TLS Crypto Seminar

February 21, 2019

Felix Günther
UC San Diego

based on joint work with Benjamin Dowling, Marc Fischlin, Sogol Mazaheri, Douglas Stebila

and discussions with many others

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DFG Deutsche Forschungsgemeinschaft
German Research Foundation

This Seminar, Part II

Part II TLS 1.3

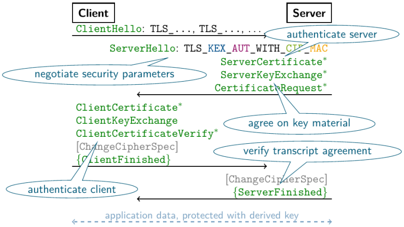
- The road to TLS 1.3 & its technical details.
- More analyses: understanding TLS 1.3's security and what drove design.

Schedule

Feb 21	**TLS 1.3** [TLS13] **& some security models** [FG17,GM17]	Felix
Feb 28	**Multiplexing channels** [PS18]	Vivek
Mar 7	**Symbolic Tamarin analysis** [CHH+17]	Baiyu
Mar 14	**Downgrade resilience** [BBF+16]	Ruth

The Road to TLS 1.3

Recap: TLS 1.2



Client **Server**

ClientHello: TLS_..., TLS_..., ...

ServerHello: TLS_KEX_AUT_WITH_CIP_MAC

ServerCertificate*

ServerKeyExchange*

CertificateRequest*

ClientCertificate*

ClientKeyExchange

ClientCertificateVerify*

[ChangeCipherSpec]

{ClientFinished}

[ChangeCipherSpec]

{ServerFinished}

application data, protected with derived key

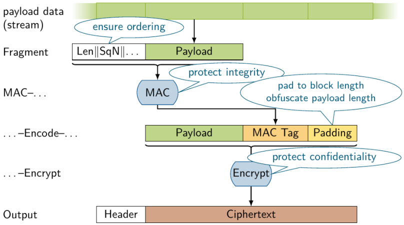
authenticate server

negotiate security parameters

agree on key material

verify transcript agreement

authenticate client



payload data (stream)

ensure ordering

Fragment: Len‖SqN‖... | Payload

protect integrity

MAC–...: MAC

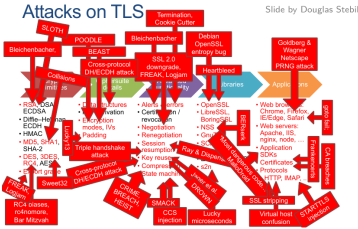
pad to block length obfuscate payload length

...–Encode–...: Payload | MAC Tag | Padding

protect confidentiality

...–Encrypt: Encrypt

Output: Header | Ciphertext



Attacks on TLS

Slide by Douglas Stebila

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

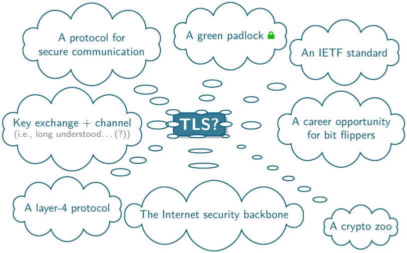
Cryptographic primitives
- RSA, DSA, ECDSA
- Diffie–Hellman, ECDH
- HMAC
- MD5, SHA1, SHA-2
- DES, 3DES, RC4, AES
- Export grade

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

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

Libraries
- OpenSSL
- LibreSSL, BoringSSL
- NSS
- GnuTLS
- SChannel
- s2n

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



A protocol for secure communication

A green padlock 🔒

An IETF standard

Key exchange + channel (i.e., long understood...(?))

TLS?

A career opportunity for bit flippers

A layer-4 protocol

The Internet security backbone

A crypto zoo

TLS 1.3

A New Hope?

- IETF TLS WG begins in **early 2014** with developing new TLS 1.3 version

So… what would you change?

TLS 1.3

Design Goals

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

TLS 1.3

Main changes (from TLS 1.2)

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Clean up

- removed **legacy and broken crypto**
  - ciphers: (3)DES, RC4, . . . , MtEE (CBC & generally) — only AEAD remains
  - hash functions: MD5, SHA1
  - authentication: Kerberos, RSA PKCS#1v1.5 key transport
  - custom (EC)DHE groups
- removed **broken features**
  - compression
  - renegotiation (but added key updates + late client auth)

quite some resistance from enterprises doing passive inspection

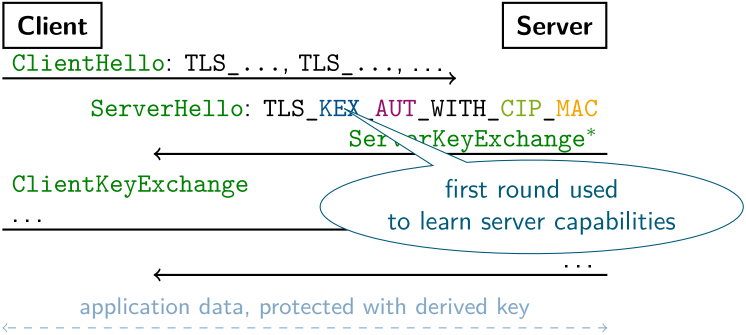
- removed **static RSA/DH**: public-key crypto = forward secrecy
- clean **key derivation** based on Extract-then-Expand HKDF
- **hardened negotiation** of version/cipher suite against downgrades

TLS 1.3

Main changes (from TLS 1.2)

Improve latency

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



Client
Server
ClientHello: TLS_..., TLS_..., ...
ServerHello: TLS_KEX_AUT_WITH_CIP_MAC
ServerKeyExchange*
ClientKeyExchange
...
...
application data, protected with derived key

first round used to learn server capabilities

TLS 1.3

Main changes (from TLS 1.2)

Improve latency

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

- TLS 1.3: **full handshake in 1 round trip**
  - feature reduction → we 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

- **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* certain security properties (will come to that)

TLS 1.3

Main changes (from TLS 1.2)

Improve privacy

- TLS 1.2: complete handshake in the clear (incl. certificates, extensions)
- TLS 1.3: **encrypts almost all handshake messages**
  - derive separate key early to protect handshake messages
  - provides security against passive/active attackers (for server/client)

Continuity

- example: complex renegotiation only used for key updates + late client auth
  - just keep these features
- interoperability (idea): let `ClientHello` look like TLS <1.3
  - Well... we'll see.

TLS 1.3

Timeline, Proposals, and Security Analyses

2014	April	draft-00	copy of TLS 1.2
	July	draft-02	1-RTT, −custom DH, −compression −static RSA/DH, −non-AEAD
	October	draft-03	ECC in base standard
2015	January	draft-04	remove renegotiation
	March	draft-05	
		draft-dh	variant based on OPTLS

↳ [KW16] OPTLS: unified design. DH/PSK/0-RTT w static DH

↳ [DF**G**S15] draft-05/dh Analysis: first KE security result

	July	draft-07	merging OPTLS (partially): key schedule, HKDF, 0-RTT
	August	draft-08/9	deprecate MD5+SHA1, add RSA-PSS signatures

↳ [BL16] SLOTH: transcript collision attacks

↳ [JSS15] TLS 1.3 vs. PKCS#1v1.5 Encryption: still bad

STANDARD UNDER CONSTRUCTION

https://tools.ietf.org/html/draft-ietf-tls-tls13

TLS 1.3

Timeline, Proposals, and Security Analyses [cont'd]

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Ruth
Mar 14

2015 October draft-10

December draft-11 + downgrade protection, + late client auth, es

↳ [BBF+16] Downgrade Resilience: proposed harde

↳ [Kra16] Post-Handshake Client Auth: formal treatment

2016 February **TRON** (TLS 1.3 – Ready or Not?) @ NDSS 2016

↳ [DF**G**S16] draft-10 Analysis: updated KE security analysis

↳ [BMM+15] Record Protocol Analysis: via constructive crypto

↳ [BBDL+16] miTLS: towards a verified implementation

↳ [CHSM16] Tamarin Analysis: symbolic, identified attack

⋮

May draft-13 restructure key schedule, only PSK-based 0-RTT

↳ [F**G**17] 0-RTT Analysis: PSK- & DH-based, security limitations

"**TRON2**" TLS 1.3 Meetup @ IEEE S&P 2016

↳ discussing key schedule, 0-RTT, early implementation results

https://tools.ietf.org/html/draft-ietf-tls-tls13

TLS 1.3

Timeline, Proposals, and Security Analyses [cont'd]

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2016 Aug-Oct `draft-15--17` lots of discussion around 0-RTT

October `draft-18`

↳ [BBK17] ProVerif Analysis: tool-based formal analysis

↳ [DLFK+17] miTLS: verified Record Protocol implementation

2017 April **TLS:DIV** (Design, Implem. & Verif.) @ EuroS&P / Eurocrypt 2017

↳ status update & still discussing 0-RTT [M . .

July `draft-21` + comment on 0-RTT security & d mitigations

↳ [CHH+17] Tamarin Analysis: updated

November `draft-22` "Implement changes for improved middlebox penetration"

↳ [Ben18] TLS Ecosystem Woes: Why your Crypto isn't Real World yet

2018 March `draft-25` include record header in associated data of

↳ [PS18] Record Protocol Model: multiplexing chan

`draft-26--28` clarifications and cleanup

Baiyu
Mar 7

Vivek
Feb 28

https://tools.ietf.org/html/draft-ietf-tls-tls13

TLS 1.3

The ~~End~~ RFC!

2018

August 10 TLS 1.3 = RFC 8446

August 19 **Crypto Welcomes TLS 1.3** @ Crypto 2018

- **already in:** Firefox, Chrome, Cloudflare, Google, Facebook, OpenSSL, ...
  - as of Sep 2018: ~5% @ Firefox, 2nd @ Cloudflare, ~50% @ Facebook
- **strong interaction:** TLS WG ↔ researchers ↔ engineers
  - high-paced draft progress (29 drafts in 4 years ≈ one every 2nd month)
  - proactive rather than reactive standardization process (see [PM16])
- **vibrant research topic:** 20+ papers sharpening understanding and tools

TLS 1.3
Handshake & Some Analysis

The TLS Protocol

Recap (again overly simplified)

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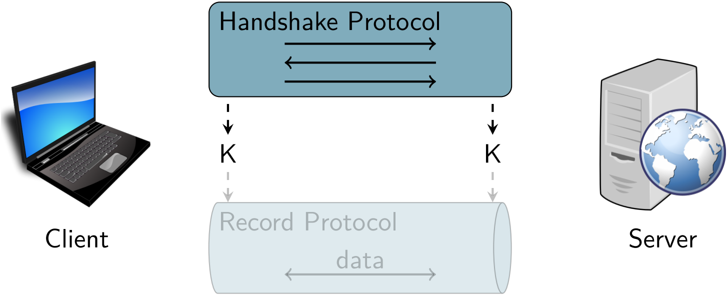
Handshake Protocol:

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

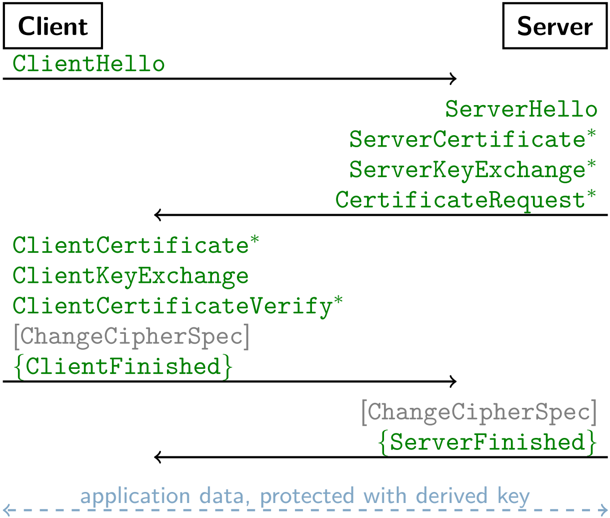


Record Protocol:

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

The TLS Protocol

Recap: Handshake Protocol Structure up to TLS 1.2



Client

Server

ClientHello

ServerHello
ServerCertificate*
ServerKeyExchange*
CertificateRequest*

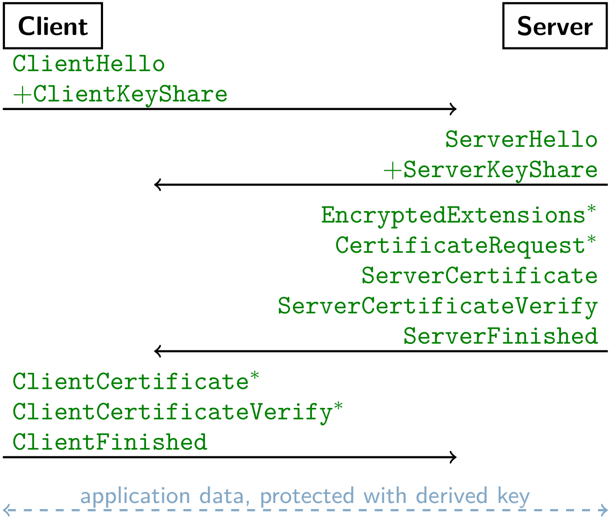
ClientCertificate*
ClientKeyExchange
ClientCertificateVerify*
[ChangeCipherSpec]
{ClientFinished}

[ChangeCipherSpec]
{ServerFinished}

application data, protected with derived key

The TLS 1.3 Handshake

Full (EC)DHE Mode



Client

Server

ClientHello
+ClientKeyShare

ServerHello
+ServerKeyShare

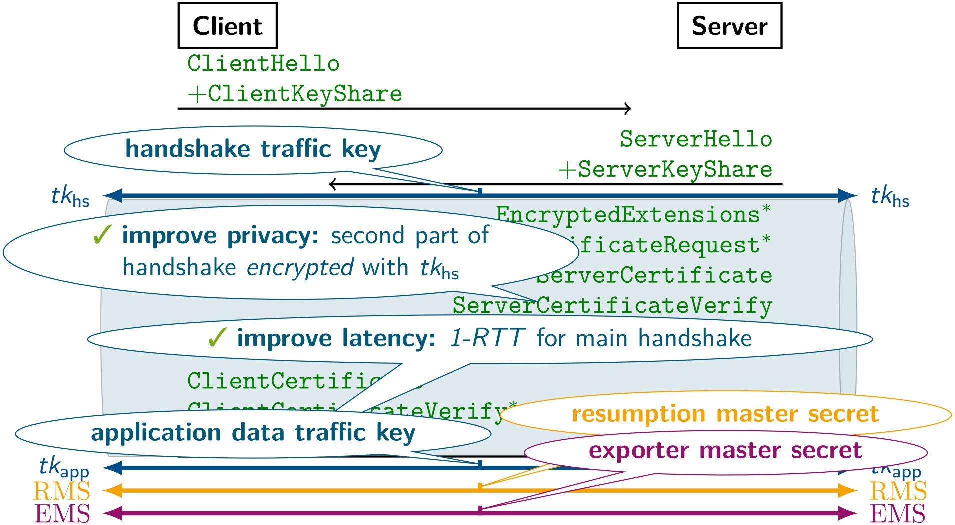
EncryptedExtensions*
CertificateRequest*
ServerCertificate
ServerCertificateVerify
ServerFinished

ClientCertificate*
ClientCertificateVerify*
ClientFinished

application data, protected with derived key

The TLS 1.3 Handshake

Full (EC)DHE Mode



Client

Server

ClientHello
+ClientKeyShare

ServerHello
+ServerKeyShare

handshake traffic key

tk_{hs} tk_{hs}

EncryptedExtensions*
ificateRequest*
erverCertificate
ServerCertificateVerify

✓ **improve privacy:** second part of handshake *encrypted* with tk_{hs}

✓ **improve latency:** *1-RTT* for main handshake

ClientCertific e
ClientCerti cateVerify*

resumption master secret

application data traffic key

exporter master secret

tk_{app} tk_{app}

RMS RMS

EMS EMS

The TLS 1.3 Handshake

PSK / PSK-(EC)DHE Resumption Mode

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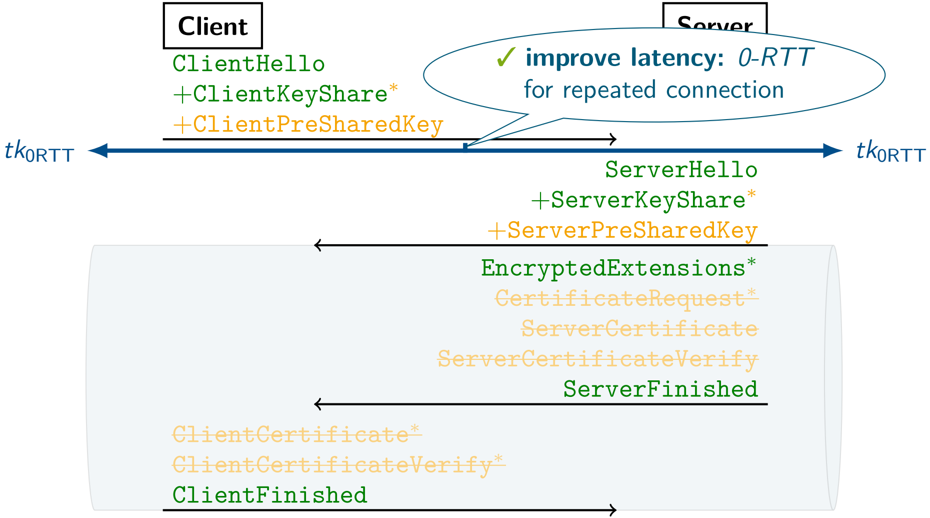


Client

Server

✓ **improve latency:** *0-RTT*
for repeated connection

ClientHello
+ClientKeyShare*
+ClientPreSharedKey

tk_{0RTT} tk_{0RTT}

ServerHello
+ServerKeyShare*
+ServerPreSharedKey

EncryptedExtensions*
~~CertificateRequest*~~
~~ServerCertificate~~
~~ServerCertificateVerify~~
ServerFinished

~~ClientCertificate*~~
~~ClientCertificateVerify*~~
ClientFinished

The TLS 1.3 Handshake

0.5-RTT and Post-Handshake Messages

Additional features (which we won't cover here...):

- **0.5-RTT**
  - server can already send data after its `Finished` message
  - client not yet authenticated, but can be done retroactively [Kra16]
- **Post-Handshake Client Authentication**
  - server can ask client to authenticate even after handshake is over
  - captures renegotiation functionality from $\leq$ TLS 1.2
  - again gives retroactive authentication [Kra16]
- **Key Updates**
  - both sides can initiate an update of the traffic key (post-handshake)
  - next key is then derived from master secret in forward-secure manner [**G**M17]

TLS 1.3 Handshake Security

- So: What kind of security do we expect for the TLS 1.3 handshake?

- **secure key exchange** (à la [BR94])

- here: **provable, game-based, reductionist security**
  - allows us to capture detailed cryptographic computations
  - get precise security bounds & crypto design recommendations

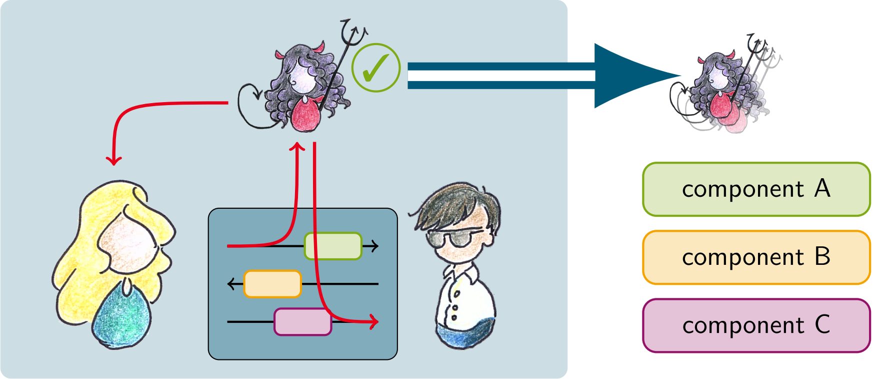
  - due to all the crypto details, security proofs can get complex
  - to handle complexity, we focus on one handshake mode at a time
  - and only look at the "cryptographic core"

  - symbolic analysis tools are better in analyzing interaction across modes
  - though somewhat coarser on the crypto details

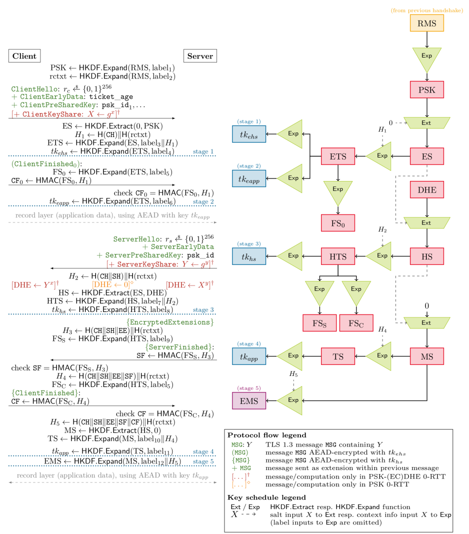
  - to be sure the actual code is secure, you need a verified implementation

Cryptographic Security Models and the Provable Security Approach

1. describe abstract protocol
2. define security
3. reduce to assumptions



TLS 1.3 Handshake as an Abstract Protocol



Client **Server**

$\mathrm{PSK} \leftarrow \mathsf{HKDF.Expand}(\mathrm{RMS}, \mathrm{label}_1)$
$\mathrm{rctxt} \leftarrow \mathsf{HKDF.Expand}(\mathrm{RMS}, \mathrm{label}_2)$

ClientHello: $r_c \xleftarrow{\$} \{0,1\}^{256}$
+ ClientEarlyData: ticket_age
+ ClientPreSharedKey: psk_id$_1, \ldots$
[+ ClientKeyShare: $X \leftarrow g^x]^\dagger$

$\mathrm{ES} \leftarrow \mathsf{HKDF.Extract}(0, \mathrm{PSK})$
$H_1 \leftarrow \mathsf{H}(\mathtt{CH}) \| \mathsf{H}(\mathrm{rctxt})$
$\mathrm{ETS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{ES}, \mathrm{label}_3 \| H_1)$
$tk_{ehs} \leftarrow \mathsf{HKDF.Expand}(\mathrm{ETS}, \mathrm{label}_4)$ stage 1

(ClientFinished$_0$):
$\mathrm{FS}_0 \leftarrow \mathsf{HKDF.Expand}(\mathrm{ETS}, \mathrm{label}_5)$
$\mathtt{CF}_0 \leftarrow \mathsf{HMAC}(\mathrm{FS}_0, H_1)$

check $\mathtt{CF}_0 = \mathsf{HMAC}(\mathrm{FS}_0, H_1)$
$tk_{eapp} \leftarrow \mathsf{HKDF.Expand}(\mathrm{ETS}, \mathrm{label}_6)$ stage 2

record layer (application data), using AEAD with key tk_{eapp}

ServerHello: $r_s \xleftarrow{\$} \{0,1\}^{256}$
+ ServerEarlyData
+ ServerPreSharedKey: psk_id
[+ ServerKeyShare: $Y \leftarrow g^y]^\dagger$

$H_2 \leftarrow \mathsf{H}(\mathtt{CH} \| \mathtt{SH}) \| \mathsf{H}(\mathrm{rctxt})$
$[\mathrm{DHE} \leftarrow Y^x]^\dagger$ $[\mathrm{DHE} \leftarrow 0]^\diamond$ $[\mathrm{DHE} \leftarrow X^y]^\dagger$
$\mathrm{HS} \leftarrow \mathsf{HKDF.Extract}(\mathrm{ES}, \mathrm{DHE})$
$\mathrm{HTS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HS}, \mathrm{label}_7 \| H_2)$
$tk_{hs} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HTS}, \mathrm{label}_8)$ stage 3

{EncryptedExtensions}
$H_3 \leftarrow \mathsf{H}(\mathtt{CH} \| \mathtt{SH} \| \mathtt{EE}) \| \mathsf{H}(\mathrm{rctxt})$
$\mathrm{FS_S} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HTS}, \mathrm{label}_9)$
{ServerFinished}:
$\mathtt{SF} \leftarrow \mathsf{HMAC}(\mathrm{FS_S}, H_3)$

check $\mathtt{SF} = \mathsf{HMAC}(\mathrm{FS_S}, H_3)$
$H_4 \leftarrow \mathsf{H}(\mathtt{CH} \| \mathtt{SH} \| \mathtt{EE} \| \mathtt{SF}) \| \mathsf{H}(\mathrm{rctxt})$
$\mathrm{FS_C} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HTS}, \mathrm{label}_5)$
{ClientFinished}:
$\mathtt{CF} \leftarrow \mathsf{HMAC}(\mathrm{FS_C}, H_4)$

check $\mathtt{CF} = \mathsf{HMAC}(\mathrm{FS_C}, H_4)$
$H_5 \leftarrow \mathsf{H}(\mathtt{CH} \| \mathtt{SH} \| \mathtt{EE} \| \mathtt{SF} \| \mathtt{CF}) \| \mathsf{H}(\mathrm{rctxt})$
$\mathrm{MS} \leftarrow \mathsf{HKDF.Extract}(\mathrm{HS}, 0)$
$\mathrm{TS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{MS}, \mathrm{label}_{10} \| H_4)$

$tk_{app} \leftarrow \mathsf{HKDF.Expand}(\mathrm{TS}, \mathrm{label}_{11})$ stage 4
$\mathrm{EMS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{MS}, \mathrm{label}_{12} \| H_5)$ stage 5

record layer (application data), using AEAD with key tk_{app}

Protocol flow legend

MSG: Y	TLS 1.3 message MSG containing Y
(MSG)	message MSG AEAD-encrypted with tk_{ehs}
{MSG}	message MSG AEAD-encrypted with tk_{hs}
+ MSG	message sent as extension within previous message
$[\ldots]^\dagger$	message/computation only in PSK-(EC)DHE 0-RTT
$[\ldots]^\diamond$	message/computation only in PSK 0-RTT

Key schedule legend

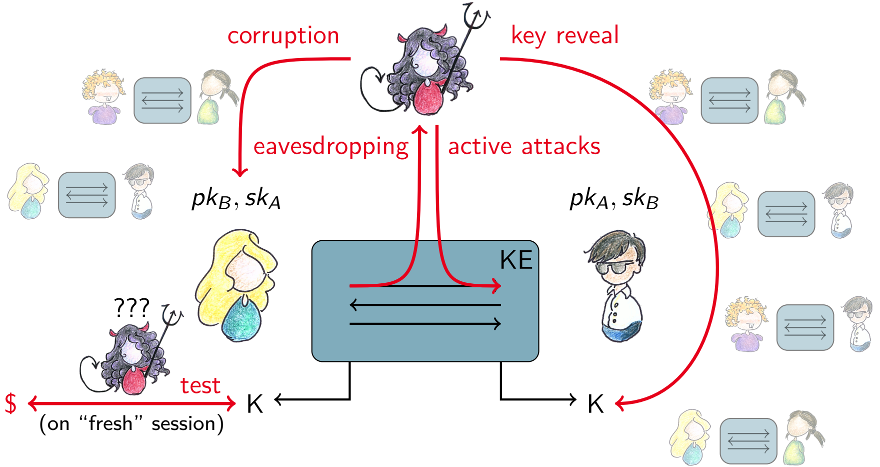
Ext / Exp	HKDF.Extract resp. HKDF.Expand function
$X \dashrightarrow$	salt input X to Ext resp. context info input X to Exp (label inputs to Exp are omitted)

Figure 7.2: The TLS 1.3 `draft-14` PSK and PSK-(EC)DHE 0-RTT handshake protocols (left) and key schedule (right).

can be done,
but let's skip that
for now. . .

Key Exchange Security

Recap: Classical Definition [BR94]

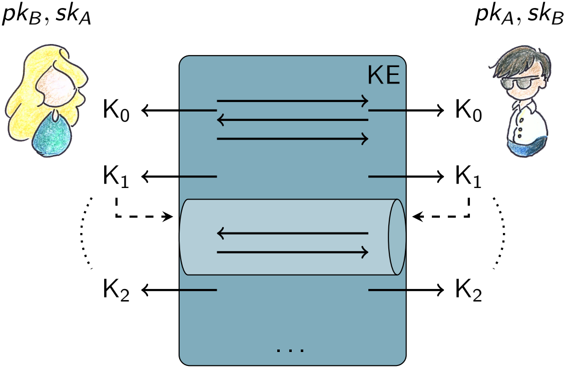


Key Exchange Security

Novel Designs

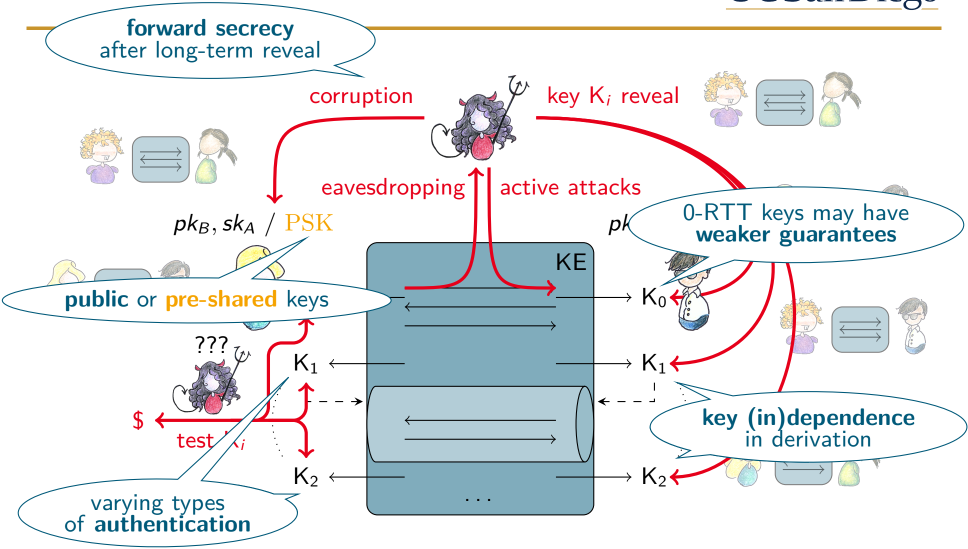
- go beyond what classical models can capture
- e.g., Google QUIC, **TLS 1.3**, Signal, . . .

- multiple keys
- potential dependencies
- mixed usage within KE
- low-latency / 0-RTT



Key Exchange Security

Multi-Stage Key Exchange



forward secrecy after long-term reveal
corruption
key K_i reveal
eavesdropping
active attacks
pk_B, sk_A / PSK
pk
0-RTT keys may have **weaker guarantees**
KE
K_0
public or **pre-shared** keys
???
K_1
K_1
$
test K_i
key (in)dependence in derivation
K_2
K_2
. . .
varying types of **authentication**

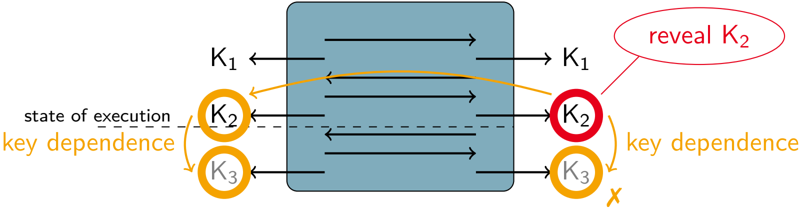
[FG14], [DFGS15], [DFGS16], [FG17], [G18]

Multi-Stage Key Exchange

Extended Properties

(In)Dependence of Session Keys

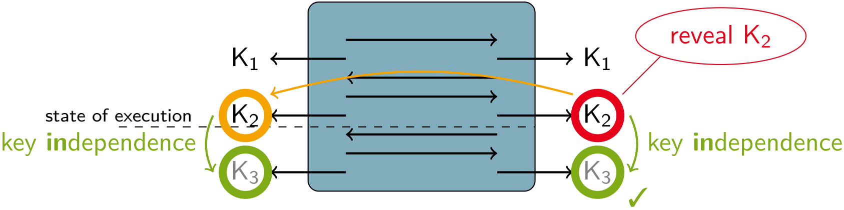
- multi-stage ⇒ derived keys might build upon each other
- **key-dependent**: reveal K_i before K_{i+1} accepted *may compromise* K_{i+1}



(In)Dependence of Session Keys

- multi-stage ⇒ derived keys might build upon each other

- **key-dependent**: reveal K_i before K_{i+1} accepted *may compromise* K_{i+1}
- **key-independent**: reveal of any K_i *never harms* any other K_{i+1}



Multi-Stage Key Exchange

Extended Properties

Forward Secrecy

- multi-stage ⇒ forward secrecy might kick in only at some stage j
- take this into account when handling corruptions

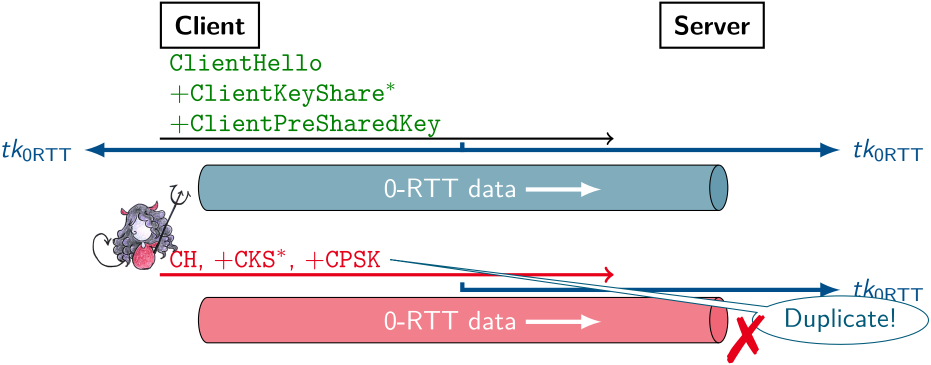
- **non-forward-secret**: all session keys compromised by corruption
- **stage-*j*-forward-secret**: accepted keys at stages $i \geq j$ remain secure

Levels of Authentication

- different stages/keys may hold different authentication properties
  - **unauthenticated** (no-one)
  - **unilateral** authentication (server-only)
  - **mutual** authentication (both)

- different types may run concurrently (TLS: adaptive client authentication)

0-RTT and Replays

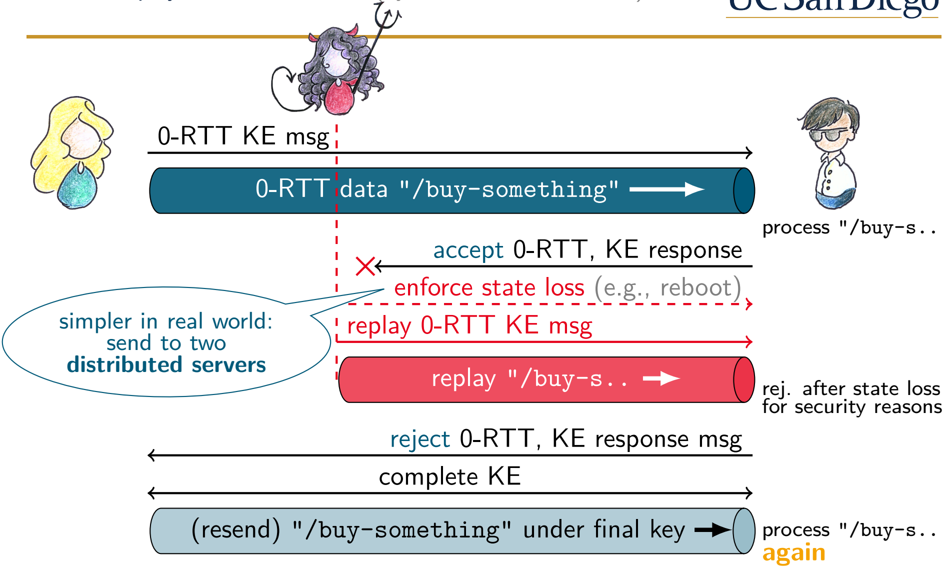


- allows client to send data without waiting for server reply
- but without server input, how does server know the request is fresh?

- 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)



0-RTT KE msg

0-RTT data "/buy-something"

process "/buy-s..

accept 0-RTT, KE response

enforce state loss (e.g., reboot)

replay 0-RTT KE msg

replay "/buy-s..

rej. after state loss
for security reasons

simpler in real world:
send to two
distributed servers

reject 0-RTT, KE response msg

complete KE

(resend) "/buy-something" under final key

process "/buy-s..
again

0-RTT and Replays

TLS 1.3's Take on Replays

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]

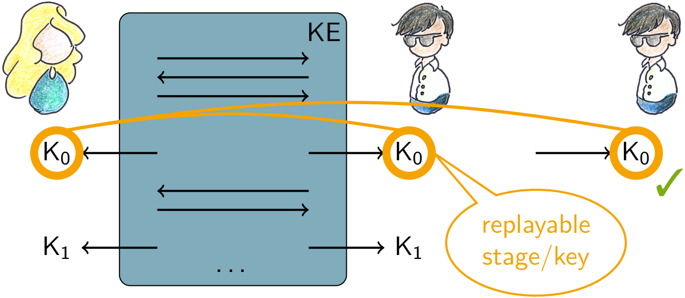
- **suggested mechanisms**
  - single-use tickets: allow each RMS to be used only once (simplest)
  - `ClientHello` recording: reject by unique identifier
  - freshness checks: reject based on `ClientHello` time
- "SHOULD" → treat 0-RTT keys generally as **replayable in analysis**
  - so, what security remains?

Multi-Stage Key Exchange

Extended Properties

Replays

- some stages' keys may be **replayable**
- may be **accepted multiple times**, this shouldn't count as an attack
- but should **still remain secret** from adversary even if replayed



The TLS 1.3 Handshake

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

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Client **Server**

CH: $r_c \leftarrow_{\$} \{0,1\}^{256}$, g^x, psk_id →

HKDF(PSK, H(CH)) tk_{0RTT}

← SH: $r_s \leftarrow_{\$} \{0,1\}^{256}$, g^y, psk_id

DHE ← g^{xy}

HS ← HKDF(PSK, DHE)

HKDF(HS, H(CH‖SH)) tk_{hs}

{EncryptedExtensions}

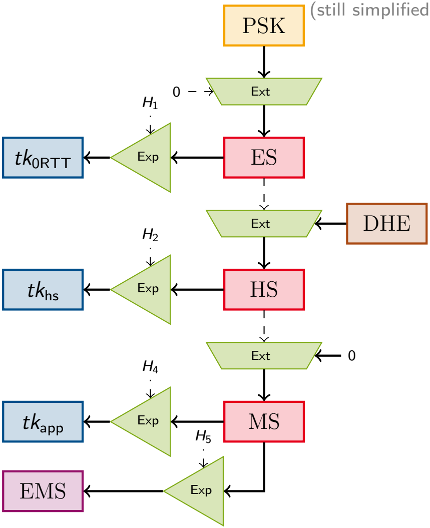
← {SF}: HMAC($\mathrm{FS_S}$, H(CH‖SH‖EE))

{CF}: HMAC($\mathrm{FS_C}$, H(CH‖ ... ‖SF)) →

HKDF(MS, H(CH‖ ... ‖SF)) tk_{app}

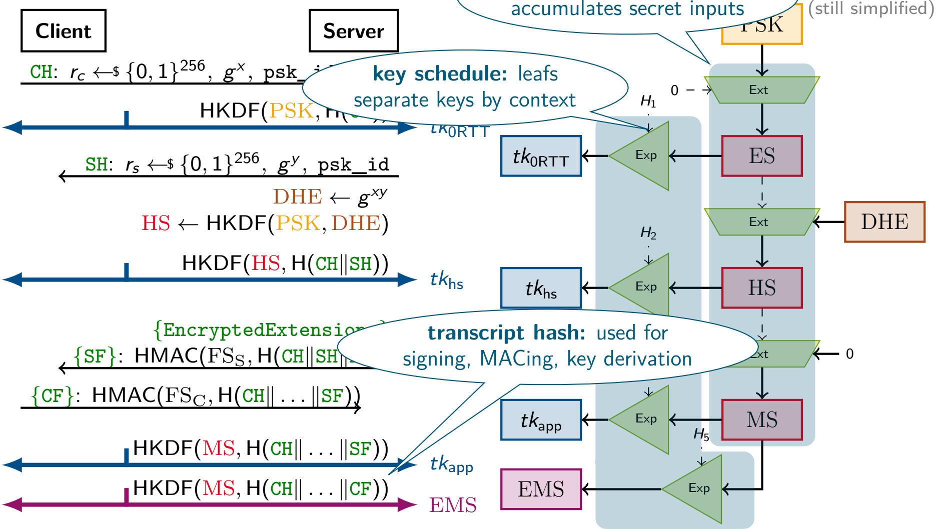
HKDF(MS, H(CH‖ ... ‖CF)) EMS

(still simplified)



The TLS 1.3 Handshake

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


Client
Server
CH: $r_c \leftarrow_{\$} \{0,1\}^{256}$, g^x, psk_i
HKDF(PSK, H(C
tk_{0RTT}
SH: $r_s \leftarrow_{\$} \{0,1\}^{256}$, g^y, psk_id
DHE $\leftarrow g^{xy}$
HS $\leftarrow$ HKDF(PSK, DHE)
HKDF(HS, H(CH$\|$SH))
tk_{hs}
{EncryptedExtensio
{SF}: HMAC($\mathrm{FS_S}$, H(CH$\|$SH$\|$
{CF}: HMAC($\mathrm{FS_C}$, H(CH$\|\ldots\|$SF))
HKDF(MS, H(CH$\|\ldots\|$SF))
tk_{app}
HKDF(MS, H(CH$\|\ldots\|$CF))
EMS
(still simplified)
PSK
0
Ext
H_1
ES
Exp
tk_{0RTT}
Ext
DHE
H_2
HS
Exp
tk_{hs}
Ext
0
Exp
tk_{app}
MS
H_5
Exp
EMS

key schedule: core accumulates secret inputs

key schedule: leafs separate keys by context

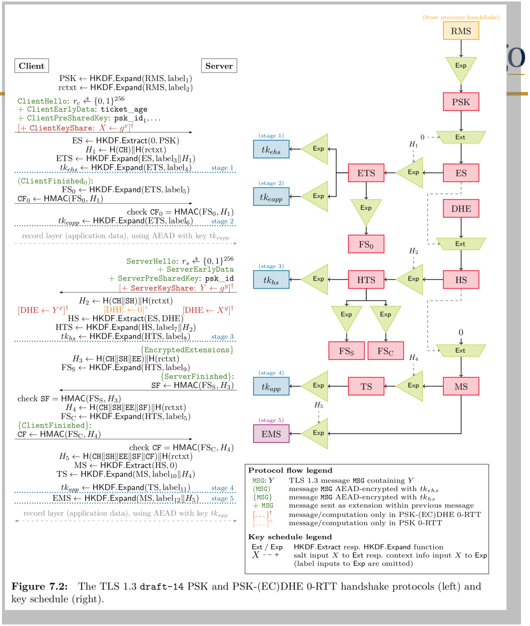
transcript hash: used for signing, MACing, key derivation

The TLS 1.3 Handshake

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

The full details. . .

- more intermediate keys (e.g., deriving MAC keys)
- a fifth key tk_{0hs} for 0-RTT handshake encryption (got dropped again later)
- and more. . .



Client **Server**

$\mathrm{PSK} \leftarrow \mathsf{HKDF.Expand}(\mathrm{RMS}, \mathrm{label}_1)$
$\mathrm{rctxt} \leftarrow \mathsf{HKDF.Expand}(\mathrm{RMS}, \mathrm{label}_2)$

`ClientHello`: $r_c \xleftarrow{\$} \{0,1\}^{256}$
+ `ClientEarlyData`: `ticket_age`
+ `ClientPreSharedKey`: `psk_id`$_1, \ldots$
[+ `ClientKeyShare`: $X \leftarrow g^x]^\dagger$

$\mathrm{ES} \leftarrow \mathsf{HKDF.Extract}(0, \mathrm{PSK})$
$H_1 \leftarrow \mathsf{H}(\mathtt{CH}) \| \mathsf{H}(\mathrm{rctxt})$
$\mathrm{ETS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{ES}, \mathrm{label}_3 \| H_1)$
$tk_{ehs} \leftarrow \mathsf{HKDF.Expand}(\mathrm{ETS}, \mathrm{label}_4)$ stage 1

(`ClientFinished`$_0$):
$\mathrm{FS}_0 \leftarrow \mathsf{HKDF.Expand}(\mathrm{ETS}, \mathrm{label}_5)$
$\mathtt{CF}_0 \leftarrow \mathsf{HMAC}(\mathrm{FS}_0, H_1)$

check $\mathtt{CF}_0 = \mathsf{HMAC}(\mathrm{FS}_0, H_1)$
$tk_{eapp} \leftarrow \mathsf{HKDF.Expand}(\mathrm{ETS}, \mathrm{label}_6)$ stage 2

record layer (application data), using AEAD with key tk_{eapp}

`ServerHello`: $r_s \xleftarrow{\$} \{0,1\}^{256}$
+ `ServerEarlyData`
+ `ServerPreSharedKey`: `psk_id`
[+ `ServerKeyShare`: $Y \leftarrow g^y]^\dagger$

$H_2 \leftarrow \mathsf{H}(\mathtt{CH}\|\mathtt{SH}) \| \mathsf{H}(\mathrm{rctxt})$
$[\mathrm{DHE} \leftarrow Y^x]^\dagger$ $[\mathrm{DHE} \leftarrow 0]^\diamond$ $[\mathrm{DHE} \leftarrow X^y]^\dagger$
$\mathrm{HS} \leftarrow \mathsf{HKDF.Extract}(\mathrm{ES}, \mathrm{DHE})$
$\mathrm{HTS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HS}, \mathrm{label}_7 \| H_2)$
$tk_{hs} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HTS}, \mathrm{label}_8)$ stage 3

{`EncryptedExtensions`}
$H_3 \leftarrow \mathsf{H}(\mathtt{CH}\|\mathtt{SH}\|\mathtt{EE}) \| \mathsf{H}(\mathrm{rctxt})$
$\mathrm{FS_S} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HTS}, \mathrm{label}_9)$
{`ServerFinished`}:
$\mathtt{SF} \leftarrow \mathsf{HMAC}(\mathrm{FS_S}, H_3)$

check $\mathtt{SF} = \mathsf{HMAC}(\mathrm{FS_S}, H_3)$
$H_4 \leftarrow \mathsf{H}(\mathtt{CH}\|\mathtt{SH}\|\mathtt{EE}\|\mathtt{SF}) \| \mathsf{H}(\mathrm{rctxt})$
$\mathrm{FS_C} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HTS}, \mathrm{label}_5)$
{`ClientFinished`}:
$\mathtt{CF} \leftarrow \mathsf{HMAC}(\mathrm{FS_C}, H_4)$

check $\mathtt{CF} = \mathsf{HMAC}(\mathrm{FS_C}, H_4)$
$H_5 \leftarrow \mathsf{H}(\mathtt{CH}\|\mathtt{SH}\|\mathtt{EE}\|\mathtt{SF}\|\mathtt{CF}) \| \mathsf{H}(\mathrm{rctxt})$
$\mathrm{MS} \leftarrow \mathsf{HKDF.Extract}(\mathrm{HS}, 0)$
$\mathrm{TS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{MS}, \mathrm{label}_{10} \| H_4)$

$tk_{app} \leftarrow \mathsf{HKDF.Expand}(\mathrm{TS}, \mathrm{label}_{11})$ stage 4
$\mathrm{EMS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{MS}, \mathrm{label}_{12} \| H_5)$ stage 5

record layer (application data), using AEAD with key tk_{app}

Protocol flow legend

`MSG`: Y	TLS 1.3 message `MSG` containing Y
(`MSG`)	message `MSG` AEAD-encrypted with tk_{ehs}
{`MSG`}	message `MSG` AEAD-encrypted with tk_{hs}
\+ `MSG`	message sent as extension within previous message
$[\ldots]^\dagger$	message/computation only in PSK-(EC)DHE 0-RTT
$[\ldots]^\diamond$	message/computation only in PSK 0-RTT

Key schedule legend

Ext / Exp	HKDF.Extract resp. HKDF.Expand function
X - - →	salt input X to Ext resp. context info input X to Exp (label inputs to Exp are omitted)

Figure 7.2: The TLS 1.3 `draft-14` PSK and PSK-(EC)DHE 0-RTT handshake protocols (left) and key schedule (right).

TLS 1.3 Handshake Security

draft-14 PSK-(EC)DHE 0-RTT as Multi-Stage KE [FG17]

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

- random-looking secret keys (tk_{0hs}, tk_{0RTT}, tk_{hs}, tk_{app}, EMS)
- forward secrecy for non–0-RTT keys
- mutual authentication wrt. PSK
- key independence
- replayable 0-RTT keys

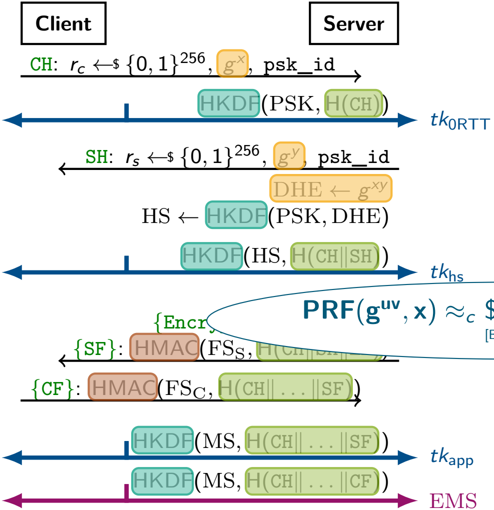
assuming . . .

Theorem 7.4. *The TLS 1.3* `draft-14` *PSK-(EC)DHE 0-RTT handshake is* **Multi-Stage-secure** *in a* ***key-independent*** *and* ***stage-3-forward-secret*** *manner with properties* (M, **AUTH**, USE, **REPLAY**).

$$
\begin{aligned}
\mathsf{Adv}^{\mathsf{Multi\text{-}Stage},\mathcal{D}}_{\mathtt{draft\text{-}14\text{-}PSK\text{-}(EC)DHE\text{-}0RTT},\mathcal{A}} \leq 5n_s \cdot \Bigg(& \mathsf{Adv}^{\mathsf{COLL}}_{\mathsf{H},\mathcal{B}_1} \\
+ n_p \cdot \Big(& \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathtt{HKDF.Expand},\mathcal{B}_2} + \mathsf{Adv}^{\mathsf{HMAC(0,\$)\text{-}\$}}_{\mathsf{HMAC},\mathcal{B}_3} \\
& + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HMAC},\mathcal{B}_4} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathtt{HKDF.Expand},\mathcal{B}_5} \Big) \\
+ n_s \cdot n_p \cdot \Big(& \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathtt{HKDF.Expand},\mathcal{B}_6} + \mathsf{Adv}^{\mathsf{HMAC(0,\$)\text{-}\$}}_{\mathsf{HMAC},\mathcal{B}_7} \\
& + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HMAC},\mathcal{B}_8} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HMAC},\mathcal{B}_9} \\
& + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathtt{HKDF.Expand},\mathcal{B}_{10}} + \mathsf{Adv}^{\mathsf{EUF\text{-}CMA}}_{\mathsf{HMAC},\mathcal{B}_{11}} \Big) \\
+ n_s \cdot n_p \cdot \Big(& \mathsf{Adv}^{\mathsf{snPRF\text{-}ODH}}_{\mathtt{HKDF.Extract},\mathbb{G},\mathcal{B}_{12}} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HMAC},\mathcal{B}_{13}} \\
& + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathtt{HKDF.Expand},\mathcal{B}_{14}} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathtt{HKDF.Expand},\mathcal{B}_{15}} \\
& + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathtt{HKDF.Expand},\mathcal{B}_{16}} \Big) \Bigg).
\end{aligned}
$$

TLS 1.3 Handshake Security

draft-14 PSK-(EC)DHE 0-RTT as Multi-Stage KE [FG17]


Client
Server
CH: $r_c \leftarrow_\$ \{0,1\}^{256}$, g^x, psk_id
HKDF(PSK, H(CH))
tk_{0RTT}
SH: $r_s \leftarrow_\$ \{0,1\}^{256}$, g^y, psk_id
DHE ← g^{xy}
HS ← HKDF(PSK, DHE)
HKDF(HS, H(CH‖SH))
tk_{hs}
{Encr
{SF}: HMAC(FS$_S$, H(CH‖SH‖
{CF}: HMAC(FS$_C$, H(CH‖ . . . ‖SF))
HKDF(MS, H(CH‖ . . . ‖SF))
tk_{app}
HKDF(MS, H(CH‖ . . . ‖CF))
EMS

Theorem 7.4. *The TLS 1.3* draft-14 *PSK-(EC)DHE 0-RTT handshake is* **Multi-Stage-secure** *in a* ***key-independent*** *and* ***stage-3-forward-secret*** *manner with properties* (M, **AUTH**, USE, **REPLAY**).

$$\mathsf{Adv}^{\mathsf{Multi\text{-}Stage},\mathcal{D}}_{\mathtt{draft\text{-}14\text{-}PSK\text{-}(EC)DHE\text{-}0RTT},\mathcal{A}} \leq 5n_s \cdot \Big(\mathsf{Adv}^{\mathsf{COLL}}_{\mathsf{H},\mathcal{B}_1}$$

$$+ n_p \cdot \Big(\mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_2} + \mathsf{Adv}^{\mathsf{HMAC(0,\$)\text{-}\$}}_{\mathsf{HMAC},\mathcal{B}_3} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HMAC},\mathcal{B}_4} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_5} \Big)$$

$$+ \mathsf{Adv}^{\mathsf{HMAC(0,\$)\text{-}\$}}_{\mathsf{HMAC},\mathcal{B}_7} \quad \mathsf{F\text{-}sec}_{\mathsf{HMAC},\mathcal{B}_9}$$

$$+ \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{10}} + \mathsf{Adv}^{\mathsf{EUF\text{-}CMA}}_{\mathsf{HMAC},\mathcal{B}_{11}} \Big)$$

$$+ n_s \cdot n_p \cdot \Big(\mathsf{Adv}^{\mathsf{snPRF\text{-}ODH}}_{\mathsf{HKDF.Extract},\mathbb{G},\mathcal{B}_{12}} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HMAC},\mathcal{B}_{13}} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{14}} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{15}} + \mathsf{Adv}^{\mathsf{PRF\text{-}sec}}_{\mathsf{HKDF.Expand},\mathcal{B}_{16}} \Big) \Big).$$

$\mathbf{PRF}(\mathbf{g}^{\mathbf{uv}}, \mathbf{x}) \approx_c \$$, given oracle $\mathbf{PRF}(\cdot^{\mathbf{u}}, \cdot)$

[BFGJ17]

TLS 1.3 Handshake Security

In perspective

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- **cryptographic design** of TLS 1.3 handshake is **sound**
- strong security results for main keys (both full and PSK handshakes)
- replays and lacking forward secrecy for 0-RTT are a (recognized) downside

- recall: focus on handshake modes in isolation, for draft-14 (and earlier)

- further analyses:
  - other computational analyses of sub-parts (e.g., post-handshake client auth)
  - tool-based/symbolic analyses up to full protocol and on multiple drafts
  - work-in-progress verified implementation

- jointly, these analyses give rise to confidence in TLS 1.3 handshake design
- still, doesn't mean there won't be any attacks (bets are on 0-RTT. . .)

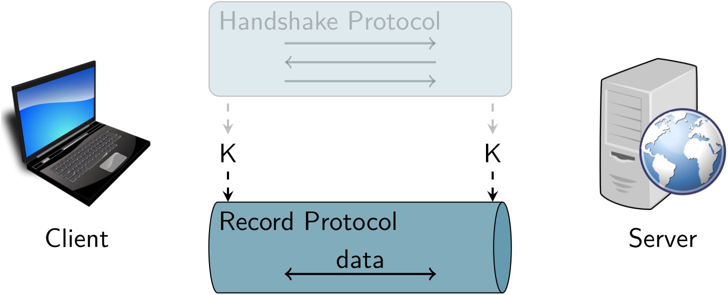
TLS 1.3
Record Protocol & Some Analysis

The TLS Protocol

So. . . what about the Record Protocol?

Handshake Protocol:

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



Handshake Protocol

K

K

Record Protocol

data

Client

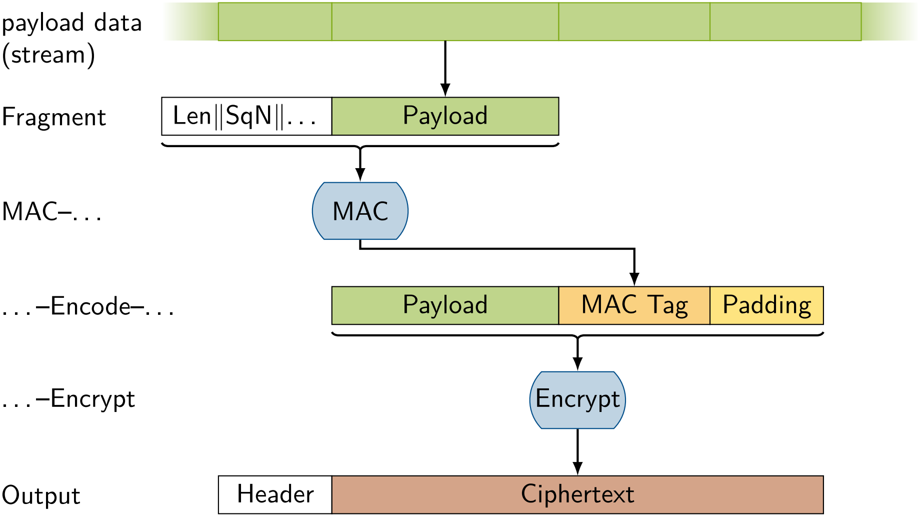
Server

Record Protocol:

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

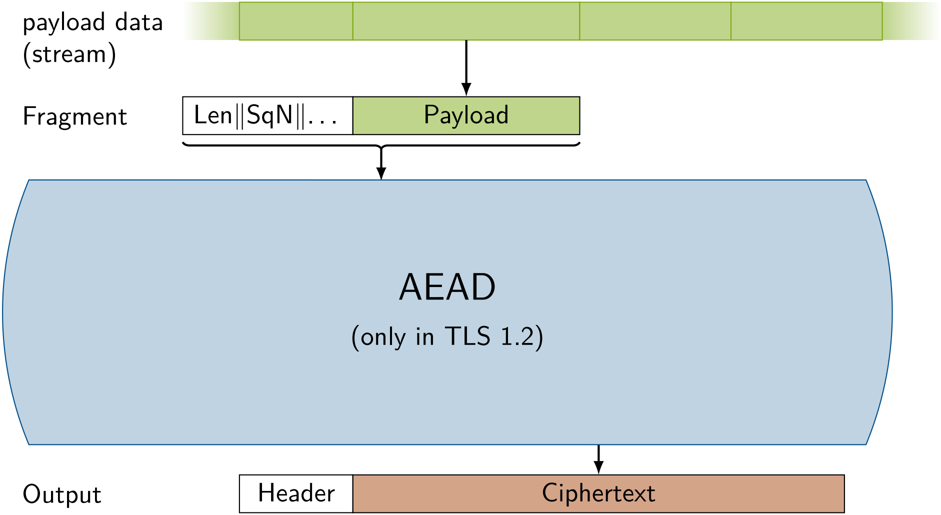
The TLS Protocol

Recap: Record Protocol Structure up to TLS 1.2

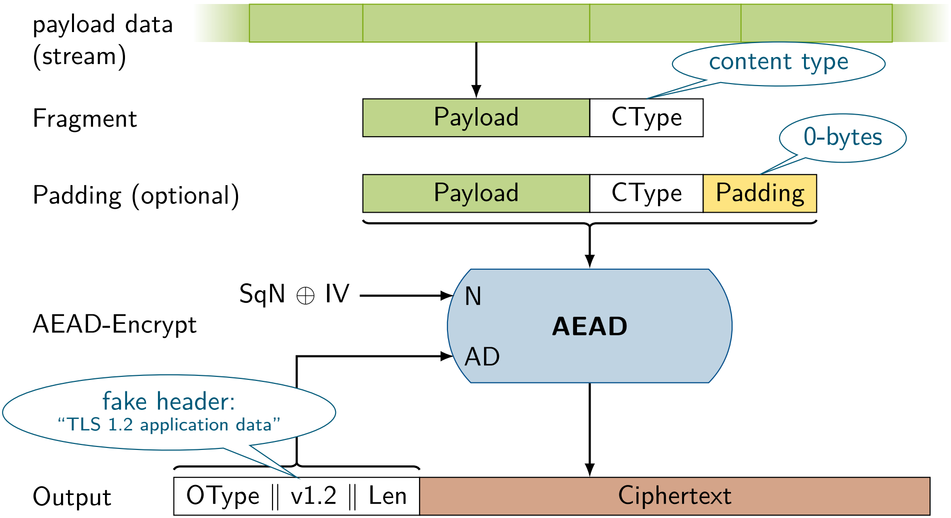


The TLS Protocol

Recap: Record Protocol Structure up to TLS 1.2

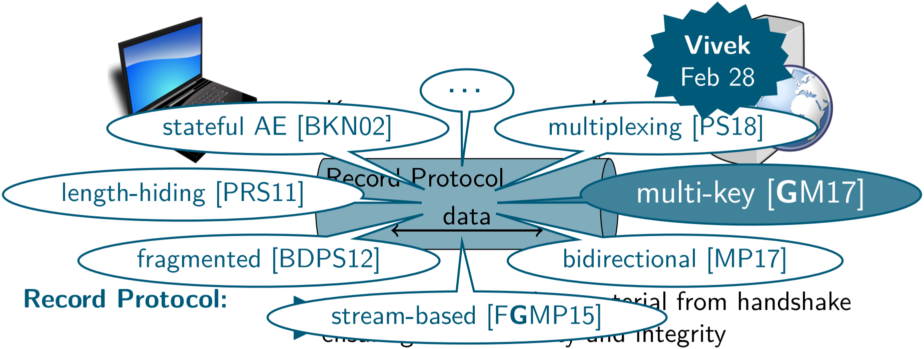


The TLS 1.3 Record Protocol



TLS 1.3 Record Protocol Security

- AEAD-based design looks sound...
- but the crypto community hasn't really conclusively ventilated the question: **What is a secure channel protocol?**

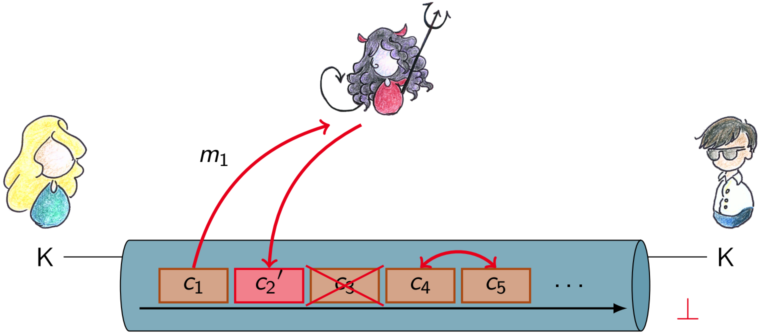


Record Protocol:

- terial from handshake
- ensu integrity

Channel Security

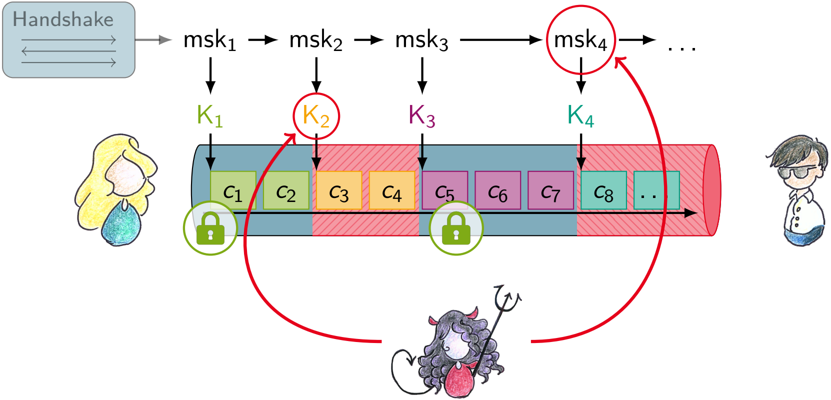
Recap: Bellare, Kohno, Namprempre 2002 [BKN02]



IND-sfCPA	(passive confidentiality)	INT-sfPTXT	(plaintext integrity)
IND-sfCCA	(active confidentiality)	INT-sfCTXT	(ciphertext integrity)

Multi-key Channels

- keys updated during channel operation (e.g., TLS 1.3, Signal, . . .)



(phase-)key insulation

forward security

[GM17]

Multi-key Channels

Security Model

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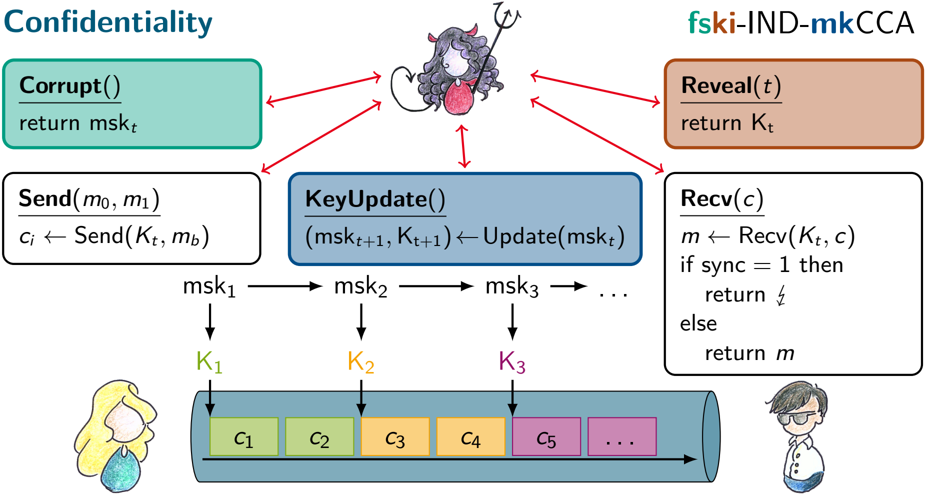
Confidentiality

fski-IND-mkCCA



Corrupt()

```
return $\mathsf{msk}_t$
```

Reveal(t)

```
return $\mathsf{K}_\mathsf{t}$
```

Send(m_0, m_1)

```
$c_i \leftarrow \mathrm{Send}(K_t, m_b)$
```

KeyUpdate()

```
$(\mathsf{msk}_{t+1}, \mathsf{K}_{\mathsf{t+1}}) \leftarrow \mathrm{Update}(\mathsf{msk}_t)$
```

Recv(c)

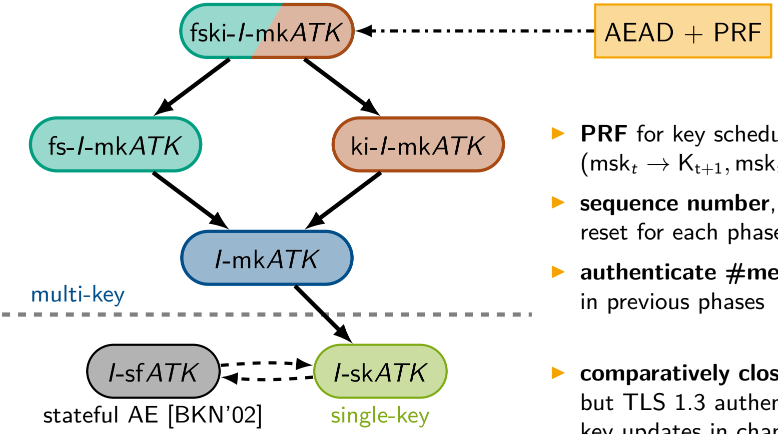
```
$m \leftarrow \mathrm{Recv}(K_t, c)$
if sync $= 1$ then
    return ↯
else
    return $m$
```

$\mathsf{msk}_1 \rightarrow \mathsf{msk}_2 \rightarrow \mathsf{msk}_3 \rightarrow \dots$
K_1
K_2
K_3
c_1
c_2
c_3
c_4
c_5
...

(simplified)

Multi-key Channels

Security Hierarchy and Instantiation



- **PRF** for key schedule ($\mathsf{msk}_t \to \mathsf{K}_{t+1}, \mathsf{msk}_{t+1}$)
- **sequence number**, reset for each phase
- **authenticate #messages** in previous phases
- **comparatively close to TLS 1.3**, but TLS 1.3 authenticates key updates in channel

$I = \mathrm{IND}, \quad ATK \in \{\mathrm{CPA}, \mathrm{CCA}\}$
$I = \mathrm{INT}, \quad ATK \in \{\mathrm{PTXT}, \mathrm{CTXT}\}$

Thank You!

TLS 1.3

Feb 21	**TLS 1.3** [TLS13] **& some security models** [FG17,GM17]	Felix
Feb 28	**Multiplexing channels** [PS18]	Vivek
Mar 7	**Symbolic Tamarin analysis** [CHH+17]	Baiyu
Mar 14	**Downgrade resilience** [BBF+16]	Ruth

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