Data Is a Stream

Security of Stream-Based Channels

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Secure Communication Needs Secure Channels

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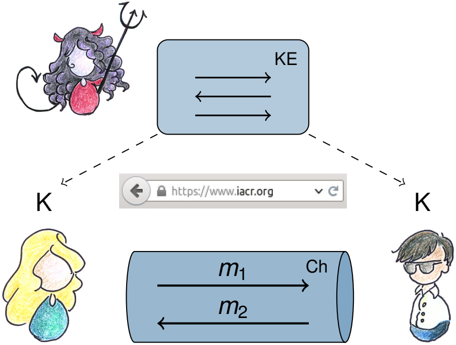


What's that secure channel precisely?

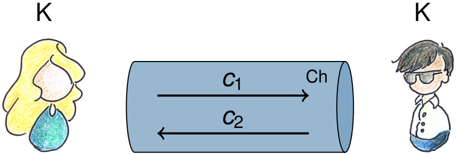
drawings by *Giorgia Azzurra Marson*

On the Origin of Channel Models

Authenticated Encryption

$c_1 \leftarrow \mathrm{Enc}_K(m_1)$

$m_2 \leftarrow \mathrm{Dec}_K(c_2)$



$m_1 \leftarrow \mathrm{Dec}_K(c_1)$

$c_2 \leftarrow \mathrm{Enc}_K(m_2)$

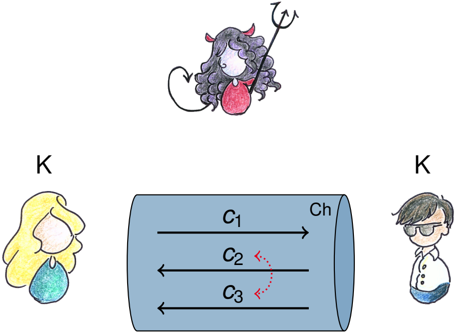
IND-CPA
(Goldwasser, Micali 1984)

IND-CCA
(Naor, Yung 1990), (Rackoff, Simon 1991)

Authenticated Encryption

INT-PTXT
(Bellare, Namprempre 2000)

INT-CTXT
(Bellare, Rogaway 2000)



Stateful Authenticated Encryption

used to analyze SSH and confirm its security

IND-sfCCA

(Bellare, Kohno, Namprempre 2002)

INT-sfCTXT

Attack on SSH

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Albrecht, Paterson, Watson 2009: **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 2002)
- …but these only allow *atomic* ciphertexts in Dec oracle

Symmetric Encryption Supporting Fragmentation

(Boldyreva, Degabriele, Paterson, Stam 2012)

- general security model for ciphertext fragmentation
- standard Enc algorithm (and left-or-right oracle)
- Dec algorithm obtains ciphertext fragments, reassembles original messages
- security notion: IND-sfCFA (chosen-fragment attack)
- focuses on confidentiality

Are we there yet?

Attack on TLS

Cutting Cookies

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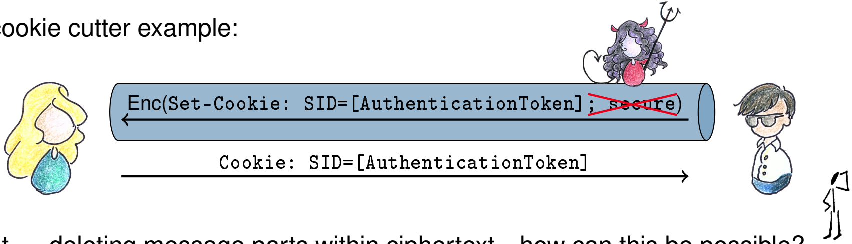
Bhargavan, Delignat-Lavaud, Fournet, Pironti, Strub 2014: **cookie cutter attack**

- 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:

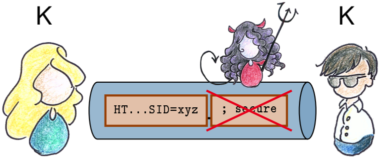


Wait... deleting message parts within ciphertext—how can this be possible?

Cookie Cutter Attack

A Closer Look

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



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

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

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 arbitrary message fragmentation / no message boundaries

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).*

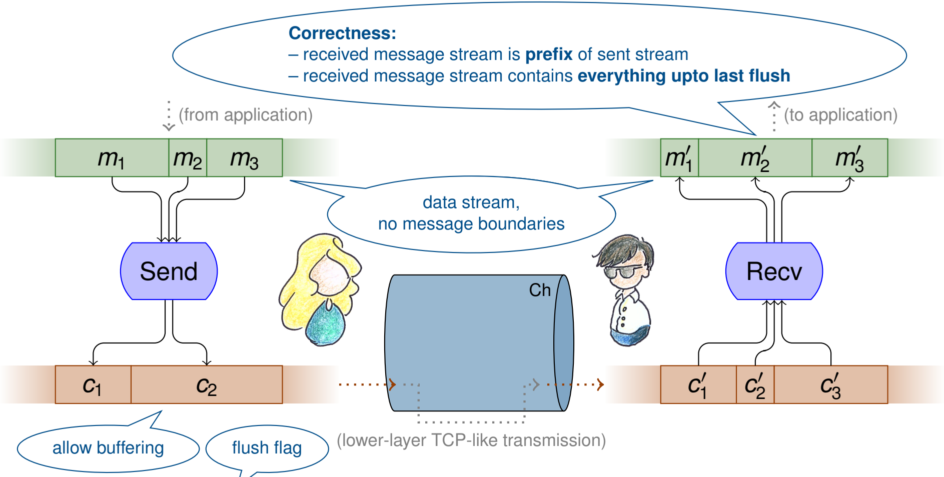
  RFC 5246 TLS v1.2

- 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



$\text{Send}(m \in \{0,1\}^*, f \in \{0,1\}) \to c \in \{0,1\}^*$

$\text{Recv}(c \in \{0,1\}^*) \to m \in \{0,1\}^* \cup \mathcal{E}$

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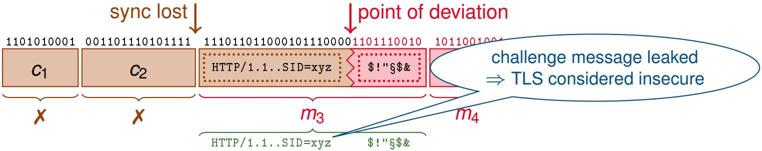
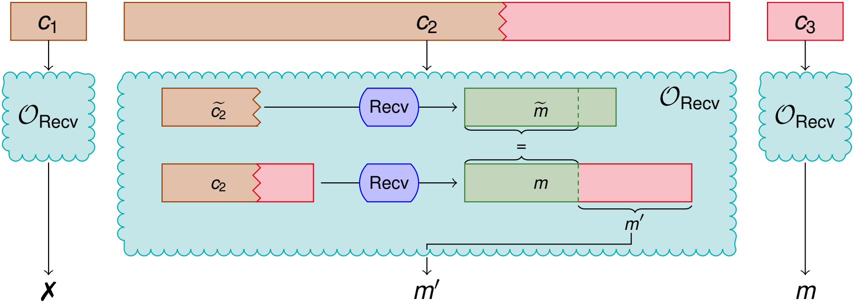
- **CPFA** case straightforward: left-or-right oracle allowing to control flush flag
- **CCFA** case more complex:
  - general idea: allow as much decryption as possible, but no trivial attacks
  - Bellare-Kohno-Namprempre approach: Recv oracle $\mathcal{O}_{\mathsf{Recv}}$ can be in/out of sync
    - in sync (original ciphertext stream): no output
    - out of sync (deviation from original stream): Recv output given to adversary
  - But where exactly shall $\mathcal{O}_{\mathsf{Recv}}$ / ciphertext stream be considered out-of-sync?
    - BDPS 2012: at ciphertext boundaries



Stream-Based Channels
Confidentiality

- key insight: there is no inherent structure on a stream!
- $\mathcal{O}_{\mathsf{Recv}}$ behavior
  - in-sync / already out-of-sync cases as always: output nothing / everything
  - loosing sync: strip longest common prefix with output of genuine ciphertext part



Relations & Composition Result

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Classic implications hold:

- confidentiality: IND-CCFA $\Rightarrow$ IND-CPFA
- integrity: INT-CST $\Rightarrow$ INT-PST (first non-atomic treatment)

Classic composition result: IND-CPA + INT-CTXT $\Rightarrow$ IND-CCA (BN 2000)

- idea: when $\mathcal{A}$ gets any $\mathcal{O}_{\text{Recv}}$ output, it broke integrity; let $\mathcal{B}$ always return $\perp$
- multi-error setting: need additional "error invariance" property (BDPS 2013)

  at most one error with non-negl. probability

- composition in stream-based setting:
  ERR-PRE + IND-CPFA + INT-CST $\Rightarrow$ IND-CCFA
  - inherently "multi-error": Recv output on deviating ciphertext can be $\perp$ *or* empty
  - we require predictability of errors by an efficient algorithm (given sent/received ciphertext stream and next ciphertext fragment)
  - sounds strong, but is achievable by natural constructions

Generic Construction

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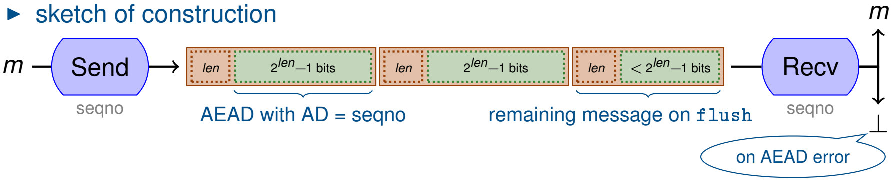
- secure stream-based channels can be built
  - based on authenticated encryption with associated data (AEAD)
  - achieving strong IND-CCFA confidentiality
  - achieving strong INT-CST integrity

- sketch of construction



- example scheme satisfying error predictability (composition theorem used)
  unencrypted length field allows to predict when error $\perp$ is output

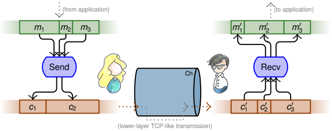
- close to TLS record layer design using AEAD (providing some validation)
  - ✓ unsent sequence number as authenticated AD
  - ✓ sent length field, unauthenticated (in TLS 1.3)
  - ✗ TLS additionally includes: version number, content type (sent + authenticated)

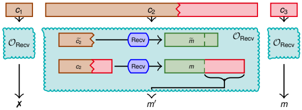
Summary

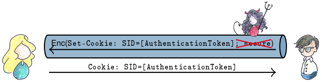
Data is a stream!

We

- formalize stream-based channels
- give adequate security notions and a composition result
- provide an AEAD-based construction close to the TLS record layer design
- shed a formal light on recent attacks







Ongoing / Future Work

- explore exact relation between atomic and stream-based notions
- additional properties: length-hiding?, multiplexing
- how to safely encode atomic messages in a stream?

Thank You!

References I

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[1] M. R. Albrecht, K. G. Paterson, and G. J. Watson.
Plaintext recovery attacks against SSH.
In *IEEE Symposium on Security and Privacy (S&P 2009)*, pages 16–26. IEEE Computer Society, 2009.

[2] M. Bellare, T. Kohno, and C. Namprempre.
Authenticated encryption in SSH: provably fixing the SSH binary packet protocol.
In *ACM Conference on Computer and Communications Security, CCS 2002*, pages 1–11. ACM, 2002.

[3] M. Bellare and C. Namprempre.
Authenticated encryption: Relations among notions and analysis of the generic composition paradigm.
In *Advances in Cryptology - ASIACRYPT 2000*, pages 531–545. Springer, 2000.

[4] M. Bellare and P. Rogaway.
Encode-then-encipher encryption: How to exploit nonces or redundancy in plaintexts for efficient cryptography.
In *Advances in Cryptology - ASIACRYPT 2000*, pages 317–330. Springer, 2000.

[5] K. Bhargavan, A. Delignat-Lavaud, C. Fournet, A. Pironti, and P. Strub.
Triple handshakes and cookie cutters: Breaking and fixing authentication over TLS.
In *IEEE Symposium on Security and Privacy, SP 2014*, pages 98–113. IEEE Computer Society, 2014.

[6] A. Boldyreva, J. P. Degabriele, K. G. Paterson, and M. Stam.
Security of symmetric encryption in the presence of ciphertext fragmentation.
In *Advances in Cryptology - EUROCRYPT 2012*, pages 682–699. Springer, 2012.

References II

[7] A. Boldyreva, J. P. Degabriele, K. G. Paterson, and M. Stam.
On symmetric encryption with distinguishable decryption failures.
In *Fast Software Encryption - 20th International Workshop, FSE 2013*, pages 367–390. Springer, 2013.

[8] C. Brzuska, N. P. Smart, B. Warinschi, and G. J. Watson.
An analysis of the EMV channel establishment protocol.
In *ACM SIGSAC Conference on Computer and Communications Security, CCS'13*, pages 373–386. ACM, 2013.

[9] T. Dierks and E. Rescorla.
The Transport Layer Security (TLS) Protocol Version 1.2.
RFC 5246 (Proposed Standard), Aug. 2008.

[10] S. Goldwasser and S. Micali.
Probabilistic encryption.
J. Comput. Syst. Sci., 28(2):270–299, 1984.

[11] M. Naor and M. Yung.
Public-key cryptosystems provably secure against chosen ciphertext attacks.
In *ACM Symposium on Theory of Computing*, pages 427–437. ACM, 1990.

[12] K. G. Paterson, T. Ristenpart, and T. Shrimpton.
Tag size does matter: Attacks and proofs for the TLS record protocol.
In *Advances in Cryptology - ASIACRYPT 2011*, pages 372–389. Springer, 2011.

References III

TECHNISCHE UNIVERSITÄT DARMSTADT

[13] K. G. Paterson and G. J. Watson.
Plaintext-dependent decryption: A formal security treatment of SSH-CTR.
In *Advances in Cryptology - EUROCRYPT 2010*, pages 345–361. Springer, 2010.

[14] C. Rackoff and D. R. Simon.
Non-interactive zero-knowledge proof of knowledge and chosen ciphertext attack.
In *Advances in Cryptology - CRYPTO '91*, pages 433–444. Springer, 1991.

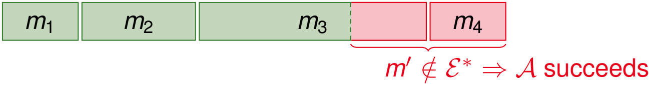
[15] P. Rogaway.
Authenticated-encryption with associated-data.
In *ACM Conference on Computer and Communications Security, CCS 2002*, pages 98–107. ACM, 2002.

[16] B. Smyth and A. Pironti.
Truncating TLS connections to violate beliefs in web applications.
In *7th USENIX Workshop on Offensive Technologies, WOOT '13*. USENIX Association, 2013.

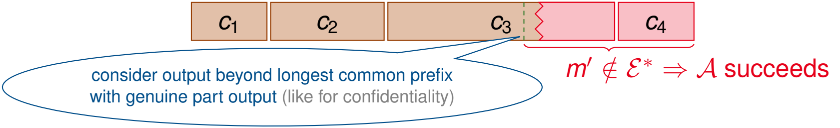
Stream-Based Channels
Integrity

(first consideration of integrity in non-atomic setting)

- **INT-PST:** plaintext-stream integrity
  no adversary can make received message stream deviate from sent stream



- **INT-CST:** ciphertext-stream integrity
  no adversary can make message bits being output after point of deviation



! stream-based confidentiality/integrity allow (genuine) **“partial message” output**
(would be considered as breaking security in atomic (and BDPS 2012) setting)