

## Lecture 06: Private-key Encryption (Definition & Security of One-time Pad)

# Objective

- First, we shall define the correctness and the security of private-key encryption schemes
- We shall argue that the one-time pad is correct and secure

# Private-key Encryption

- Three algorithms
  - Key Generation: Generate the secret key  $sk$
  - Encryption: Given the secret key  $sk$  and a message  $m$ , it outputs the cipher-text  $c$  (Note that the encryption algorithm can be a randomized algorithm)
  - Decryption: Given the secret key  $sk$  and the cipher-text  $c$ , it outputs a message  $m'$  (Note that the decryption algorithm can be a randomized algorithm)

# Story of the Private-key Encryption Process

- Yesterday Alice and Bob met and generated a secret key  $sk \sim \text{Gen}()$ 
  - Read as: the secret key  $sk$  is sampled according to the distribution  $\text{Gen}()$
- Today Alice wants to encrypt a message  $m$  using the secret key  $sk$ . Alice encrypts  $c \sim \text{Enc}_{sk}(m)$ 
  - Read as: the cipher-text  $c$  is sampled according to the distribution  $\text{Enc}_{sk}(m)$
- Then Alice sends the cipher-text  $c$  to Bob. An eavesdropper gets to see the cipher-text  $c$
- After receiving the cipher-text  $c$  Bob decrypts it using the secret key  $sk$ . Bob decrypts  $m' \sim \text{Dec}_{sk}(c)$ 
  - Read as: the decoded message  $m'$  is sampled according to the distribution  $\text{Dec}_{sk}(c)$

- We want the decoded message obtained by Bob to be identical to the original message of Alice with high probability
- We insist

$$\mathbb{P} [M = M'] = 1$$

- Recall we use capital alphabets to represent the random variable corresponding to the variable (so,  $M$  is the random variable for the message encoded by Alice and  $M'$  is the random variable for the message recovered by Bob)

- We want to say that the cipher-text  $c$  provides the adversary no additional information about the message
- We insist that, for all message  $m$ , we have

$$\mathbb{P} [M = m | C = c] = \mathbb{P} [M = m]$$

# Cropping any Constraint makes the Problem Trivial

- Suppose we insist only on correctness and not on security
  - The trivial scheme where  $\text{Enc}_{\text{sk}}(m) = m$ , i.e. the encryption of any message  $m$  using any secret key  $\text{sk}$  is the message itself, satisfies correctness. But is completely insecure!
- Suppose we insist only on security and not on correctness
  - The trivial scheme where  $\text{Enc}_{\text{sk}}(m) = 0$ , i.e. the encryption of any message  $m$  using any secret key  $\text{sk}$  is 0, satisfies this security. But Bob cannot correctly recover the original message  $m$  with certainty!
- So, the non-triviality is to simultaneously achieve correctness and security

# One-time Pad

- Let  $(G, \circ)$  be a group
- Secret-key Generation:

Gen() :

- Return  $sk \xleftarrow{\$} G$

- Encryption:

Enc<sub>sk</sub>( $m$ ) :

- Return  $c := m \circ sk$

- Decryption:

Dec<sub>sk</sub>( $c$ ) :

- Return  $m' := c \circ \text{inv}(sk)$

- Note that Encryption and Decryption is deterministic
- The only randomized step is the choice of  $sk$  during the secret-key generation algorithm



# Correctness of One-time Pad

- It is trivial to see that

$$\mathbb{P} [M = M'] = 1$$

- So, one-time pad is correct!

# Security of One-time Pad I

- We want to simplify the probability

$$\mathbb{P} [M = m | C = c]$$

- Using Bayes' Rule, we have

$$= \frac{\mathbb{P} [M = m, C = c]}{\mathbb{P} [C = c]}$$

- Using the fact that  $\mathbb{P} [C = c] = \sum_{x \in G} \mathbb{P} [M = x, C = c]$ , we get

$$= \frac{\mathbb{P} [M = m, C = c]}{\sum_{x \in G} \mathbb{P} [M = x, C = c]}$$

## Security of One-time Pad II

- We will prove the following claim later

### Claim

*For any  $x, y \in G$ , we have*

$$\mathbb{P}[M = x, C = y] = \mathbb{P}[M = x] \cdot \frac{1}{|G|}$$

- Using this claim, we can simplify the expression as

$$\begin{aligned} & \mathbb{P}[M = m] \cdot \frac{1}{|G|} \\ = & \frac{\mathbb{P}[M = m] \cdot \frac{1}{|G|}}{\sum_{x \in G} \mathbb{P}[M = x] \cdot \frac{1}{|G|}} \\ = & \frac{\mathbb{P}[M = m]}{\sum_{x \in G} \mathbb{P}[M = x]} \end{aligned}$$

# Security of One-time Pad III

- Using the fact that  $\sum_{x \in G} \mathbb{P}[M = x] = 1$ , we get that the previous expression is

$$= \mathbb{P}[M = m]$$

- This proves that  $\mathbb{P}[M = m | C = c] = \mathbb{P}[M = m]$ , for all  $m$  and  $c$ . This proves that the one-time pad encryption scheme is secure!

# Proof of Claim 1

- You will prove the following statement in the homework: If there exists  $sk$  such that  $x \circ sk = y$  then  $sk$  is unique (i.e., there does not exist  $sk' \neq sk$  such that  $x \circ sk' = y$ )
- Using this result, we get the following. Suppose  $z \in G$  be the unique element such that  $x \circ z = y$ . Then we have:

$$\mathbb{P}[M = x, C = y] = \mathbb{P}[M = x, SK = z]$$

- Note that the secret-key is sample independent of the message  $x$ . So, we have

$$\mathbb{P}[M = x, SK = z] = \mathbb{P}[M = x] \cdot \mathbb{P}[SK = z]$$

- Note that  $sk$  is sampled uniformly at random from the set  $G$ . So, we have

$$\mathbb{P}[M = x, SK = z] = \mathbb{P}[M = x] \cdot \frac{1}{|G|}$$

# Example 1

- Encrypting bit messages
  - Consider  $(G, \circ) = (\mathbb{Z}_2, + \text{ mod } 2)$

## Example II

- Encrypting  $n$ -bit strings
  - Consider  $G = \{0, 1\}^n$
  - Define  $(x_1, \dots, x_n) \circ (y_1, \dots, y_n) = (x_1 + y_1 \text{ mod } 2, \dots, x_n + y_n \text{ mod } 2)$

## Example III

- Encrypting an alphabet
  - Consider  $G = \mathbb{Z}_{26}$
  - Define  $\circ$  as  $+ \pmod{26}$
- You will construct one more scheme in the homework by interpreting the set of alphabets as  $\mathbb{Z}_{27}^*$



# Example IV

- Encrypting  $n$ -alphabet words
  - Consider  $G = \mathbb{Z}_{26}^n$
  - Define  $\circ$  as the coordinate-wise  $+$  mod 26