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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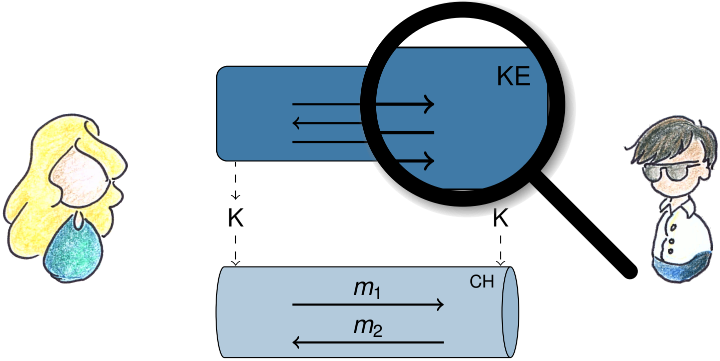
Cryptography & Complexity Theory
Technische Universität Darmstadt
www.cryptoplexity.de

Secure Connections – Everywhere

Security goals:

- confidentiality
- authenticity
- integrity

Secure Connections – Cryptographically



drawings by *Giorgia Azzurra Marson*

Key Exchange à la Diffie–Hellman (1976)

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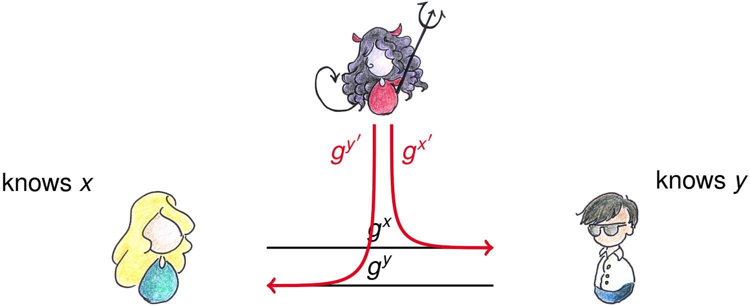
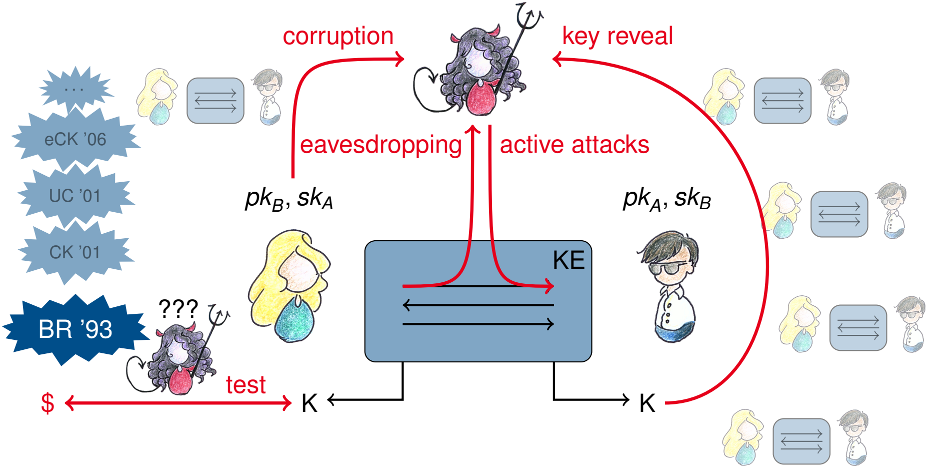


$K = (g^y)^x = g^{xy}$ $\quad$ $K = (g^x)^y = g^{xy}$

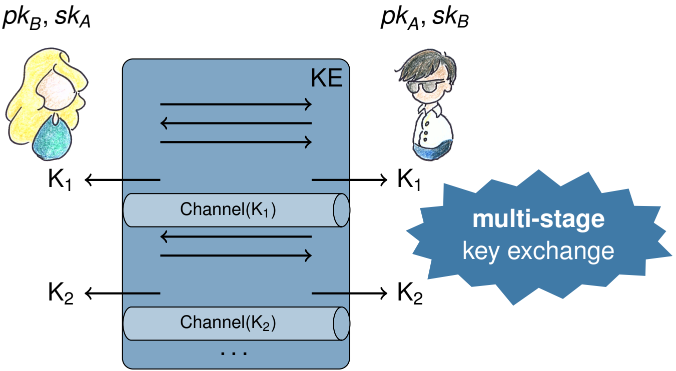
$K' = (g^{y'})^x = g^{xy'}$ $\quad$ $K'' = (g^{x'})^y = g^{x'y}$

- 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

Should we care?

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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

Should we care?

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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. deprecating some crypto algorithms (RC4, SHA-1, key transport, MtEE, etc.)
  3. using only AEAD schemes for the record layer encryption
  4. providing reduced-latency 0-RTT handshake
  5. ...

TLS 1.3 Full Handshake (simplified)

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

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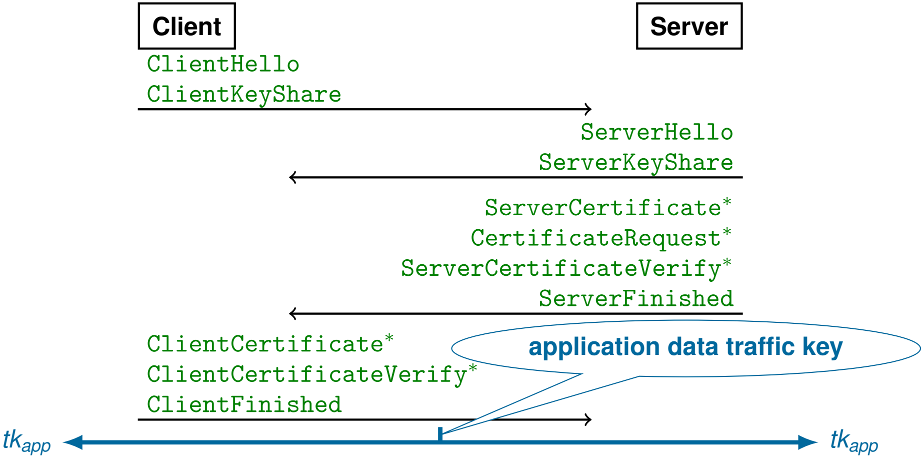
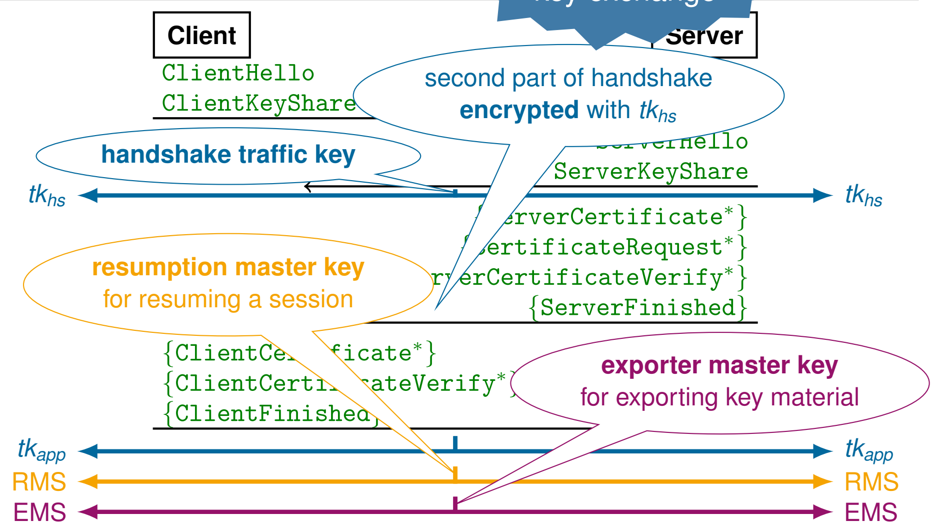


... actually, there is more ...

TLS 1.3 Full Handshake (still simplified)

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



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

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- 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

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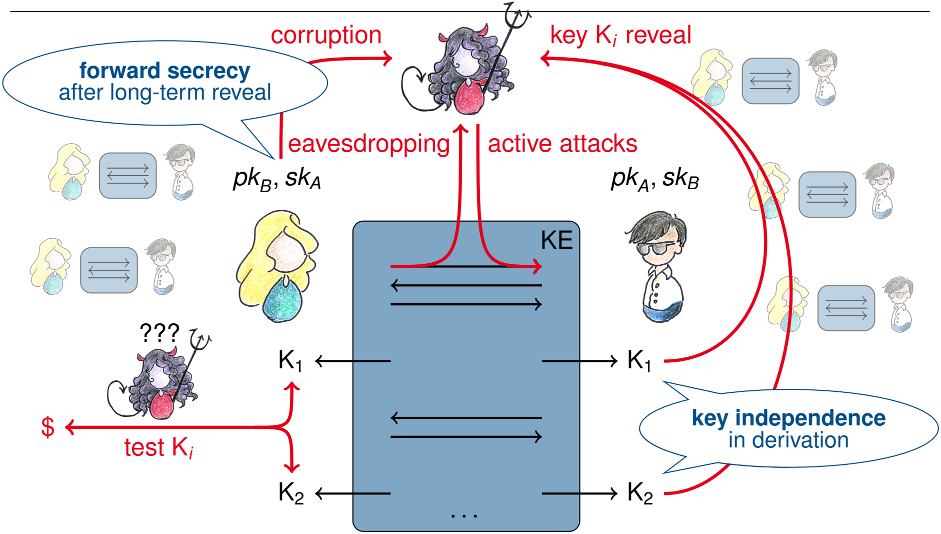
- Arai, Matsuo [CELLOS] (TLS mailing list 2016): ProVerif Analysis
- Badertscher, Matt, Maurer, Rogaway, Tackmann (ProvSec 2015): Record Layer
- Bellare, Tackmann (Crypto 2016): Security of AES-GCM Usage
- Beurdouche, Bhargavan, Blanchet, Delignat-Lavaud, Fournet, Ishtiaq, Kobeissi, Kohlweiss, Pan, Protzenko, Rastogi, Swamy, Zanella-Bguelin, Zinzindohoué [INRIA/Microsoft] (TRON 2016, S&P 2017, . . .): 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
- . . .

(alphabetical order)

Multi-Stage Key Exchange Security

game-based model, "provable security" paradigm



TLS 1.3 Handshake Security

draft-10 Full Handshake

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(still simplified)

Client | **Server**

`ClientHello`: $r_c \xleftarrow{\$} \{0,1\}^{256}$
`ClientKeyShare`: $X \leftarrow g^x$ →

`ServerHello`: $r_s \xleftarrow{\$} \{0,1\}^{256}$
`ServerKeyShare`: $Y \leftarrow g^y$ ←

$H_1 \leftarrow \mathrm{H}(\mathtt{CH} \| \ldots \| \mathtt{SKS})$
$\mathrm{ES} \leftarrow X^y$

→ tk_{hs}

$\{\mathtt{ServerCertificate}^*\}$
$H_2 \leftarrow \mathrm{H}(\mathtt{CH} \| \ldots \| \mathtt{SCRT}^* \| \ldots)$
$\{\mathtt{SCertVerify}^*\}$: $\boxed{\mathrm{Sign}_{sk_S}(H_2)}$
$\{\mathtt{ServerFinished}\}$ ←

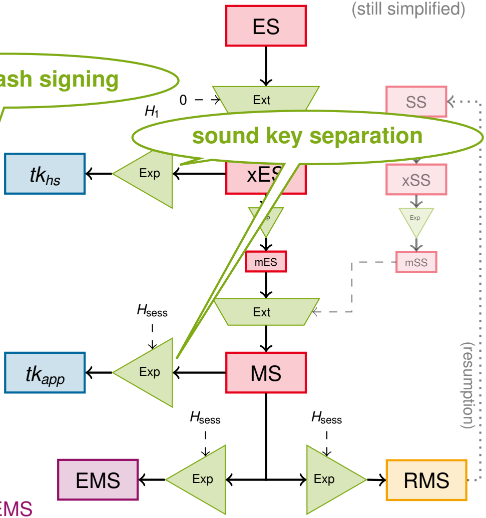
$\{\mathtt{CCert}^*\}$,$\{\mathtt{CCertVerify}^*\}$,$\{\mathtt{CFin}\}$ →

$H_{\mathrm{sess}} \leftarrow \mathrm{H}(\mathtt{CH} \| \ldots \| \mathtt{CCV}^*)$

→ tk_{app}

→ RMS,EMS

session hash signing



TLS 1.3 Handshake Security

draft-10 Full Handshake

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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

- 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

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- **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

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- **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

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

- **Signal:** Ratcheting in Secure Messaging
  - frequent key updates / new session key with every message
  - advanced security properties, future/post-compromise security

- **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

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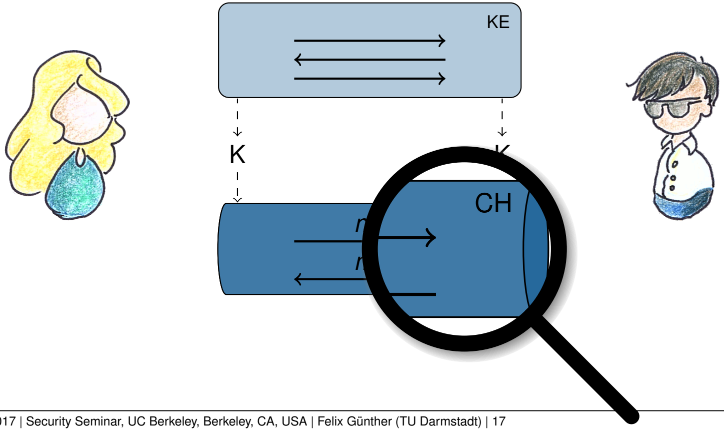

On the Origin of Channel Models

Confidentiality

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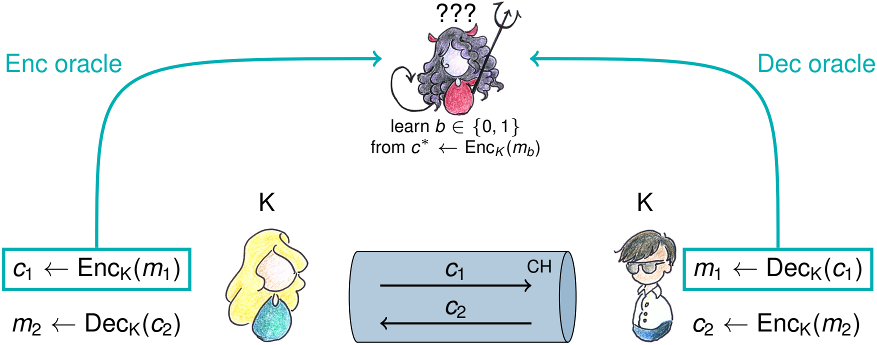

IND-CPA

[Goldwasser, Micali'84]

IND-CCA

[Naor, Yung'90], [Rackoff, Simon'91]

On the Origin of Channel Models

Integrity

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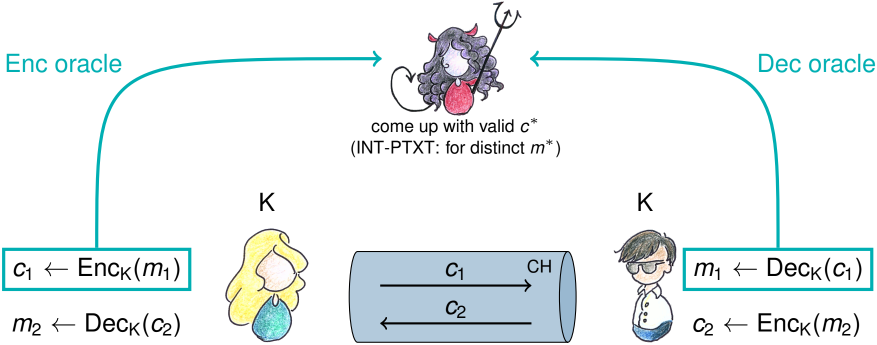

INT-PTXT
[Bellare, Namprempre'00]

Authenticated Encryption
IND-CPA + INT-CTXT
($\Rightarrow$ IND-CCA)

INT-CTXT
[Bellare, Rogaway'00]

On the Origin of Channel Models

Stateful Authenticated Encryption

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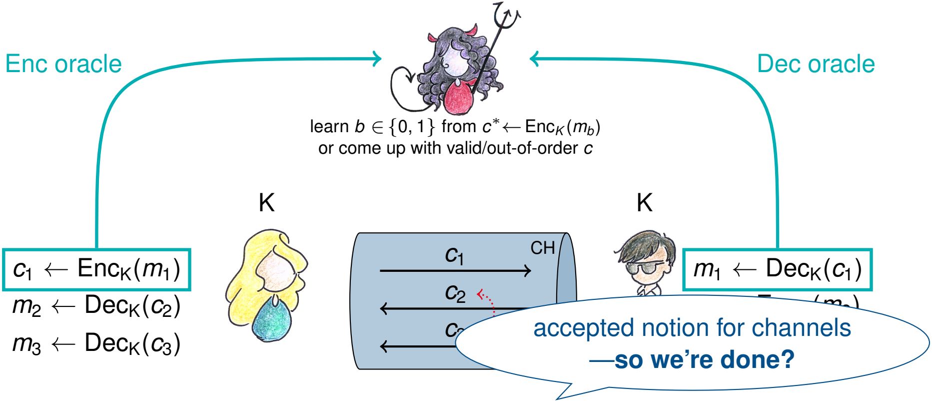

Stateful Authenticated Encryption

used to analyze SSH

IND-sfCCA [Bellare, Kohno, Namprempre'02] INT-sfCTXT

Attack on SSH

[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

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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

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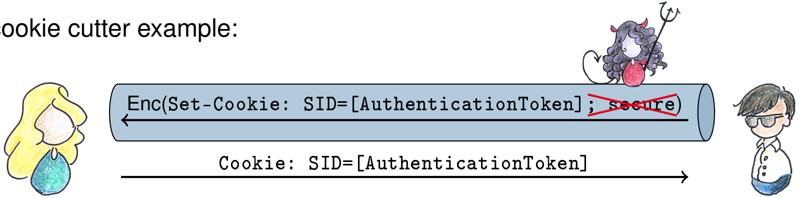
[Bhargavan, Delignat-Lavaud, Fournet, Pironti, Strub'14]: **cookie cutter attack**

- 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

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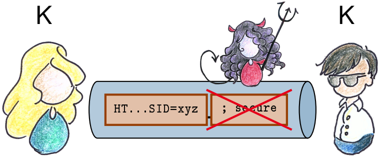
$c \leftarrow$ Enc(`HTTP/1.1 200 OK`

`...`

`Set-Cookie: SID=xyz; secure`)

K K




```
#include <openssl/ssl.h>
SSL_write("HTTP/1.1 200 OK
         ...
         Set-Cookie: SID=xyz; secure")
```

```
HTTP/1.1 200 OK
...
Set-Cookie: SID=xyz
```

2 TLS records

`HTTP/1.1 200 OK` `...` `Set-Cookie: SID=xyz`	`; secure`

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

An Interface Misunderstanding: Data Is a Stream!

. . . and TLS is not alone

- 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

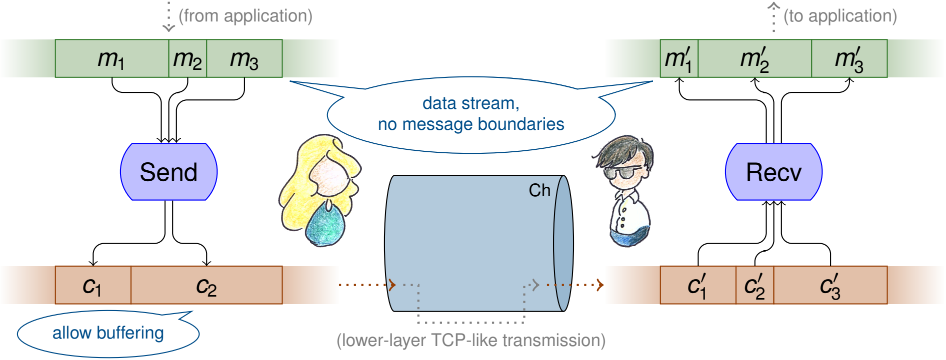
- TLS never promised to treat messages atomically!
- indeed, many important channel protocols treat data as a stream
  - TLS
  - SSH tunnel-mode
  - QUIC

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

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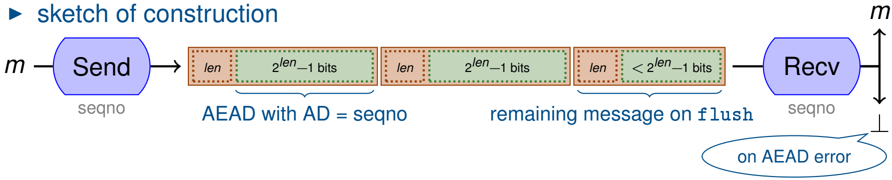
- secure stream-based channels can be built
  - based on authenticated encryption with associated data (AEAD)
  - achieving strong IND-CCFA confidentiality
  - achieving strong INT-CST integrity

- 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)

The Journey Continues...

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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

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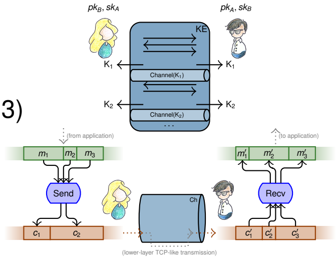
- basic properties of key exchange and secure channels are well-understood ?
- but advanced properties pose new challenges for security models
- in this talk:
  - **multi-stage key exchange** (QUIC, TLS 1.3)
  - **stream-based channels** (generic, TLS)



- **positive:** interaction of crypto, formal methods, and engineering communities in development of TLS 1.3

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Thank You!