Security

CS 240: Computing Systems and Concurrency
Lecture 19

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Selected content adapted from M. Canini and D. Boneh.

Today

1. **Introdution to Computer Security**
   – What do we mean by security?
2. Introduction to Cryptography
   – Symmetric-key crypto
   – Public-key crypto
   – Crypto hash functions

The computer security problem

Two factors:

- **Lots of buggy software** (and gullible users)
- **Money can be made from finding and exploiting vulnerabilities**

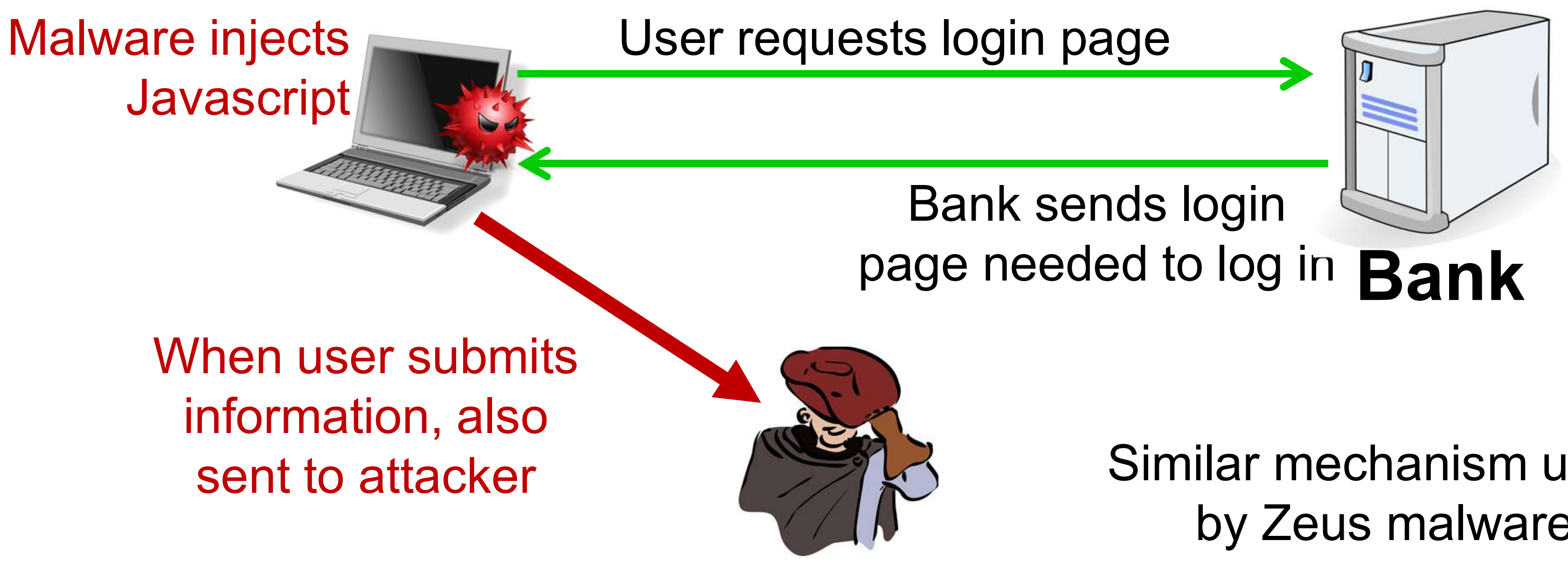
1. Marketplace for vulnerabilities
2. Marketplace for owned machines (PPI)
3. Many methods to profit from owned client machines

current state of computer security

Why own machines:
1. Steal user credentials

keylog for banking passwords, web pwds., gaming pwds.

Example: SilentBanker (and many like it)


Malware injects Javascript
User requests login page
Bank sends login page needed to log in
Bank
When user submits information, also sent to attacker

Similar mechanism used by Zeus malware

Why own machines:
2. IP address and bandwidth stealing

Attacker’s goal: look like a random Internet user

Use the IP address of infected machine or phone for:

- **Spam** (e.g. the storm botnet)

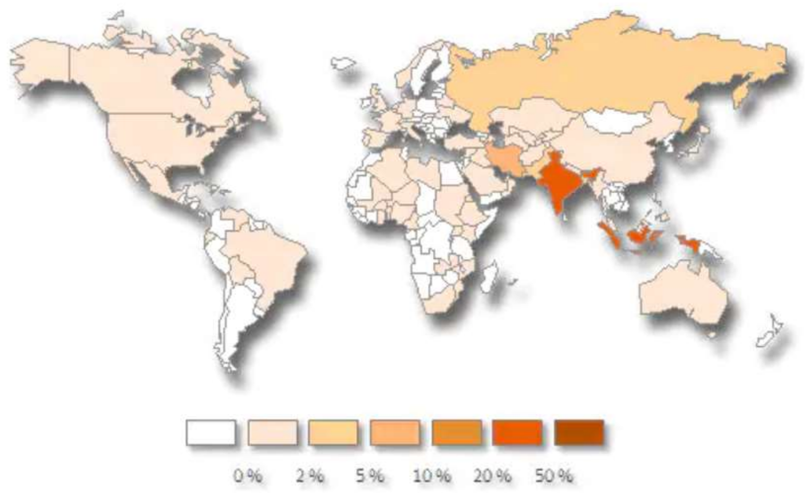
  Spamalytics: 1:12M pharma spams leads to purchase
  1:260K greeting card spams leads to infection

- **Denial of Service:** Services: 1h (20$), 24h (100$)

- **Click fraud** (e.g. Clickbot.a)

Why own machines:
3. Spread to isolated systems

GEOGRAPHICAL DISTRIBUTION
Symantec has observed the following geographic distribution of this threat.



Example: **Stuxtnet**

Windows infection ⇒

Siemens PCS 7 SCADA control software on Windows ⇒

Siemens device controller on isolated network

Stuxnet

Stuxnet: Anatomy of a Computer Virus (watch at https://vimeo.com/25118844)
Direction and Motion Graphics: Patrick Clair http://patrickclair.com
Written by: Scott Mitchell
Production Company: Zapruder's Other Films.

What do we mean by security?

What do we mean by security?

- Information security is larger than computer security
  - Defending information from unauthorized access, use, disclosure, disruption, modification, perusal, inspection, recording or destruction

- What does it mean for a computer system to be secure?

What do we mean by security?

- What does it mean for a computer system to be secure?
  - Achieving some goal in the presence of an adversary

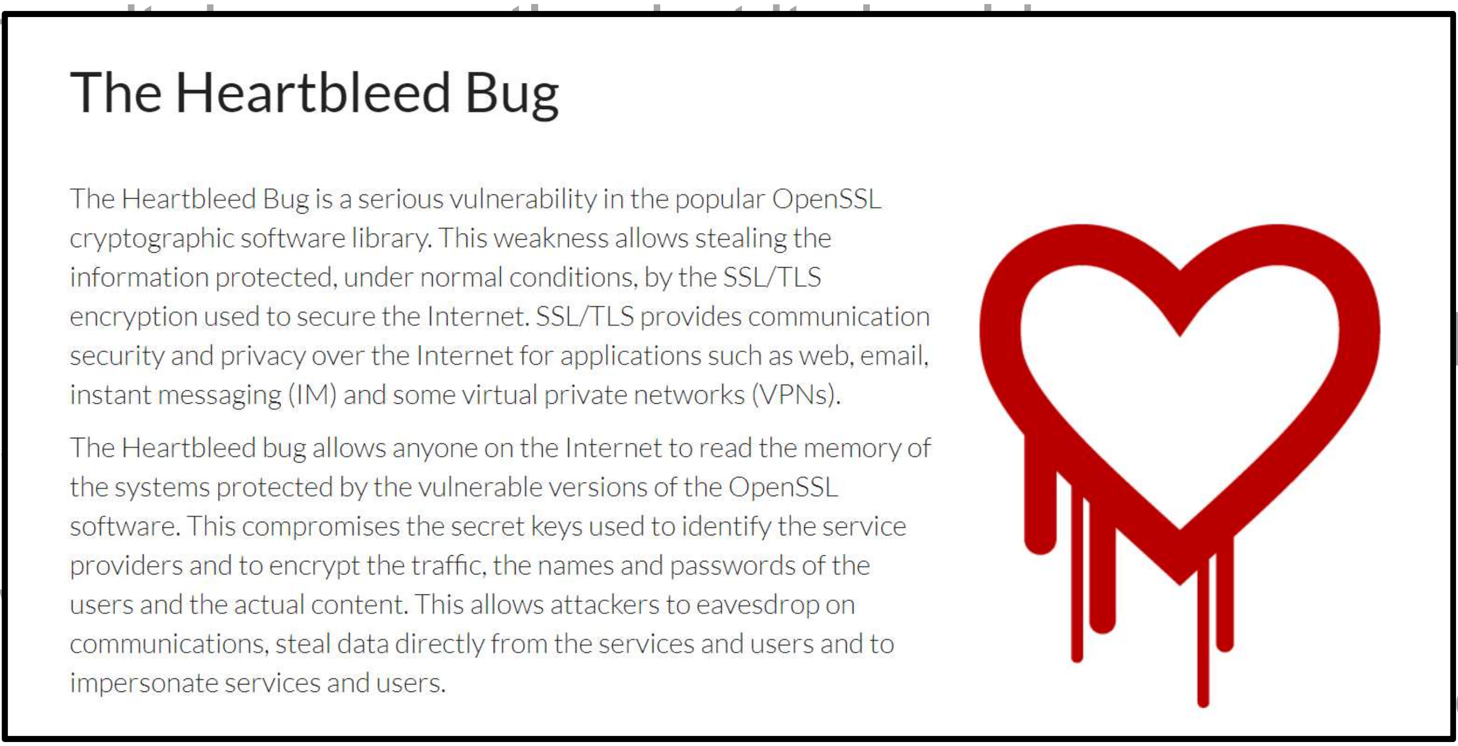
  - The system only does what it is expected to
  - Should prevent unauthorized use
  - What is “unauthorized”?
  - What about spam?

When is a computer system secure?

- When it does exactly what it should
  - Not more
  - Not less
- But how to know what a system is supposed to do?
  - Somebody tells us?
    - But do we trust them?
  - We write the specification ourselves?
    - How do we verify that the software meets the specification?
  - We write the code ourselves?
    - But what fraction of the software you use have you written?
    - Can you trust the hardware it runs on?

When is a computer system secure?

- Wh
  –
  –
- Bu lo?
  –
  – on?
  – We write the code ourselves?
    - **But what fraction of the software you use have you written?**
    - Can you trust the hardware it runs on?

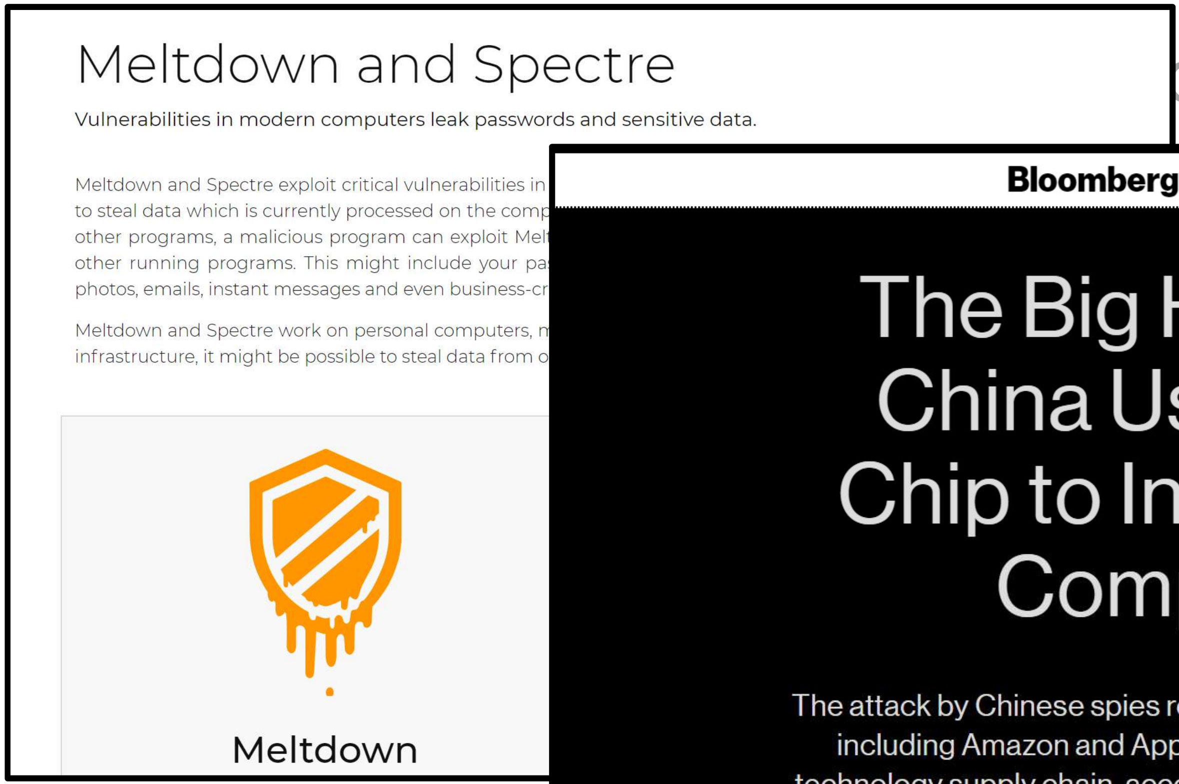


The Heartbleed Bug

The Heartbleed Bug is a serious vulnerability in the popular OpenSSL cryptographic software library. This weakness allows stealing the information protected, under normal conditions, by the SSL/TLS encryption used to secure the Internet. SSL/TLS provides communication security and privacy over the Internet for applications such as web, email, instant messaging (IM) and some virtual private networks (VPNs).

The Heartbleed bug allows anyone on the Internet to read the memory of the systems protected by the vulnerable versions of the OpenSSL software. This compromises the secret keys used to identify the service providers and to encrypt the traffic, the names and passwords of the users and the actual content. This allows attackers to eavesdrop on communications, steal data directly from the services and users and to impersonate services and users.

When is a computer system secure?

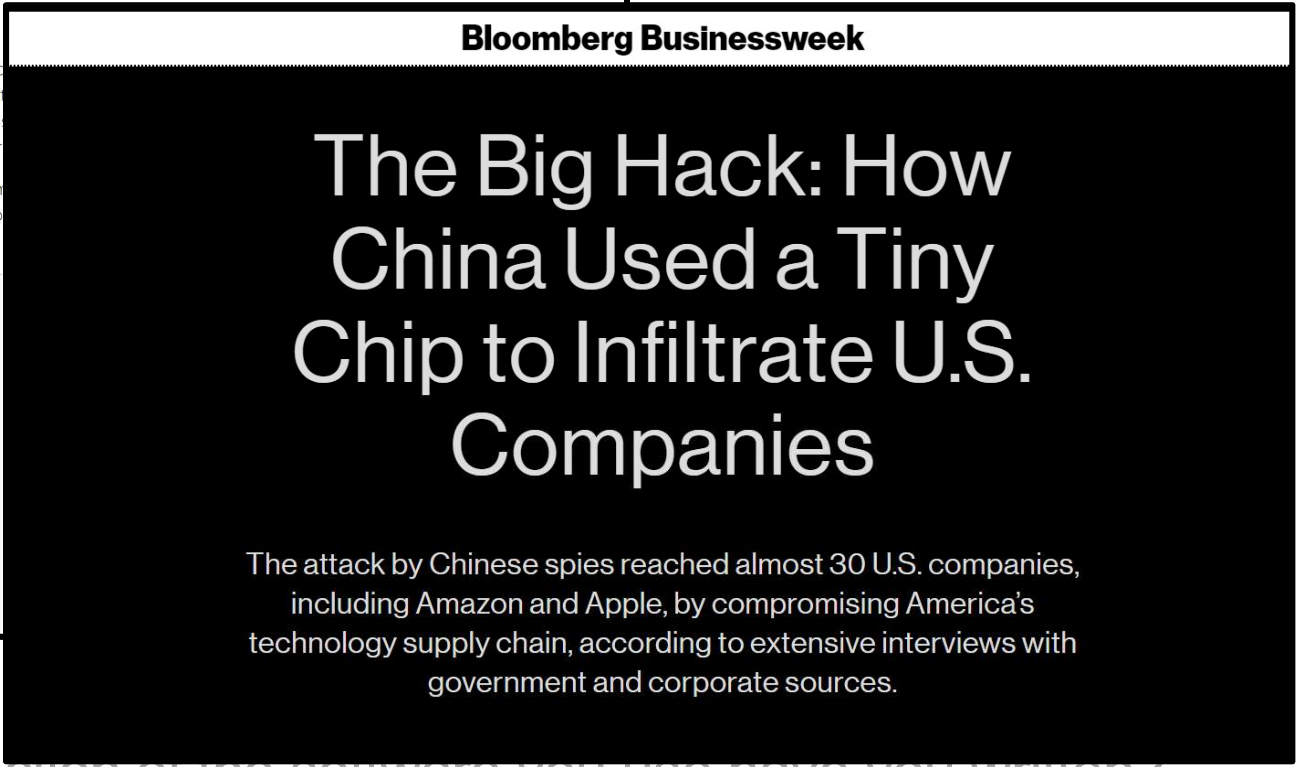


Meltdown and Spectre

Vulnerabilities in modern computers leak passwords and sensitive data.

Meltdown and Spectre exploit critical vulnerabilities in
to steal data which is currently processed on the comp
other programs, a malicious program can exploit Melt
other running programs. This might include your pa
photos, emails, instant messages and even business-cr

Meltdown and Spectre work on personal computers, m
infrastructure, it might be possible to steal data from o



Bloomberg Businessweek

The Big Hack: How China Used a Tiny Chip to Infiltrate U.S. Companies

The attack by Chinese spies reached almost 30 U.S. companies, including Amazon and Apple, by compromising America's technology supply chain, according to extensive interviews with government and corporate sources.

d

– We write the

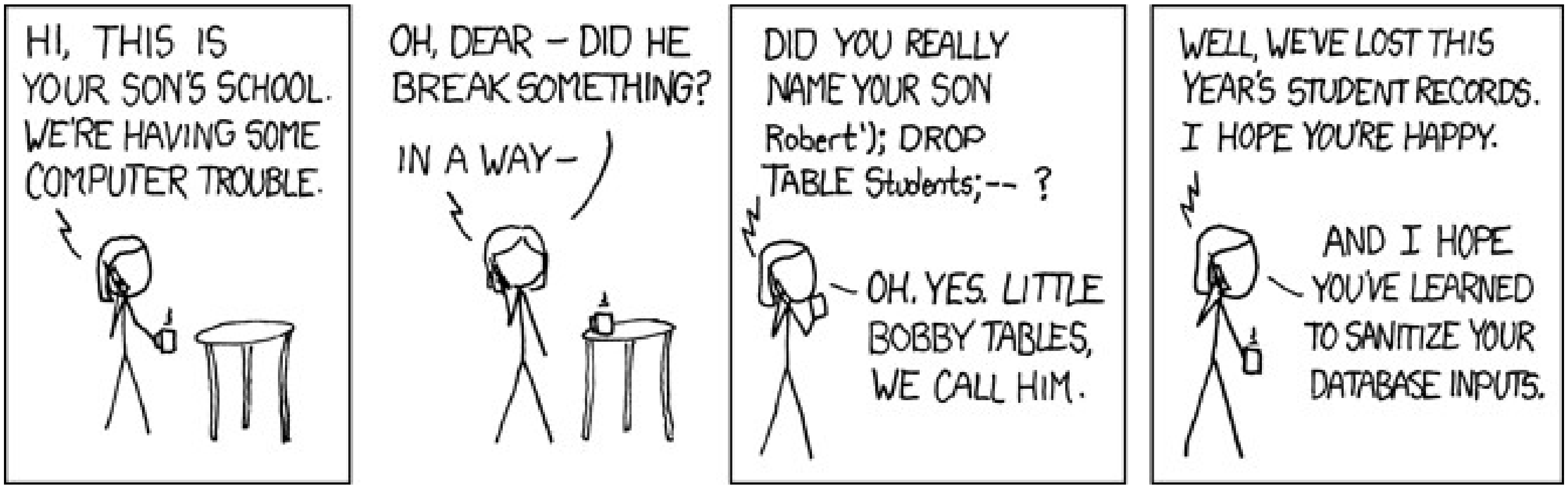
- But what fraction of the software you use have you written?
- **Can you trust the hardware it runs on?**

When is a computer system secure?

- A program is secure when it doesn’t do something it shouldn’t
- Easier to specify a list of “bad” things:
  - Delete or corrupt important files
  - Crash my system
  - Send my password or credit card details over the Internet
- But... what if most of the time the program doesn’t do bad things, but occasionally it does? Is it secure?
- Difficult to verify that a system does what it is expected to, impossible to verify that it does not what it is not expected to

When is a computer system secure?

E.g. SQL injection


HI, THIS IS YOUR SON'S SCHOOL. WE'RE HAVING SOME COMPUTER TROUBLE.
OH, DEAR – DID HE BREAK SOMETHING?
IN A WAY–
DID YOU REALLY NAME YOUR SON Robert'); DROP TABLE Students;-- ?
OH. YES. LITTLE BOBBY TABLES, WE CALL HIM.
WELL, WE'VE LOST THIS YEAR'S STUDENT RECORDS. I HOPE YOU'RE HAPPY.
AND I HOPE YOU'VE LEARNED TO SANITIZE YOUR DATABASE INPUTS.

“Security is mostly a superstition” – Helen Keller (1880-1968), American writer and activist

- **Security is all about trade-offs**
  - Performance
  - Cost
  - Usability
  - Functionality
- The right question is: **how do you know when something is secure enough?**
  - Manage security risks vs benefits
  - Requires understanding of the trade-offs involved

How to think about trade-offs?

- What are you trying to protect? How valuable is it?
  - Nuclear missile launch station vs. … coffee machine

UH, CECILIA?
EXCUSE ME?
DO YOU REALIZE HOW UNSECURE YOUR COFFEE DISTRIBUTION SYSTEM IS?
ANYONE COULD CLAIM TO BE ME AND GET MY COFFEE!
YOU SHOULD BE USING AT LEAST A 2-FACTOR AUTHENTICATION PROTOCOL WITH DATA ENCRYPTION AND BIOMETRIC VERIFICATION. IT'S BASIC IDENTITY PROTECTION!
WE KNOW. YOU TELL US THAT EVERY TIME YOU COME IN HERE.
THAT'S HOW YOU KNOW IT'S ME.
JORGE CHAM © 2013
WWW.PHDCOMICS.COM

- In what way is it valuable?
  - May be important only to one person (e.g. private e-mail or passwords)
  - May be important because accurate and reliable (e.g. bank’s accounting logs)
  - May be important because of a service it provides (e.g. Google’s web servers)

High level plan

- **Policy**: the goal you want to achieve
  - e.g. only Alice should read file F
- **Threat model**: assumptions about what the attacker could do
  - e.g. can guess passwords, cannot physically grab file server
  - Better to err on the side of assuming attacker can do something
- **Mechanism**: knobs that your system provides to help uphold policy
  - e.g. user accounts, passwords, file permissions, encryption
- **Resulting goal**: no way for adversary within threat model to violate policy
  - Note that goal has nothing to say about mechanism

Security goals

- **Prevent common vulnerabilities from occurring (e.g. buffer overflows)**
  - Recover from attacks
- **Traceability, accountability and auditing of security-relevant actions**
  - Monitoring
- **Detect attacks**
  - Privacy, confidentiality, anonymity
  - Protect secrets
- **Authenticity**
  - Needed for access control, authorization, etc.
- **Integrity**
  - Prevent unwanted modification or tampering
- **Availability and reliability**
  - Reduce risk of DoS

Classic CIA triad

- **Confidentiality**
  - NO unauthorized disclosure of information
    - E.g. a credit card transaction system attempts to enforce confidentiality by encrypting credit card details over the Internet and in the transaction processing network
- **Integrity**
  - NO unauthorized information modification
    - E.g. traditional Unix file permissions can be an important factor in single system measures for protecting data integrity
- **Availability**
  - Information or system remains available despite attacks
    - High availability systems aim to remain available at all times, preventing disruptions due to power outages, upgrades, hardware failures, Denial of Service (DoS) attacks, …

Example security mechanisms

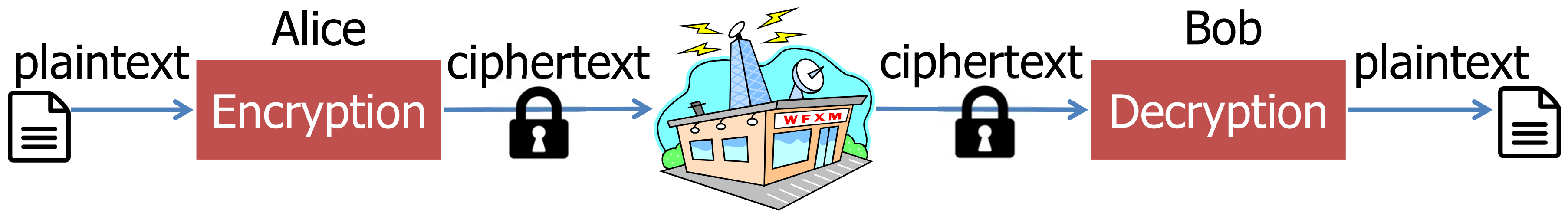
- Verifying the identity of a prospective user by demanding a password
  - Authentication
- Shielding the computer to prevent interception and subsequent interpretation of electromagnetic radiation
  - Covert channels
- Enciphering information sent communication channels
  - Cryptography
- Locking the room containing the computer
  - Physical aspects of security
- Controlling who is allowed to make changes to a computer system
  - Social aspects of security

Introduction to cryptography

κρμπτο γραφη (Cryptography)

- Greek for “secret writing”
- **Confidentiality**
  - – Obscure a message from eavesdroppers
- **Integrity**
  - – Assure recipient that the message was not altered
- **Authentication**
  - – Verify the identity of the source of a message
- **Non-repudiation**
  - – Convince a 3rd party that what was said is accurate

Terminology



- Encryption algorithm
  - Transforms a **plaintext** into a **ciphertext** that is **unintelligible for non-authorized parties**
  - Usually parametrized with a cryptographic key
- **Asymmetric (Public) key cryptography**
  - Crypto system: encryption + decryption algorithms + key generation
- **Symmetric (Shared) key cryptography**
  - Cipher/decipher: symmetric-key encryption/decryption algorithms

Security through obscurity

Should the encryption algorithm be kept secret?

Kerckhoffs's principle

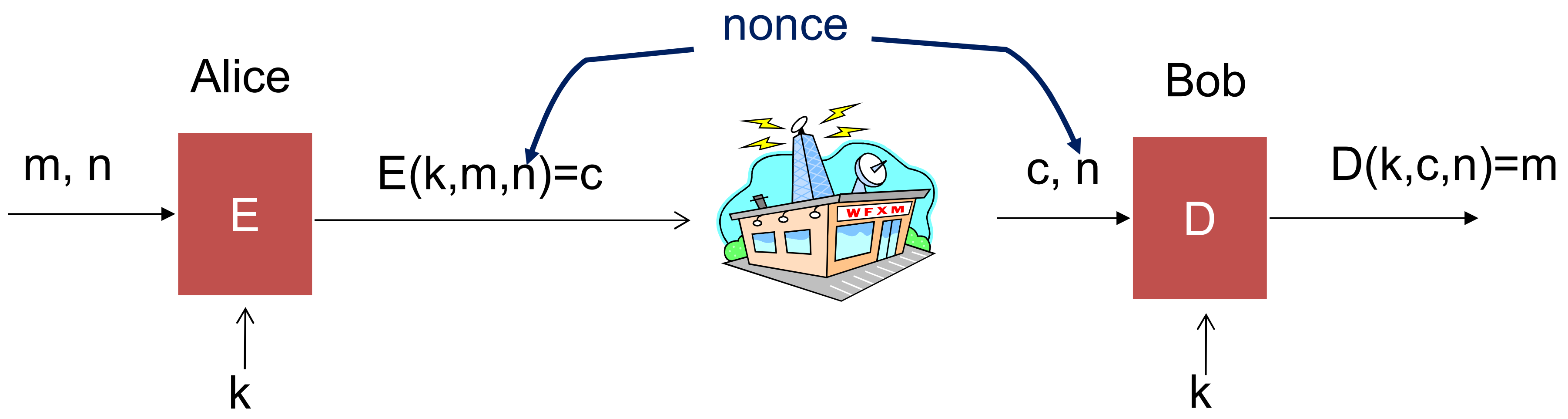
“*A cryptosystem should be secure even if* ***everything*** *about the system, except the secret key,* ***is public knowledge****.*”

Auguste Kerckhoffs, 1883

Symmetric cryptography

Assumes parties already share a secret key
Same secret key for both encryption and decryption

Building block: sym. encryption



E, D: cipher   k: secret key (e.g. 128 bits)

m, c: plaintext, ciphertext   n: nonce (aka IV)

Encryption algorithm is **publicly known**

- Never use a proprietary cipher

Use Cases

- **Single use key**: (one time key)
  - Key is only used to encrypt one message
    - encrypted email: new key generated for every email
  - No need for nonce (set to 0)
- **Multi use key**: (many time key)
  - Key used to encrypt multiple messages
    - SSL/TLS: same key used to encrypt many packets
  - Need either *unique* nonce or *random* nonce

First example: One Time Pad (single use key)

- Vernam (1917)

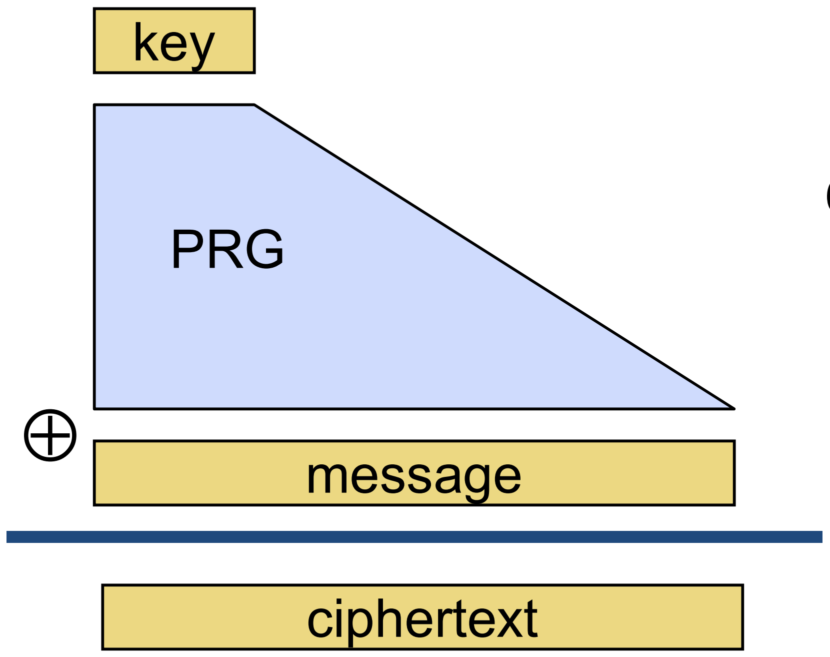
Key:	0	1	0	1	1	1	0	0	1	0	
Plaintext:	1	1	0	0	0	1	1	0	0	0	$\oplus$
Ciphertext:	1	0	0	1	1	0	1	0	1	0	

- Shannon '49:
  - OTP is "secure" against ciphertext-only attacks

Stream ciphers (single use key)

Problem: OTP key is as long as the message

Solution: Pseudo random key -- stream ciphers



$c \leftarrow \mathrm{PRG}(k) \oplus m$

Stream ciphers: RC4 (126 MB/sec) , Salsa20/12 (643 MB/sec)

Dangers in using stream ciphers

One time key !!   "Two time pad" is insecure:

$$\begin{cases} C_1 \leftarrow m_1 \oplus PRG(k) \\ C_2 \leftarrow m_2 \oplus PRG(k) \end{cases}$$

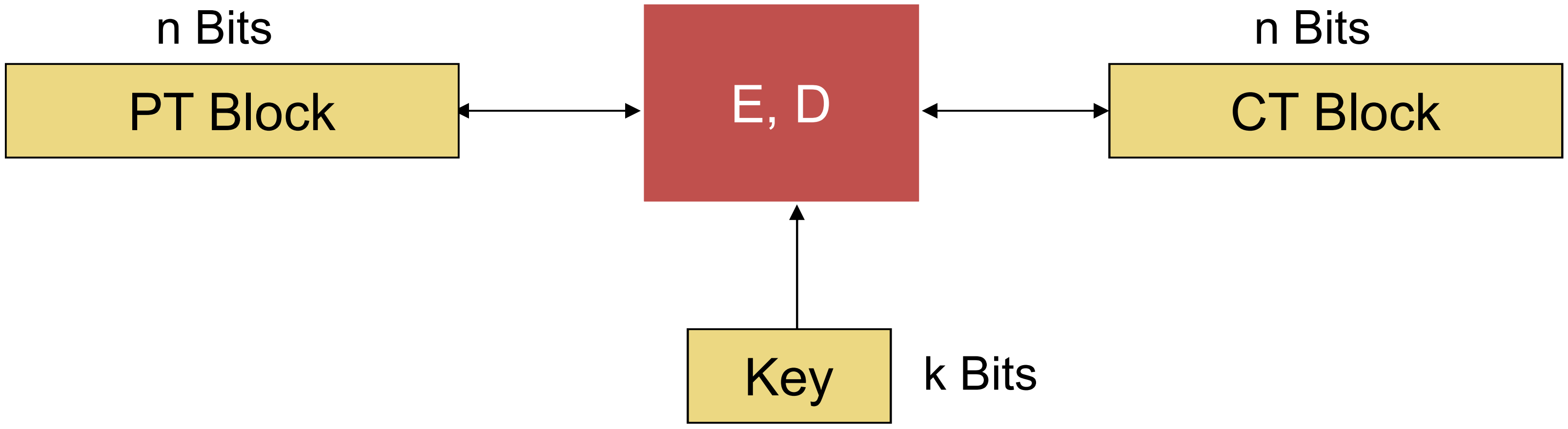
Eavesdropper does:

$$C_1 \oplus C_2 \quad \rightarrow \quad m_1 \oplus m_2$$

Enough redundancy in English encoding that:

$$m_1 \oplus m_2 \rightarrow \quad m_1 , m_2$$

Block ciphers: crypto work horse



Canonical examples:

1. 3DES: n= <u>64</u> bits, k = <u>168</u> bits <u>13</u> MB/s
2. AES: n=<u>128</u> bits, k = <u>128</u>, 192, 256 bits <u>109</u> MB/s

IV handled as part of PT block

Building a block cipher

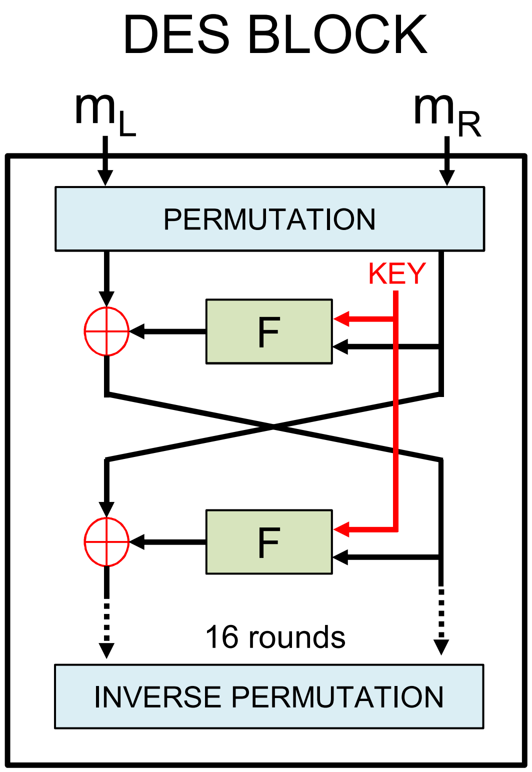
Input: (m, k)

Repeat simple "mixing" operation several times

- DES: Repeat 16 times:

$$\begin{cases} m_L \leftarrow m_R \\ m_R \leftarrow m_L \oplus F(k, m_R) \end{cases}$$

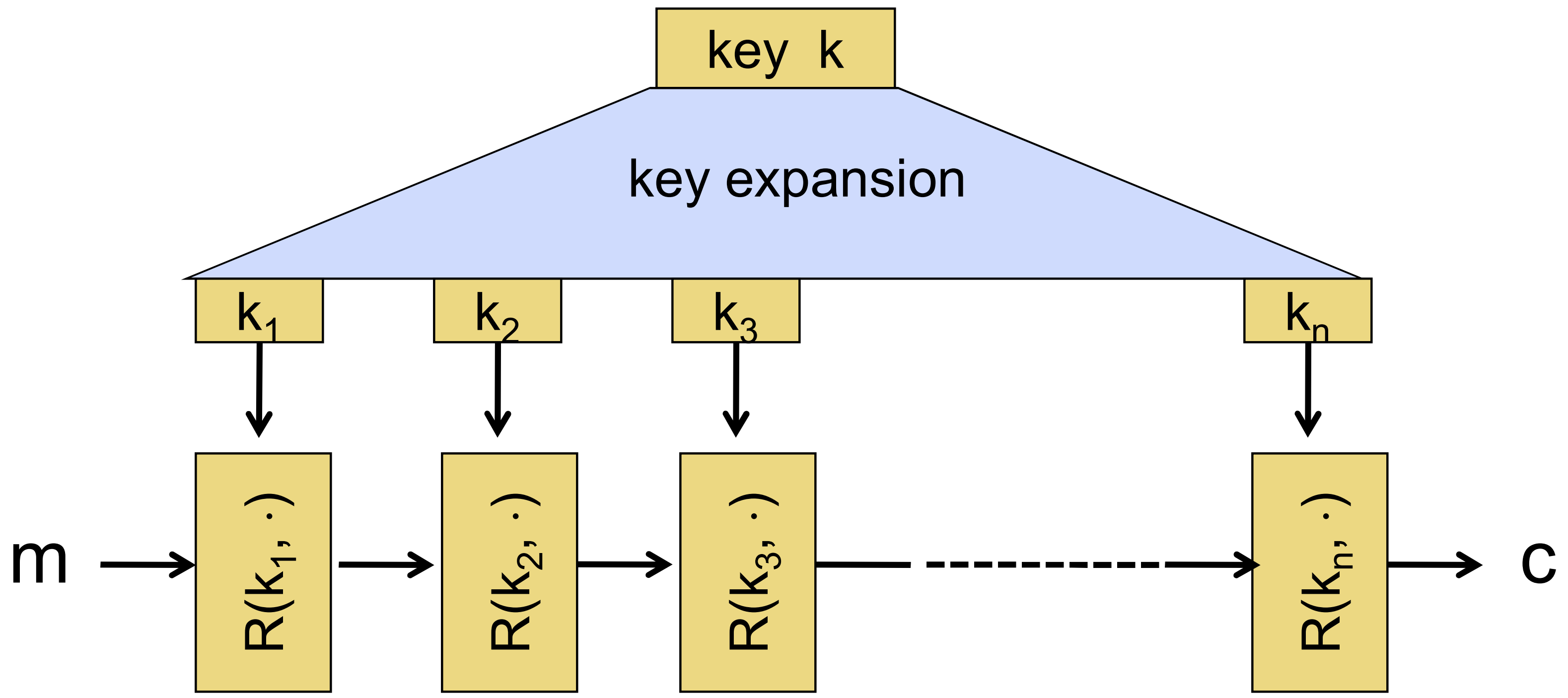
- AES-128: Mixing step repeated 10 times



Difficult to design: must resist subtle attacks

- differential attacks, linear attacks, brute-force, …

Block ciphers built by iteration

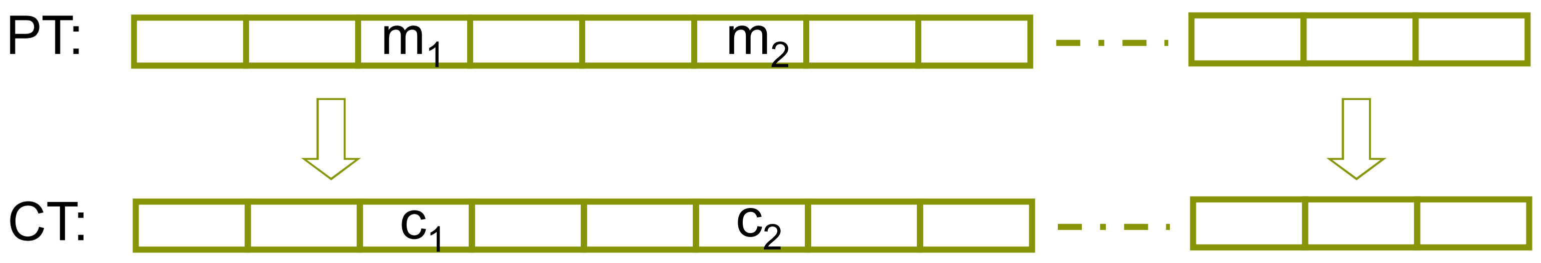


R(k,m): round function

for DES (n=16), for AES (n=10)

Incorrect use of block ciphers

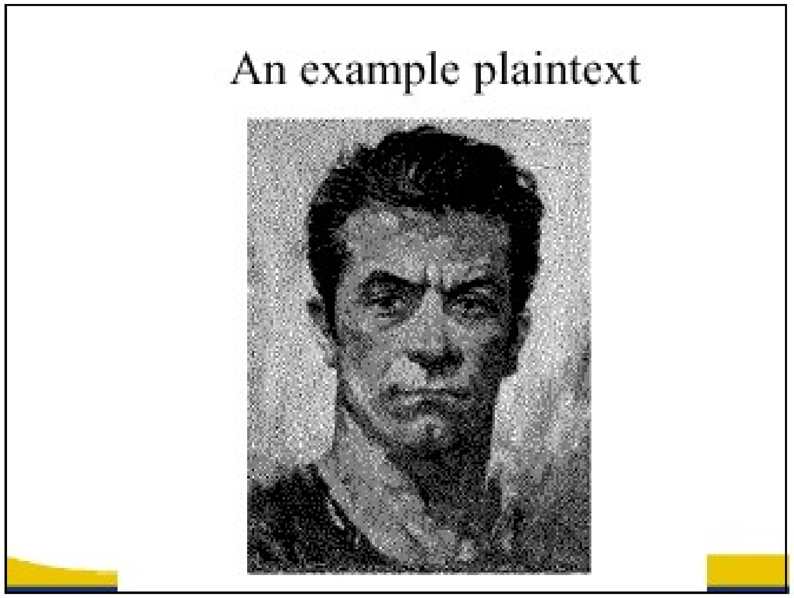
Electronic Code Book (ECB):

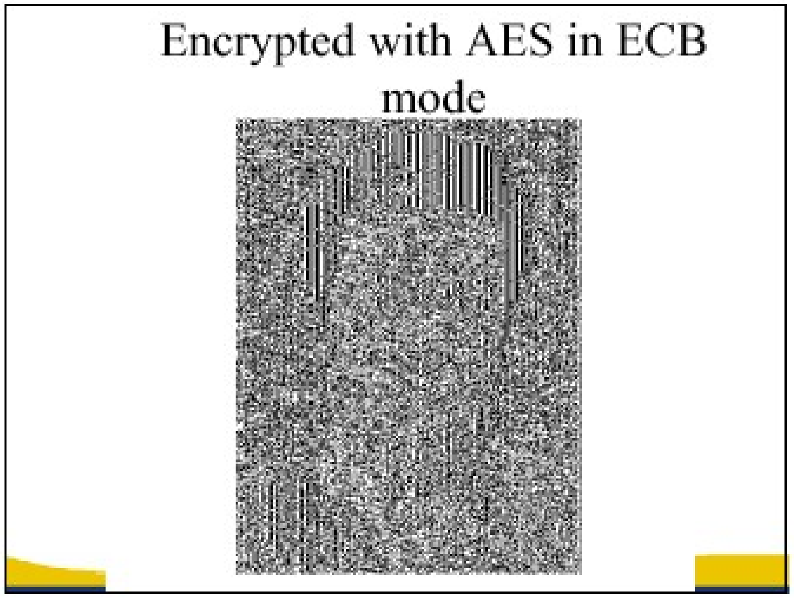


Problem:

– if $m_1=m_2$ then $c_1=c_2$

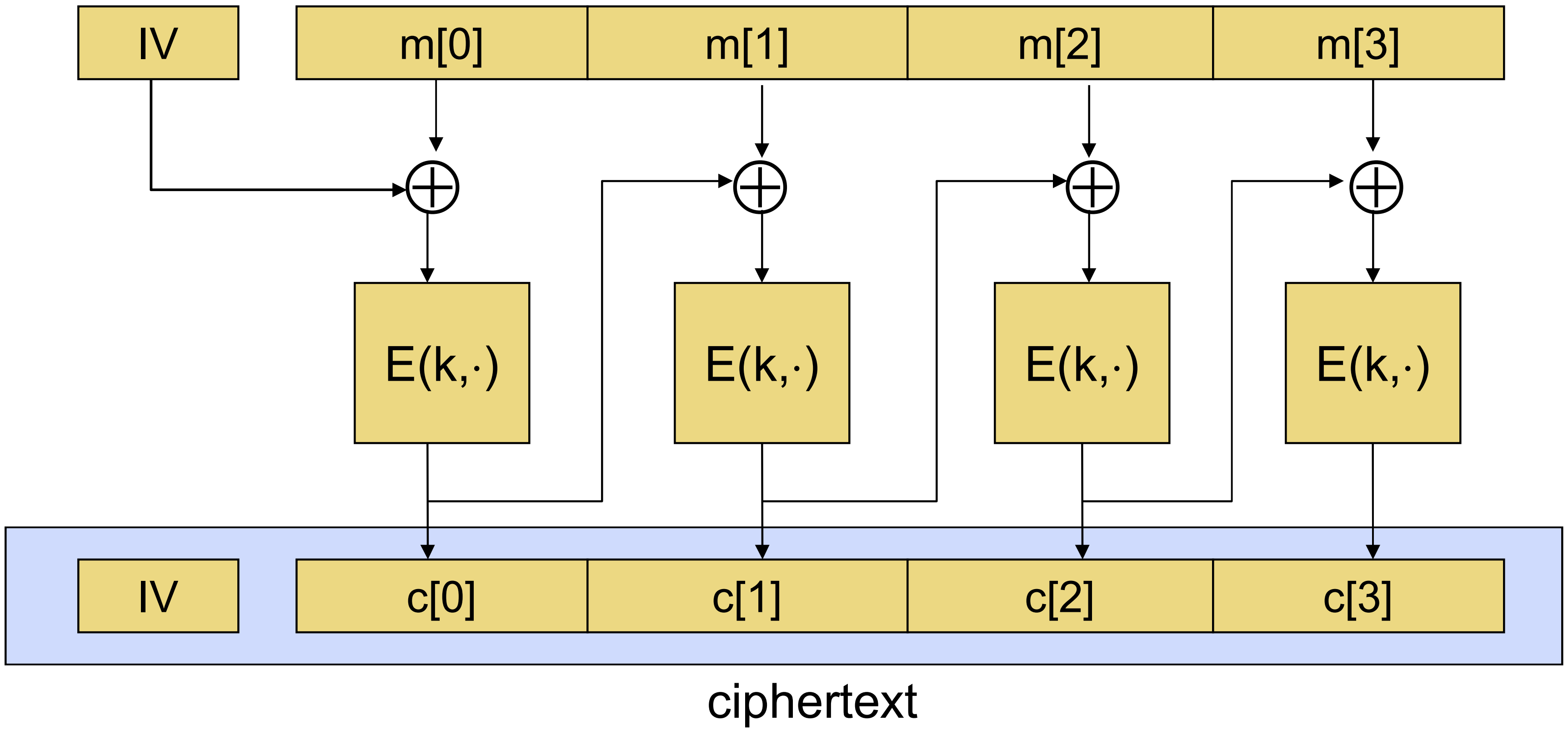
In pictures





Correct use of block ciphers: CBC mode

<u>Cipher Block Chaining</u> with random IV:



Q: how to do decryption?

Use cases: how to choose an IV

Single use key: no IV needed (IV=0)

Multi use key:

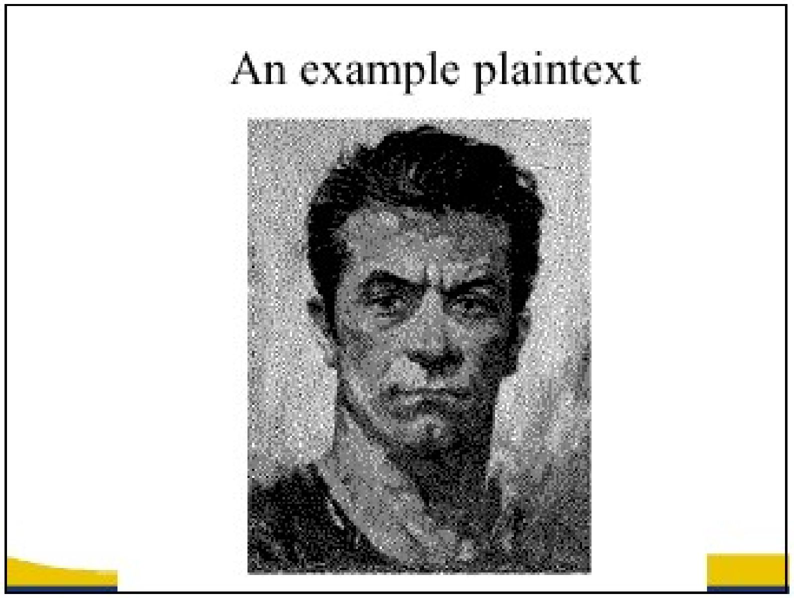
Best: use a fresh *random* IV for every message

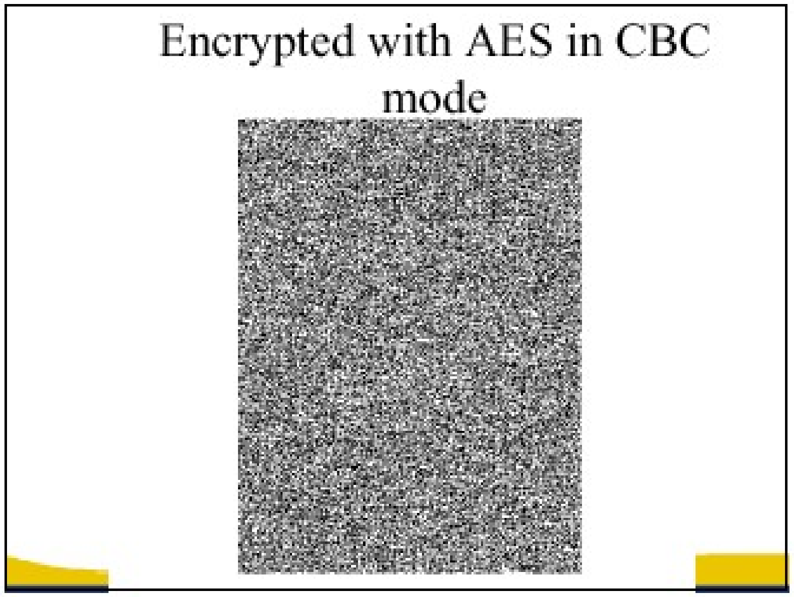
Can use *unique* IV (e.g counter)

but then first step in CBC must be $IV' \leftarrow E(k_1, IV)$

benefit: may save transmitting IV with ciphertext

In pictures


An example plaintext

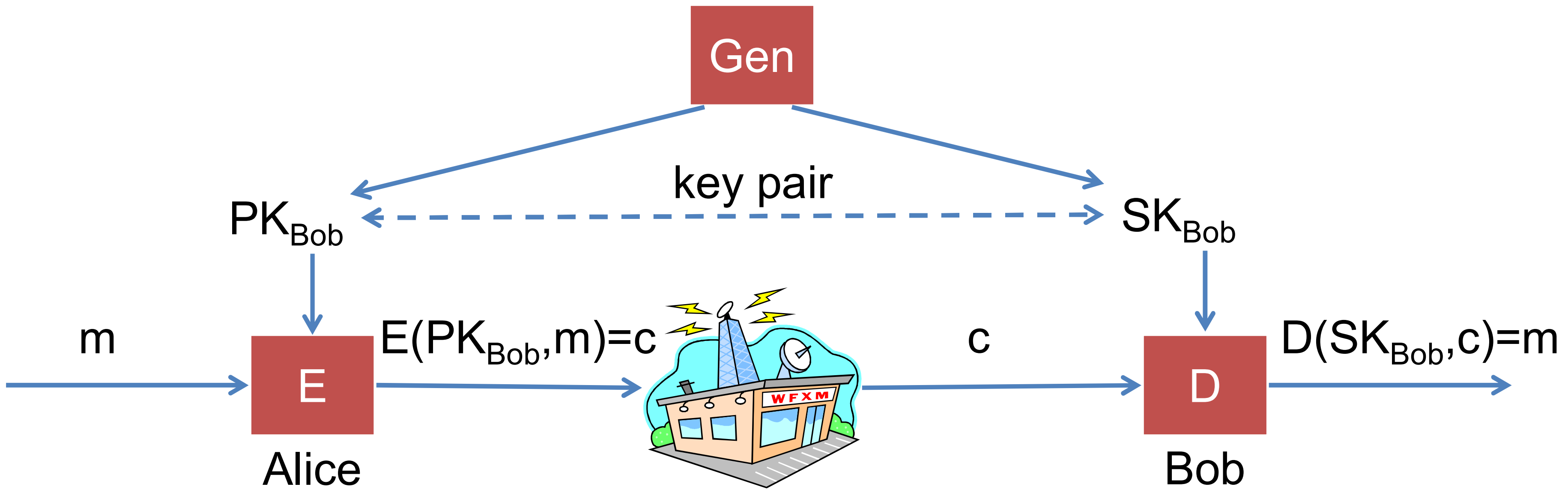

Encrypted with AES in CBC mode

Problems with shared key crypto

- Compromised key means interceptors can decrypt any ciphertext they've acquired
  - Change keys frequently to limit damage
- Distribution of keys is problematic
  - Keys must be transmitted securely
  - Use couriers?
  - Distribute in pieces over separate channels?

Public key cryptography

Public Key Encryption

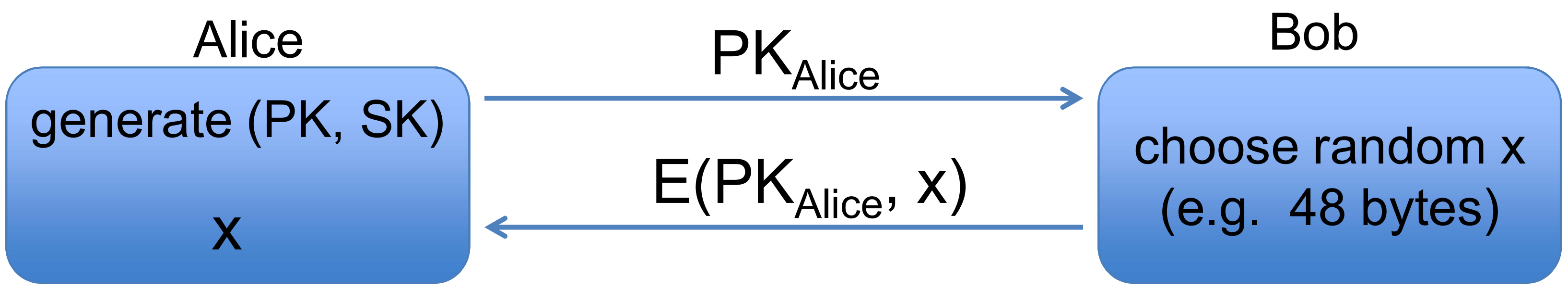


PK: public key ,   SK: secret key (e.g., 1024 bits)

Example: Bob generates (PK_{Bob}, SK_{Bob}) and gives PK_{Bob} to Alice

Applications

Session setup (only eavesdropping security)



Non-interactive applications: (e.g. Email)

- Bob sends email to Alice encrypted using PK_{Alice}
- Note: Bob needs PK_{Alice} (public key management)

(Simple) RSA Algorithm

- Generating a key:
  - Generate composite **$n = p * q$**, where p and q are **secret primes**
  - Pick public exponent **e**
  - Solve for secret exponent **d** in $d \cdot e \equiv 1 \pmod{(p-1)(q-1)}$
  - Public key = (e, n), private key = d

- Encrypting message m: $c = m^e \bmod n$
- Decrypting ciphertext c: $m = c^d \bmod n$

- **Security** due to cost of factoring large numbers
  - Finding **(p,q)** given **n** takes $O(e^{\log n \log \log n})$ operations
  - n chosen to be 2048 or 4096 bits long

Applications

- Public-key encryption
  - Alice public key for encryption
  - Anyone can send encrypted message
  - Only Alice can decrypt messages (with secret key)

- Digital signature scheme
  - Alice public key for verifying signatures
  - Anyone can check a message signed by Alice
  - Only Alice can sign messages (with secret key)

Establishing a shared secret

<u>Alice</u> <u>Bob</u>

$(pk, sk) \leftarrow G()$

$$\xrightarrow{\text{“Alice”},\quad pk}$$

choose random x

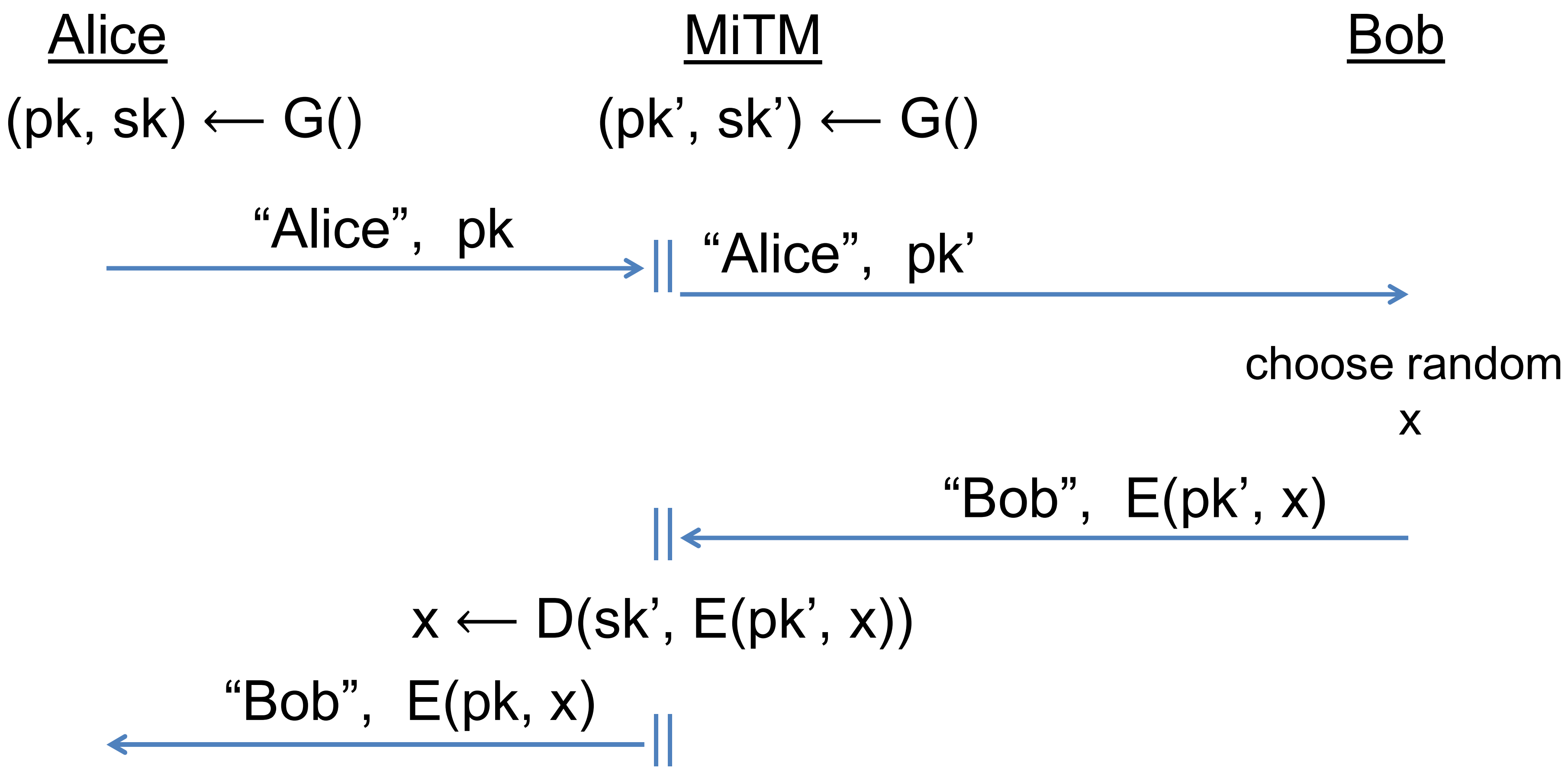
$$\xleftarrow{\text{“Bob”},\quad c \leftarrow E(pk,x)}$$

$D(sk,c) \longrightarrow x$

x shared secret

Insecure against man in the middle

The protocol is insecure against **active** attacks



Authenticated channel

- You should always expect a **man-in-the-middle**
  - e.g. on the internet, your messages go through many intermediaries

- Solution: Use an authenticated channel
  - For instance, Alice and Bob have certificates that contain a public key, and exchange them prior to the msg exchange
  - They use them to authenticate the values in the session setup phase

Public-Key authenticity

- How do we know that a public key belongs to Alice?

- Solution 1: **Public-Key Infrastructure (PKI)** → SSL/TLS
  - Trusted root Certificate Authority (e.g. Symantec)
    - Everyone must know the verification key of root CA
    - Check your browser; there are hundreds!!
  - Root authority signs intermediate CA
  - Results in a certificate chain
- Solution 2: **Web of Trust (WOT)**
  - Decentralized trust model
  - Users endorse the public key
  - Key signing parties

Trade-offs for Public Key Crypto

- More computationally expensive than symmetric (shared) key crypto
  - Algorithms are harder to implement
  - Require more complex machinery
- More formal justification of difficulty
  - Hardness based on complexity-theoretic results
- A principal needs 1 private key and 1 public key
  - Number of keys is O(n)

Cryptographic hash functions

Hash Algorithms

- Take a variable length string

$$h:\{0,1\}^{*} \xrightarrow{\text{hash}} \{0,1\}^{n}$$

- Produce a fixed length digest
  - Different strings can have the same hash

- (Non-cryptographic) Examples:
  - Parity (or byte-wise XOR)
  - CRC
- Realistic Example:
  - The NIST Secure Hash Algorithm (SHA) takes a message of less than 2^{64} bits and produces a digest of 160 bits

Cryptographic Hashes

- Create a hard-to-invert summary of input data
- Like a check-sum or error detection code
  - Uses a cryptographic algorithm internally
  - More expensive to compute
- Sometimes called a Message Digest
- Examples:
  - Secure Hash Algorithm (SHA)
  - Message Digest (MD4, MD5)

Desired Properties

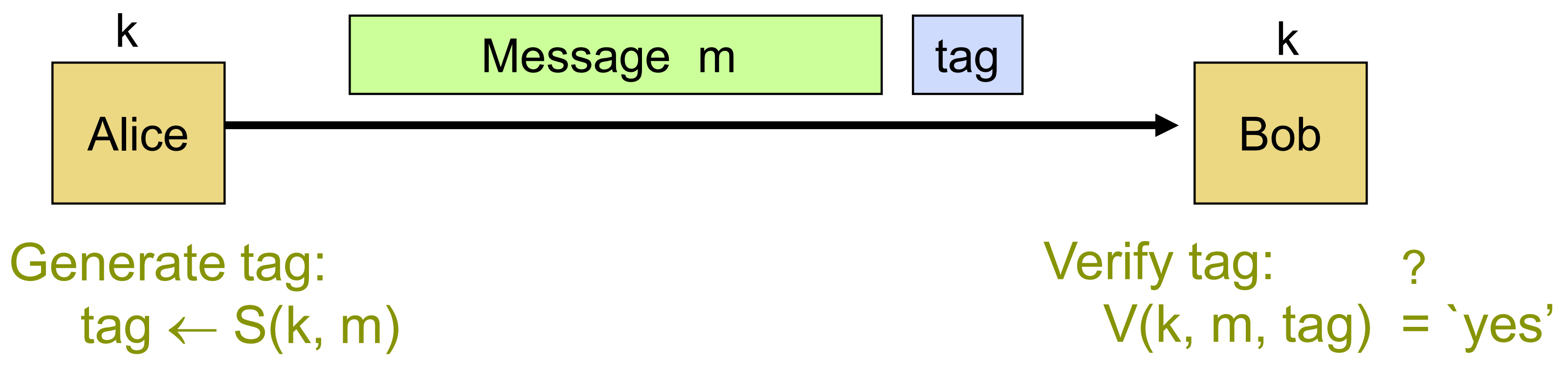
- One way hash function
  - Given a hash value y, it should be infeasible to find m s.t. $\mathrm{h}(m)=y$
- Collision resistance
  - It should be infeasible to find two different messages m_1 and m_2 s.t. $\mathrm{h}(m_1)=\mathrm{h}(m_2)$
- Random oracle property
  - $\mathrm{h}(m)$ is indistinguishable from a random n-bit value
  - Attacker must spend a lot of effort to be able to modify the message without altering the hash value

Data integrity

Message Authentication Codes

Message Integrity: MACs

- Goal: message integrity. No confidentiality.
  - ex: Protecting public binaries on disk.



note: non-keyed checksum (CRC) is an insecure MAC !!

Secure MACs

- Attacker's power: chosen message attack
  - for $m_1, m_2, \ldots, m_q$ attacker is given $t_i \leftarrow S(k, m_i)$

- Attacker's goal: existential forgery
  - produce some **<u>new</u>** valid message/tag pair (m,t)

$$(m,t) \notin \{ (m_1,t_1), \ldots, (m_q,t_q) \}$$

- A secure PRF (hash function) gives a secure MAC:
  - $S(k,m) = F(k,m)$
  - $V(k,m,t)$: `yes' if $t = F(k,m)$ and `no' otherwise.

Standardized method: HMAC (Hash-MAC)

Most widely used MAC on the Internet

H: hash function.

example: SHA-256 ; output is 256 bits

Building a MAC out of a hash function:

HMAC: $S(k, m) = H(k \oplus \text{opad} \,||\, \mathbf{H(k \oplus ipad \,||\, m)})$

Maintains performance of the original hash function

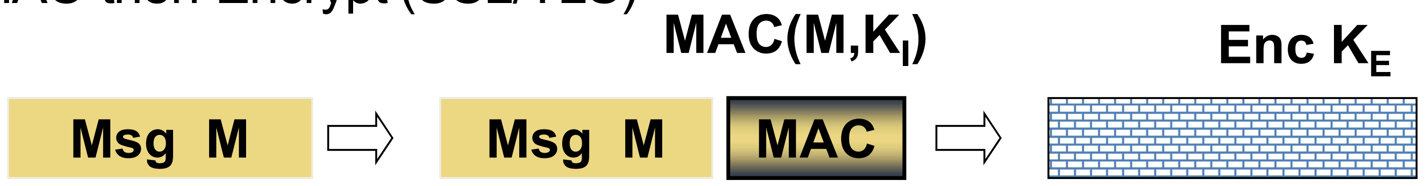
Authenticated Encryption

Encryption + MAC

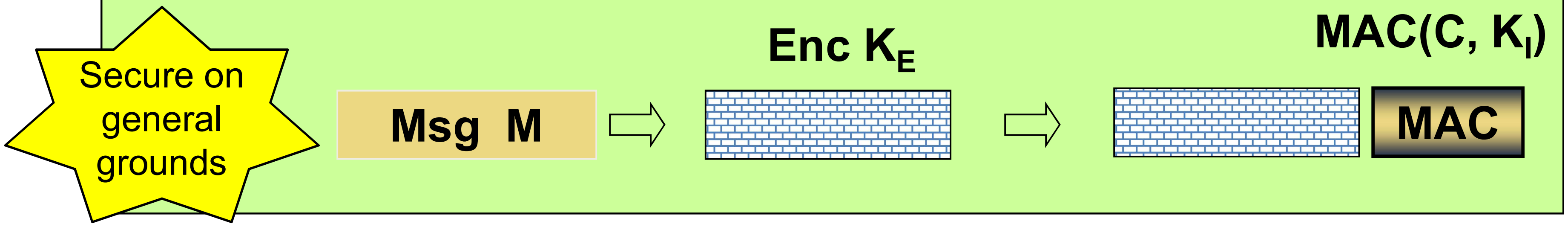
Combining MAC and ENC

Encryption key K_E MAC key = K_I

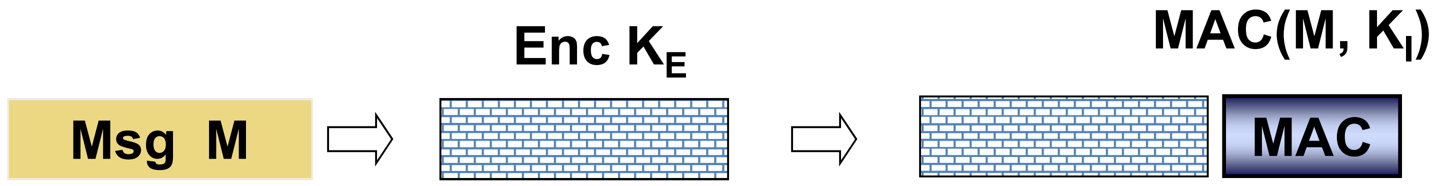
Option 1: MAC-then-Encrypt (SSL/TLS)



Option 2: Encrypt-then-MAC (IPsec)



Option 3: Encrypt-and-MAC (SSH)



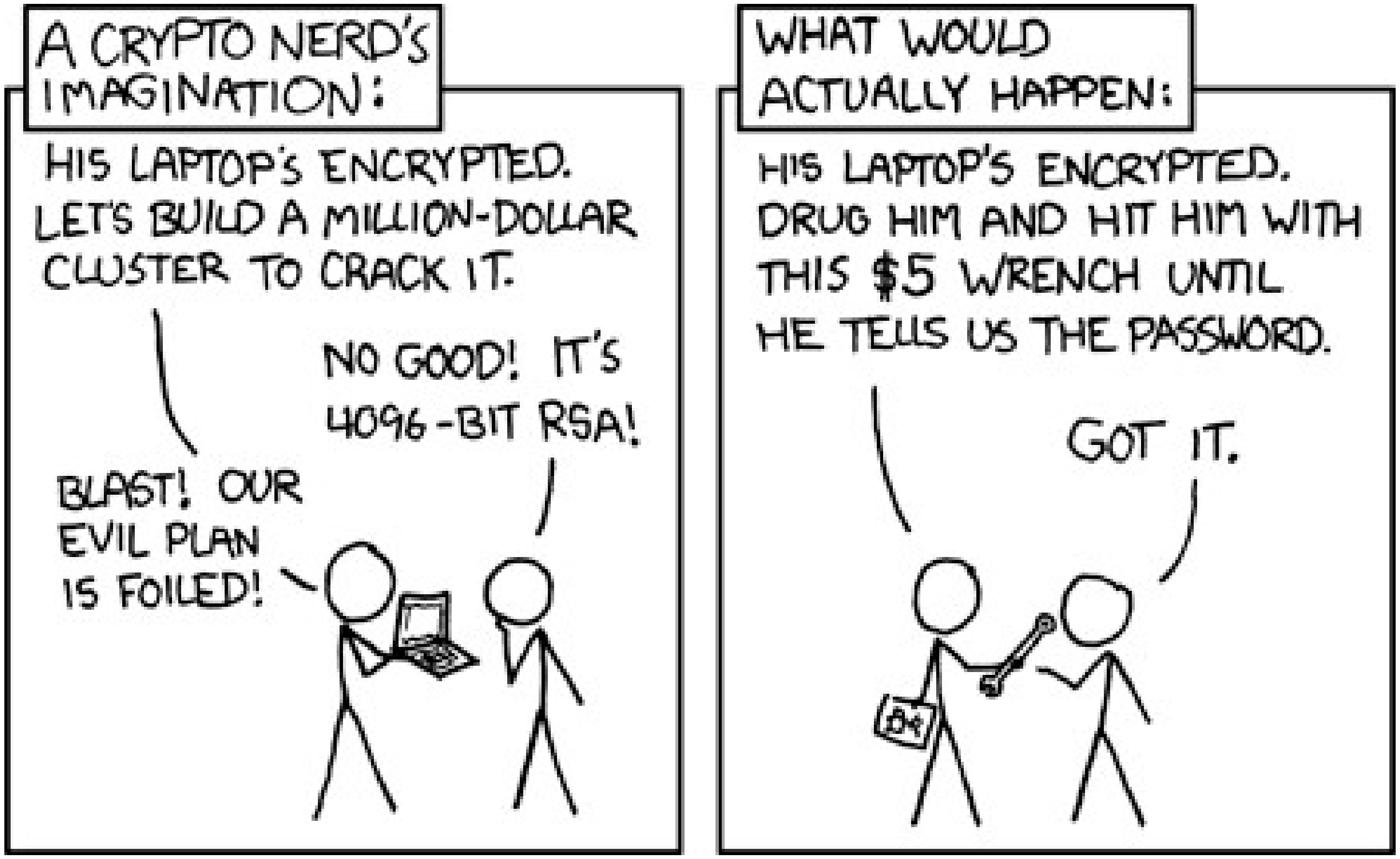
To remember

Limitations of cryptography

- Most security problems are not crypto problems
  - This is good: cryptography works!
  - This is bad
    - People make other mistakes; crypto doesn’t solve them

- Misuse of cryptography is fatal for security
  - WEP – ineffective, highly embarrassing for industry
  - Occasional unexpected attacks on systems subjected to serious review

In reality


A CRYPTO NERD'S IMAGINATION:
HIS LAPTOP'S ENCRYPTED. LET'S BUILD A MILLION-DOLLAR CLUSTER TO CRACK IT.
NO GOOD! IT'S 4096-BIT RSA!
BLAST! OUR EVIL PLAN IS FOILED!
WHAT WOULD ACTUALLY HAPPEN:
HIS LAPTOP'S ENCRYPTED. DRUG HIM AND HIT HIM WITH THIS $5 WRENCH UNTIL HE TELLS US THE PASSWORD.
GOT IT.

Next topic:
Blockchains