Introduction to TLS

TLS ≤1.2 & Cryptographic Background

UC San Diego

TLS Crypto Seminar

January 17, 2019

Felix Günther
UC San Diego

special thanks to Kenny Paterson

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DFG Deutsche Forschungsgemeinschaft
German Research Foundation

This Seminar

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Goal

- gain (some) understanding of a complex real-world protocol and its crypto
- partially *lecture-style* introduction to protocol and crypto background
- partially *reading-group–style* covering specific results (thanks to presenters!)

Part I TLS ≤1.2

- The Transport Layer Security (TLS) protocol: intro and crypto background.
- Attacks and analyses: understanding past weaknesses and hurdles.

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

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TLS ≤1.2

Jan 17	**TLS intro** [TLS12] **& crypto backround** [BR94,BKN02]	Felix
Jan 24	**Lucky 13** [AP13]	Nicholas
Jan 31	no seminar	-
Feb 7	**The ACCE model** [JKSS12,KPW13]	Joseph
Feb 14	**Logjam** [ABD+15]	Mark

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

Introduction to TLS

So What Is TLS?

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The Transport Layer Security (TLS) Protocol

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TLS allows client/server applications to communicate over the Internet in a way that is designed to prevent eavesdropping, tampering, and message forgery.

TLS 1.3 [RFC 8446]

1994	**SSL 1.0** (unpublished)	all considered seriously broken today
1995	**SSL 2.0**	
1996	**SSL 3.0**	
1999	**TLS 1.0** – RFC 2246	≈ SSL 3.0, adopted by IETF
2006	**TLS 1.1** – RFC 4346	maintained by IETF TLS working group
2008	**TLS 1.2** – RFC 5246	a team effort, editor: Eric Rescorla
2018	**TLS 1.3** – RFC 8446	

IETF

So What Is TLS?

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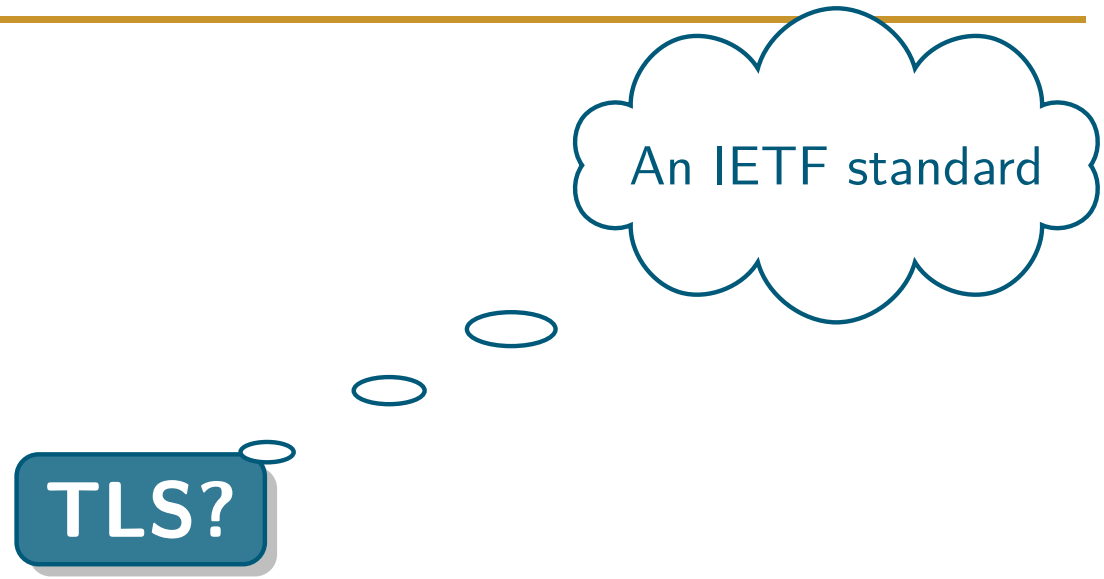

The TLS Protocol

A Story of Success . . . and Failures

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- initially introduced by Netscape to enable e-commerce on the WWW
- today: protecting billions of Internet connections every day
  - web, email, messaging, VoIP, banking, payments, e-health, . . .
  - $>80\%$ of web traffic is encrypted[1]
- an exposed target for attacks with a track record of critical flaws
  - structural/design errors
  - weaknesses in cryptographic primitives
  - implementation flaws
  - . . .
- crypto and security research important to understand and improve security
  - finding protocol flaws, guiding design, discussing security trade-offs

[1] e.g., `https://www.f5.com/labs/articles/threat-intelligence/the-2017-tls-telemetry-report`

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The TLS Protocol

High-level Goals

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(from TLS 1.3, RFC 8446)

"The primary goal of TLS is to provide a **secure channel between two peers**"

- only requirement from underlying transport: reliable, in-order data stream
- **Authentication**
  - **server** side of the channel is **always authenticated**
  - **client** side is **optionally authenticated**
  - via **asymmetric crypto** (e.g., signatures) or a symmetric **pre-shared key**
- **Confidentiality**
  - **data** sent over the channel is **only visible to the endpoints**
  - TLS does **not hide the length** of the data it transmits (but allows padding)
- **Integrity**
  - **data** sent over the channel **cannot be modified** without detection
- security in the face of **attacker who has complete control of the network**

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The TLS Protocol

Overly Simplified

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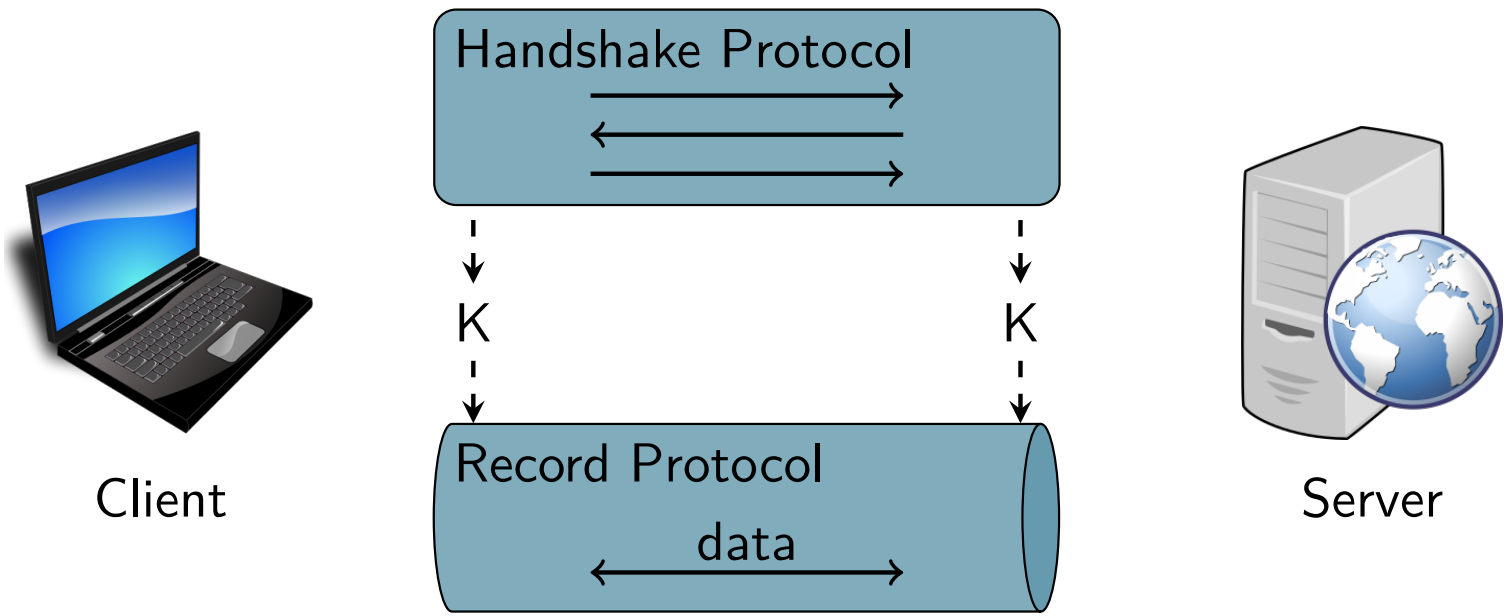
Handshake Protocol:

- 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

So What Is TLS?

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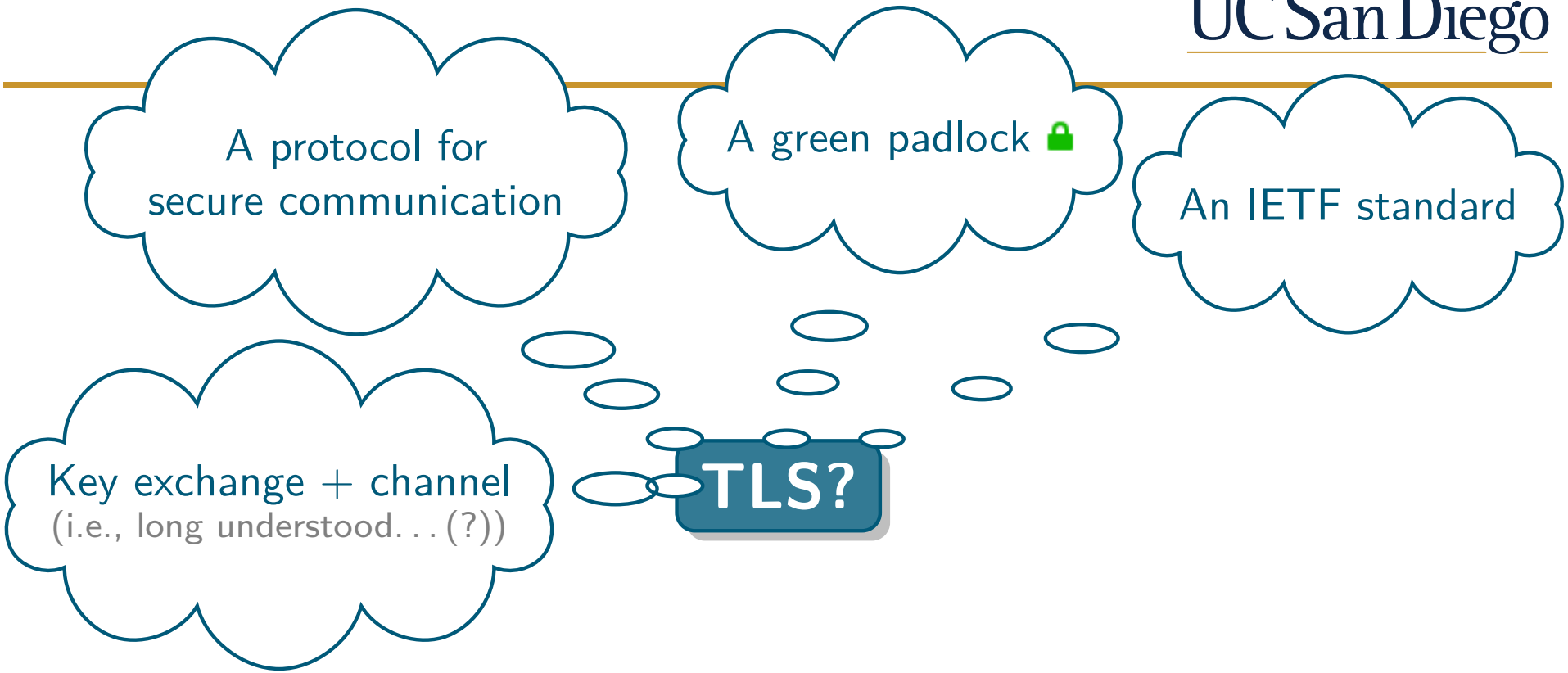

The TLS Protocol

Architecture within Network Stack

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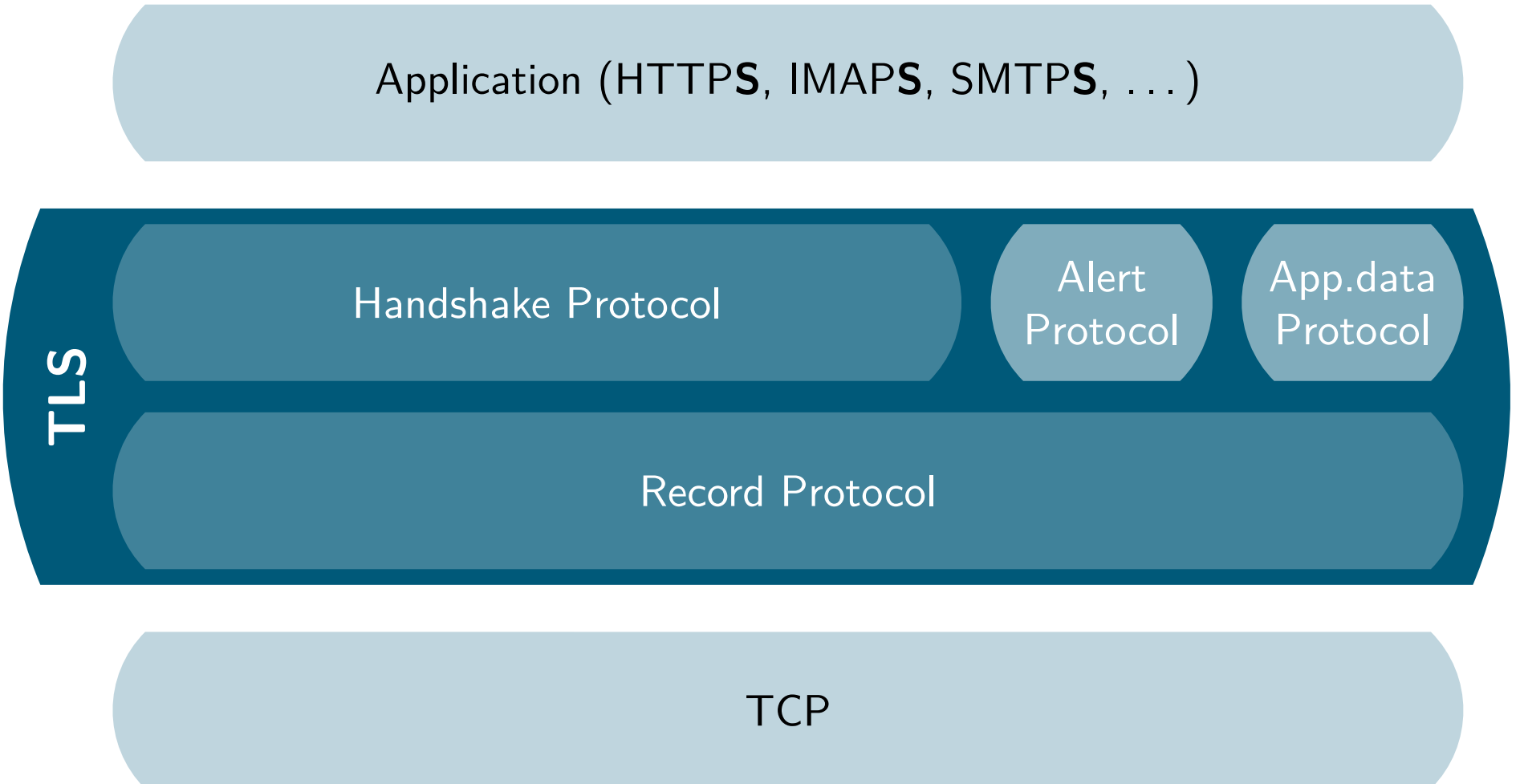

So What Is TLS?

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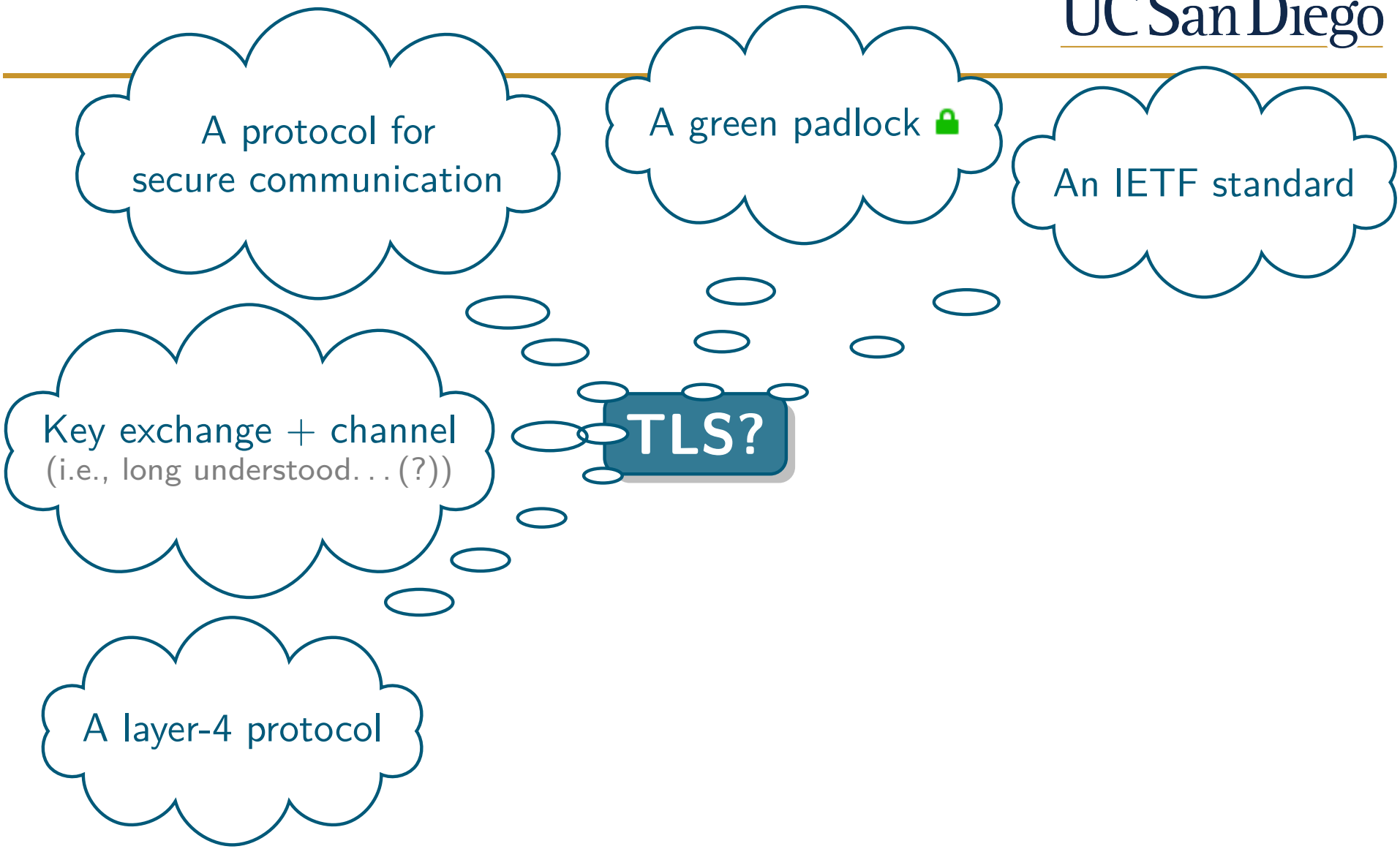

The TLS Protocol

Actors

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- with billions of users come **billions of devices** (for servers and clients)
- of all types, from *laptop* $\leftrightarrow$ *cloud* to *embedded device* $\leftrightarrow$ *smart home hub*

- running **various implementations** of TLS, in software and hardware
- from widely-used libraries (OpenSSL, Google's BoringSSL, ...)
  to small or even ad-hoc implementations

- authentication via **Certification Authorities** (100+ in standard browser)
- highly trusted and single-point-of-failure

So What Is TLS?

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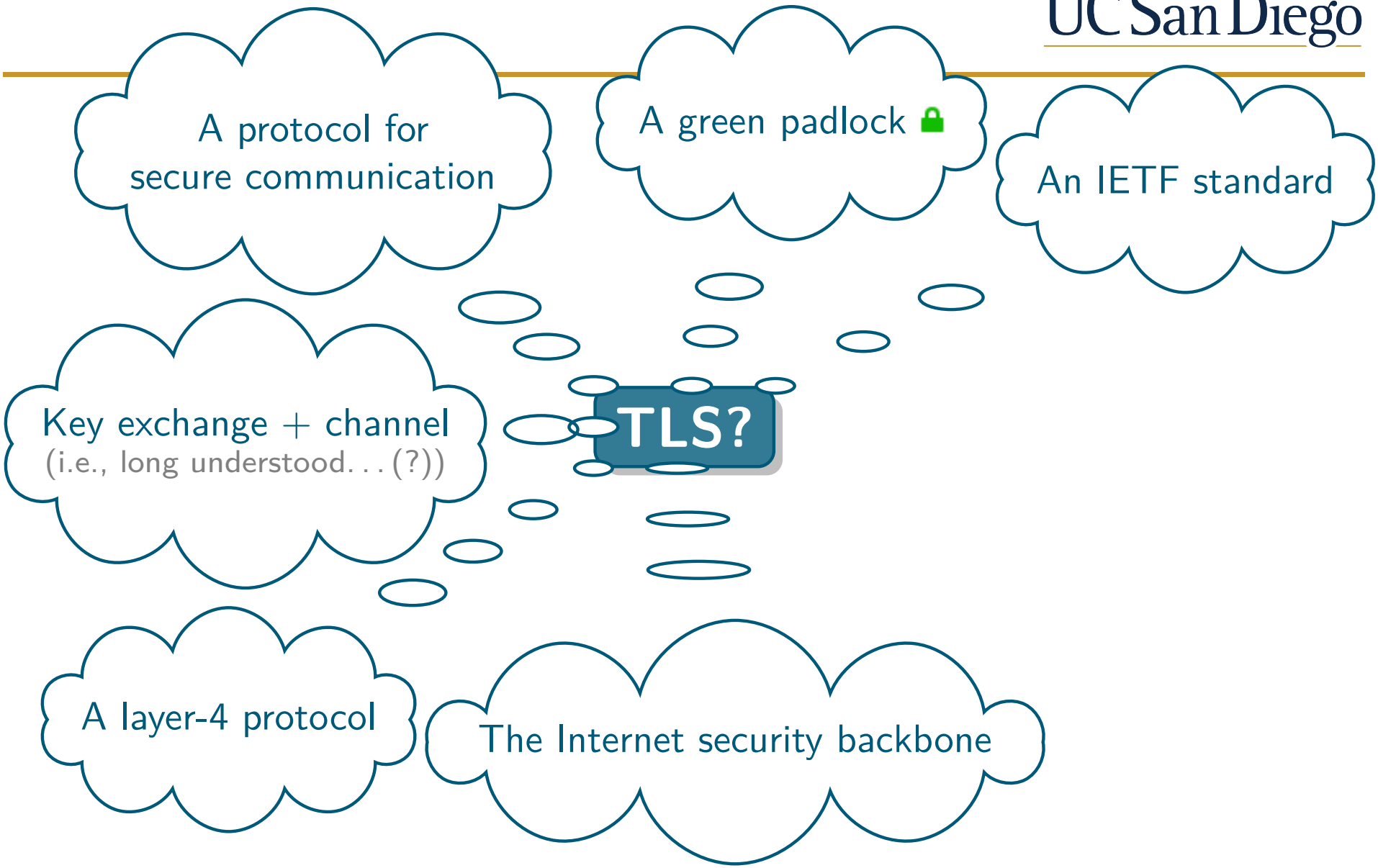

The TLS Protocol

Components

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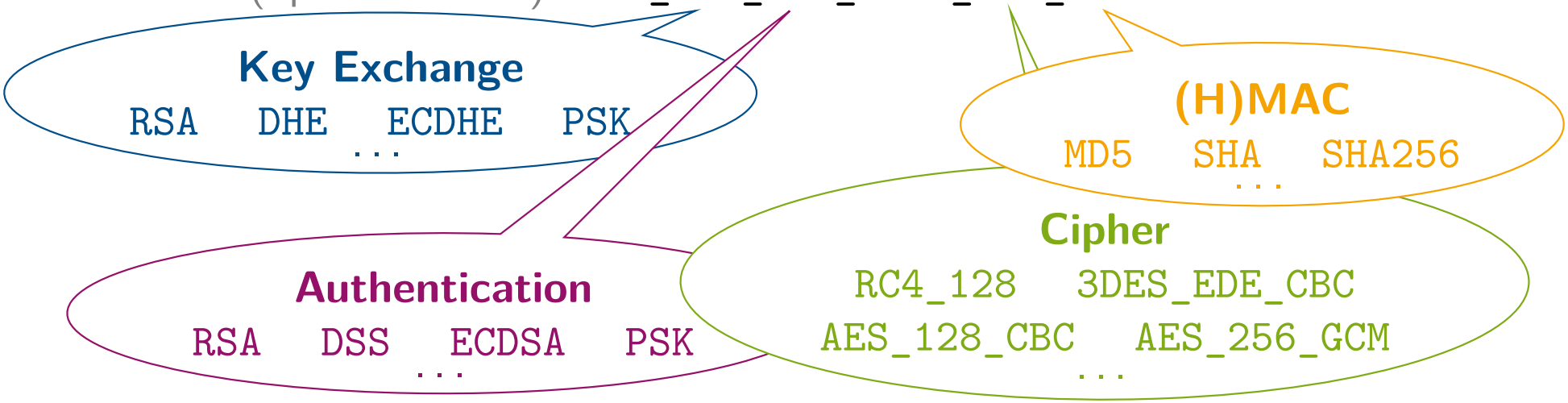
- TLS is a **"self-negotiating"** protocol
- handshake first of all agrees on TLS version and cipher suite to use

- **Cipher suites:** client proposes list, server picks
- fixes crypto algorithms to be used for that session
- format (up to TLS 1.2): `TLS_KEX_AUT_WITH_CIP_MAC`



The TLS Protocol

Handshake Protocol Structure

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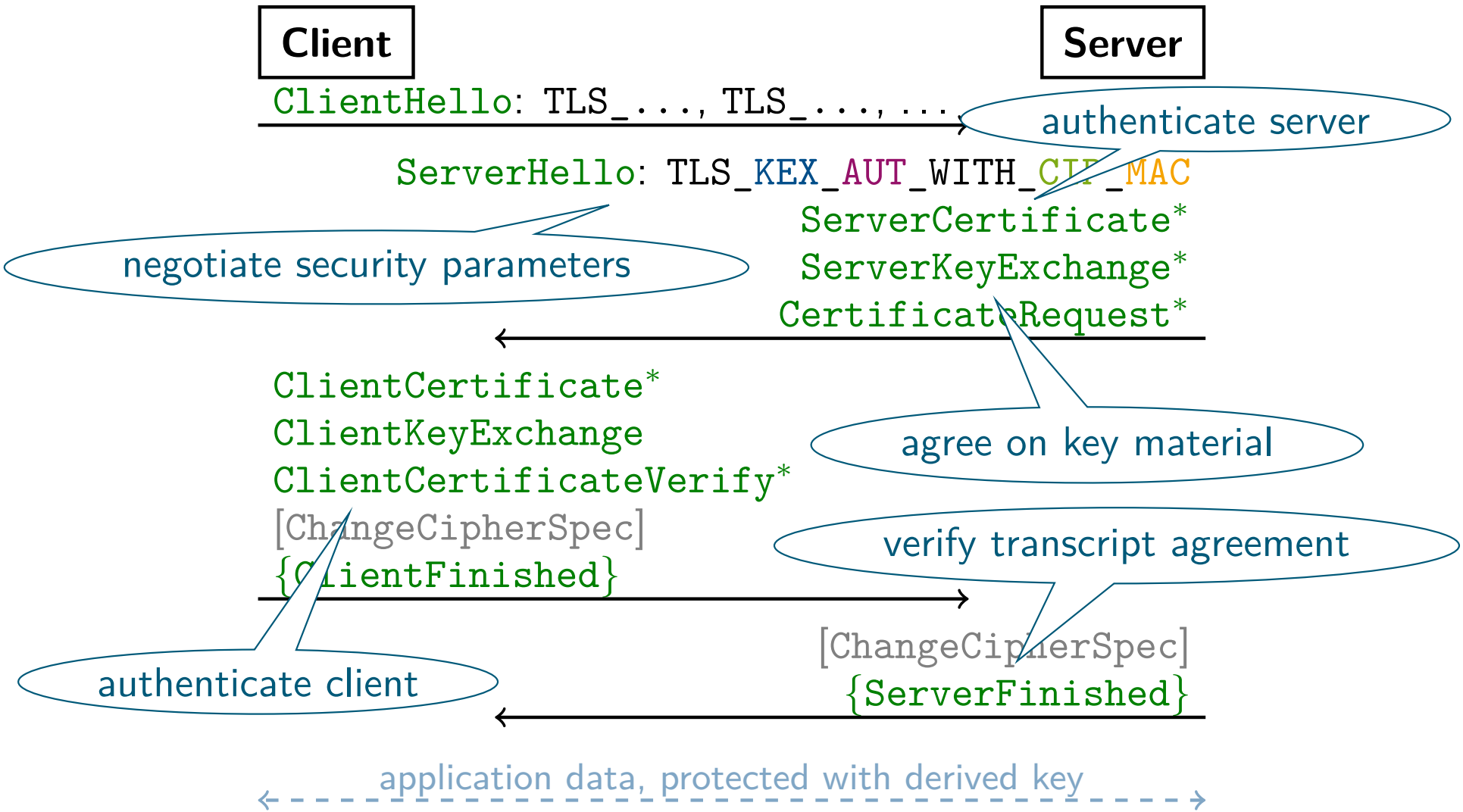

The TLS Protocol

Record Protocol Structure

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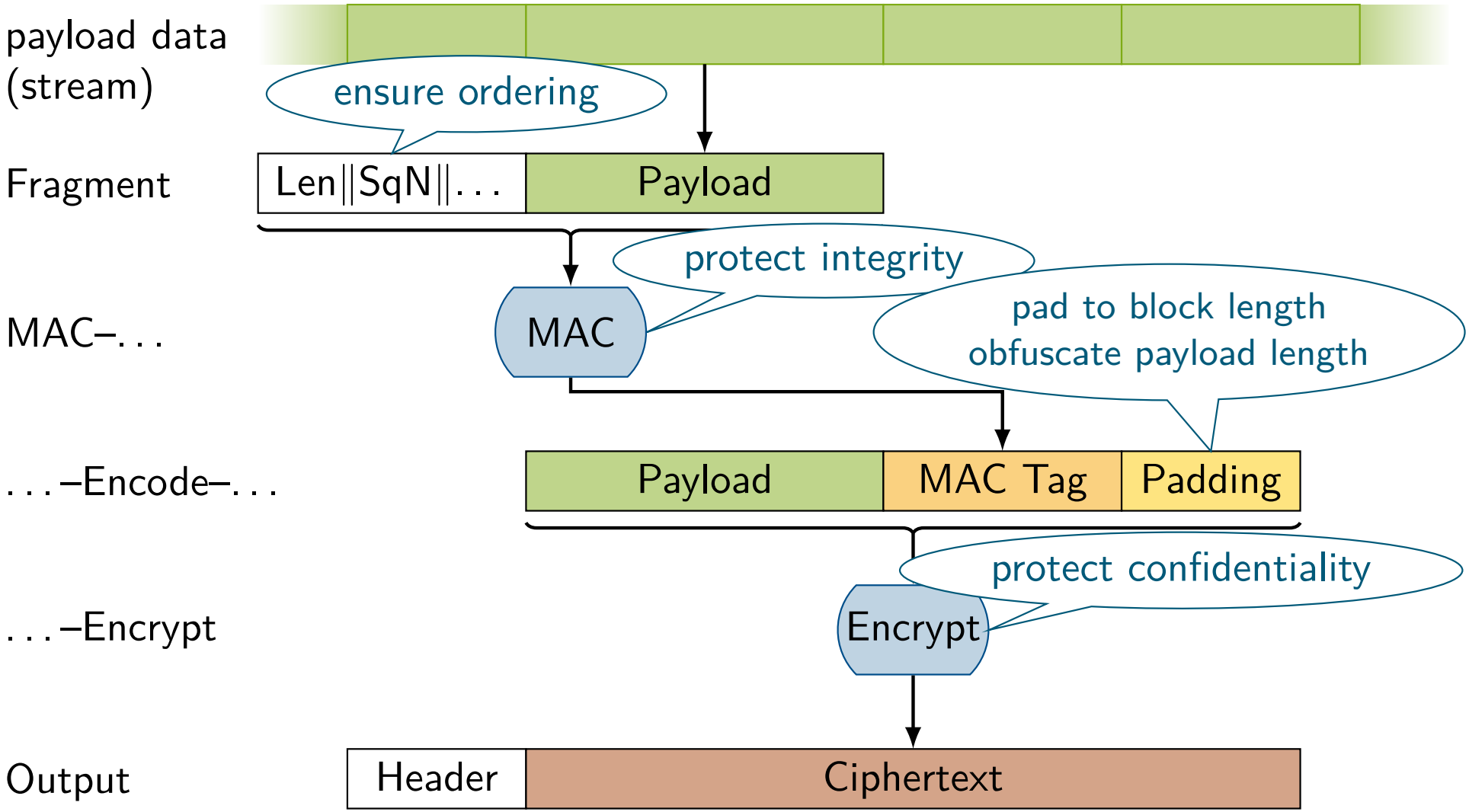

The TLS Protocol

Example: TLS_RSA_WITH_AES_128_CBC_SHA
— Handshake

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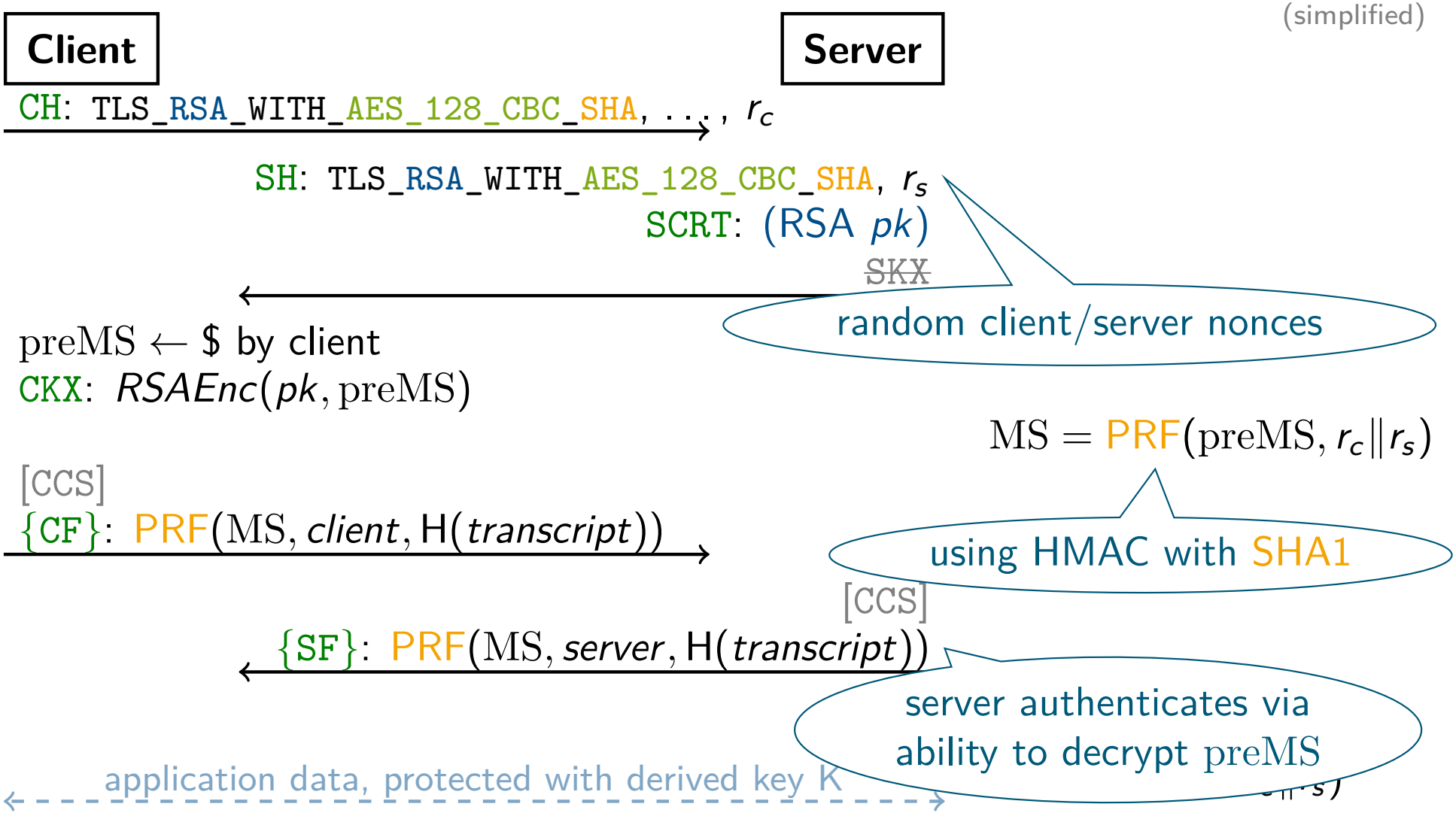
(simplified)



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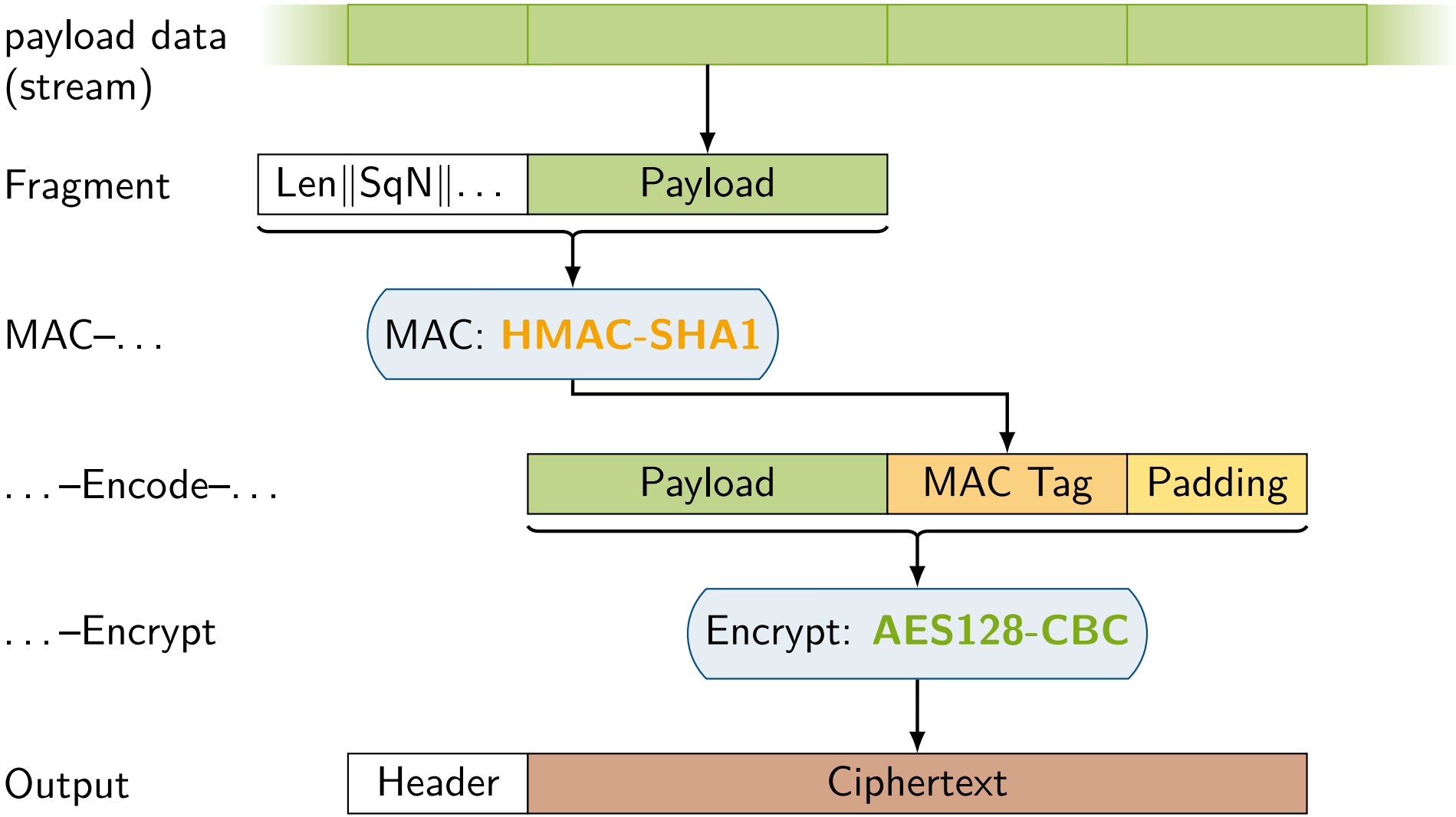

The TLS Protocol

Example: TLS_DHE_RSA_WITH_AES_256_GCM_SHA384
— Handshake

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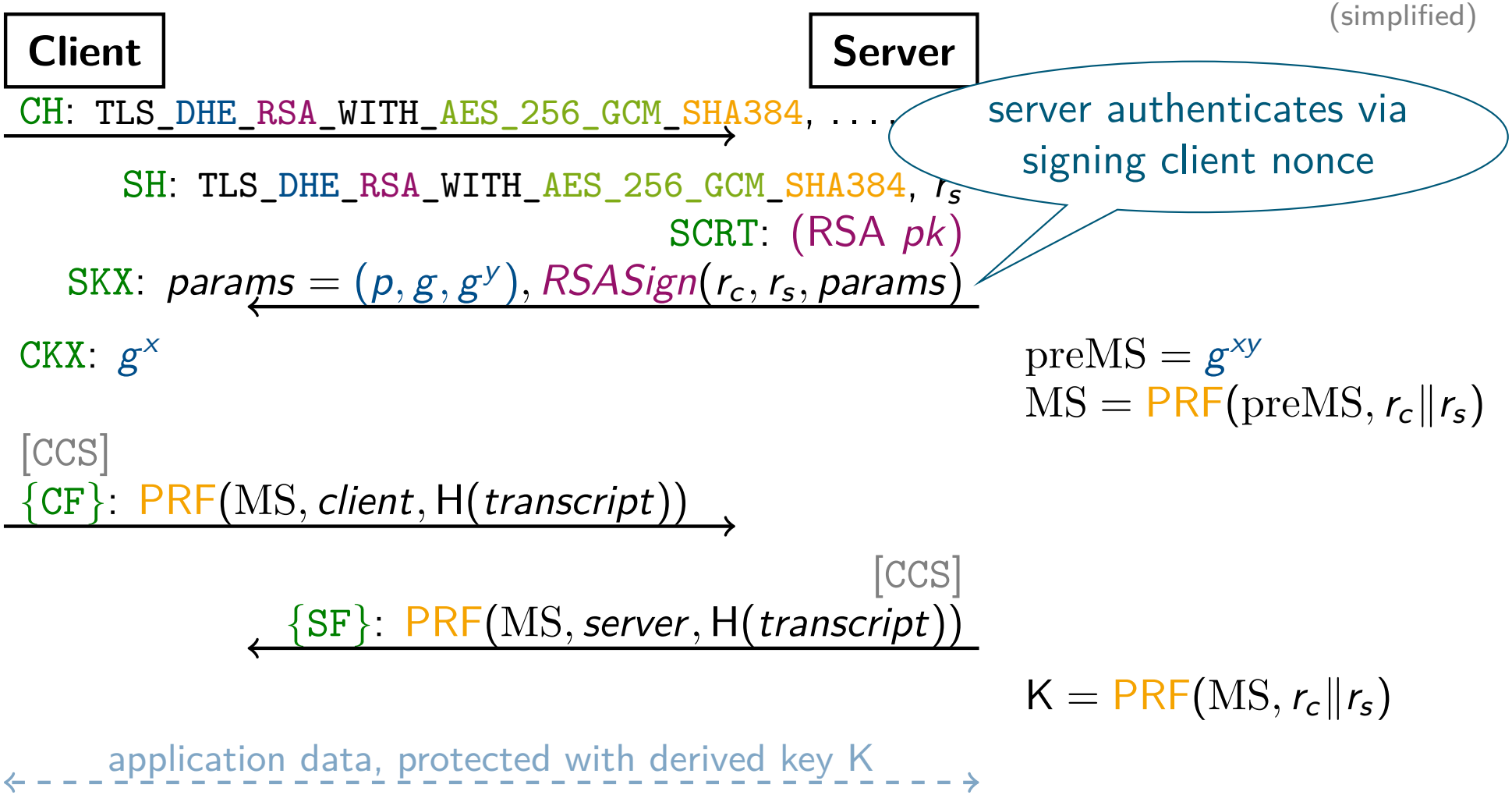
(simplified)



The TLS Protocol

Example: TLS_DHE_RSA_WITH_AES_256_GCM_SHA384

— Record Protocol

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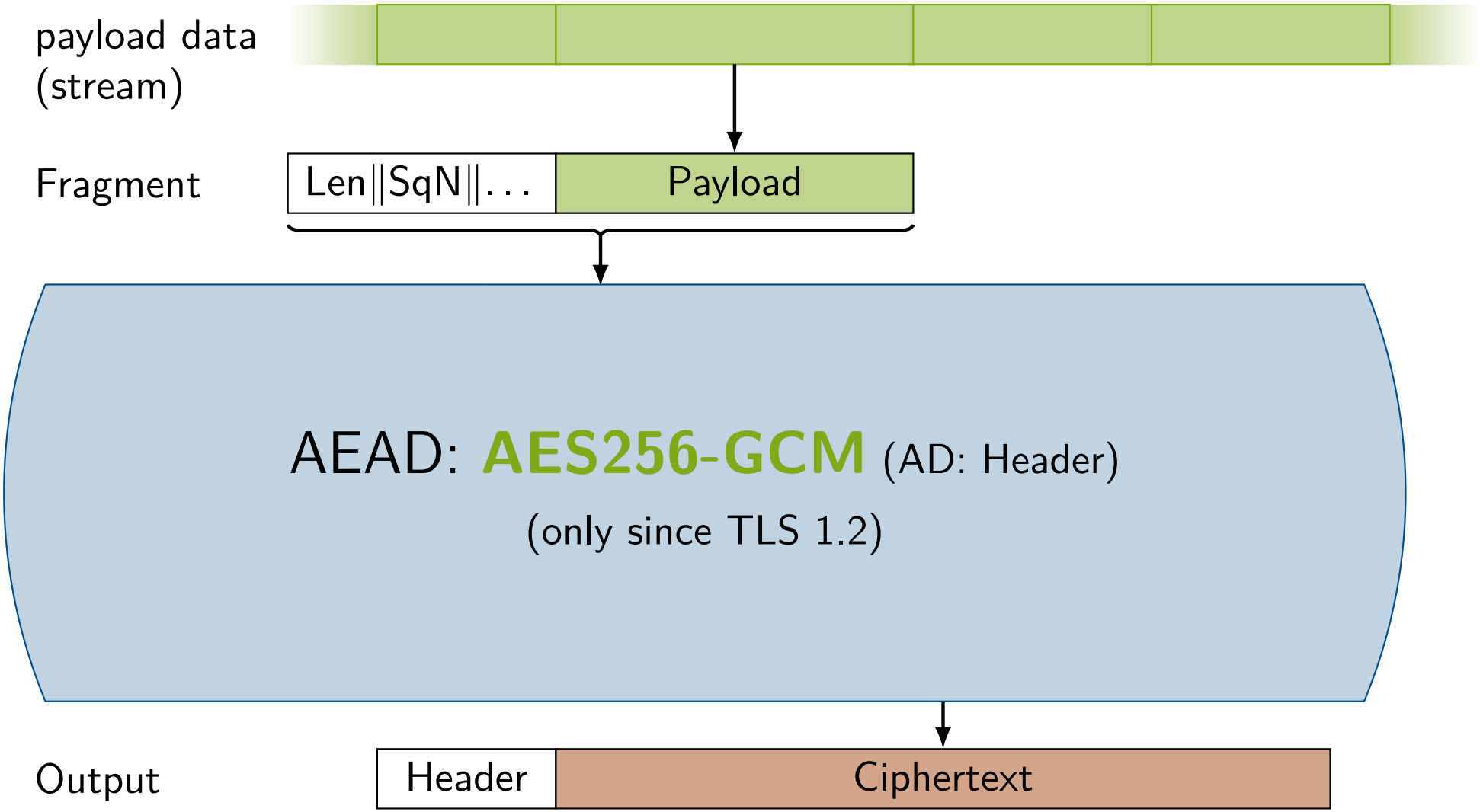

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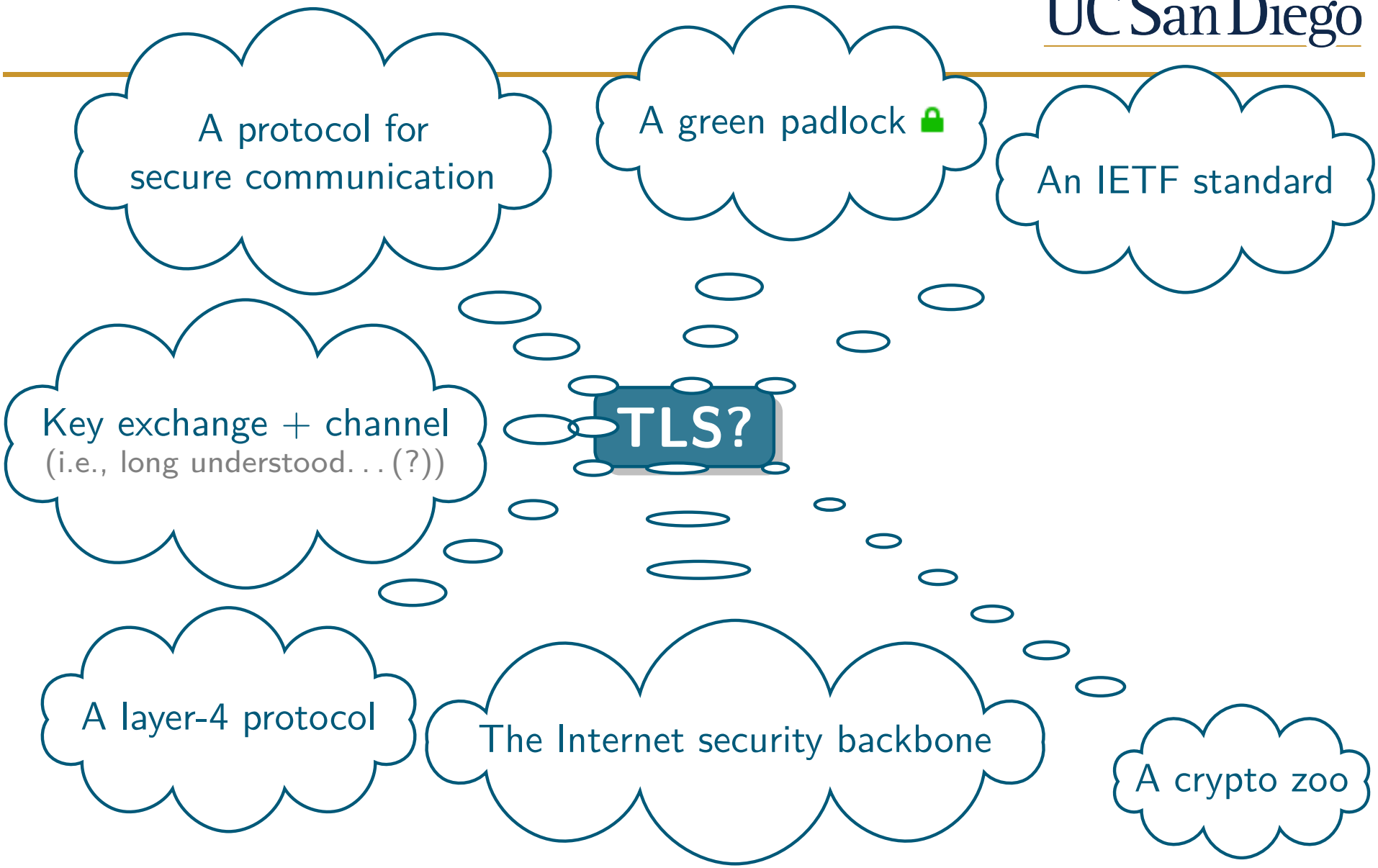

The TLS Protocol

Resumption, Renegotiation, Extensions, ...

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- **(Session) Resumption**
  - abbreviated handshake based on previously established shared secret
  - multiple and possibly parallel connections from same initial secret
- **Renegotiation**
  - change of cipher suite (and keys) within session, protected by Record Protocol
  - used, e.g., for late client authentication (hiding client's identity)
    or key renewal on long-lived connections without re-establishing connection
- **Extensions & Variants**
  - extensions specify additional functionality and/or security features
  - e.g.: AEAD cipher suites, ECC, connections to other protocols, ...
  - some mandatory to implement, some security-critical patches
  - DTLS: variant for TLS over UDP
- **TLS: complex protocol with many subtly interacting sub-components**

"What could possibly go wrong?" :-) (Kenny Paterson)

TLS Security Issues

Well. . .

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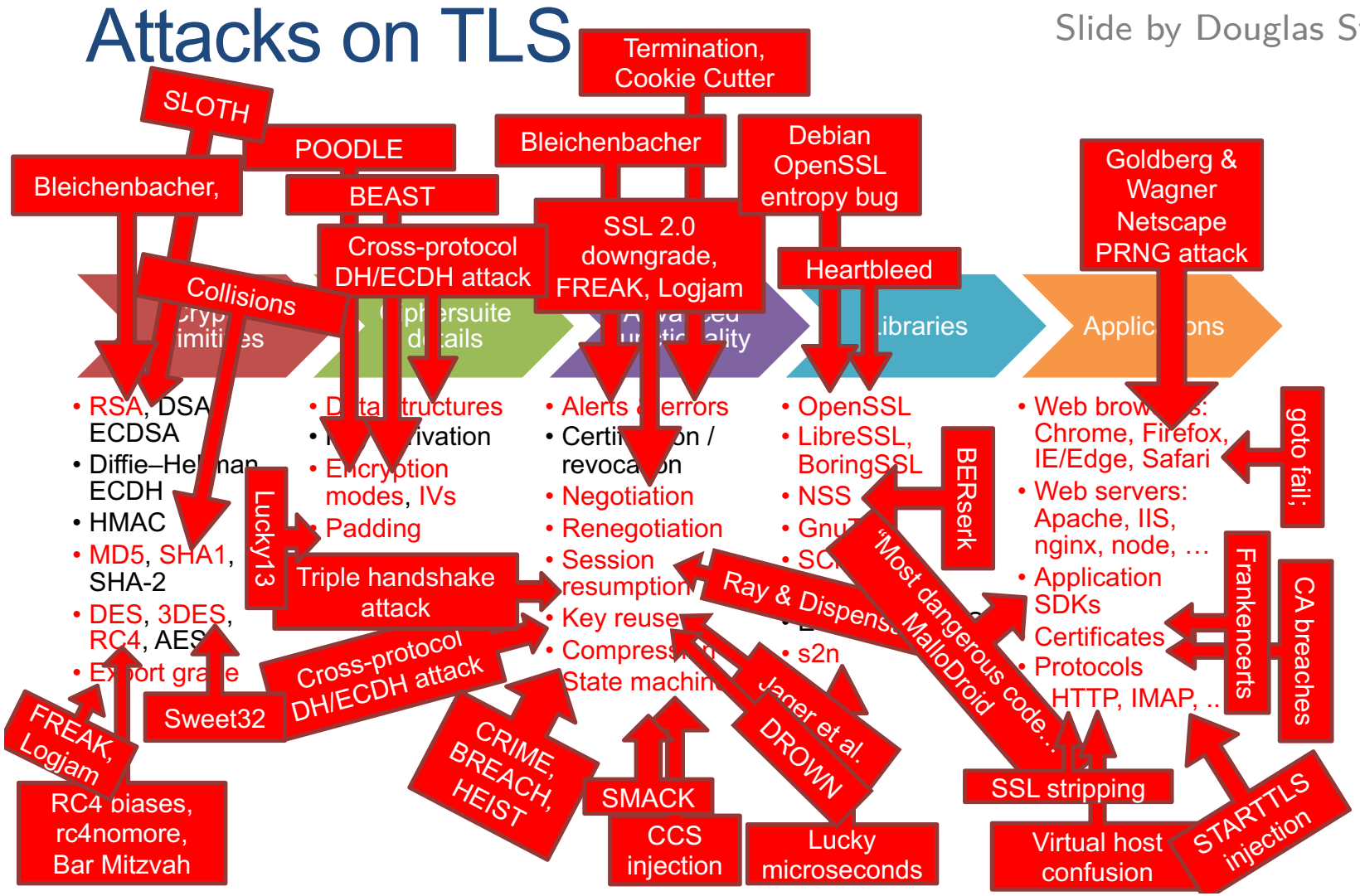

TLS Security Issues

@Crypto: MAC-Encode-Encrypt and Lucky13

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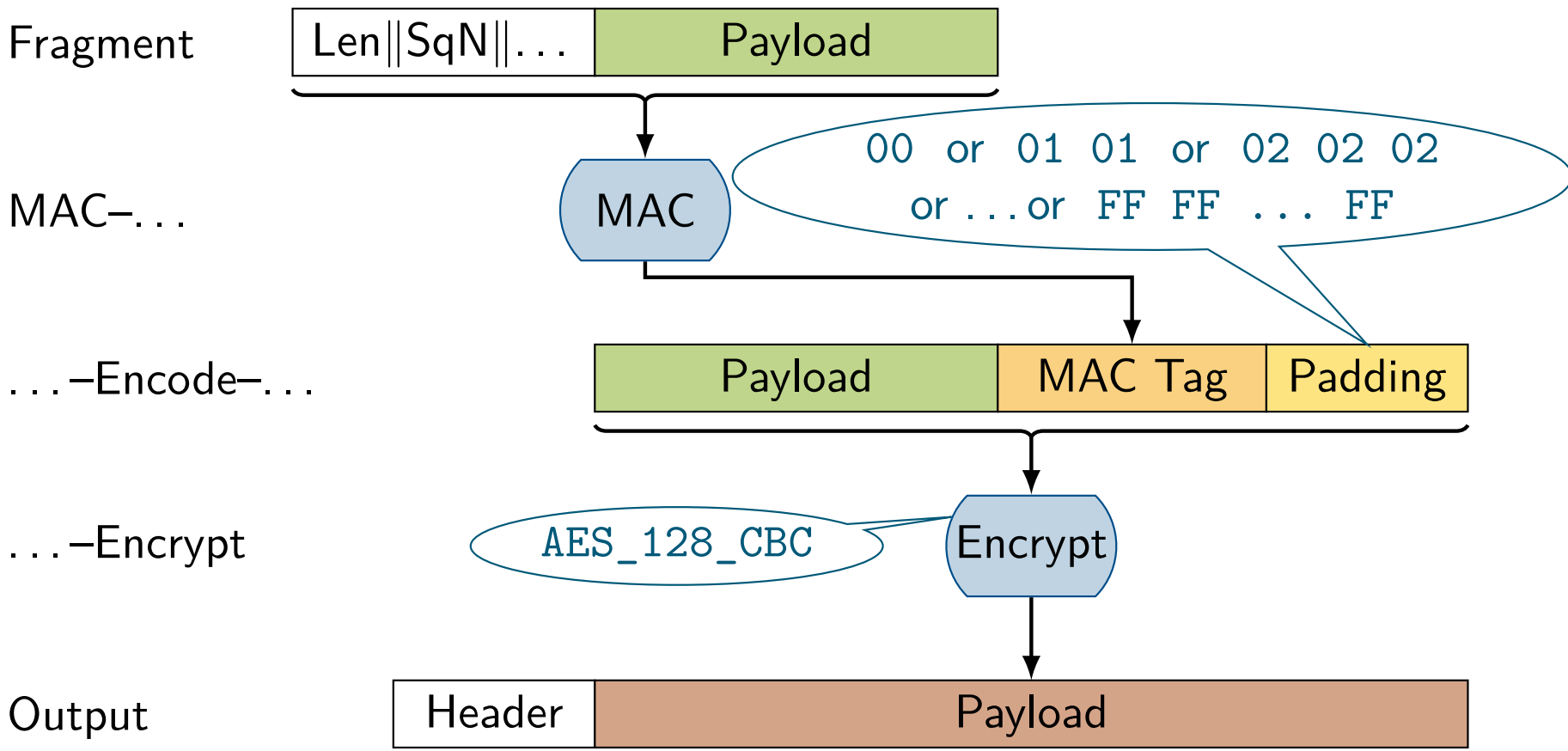
- core issue: (good) MAC –then– (good) Encrypt $\neq$ **CCA-secure** AE [BN00]



TLS Security Issues

@Crypto: MAC-Encode-Encrypt and Lucky13

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- core issue: (good) MAC –then– (good) Encrypt $\neq$ **CCA-secure** AE [BN00]
- **MAC–then–AES-CBC Decryption**
  - decrypt ciphertext to obtain Payload $\|$ MAC Tag $\|$ Padding
  - remove padding — what if padding is incorrect?
  - check MAC
- A padding oracle
  - in a modified ciphertext, either the padding check fails. . .
  - . . . or the MAC check fails
  - if the two are distinguishable: padding oracle
  - can lift a padding oracle to a **decryption oracle** [Vau02] (conditions apply)
- instead of switch to CCA-secure Enc-then-MAC, TLS tried hiding error signal
  - "compute MAC w/ zero padding"
  - "leaves a [non-exploitable] small timing channel"
  - **Lucky13** [AP13]: HMAC timing difference still big enough
  - really need constant time—which is extremely difficult!

TLS Security Issues

@Protocol Design: Weak DH Negotiation and Logjam

Mark
Feb 14

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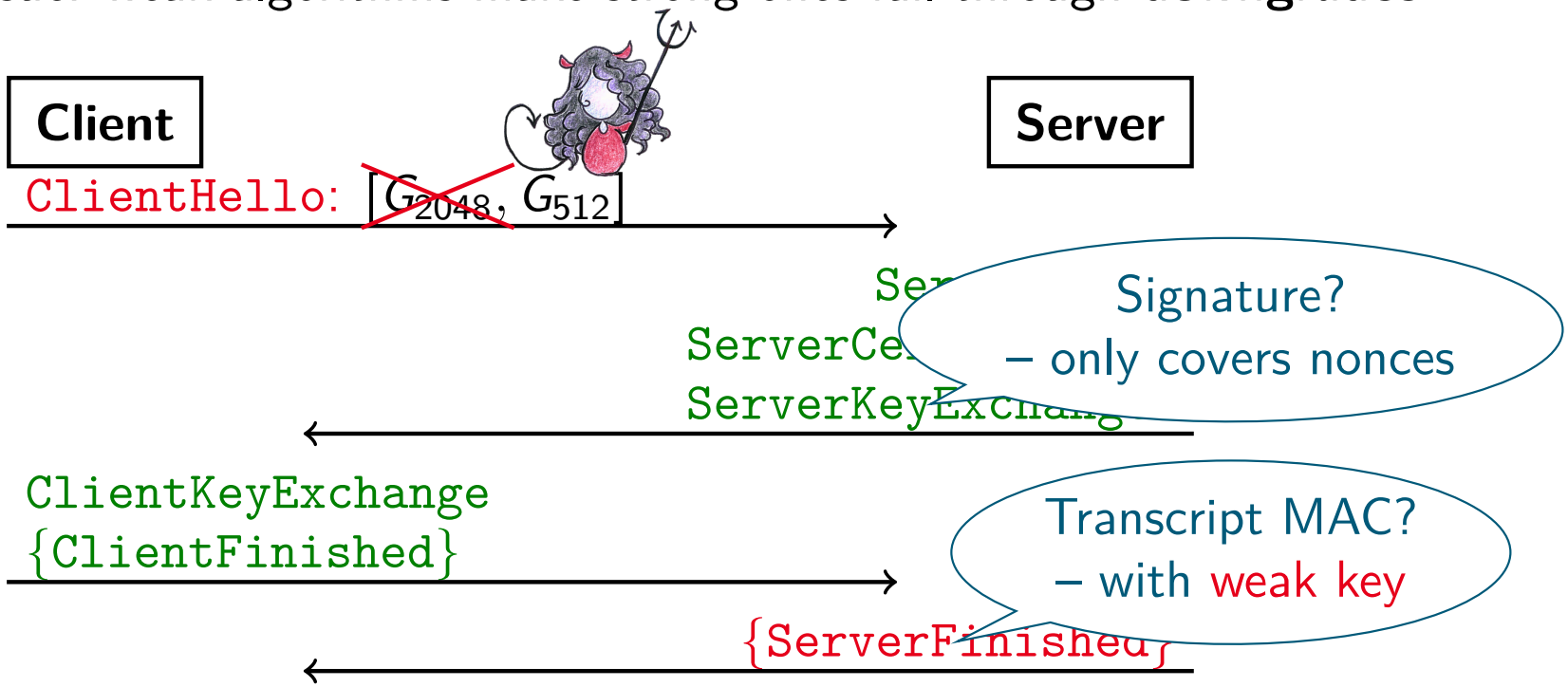
- core issue: weak algorithms make strong ones fail through **downgrades**



- **Logjam** [ABD+15]: How Diffie–Hellman Fails in Practice
  - server impersonation through support of (also) weak DH groups

drawings by *Giorgia Azzurra Marson*

TLS Security Issues

@Implementation: Buffers and Heartbleed

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- core issue: **buffer over-read** in OpenSSL
- **Heartbeat** extension (RFC 6520)
  - client sends "ping back those 4 bytes: `00 01 02 03`"
  - server responds "`00 01 02 03`"
- **Heartbleed** attack [Hea]
  - client sends "ping back those **16 Kbytes**: `00 01 02 03`"
  - server responds "`00 01 02 03 ...<memory dump>`"
  - possibly including sensitive data like server private key etc.
- high severity & public attention — and a catchy logo

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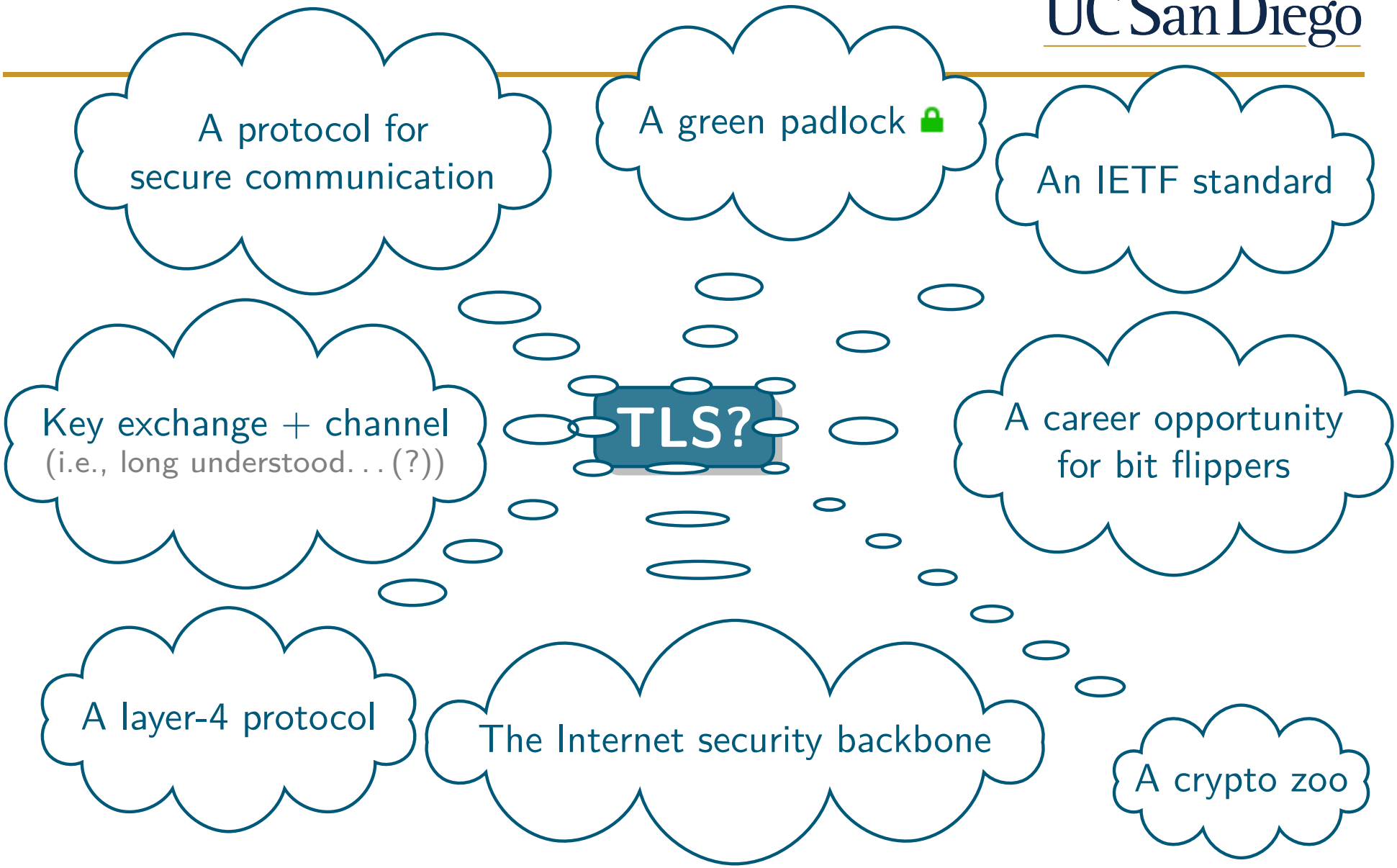

Cryptographic Background

The TLS Protocol Components

(Again, overly simplified)

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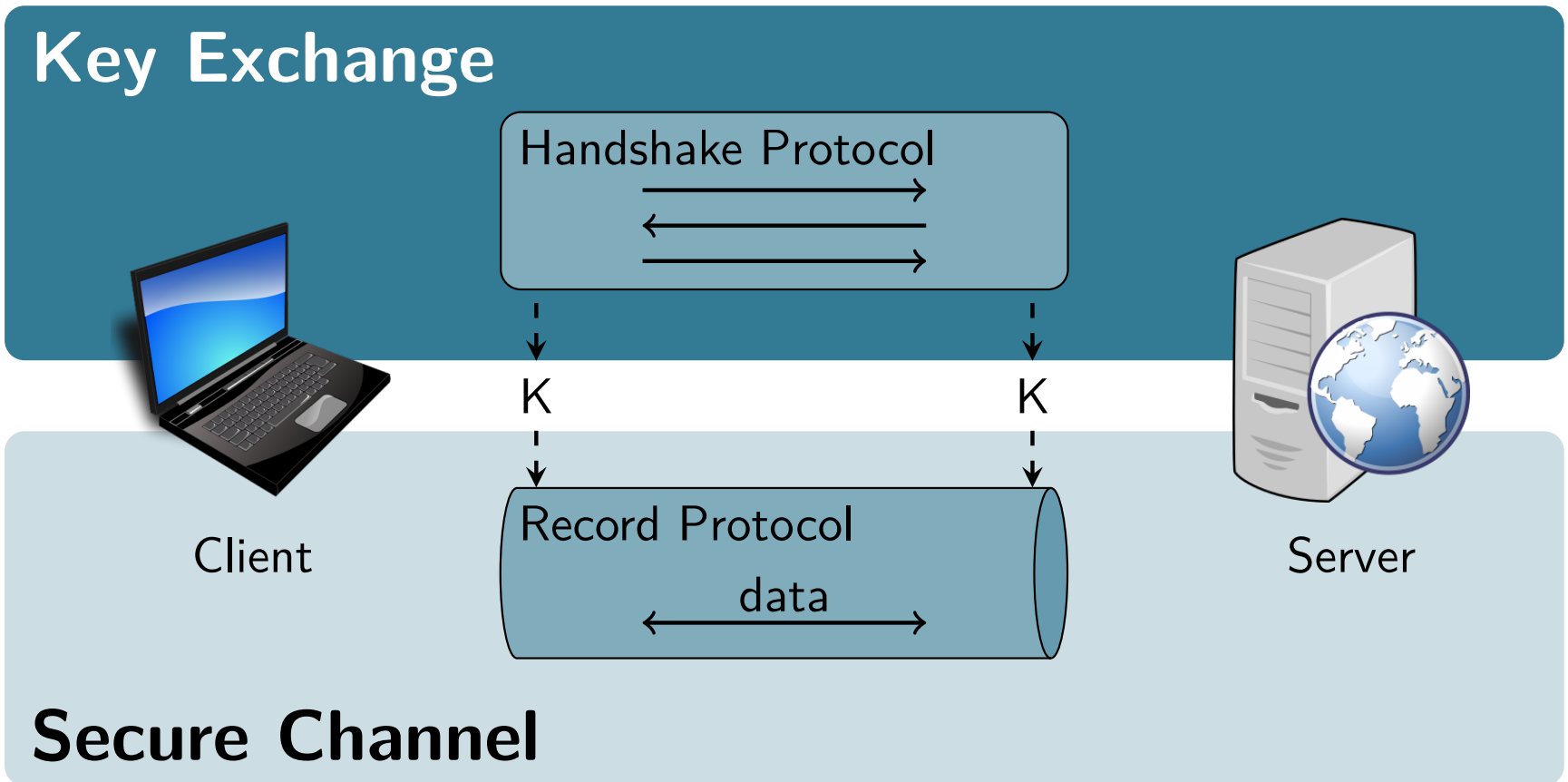

Key Exchange Security

Bellare, Rogaway 1993 [BR94]

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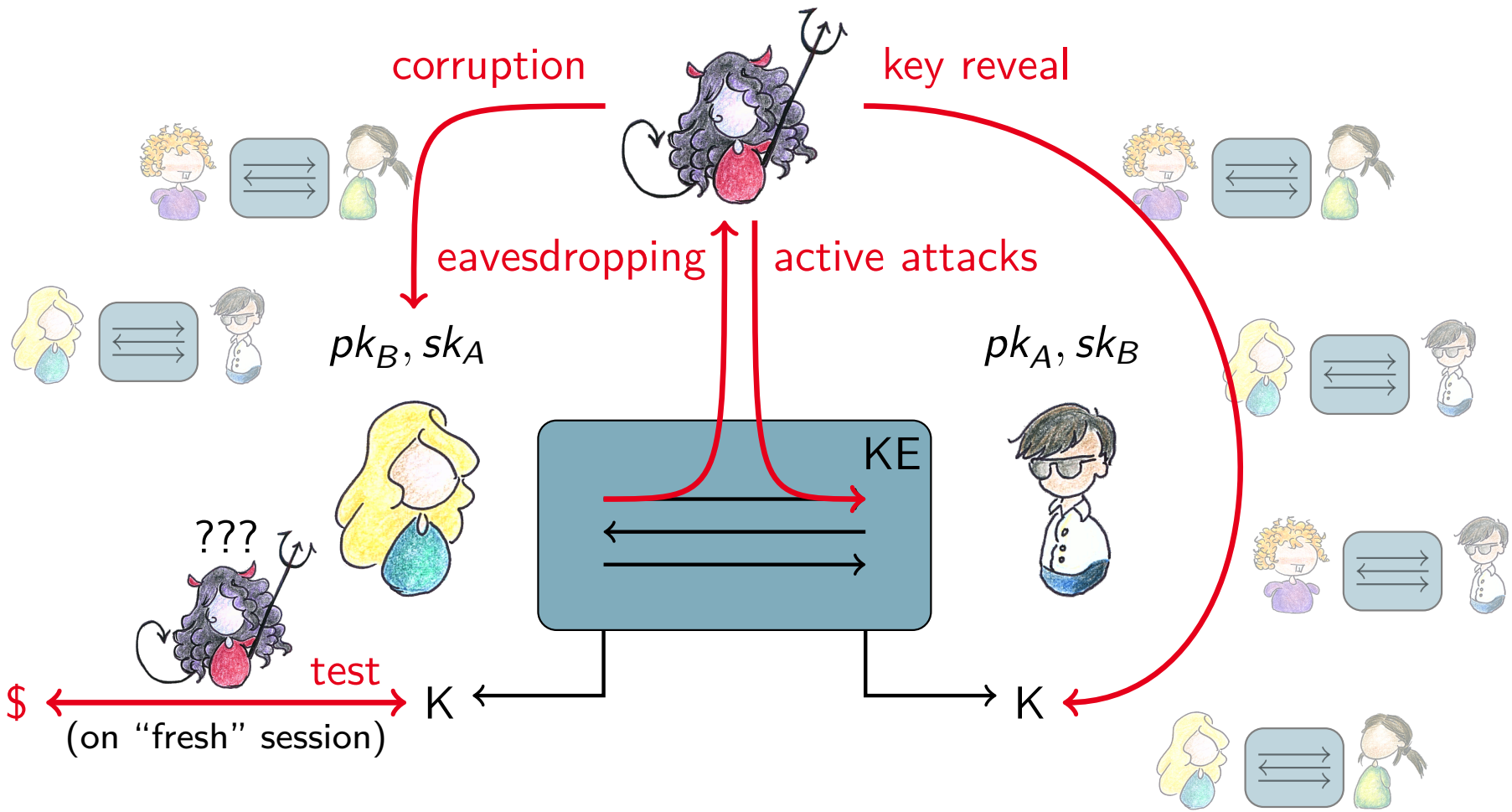

Key Exchange Security

The communication/security model

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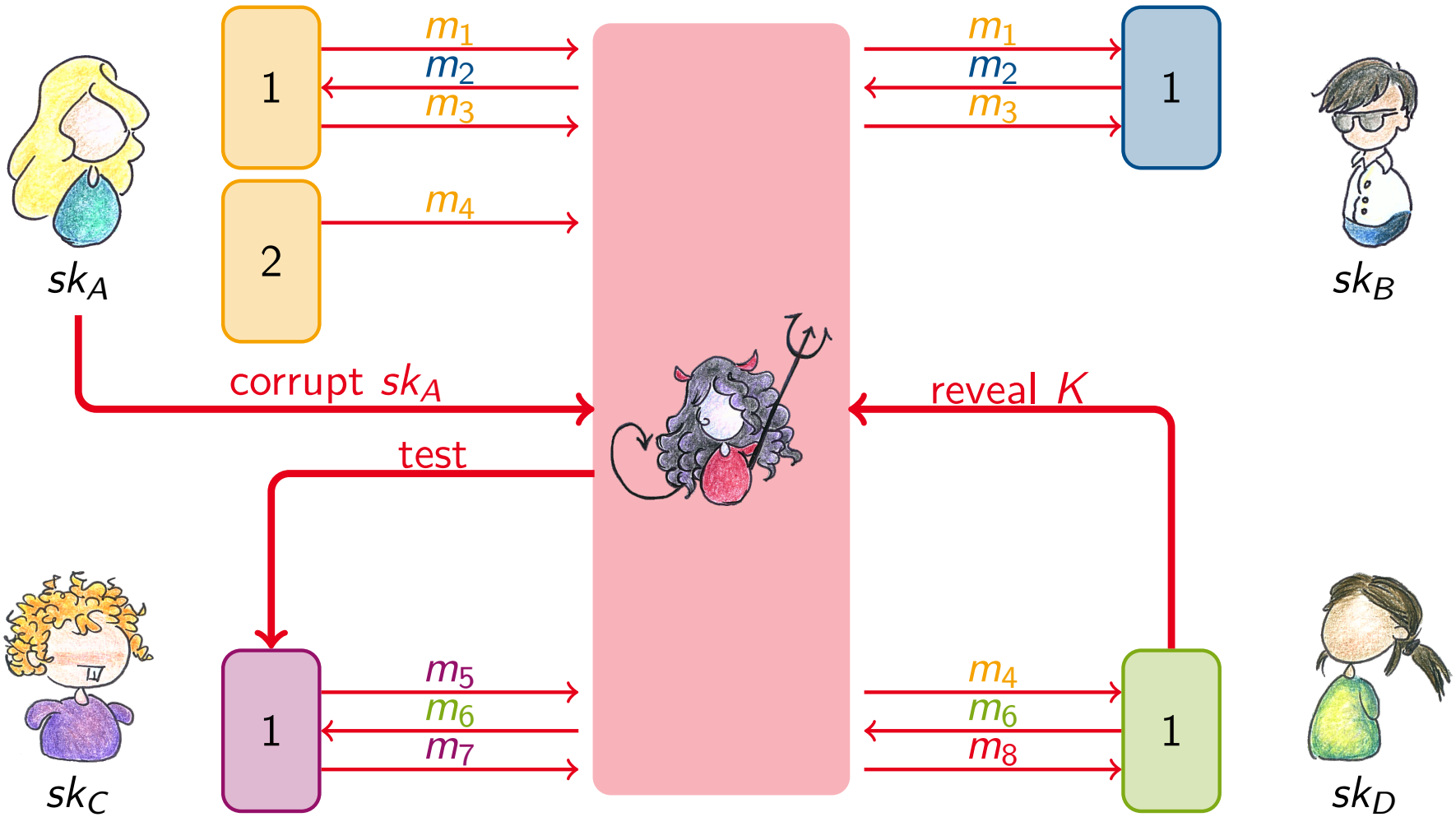
$$\mathsf{KE}(id, pid, sk_{id}, pk_{pid}, transcript, \dots) \mapsto (msg, status, K, \dots)$$



Key Exchange Security

What we want

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Authentication

"Adversary can just relay message / act as a wire"

- relaying is the only way adversary can make sessions accept
- session accepts $\Longrightarrow \exists$ other session with matching transcript

Key Secrecy

"uncompromised session keys look random to adversary"

- Test query with hidden bit b
- outputs real K if $b = 0$, else random key $\leftarrow\!\!\$ \{0,1\}^{|K|}$
- adversary is only allowed to issue Test on "fresh"/uncompromised sessions
- $\Pr[\mathcal{A} \Rightarrow b] - \frac{1}{2} \approx \text{negl}.$

The TLS (1.2) Handshake

Why is it not BR-secure?

Joseph
Feb 7

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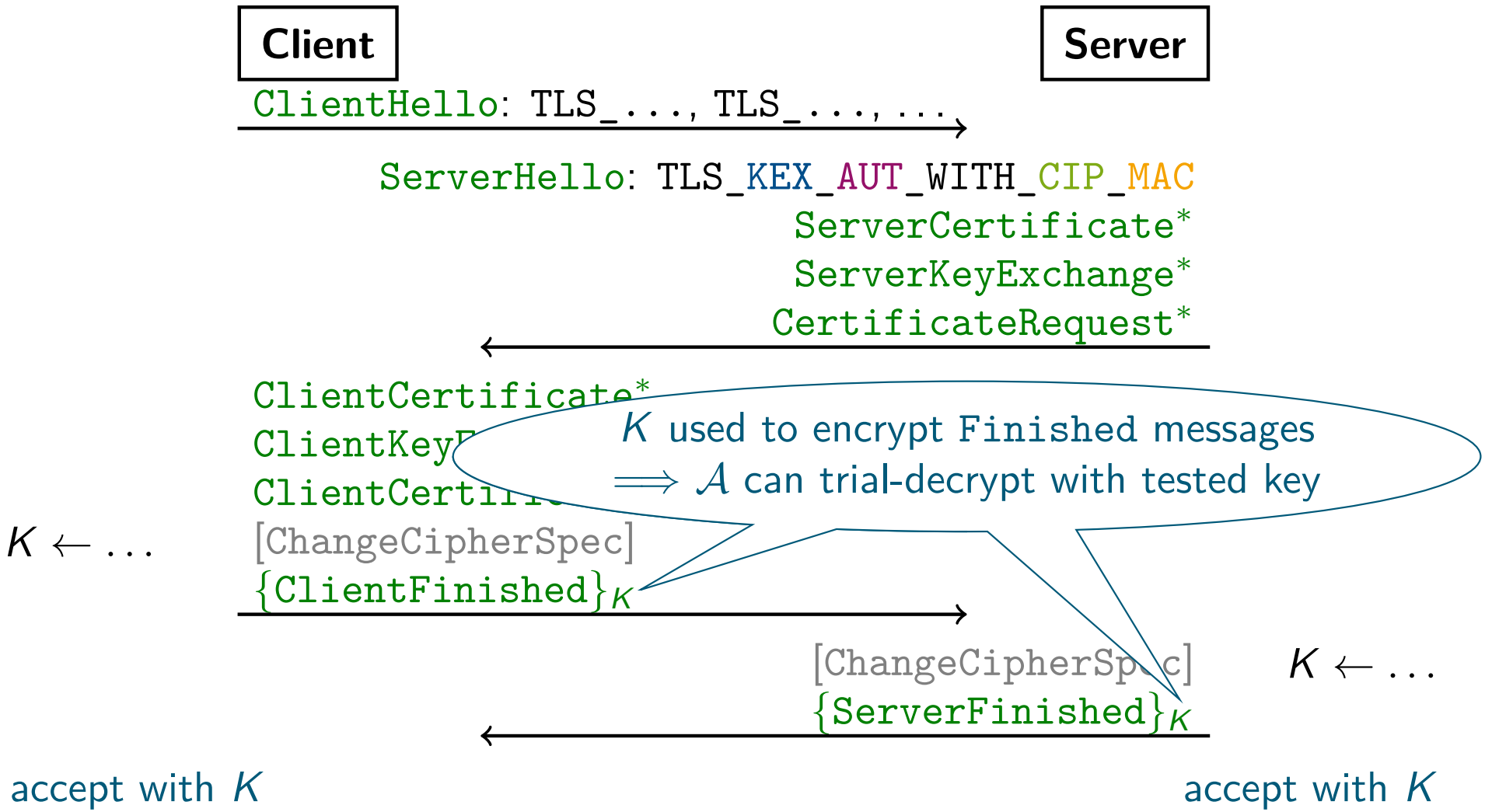

The TLS Protocol Components

(Again, overly simplified)

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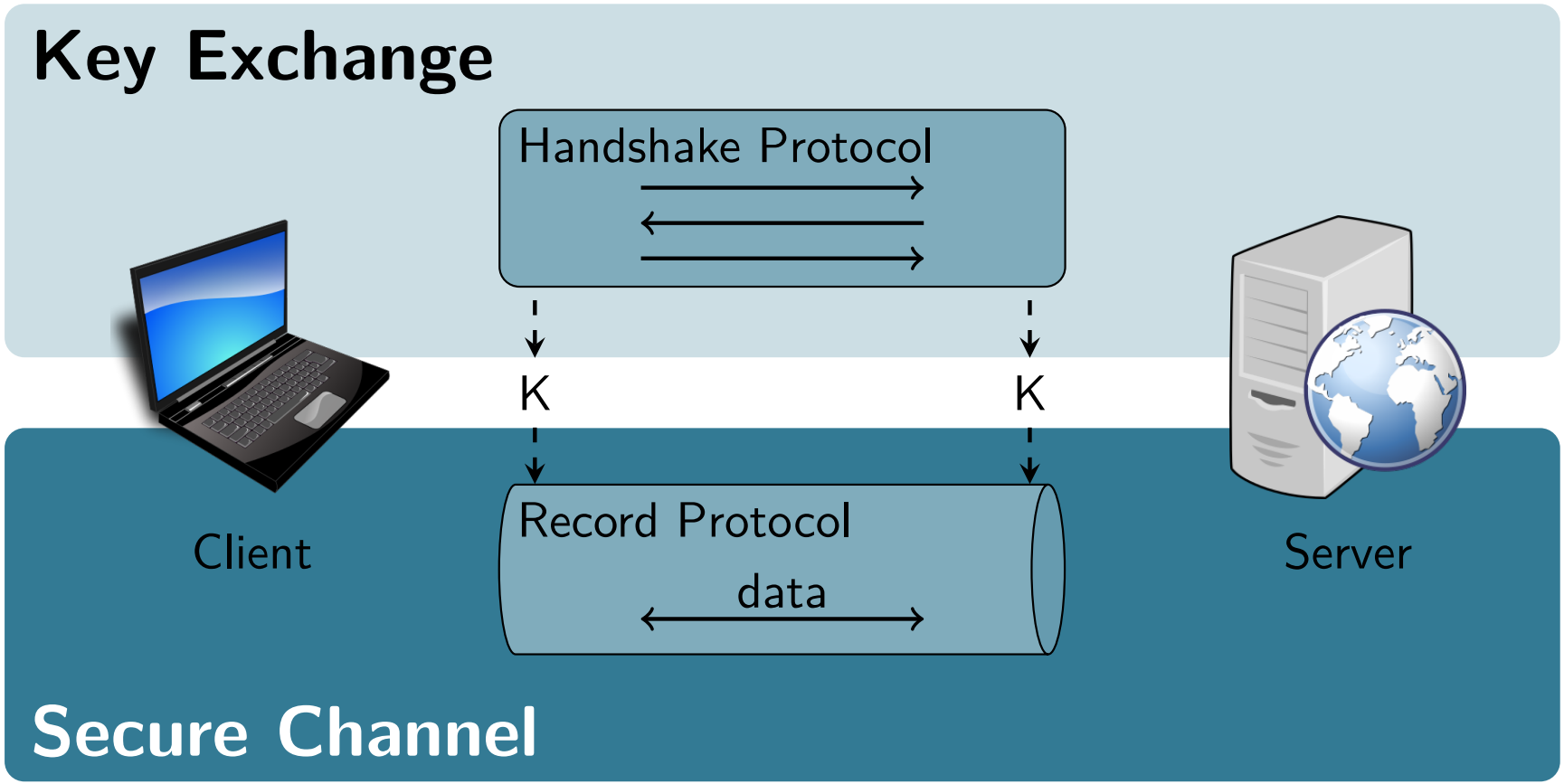

Channel Security

Bellare, Kohno, Namprempre 2002 [BKN02]

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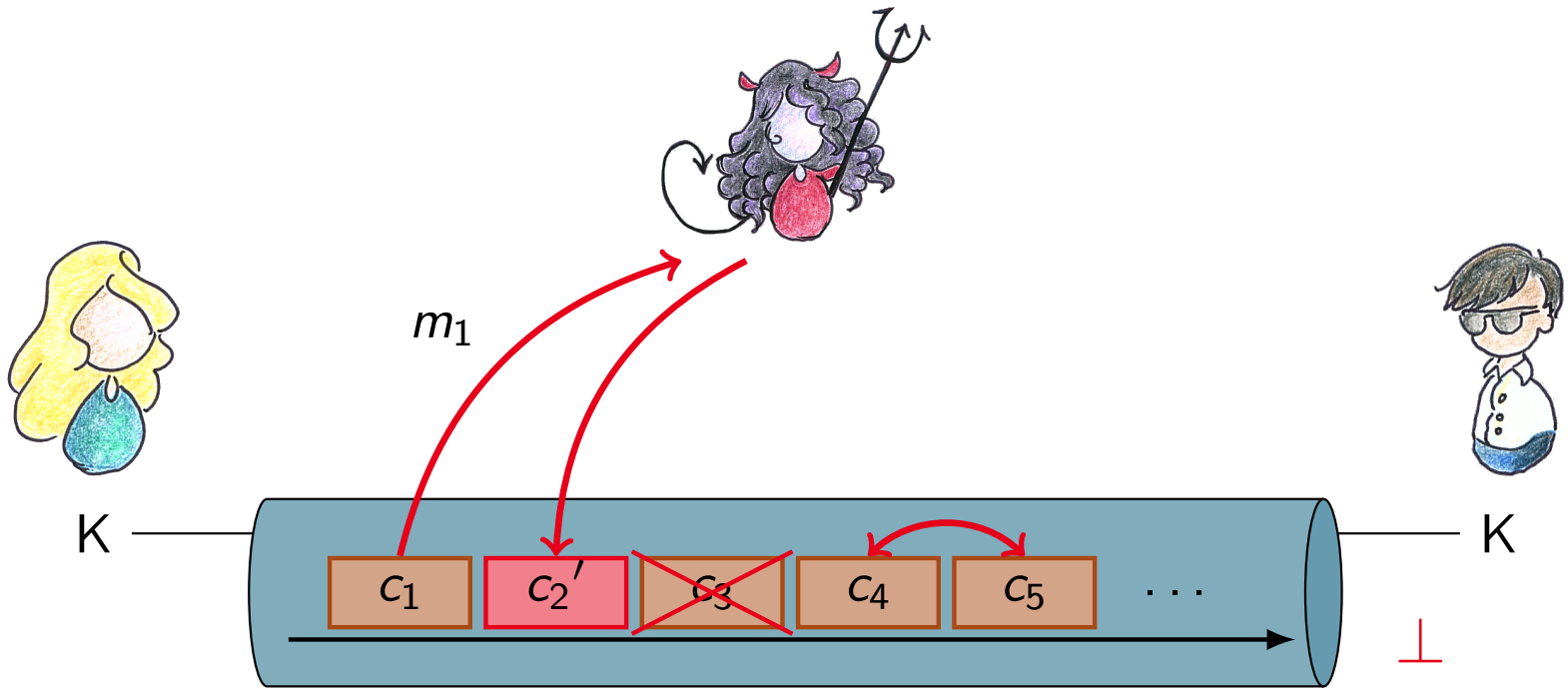

IND-sfCPA (passive confidentiality)

IND-sfCCA (active confidentiality)

INT-sfPTXT (plaintext integrity)

INT-sfCTXT (ciphertext integrity)

Channel Security

Security notions [BKN02]

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IND-sfCCA Security

$\mathrm{Expt}^{\text{IND-sfCCA}}_{\mathcal{E},\mathcal{A}}(1^\lambda)$:

1. $K \leftarrow\!\!\$\ \mathrm{KGen}(1^\lambda)$, $b \leftarrow\!\!\$\ \{0,1\}$
2. $i, j \leftarrow 0$, sync $\leftarrow 1$
3. $b' \leftarrow\!\!\$\ \mathcal{A}(1^\lambda)^{\mathcal{O}_{\mathrm{LoR}}(K,\cdot,\cdot),\mathcal{O}_{\mathrm{Dec}}(K,\cdot)}$
4. return $b = b'$

$\mathcal{O}_{\mathrm{LoR}}(K, m_0, m_1)$: // $|m_0| = |m_1|$

1. $i \leftarrow i + 1$
2. return $c_i \leftarrow \mathrm{Enc}(K, m_b)$

$\mathcal{O}_{\mathrm{Dec}}(K, c)$:

1. $j \leftarrow j + 1$
2. if $j > i$ or $c \neq c_j$: sync $\leftarrow 0$
3. if sync $= 0$: return $m \leftarrow \mathrm{Dec}(K, c)$

INT-sfCTXT Security

$\mathrm{Expt}^{\text{INT-sfCTXT}}_{\mathcal{E},\mathcal{A}}(1^\lambda)$:

1. $K \leftarrow\!\!\$\ \mathrm{KGen}(1^\lambda)$
2. $i, j \leftarrow 0$, sync $\leftarrow 1$, win $\leftarrow 0$
3. $\mathcal{A}(1^\lambda)^{\mathcal{O}_{\mathrm{Enc}}(K,\cdot),\mathcal{O}_{\mathrm{Dec}}(K,\cdot)}$
4. return win

$\mathcal{O}_{\mathrm{Enc}}(K, m)$:

1. $i \leftarrow i + 1$
2. return $c_i \leftarrow \mathrm{Enc}(K, m)$

$\mathcal{O}_{\mathrm{Dec}}(K, c)$:

1. $j \leftarrow j + 1$, $m \leftarrow \mathrm{Dec}(K, c)$
2. if $j > i$ or $c \neq c_j$: sync $\leftarrow 0$
3. if sync $= 0$ and $m \neq \perp$: win $\leftarrow 1$

Channel Security

Still work in progress. . .

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- Many more aspects to consider for secure channels in practice:
  - length-hiding / padding [PRS11]
  - fragmentation of ciphertexts [BDPS12]
  - stream-based data [FGMP15]
  - bidirectionality [MP17]
  - multiple keys [GM17]
  - multiplexing [PS18]
  - . . .

- despite being intuitively simple, the crypto community still hasn't really conclusively ventilated the question: What is a secure channel protocol?

Thank You!

TLS ≤1.2

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