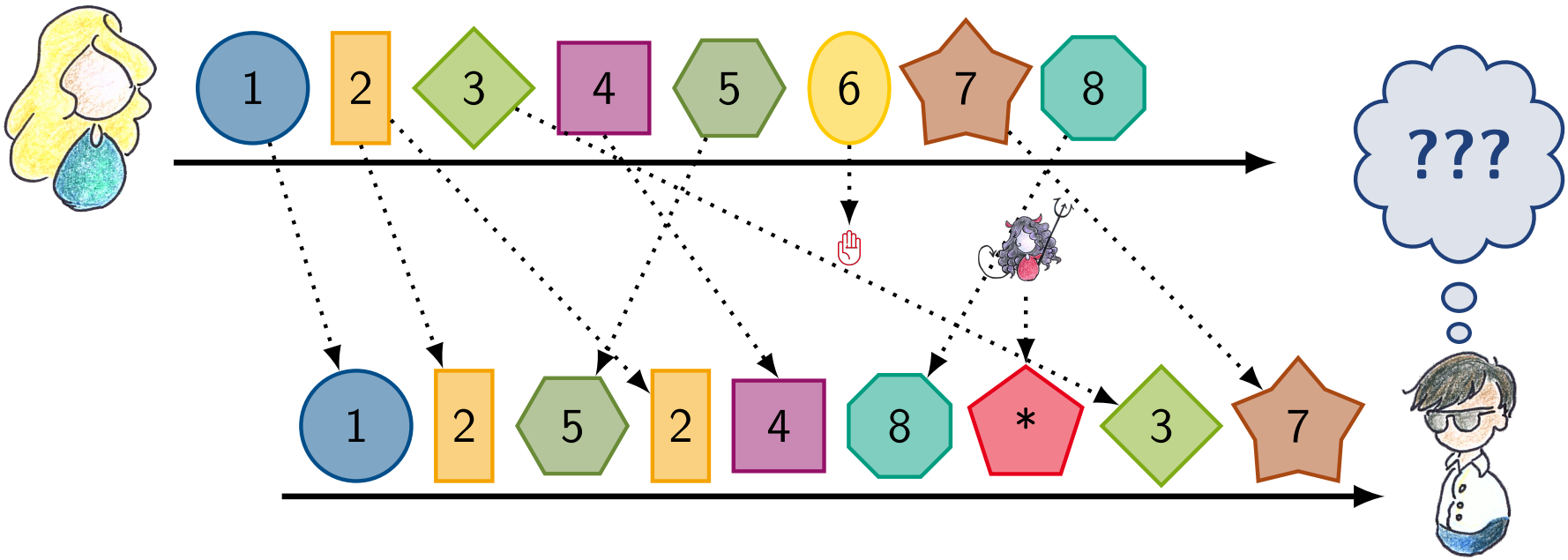

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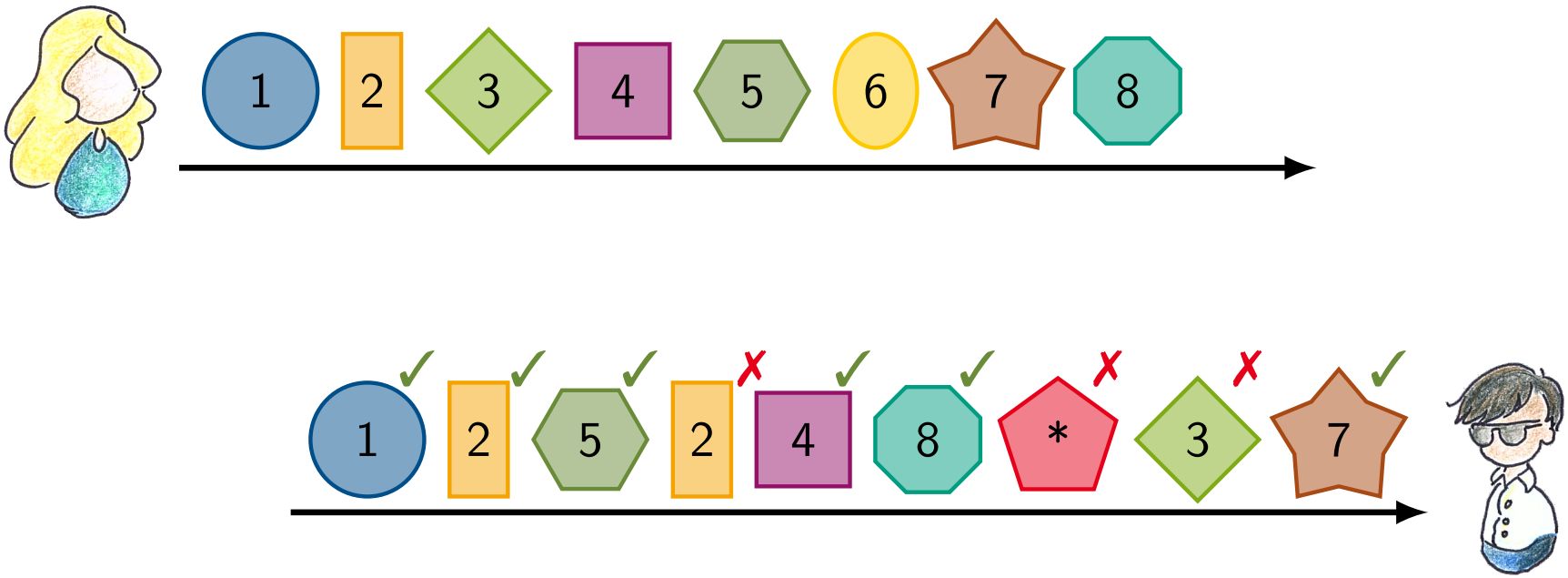

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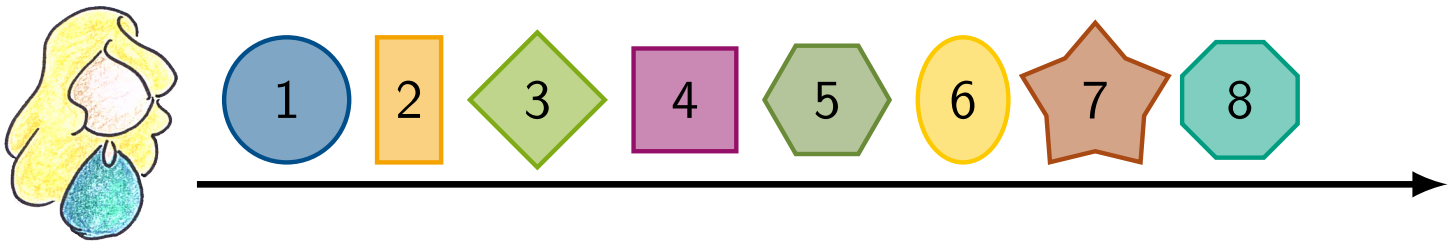

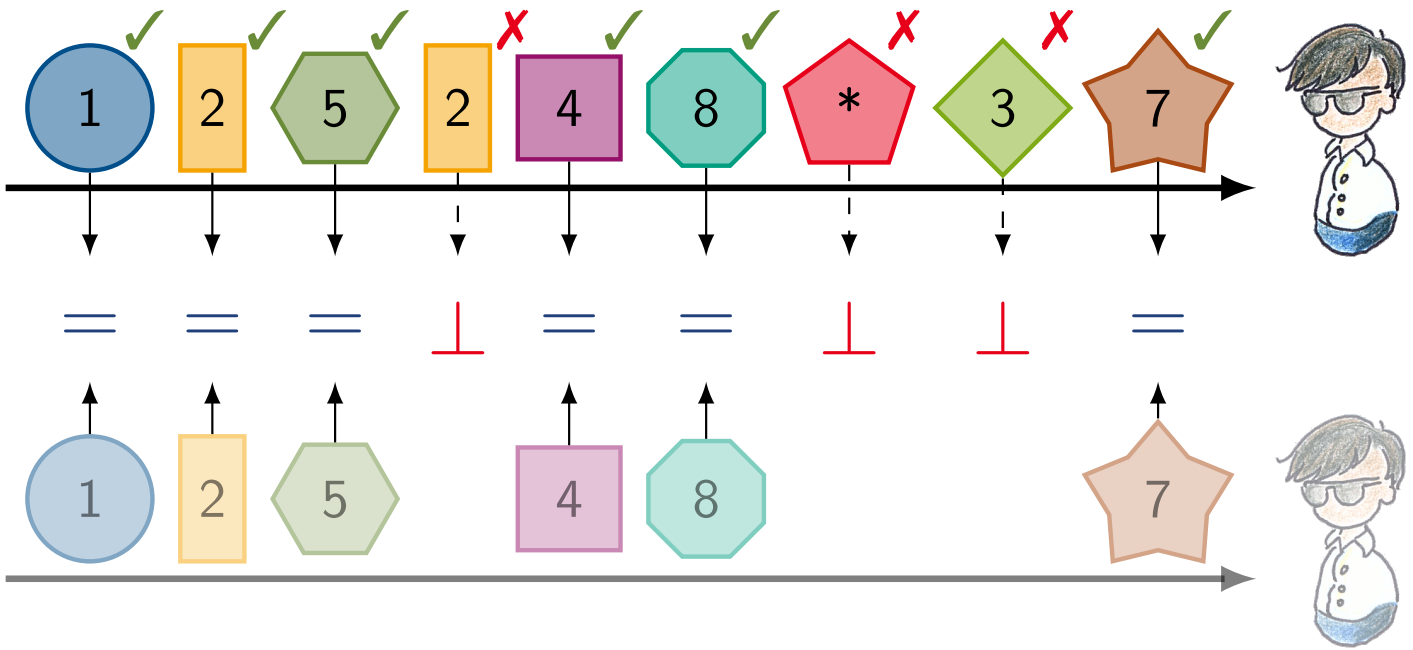

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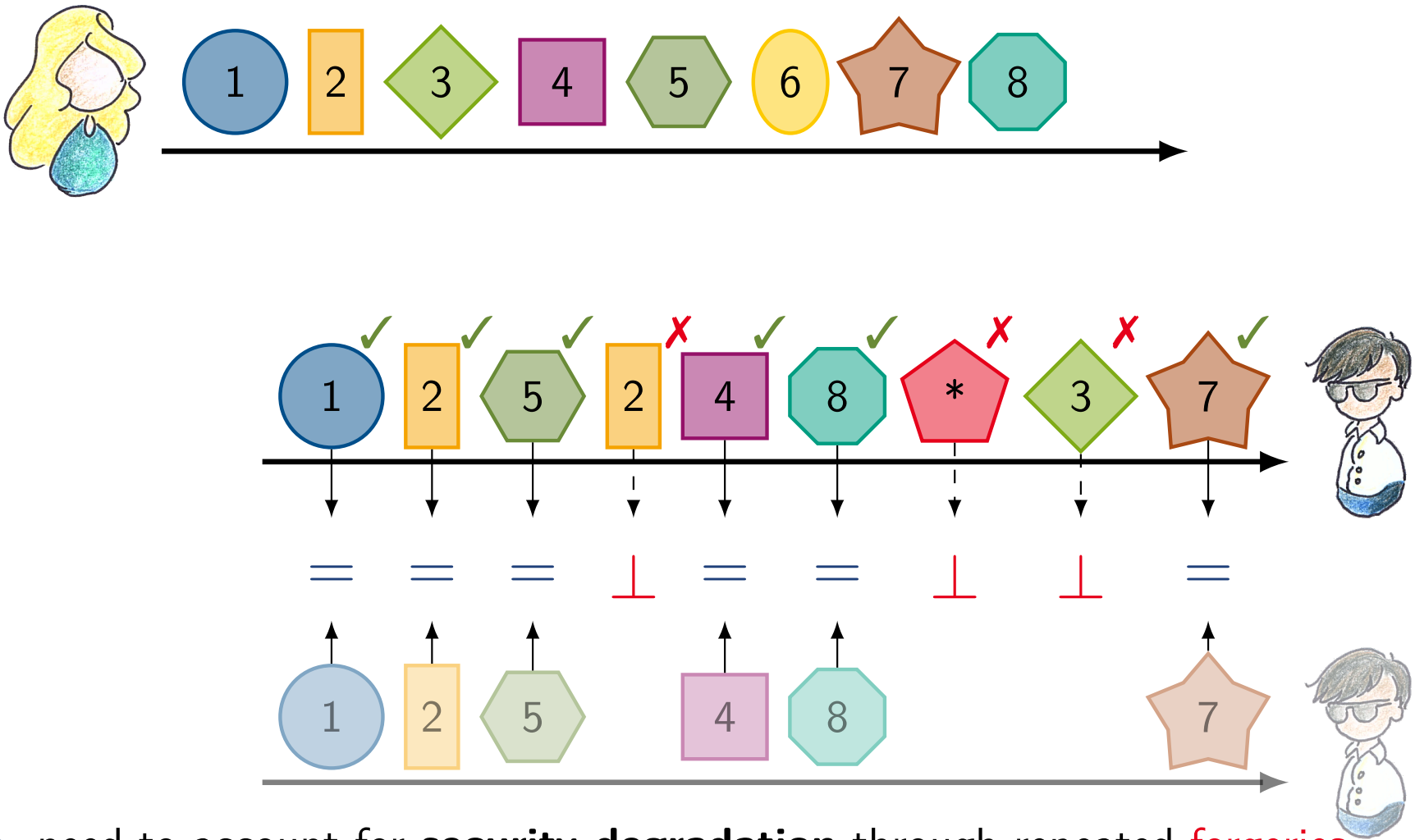

- need to account for **security degradation** through repeated forgeries

Conclusions

TLS 1.3 Security Analysis

Many more analyses. . .

(a selection from the standardization process)

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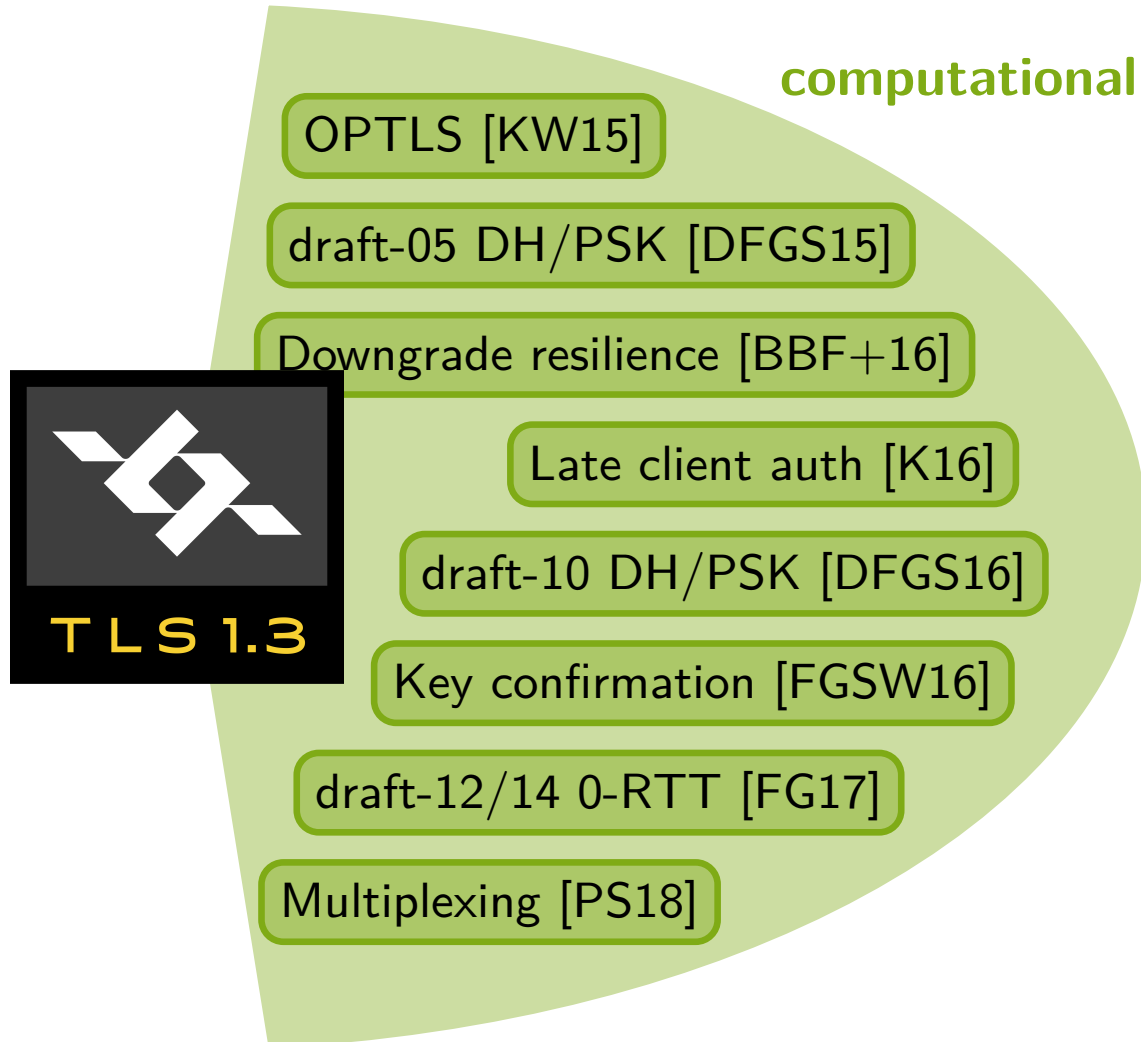

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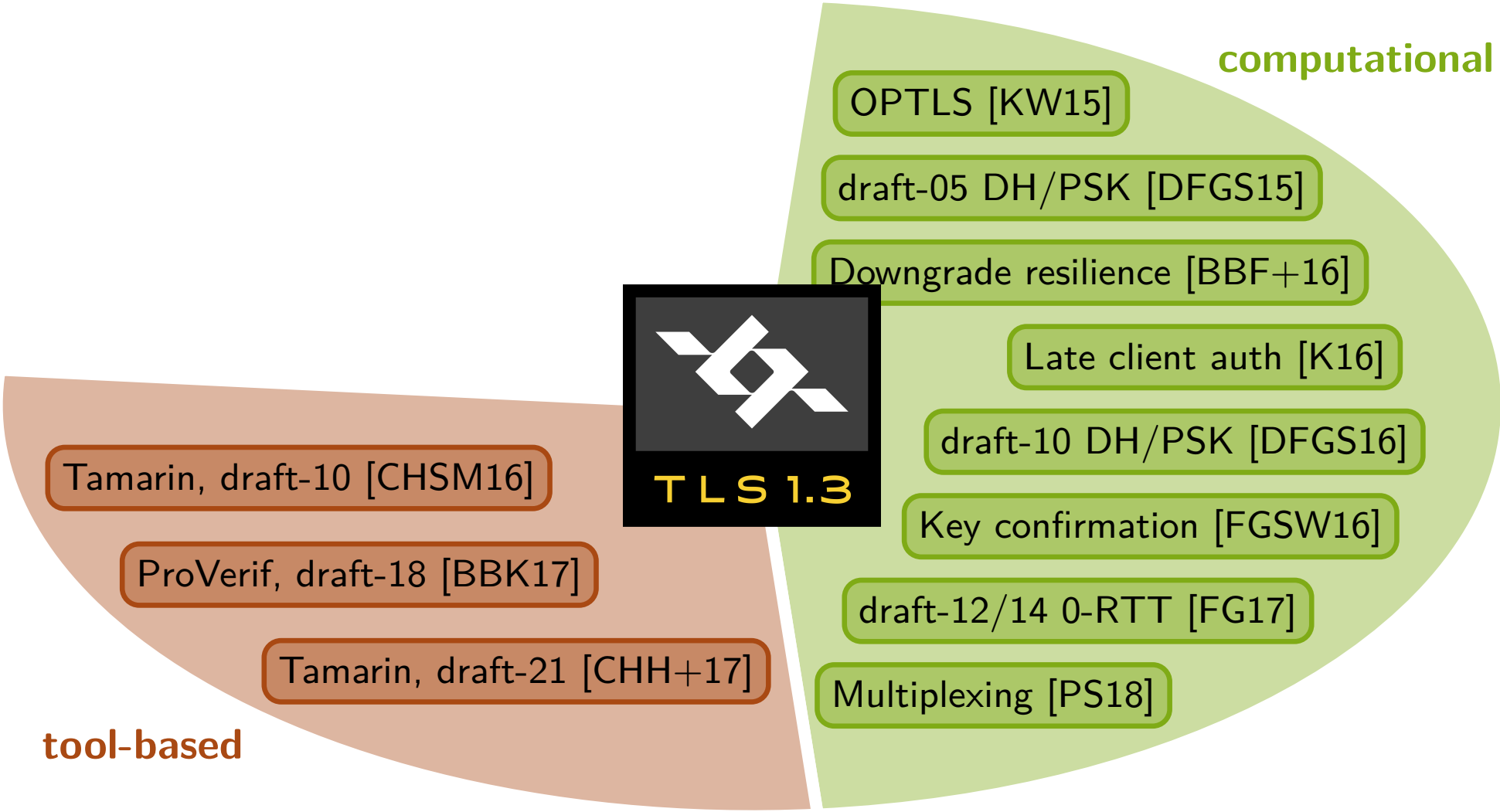

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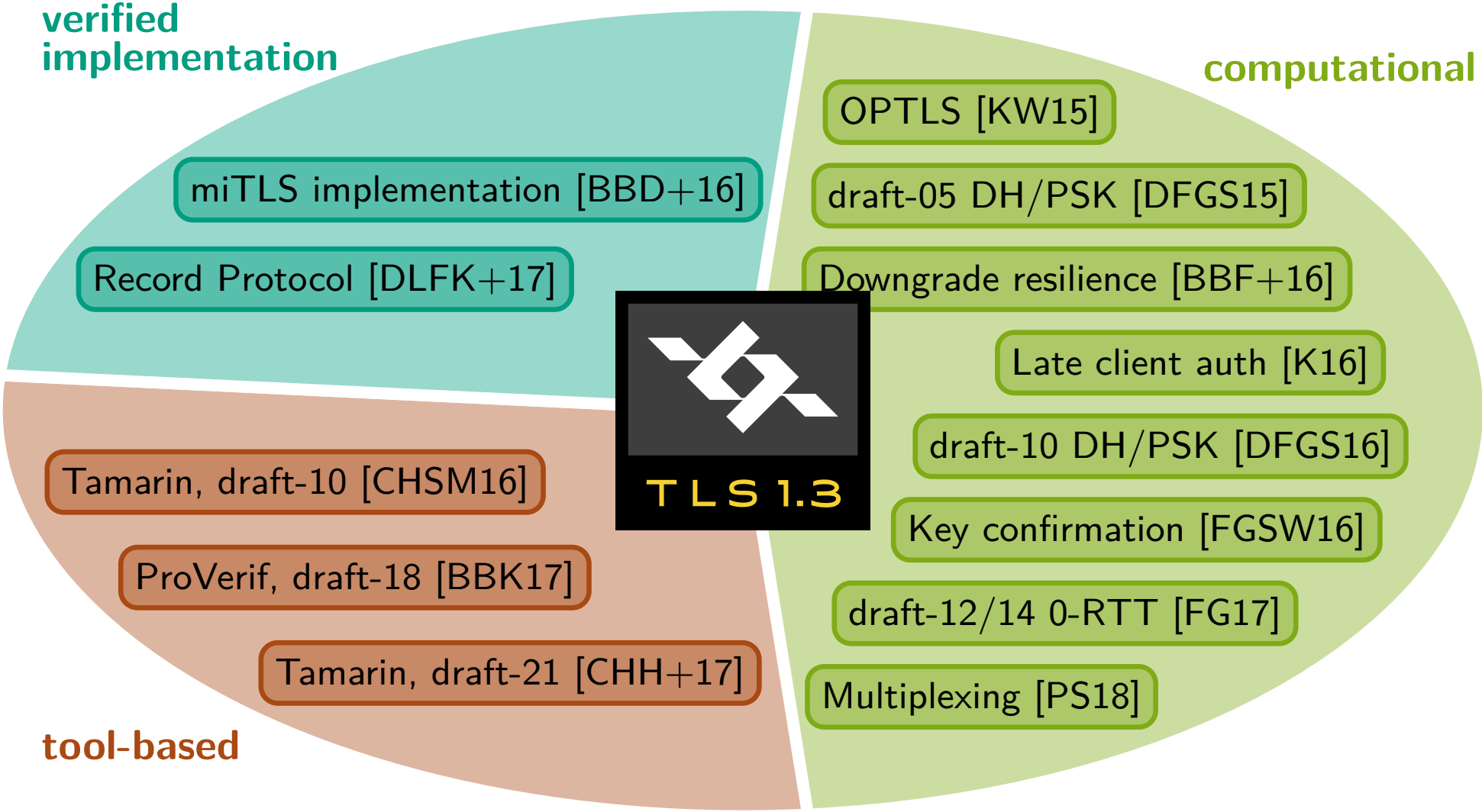

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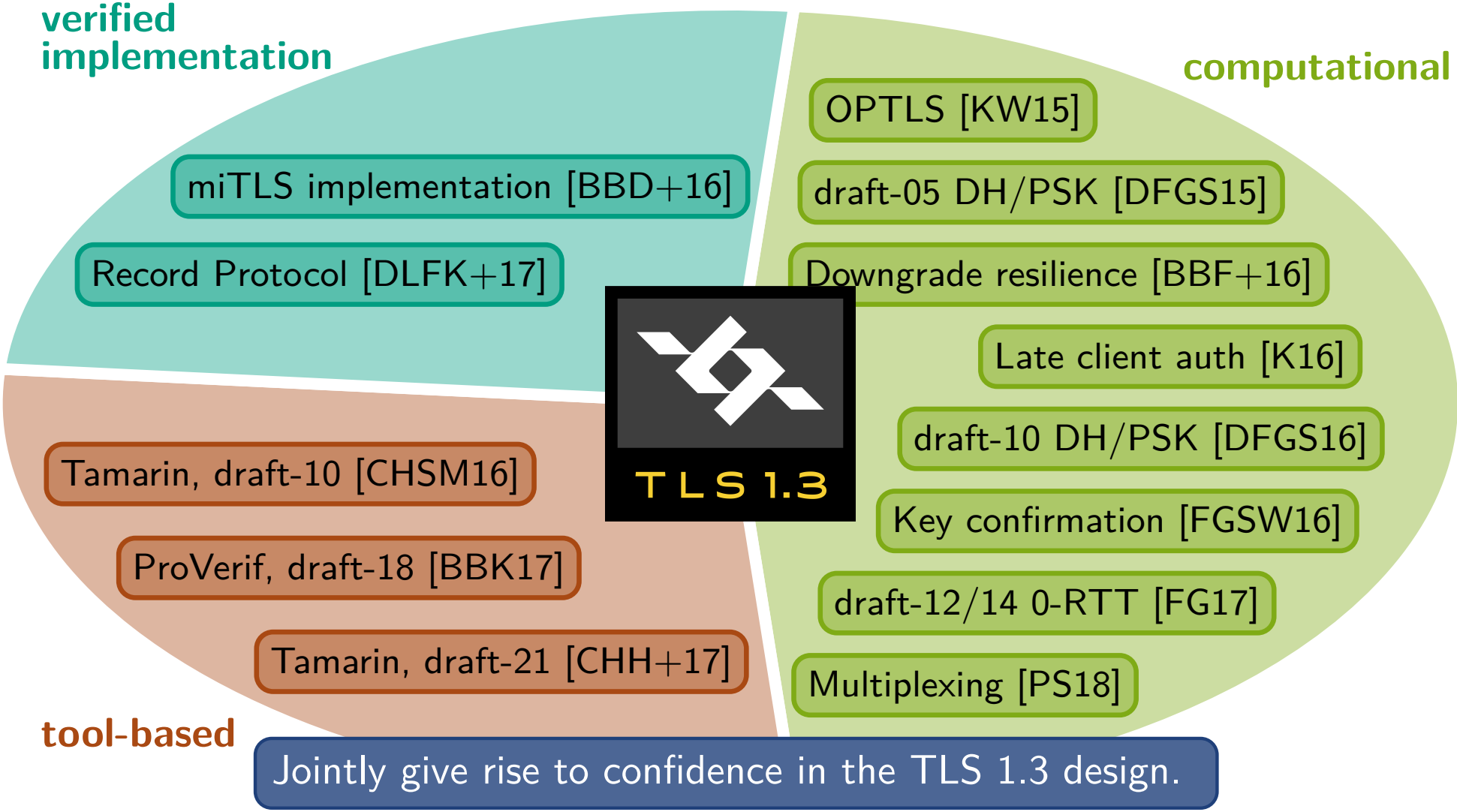

TLS 1.3 Security Analysis

All good?

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Selfie: reflections on TLS 1.3 with PSK

Nir Drucker and Shay Gueron

University of Haifa, Israel,
and
Amazon, Seattle, USA

Abstract. TLS 1.3 allows two parties to establish a shared session key from an out-of-band agreed Pre Shared Key (PSK). The PSK is used to mutually authenticate the parties, under the assumption that it is not shared with others. This allows the parties to skip the certificate verification steps, saving bandwidth, communication rounds, and latency.
We identify a security vulnerability in this TLS 1.3 path, by showing a new reflection attack that we call "Selfie". The Selfie attack breaks the mutual authentication. It leverages the fact that TLS does not mandate explicit authentication of the server and the client in every message.
The paper explains the root cause of this TLS 1.3 vulnerability, demonstrates the Selfie attack on the TLS implementation of OpenSSL and proposes appropriate mitigation.
The attack is surprising because it breaks some assumptions and uncovers an interesting gap in the existing TLS security proofs. We explain the gap in the model assumptions and subsequently in the security proofs. We also provide an enhanced Multi-Stage Key Exchange (MSKE) model that captures the additional required assumptions of TLS 1.3 in its current state. The resulting security claims in the case of external PSKs are accordingly different.

Keywords: TLS 1.3 · Selfie Attack · Reflection attack · Network security · Multi-Stage Key Exchange model

Selfie attack [DG21]

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Selfie attack [DG21]

Models are just models. . .
("All models are wrong but some are useful." — George Box)

Conclusions

ETH zürich

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TLS 1.3

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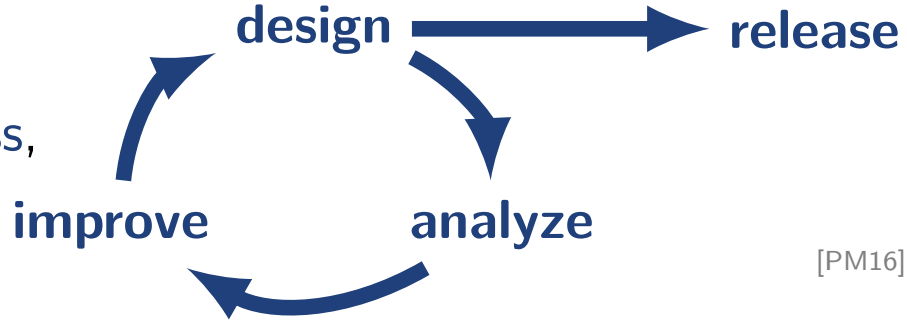
TLS 1.3

- commendable standardization process, highly interactive



[PM16]

Conclusions

TLS 1.3

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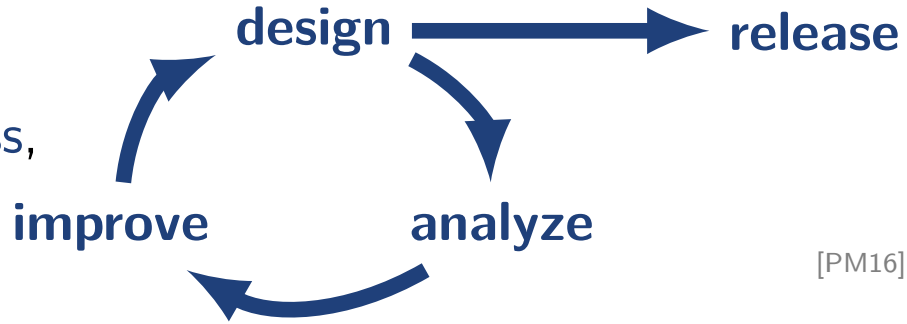
  - improving substantially over prior versions
  - yet with possibly easy-to-misuse 0-RTT mode



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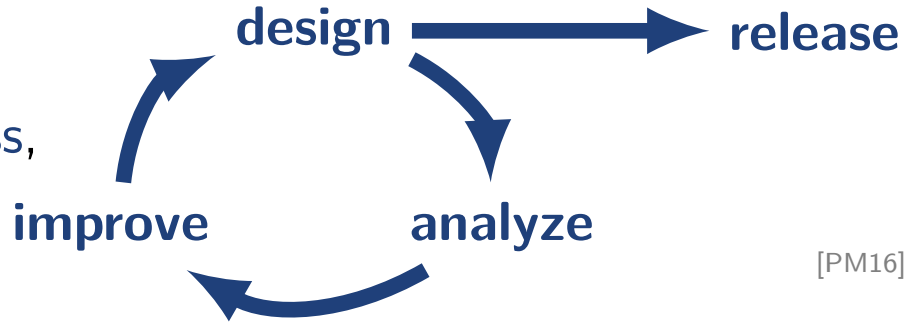

[PM16]

Design & Research

- crypto protocol design is highly complex
  - even when from "boring crypto" components (that's a plus!)
  - even when looking only at the "cryptographic core"

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ETH zürich

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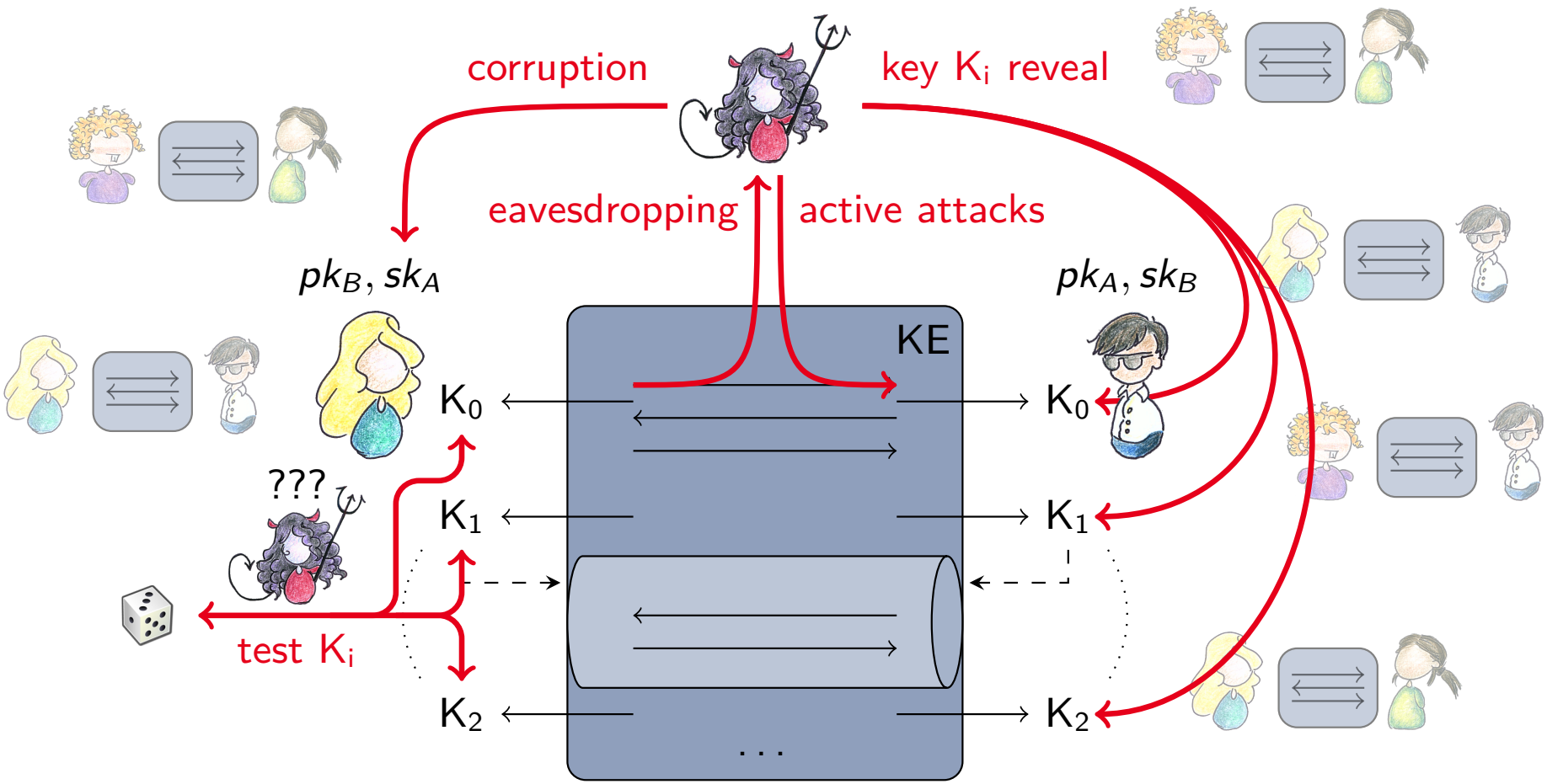
Extra Slides

Multi-Stage Key Exchange Security

ETH zürich

(extending [Bellare–Rogaway93])



[FG14], [Dow+15], [Dow+16], [FG17], [Gün18], [Dow+21]

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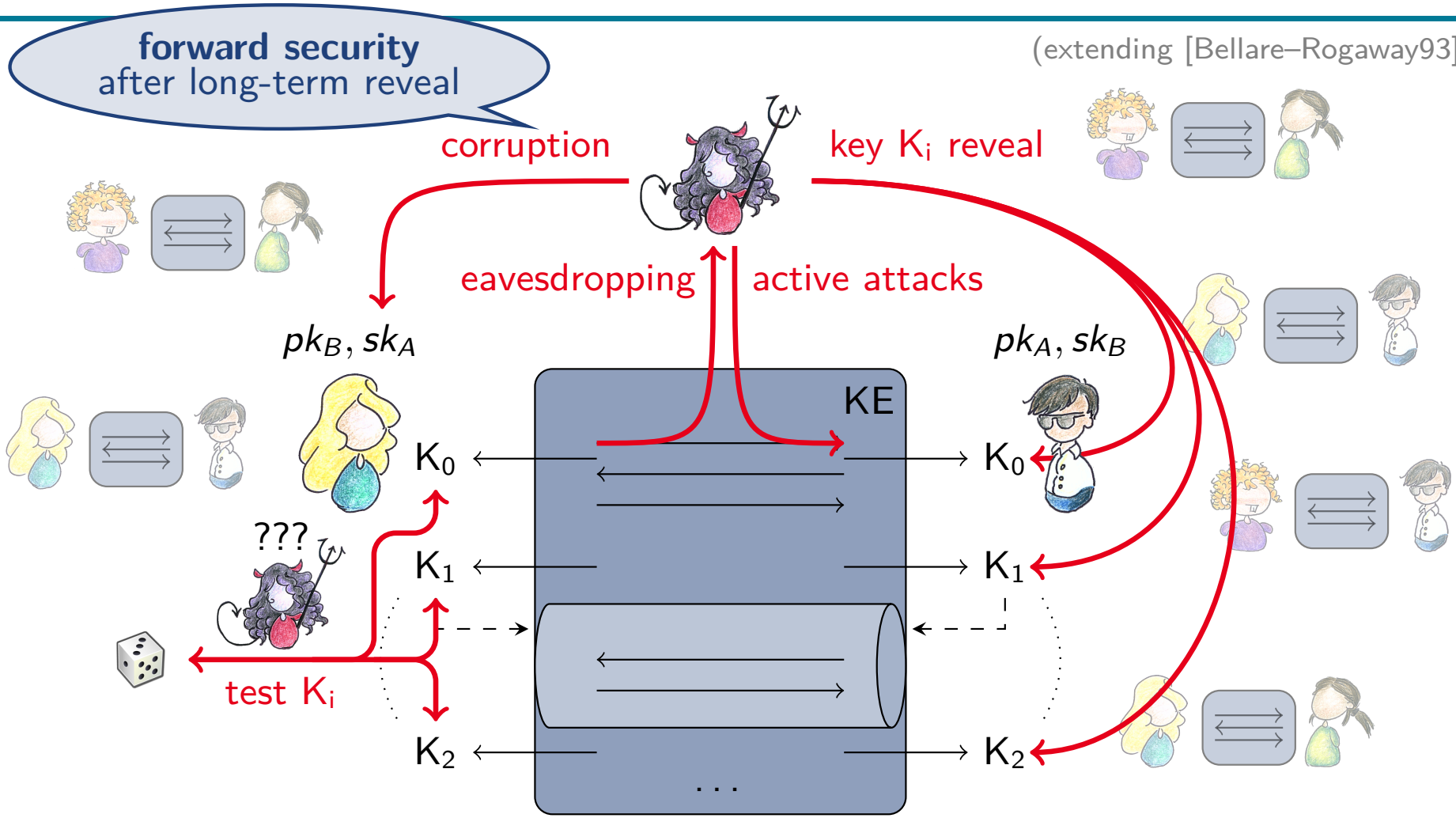

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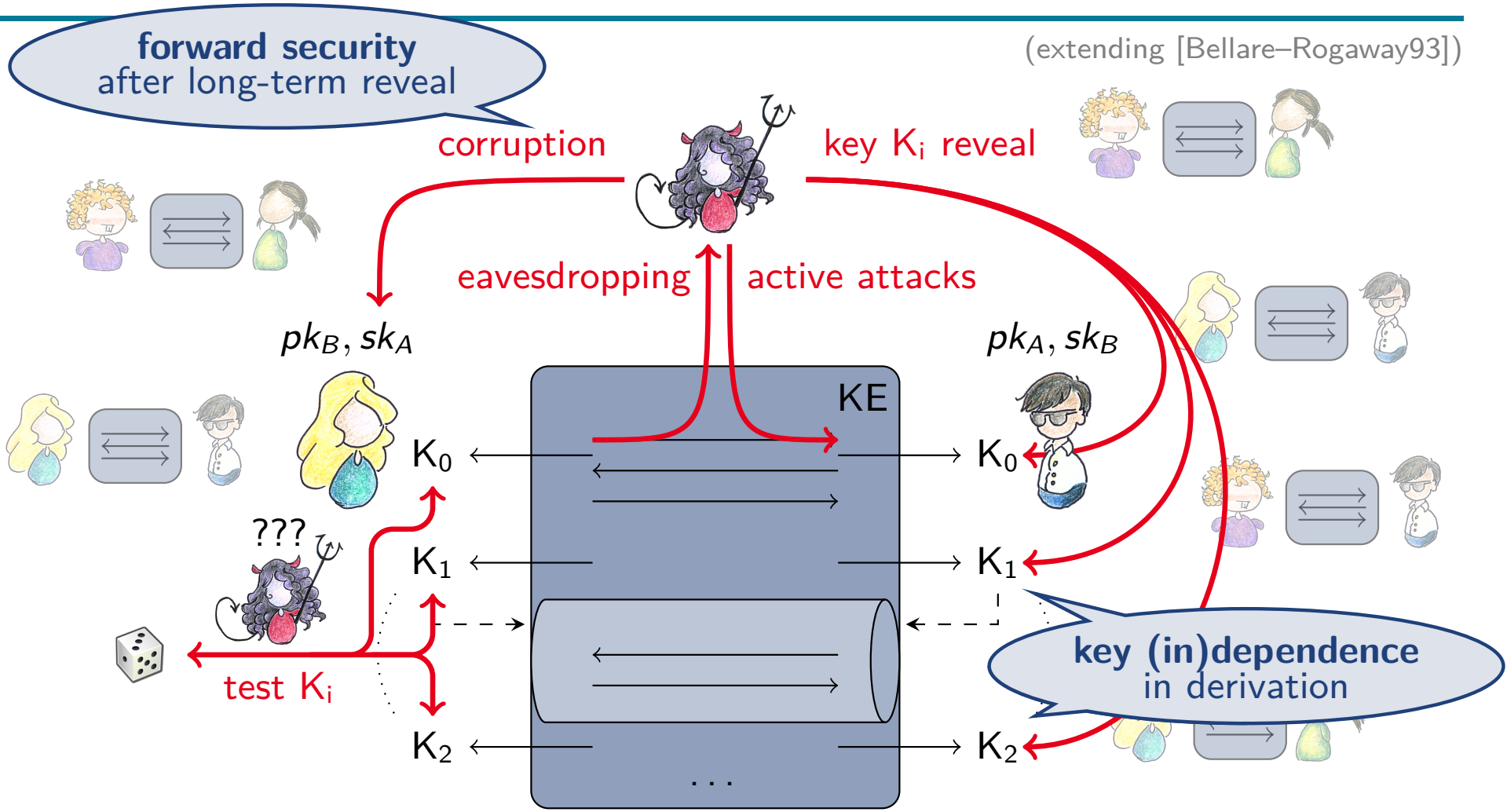

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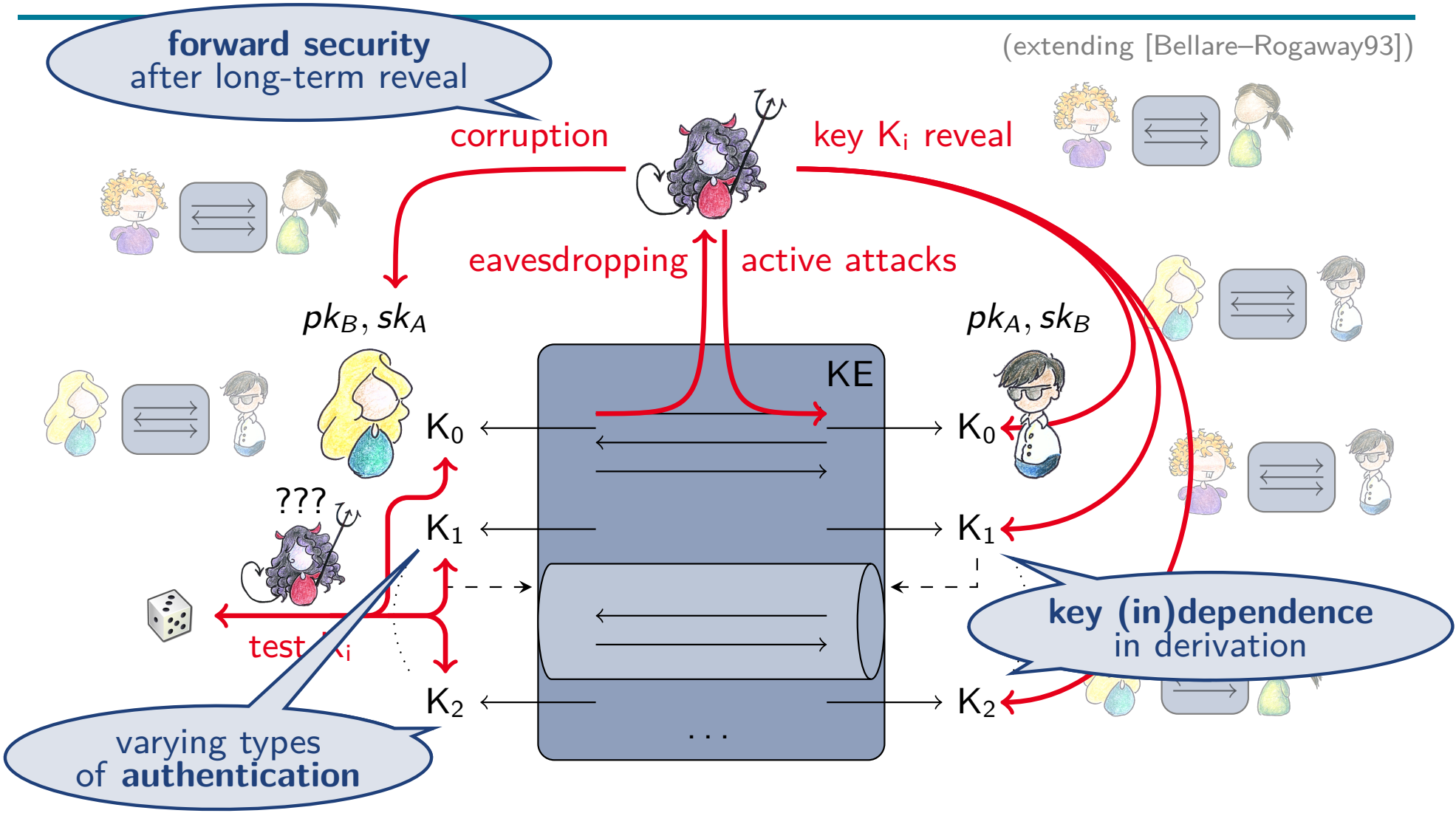

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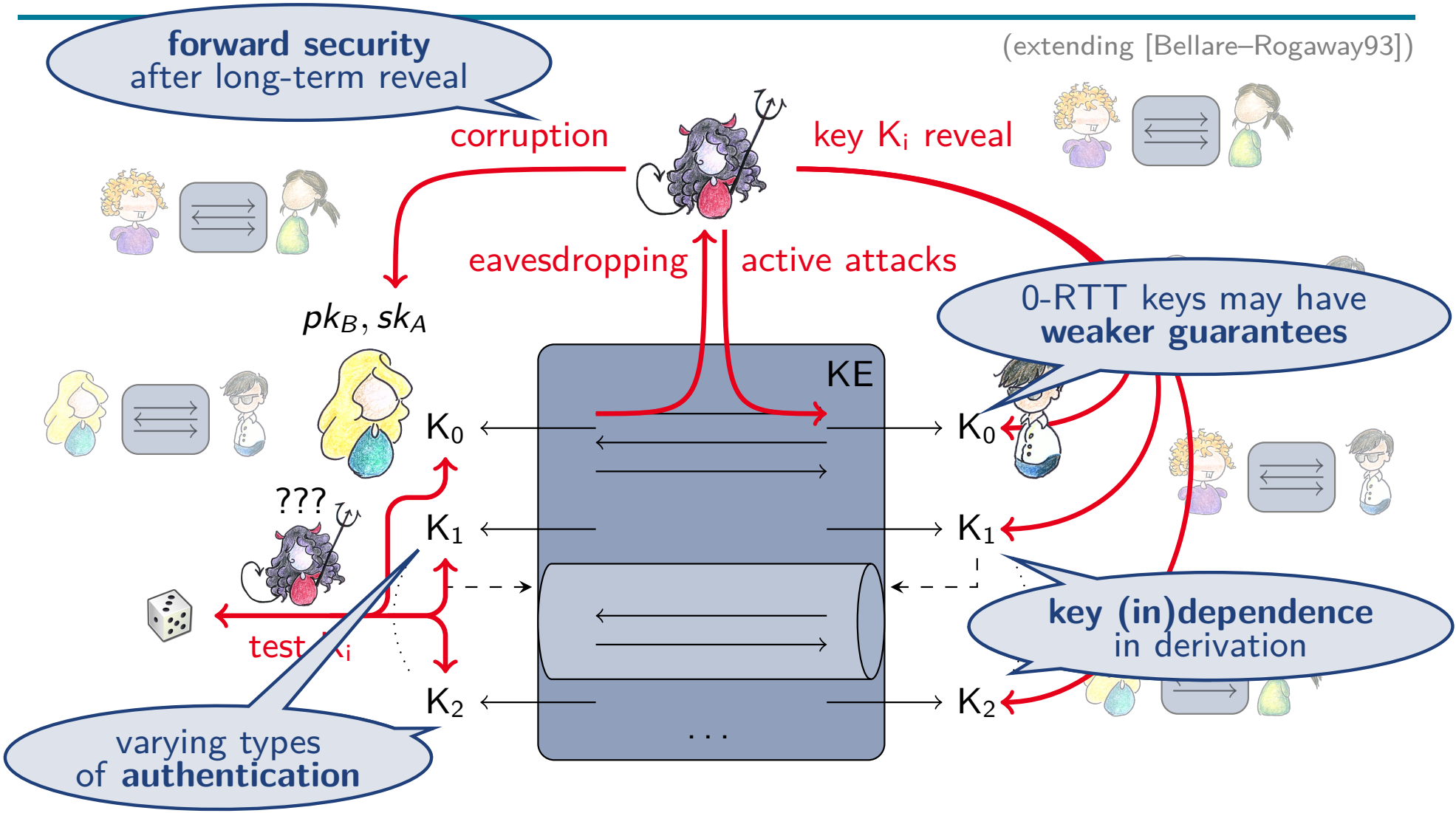

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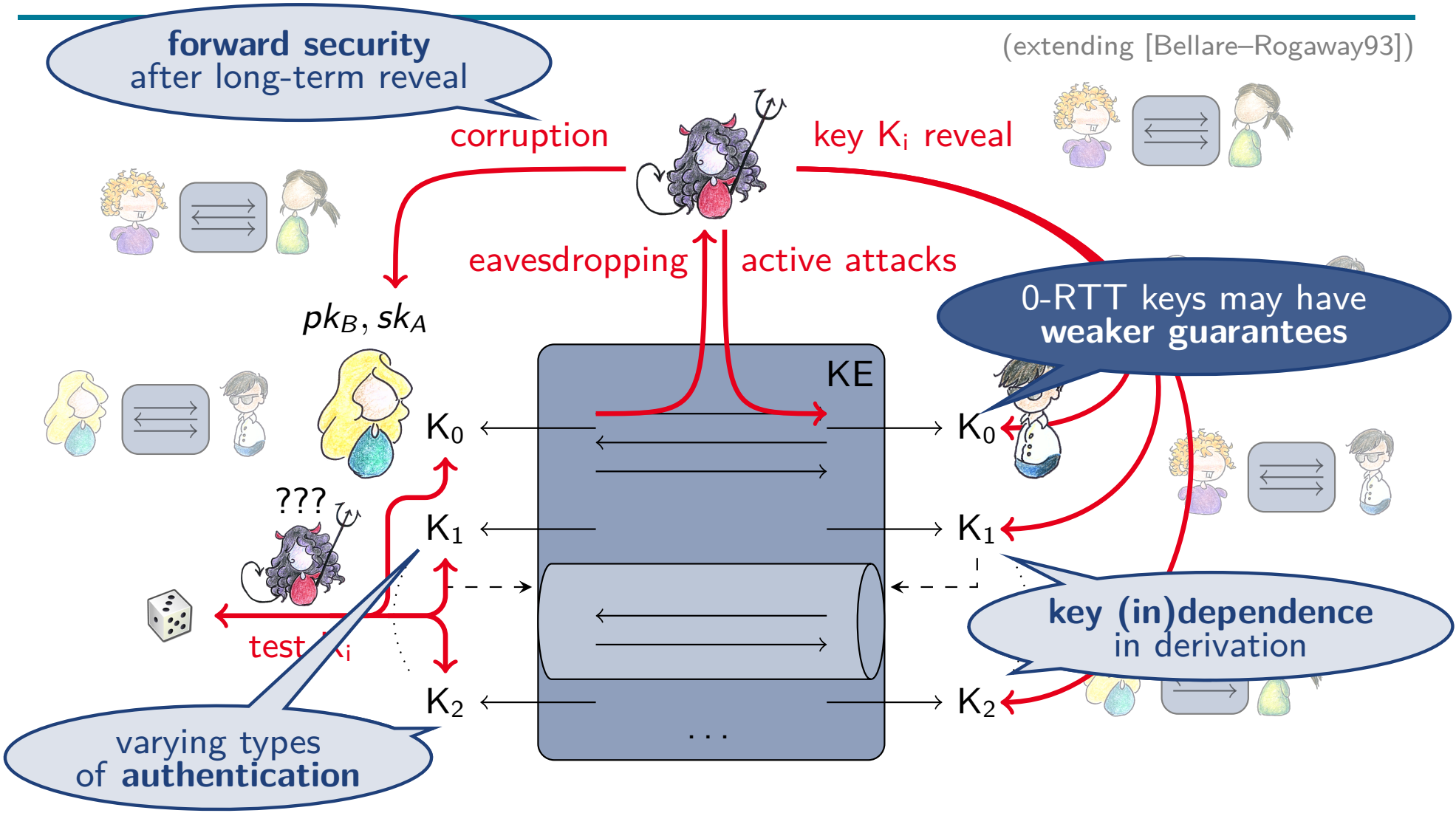

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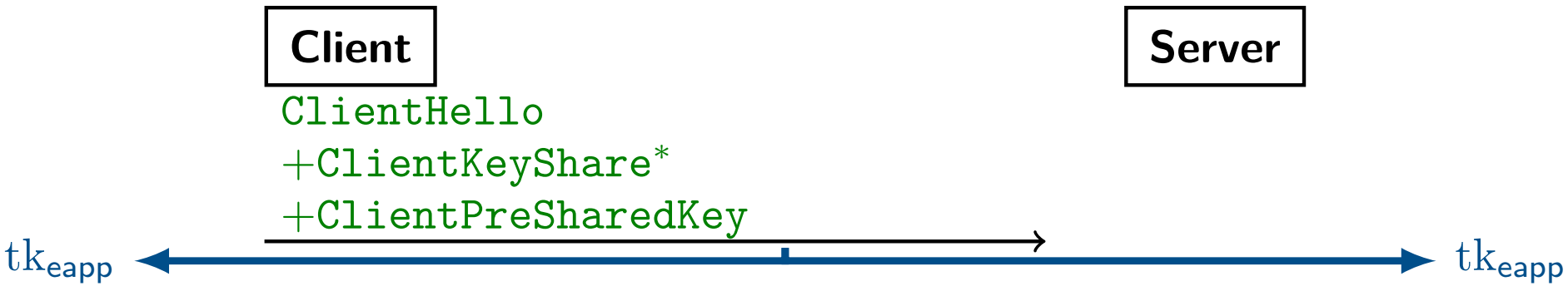
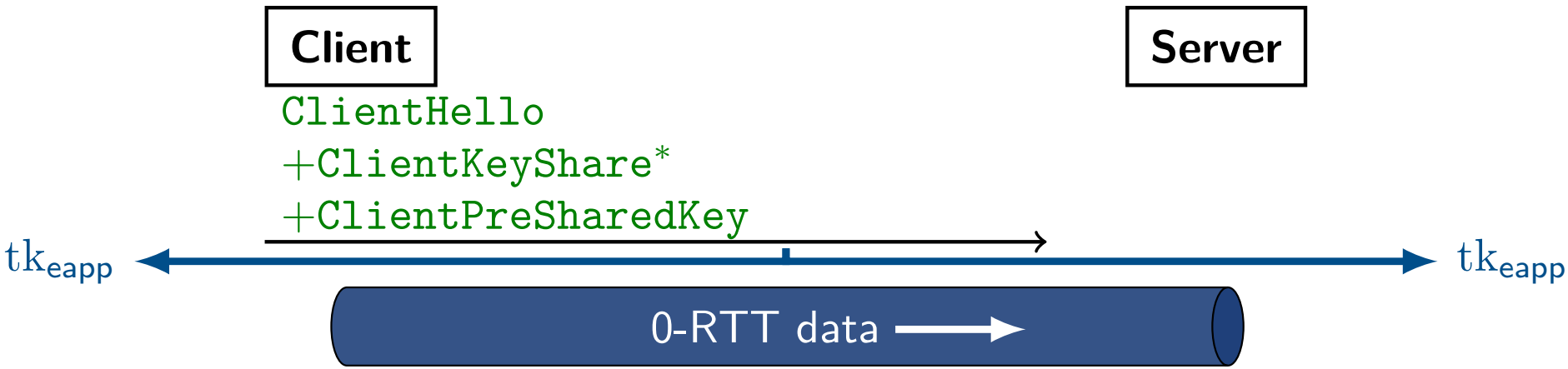
0-RTT and Replays



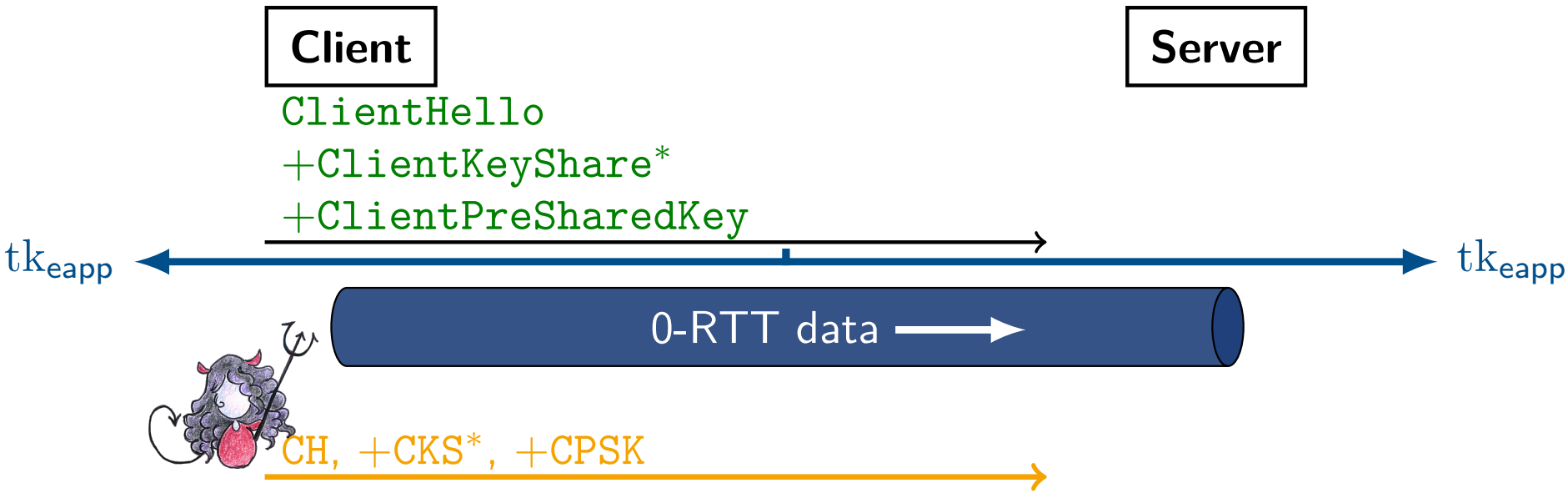
0-RTT and Replays

ETH zürich



- allows client to send data without waiting for server reply
- but without server input, how does server know the request is fresh?

0-RTT and Replays



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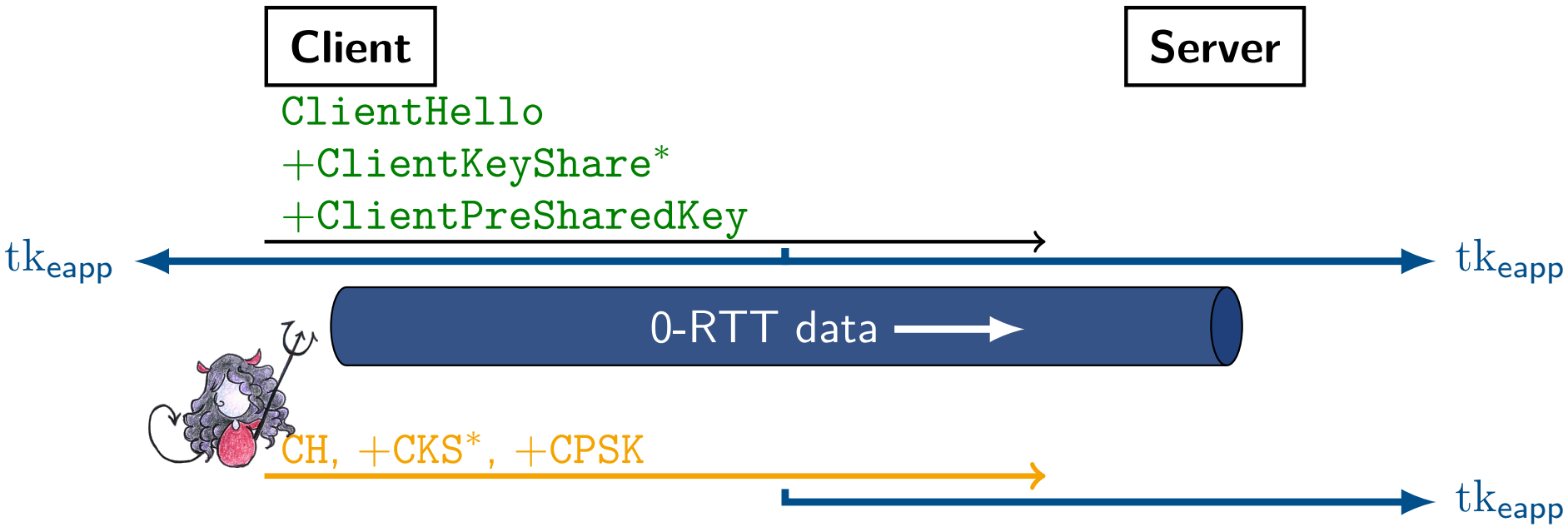
0-RTT and Replays

ETH zürich



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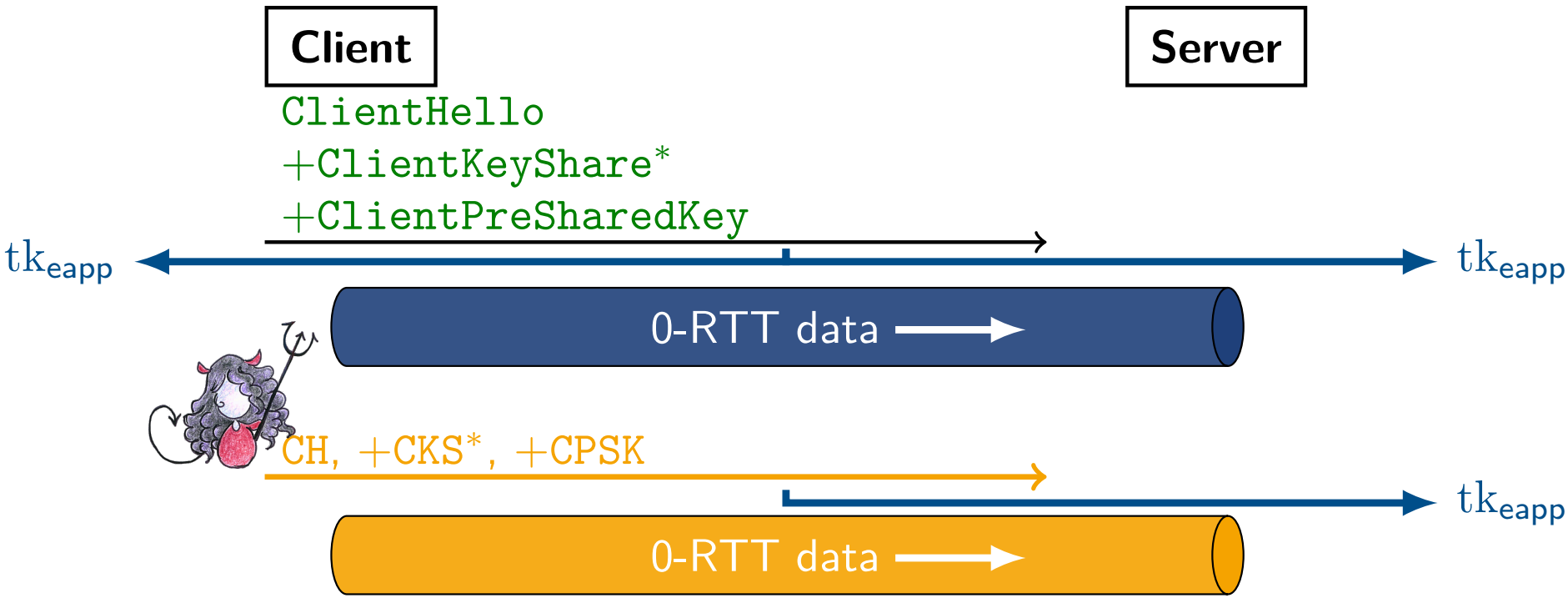

- allows client to send data without waiting for server reply
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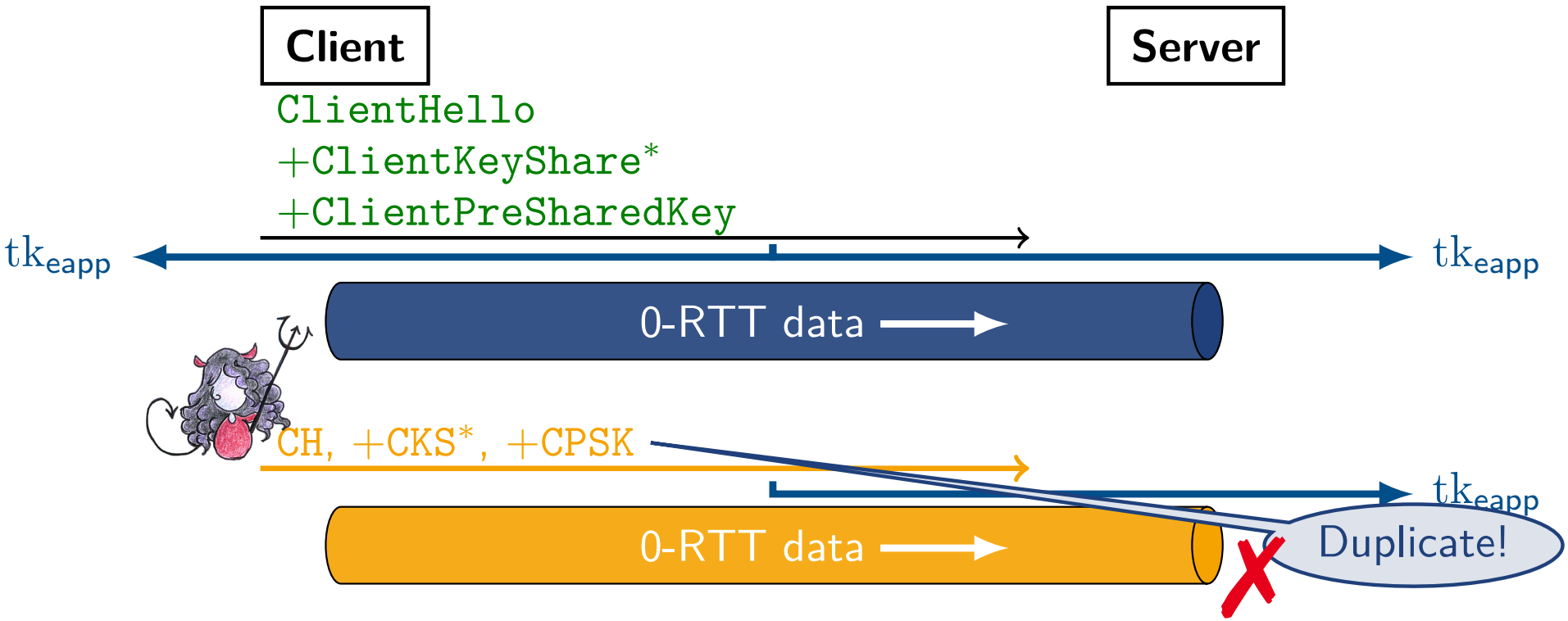
- adversary can **replay** `ClientHello` together with 0-RTT data

0-RTT and Replays

ETH zürich

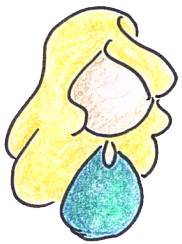


- allows client to send data without waiting for server reply
- but without server input, how does server know the request is fresh?
- adversary can **replay** `ClientHello` together with 0-RTT data
- idea: remember `ClientHello` identifier and reject duplicates

0-RTT and Replays

Generic Replay Attack on 0-RTT (by Daniel Kahn Gillmore)

ETH zürich



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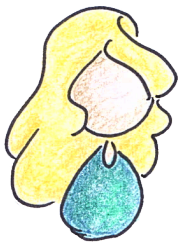

0-RTT KE msg

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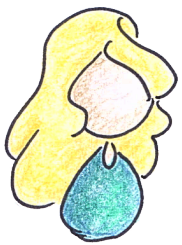

0-RTT KE msg

0-RTT request

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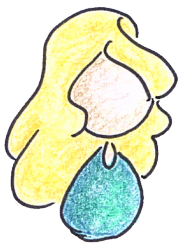

0-RTT KE msg

0-RTT request

process request

0-RTT and Replays

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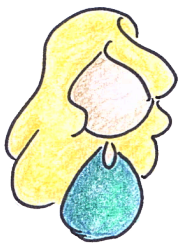

0-RTT KE msg

0-RTT request

process request

accept 0-RTT, KE response

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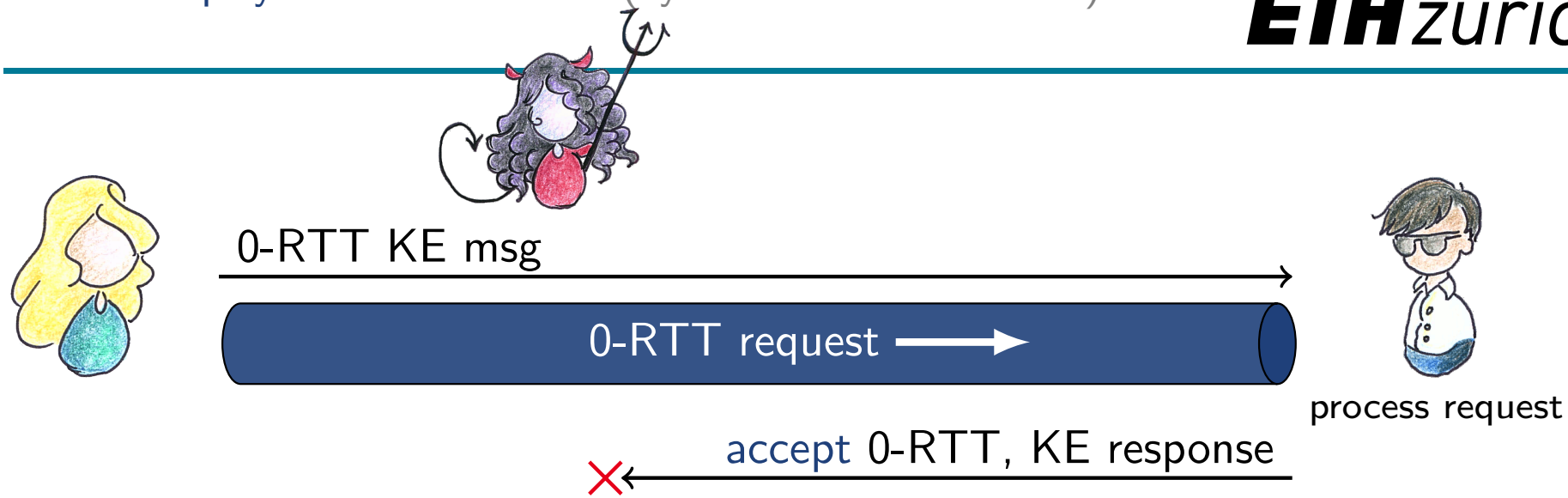

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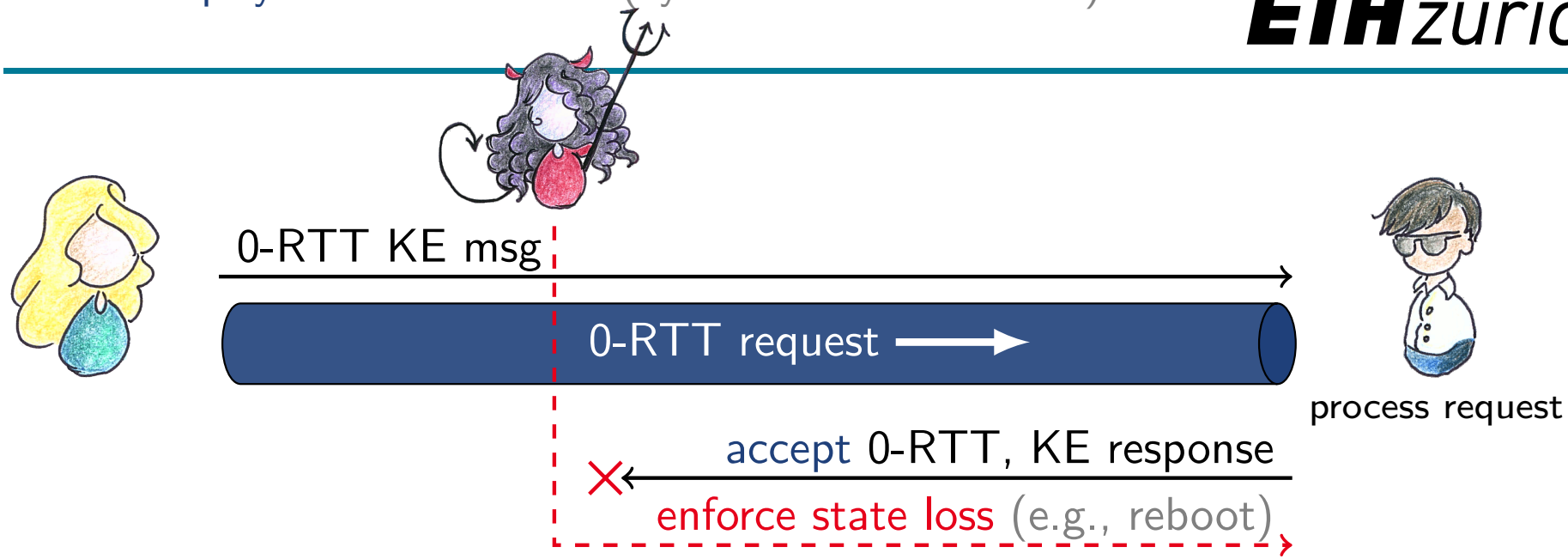

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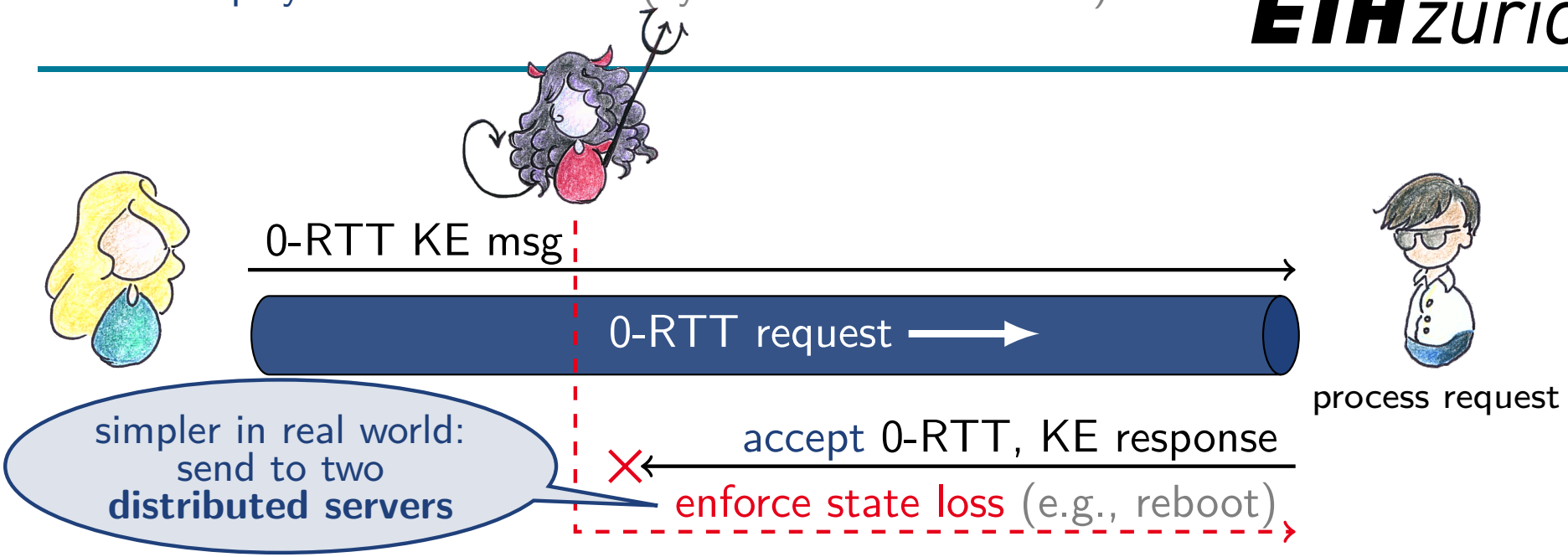

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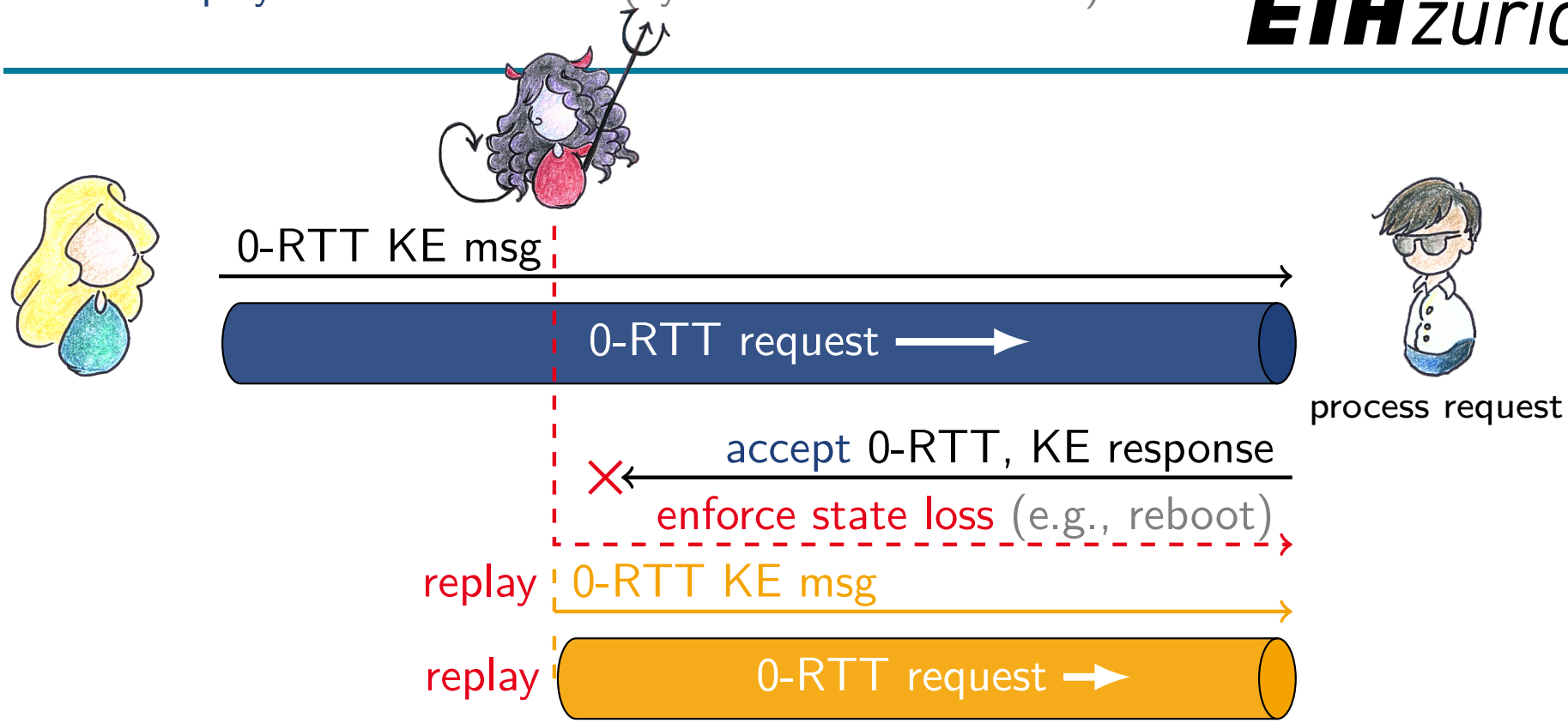

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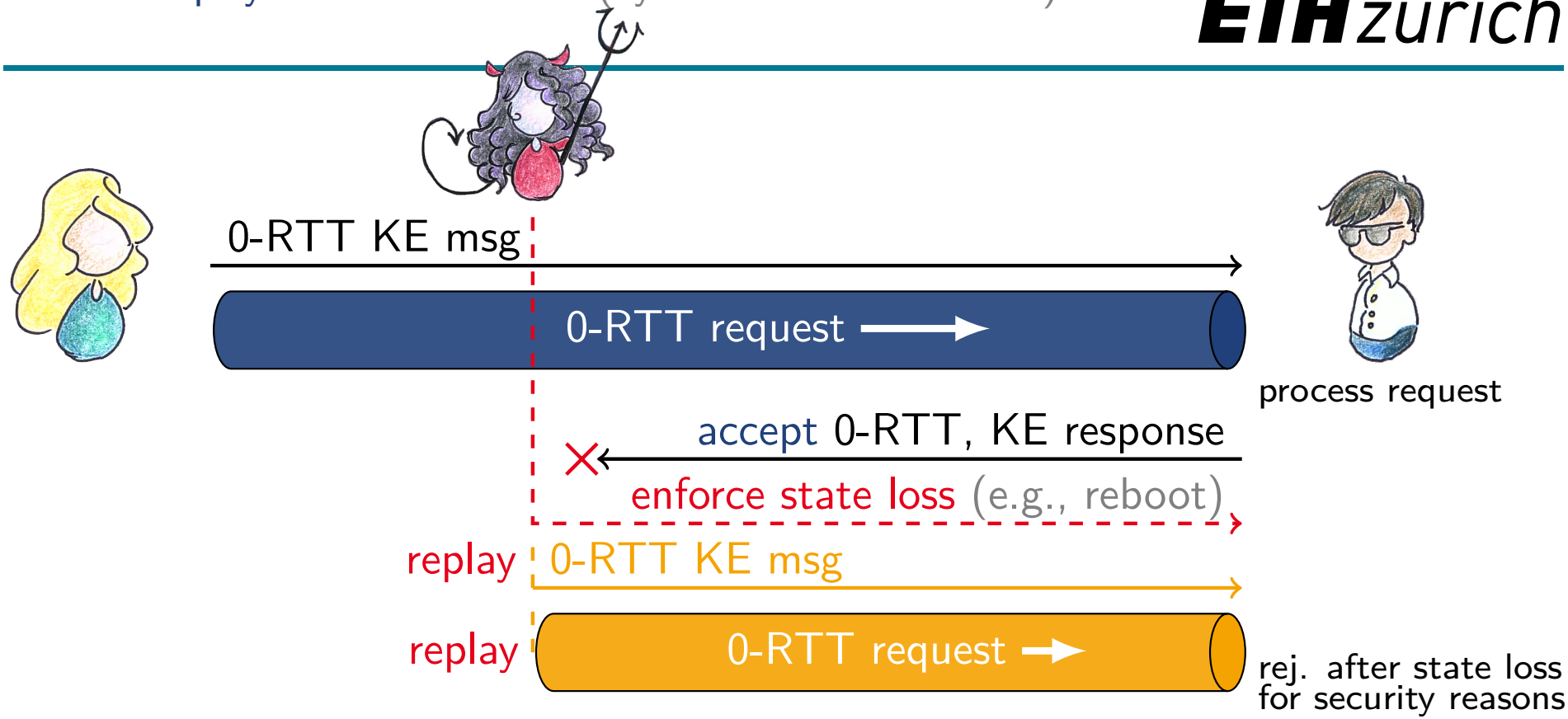

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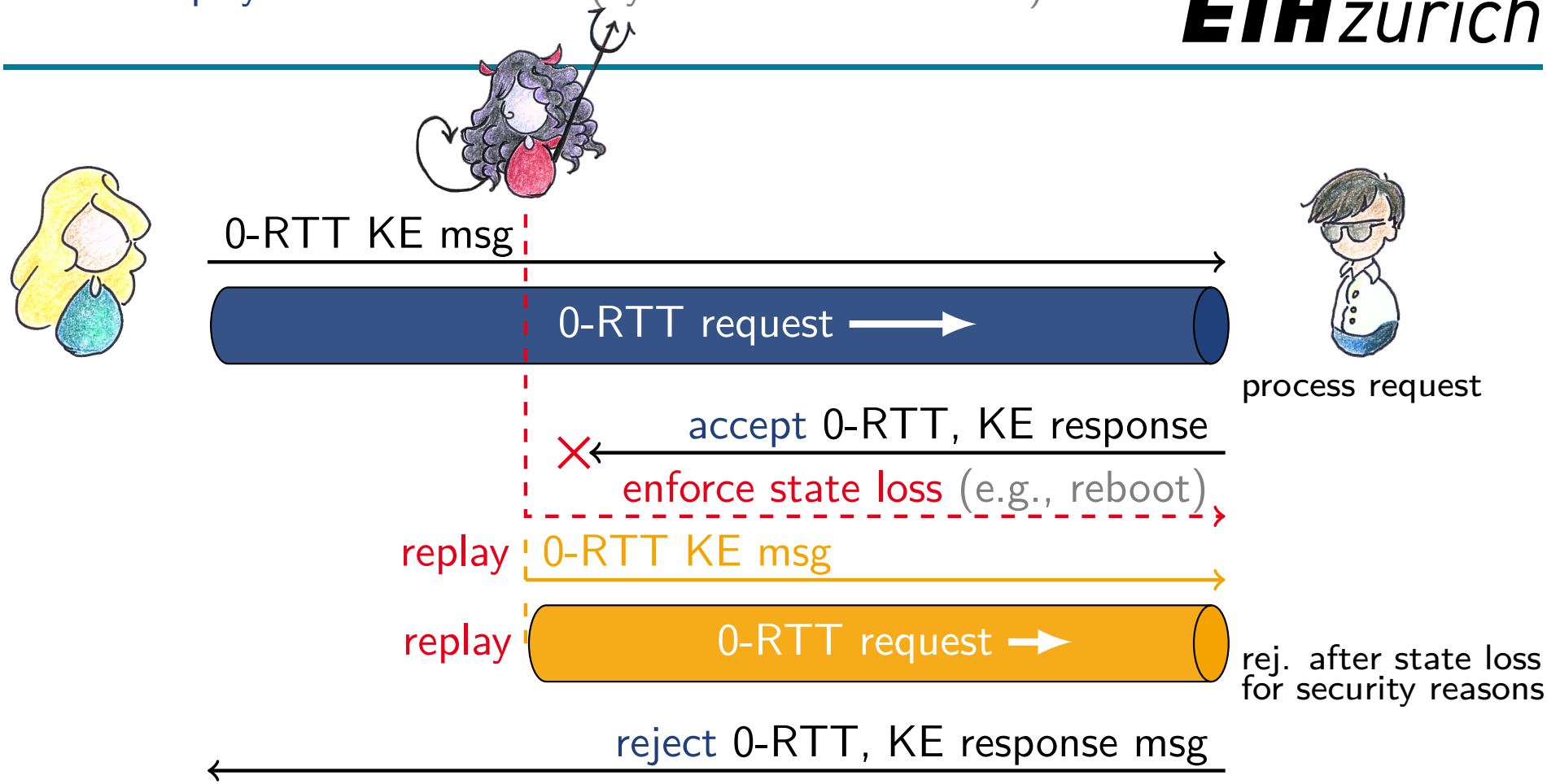

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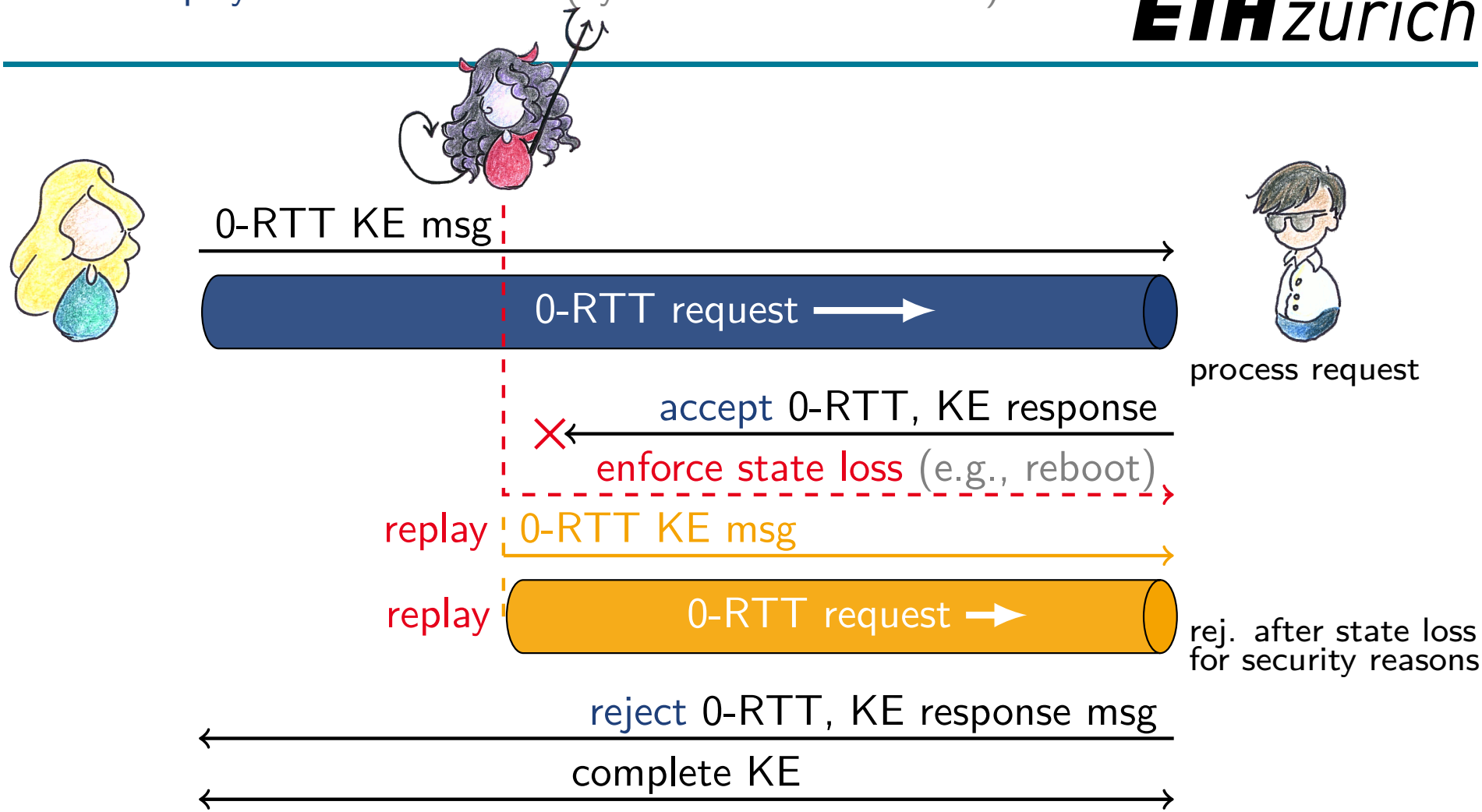

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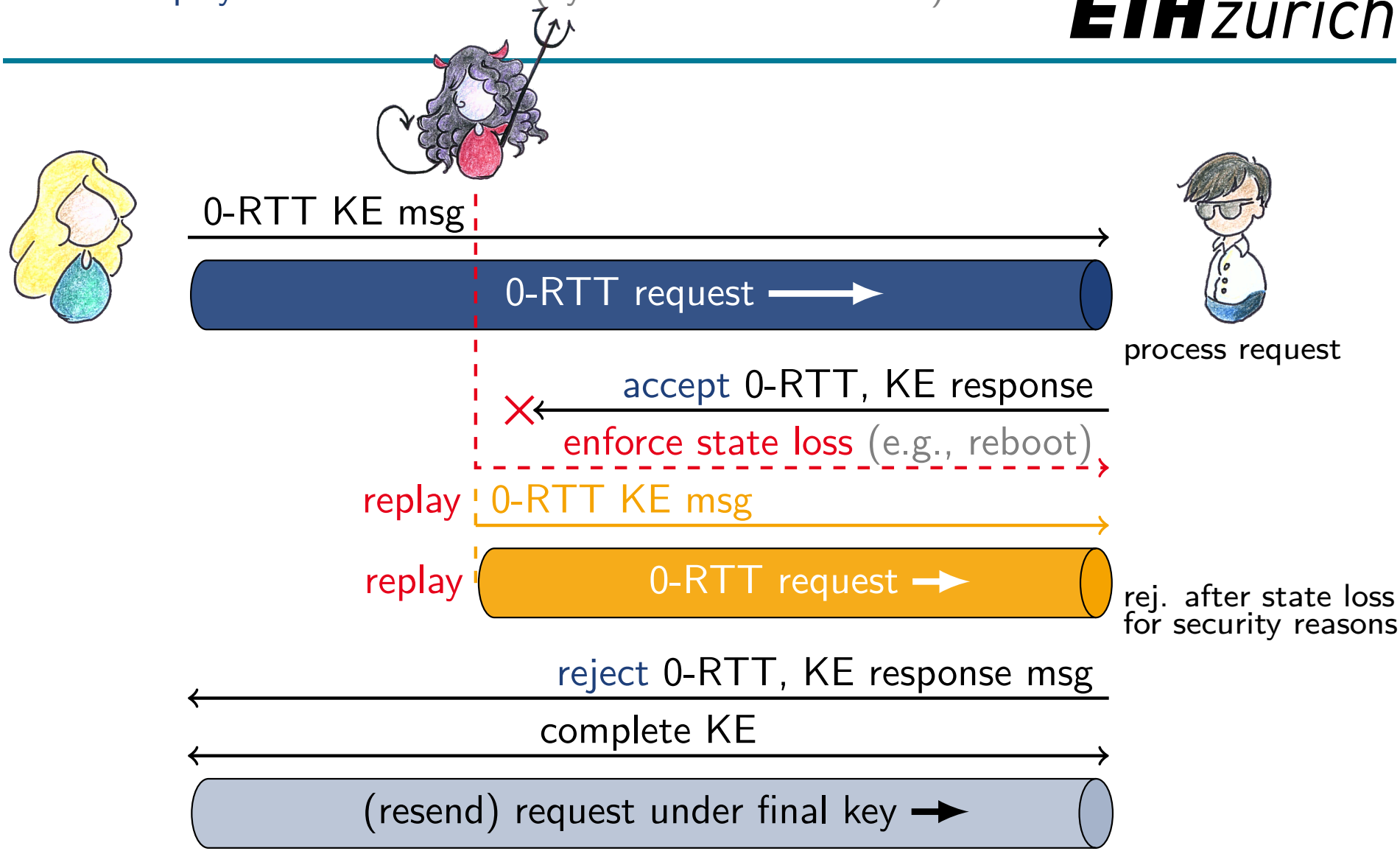

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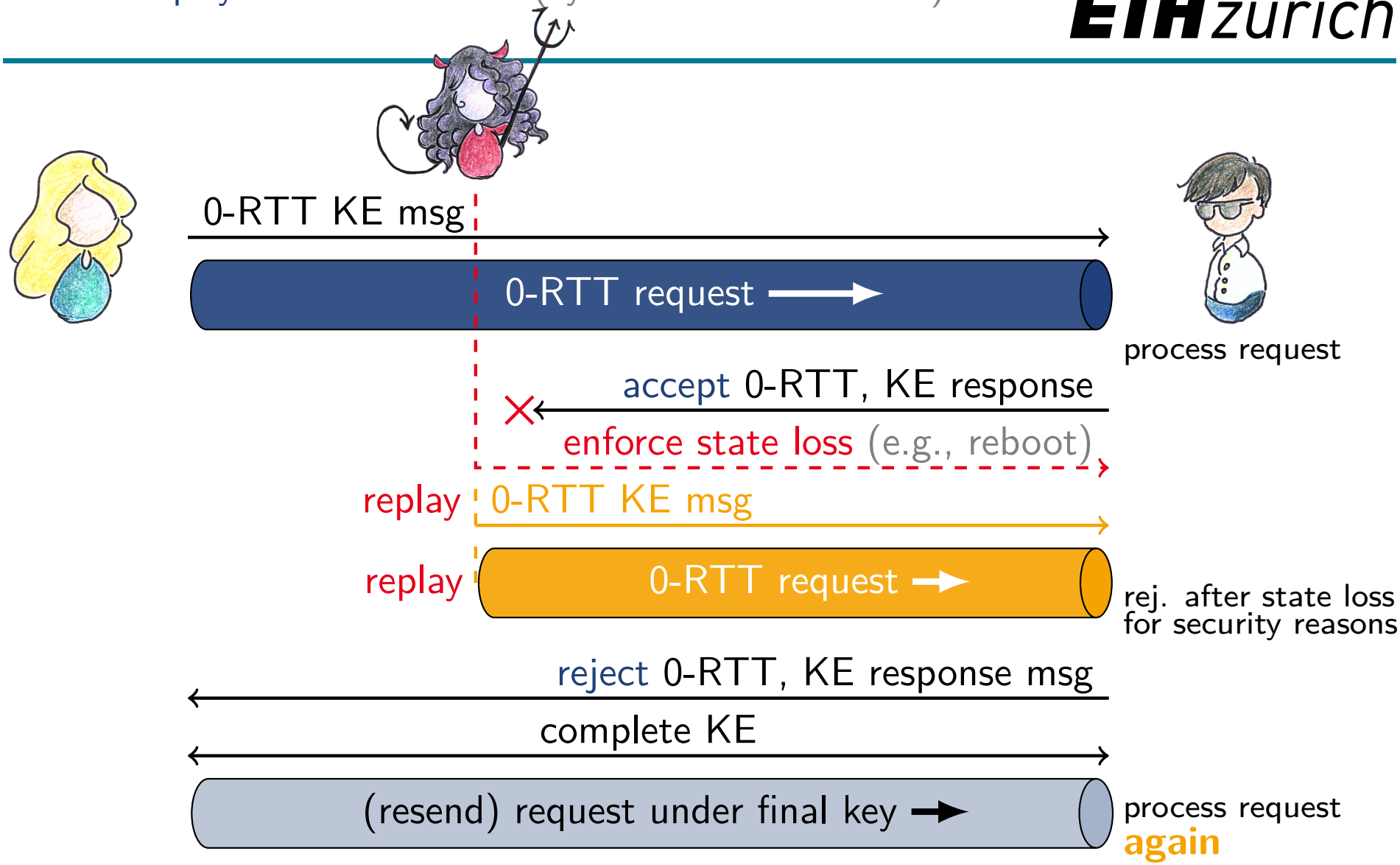

0-RTT and Replays

TLS 1.3's take on replays

ETH zürich

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ETH zürich

TLS does not provide inherent replay protection for 0-RTT data.

[Simple duplicates] can be prevented by sharing state to guarantee that the 0-RTT data is accepted at most once.

Servers SHOULD provide that level of replay safety by implementing one of the methods described in this section [. . .] [RFC 8446, Section 8]

0-RTT and Replays

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- **suggested mechanisms**
  - single-use tickets: allow each RMS to be used only once (simplest)
  - `ClientHello` recording: reject by unique identifier
  - freshness checks: reject based on `ClientHello` time
- very much leaves things to the application/implementer...