# 01. Introduction to Information Security and Cryptography

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# Introduction to Information Security

# Computer Security

## Computer Security [NIST95]

The protection afforded to an automated information system in order to attain the applicable objectives of preserving the **integrity, availability, and confidentiality** of information system resources (includes hardware, software, firmware, information/data, and telecommuncations)

- **CIA triad**
  1. **Confidentiality**: Data confidentiality, privacy
  2. **Integrity**: Data integrity, system integrity
  3. **Availability**
- Additional requirements: Authenticity, Accountability

# Security Terminology (from RFC 2828)

- **Adversary (threat agent)**: An entity that attacks a system
- **Attack**: An assault on system security that derives from an intelligent threat
- **Countermeasure**: An action, device, procedure, or technique that reduces a threat, a vulnerability, or an attack
- **Risk**: An expectation of loss expressed as the probability that a particular threat will exploit a particular vulnerability with a particular harmful result
- **Security Policy**: A set of rules and practices that specify or regulate how a system or organization provides security services to protect sensitive and critical assets
- **System Resource (Asset)**: Data contained in an information system; or a service provided by a system; or a system capability; or a facility that houses system operations and equipment
- **Threat**: A potential violation of security, which exists when there is a circumstance, capability, action, or event, that could breach security and cause harm
- **Vulnerability**: A flaw or weakness in a system's design, implementation, or operation and management that could be exploited to violate the system's security policy

# Security Concept and Relations

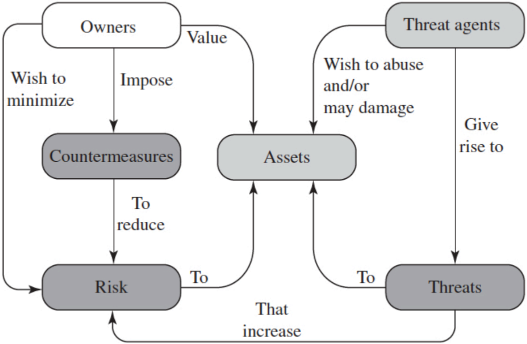



**Figure 1.1 Security Concepts and Relationships**

# Types of Vulnerability, Attacks and Countermeasure

- Vulnerability
  - Corrupted (loss of integrity)
  - Leaky (loss of confidentiality)
  - Unavailable or very slow (loss of availability)
- Attacks
  - Passive vs. Active
  - Insider vs. Outsider
- Countermeasure
  - Prevent
  - Detect
  - Recover

# Scope of Computer Security

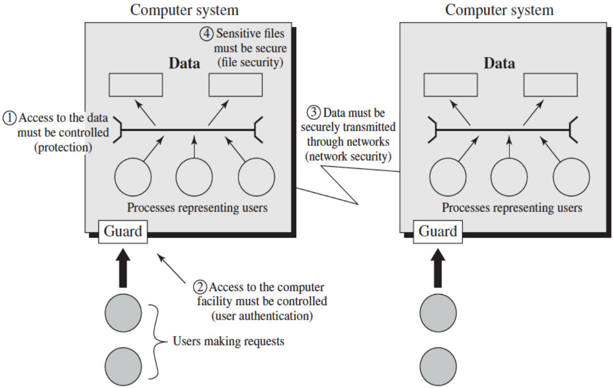



Figure 1.2 **Scope of Computer Security**

# Fundamental Security Design Principles

- Economy of mechanism
- Fail-safe defaults
- Complete mediation
- Open design
- Separation of privilege
- Least privilege
- Least common mechanism
- Psychological acceptability
- Isolation
- Encapsulation
- Modularity
- Layering
- Least astonishment

# Attack Surfaces

- Attack surface: consists of the reachable and exploitable vulnerabilities in a system
  - **Network**: vulnerabilities over an enterprises, wide-area network, or the Internet, particularly, included in this category are network protocol vulnerabilities, e.g., a denial-of-service attack, disruption of communications links
  - **Software**: vulnerabilities in application, utility, or operating system code
  - **Human**: vulnerabilities created by personnel or outsiders, such as social engineering, human error, and trusted insiders

# Computer Security Strategy

- **Security policy**: a formal statement of rules and practices that specify or regulate how a system or organization provides security services to protect sensitive and critical system resources
- **Security implementation**: involves prevention, detection, response, and recovery
- **Security assurance**: the degree of confidence one has that the security measures work as intended to protect the system and the information it processes
- **Security evaluation**: the process of examining a computer product or system with respect to certain creteria

# Introduction to Cryptography

# Classical Cryptography

## Concise Oxford Dictionary (2006) [KL08]

The art of writing or solving codes

- Consider secure communication
- Codes? Is Robert Langdon a cryptographer?


- Code, decode, encipher, decipher...
  - Unused terminology in "modern" cryptography

# Modern Cryptography

## Modern Cryptography [KL08, Chapter 1]

The scientific study of techniques for securing digital information, transactions, and distributed computations

- Range of modern cryptography
  - Primitives: Hash function (for data integrity), random number generator
  - Schemes: Encryption (for confidentiality), Signature (for data integrity)
  - Protocols: Identification (for authenticity), Key establishment, Secret sharing
  - Cryptographic applications: secure internet protocols, electronic cash

# Encryption

- A technique to provide data confidentiality
- Symmetric (key) encryption (a.k.a, Secret key/Private key encryption)
  - Block cipher
  - Stream cipher
- Asymmetric (key) encryption (a.k.a, Public key encryption)
  - Factoring-based
  - Discrete Logarithm-based
  - Post-quantum secure encryption: Lattice-based, Code-based, $\cdots$
- Consist of the following three algorithms:
  - Setup algorithm: Setup($\lambda$)$\rightarrow$ ($K_{\text{Enc}}$, $K_{\text{Dec}}$)
  - Encryption algorithm: Enc($K_{\text{Enc}}$, M)$\rightarrow$ CT
  - Decryption algorithm: Dec($K_{\text{Dec}}$, C)$\rightarrow$ M

# Symmetric Encryption

- Assume that a sender and a receiver have the same key
  $\Rightarrow$ Symmetric/Private key

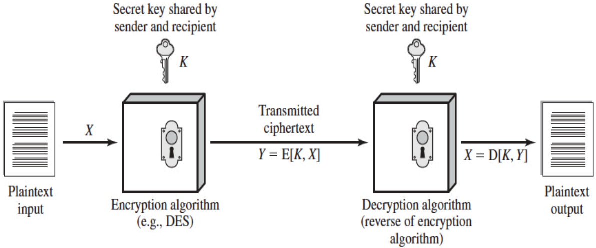


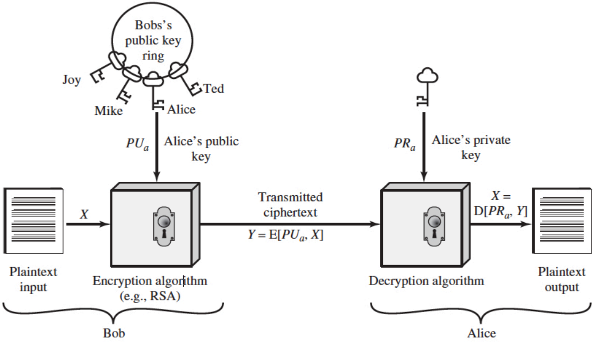

Figure 2.1 **Simplified Model of Symmetric Encryption**

- Classical encryption, block cipher (DES, AES, ARIA, SEED), stream cipher (RC4, ChaCha)
- Pros: Faster than asymmetric (public key) encryption
- Cons: Key share problem, large number of keys

Picture from [SB15]

# Asymmetric Encryption

- A key for encryption is different from a key for decryption




(a) Encryption with public key

- RSA, ElGamal, NTRU
- Pros: Easy for key sharing, small number of keys
- Cons: Slower than symmetric (private key) encryption

Picture from [SB15]

# Terminology for Encryption

- **Plaintext**: The original message or data that is fed into the algorithm as input
- **Ciphertext**: An output of an encryption algorithm
- **Encryption (algorithm)**: An algorithm that takes a plaintext and a key as inputs, and returns a ciphertext
- **Decryption (algorithm)**: An algorithm that takes a ciphertext and a key as inputs, and returns a plaintext
- **Private key** (for symmetric encryption): An input of encryption and decryption algorithms, those algorithms depend on a private key
- **Public key and private key** (for public key encryption): A pair of keys that have been selected for encryption and decryption, respectively

# Kerckhoff's Principle

- Stated by Dutch cryptographer Auguste Kerckhoffs in the late 19th century
- Recall **Open Design** in fundamental security design principles

**Kerckhoff's principle [KL08]**

The cipher method (= encryption and decryption algorithms) must not be required to be secret, and it must be able to fall into the hands of the enemy (=adversary) without inconvenience.

- Primary arguments in favor of Kerckhoff's principle
  - Easier for parties to maintain a secrecy of a short key than an algorithm
  - Easier to maintain a system once a key is exposed
  - Easier for parties to communicate with others by using different keys, not algorithms

# Basic Types of Attacks against Encryption

1. Brute-force attack: An attack that tries all possible keys on a target ciphertext until intelligible translation into plaintext is obtained

2. Cryptanalysis

| Types of attacks | Information given to an adversary |
|---|---|
| Ciphertext only | ciphertexts |
| Known plaintext | pairs of plaintexts and ciphertexts |
| Chosen plaintext | ciphertexts of plaintexts chosen by an adversary |
| Chosen ciphertext | plaintexts of ciphertexts chosen by an adversary |

# Classical Encryption

# Notations

- $\mathbb{Z}_m = \{0, 1, \ldots, m-1\}$
- $a$ mod $p$: $a$를 $p$로 나눈 나머지

$$\begin{aligned} 10 \bmod 3 &= 1 \\ 729 \bmod 31 &= 16 \ (\because 729 = 23 \cdot 31 + 16) \\ -7 \bmod 26 &= 19 \ (\because -7 = 26 \cdot (-1) + 19) \end{aligned}$$

- Plaintext space = Ciphertext space = $\{$Alphabet characters$\}$ = $\mathbb{Z}_{26}$

| a | b | c | d | e | f | g | h | i | j | k | l | m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |

| n | o | p | q | r | s | t | u | v | w | x | y | z |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |

# Shift Cipher

## Shift Cipher

For $0 \leq K \leq 25$,

- $\mathrm{Enc}(K, x) = (x + K) \bmod 26$ (cf. $K = 3$: Caesar Cipher)
- $\mathrm{Dec}(K, Y) = (Y - K) \bmod 26$

## Example: $K = 9$

- shift ( 18 7 8 5 19 ) $\xrightarrow{+9 \bmod 26}$ (1 16 17 14 2) BQROC
- BQROC (1 16 17 14 2) $\xrightarrow{-9 \bmod 26}$ ( 18 7 8 5 19 ) shift

## Attacks

- Brute-force attack: There are only 26 candidates for private key.
- Known plaintext attack: Given (shift, BQROC),

$$K = \mathrm{B} - \mathrm{s} = (1 - 18) \bmod 26 = 9$$

# Affine Cipher

## Affine Cipher

For $K = (\alpha, \beta)$ where $\alpha, \beta \in \mathbb{Z}_{26}$ and $\gcd(\alpha, 26) = 1$,

- $\mathrm{Enc}(K, x) = \alpha x + \beta \bmod 26$
- $\mathrm{Dec}(K, Y) = \alpha^{-1}(Y - \beta) \bmod 26$

## Example: $K = (\alpha, \beta) = (7, 3)$

hot ( 7 14 19 ) $\xrightarrow{(\alpha,\beta)=(7,3)}$ ( 52 101 136 ) mod26 = ( 0 23 6 ) AXG

## Attacks

- Brute-force attack: There are only $12 \times 26 = 312$ candidates for private key. ($\alpha$ such that $\gcd(\alpha, 26) = 1$: 1, 3, 5, 7, 9, 11, 15, 17, 19, 21, 23, 25)
- Known plaintext attack: Given (hot, AXG),

$$\begin{cases} 7\alpha + \beta = 0 \bmod 26 \\ 14\alpha + \beta = 23 \bmod 26 \end{cases} \Rightarrow \alpha = 7, \beta = 3$$

$$(\text{cf. } 7^{-1} = 15 \bmod 26 \ (\because 15 \cdot 7 = 105 = 1 \bmod 26)$$

# Substitution Cipher

## Substitution Cipher

For K $= \pi$ where $\pi$ is a permutation on $\mathbb{Z}_{26}$,

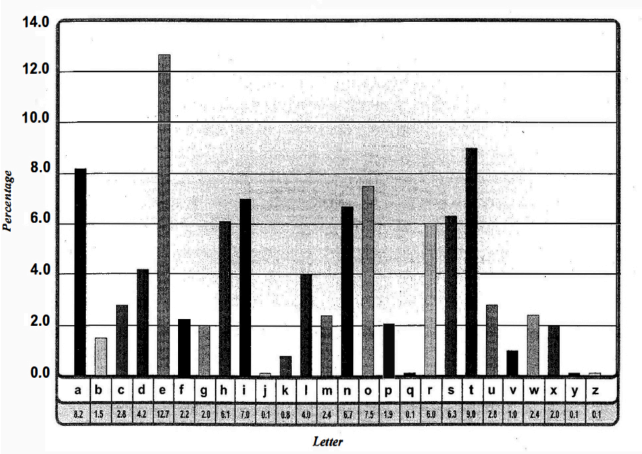
- $\text{Enc}(K, x) = \pi(x)$
- $\text{Dec}(K, Y) = \pi^{-1}(Y)$

## Attacks

- Brute-force attack: There are 26! candidates for private keys.
  $\Rightarrow 26! \approx 4 \times 10^{26} \approx 2^{88.3}$
- Chosen-plaintext attack? If $n$ pairs are given, the number of candidates is reduced to $(26 - n)!$.

# Statistical Test

- Use average letter frequencies for English-language text




Picture from [KL08]

# Example: Statistical Test

## Ciphertext [Sti06, Section 1.2.2]

YIFQFMZRWQFYVECFMDZPCVMRZWNMDZVEJBTXCDDUMJ
NDIFEFMDZCDMQZKCEYFCJMYRNCWJCSZREXCHZUNMXZ
NZUCDRJXYYSMRTMEYIFZWDYVZVYFZUMRZCRWNZDZJJ
XZWGCHSMRNMDHNCMFQCHZJMXJZWIEJYUCFWDJNZDIR

| Letter | Frequency | Letter | Frequency | Letter | Frequency | Letter | Frequency |
|---|---|---|---|---|---|---|---|
| A | 0 | H | 4 | O | 0 | V | 5 |
| B | 1 | I | 5 | P | 1 | W | 8 |
| C | 15 | J | 11 | Q | 4 | X | 6 |
| D | 13 | K | 1 | R | 10 | Y | 10 |
| E | 7 | L | 0 | S | 3 | Z | 20 |
| F | 11 | M | 16 | T | 2 | | |
| G | 1 | N | 9 | U | 5 | | |

- $\mathrm{Dec}(K, Z) = \mathrm{e} \Rightarrow \ldots$

# Example: Solution

## Solution

Our friend from Paris examined his empty glass with surprise, as if evaporation had taken place while he wasn't looking. I poured some more wine and he settled back in his chair, face tilted up towards the sum.

# Vigenère Cipher

- Named after Blaise de Vigenère who lived in the 16th century
- Monoalphabetic $\Rightarrow$ Polyalphabetic

## Vigenère Cipher

For $K = (k_1, k_2, \ldots, k_m) \in (\mathbb{Z}_{26})^m$,

- $\mathrm{Enc}(K, x_1, \ldots, x_m) = (x_1 + k_1, \ldots, x_m + k_m)$
- $\mathrm{Dec}(K, Y_1, \ldots, Y_m) = (Y_1 - k_1, \ldots, Y_m - k_m)$

## Attacks

- Brute-force attack: There are $26^m$ candidates for private keys.
  $\Rightarrow m = 18 : 26^{18} \approx 2^{84.6}$
- Ciphertext only attack: Statistical test such as Kasiski test
- Known plaintext attack: Easy (if $m$ is known)

# Permutation Cipher

## Permutation Cipher

For a key $K = \pi$ where $\pi$ is a permutation of $\{1, \ldots m\}$,

- $\mathrm{Enc}(K, x_1, \ldots, x_m) = (x_{\pi(1)}, \ldots, x_{\pi(m)})$
- $\mathrm{Dec}(K, Y_1, \ldots, Y_m) = (Y_{\pi^{-1}(1)}, \ldots, Y_{\pi^{-1}(m)})$

- We can interpret the above encryption algorithm as

$$(x_1 \ \ldots x_m)P = (Y_1 \ \ldots Y_m)$$

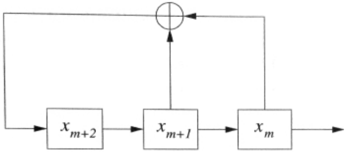
  where $P$ is a permutation matrix.
- If $P$ is an inverse matrix, it is Hill cipher.

## Attacks

- Brute-force attack: There are $m!$ candidates for private keys.
  $\Rightarrow 25! \approx 2^{83.68}$
- Known plaintext/Chosen plaintext attacks: Need $m$ "independent" ciphertexts to obtain $P^{-1}$

# Linear Feedback Shift Register (LFSR)

- A shift register whose input bit is a linear function of its previous state
- Example I: a shift register satisfying $\underbrace{x_{m+3} = x_{m+1} + x_m}_{\text{linear relation}}$




- Example II: The sequence

$$01000010010110011111000 11$$

is generated by giving initial values $x_1 = 0, x_2 = 1, x_3 = 0, x_4 = 0$, and $x_5 = 0$, and the linear relation

$$x_{n+5} = x_n + x_{n+2} \bmod 2.$$

Picture and example from [TW06]

# LFSR Cipher

## LFSR Cipher

For a linear function $f(z_1, \dots z_\ell) = \sum_{i=1}^{\ell} c_i z_i$ with constant $c_i$'s and a key $K = (k_1, \dots, k_\ell) \in (\mathbb{Z}_2)^\ell$

- $\mathrm{Enc}(K, (x_1, \dots, x_m)) = (x_1 \oplus k_1, \dots, x_m \oplus k_m)$
- $\mathrm{Dec}(K, (y_1, \dots, y_m)) = (y_1 \oplus k_1, \dots, y_m \oplus k_m)$

where $k_j = f(k_{j-\ell}, k_{j-\ell+1}, \dots k_{j-1})$ for $\ell + 1 \leq j \leq m$

## Known Plaintext Attack

1. Find $k_1, \dots, k_\ell$ from $((x_1, \dots, x_m), (y_1, \dots, y_m))$.
2. Build

$$\underbrace{\begin{pmatrix} k_1 & k_2 & \cdots & k_\ell \\ k_2 & k_3 & \cdots & k_{\ell+1} \\ \vdots & \vdots & \ddots & \vdots \\ k_\ell & k_{\ell+1} & \cdots & k_{2\ell-1} \end{pmatrix}}_{:=\mathbf{K}} \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_\ell \end{pmatrix} = \begin{pmatrix} k_{\ell+1} \\ k_{\ell+2} \\ \vdots \\ k_{2\ell} \end{pmatrix}.$$

3. Obtain $(k_1, \dots, k_m)$ if the matrix $\mathbf{K}$ is invertible.

# One-Time Pads

- Developed by Gilbert Vernam and Joseph Mauborgne in 1918

## One-Time Pads

- Plaintext space = Ciphertext space = Key space = $(\mathbb{Z}_2)^m$
- For a key $K = (k_1, \ldots, k_m) \in (\mathbb{Z}_2)^m$,
  - $\mathrm{Enc}(K, x_1, \ldots, x_m) = K \oplus (x_1, \ldots, x_m)$
  - $\mathrm{Dec}(K, Y_1, \ldots, Y_m) = K \oplus (Y_1, \ldots, Y_m)$

- Use a key $K$ only once and throw it away
- Pros: Perfect secrecy - unbreakable cryptosystem
- Cons: Efficiency - Need a different key at each time

# References


KL08 J. Katz and Y. Lindell, Introduction to Modern Cryptography, Chapman & Hall/CRC, 2008 (Chapter 1).

SB15 W. Stallings and L. Brown, Computer Security: Principles and Practice, 3rd edition, Pearson Prentice Hall, 2015 (Chapters 2, 20, & 21)

Sti06 D. R. Stinson, Cryptography: Theory and Practice, 3rd edition, Chapman & Hall/CRC, 2006 (Chapter 1).

TW06 W. Trappe and L. C. Washington, Introduction to Cryptography with Coding Theory, 2nd edition, Pearson Prentice Hall, 2006 (Chapters 1 & 2)