A Cryptographic Analysis of the TLS 1.3 Handshake Protocol

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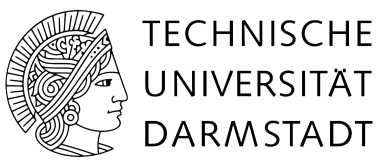
joint work with Benjamin Dowling, Marc Fischlin, and Douglas Stebila



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TLS:DIV

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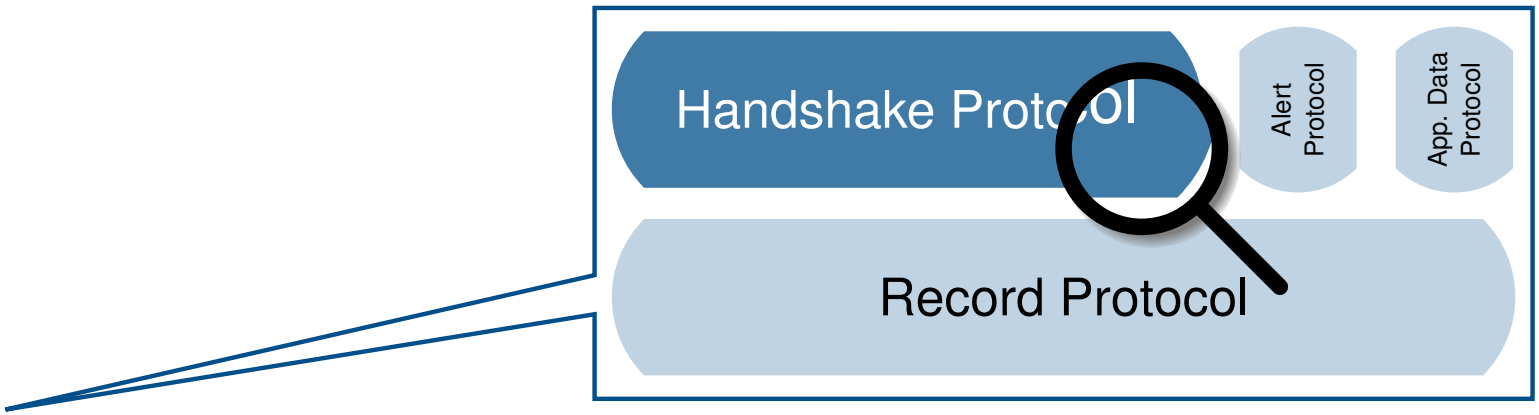

TLS 1.3: Design, Implementation & Verification

(Provable) Security

Our Analyses

What we prove

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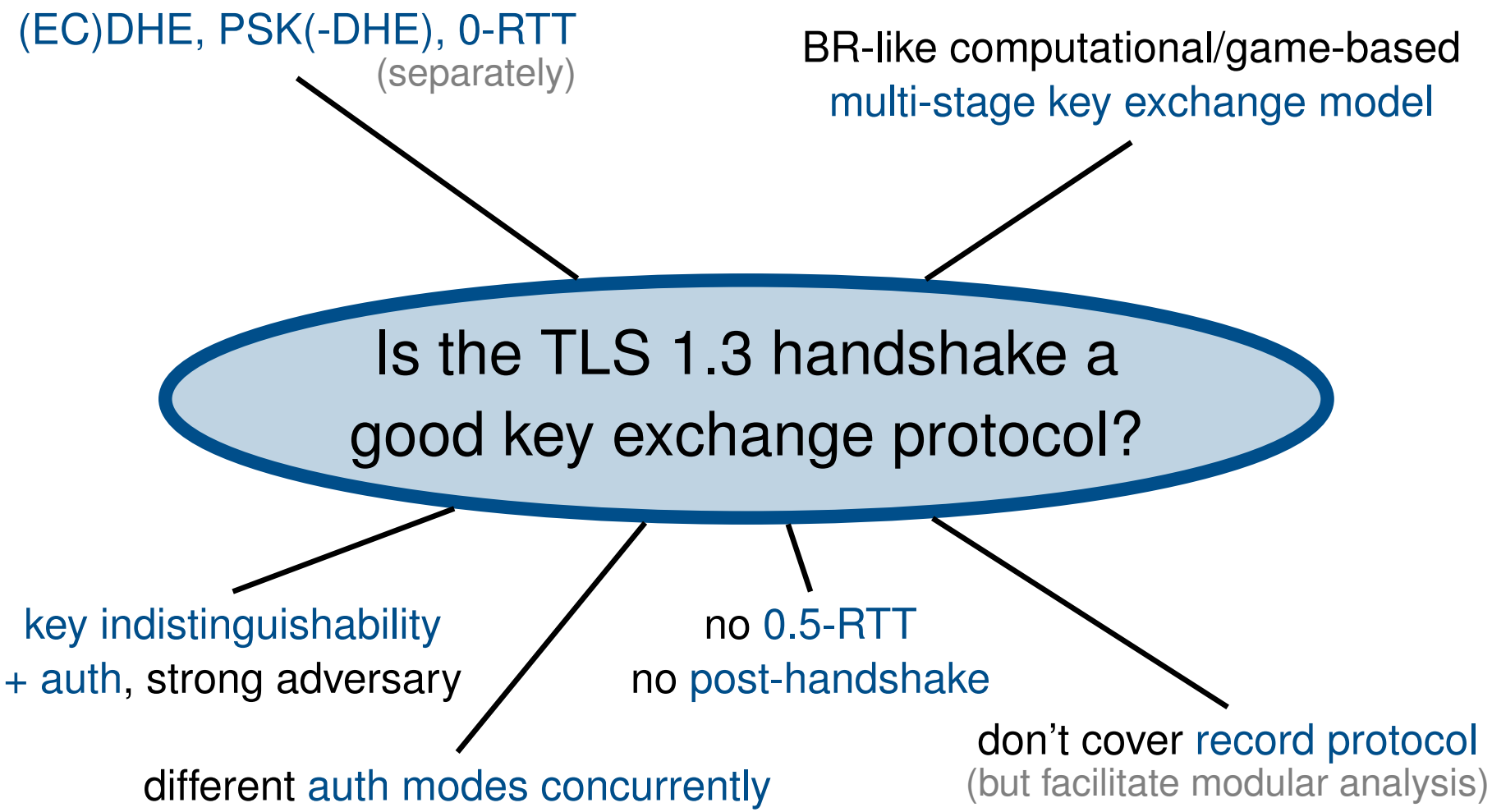

Our Analyses

Timeline

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2014

- April — `draft-00` — copy of TLS 1.2
- July — `draft-02` — first changes

2015

- March — `draft-05`, `draft-dh` — variant based on OPTLS
  - → full/(EC)DHE and resumption (≈ PSK) handshake
  - [Dowling, Fischlin, Günther, Stebila @ ACM CCS 2015]
- October — `draft-10` — integrate OPTLS, add PSK-DHE, 0-RTT, . . .
  - → full/(EC)DHE and PSK/PSK-DHE handshake
  - [Dowling, Fischlin, Günther, Stebila @ TRON 2016]

2016

- March — `draft-12` — last version with DH-based 0-RTT
- July — `draft-14` — only PSK-based 0-RTT, restructure key schedule
  - → DH- and PSK-based 0-RTT handshake
  - [Fischlin, Günther @ EuroS&P 2017]

2017

- April 30 — `draft-20` — key schedule changes, . . .

TLS 1.3 Full/(EC)DHE Handshake
(simplified)

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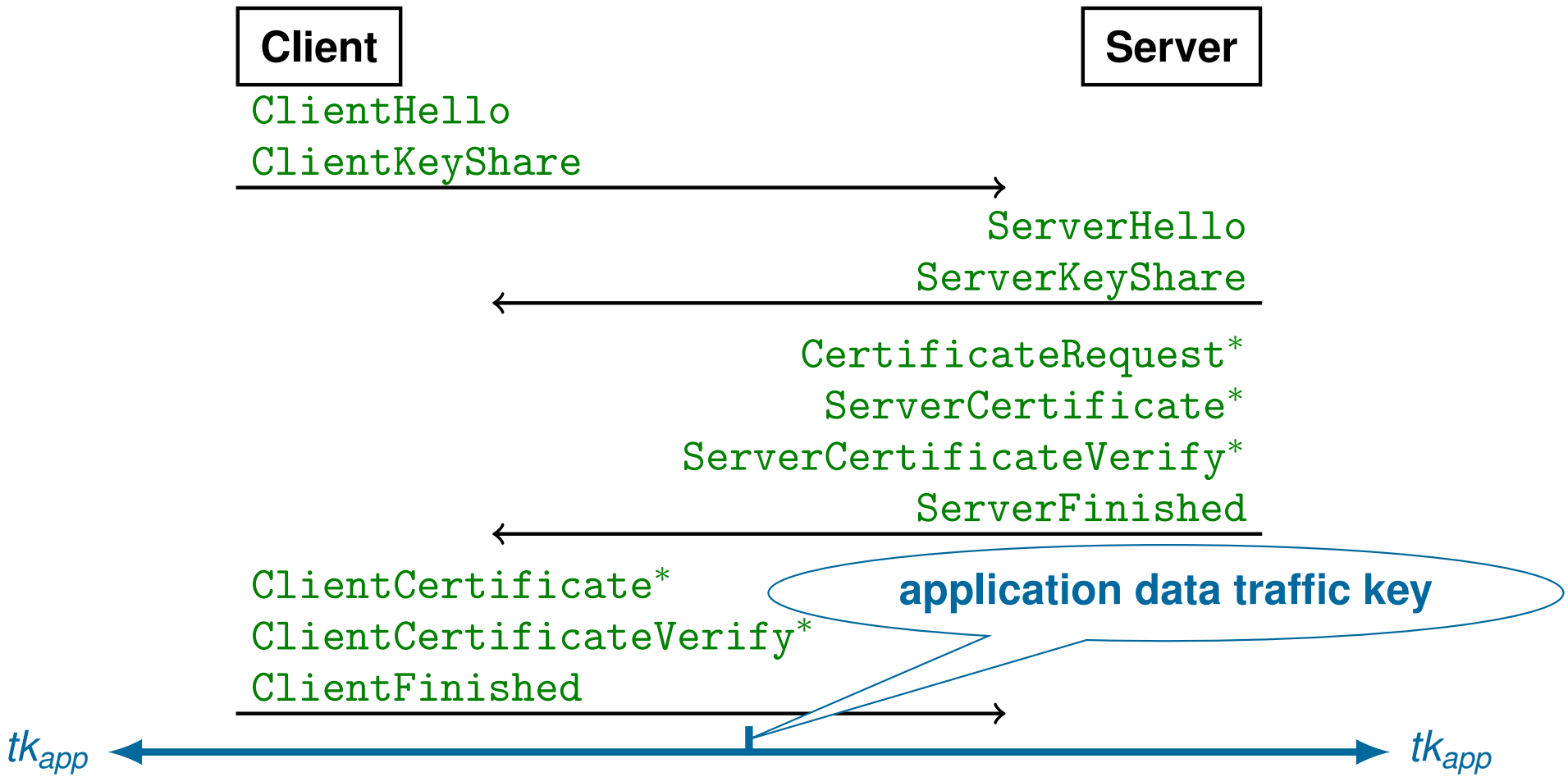

. . . actually, there is more . . .

TLS 1.3 Full/(EC)DHE and PSK(-DHE) Handshake
(simplified)

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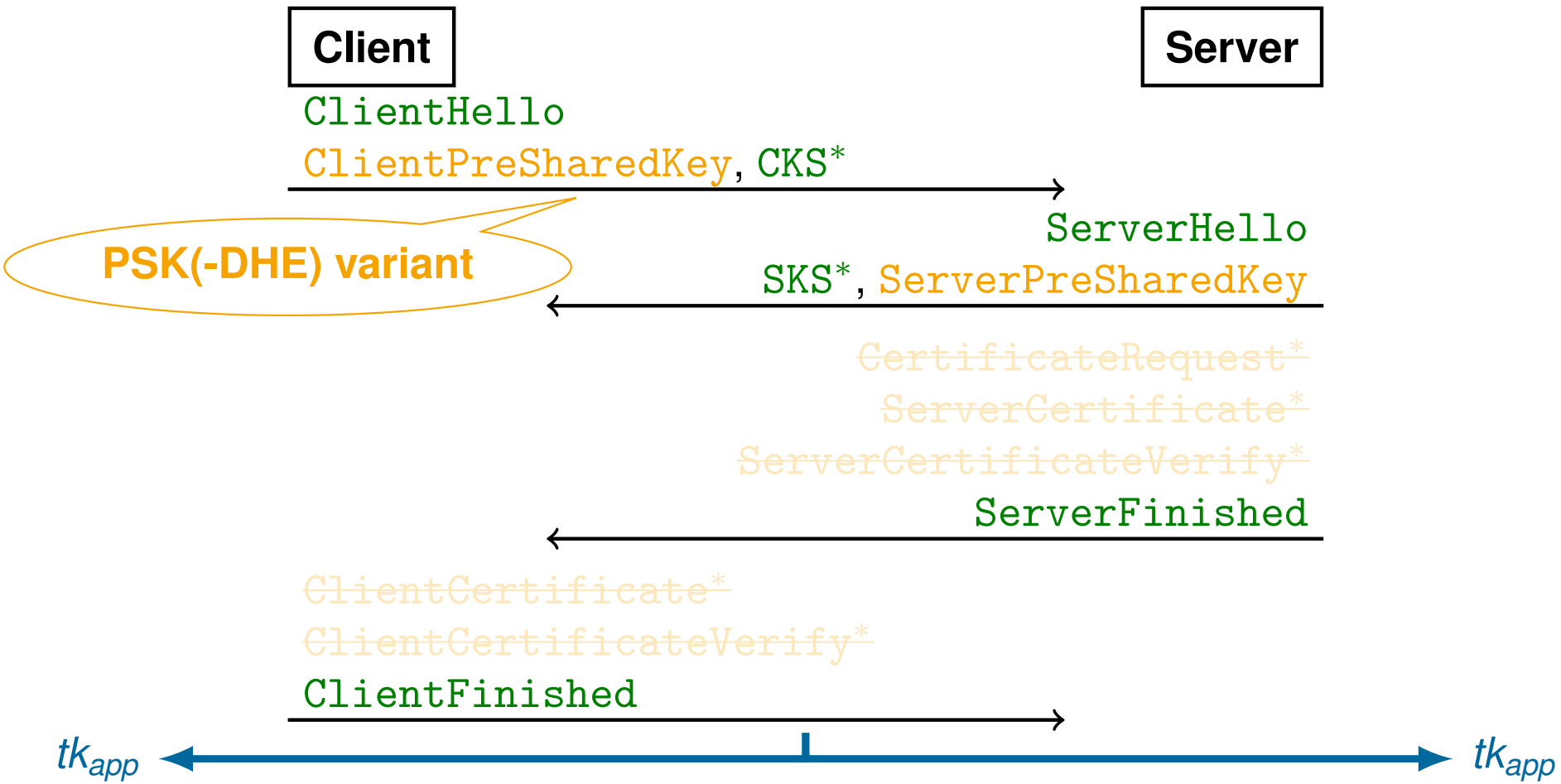

TLS 1.3 Full/(EC)DHE and PSK(-DHE) Handshake

(still simplified)

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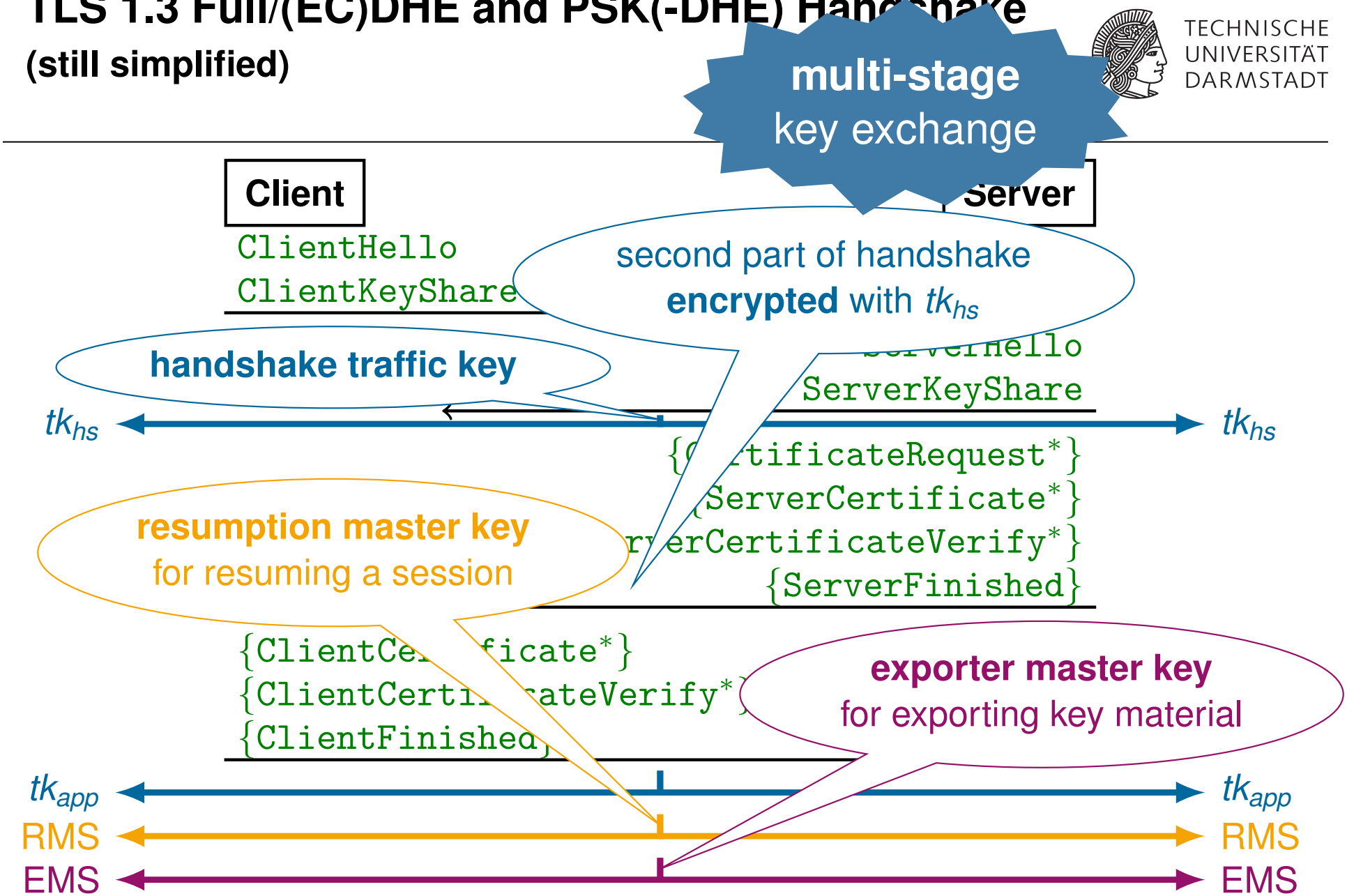

Multi-Stage Key Exchange (Security)

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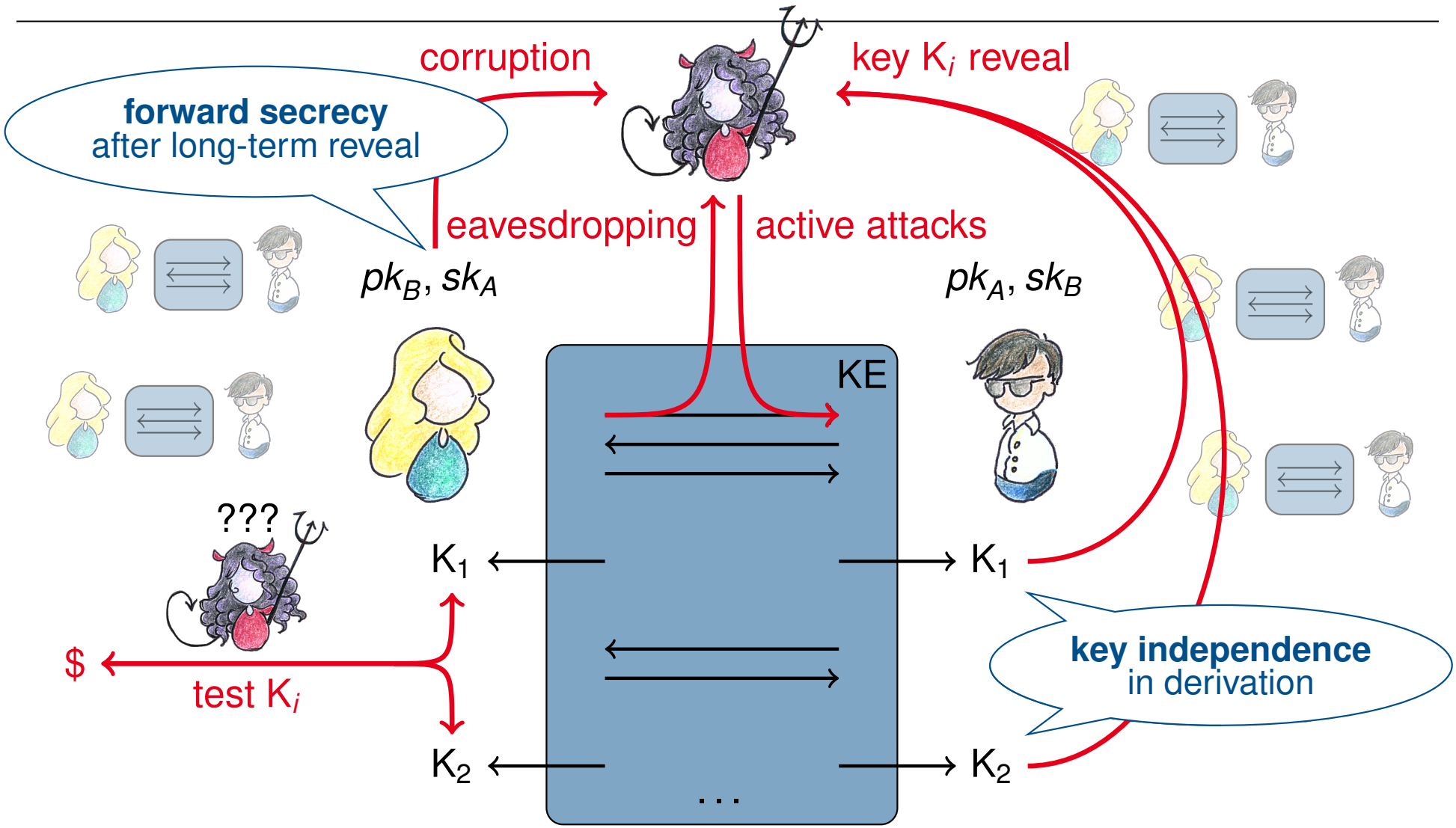

Multi-Stage Key Exchange (Security)

Capturing the Compromise of Secrets

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Secret Compromise Paradigm

- We consider leakage of:
  - **long-term/static secret keys** (signing/pre-shared keys of server/client)
    high potential of compromise, necessary to model forward secrecy
  - **session keys** (traffic keys tk_{hs} and tk_{app}, RMS, EMS)
    outputs of handshake used *outside* the key exchange for encryption, resumption, exporting

- We do not permit leakage of:
  - **ephemeral secret keys** (DH exponents, signature randomness)
  - **internal values / session state** (master secrets, intermediate values)

    TLS 1.3 handshake not designed to be secure against such compromise

Security of the TLS 1.3 Handshakes

Cryptographic Components

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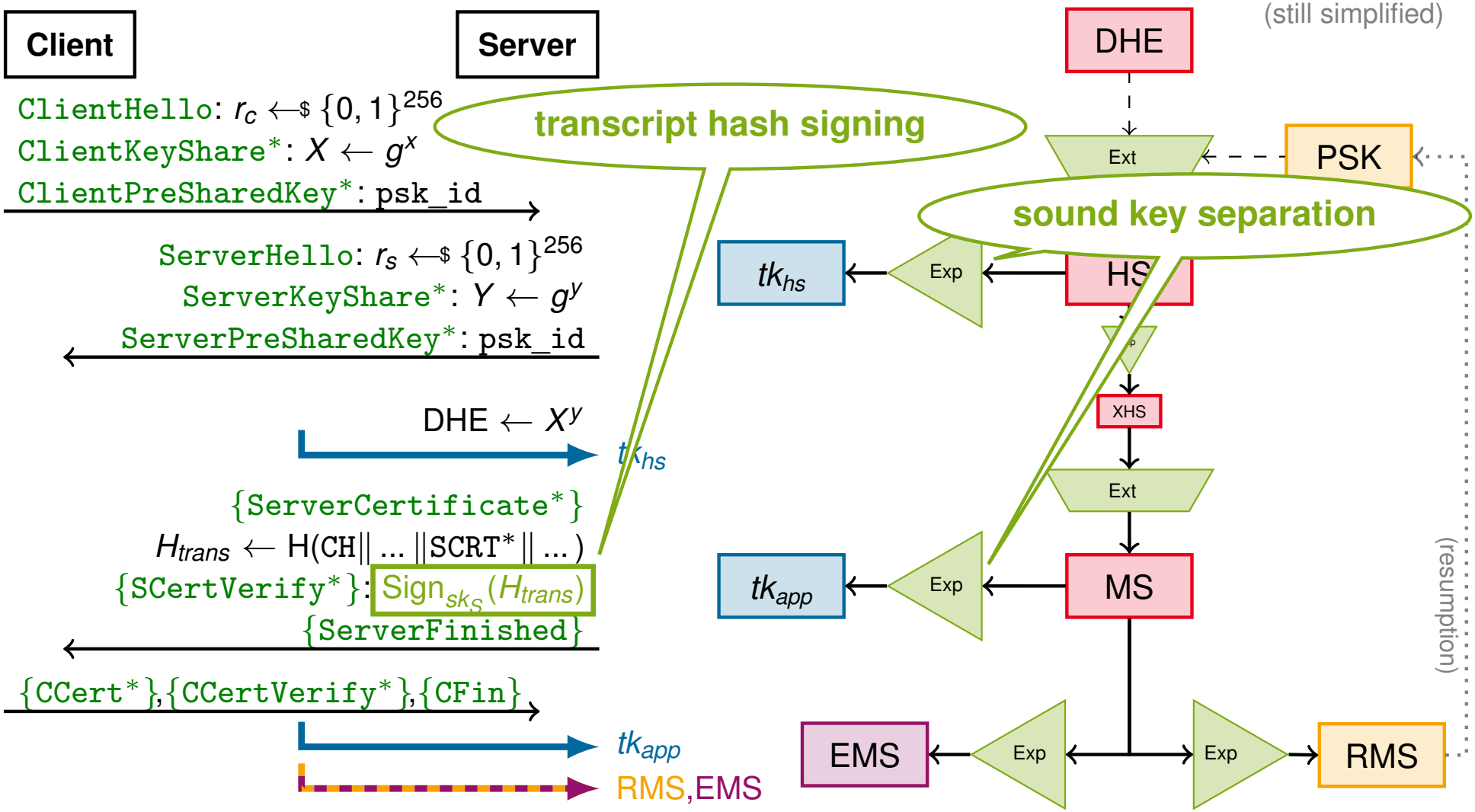

Security of the TLS 1.3 Handshakes

draft-10 Full/(EC)DHE Handshake

similar results expected for **draft-19**

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We show that the draft-10 full (EC)DHE handshake establishes

- random-looking keys (tk_{hs}, tk_{app}, RMS, EMS) tolerating adversary that corrupts other users and reveals other session keys
- forward secrecy for all these keys
- concurrent security of anonymous, unilateral, mutual authentication
- key independence (leakage of traffic/resumption/exporter keys in same session does not compromise each other's security)

assuming

- hash function collision resistance
- signature unforgeability
- HKDF is pseudorandom function
- PRF-ODH assumption holds

standard key exchange security
under **standard~~(-model)~~ assumptions**
?

Brendel, Fischlin, Günther, Janson
PRF-ODH: Relations, Instantiations, and Impossibility Results

0-RTT and its Drawbacks

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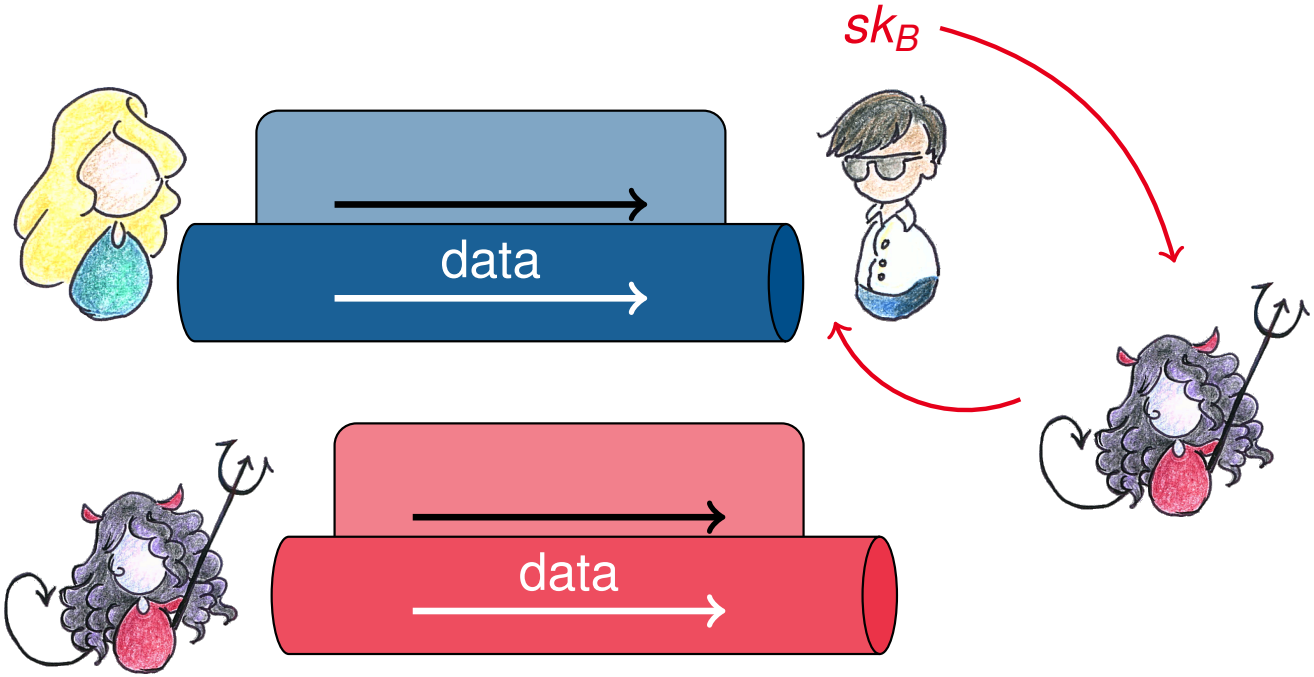

replays
(partially unavoidable)

~~no~~ **forward secrecy**
[GHJL@Eurocrypt17]

TLS 1.3 draft-14 PSK(-DHE) 0-RTT

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(pre-)shared key *PSK*

Client

(earlier full handshake)

Server

(pre-)shared key *PSK*

`ClientHello`: $nonce_c$

`ClientPreSharedKey`: `psk_id`

`ClientKeyShare`: g^x (optional)

new: with **replays**

tk_{ehs} tk_{ehs}

(`ClientFinished`$_0$): MAC(*trans*)

tk_{ead} tk_{ead}

0-RTT data

`ServerHello`: $nonce_s$

`ServerPreSharedKey`: `psk_id`

(optional) `ServerKeyShare`: g^y

tk_{hs} tk_{hs}

{`Certificate`, `Signature`, `MAC`}

{`Certificate`, `Signature`, `MAC`}

tk_{app} tk_{app}

Multi-Stage Key Exchange (Security)

with replays

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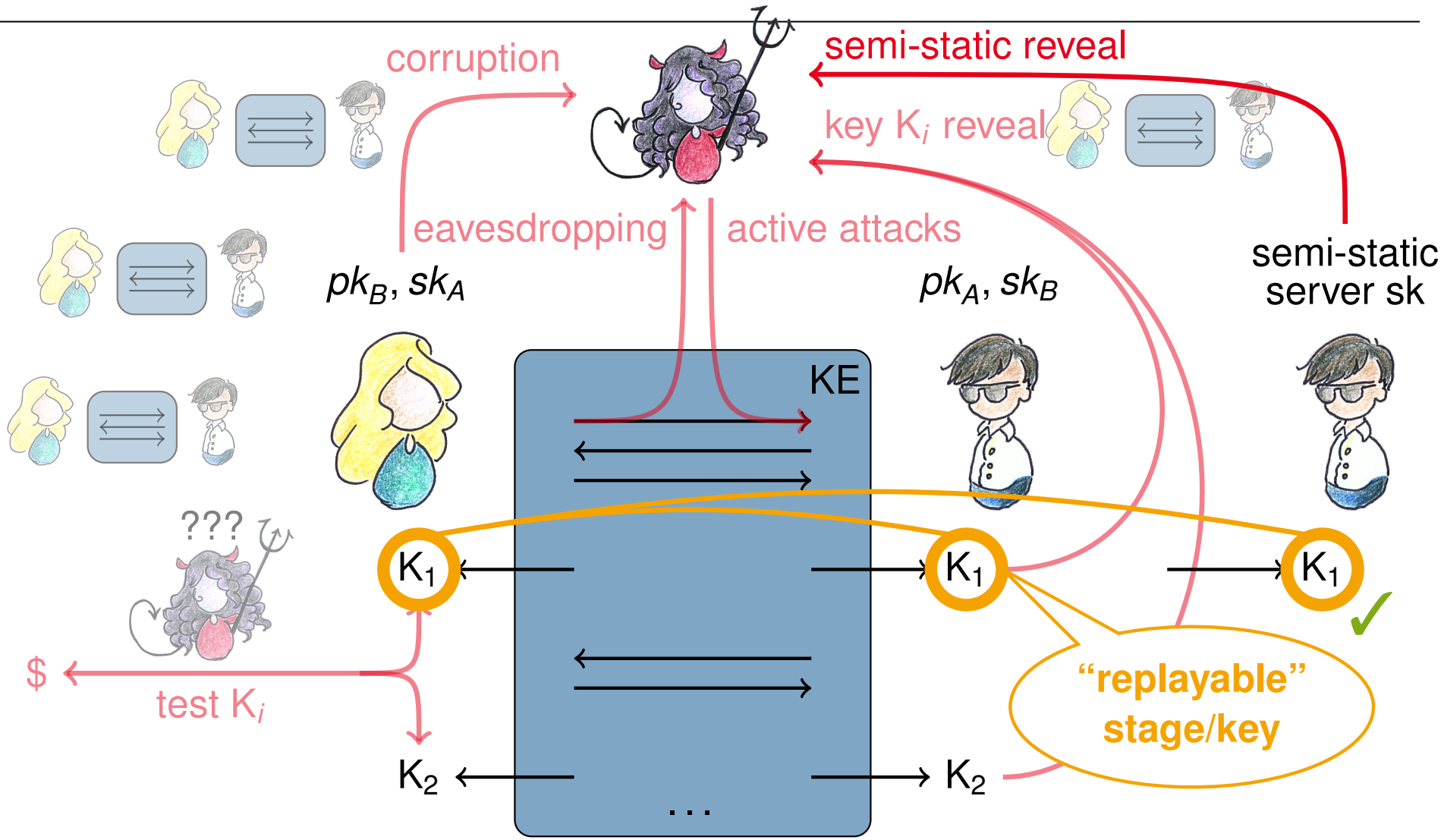

Security of the TLS 1.3 Handshakes

draft-14 PSK(-DHE) 0-RTT Handshake

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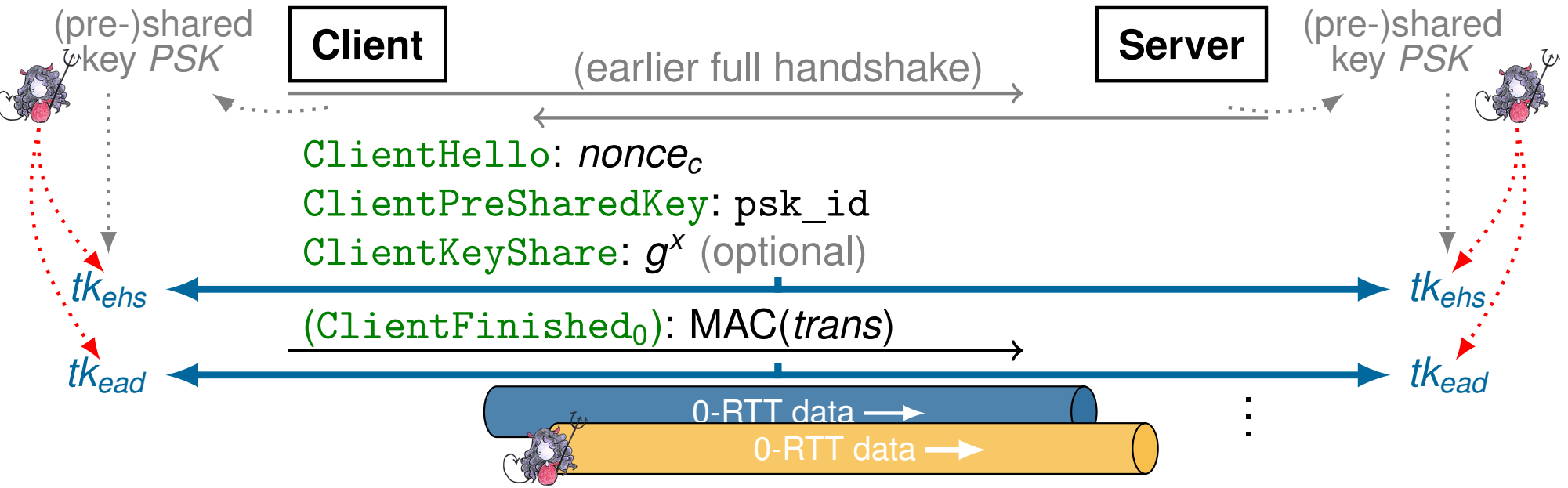

- random-looking keys tk_{ehs}, tk_{ead} (and all subsequent keys)
- 0-RTT keys & data can be replayed
- no forward secrecy for 0-RTT keys

Assuming:

- hash function collision resistance
- HKDF is pseudorandom function
- HMAC unforgeability (DHE)
- PRF-ODH assumption holds (DHE)

Composition

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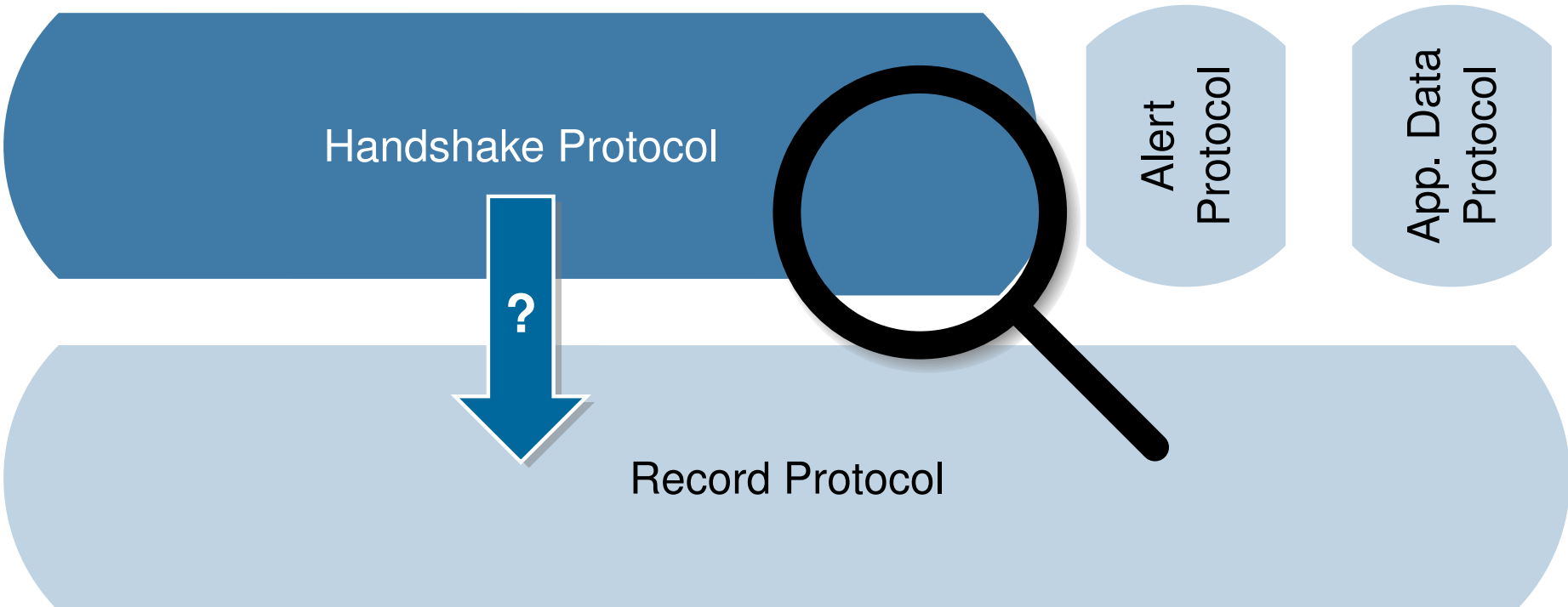

- we established security of the keys derived in the TLS 1.3 handshakes
- what about the usage of those keys, e.g., in the Record Protocol, key export?

Composition

Results for TLS 1.3

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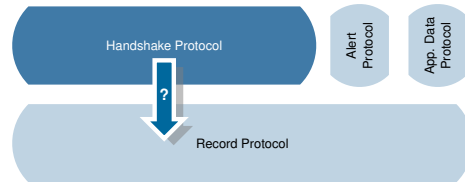
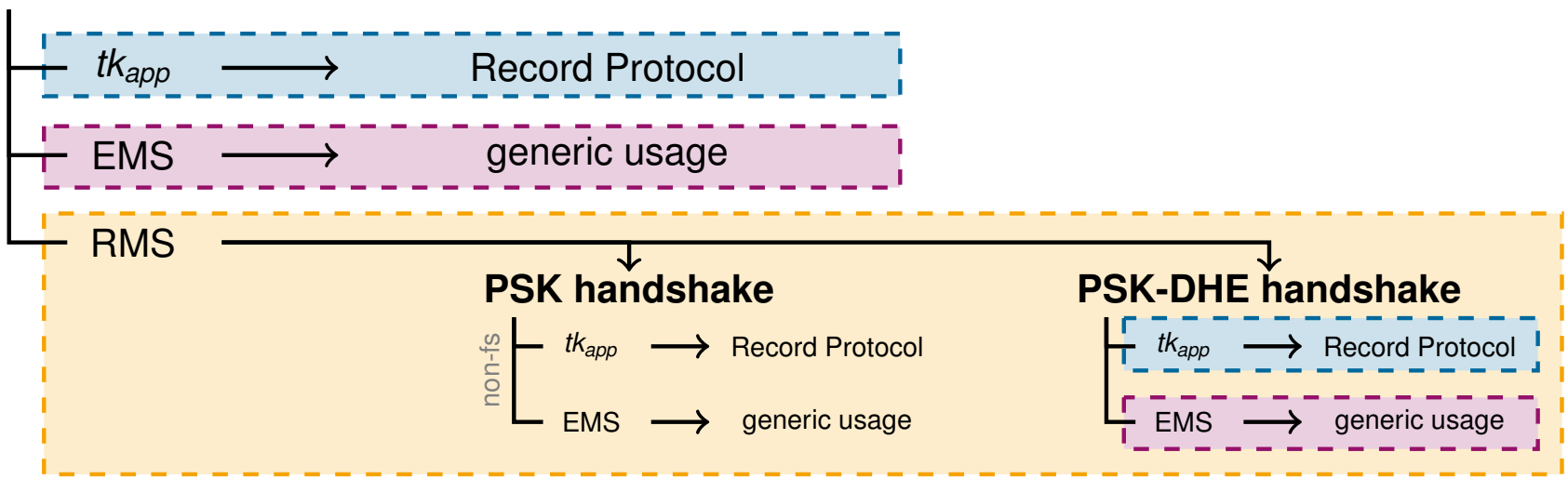


- we facilitate a modular, compositional approach
- we show: using external, forward-secret keys in any symmetric-key protocol is safe
- supports independent analysis of record protocol
- also captures use of exported EMS and RMS for resumption (cascading)

full (EC)DHE handshake



Main Comments on TLS 1.3 from Our Analysis

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1. **Separations in key schedule**
   - separate keys for (main) handshake and application data encryption
   - allows to achieve standard key exchange security under standard assumptions
   - enables key independence: neither key affected by other's compromise
   - thereby facilitating a compositional approach to analyzing the record protocol
2. **Full transcript authentication**
   - full transcript authenticated through signature/MAC
   - makes proof easier and allows for standard assumptions
3. **Encryption of handshake messages**
   - tk_{hs} secure against passive adversaries, hence can indeed increase privacy
   - we confirm there are no negative effects on main key secrecy goal
4. **0-RTT replays and non–forward secrecy**
   - stronger anti-replay mechanisms on key exchange level debatable
   - DH-based 0-RTT had slightly better forward-secrecy properties

Summary

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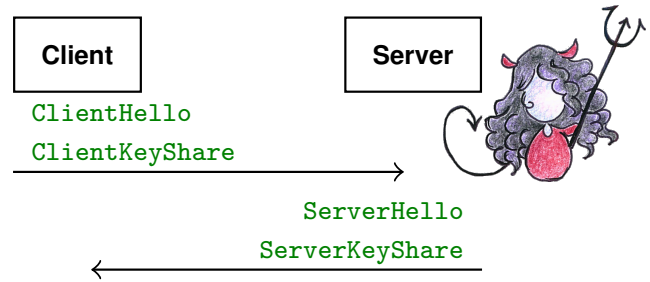
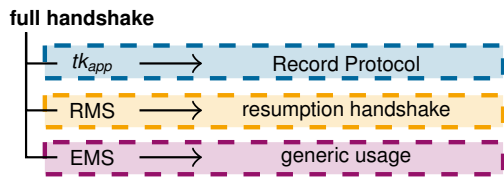
We

- analyze TLS 1.3 (drafts 05, dh, 10, 12, 14)
  full (EC)DHE, PSK(-DHE), and 0-RTT handshakes
  in a computational multi-stage key exchange model
- establish standard computational key secrecy notions
  - with forward secrecy (for full/PSK-DHE)
  - capturing replayable 0-RTT keys
  - running all authentication modes concurrently
  - under standard assumptions
- provide composition result for modular analysis
- are looking into latest/last TLS 1.3 draft for updated analysis





full versions @ IACR ePrint

- `http://ia.cr/2017/082` (DH/PSK 0-RTT @ draft-12/14)
- `http://ia.cr/2016/081` (full/PSK @ draft-10)
- `http://ia.cr/2015/914` (full/PSK @ draft-05/dh)

Thank You!

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