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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Cryptoplexity
Cryptography & Complexity Theory
Technische Universität Darmstadt
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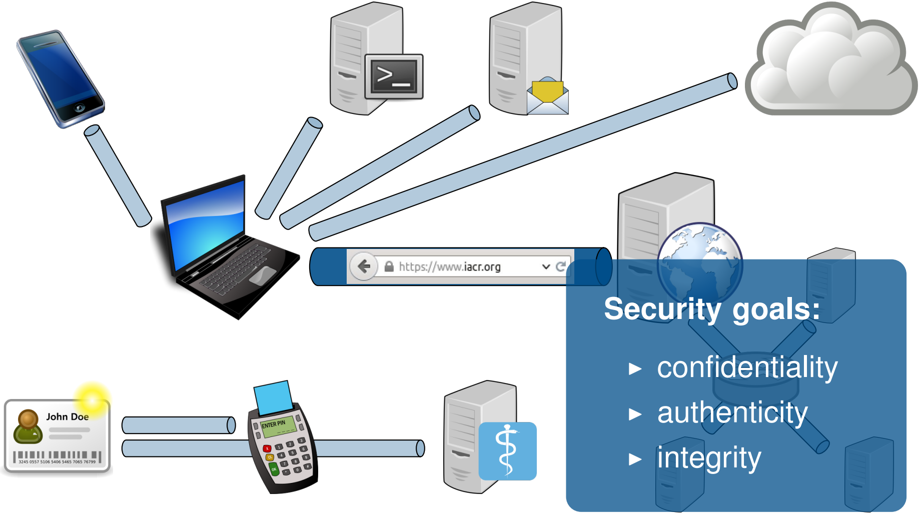
Secure Connections – Everywhere



Security goals:

- confidentiality
- authenticity
- integrity

Secure Connections – Cryptographically

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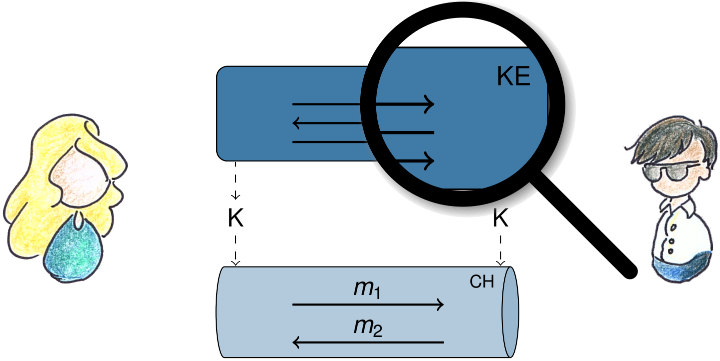
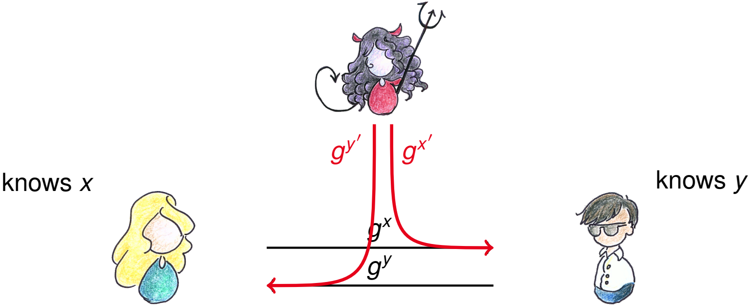


drawings by *Giorgia Azzurra Marson*

Key Exchange à la Diffie–Hellman (1976)



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

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

- 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)

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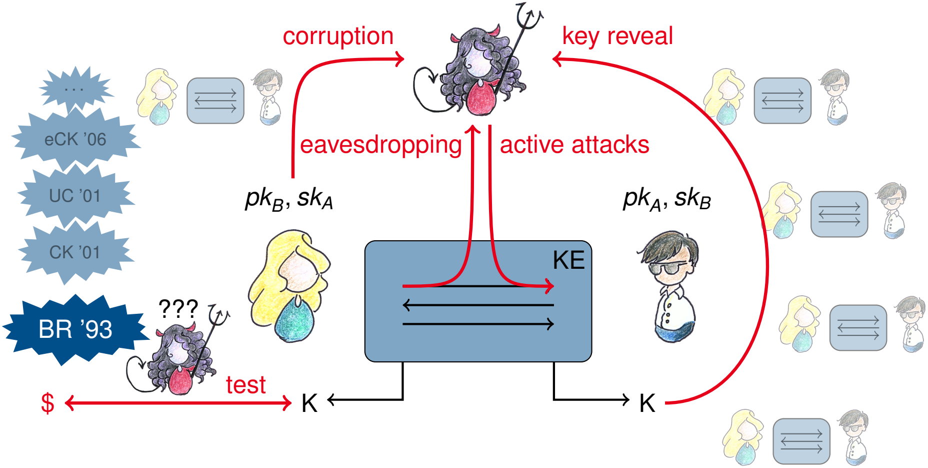

But what if. . . ?

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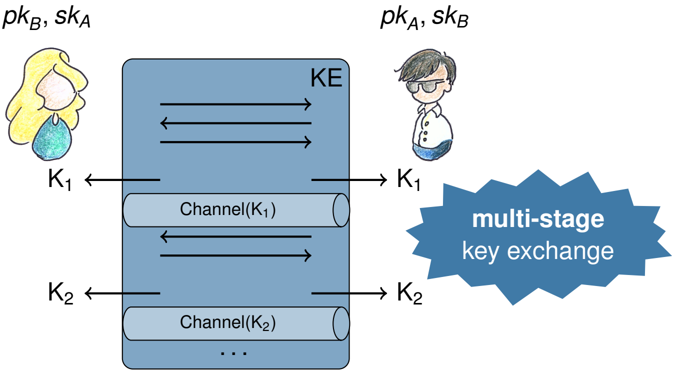

- key exchange establishes more than one key?
- . . . even uses the intermediary keys within the key exchange or channel?
- not covered by classical key exchange models

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. 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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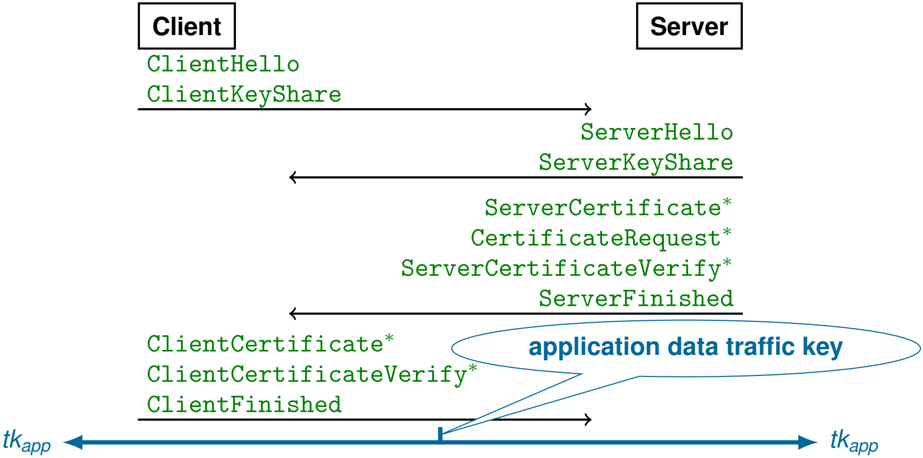
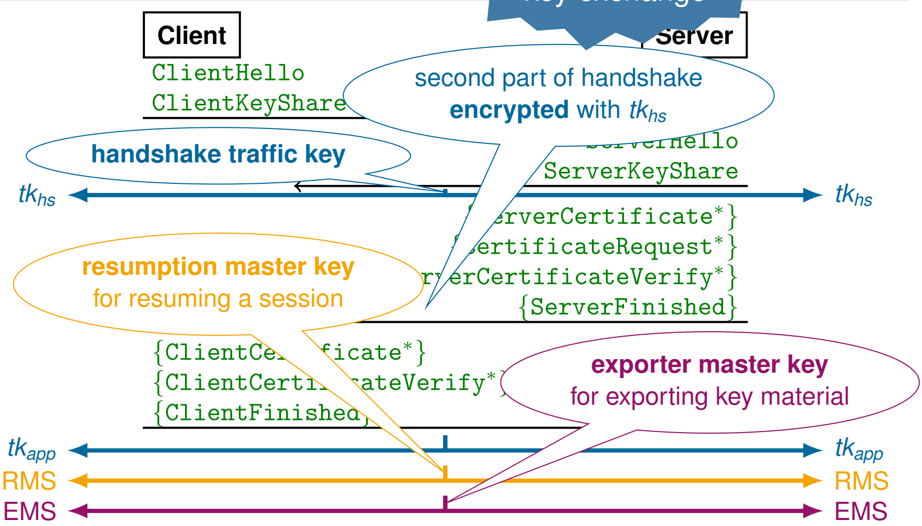


... actually, there is more ...

TLS 1.3 Full Handshake (still simplified)

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



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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(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

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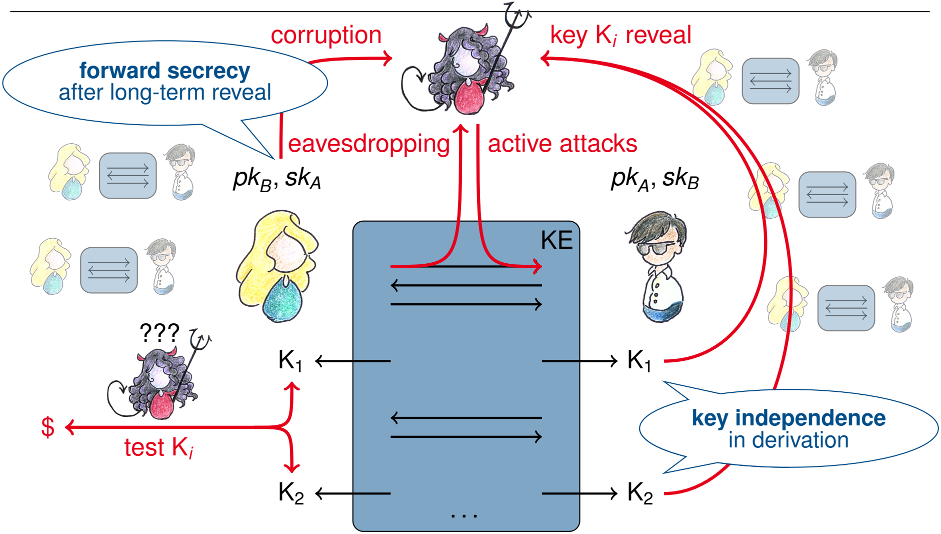

TLS 1.3 Handshake Security

draft-10 Full Handshake

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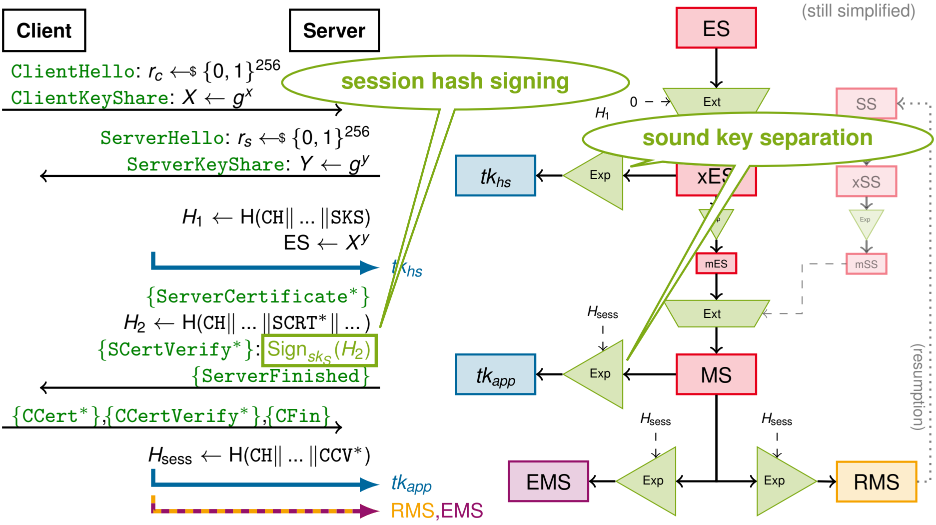

TLS 1.3 Handshake Security

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

- **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

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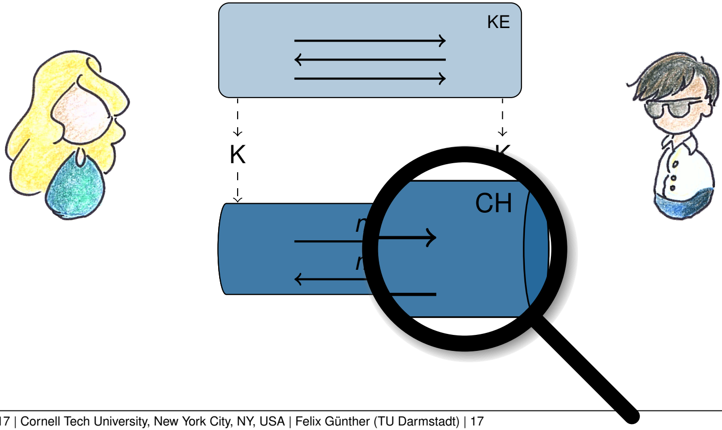
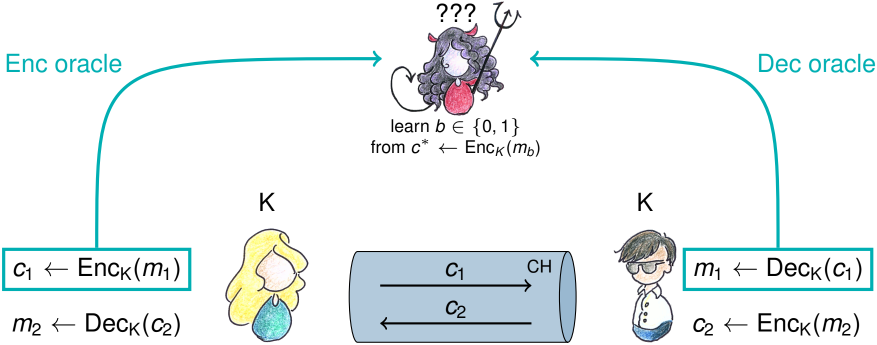


On the Origin of Channel Models

Confidentiality



IND-CPA
[Goldwasser, Micali'84]

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

On the Origin of Channel Models

Integrity

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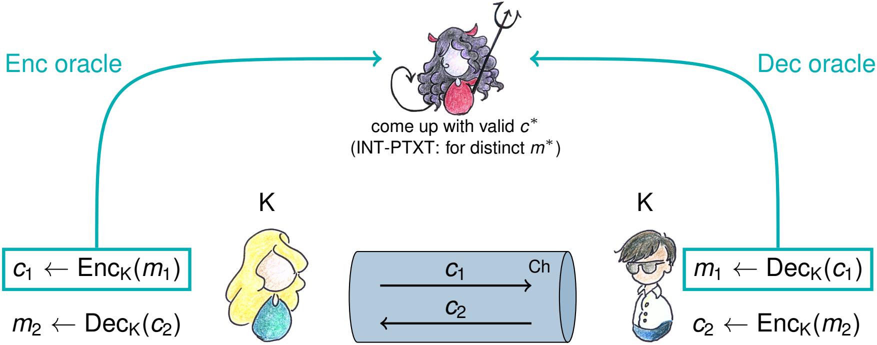

Authenticated Encryption

IND-CPA + INT-CTXT

($\Rightarrow$ IND-CCA)

INT-PTXT

[Bellare, Namprempre'00]

INT-CTXT

[Bellare, Rogaway'00]

On the Origin of Channel Models

Stateful Authenticated Encryption

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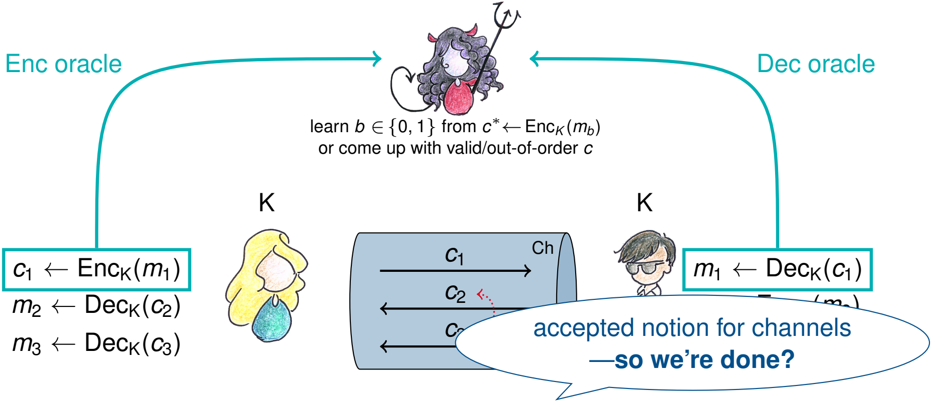

Stateful Authenticated Encryption

used to analyze SSH

IND-sfCCA

[Bellare, Kohno, Namprempre'02]

INT-sfCTXT

Attack on SSH

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[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 $\rightarrow$ confidentiality break

Wait. . .

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

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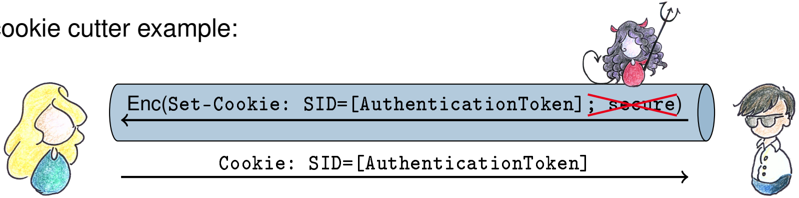
[Bhargavan, Delignat-Lavaud, Fournet, Pironti, Strub'14]: **cookie cutter attack**

- 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:

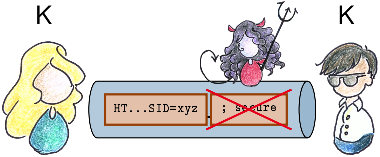


Wait. . . deleting message parts within ciphertext—how can this be possible?

Cookie Cutter Attack

A Closer Look

$c \leftarrow \mathrm{Enc}($`HTTP/1.1 200 OK`
```
...
Set-Cookie: SID=xyz; secure)
```




```
#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
  → receiver sees arbitrarily fragmented messages / no message boundaries

An Interface Misunderstanding: Data Is a Stream!

. . . and TLS is not alone

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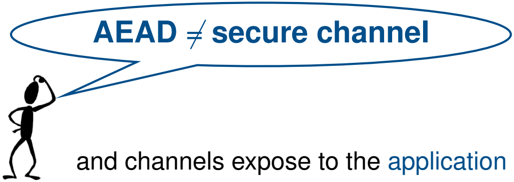
- That behavior is actually okay—and specified:

  > *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

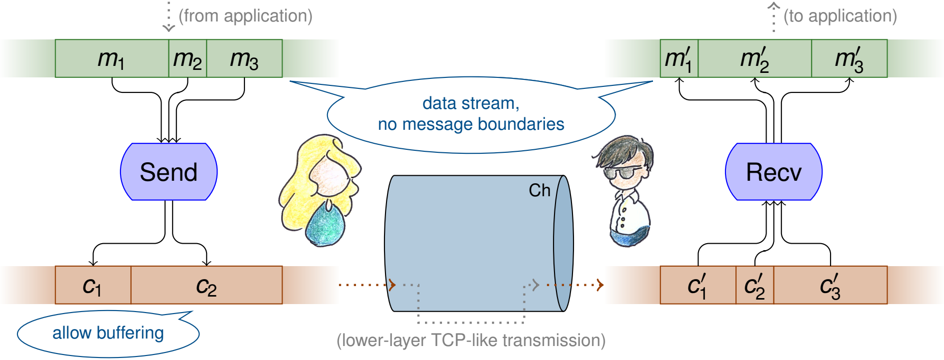


- so, there's a gap between what channel models capture and channels expose to the application

Stream-Based Channels

Intuition and Security Notions

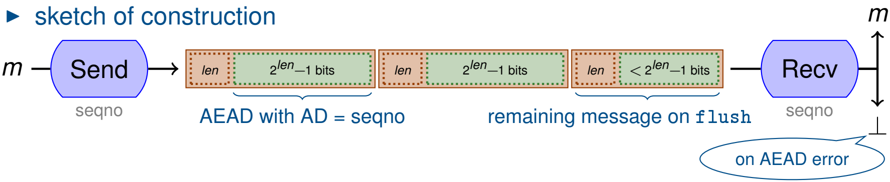
Fischlin, Günther, Marson, Paterson
Data Is a Stream: Security of Stream-Based Channels
Crypto 2015



- 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)

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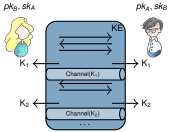
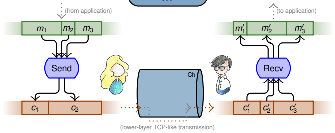
- basic properties of key exchange and secure channels are well-understood ?
- but advanced properties pose new challenges for security models
- in this talk:
  - **multi-stage key exchange** (QUIC, TLS 1.3)



  - **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!