

Establishing Secure Connections

A Cryptographer's Perspective and the Case of TLS 1.3



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based on joint work with

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Kenneth G. Paterson, Benedikt Schmidt, Douglas Stebila, Bogdan Warinschi



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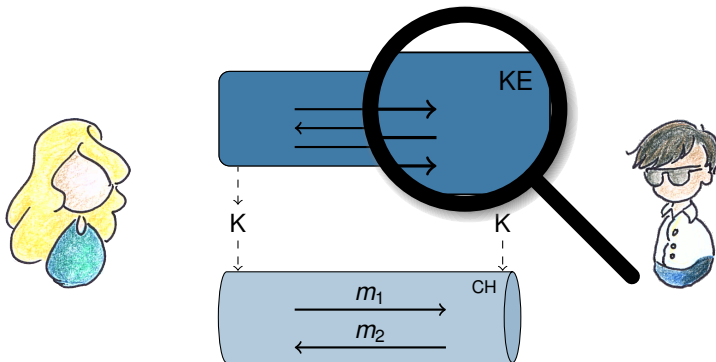
Cryptoplicity
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Technische Universität Darmstadt
www.cryptoplicity.de



Secure Connections – Everywhere

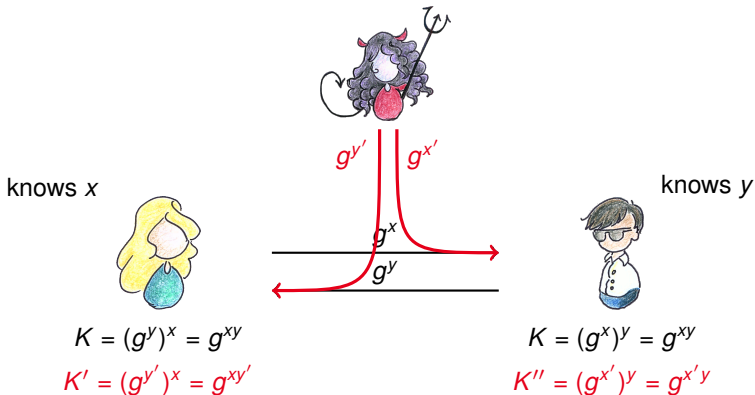


Secure Connections – Cryptographically



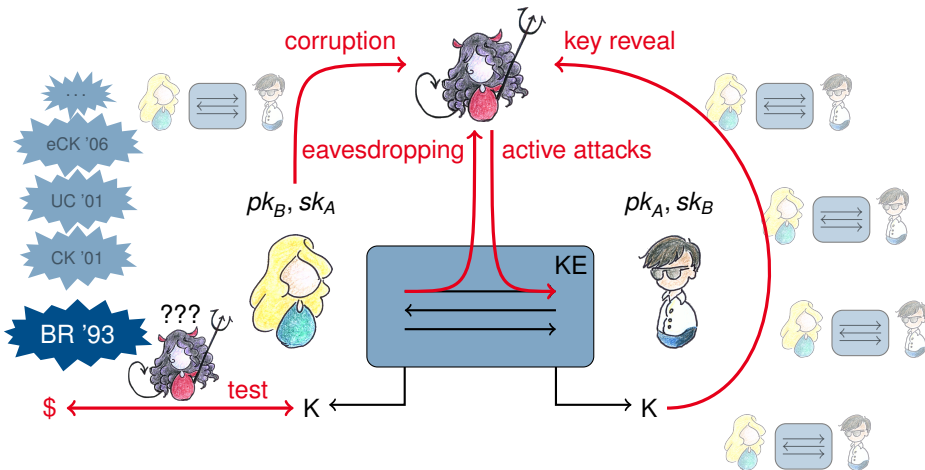
drawings by *Giorgia Azzurra Marson*

Key Exchange à la Diffie–Hellman (1976)

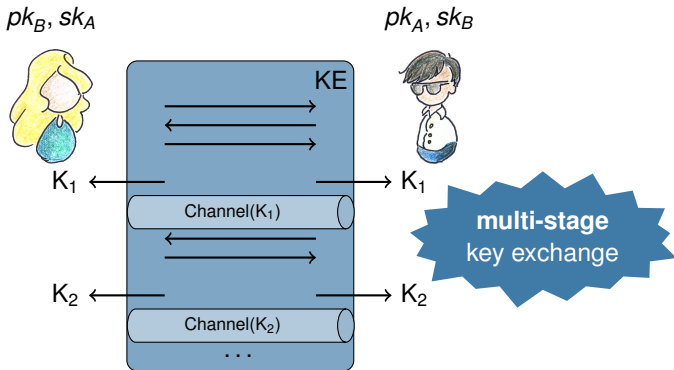


- ▶ **key secrecy:** given only g^x , g^y , key $K = g^{xy}$ remains secret
- ▶ **no authentication:** susceptible to man-in-the-middle attack

Key Exchange Security à la Bellare–Rogaway (1993)



But what if... ?



- ▶ key exchange establishes more than one key?
- ▶ ... even uses the intermediary keys within the key exchange or channel?
- ▶ not covered by classical key exchange models

QUIC (“Quick UDP Internet Connections”, Google 2013)

- ▶ “low-latency transport protocol with security equivalent to TLS”
- ▶ Diffie–Hellman-based key exchange
- ▶ aims at 0-RTT, i.e., immediately encrypts under intermediate key K_1
- ▶ later rekeys to forward-secret K_2
- ▶ intermediate key K_1 used to establish K_2 (i.e., in KE part)

 Fischlin, Günther
Multi-Stage Key Exchange and the Case of Google’s QUIC Protocol
ACM CCS 2014

TLS 1.3

- ▶ next TLS version, **currently being specified**
 - ▶ now in **IETF Working Group Last Call (WGLC)**
 - ▶ latest: draft-18, Oct 2016

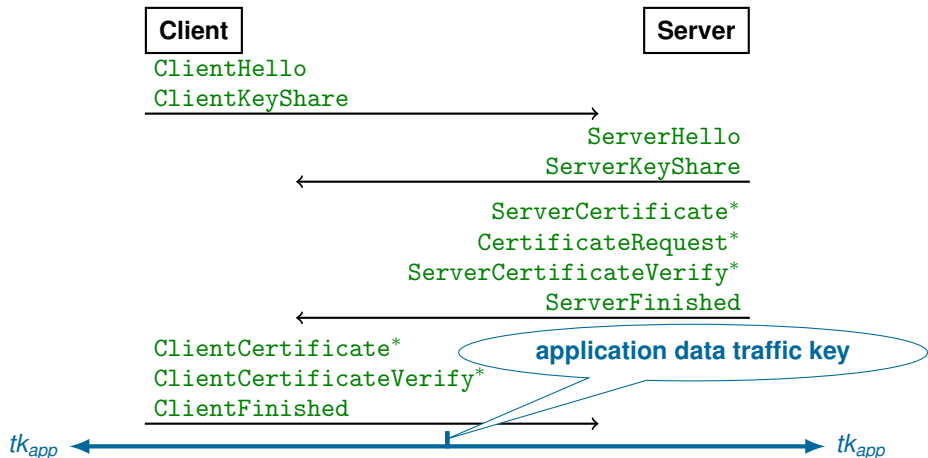
- ▶ several **substantial cryptographic changes** (compared to TLS 1.2), incl.
 1. **encrypting some handshake messages** with intermediate session key
 2. using only **AEAD schemes** for the record layer encryption
 3. providing reduced-latency **0-RTT handshake**
 4. ...

TLS 1.3 Full Handshake (simplified)

draft-ietf-tls-tls13-10 (Oct 2015)



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... actually, there is more ...

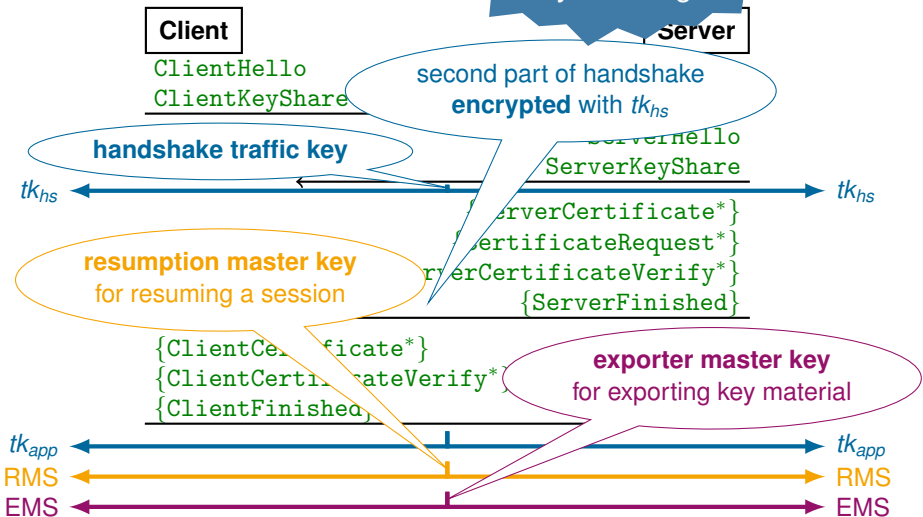
TLS 1.3 Full Handshake (still simplified)

draft-ietf-tls-tls13-10 (Oct 2015)



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multi-stage
key exchange



Multi-Stage Key Exchange Analyses of TLS 1.3 Handshake Protocol Candidates

- ▶ full (DH) and preshared-key (resumption) handshakes (draft-10 & earlier)



Dowling, Fischlin, Günther, Stebila

A Cryptographic Analysis of the TLS 1.3 ... Handshake Protocol ...

ACM CCS 2015, TRON workshop @ NDSS 2016

- ▶ 0-RTT handshake, DH-based (draft-12) & PSK-based (draft-14)



Fischlin, Günther

Replay Attacks on Zero Round-Trip Time: The Case of the TLS 1.3 Handshake Candidates

IEEE EuroS&P 2017

- ▶ analyses of work-in-progress drafts (i.e., not definitive)
 - ▶ contribution to and involved in working group discussion
 - ▶ and part of a **great community effort of many people**



STANDARD UNDER CONSTRUCTION

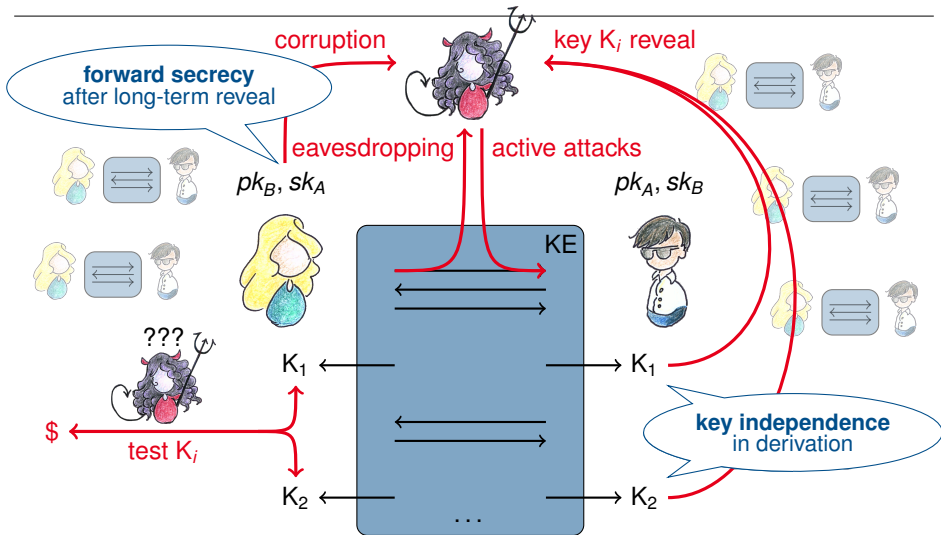
... and Many More Analyses

(alphabetical order)

- ▶ Arai, Matsuo [CELLOS] (TLS mailing list 2016): [ProVerif Analysis](#)
- ▶ Badertscher, Matt, Maurer, Rogaway, Tackmann (ProvSec 2015): [Record Layer](#)
- ▶ Beurdouche, Bhargavan, Blanchet, Delignat-Lavaud, Fournet, Ishtiaq, Kobeissi, Kohlweiss, Pan, Protzenko, Rastogi, Swamy, Zanella-Bguelin, Zinzindohoué [INRIA/Microsoft] (TRON 2016, ePrint 2016, ...): [Verified Implementations of Handshake and Record Layer](#)
- ▶ Bhargavan, Brzuska, Fournet, Green, Kohlweiss, Zanella-Beguellin (S&P 2016): [Downgrade Resilience](#)
- ▶ Cremers, Horvat, Scott, van der Merwe (S&P 2016): [Tamarin Analysis](#)
- ▶ Jager, Schwenk, Somorovsky (CCS 2015): [Bleichenbacher's Attack](#)
- ▶ Kohlweiss, Maurer, Onete, Tackmann, Venturi (ePrint 2015): [Constructive Crypto](#)
- ▶ Krawczyk, Wee (EuroS&P 2016): [OPTLS](#)
- ▶ Krawczyk (CCS 2016): [Unilateral-to-Mutual Authentication Compiler](#)
- ▶ Li, Xu, Zhang, Feng, Hu (S&P 2016): [Multi-Handshake Security](#)
- ▶ ...

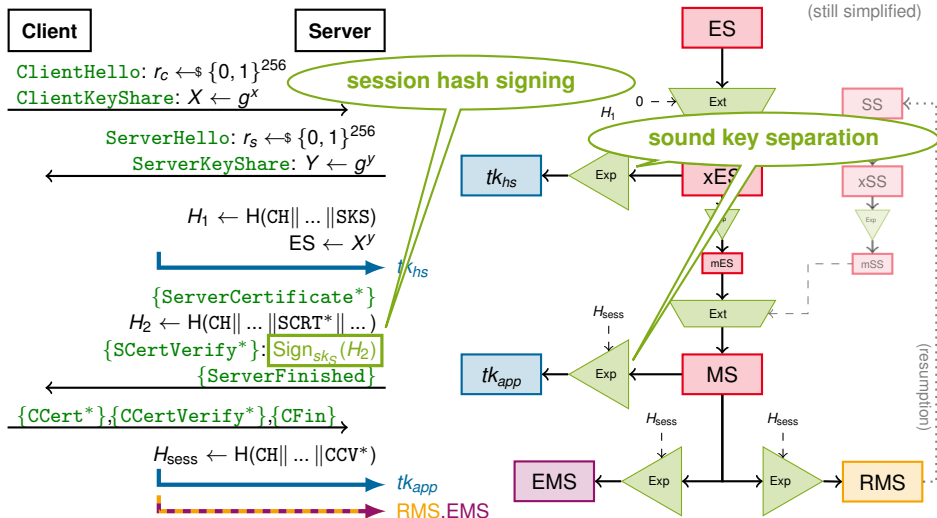
Multi-Stage Key Exchange Security

game-based model, “provable security” paradigm



TLS 1.3 Handshake Security

draft-10 Full Handshake



TLS 1.3 Handshake Security

draft-10 Full Handshake

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

- ▶ **collision-resistant** hashing
- ▶ **unforgeable** signatures
- ▶ **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


TLS 1.3 Handshake Security

Further Modes & Beyond



- ▶ **PSK/PSK-DHE handshake** (draft-10)
 - ▶ similar results as for full handshake
 - ▶ DHE variant enables **forward secrecy**

 - ▶ **0-RTT handshake** (draft-12/14)
 - ▶ 0-RTT messages/key can be **replayed**
 - ▶ **weaker forward secrecy** guarantees

 - ▶ **Key confirmation properties** (draft-10)
 - ▶ assurance that communication partner actually **holds the shared key**
-  Fischlin, Günther, Schmidt, Warinschi
Key Confirmation in Key Exchange: A Formal Treatment and Implications for TLS 1.3
IEEE S&P 2016

More Key Exchange Challenges



▶ **TLS 1.3: Post-handshake messages & Early (0.5-RTT) server data**

- ▶ post-handshake late client authentication, key updates, and more
- ▶ early server data before handshake is over
- ▶ changing authentication of session key in use
- ▶ beyond what classical key exchange models capture

[Krawczyk'16]: can work as
Unilateral-to-Mutual Compiler

▶ **Signal: Ratcheting in Secure Messaging**

- ▶ frequent key updates / new session key with every message
- ▶ advanced security properties, future/post-compromise security

[Cohn-Gordon CDGS'17]
security proof in MSKE model

▶ **Forward-secret 0-RTT key exchange**

- ▶ in current designs, forward secrecy is sacrificed in 0-RTT modes
- ▶ new idea: leverage puncturable forward-secret encryption [Green, Miers'15]
- ▶ enables fully forward-secret 0-RTT (generically from any HIBKEM)

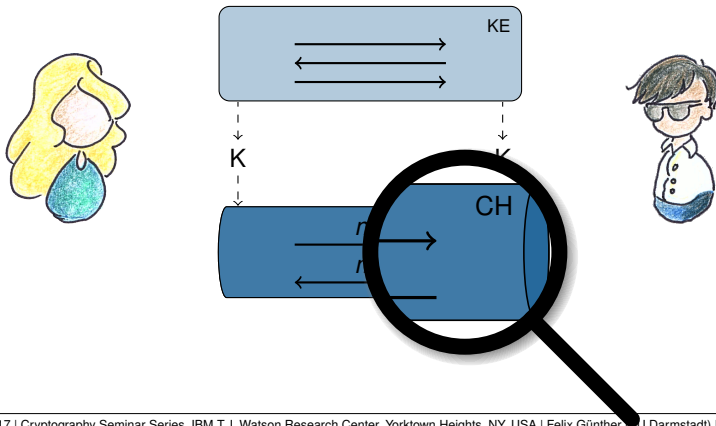


Günther, Hale, Jager, Lauer

0-RTT Key Exchange with Full Forward Secrecy

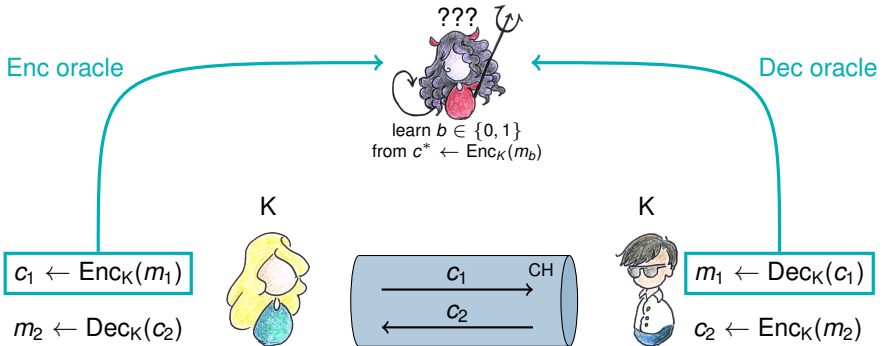
Eurocrypt 2017

Secure Connections – Cryptographically



On the Origin of Channel Models

Confidentiality

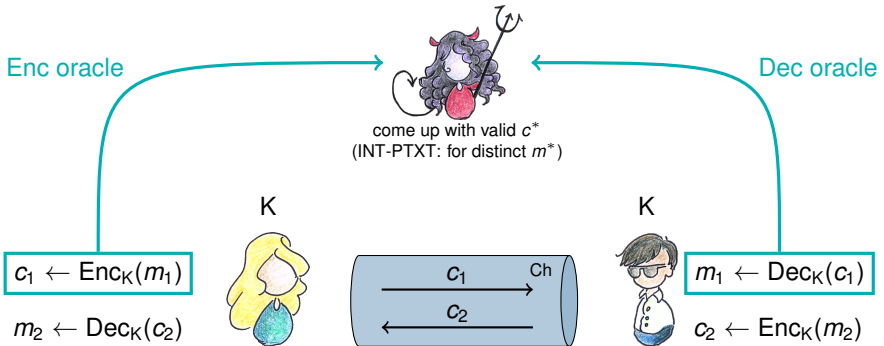


IND-CPA
[Goldwasser, Micali'84]

IND-CCA
[Naor, Yung'90], [Rackoff, Simon'91]

On the Origin of Channel Models

Integrity



Authenticated Encryption

IND-CPA + INT-CTXT
(\Rightarrow IND-CCA)

INT-PTXT

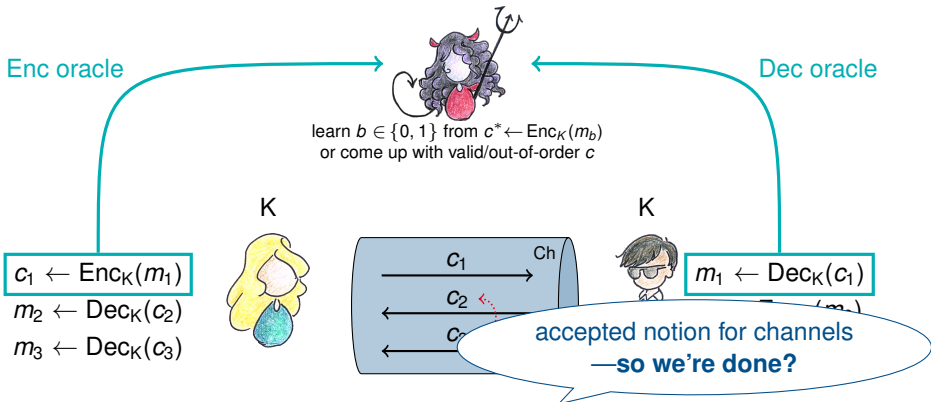
[Bellare, Namprepre'00]

INT-CTXT

[Bellare, Rogaway'00]

On the Origin of Channel Models

Stateful Authenticated Encryption



Stateful Authenticated Encryption

used to analyze SSH

IND-sfCCA

[Bellare, Kohno, Namprempre'02]

INT-sfCTXT

[Albrecht, Paterson, Watson'09]: **plaintext recovery attack against SSH**
(SSH Binary Packet Protocol with CBC-mode Encode-then-Encrypt&MAC)

- ▶ adversary feeds ciphertext in *block-wise* (via TCP fragmentation)
- ▶ observable MAC failure can be used to leak plaintext → **confidentiality break**

Wait. . .

- ▶ SSH was proven IND-sfCCA and INT-sfCTXT secure! [BKN'02]
- ▶ . . . but these only allow *atomic ciphertexts in Dec oracle*



On the Origin of Channel Models

Symmetric Encryption Supporting Fragmentation



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Symmetric Encryption Supporting Fragmentation

[Boldyreva, Degabriele, Paterson, Stam'12]

- ▶ general security model for **ciphertext fragmentation**
- ▶ standard Enc algorithm (and left-or-right oracle)
- ▶ Dec algorithm obtains **ciphertext fragments**, reassembles **original messages**

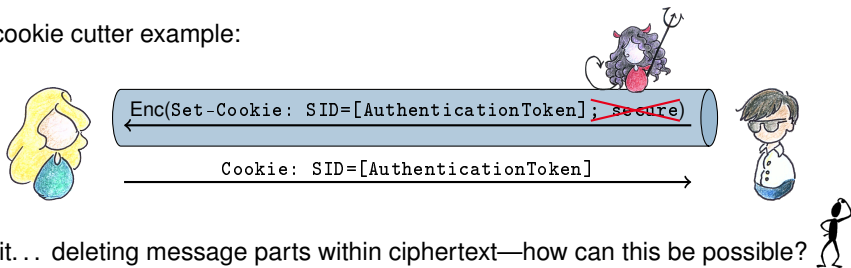
Are we there yet?

Attack on TLS

Cutting Cookies

[Bhargavan, Delignat-Lavaud, Fournet, Pironti, Strub'14]: **cookie cutter attack**

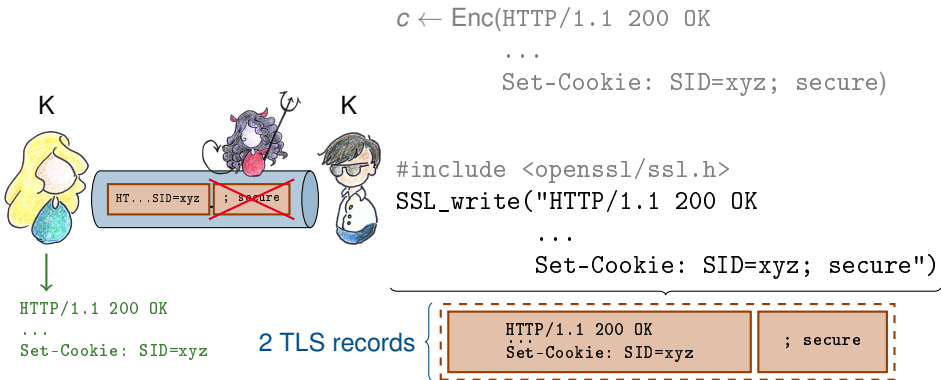
- ▶ attacker **truncates TLS connection** by closing underlying TCP connection
- ▶ forces part of the HTTP header (e.g., cookie) to be cut off
- ▶ **partial message/header arrives** and might be misinterpreted
- ▶ cookie cutter example:



Wait... deleting message parts within ciphertext—how can this be possible?

Cookie Cutter Attack

A Closer Look



- ▶ fragmentation in TLS is **implementation-specific**
- ▶ adversary can potentially enforce a split at any point
→ receiver sees **arbitrarily fragmented messages / no message boundaries**

An Interface Misunderstanding: Data Is a Stream!

... and TLS is not alone



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- ▶ That behavior is actually okay—and specified:

6.2.1. Fragmentation

*The record layer fragments information blocks into TLSPlaintext records [...]. Client **message boundaries are not preserved** in the record layer (i.e., multiple client messages of the same ContentType MAY be coalesced into a single TLSPlaintext record, or a single message MAY be fragmented across several records).*

RFC 5246 TLS v1.2

- ▶ TLS never promised to treat messages atomically!
- ▶ indeed, many important channel protocols treat **data as a stream**
 - ▶ TLS
 - ▶ SSH tunnel-mode
 - ▶ QUIC

- ▶ so, there's a **gap** between what **channel models** capture



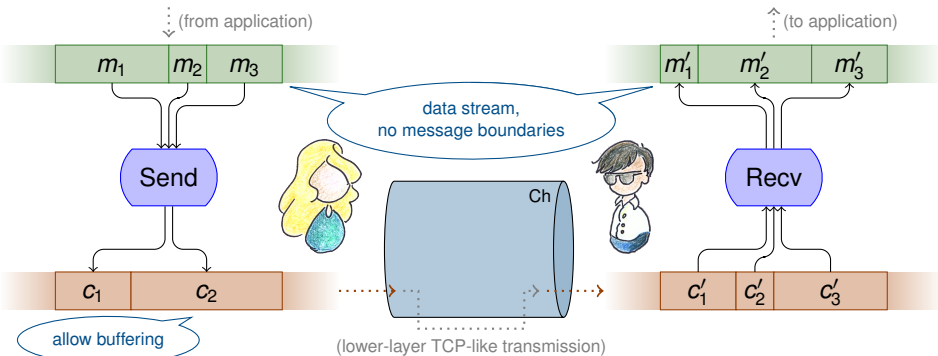
AEAD \neq secure channel

and channels expose to the **application**

Stream-Based Channels

Intuition and Security Notions

 Fischlin, Günther, Marson, Paterson
Data Is a Stream: Security of Stream-Based Channels
Crypto 2015



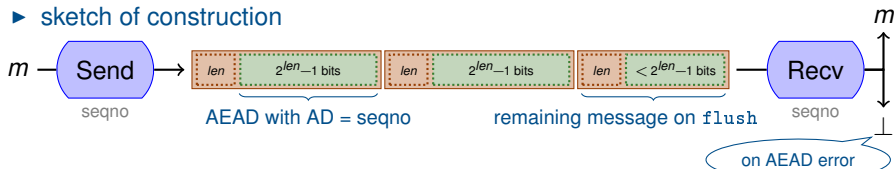
- ▶ adapted confidentiality and integrity notions for the stream-based setting

Stream-Based Channels

Generic Construction

- ▶ secure stream-based channels can be built
 - ▶ based on authenticated encryption with associated data (AEAD)
 - ▶ achieving strong IND-CCFA confidentiality
 - ▶ achieving strong INT-CST integrity

▶ sketch of construction



- ▶ close to TLS record layer design using AEAD (providing some validation)
 - ✓ sequence number authenticated, but not sent
 - ✓ sent length field, unauthenticated (in TLS 1.3)
 - ✗ TLS additionally includes, e.g., content type (sent authenticated)

Further Properties

- ▶ Length-hiding [Paterson, Ristenpart, Shrimpton'11] for streams?
- ▶ Multiplexing of data (explicitly in QUIC, implicitly in TLS)
- ▶ How to safely **encode atomic messages** in a stream?
(upcoming extended version)

TLS 1.3 Record Protocol

- ▶ employs **several traffic keys** in the same protocol (for handshake + data)
- ▶ **key switching** requires care to prevent truncation attacks [miTLS team]



Günther, Mazaheri

A Formal Treatment of Multi-key Channels

[miTLS team'16]: verified
TLS 1.3 Record Layer implementation

Conclusions

- ▶ **basic properties** of key exchange and secure channels are **well-understood** ?
- ▶ but **advanced properties** pose **new challenges** for security models

▶ in this talk:

- ▶ **multi-stage key exchange** (QUIC, TLS 1.3)
- ▶ **stream-based channels** (generic, TLS)
- ▶ **positive:** interaction of **crypto, formal methods, and engineering** communities in development of TLS 1.3

