Introduction to Cryptography

System Security (CM0625, CM0631) 2025-26
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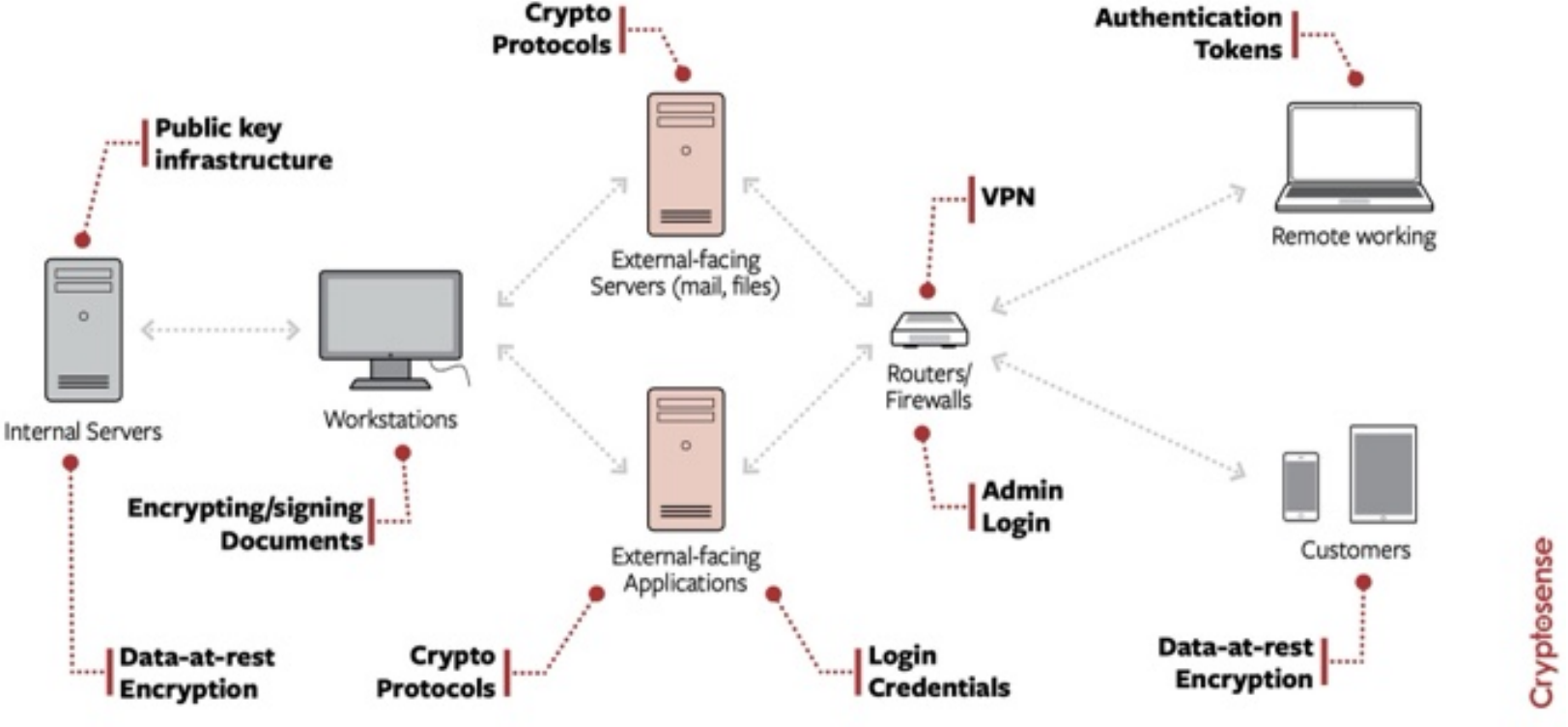
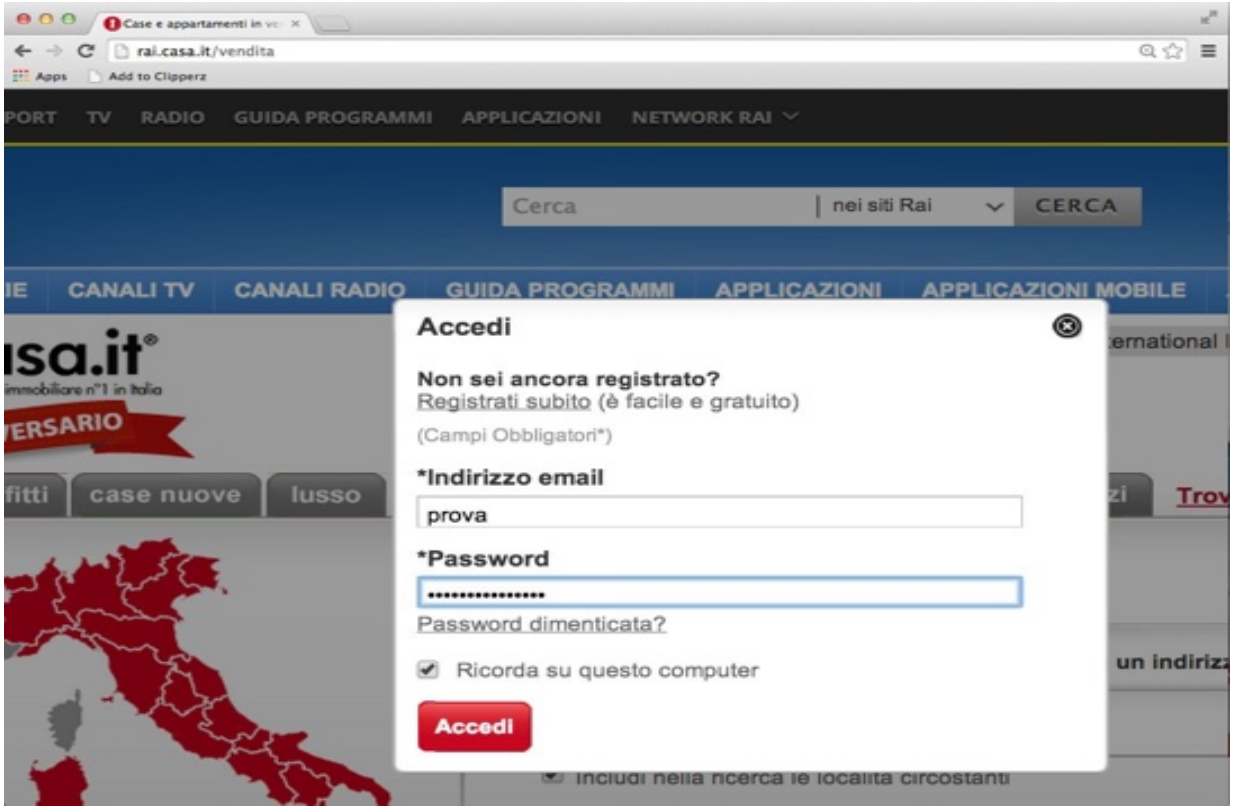
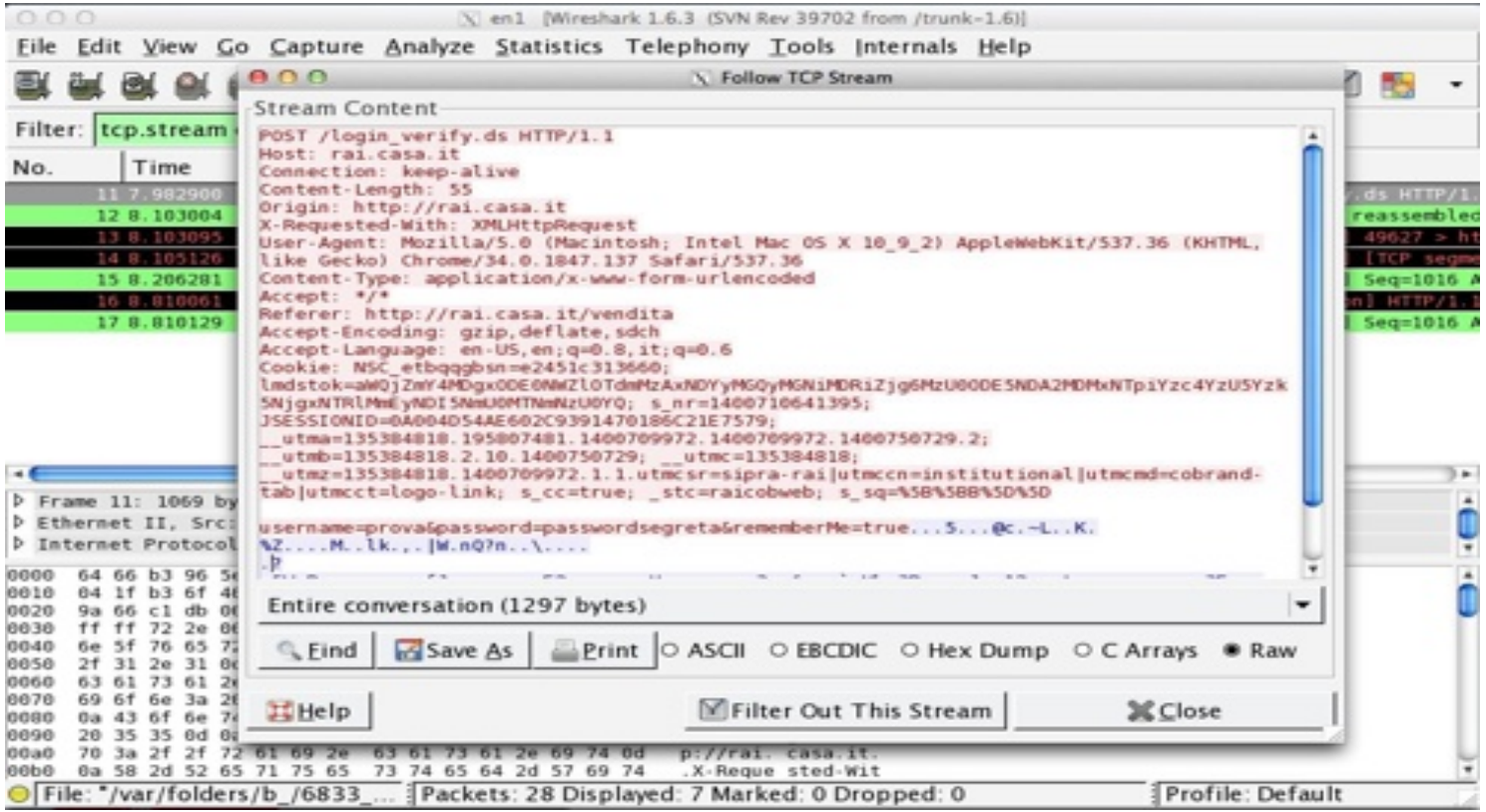
Cryptography is *everywhere*



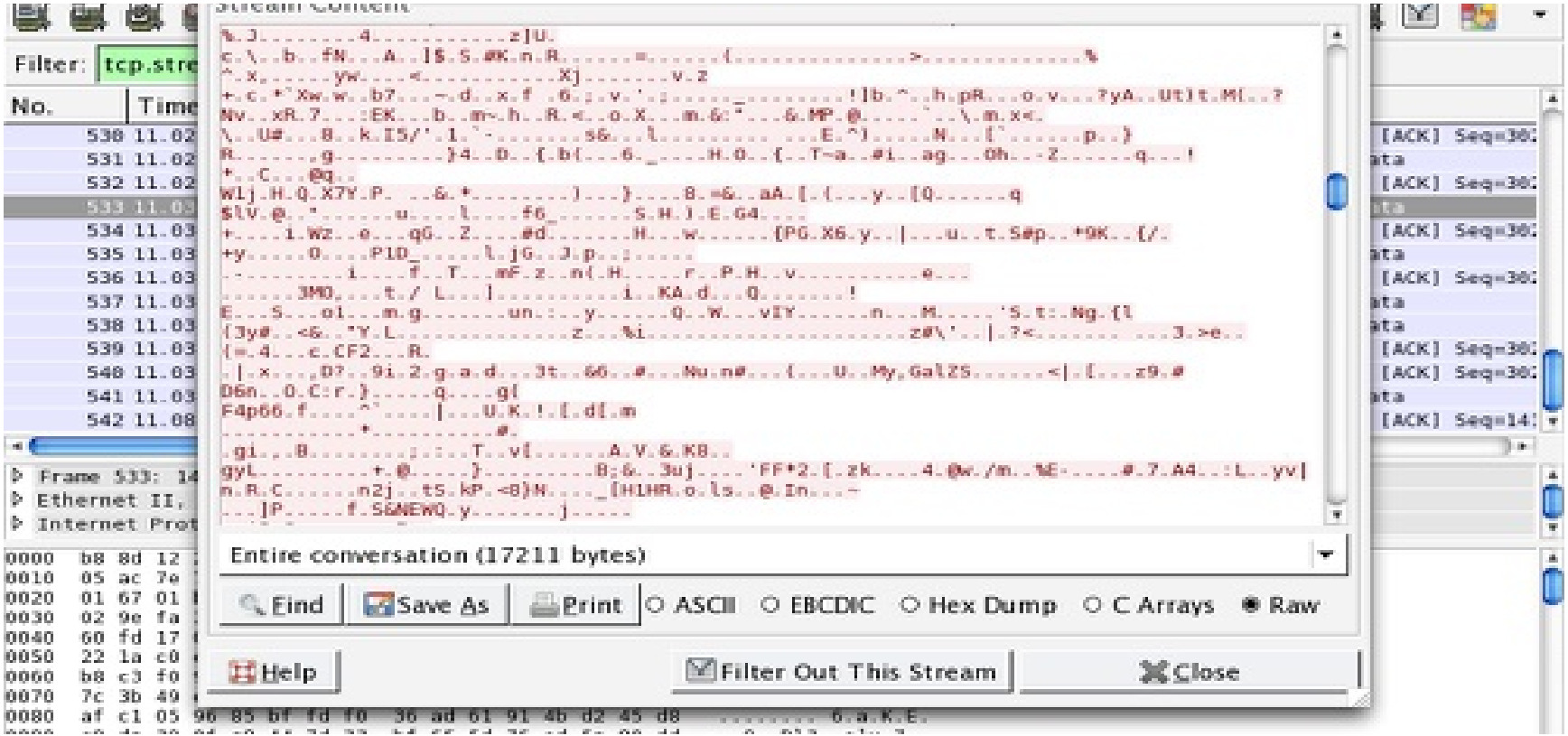
Example: cryptography over the web



http: no protection!



https: communication is encrypted



Cryptography in embedded devices

Cryptography in banks

Payments, ATMs, money transfers, ...

Hardware Security Module (HSM)

- Costs about 5k-20k € for a market of 200M € a year
- Now available in the Cloud (CloudHSM)

What is a Cipher?

A cipher is defined through two functions

- **Encryption**: given a plaintext and a key K1 returns a ciphertext

$$\mathbf{E}_{K1}(X) = Y$$

- **Decryption**: given a ciphertext and a key K2 returns a plaintext

$$\mathbf{D}_{K2}(Y) = X$$

Symmetric and asymmetric ciphers

Keys K1 and K2 are related: decrypting the encryption of X we obtain X:

$$D_{K2}(E_{K1}(X)) = X$$

- When K1=K2 we have a **symmetric** key cipher (example: AES)
- When K1≠K2 we have an **asymmetric** key cipher (example: RSA)

Security (*known plaintext* scenario): it should be ***infeasible*** to compute X or K2 from Y even knowing other pairs (X_1,Y_1), … , (X_n,Y_n)

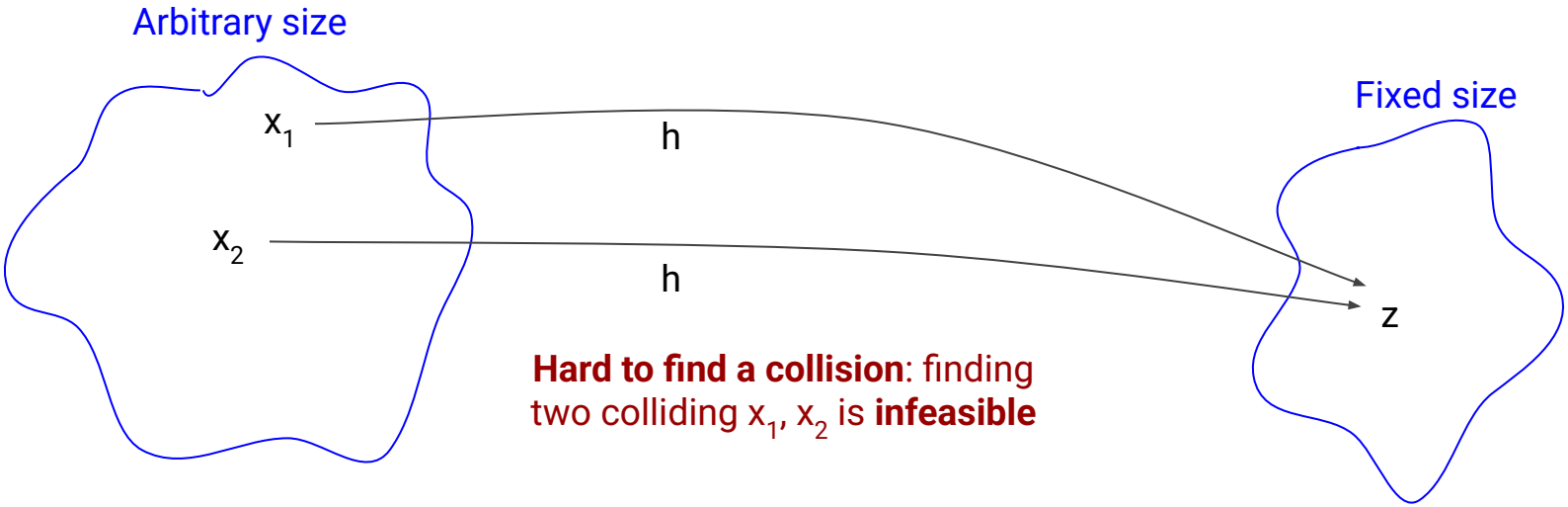
Cryptographic hash functions

Recall what a hash function is:

Definition (***hash function***). A hash function h computes efficiently a **fixed length** value h(x)=z called **digest**, from an x of **arbitrary size**.

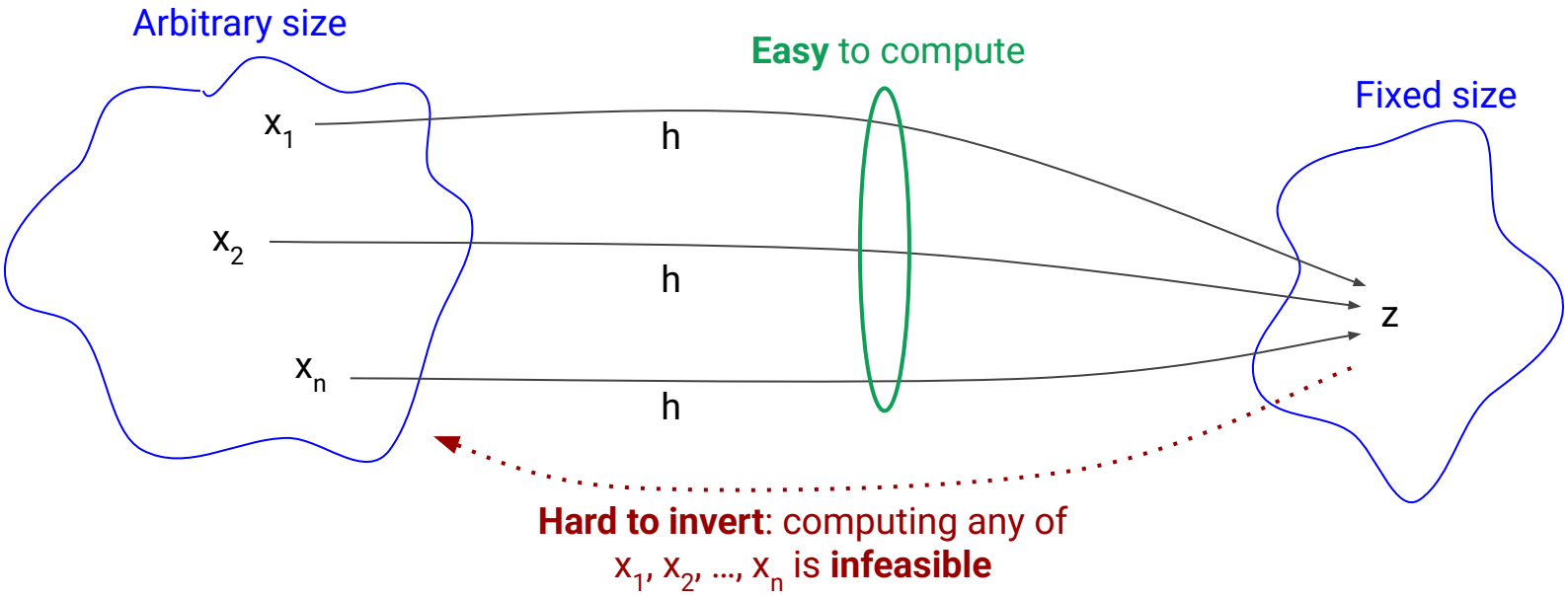
NOTE: **Collisions** are possible: h(x1) = h(x2)

Collision resistant hash function



Definition (***collision resistant hash function***). A hash function h is **collision resistant** if it is infeasible to compute different x1, x2 such that h(x1) = h(x2)

One-way hash function



Definition (***one-way hash function***). A hash function h is **one-way** if, given a digest z, it is ***infeasible*** **to compute a preimage** x' such that h(x')=z

Nice and elegant … but things can go wrong

Many attacks on real world cryptography in the last years:

- S Calzavara, R Focardi, M Nemec, A Rabitti, M Squarcina. **Postcards from the post-HTTP world: amplification of HTTPS vulnerabilities in the web ecosystem**. IEEE S&P 2019
- R Focardi, F Palmarini, M Squarcina, G Steel, M Tempesta. **Mind Your Keys? A Security Evaluation of Java Keystores**. NDSS 2018
- R. Verdult, F. D. Garcia and B. Ege. **Dismantling Megamos Crypto: Wirelessly Lockpicking a Vehicle Immobilizer**. USENIX Security 2013
- R. Bardou, R. Focardi, Y. Kawamoto, L. Simionato, G. Steel, J. Tsay. **Efficient Padding Oracle Attacks on Cryptographic Hardware**. CRYPTO 2012
- M. Bortolozzo, M. Centenaro, R. Focardi, G. Steel. **Attacking and fixing PKCS#11 security tokens**. ACM CCS 2010
- F. D. Garcia, P. van Rossum, R. Verdult and R. Wichers Schreur. **Wirelessly Pickpocketing a Mifare Classic Card**. IEEE S&P 2009

Amplification of HTTPS vulnerabilities in the web ecosystem. IEEE S&P 2019

Smartcards and crypto tokens

Device		Supported Functionality						Attacks found				
Brand	Model	s	as	cobj	chan	w	ws	wd	rs	ru	su	Tk
Aladdin	eToken PRO	✓	✓	✓	✓	✓	✓	✓				wd
Athena	ASEKey	✓	✓	✓								
Bull	Trustway RCI	✓	✓	✓	✓	✓	✓	✓				wd
Eutron	Crypto Id. ITSEC		✓	✓								
Feitian	StorePass2000	✓	✓	✓	✓	✓	✓	✓	✓	✓		rs
Feitian	ePass2000	✓	✓	✓	✓	✓	✓	✓	✓	✓		rs
Feitian	ePass3003Auto	✓	✓	✓	✓	✓	✓	✓	✓	✓		rs
Gemalto	SEG		✓		✓							
MXI	Stealth MXP Bio	✓	✓		✓							
RSA	SecurID 800	✓	✓	✓	✓				✓	✓	✓	rs
SafeNet	iKey 2032	✓	✓	✓		✓						
Sata	DKey	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	rs
ACS	ACOS5	✓	✓	✓	✓							
Athena	ASE Smartcard	✓	✓	✓								
Gemalto	Cyberflex V2	✓	✓	✓		✓	✓	✓				wd
Gemalto	SafeSite V1		✓		✓							
Gemalto	SafeSite V2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	rs
Siemens	CardOS V4.3 B	✓	✓	✓		✓				✓		ru

Real attacks!

20 February 2013

35 000 000 € stolen from ATMs in **less than 10 hours**

People think crypto look like this ...

… but it is more like this!

16th Century, Citadel of Dinant, Belgium.

Cryptographic vulnerabilities

Vulnerabilities in applications: can reveal keys or downgrade to less secure mechanisms

(In)security of mechanisms: Crypto mechanisms **are not** equally secure

Configuration and management: The **configuration and management** of cryptographic systems is complex and error prone

Cryptanalysis: Improvements in **technology** and **cryptanalysis** require better crypto

Vulnerabilities in applications

Heartbleed

Vulnerability in **OpenSSL**, the protocol underneath https

An *over-read* allows for accessing process memory where **server keys** are stored

Once those keys are leaked it is possible to mount a **MITM attack** and intercept the whole Web session

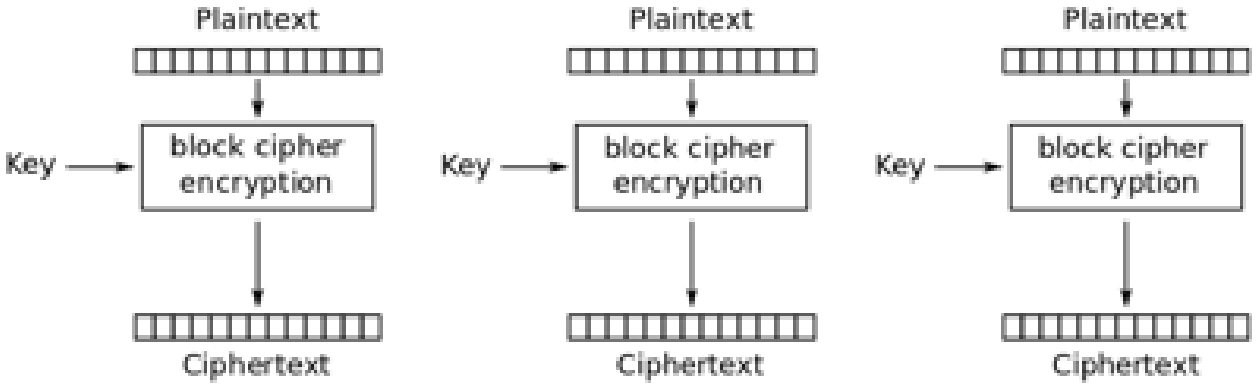
http://heartbleed.com/

(In)security of mechanisms

Modes of operation

Needed, for example, when data is bigger than the block size

Example: AES-ECB is a mode of operation that splits long messages into blocks of 16 bytes (the size of AES block)



ECB weaknesses

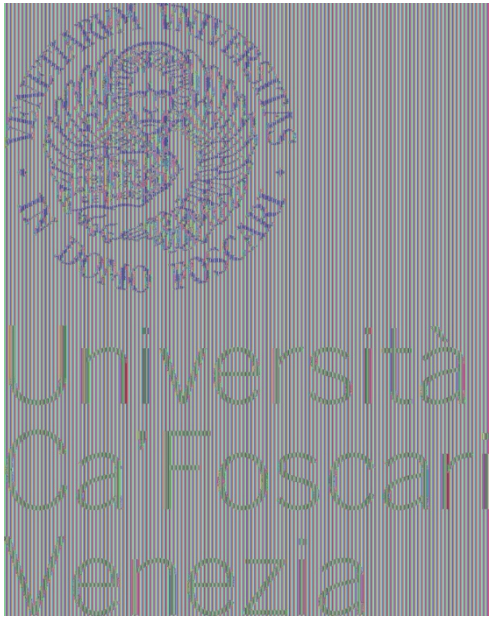
In ECB blocks are encrypted **independently** under the same key

- **Problem 1**: Equal blocks are encrypted in the same way
- **Problem 2**: Swapping encrypted blocks also swaps plaintext blocks

⇒ Poor confidentiality and integrity

Example 1: poor confidentiality

plaintext



ciphertext (ECB)

Example 1: simple substitutions of blocks

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plaintext

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ciphertext, after simple substitutions

Example 1: using CBC!

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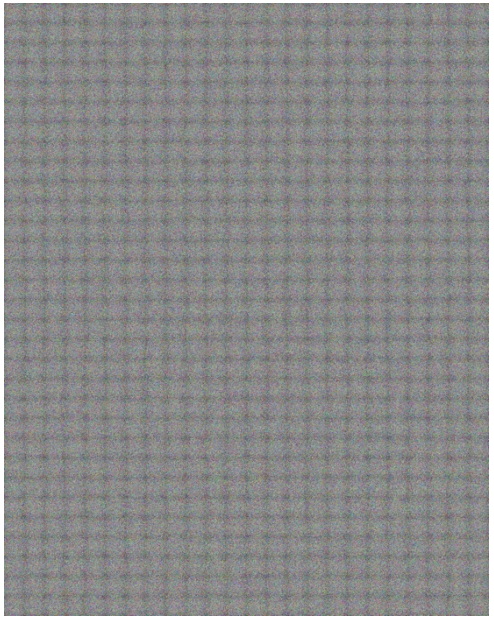


plaintext

ciphertext (CBC mode)

Example 2: breaking integrity

Consider sentences:

- `Security course is great!!`
- `Today's weather is really bad!`

When splitted in 16 bytes (AES) blocks they become:

- `Security course` `is great!!`
- `Today's weather` `is really bad!`

Task: given the two ciphertexts in AES-ECB, forge a new valid ciphertext putting the security course in a bad light 😅

Chosen plaintext attack in ECB

If an attacker can prepend arbitrary prefix to the plaintext they can bruteforce blocks byte after byte

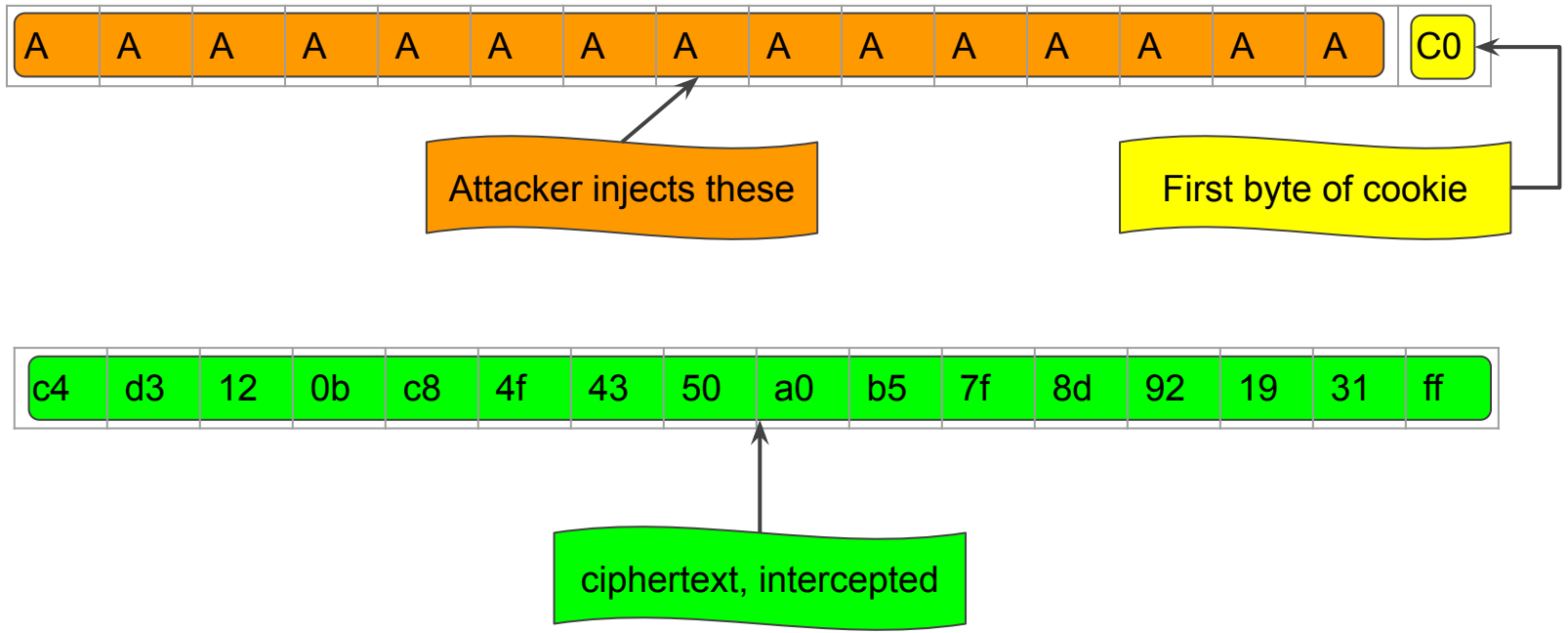
Intuitively:

- prepend 15 known bytes
- bruteforce byte 16
- iterate over all bytes

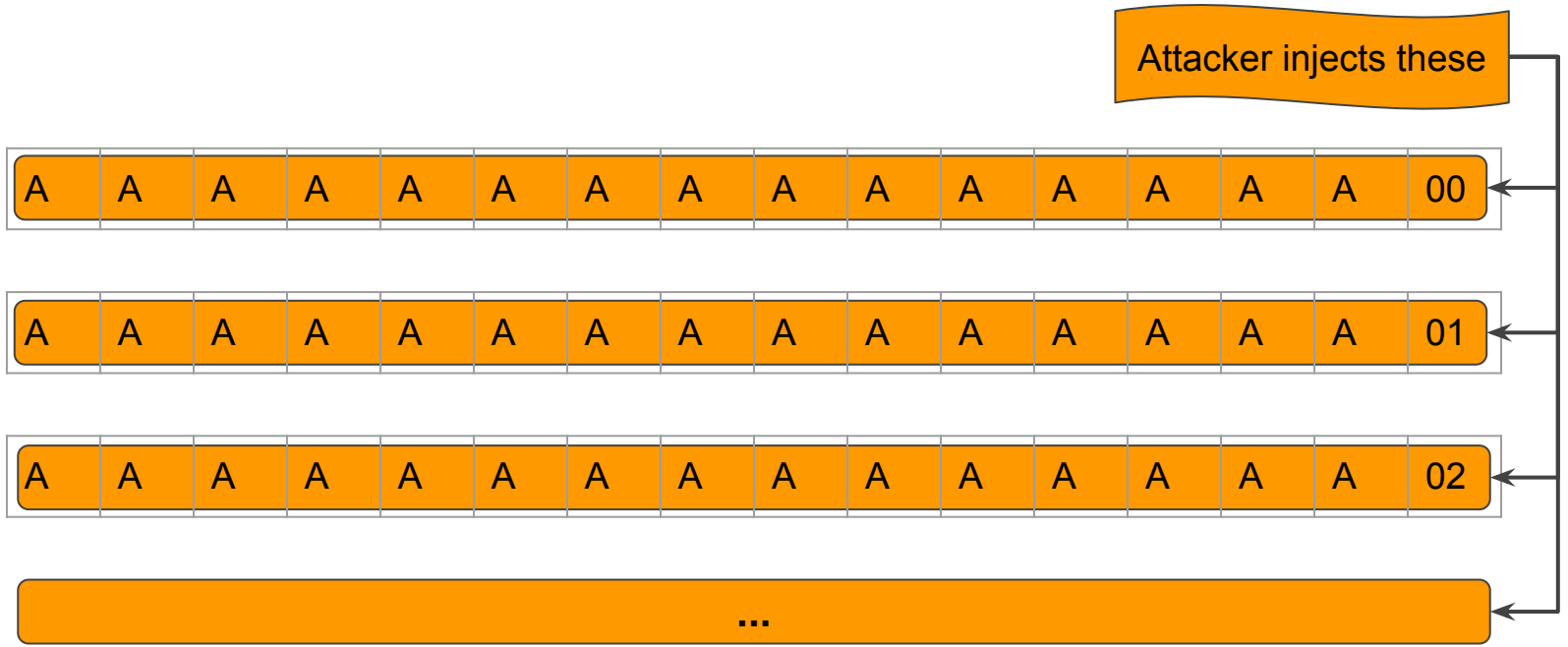
Realistic scenario (similar to the one in the BEAST attack):

- Secure session cookies are sent over HTTPS
- Javascript cannot access them
- Malicious javascript can forge cross-domain requests to honest domains (cookie is sent!)
- Attacker can add plaintext before the cookie value!

The attack in detail (1)

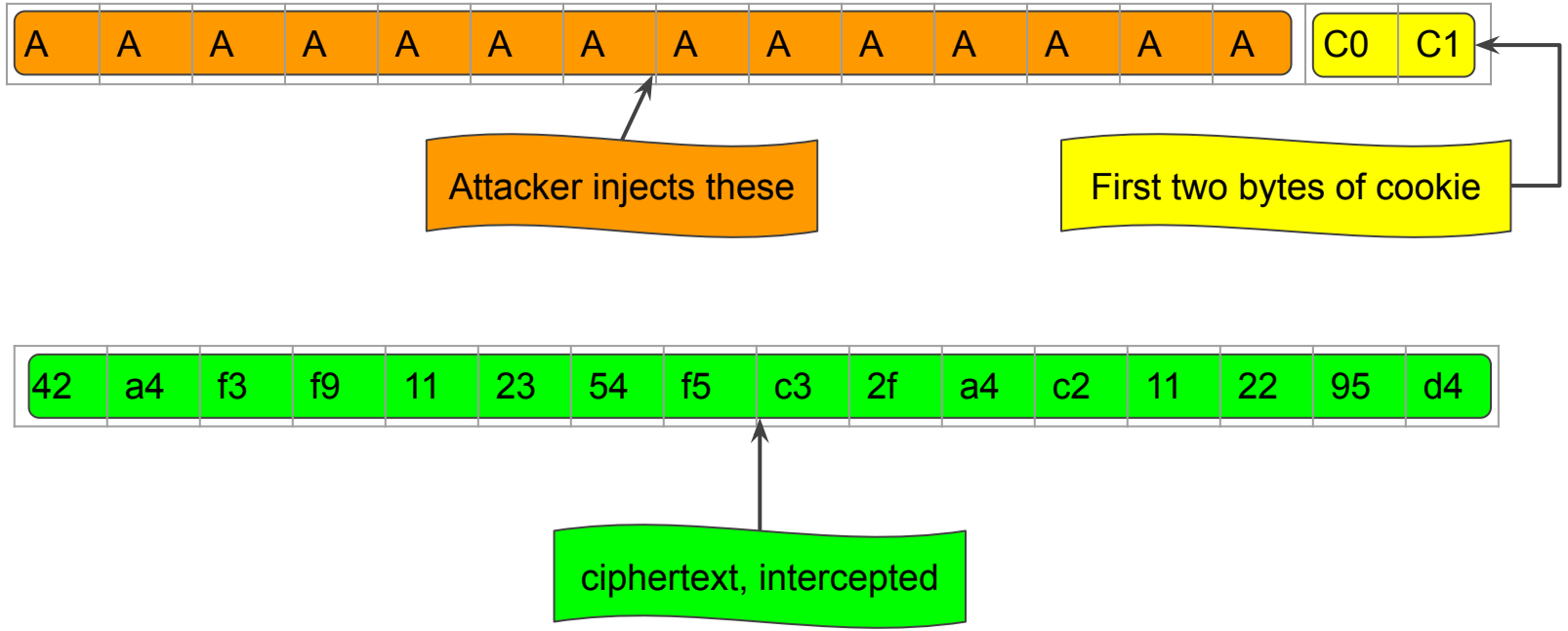


The attack in detail (2)

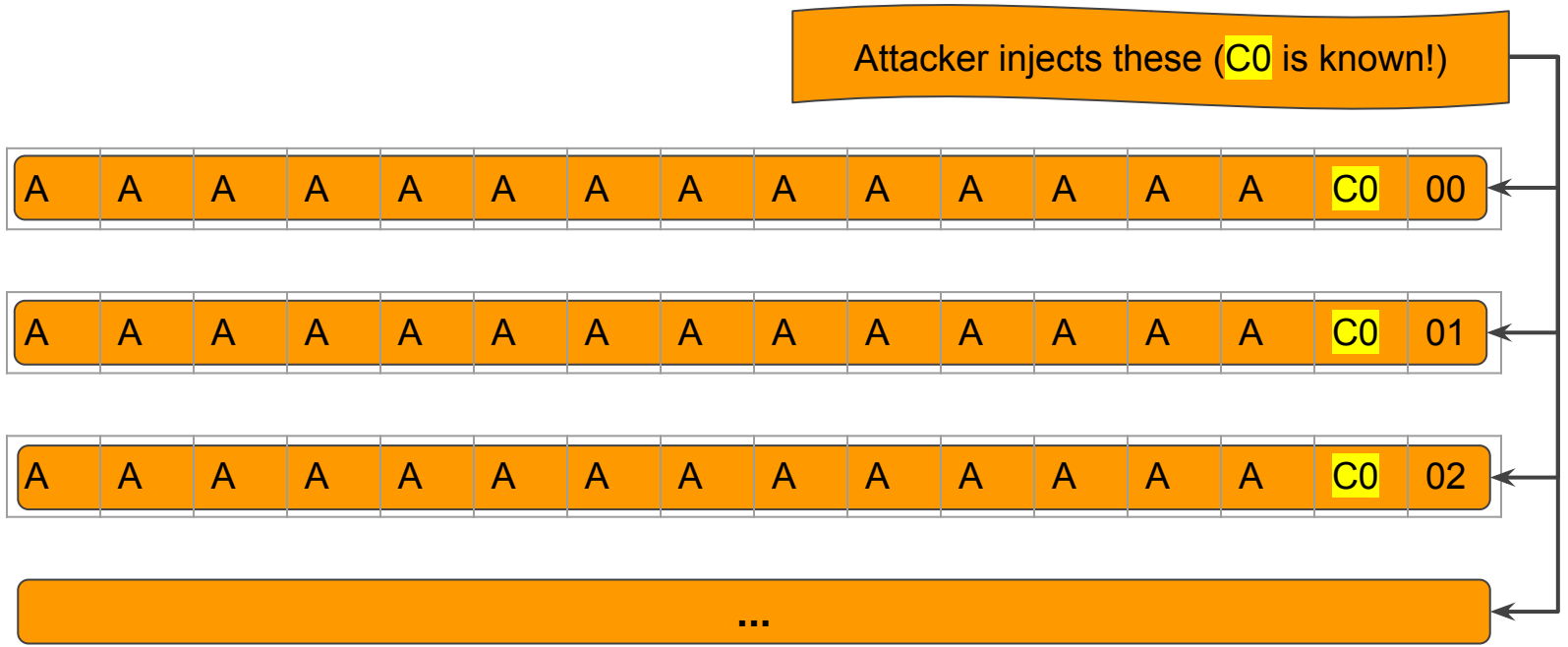


… until the ciphertext matches the previous one ⇒ C0 is leaked!

The attack in detail (3)



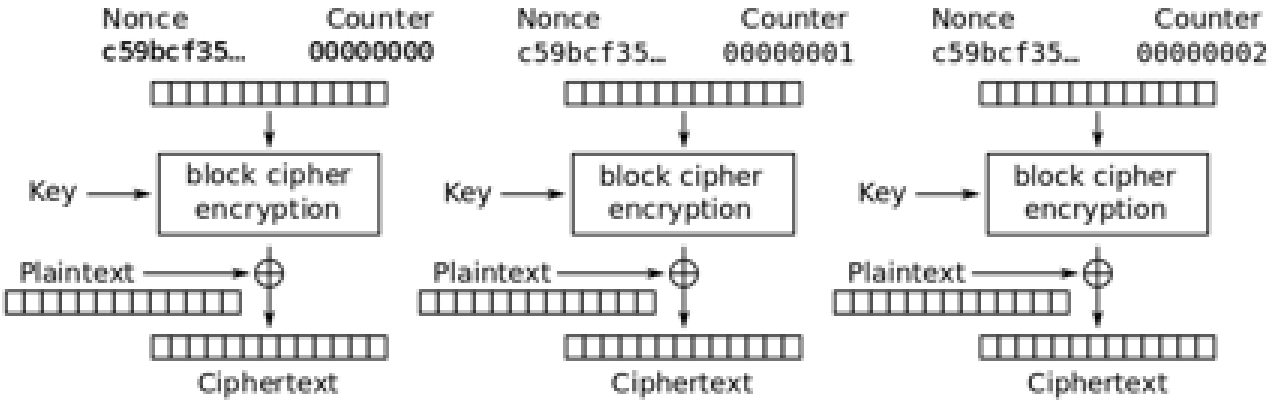
The attack in detail (4)



… until the ciphertext matches the previous one ⇒ C1 is leaked!

Configuration and Management

CTR: stream cipher



Counter (CTR) mode encryption

⇒ The random *nonce* (called the *Initialization Vector* **IV**) is fundamental for security!

Fixed IV is a typical configuration mistake!

ciphertext 1:

```
8f079a817d1dfa5bb2b1e069b0f4027abc65db6d130e6f3c154611d165d66b0a2342473479
0df0769cc3c4f4f289e784ac0cc5cab7e47c5c1a
```

ciphertext 2:

```
9f0a92807d33fb1ab7a9ad36e5cd4064a320da7a56122e21004c42c46d93214b28595b7776
12e46c9dc3c4eefedde88ee31c97c1b1e834135c
```

Leaked plaintext 1:

```
Dear Graham, I'll be happy to participate in the training
```

A CTR with **fixed nonce** has been used

… how would you break the other ciphertext?

Solution

P1, P2 plaintexts and C1, C2 corresponding ciphertext

Same nonce means same key K

$$P1 \oplus K = C1$$
$$P2 \oplus K = C2$$

thus

$$P1 \oplus P2 = C1 \oplus C2$$
$$P2 = P1 \oplus C1 \oplus C2$$

Key Management

RSA SecurID Breach (March 2011)

- Seed values (i.e., secret keys) for devices **stored insecurely**, compromised after phishing breach
- **40M devices replaced**, big companies breached, massive brand damage

Cryptanalysis

Sophisticated attacks on crypto

May 2012, sophisticated attack on Iranian nuclear programme named **FLAME** (and related to Stuxnet)

- **A fake certificate** using an MD5 collision was used to install the malware, bypassing software update check
- The MD5 collision method used was **different from the one publicly known**

⇒ State-level cyber-attack!!

NOTE: MD5 is now deprecated and should not be used for cryptographic applications

Cryptographic vulnerabilities (summary)

Vulnerabilities in applications: can reveal keys or downgrade to less secure mechanisms

Example: Heartbleed

(In)security of mechanisms: Crypto mechanisms **are not** equally secure

Example: Weaks modes of operation (ECB), padding oracles (PKCS7)

Management: The **configuration and management** of cryptographic systems is complex and error prone

Examples: Fixed IV, bad key management

Cryptanalysis: Improvement in **technology/cryptanalysis** requires better crypto

Example: broken cryptographic hashes