CSE508 Network Security (PhD Section)

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Encrypted Communication

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Cryptography

Goals

Confidentiality

Keep content secret from all but authorized entities

Integrity

Protect content from unauthorized alteration

Authentication

Identification of data or communicating entities

Non-repudiation

Prevent entities from denying previous commitments or actions

Basic Terminology

Plaintext: the original message

Ciphertext: the coded message

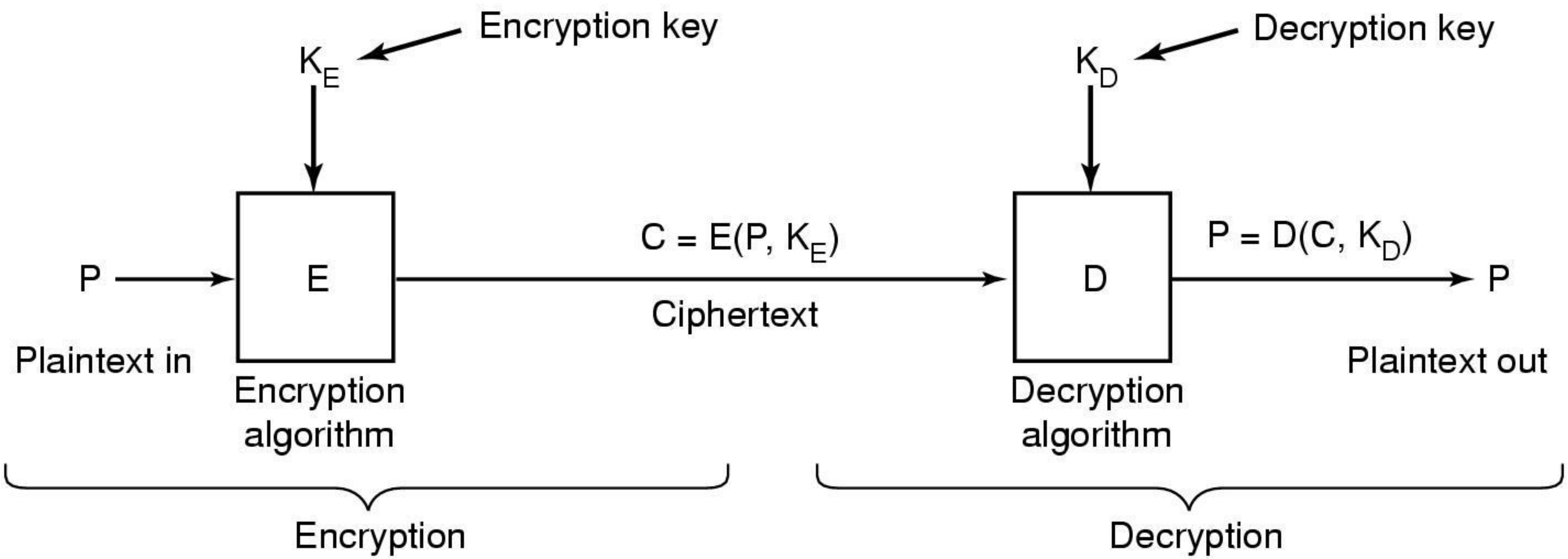
Cipher: algorithm for transforming plaintext to ciphertext (encryption) and back (decryption)

Key: info used in cipher known to sender and receiver

Cryptanalysis (codebreaking): the study of methods of deciphering ciphertext without knowing the key

Cryptology: the field of both cryptography and cryptanalysis

Plaintext vs. Ciphertext



Kerckhoffs's Principle

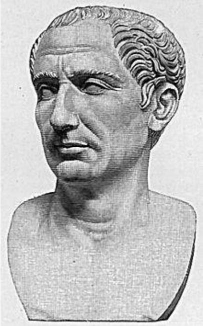
A cryptosystem should be secure even if everything about the system, except the key, is public knowledge

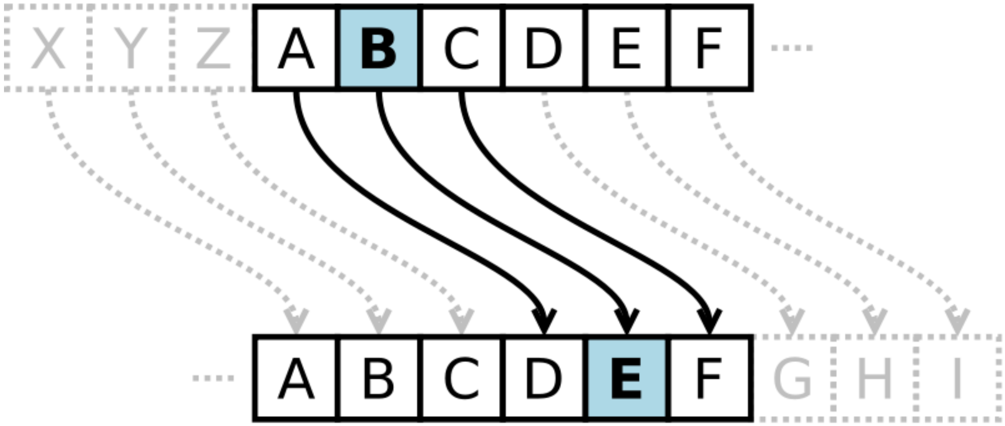
The security of the system must rest entirely on the secrecy of the key

- Only brute force attacks are possible
- Otherwise the algorithm is broken

Contrast with security by obscurity: every secret creates a potential failure point

Caesar Cipher



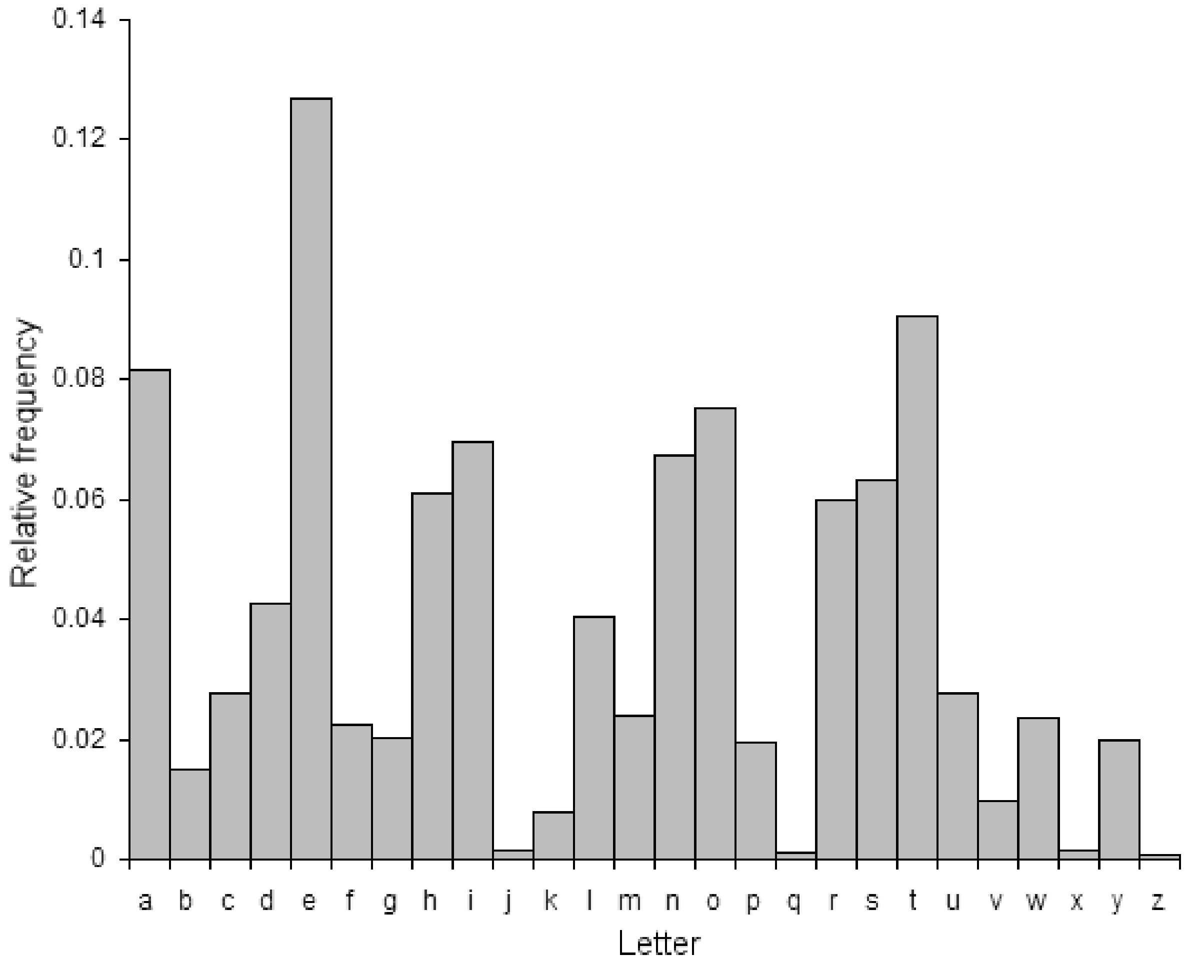



```
Ciphertext: WKH TXLFN EURZQ IRA MXPSV RYHU WKH ODCB GRJ
Plaintext:  the quick brown fox jumps over the lazy dog
```

Shift by X (e.g., ROT-13)

Monoalphabetic substitution

Easy to break using frequency analysis



Distribution of letters in a typical sample of English language text

Vigenère Cipher

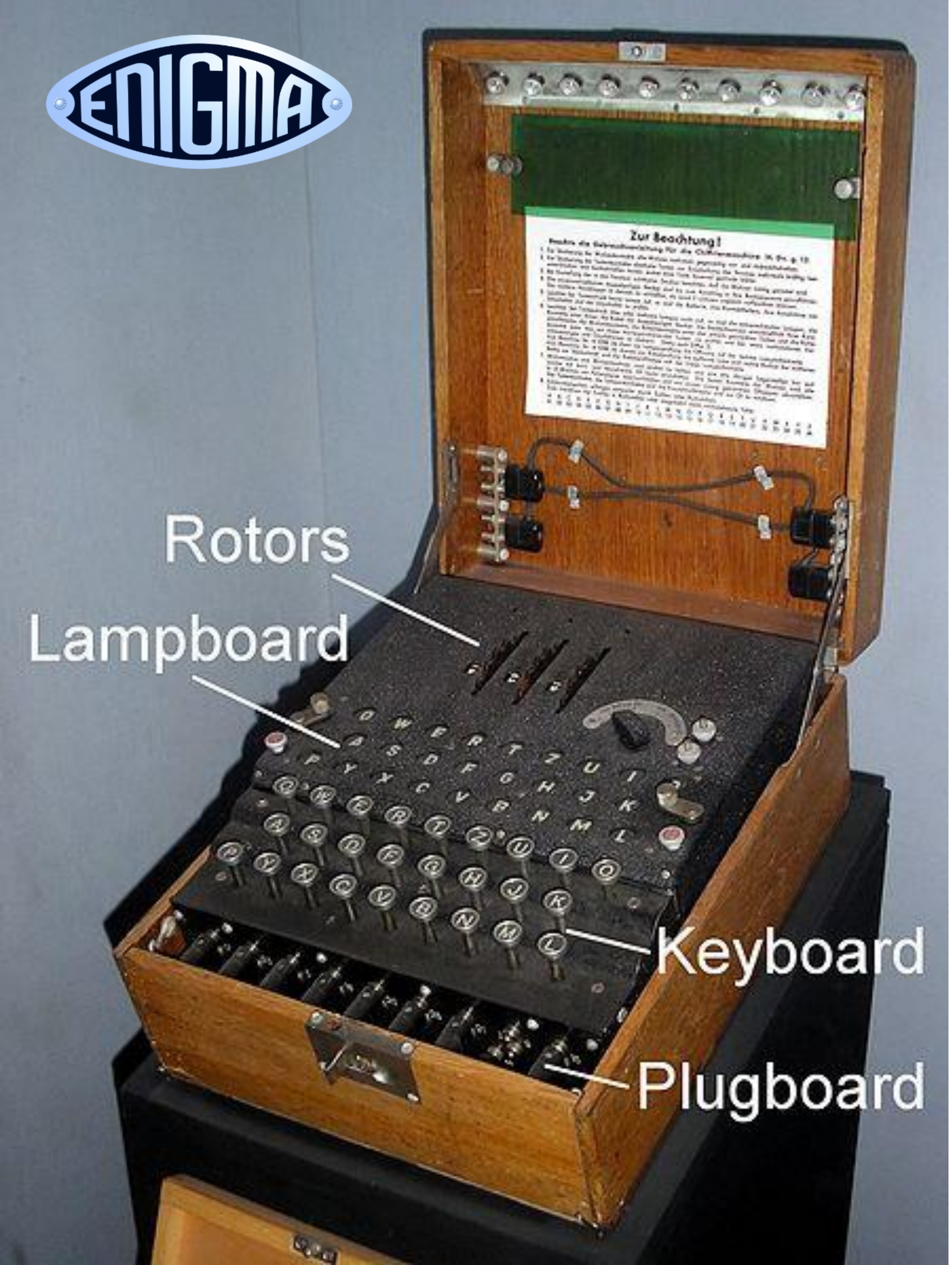
```
Plaintext:  ATTACKATDAWN
Key:        LEMONLEMONLE
Ciphertext: LXFOPVEFRNHR
```

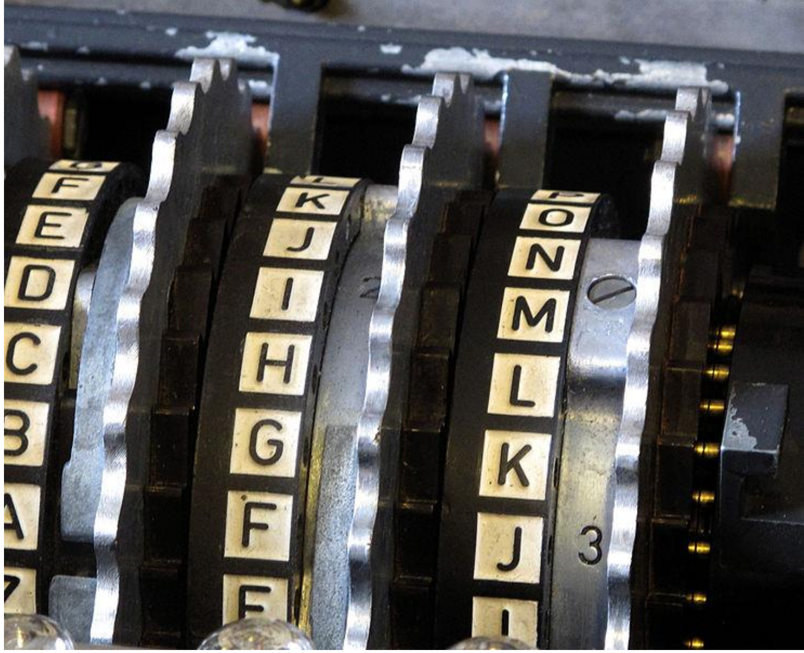
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
B	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A
C	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B
D	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C
E	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D
F	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E
G	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F
H	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G
I	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H
J	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I
K	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J
L	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K
M	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L
N	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M
O	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N
P	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Q	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
R	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
S	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
T	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
U	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
V	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
W	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
X	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
Y	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Z	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y

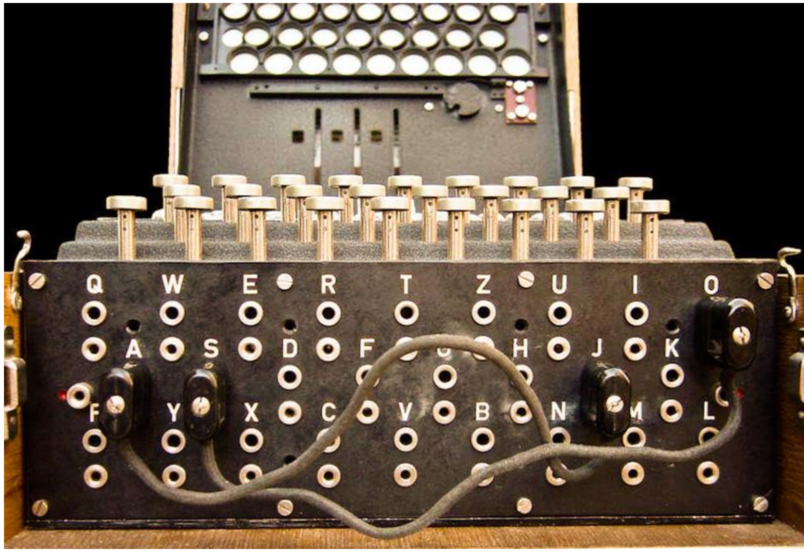
Successive Ceasar ciphers with different shift values

Polyalphabetic substitution

- Defeats simple frequency analysis, but still breakable


ENIGMA
Rotors
Lampboard
Keyboard
Plugboard





Properties of a Good Cryptosystem

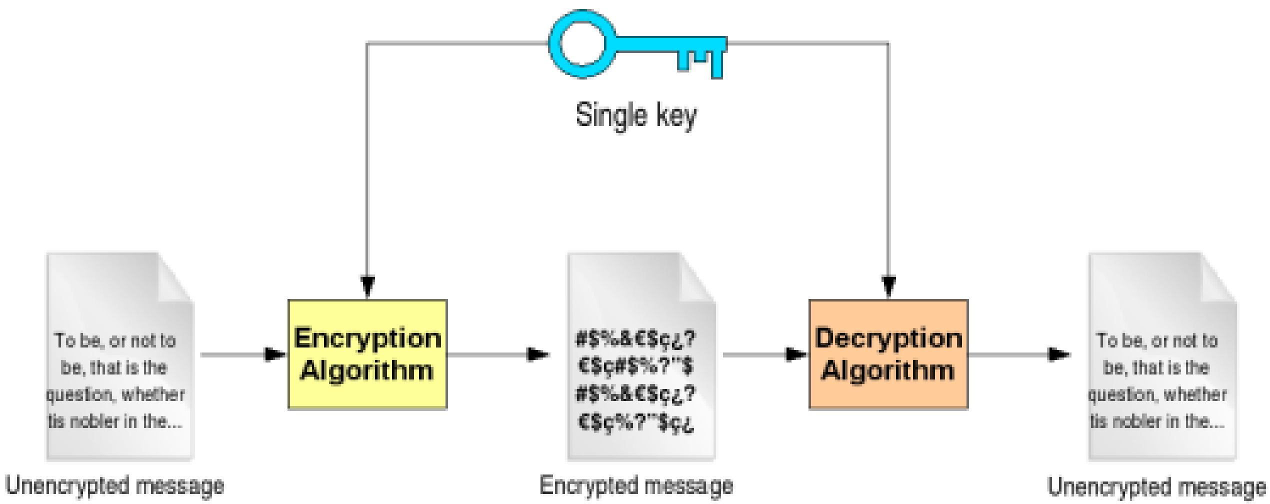
Given the ciphertext, an adversary should not be able to recover the original message

- Enumerating all possible keys must be infeasible
- There should be no way to produce plaintext from ciphertext without the key

The ciphertext must be indistinguishable from true random values

- Given a ciphertext, the probability of any possible plaintext being encrypted should be the same

Symmetric Key Cryptography



Pros:
Fast
Short keys
Well known
Simple key generation

Cons:
Secrecy of keys
Management of keys
Number of keys

One-time Pad

XOR plaintext with a keystream

- 1882 Frank Miller [Bellovin '11]
- 1917 Vernam/Mauborgne cipher

"Information-theoretically secure" against ciphertext-only attacks (Shannon 1949)

The keystream must be

- Truly random
- As long as the plaintext
- Used only once
- Kept completely secret

Block Ciphers

Process one block at a time

Substitution and transposition (permutation) techniques

Examples: DES, AES, …

Stream Ciphers

Process one bit or byte at a time

Plaintext is combined (XOR) with a *pseudorandom* keystream (NOT the same as one-time pad)

Synchronous vs. asynchronous (self-synchronizing)

Examples: RC4, any block cipher in OFB or CTR mode, …

Block Ciphers

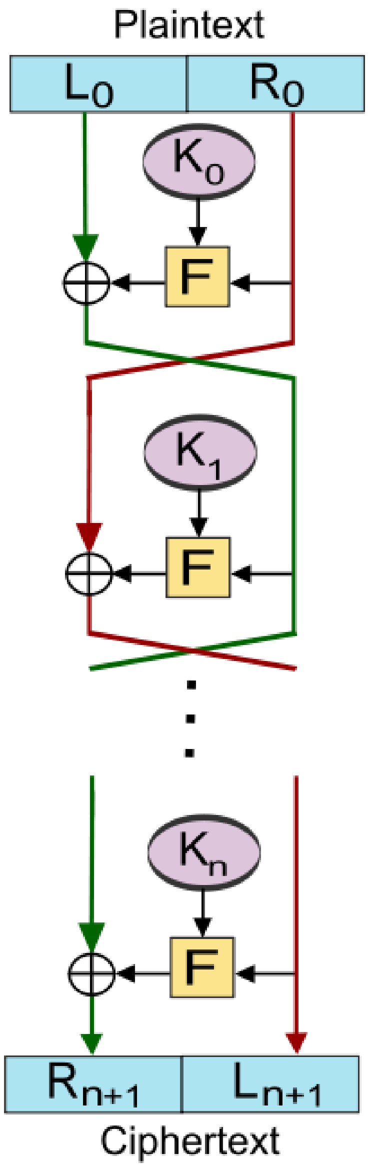
Multiple rounds of substitution, permutation, …

Confusion: each character of the ciphertext should depend on several parts of the key

Diffusion: changing a plaintext character should result in several changed ciphertext characters

	DES	AES
Key length	56 bits	128, 192, 256 bits
Block size	64 bits	128 bits
Rounds	16	10, 12, 14
Construction	Substitution, permutation	Substitution, permutation, mixing, addition
Developed	1977	1998
Status	Broken!	OK (for now)

DES rounds



Modes of Operation

Direct use of block ciphers is not very useful

- Enemy can build a “code book” of plaintext/ciphertext equivalents
- Message length should be multiple of the cipher block size

How to repeatedly apply a block cipher to securely encrypt/decrypt arbitrary inputs?

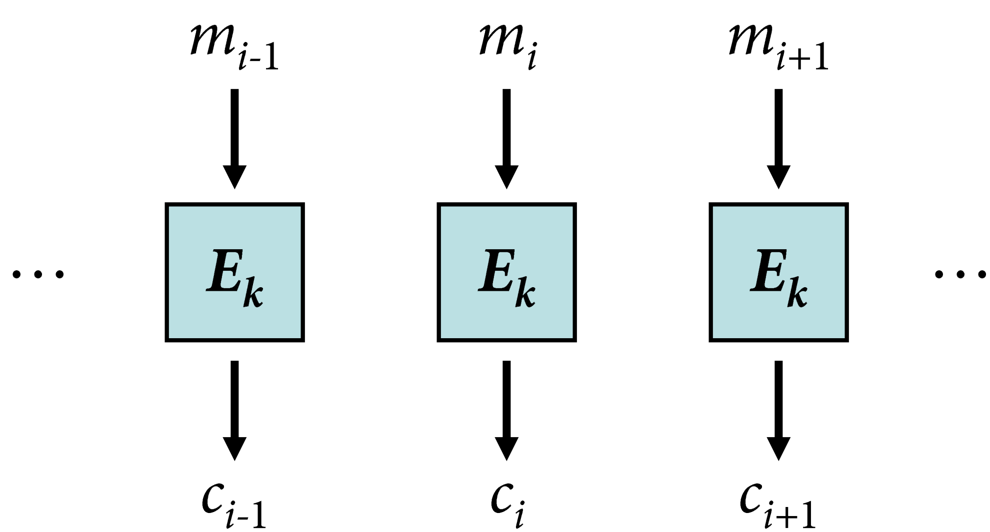
Five standard modes

- ECB: Electronic Code Book
- CBC: Cipher Block Chaining
- CFB: Cipher Feedback
- OFB: Output Feedback
- CTR: Counter

ECB: Electronic Code Book Mode

Direct use of the block cipher

- Each block is encrypted independently
- No chaining, no error propagation



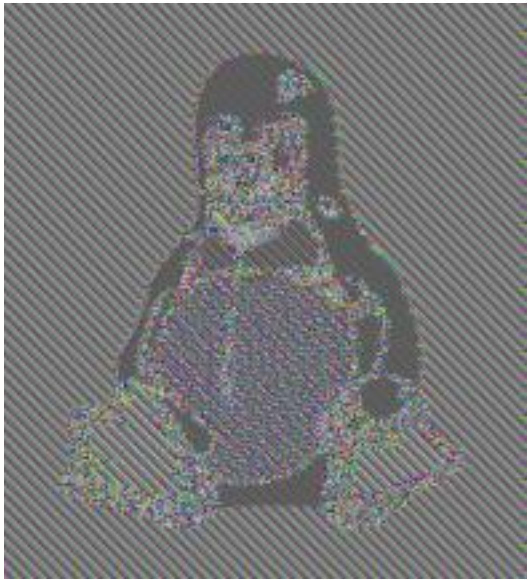
Problem: if $m_i = m_j$ then $c_i = c_j$

ECB: Electronic Code Book Mode

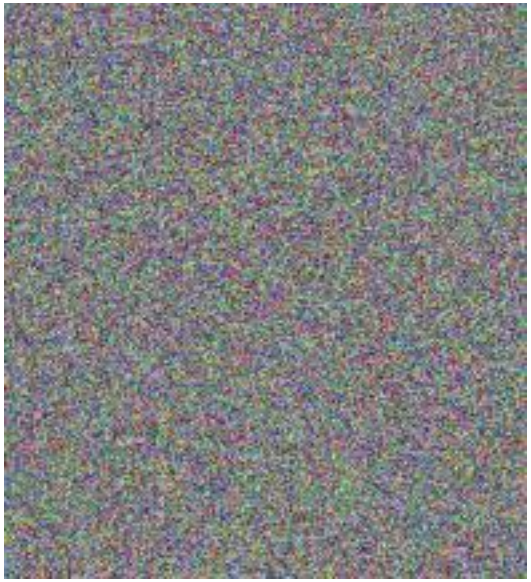
Data patterns may remain visible

Susceptible to replay attacks, block insertion/deletion

Plaintext



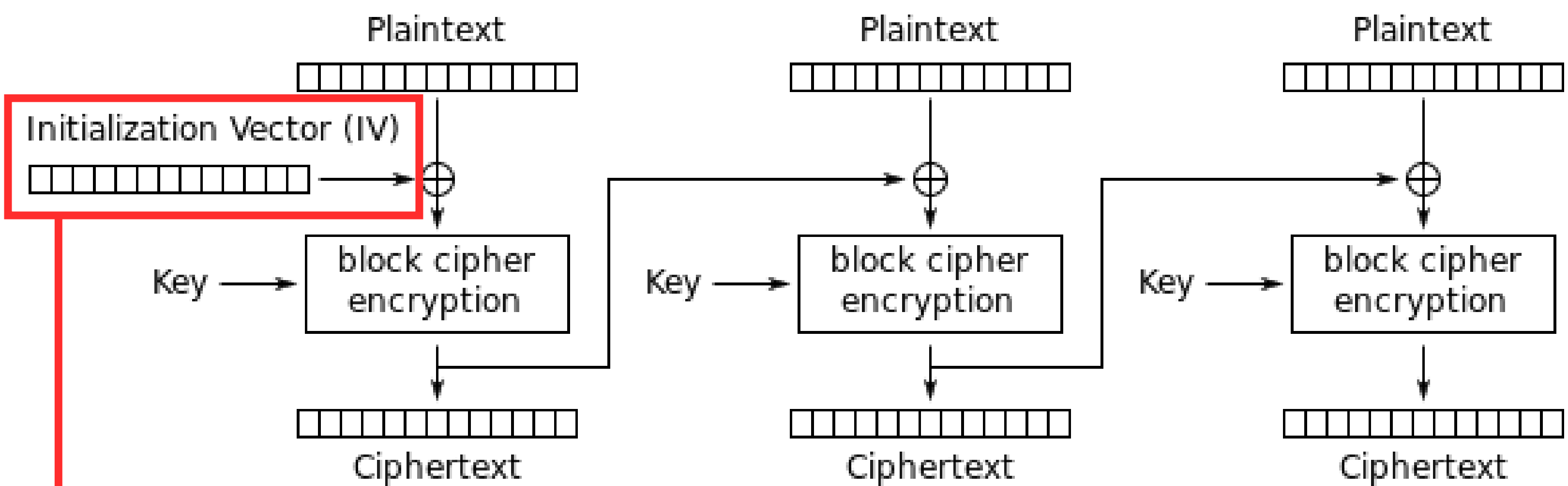
ECB Mode Encryption



CBC/Other Modes

CBC: Cipher Block Chaining Mode

Each plaintext block is XORed with the previous ciphertext block before being encrypted



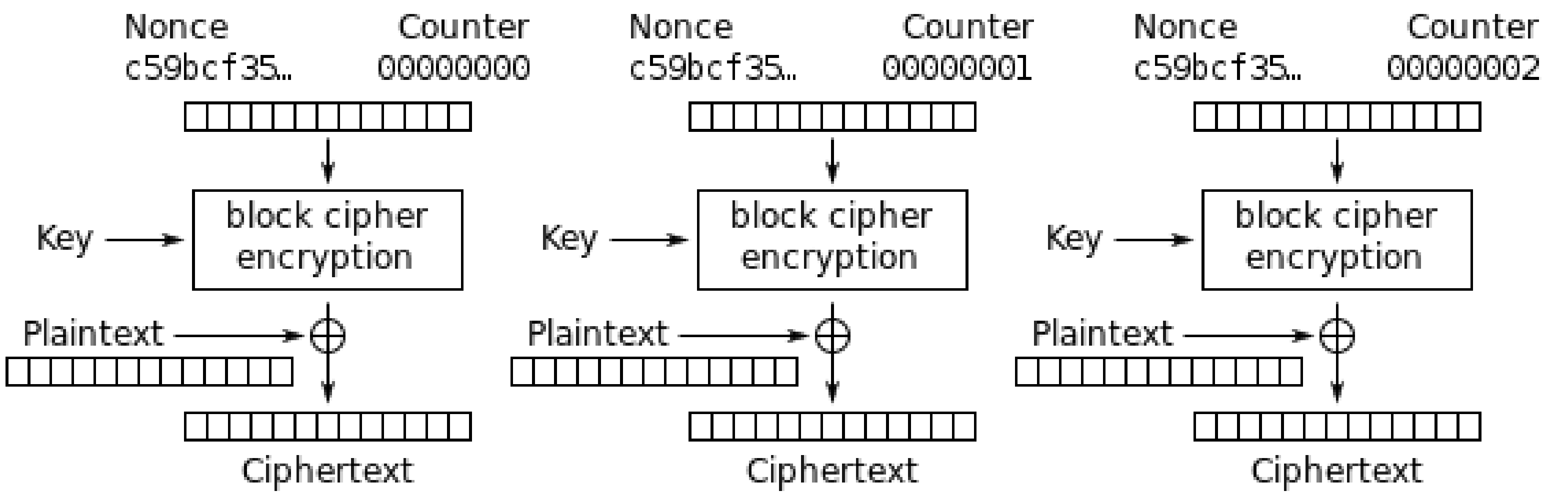
Cipher Block Chaining (CBC) mode encryption

Must be random!
Must never be reused!

CTR: Counter Mode

Turns a block cipher into a stream cipher

- Next keystream block is generated by encrypting successive values of a counter combined with a nonce (IV)



Counter (CTR) mode encryption

Diffie–Hellman Key Exchange

Allows two parties to jointly establish a shared secret key over an insecure communication channel

- The established key can then be used to encrypt subsequent communication using a symmetric key cipher
- "New Directions in Cryptography" by Whitfield Diffie and Martin Hellman, 1976

Based on the discrete logarithm problem

$$3^{29} \bmod 17 \xrightarrow{\textit{easy}} ??$$

$$3^{??} \bmod 17 \xleftarrow{\textit{hard}} 12$$

Diffie–Hellman Key Exchange

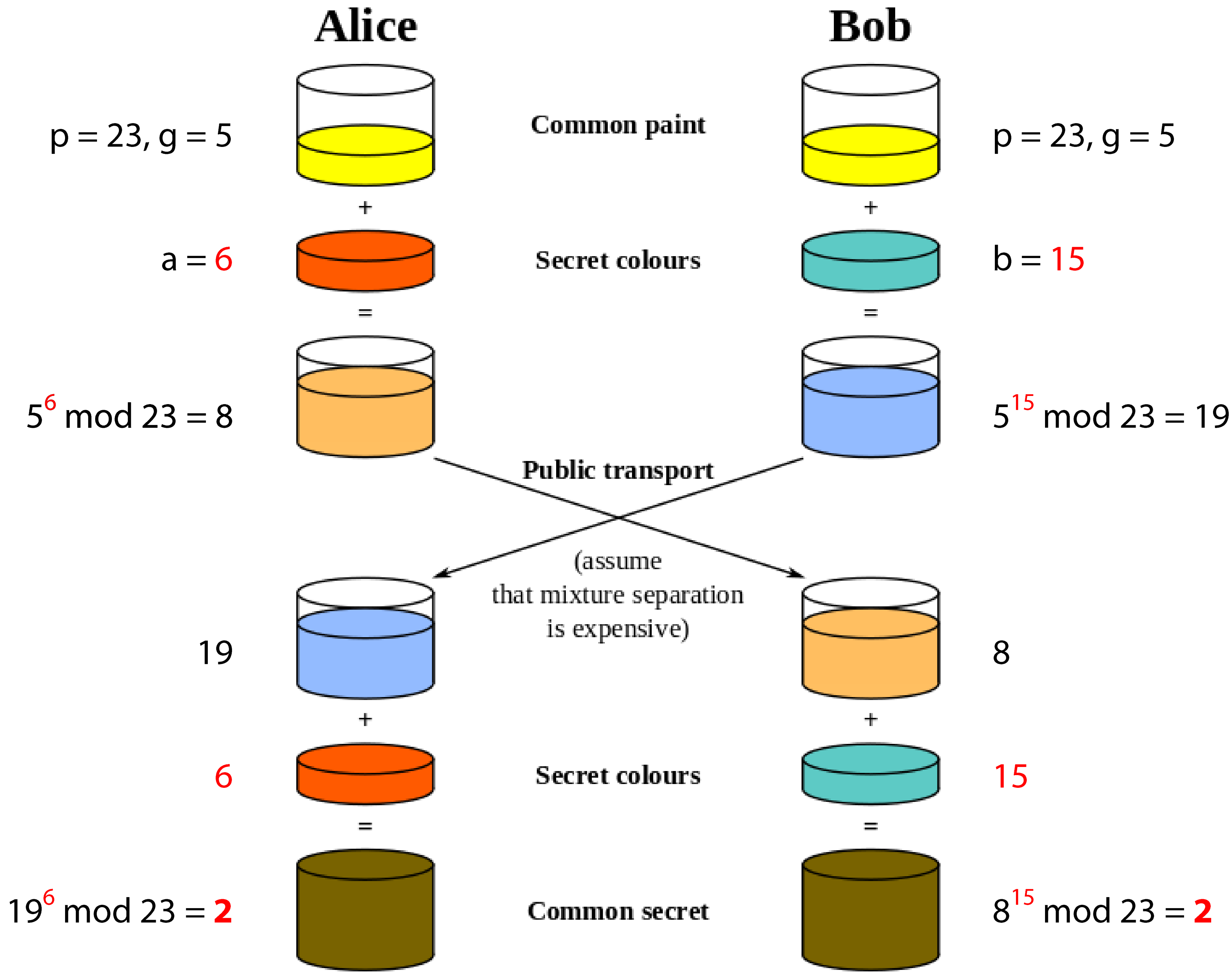
Alice and Bob agree on a large (at least 1024 bit) prime number p and a base g

- p is usually of the form $2q+1$ where q is also prime
- g is a generator of the multiplicative group of integers modulo p (for every x coprime to p there is a k such that $g^k \equiv x \bmod p$

Alice picks a secret (private) large random number a and sends to Bob $g^a \bmod p$

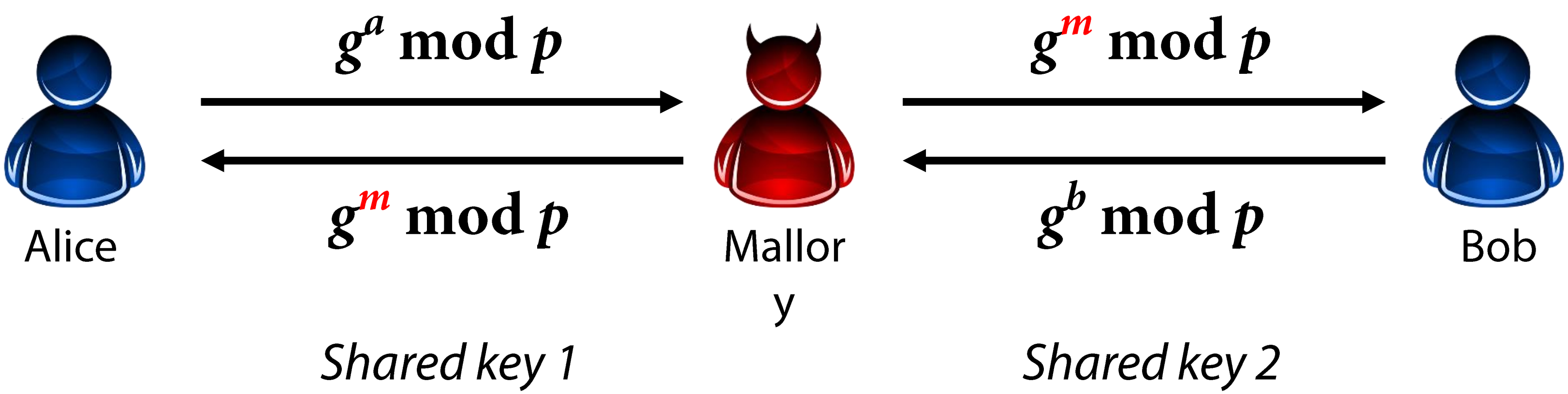
Bob picks a secret large random number b and sends to Alice $g^b \bmod p$

$$\left.\begin{array}{l}\text{Alice calculates } s = (g^b \bmod p)^a = g^{ba} \bmod p \\ \text{Bob calculates } s = (g^a \bmod p)^b = g^{ab} \bmod p\end{array}\right\} \textbf{\textit{shared key}}$$


Alice
Bob
p = 23, g = 5
Common paint
p = 23, g = 5
+
+
a = 6
Secret colours
b = 15
=
=
5^6 mod 23 = 8
5^{15} mod 23 = 19
Public transport
(assume that mixture separation is expensive)
19
8
+
+
6
Secret colours
15
=
=
19^6 mod 23 = **2**
Common secret
8^{15} mod 23 = **2**

Man-in-the-Middle Attack

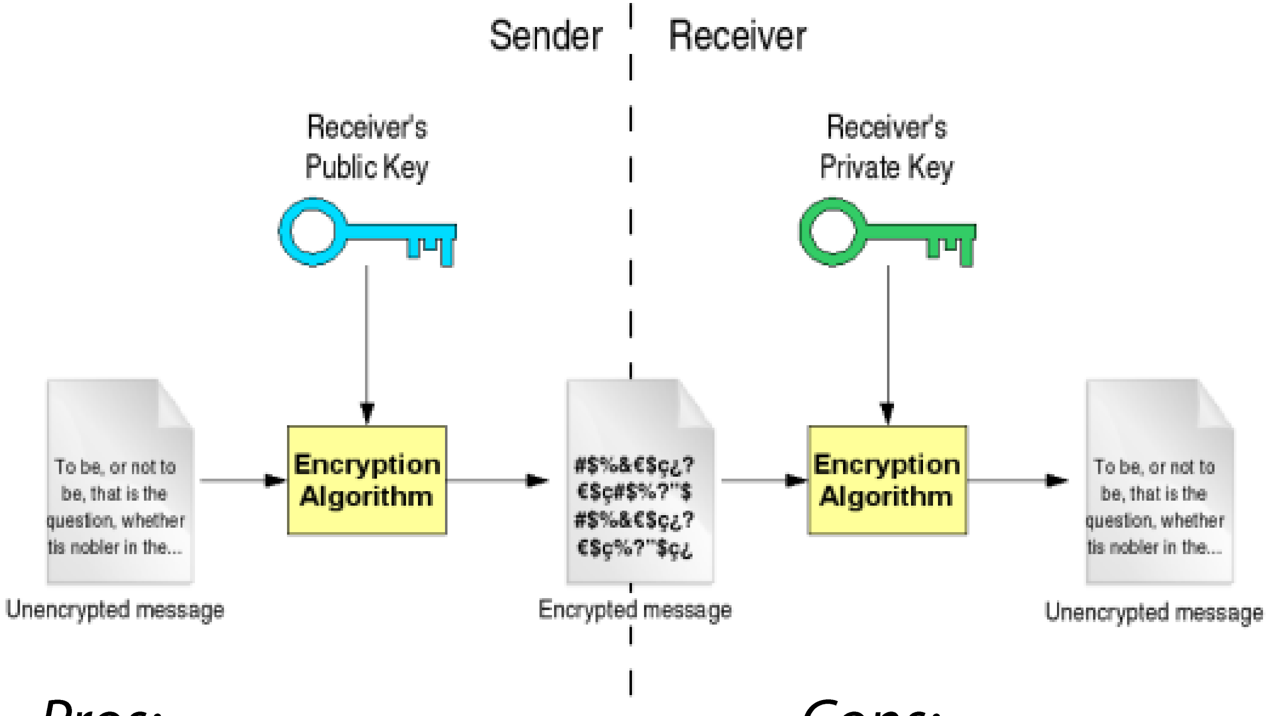
Alice and Bob share no secrets



Mallory actively decrypts and re-encrypts all traffic

- Alice and Bob think they communicate directly
- General problem: *need for a root of trust*

Public Key Cryptography



Pros:

No shared secrets

Easier key management

Provides secrecy and authenticity

Cons:

Slow

Large keys

Key generation is more difficult

RSA

Named after its inventors Rivest, Shamir, Adleman

Based on the problem of factoring large numbers

- Choose two distinct large prime numbers p and q
- Let $n = pq$ (modulus)
- Select e as a relative prime to $(p - 1)(q - 1)$
- Calculate d such that $ed \equiv 1 \bmod (p - 1)(q - 1)$
- Public key = (e, n)
- Private key = (d, n)
- To encrypt m, calculate $c = m^e \bmod n$
- To decrypt c, calculate $m = c^d \bmod n$

RSA in Practice

RSA calculations are computationally expensive

Use RSA in combination with a symmetric key

Send an encrypted message:

- Encrypt message with a random symmetric key
- Encrypt symmetric key with recipient's public key
- Transmit both the encrypted message and the encrypted key

Set up an encrypted communication channel:

- Negotiate a symmetric key using RSA
- Use the symmetric key for subsequent communication

Forward Secrecy

Threat: capture encrypted traffic now, use in the future

- Private keys may be compromised (e.g., infiltrate system)
- Cryptanalytic breakthrough

FS: Ensure that even if current keys are compromised, past encrypted traffic cannot be compromised

- Cannot read old messages
- Cannot forge a message and claim that it was sent in the past

Support

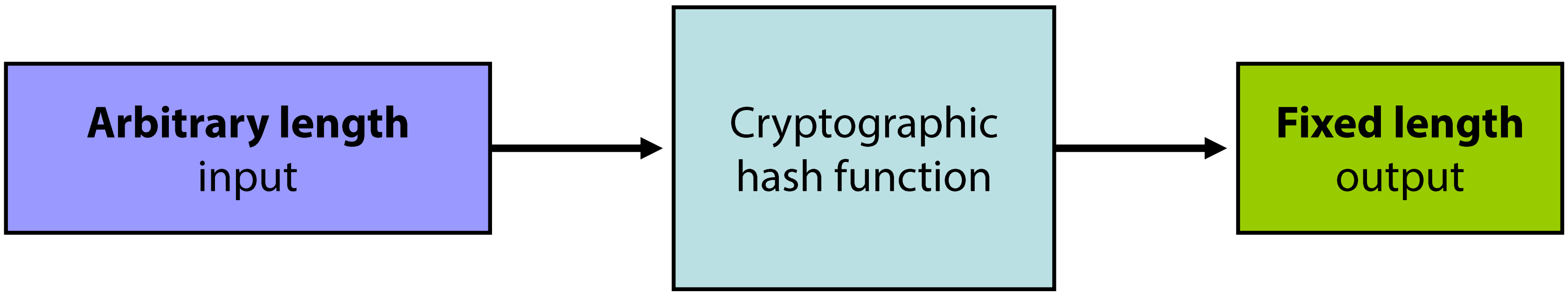
- IPsec, SSH, Off-the-Record messaging (OTR)
- TLS (Diffie–Hellman instead of RSA key exchange)

Note a panacea

- Session keys might be kept in memory for hours
- Server could be forced to record all session keys
- TLS Session tickets need careful treatment

Cryptographic Hash Functions

Hash functions that are considered practically impossible to invert



Properties of an ideal cryptographic hash function

- Easy to compute the hash value for any given message
- Infeasible to generate a message that has a given hash
- Infeasible to modify a message without changing the hash
- Infeasible to find two different messages with the same hash

Many-to-one function: *collisions can happen*

Cryptographic Hash Function Properties

Pre-image resistance

Given a hash value h it should be computationally infeasible to find any input m such that $h = \text{hash}(m)$

Example: break a hashed password

Second pre-image resistance

Given m_1 it should be computationally infeasible to find m_2 such that $m_1 \neq m_2$ and $\text{hash}(m_1) = \text{hash}(m_2)$

Example: forge an existing certificate

Collision Resistance

It should be computationally infeasible to find two different inputs m_1 and m_2 such that $\text{hash}(m_1) = \text{hash}(m_2)$ (collision)

Example: prepare two contradicting versions of a contract

Birthday Paradox

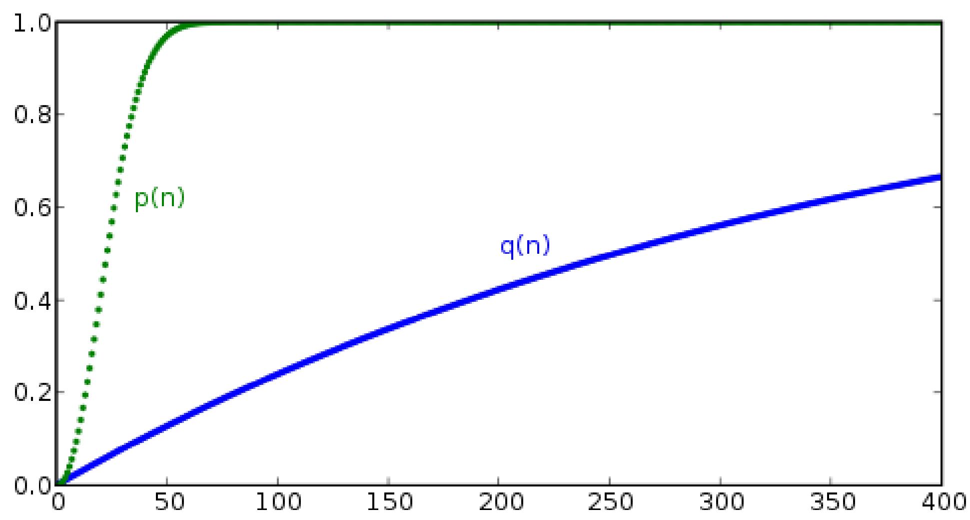
How many people does it take before the odds are 50% or better of having…

…another person with the same birthday as *you*? **253**

Second pre-image resistance

…two people with the same birthday? **23**

Collision resistance



Uses of Cryptographic Hash Functions

Data integrity

Digital signatures

Message authentication

User authentication

Timestamping

Certificate revocation management

Common Hash Functions

MD5: 128-bit output

1993: Boer and Bosselaers, "pseudo-collision" of the MD5 compression function: 2 different IVs which produce an identical digest

1996: Dobbertin, collision of the MD5 compression function

2004: Wang, Feng, Lai, and Yu, collisions for the full MD5

2005: Lenstra, Wang, and de Weger, construction of two X.509 certificates with different public keys but same hash

2008: Sotirov, Stevens, Appelbaum, Lenstra, Molnar, Osvik, de Wege, creating rogue CA certificates

Use it? NO, it's unsafe

SHA-1: 160-bit output

2005: Rijmen and Oswald, attack on a reduced version of SHA1 (53 out of 80 rounds)

2005: Wang, Yao, and Yao, an improvement, lowering complexity for finding a collision to 2^{63}

2006: Rechberger, attack with 2^{35} compression function evaluations

Use it? Use SHA-256 or better instead

Security Research and Defense Blog

Flame malware collision attack explained

swiat | 6 Jun 2012 9:57 AM | 0

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Security Newsletter

Report a Vulnerability

Since our last MSRC blog post, we've received questions on the nature of the cryptographic attack we saw in the complex, targeted malware known as Flame. This blog summarizes what our research revealed and why we made the decision to release Security Advisory 2718704 on Sunday night PDT. In short, by default the attacker's certificate would not work on Windows Vista or more recent versions of Windows. They had to perform a collision attack to forge a certificate that would be valid for code signing on Windows Vista or more recent versions of Windows. On systems that pre-date Windows Vista, an attack is possible without an MD5 hash collision. This certificate and all certificates from the involved certificate authorities were invalidated in Security Advisory 2718704. We continue to encourage all customers who are not installing updates automatically to do so immediately.

Mysterious Missing Extensions

When we first examined the Flame malware, we saw a file that had a valid digital signature that chained up to a Microsoft Root authority. As we reviewed this certificate, we noticed several irregularities. First, it had no X.509 extension fields, which was not consistent with the certificates we issued from the Terminal Server licensing infrastructure. We expected to find a Certificate Revocation List (CRL) Distribution Point (CDP) extension, an Authority Information Access (AIA) extension, and a "Microsoft Hydra" critical

Message Authentication Codes (MACs)

Verify both message integrity and authenticity

Keyed-hash message authentication code (HMAC)

- For a cryptographic hash function H:
- HMAC(K, m) = H(($K \oplus opad$) || H($K \oplus ipad$ || m))
- *opad/ipad*: outer/inner padding
- || denotes concatenation

Impossible to generate the HMAC of a message without knowing the secret key

Order of Encryption and MACing

Encrypted data usually must be protected with a MAC

Encryption alone protects only against passive adversaries

Different options:

Encrypt-and-MAC $E(P) \| M(P)$

No integrity of the ciphertext

MAC-then-Encrypt $E(P \| M(P))$

No integrity of the ciphertext (have to decrypt it first)

Encrypt-then-MAC $E(P) \| M(E(P))$

Preferable option – *always MAC the ciphertext*

Digital Signatures

Use RSA backwards:

- Sign (encrypt) with the private key
- Verify (decrypt) with the public key

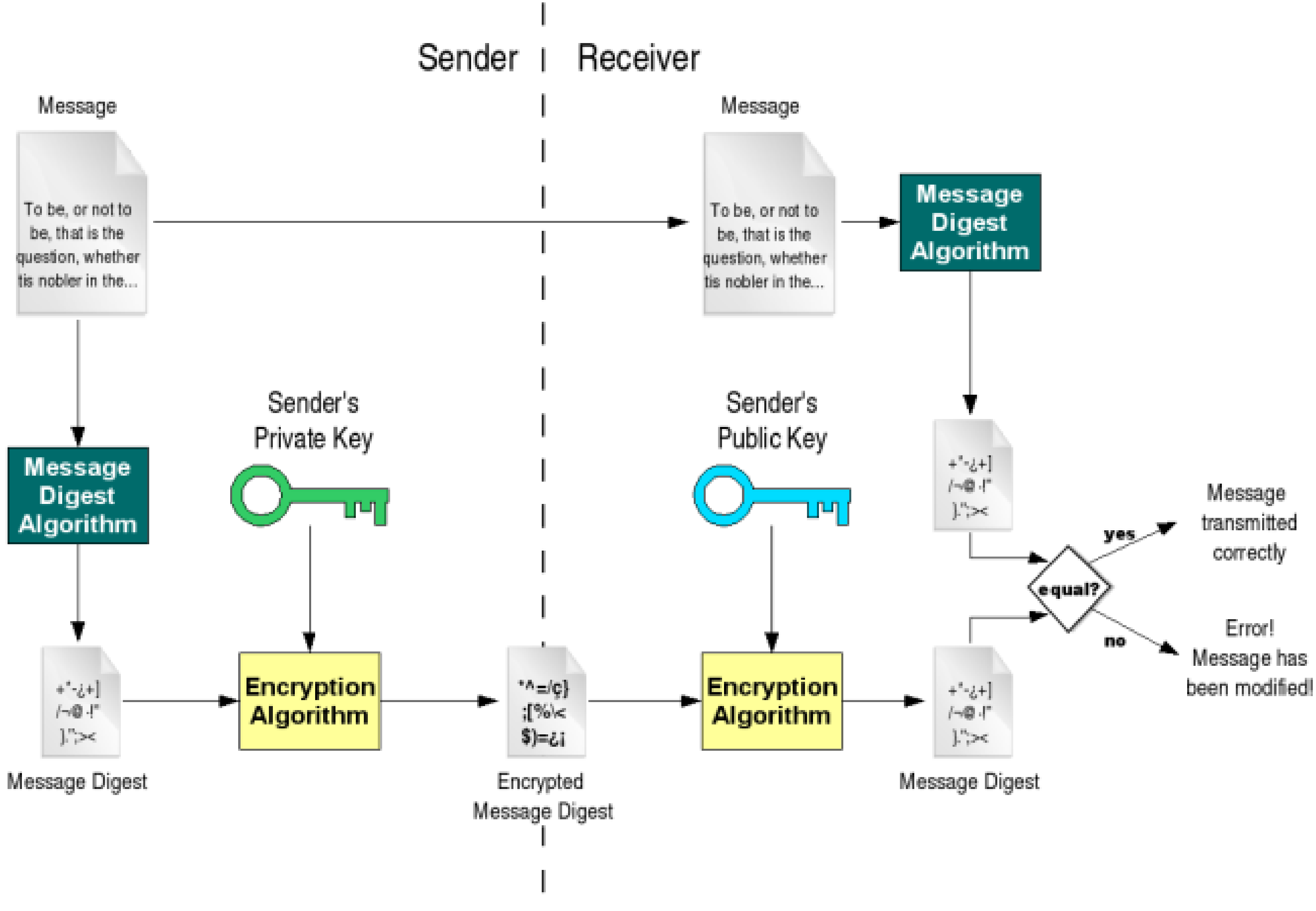
Ownership of a private key turns it into a *digital signature*

- Anyone can verify that a message was signed by its owner
- What if a private key was stolen or deliberately leaked?
- *Non-repudiation*

Again, too expensive to sign the whole message

- Calculate a cryptographic hash of the message and sign the hash

Digital Signatures



Hashes vs. MACs vs. Digital Signatures

	Hash	**MAC**	**Signature**
Integrity	✓	✓	✓
Authentication		✓	✓
Non-repudiation			✓
Keys	None	Symmetric	Asymmetric

Public Key Authenticity

Authentication without confidence in the keys used is pointless

Need to gain confidence or proof that a particular public key is authentic

- It is correct and belongs to the person or entity claimed
- Has not been tampered with or replaced by an attacker

Different ways to establish trust

- TOFU: trust on first use (e.g., SSH)
- Web of trust – decentralized (P2P) trust model (e.g., PGP)
- PKI: public key infrastructure (e.g., SSL)
- (subject of future lecture)

Shamir: Crypto is usually not broken, but bypassed