Module 3

Internet Security and Privacy

Some communication mediums are unsafe

What can be eavesdropped upon?

- Air (for broadcast messages such as wireless)
- Copper wires (vampire tap)
- Optical fiber 光纤
- Devices (phones, computers, etc.)

<u>Our goals:</u>

- **Confidentiality** – Safeguard packets from eavesdropping
- **Integrity** – Prevent packet modification in transmission
- **Authenticity** – Prove the identity of the sender

Cryptography

A <u>cryptosystem</u> consists of:

- Key(s)
- Encryption mechanism
- Decryption mechanism

Kerckhoffs' Principle states that:

The key(s) of a cryptosystem should be hidden,
but the mechanisms should be public.

(Why?)

The XOR function $\oplus$

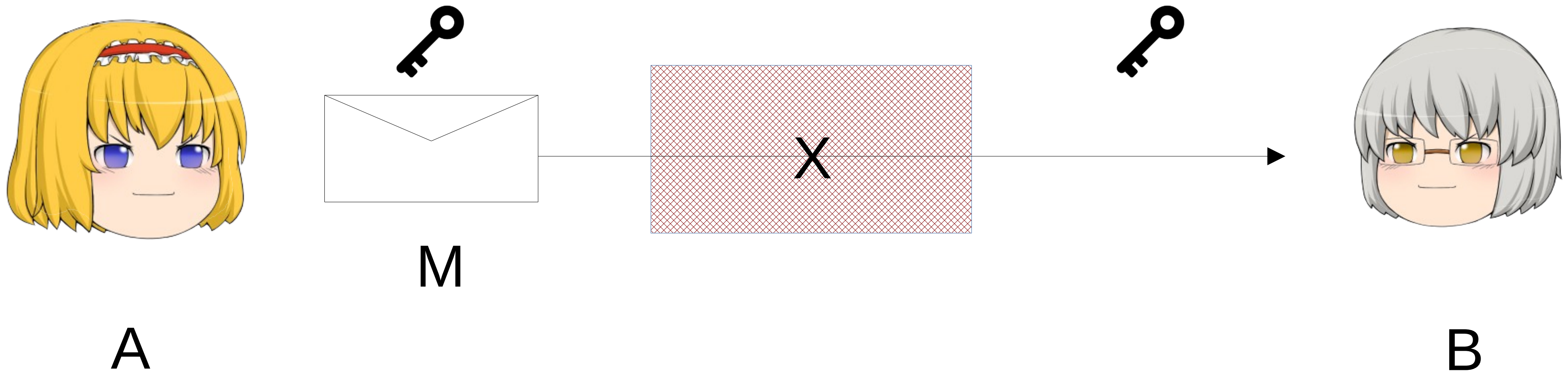
Value table of XOR:

$\oplus$	**0**	**1**
0	0	1
1	1	0

XOR is the same as “Addition modulo 2”.
Bit-by-bit XOR of two bit strings:

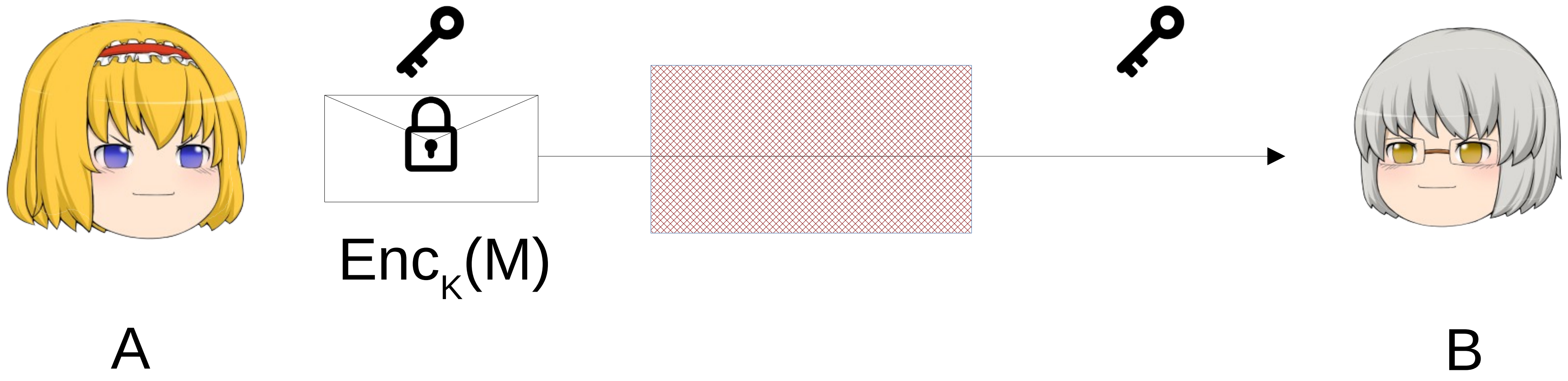
$$(0110) \oplus (1011) = (1101)$$

Encryption and decryption



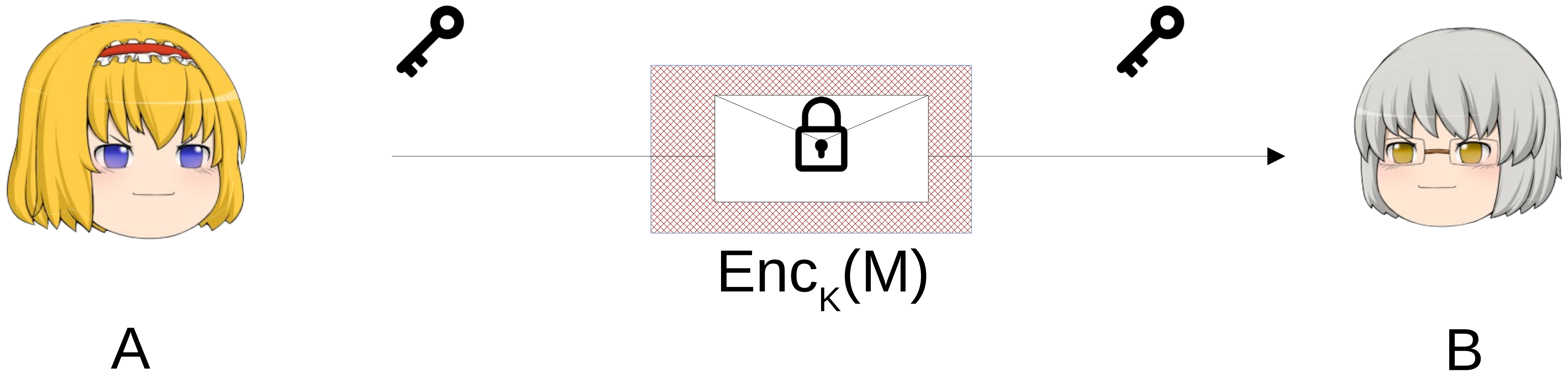
Scenario: A wants to send **plaintext** M to B, but doesn't want the attacker to see M when it passes through the unsafe medium (red).
A and B both already know some key K.

Encryption and decryption



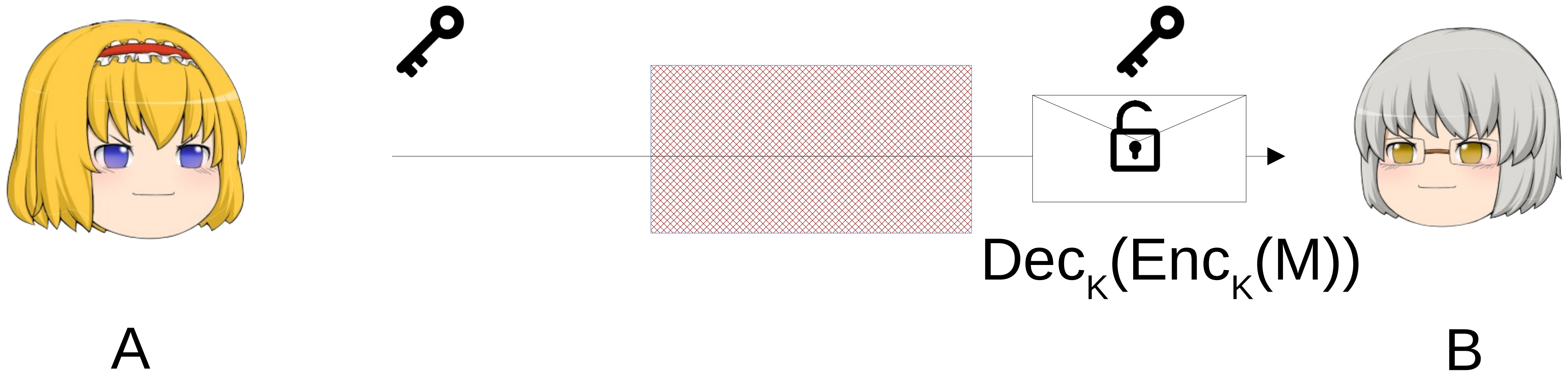
1. Using the encryption mechanism Enc() and key K, A encrypts M to a **ciphertext**, $\text{Enc}_K(M)$.

Encryption and decryption



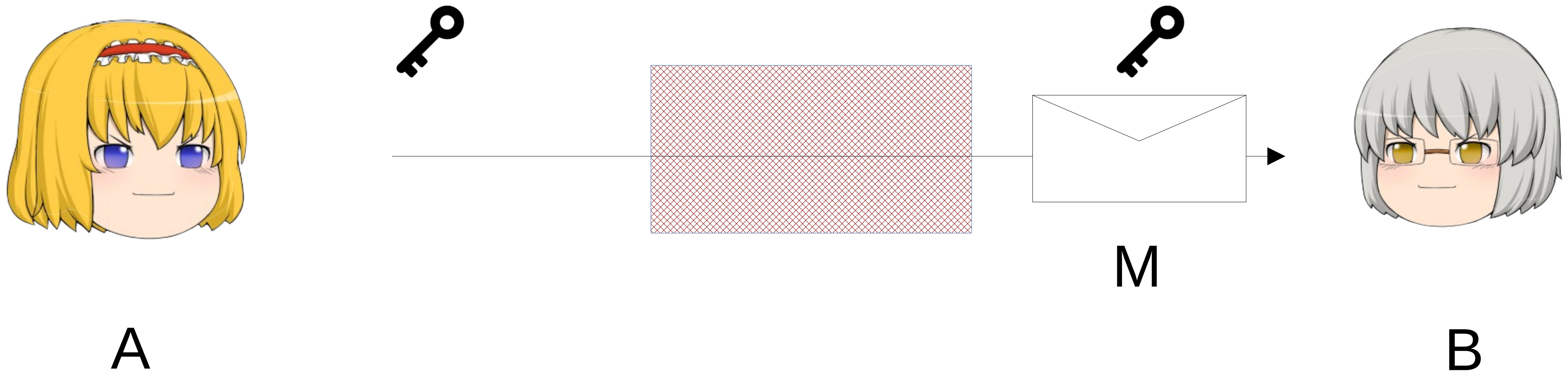
2. A sends $\text{Enc}_K(M)$ across the channel.

Encryption and decryption



3. B receives $\mathrm{Enc}_K(M)$, and decrypts it using the decryption procedure Dec() and key K.

Encryption and decryption



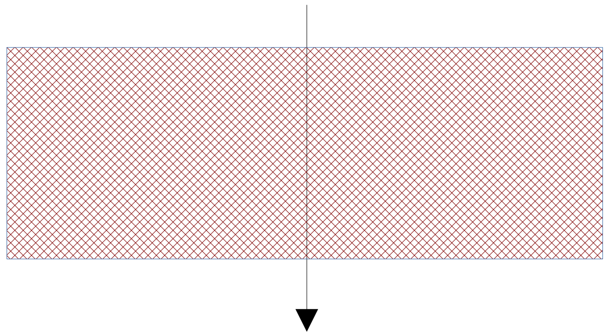
4. Dec(Enc(M)) = M; B receives the plaintext message M.

Simple System: The Caesar Cipher

Plaintext: `ATTACK “LONG A”`

Encryption: Add K letters (K=1 here)

Ciphertext: `BUUBDL “MPOH B”`



Unsafe medium

Ciphertext: `BUUBDL “MPOH B”`

Decryption: Subtract K letters (K=1 here)

Plaintext: `ATTACK “LONG A”`

Simple System: The Caesar Cipher

Problems of this cryptosystem:

- **Ciphertext Repetition**: What if you see `BUUBDL “MPOH B” and then EFGFOE “MPOH B”`?
- **Key Update:** For security, we should update the key frequently. How can we do so?
- **Short Key Length:** How many possibilities are there for the encryption/decryption mechanism?
- **Frequency analysis:** If the letter “F” appears most frequently in ciphertexts, what does it mean?

Solving the Ciphertext Repetition Problem

Use a Initialization Vector (IV):

- The IV “modifies” the key for encryption

$$\mathrm{Enc}_{K,\ IV}(M)$$

- Each message must have a different IV

  -> Even with the same key and plaintext, a different IV will produce a different ciphertext

- The IV is sent **publicly** alongside the message – it does not matter if the attacker sees it

Solving the Ciphertext Repetition Problem

Plaintext: `ATTACK “LONG A”`

Encryption: Add K+3 letters (K=1)

Ciphertext: `EXXEGO “PSRK E”, +3`

IV

Unsafe medium

Ciphertext: `EXXEGO “PSRK E”, +3`

Decryption: Subtract K+3 letters (K=1)

Plaintext: `ATTACK “LONG A”`

Solving the Key Update Problem

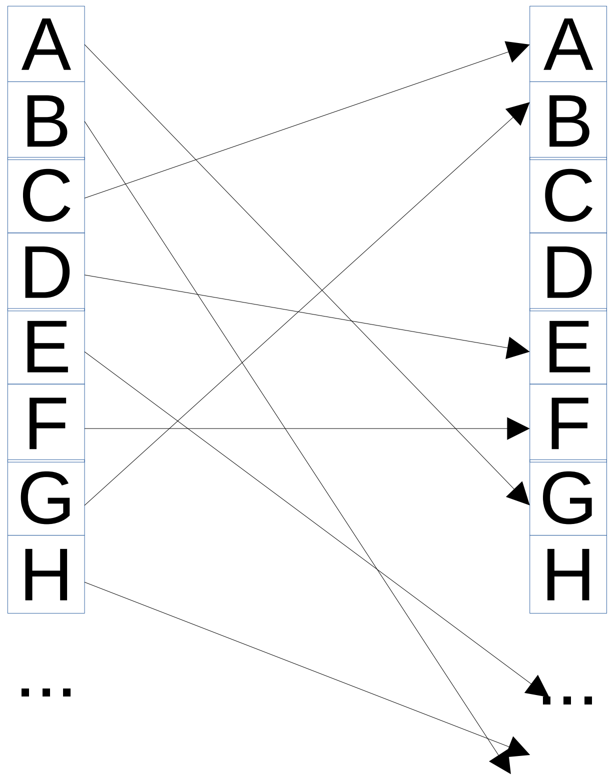
Find a safe channel to deliver the key instead

- Hand-delivered documents, cards
- Not practical for computer systems

Public Key Encryption

- In PKE, the encryption and decryption keys are different
- This can be used to create a safe channel on an unsafe one
- Only send the encryption key across the channel
- More later

Solving the Key Length Problem (Substitution Cipher)



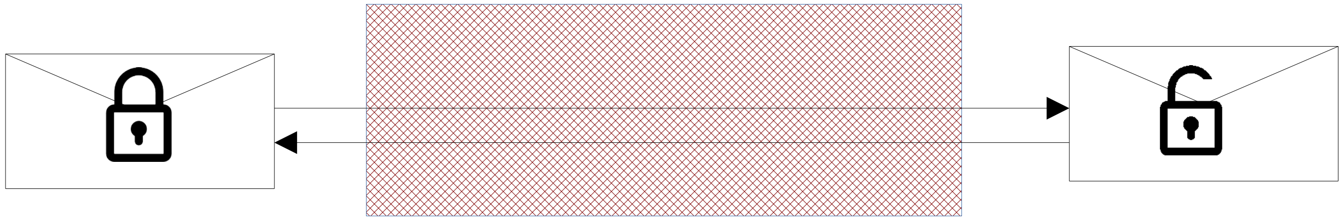
Plaintext Ciphertext

How many variations are there?
26! ~= 2^{88} => Key length is “88 bits”

Solving the Key Length Problem (Substitution Cipher)

We will use variation number 309273 to converse.

Sent in safe channel



$\mathrm{Enc}_{309273}(M)$ $\mathrm{Dec}_{309273}(M)$

The “variation number” is the cryptosystem's **key**

Solving the Frequency Analysis Problem

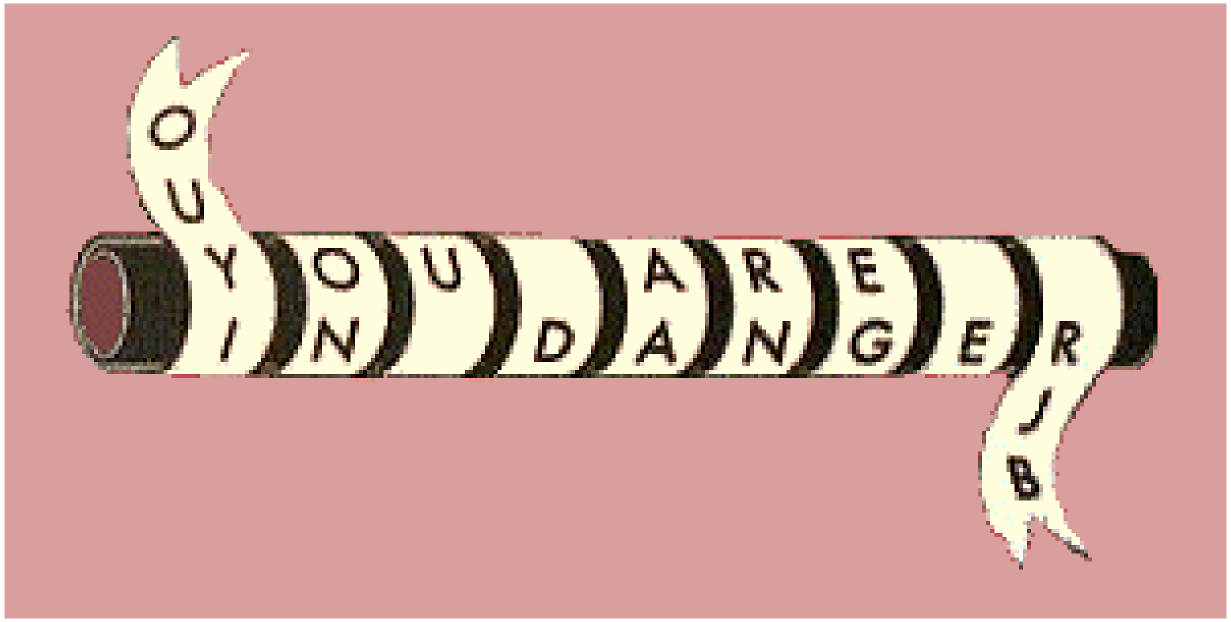
- We cannot do this easily – all substitution ciphers are weak to frequency analysis (cryptograms!)
- One suggested solution (Vignere ciphers): shift different letters based on their position using a key
  - e.g. key = DOG (4 15 7), then shift 1st letter by 4, 2nd by 15, 3rd by 7, 4th by 4, 5th by 15, ...
  - Easily defeated! (How?) 有足够时间，会找到cycle并且破解
- Broader category of cryptanalysis can defeat almost all “homemade” cryptography

Symmetric Key Encryption (SKE)

- A type of cryptosystem where *the two parties both know a secret key.*
- If the key is K, then the encryption and decryption algorithms are $\text{Enc}_K()$ and $\text{Dec}_K()$.
- $\text{Enc}_K()$ and $\text{Dec}_K()$ are public, but K must be secret.
- $\text{Enc}_K(M)$ should not reveal either K or M.
- Both parties can encrypt and decrypt.

We will discuss three types: OTP, Stream Ciphers and Block Ciphers

Scytale

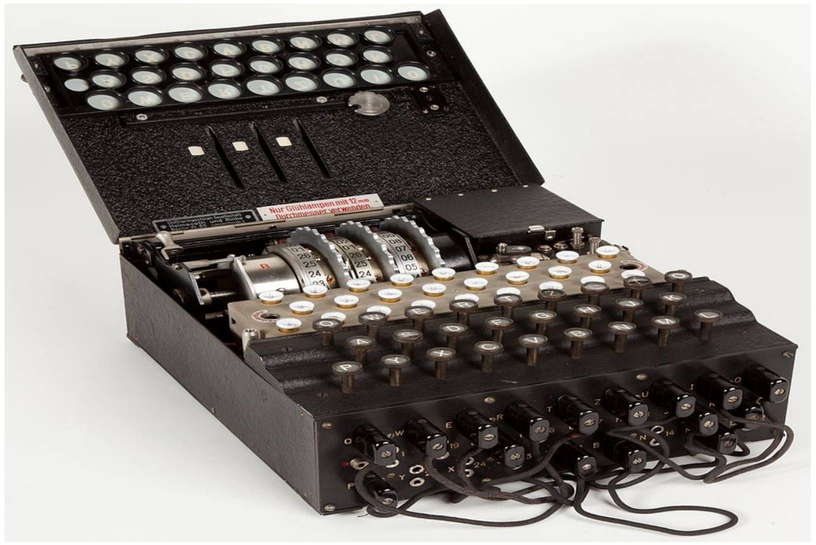


What is the key in this cryptosystem?

Enigma machine

- The key is the rotor position
- Codebook contains an initial position

1) Set to initial position
2) Type a new position
3) Set machine to new position
4) Type message



One-Time Pad

Plaintext:	Write in bit form (e.g. “ABC”) `01000001 01000010 01000011`
Key:	Uniformly random bit sequence `10110100 01010101 10001111`
Encrypt:	Bit-by-bit XOR key with plaintext
Ciphertext:	`11110101 00010111 11001100`
Decrypt:	Bit-by-bit XOR key with ciphertext
	`01000001 01000010 01000011`

One-Time Pad

"Perfectly" information secure if:

- Key is truly uniformly random
- Key is only used once, ever

(Why is it perfectly secure?)

VENONA project code-breakers (1943)

One-Time Pad

<u>Breaking a Two-Time Pad:</u>

Suppose the attacker intercepts two ciphertexts:

$$C = M \oplus K \text{ and } C' = M' \oplus K$$

The attacker applies XOR to the ciphertexts to obtain:

$$\begin{aligned} C \oplus C' &= M \oplus K \oplus M' \oplus K \\ &= M \oplus M' \end{aligned}$$

The result is the XOR of the plaintexts.

- If the attacker correctly guesses M, he can obtain M' by $M \oplus C \oplus C'$.
- If the attacker correctly guesses only one word of M (and its position), he can still obtain some letters in M' (at the same position) – he can drag this guess around and observe the result, known as crib-dragging.

Stream cipher

Generates keystream of any length
from **random seed**

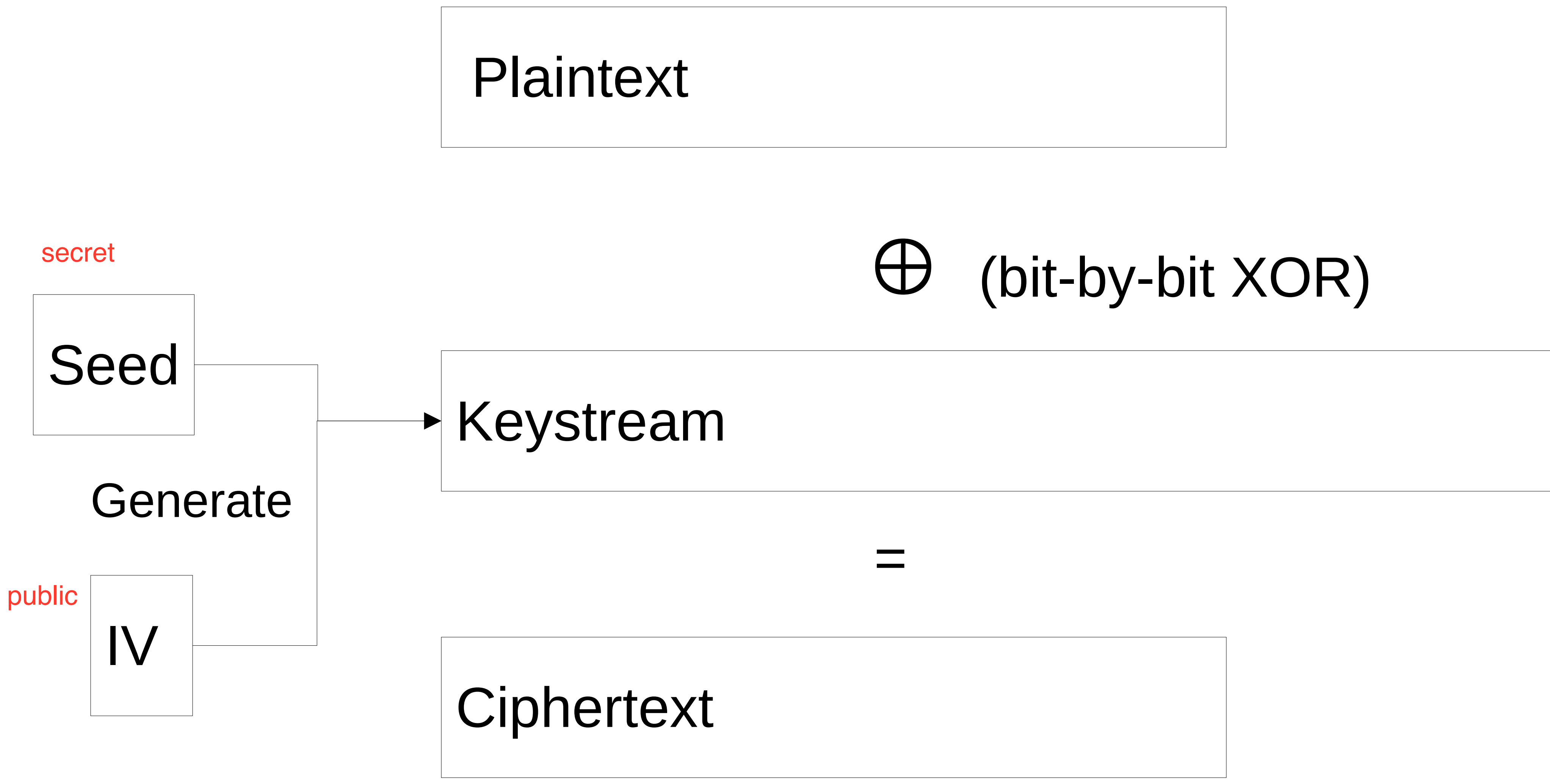
- Keystream is pseudorandom
- ~~Key is truly uniformly random~~
- Seed and IV are only used once, ever

can reuse the seed but the combination of seed and IV are only once

$$\text{Enc}_{\text{seed, IV}}(M) = \text{Keystream}_{\text{seed, IV}} \oplus M$$

Currently used: A5/1 (cell phones), Salsa20 (TLS)

Stream cipher (Enc/Dec)

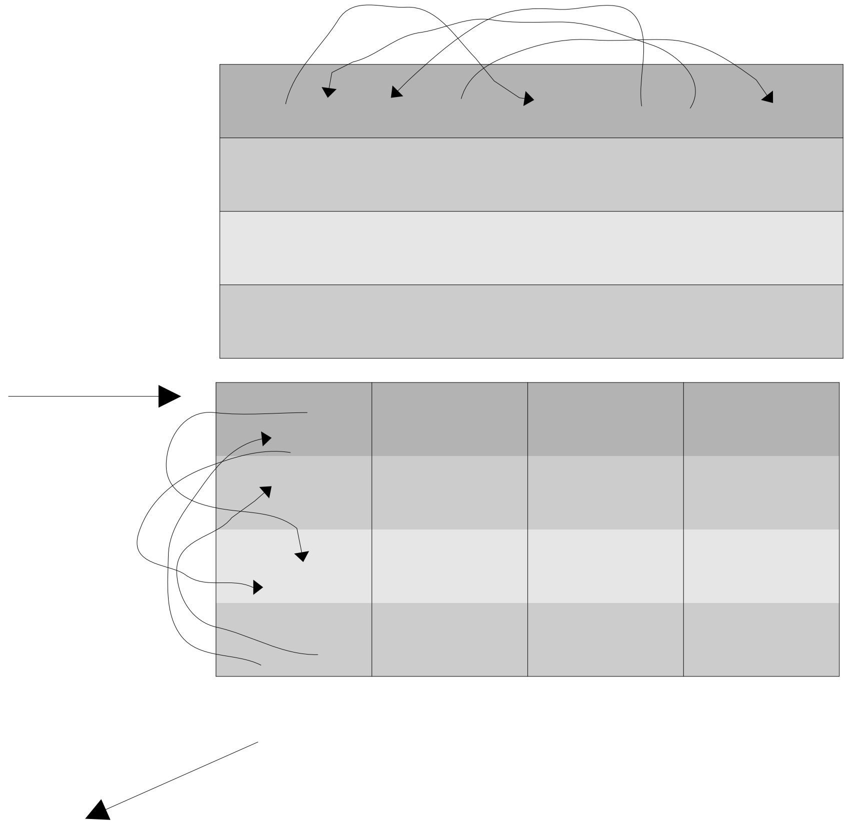


Salsa20 example

Place seed, IV, and position in a 16-by-16 matrix
Each entry is 4 bytes

“expa”	Seed	Seed	Seed
Seed	*“nd 3”*	IV	IV
Position	Position	*“2-by”*	Seed
Seed	Seed	Seed	*“te k”*

Alternatively, scramble each row and scramble each column (10 times each)



Output all bits as keystream

Block cipher

Difference from stream ciphers:

- There is a fixed block size (128 bits for AES)
- Plaintext is divided into blocks of this size
- We encrypt each block to produce ciphertext
- The “same” key is used for each block

We must change something,
or we run into the ciphertext repetition problem!

Block cipher

We use the **mode** to avoid the ciphertext repetition problem between blocks:

- <u>Electronic codebook (ECB):</u>

  All keys are the same (no defense against ciphertext repetition)

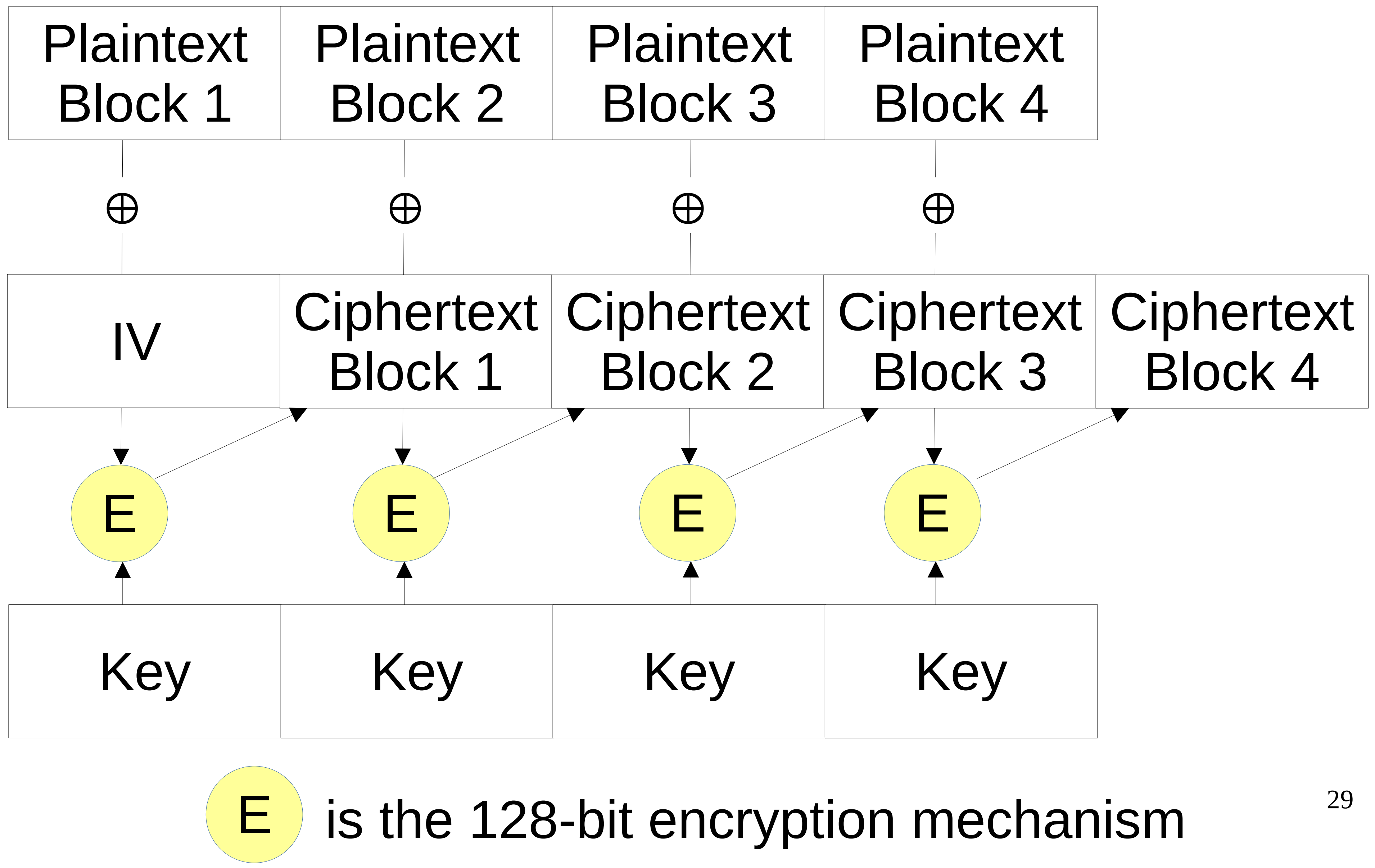
- <u>Cipher Block Chaining (CBC):</u>

  Plaintext block X is XOR'd with Ciphertext block (X-1) before encryption

- <u>Counter (CTR):</u>

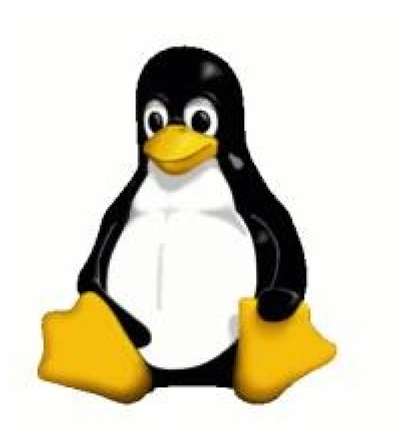
  Plaintext block X is XOR’d with a “keyblock” X, generated by an encryption of counter X with an IV

CBC mode (AES):

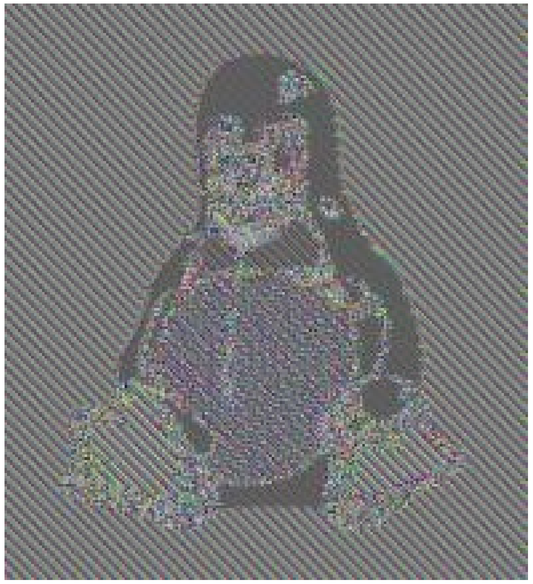


is the 128-bit encryption mechanism

Block cipher



Plaintext

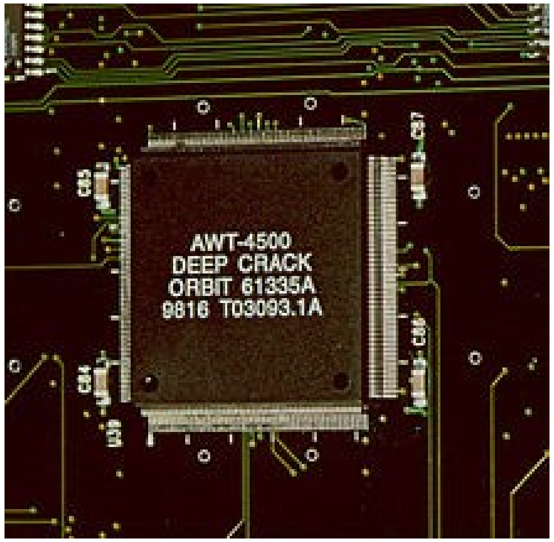


ECB mode

ECB mode is insecure!

Block cipher

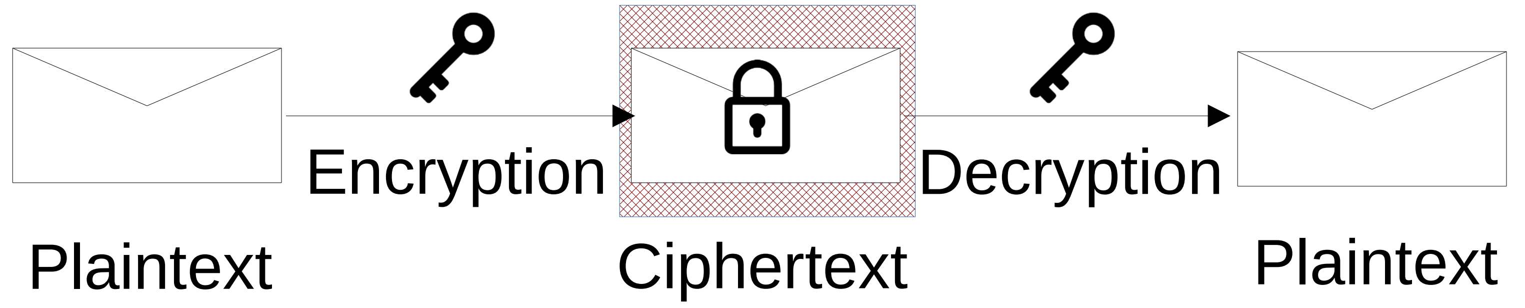
- Includes DES (56-bit), AES (128-bit)
- DES was shown to be too weak in 1998
- AES is the current standard; widely used
- Stream ciphers are generally faster (and keystream can be generated ahead of time)



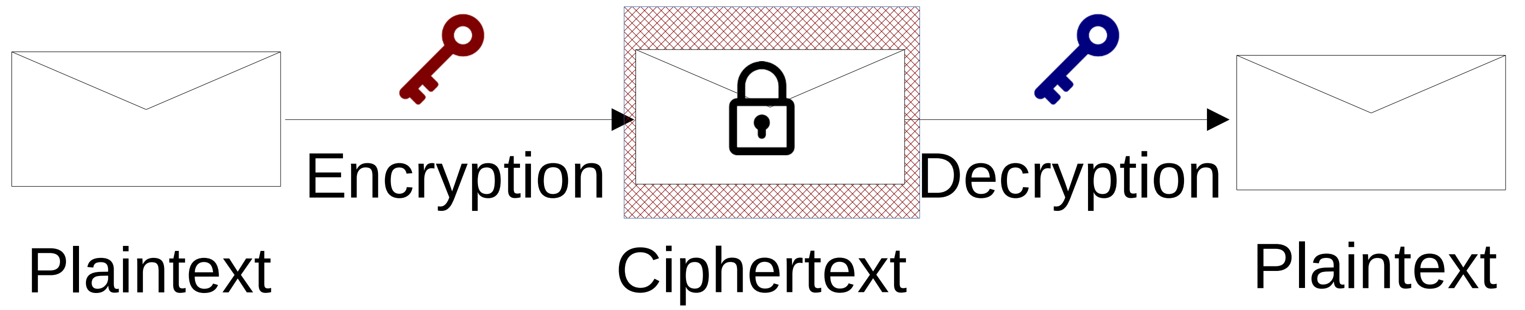
"Deep crack" DES cracker

Public Key Encryption (PKE)

In SKE, locking and opening require the *same key*



What if we want them to require *different keys*?



This is known as *Public Key Encryption*

Public Key Encryption (PKE)

Has two keys for two procedures:

Public key is used for encryption

Private key is used for decryption

Alice generates both keys.

(They are mathematically related.)

Then, Alice publishes her public key:

Anyone can encrypt

Only Alice can decrypt

Anyone can write a message that only Alice can read.

Examples: RSA, ElGamal, ECC

RSA

- First PKE (1977), widely used now in encryption
- Requires much longer keys (2048/4096 bits)
- Less efficient than SKE
- No “perfect security”; can be broken by quantum computers

PKE and SKE

	<u>PKE</u>	<u>SKE</u>
Key	Two: public/private	One: secret
Key setup	Share public key	Need safe channel
Encrypt	Anyone	Both participants
Decrypt	Only key generator	Both participants
Efficiency	Costly to encrypt/decrypt	Cheap

We can combine PKE and SKE to cover their weaknesses

Key Exchange (using PKE)

1. Alice generates a public/private key pair
2. Alice shares the public encryption key
3. Bob generates a secret key,
   encrypts it with PKE , and sends it to Alice
4. Alice decrypts the secret key,
   and uses it for SKE from now on

What if the private key is leaked?

In practice, the public/private key pair is **short-lived** to guranatee **forward secrecy**

Key Establishment (using Diffie-Hellman)

1. Alice and Bob use some g and prime p, where g generates integers modulo p
2. Alice generates and sends $g^A \bmod p$
3. Bob generates and sends $g^B \bmod p$
4. Alice and Bob compute secret key $g^{AB} \bmod p$
   Alice: $(g^B \bmod p)^A = g^{AB} \bmod p$
   Bob: $(g^A \bmod p)^B = g^{AB} \bmod p$

Other cryptographic tools

We may also want **integrity** and **authenticity**

- Confidentiality: The message is secret
- Integrity: The message is correct
- Authenticity: The sender/receiver's identity is correct

For this, we need other tools:

- Cryptographic hash
- Message Authentication Code (MAC)
- Digital signature

Cryptographic Hash

Cryptographic hashes are irreversible *one-way functions:*

$$\text{MESSAGE} \xrightarrow{\text{Hash}} \text{b194 d920}$$

Properties:

- Output is small, fixed size
- Different inputs may give same output
- Function is publicly known

Examples: MD5 (insecure!), SHA1, SHA2, SHA3

Cryptographic Hash

Cryptograhic hashes need to be difficult for the attacker to reverse or manipulate:

1) Given the output, it is hard to find an input hashing to that output

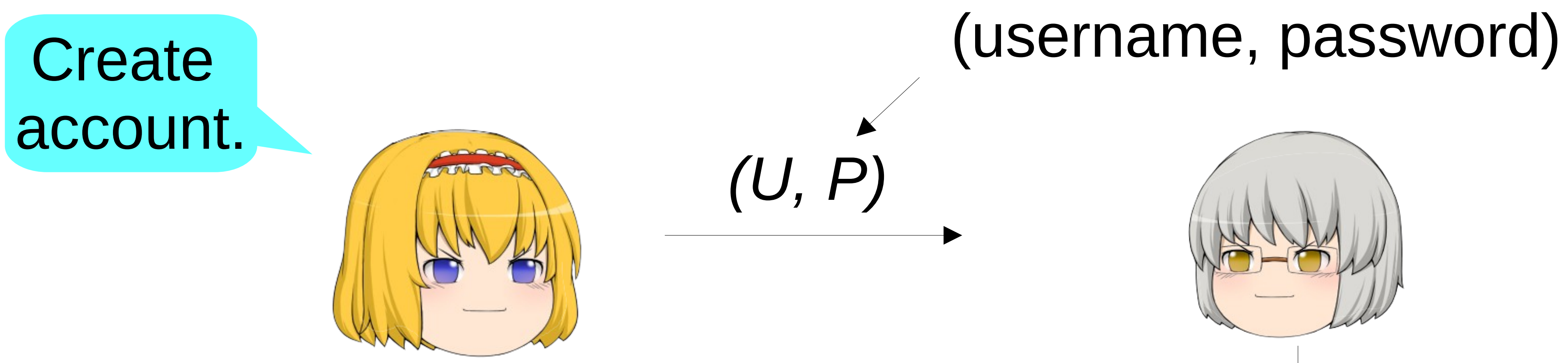
$$\text{????} \xrightarrow{\text{Hash}} \text{5e88 4898}$$

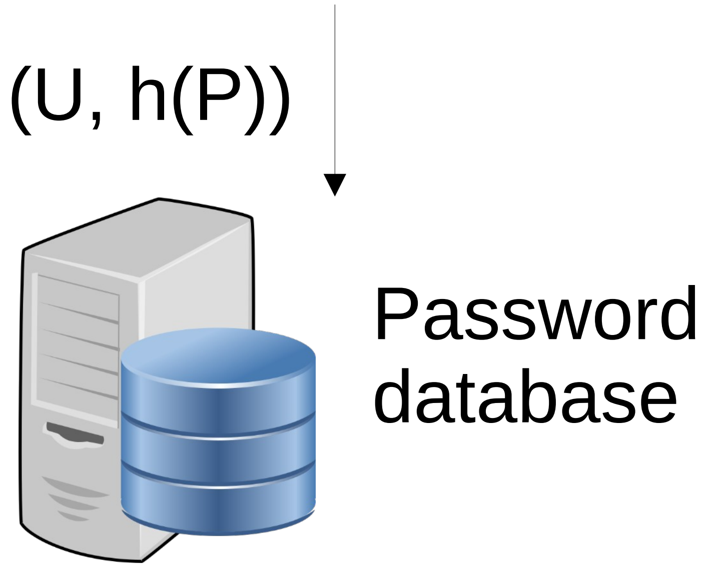
2) A small input change should produce an unpredictable output change

$$\text{MESSAGE} \xrightarrow{\text{Hash}} \text{b194 d920}$$

$$\text{MESSAGF} \xrightarrow{\text{Hash}} \text{e460 d5cf}$$

Cryptographic Hash Password Storage





P is never stored directly or encrypted because the password database can be stolen (even the key!)

Instead, it is hashed for storage

What if two users have the same password?

Cryptographic Hash Password Storage

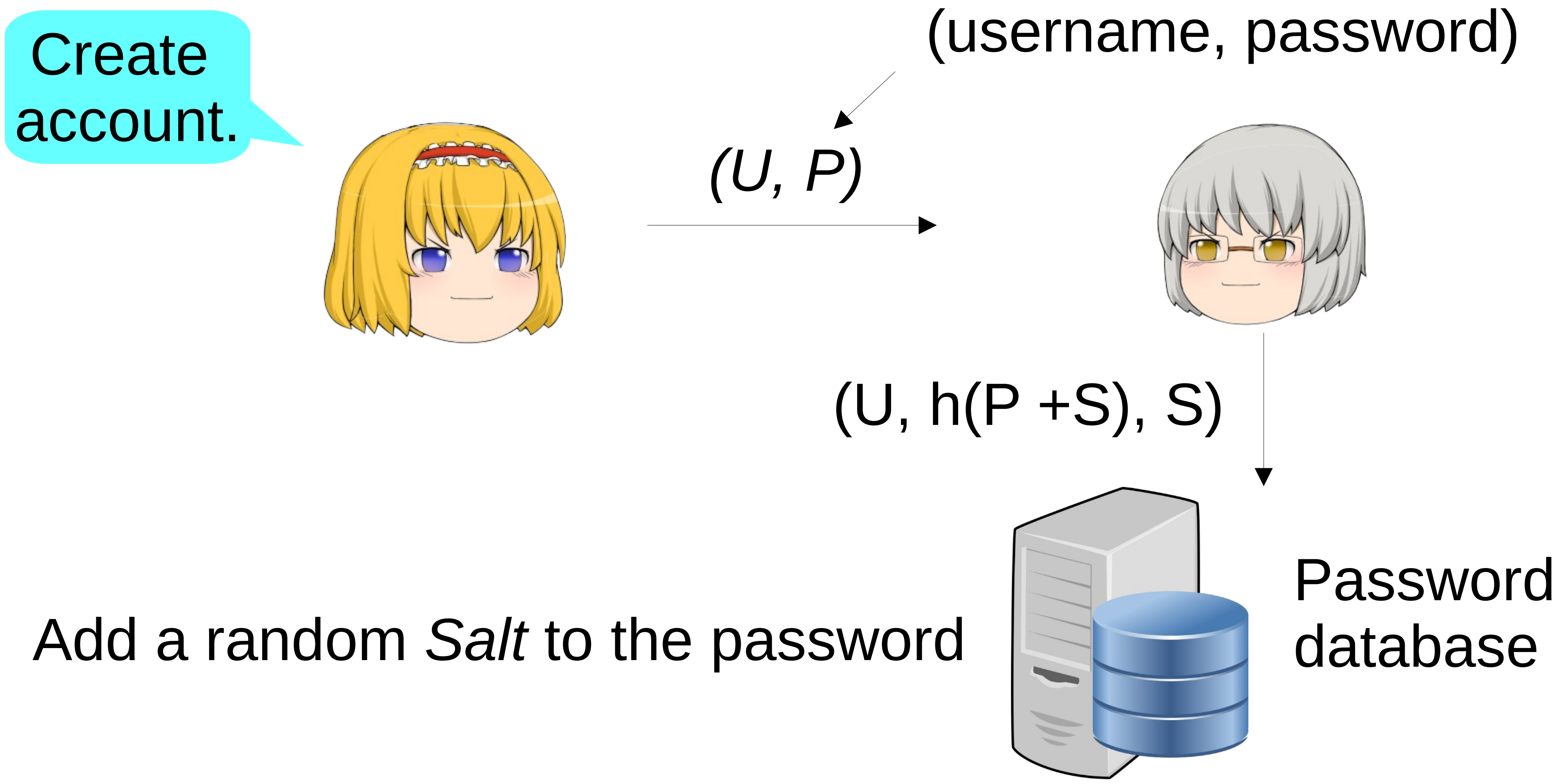
Attacker can *precompute* a hash table:

Guess password	Hash
123456	h(123456)
abc	h(abc)
...	...

When hashed passwords are stolen, attacker
simply has to do a matching exercise to “invert” the hash!

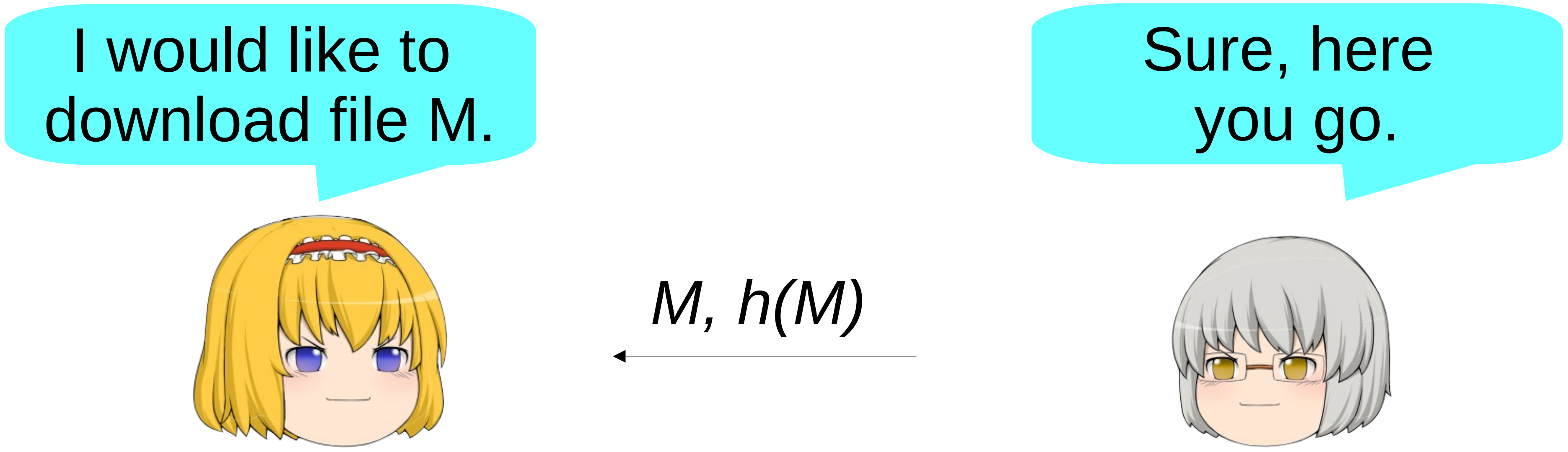
This is exactly like the ciphertext repetition problem

Cryptographic Hash Password Storage



Add a random *Salt* to the password

Cryptographic Hash
Verifying Integrity



verify h(M)

Good against unintentional errors, random errors

What about a malicious MITM attacker?

Message Authentication Code

A MAC is attached to messages for authentication:

- The two parties both need to have the secret key (like SKE)
- An attacker cannot “forge” a MAC
- **Authenticates** the message
- Can be built from a hash (this is called HMAC):

$$h(K||M)$$

Message Authentication Code

Alice sends M, h(K||M) to Bob

Verification: Bob, using his key, verifies h(K||M) is correct.

Resistance against MITM: Mallory, who does not have the key, cannot produce the HMAC. Specifically, if Mallory changes M to M’, he cannot also replace h(K||M) with h(K||M’). If he attempts to change any part of the message, Bob’s verification will fail.

Signatures

What if we reversed the roles of 🔑 and 🔑 ?

~~“Encrypting”~~ would be limited but everyone could ~~“decrypt”~~

Signing verify

🔑 Private signing key: signs the message

🔑 Public verification key: verifies the message

Achieves authentication if you know the correct public verification key

In practice, sign/verify keys are long-lasting while encrypt/decrypt keys are short-lived

Public Key Infrastructure

Hello! I am Alice. Here is my signature! *Sign* (*h*(*M*))
You can verify it with this public verification key.

How can you trust Alice?

Public Key Infrastructure

Delivering the right public verification key to users

We will examine PKI in three technologies:

- SSH tunneling
- PGP
- SSL/TLS

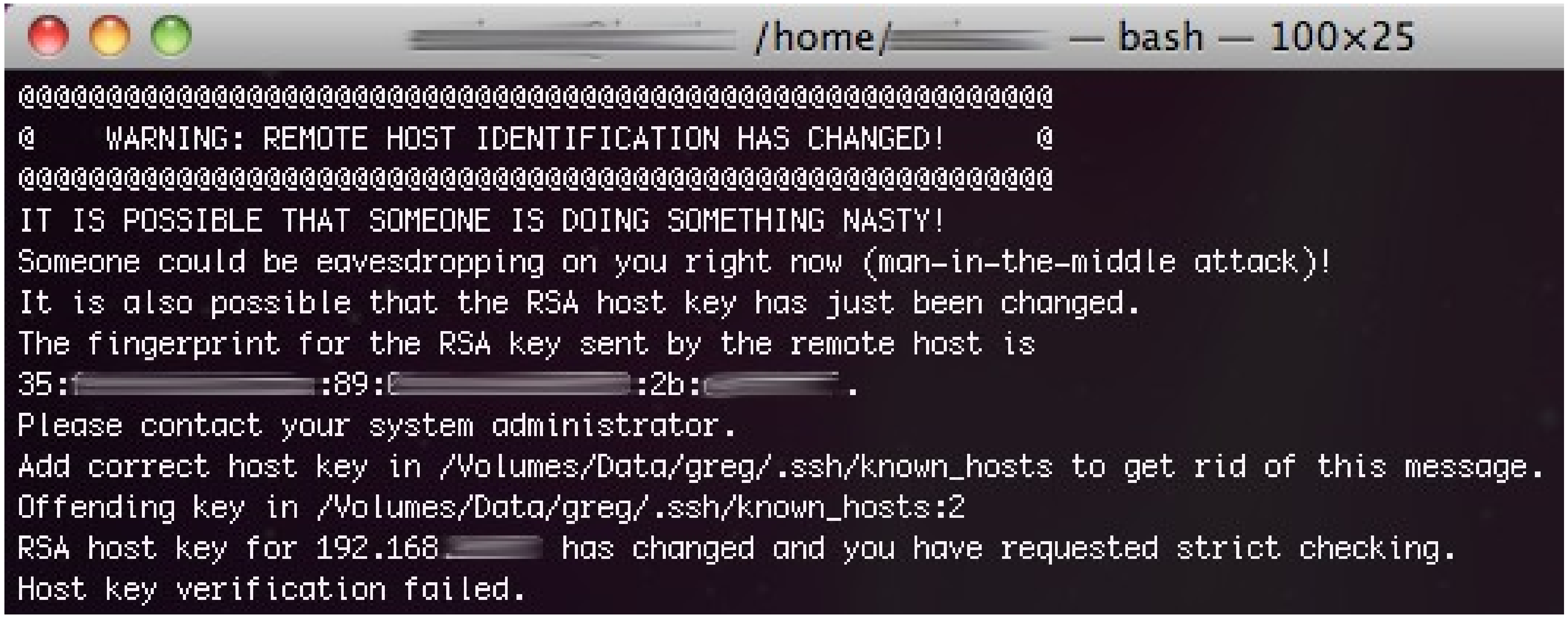
SSH tunneling

Used for connecting to remote machine

TOFU (Trust On First Use):

- When connecting for the first time, the server shows the public key
- You are asked if you trust the public key (yes/no)
- If “yes”, you will not be asked again unless the key changes
- If “no”, you will be disconnected

SSH tunneling



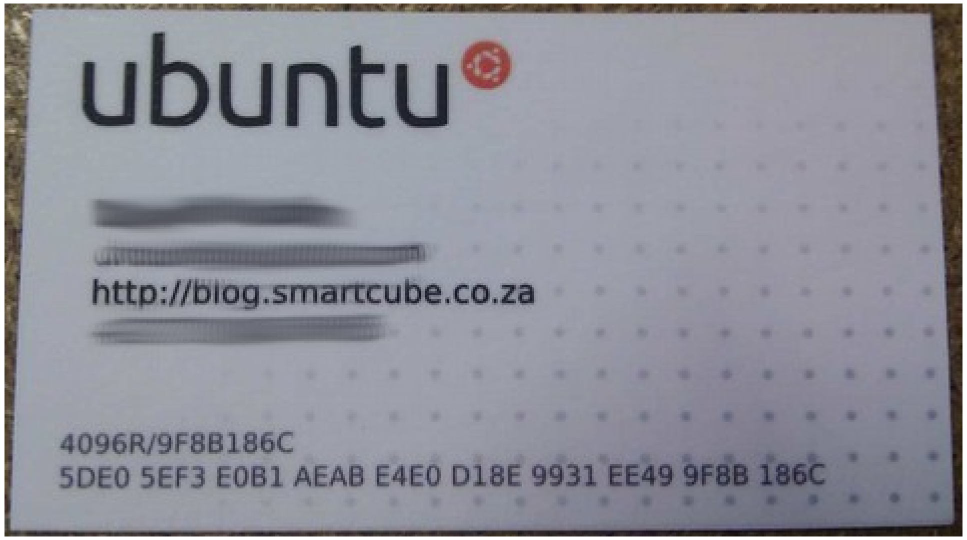
```
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@    WARNING: REMOTE HOST IDENTIFICATION HAS CHANGED!     @
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
IT IS POSSIBLE THAT SOMEONE IS DOING SOMETHING NASTY!
Someone could be eavesdropping on you right now (man-in-the-middle attack)!
It is also possible that the RSA host key has just been changed.
The fingerprint for the RSA key sent by the remote host is
35:[redacted]:89:[redacted]:2b:[redacted].
Please contact your system administrator.
Add correct host key in /Volumes/Data/greg/.ssh/known_hosts to get rid of this message.
Offending key in /Volumes/Data/greg/.ssh/known_hosts:2
RSA host key for 192.168[redacted] has changed and you have requested strict checking.
Host key verification failed.
```

PGP

Used in e-mails

Pretty Good Privacy

- Developed in 1991
- Needs setup
- Used by some professionals, privacy-sensitive circles



ubuntu

[redacted]

http://blog.smartcube.co.za

[redacted]

4096R/9F8B186C
5DE0 5EF3 E0B1 AEAB E4E0 D18E 9931 EE49 9F8B 186C

PGP

Used in e-mails

Web of Trust:

- Trust is transitive
- Alice can trust Bob directly (like TOFU)
- Alice can trust Carol indirectly – if Alice trusts Bob, and Bob trusts Carol
- Bob signs Carol's key, and Alice verifies Bob's signature

SSL/TLS

Used in HTTP

- Most widely used crypto-technology
- First appeared in Netscape for e-commerce
- Used by default in (increasingly) many websites
- Uses almost all of the tools in this module
- Versions: SSL1, SSL2, SSL3, TLS1.0, TLS1.1, TLS1.2, TLS1.3
- Current trend: removing bad encryption

SSL/TLS

Certificate system:

- By default, browsers will trust a set of **Ceritifcate Authorities** (CA)
- CA can sign any website's public key; the CA's signature is called a certificate
- The website presents its certificate when you connect to it
- Certificates can also be transitive

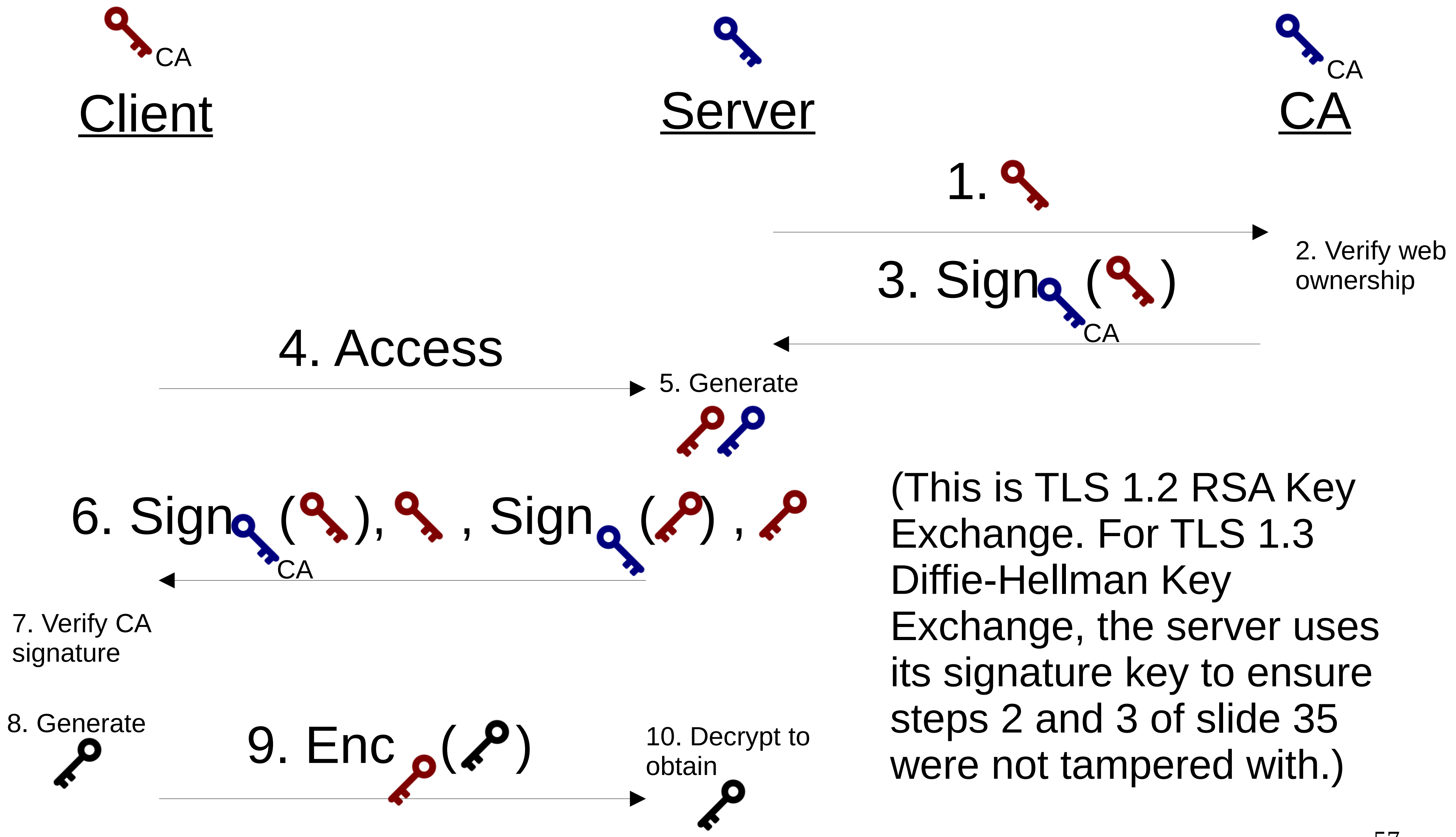
SSL/TLS

A basic connection uses most of this module's tools.

Key:

- 🔑$_{CA}$ Root CA’s public verification key
- 🔑$_{CA}$ Root CA’s private signature key
- 🔑 Web server’s public verification key
- 🔑 Web server’s private signature key
- 🔑 Web server’s public encryption key
- 🔑 Web server’s private decryption key
- 🔑 Secret key negotiated between client and web server

SSL/TLS



(This is TLS 1.2 RSA Key Exchange. For TLS 1.3 Diffie-Hellman Key Exchange, the server uses its signature key to ensure steps 2 and 3 of slide 35 were not tampered with.)

SSL/TLS

1. Server sends its public verification key to the root CA.
2. Root CA checks that person really owns the web server.
3. Root CA signs the web server's public verification key and sends it back (the cert).
(After some time)
4. The client accesses the web server.
5. Server generates an ephemeral PKE key pair.
6. Server sends the cert to client, along with both public keys and a signed version of the public encryption key to avoid tampering.
7. Client checks signature on cert to verify the server's public verification key, then uses that to verify the server's public encryption key.
8. Client generates secret key.
9. Client encrypts secret key with server's public encryption key and sends it to server.
10. Server decrypts to obtain secret key.

From this point onward all communication will use that secret key (most likely 128-bit AES CBC with SHA-256 for HMAC).

Attacks on Cryptosystems

Cryptanalysis

- Find mathematical weaknesses in cryptography
- For example:
  - DES key length is too short
  - RC4 does not have enough initial rounds
  - MD5, SHA-1 are vulnerable to a “collision attack”
    - This is a problem for HMACs

Attacks on Cryptosystems

Root CA compromise:

- DigiNotar, dutch root CA (2011)
  - Issued fake certs for google.com
  - Breach was hidden
  - Web browsers removed DigiNotar as root CA
- Comodo (2011)
  - Issued fake certs for google, yahoo, etc.
  - Certificates were immediately revoked
- Kazakhstan’s government issues all certificates (i.e. can read/intercept all HTTPS)

Attacks on Cryptosystems

Yahoo hacks (2014, 2016, 2017)

- Authentication cookies are generated from secret seeds
- Seeds were stolen at some point
- User data stolen by criminals, sold several times

The stolen user account information may have included names, email addresses, ..., hashed passwords ***(using MD5)****...*

Recap

SKE	is efficient and hard to break cryptographically
	but it needs a shared key
PKE	can be used to share the SKE key
	but text and public key are not authenticated
MAC	can authenticate text
	but it needs a shared key
PKI	can authenticate public key
TOFU *Web of Trust* *PKI*	*but they each have their own problems*