

Homework 2

1. **Defining Multiplication over \mathbb{Z}_{27}^* .** In the class, we had considered the group $(\mathbb{Z}_{26}, +)$ to construct a one-time pad for one alphabet messages. A few students were interested to define a group with 26 elements using a “multiplication”-like operation. This problem will assist you to define the $(\mathbb{Z}_{27}^*, \times)$ group.

Interpret \mathbb{Z}_{27}^* as the set of all triplets (a_0, a_1, a_2) such that $a_0, a_1, a_2 \in \mathbb{Z}_3$ and at least one of them is non-zero (you can think of the triplets as the ternary representation of the elements in \mathbb{Z}_{27}^*). We shall equivalently interpret the element (a_0, a_1, a_2) as the polynomial $a_0 + a_1X + a_2X^2$. So, every element in \mathbb{Z}_{27}^* has an associated non-zero polynomial of degree at most 2, and every non-zero polynomial of degree at most 2 has an element in \mathbb{Z}_{27}^* associated with it.

The multiplication (\times operator) of the element (a_0, a_1, a_2) with the element (b_0, b_1, b_2) is defined as the element corresponding to the polynomial

$$(a_0 + a_1X + a_2X^2) \times (b_0 + b_1X + b_2X^2) \pmod{X^3 + 2X + 2}$$

According to this definition of the \times operator, find

- (10 points) $(1, 2, 1) \times (2, 2, 1)$
- (15 points) the inverse of $(1, 2, 1)$.

Solution.

- $(1, 2, 1) \times (2, 2, 1)$

$$(a_0 + a_1X + a_2X^2) \times (b_0 + b_1X + b_2X^2) \pmod{X^3 + 2X + 22}$$

$$(1 + 2X + X^2) \times (2 + 2X + X^2) \pmod{X^3 + 2X + 2}$$

$$2 + 4X + 2X^2 + (2X + 4X^2 + 2X^3) + (X^2 + 2X^3 + X^4) \pmod{X^3 + 2X + 2}$$

$$2 + 0X + X^2 + X^3 + X^4 \pmod{X^3 + 2X + 2}$$

$$2 + 0X + X^2 - (2X + 2) - (2X^2 + 2X) \pmod{X^3 + 2X + 2}$$

$$0 + 2X + 2X^2 \pmod{X^3 + 2X + 2}$$

$$(0, 2, 2)$$

- the inverse of $(1, 2, 1)$.

$$(1 + 2X + X^2) \times (b_0 + b_1X + b_2X^2) \mod X^3 + 2X + 2$$

$$(b_0 + b_1X + b_2X^2) + (2b_0X + 2b_1X^2 + 2b_2X^3) + (b_0X^2 + b_1X^3 + b_2X^4) \mod X^3 + 2X + 2$$

$$b_0 + (b_1 + 2b_0)X + (b_2 + 2b_1 + b_0)X^2 + (2b_2 + b_1)X^3 + b_2X^4 \mod X^3 + 2X + 2$$

$$b_0 + (b_1 + 2b_0)X + (b_2 + 2b_1 + b_0)X^2 - (2b_2 + b_1)(2X + 2) - b_2(2X^2 + 2X) \mod X^3 + 2X + 2$$

$$b_0 + (b_1 + 2b_0)X + (b_2 + 2b_1 + b_0)X^2 - (b_2 + 2b_1) - (b_2 + 2b_1)X - (2b_2)X - (2b_2)X^2 \mod X^3 + 2X + 2$$

$$(b_0 + b_1 + 2b_2) + (2b_0 + 2b_1)X + (2b_2 + 2b_1 + b_0)X^2 \mod X^3 + 2X + 2$$

$$(0, 0, 0) \text{ when } b_0 = 2, b_1 = 2, b_2 = 1$$

$$(1, 2, 2)$$

2. **One-time Pad for 3-Alphabet Words.** We interpret a, b, \dots, z as $0, 1, \dots, 25$. We will work over the group $(\mathbb{Z}_{26}^3, +)$, where $+$ is coordinate-wise integer-sum mod 26. For example, $abx + acd = ada$.

Now, consider the one-time pad encryption scheme over the group $(\mathbb{Z}_{26}^3, +)$.

- (12.5 points) What is the probability that the encryption of the message *cat* is the cipher text *cat*?

$$P(\text{cipher} = \text{"cat"} \mid \text{givenmessage} = \text{"cat"}) = P(\text{secretkey} = \text{"aaa"}) = (1/26)^3 = 0.0000569$$

- (12.5 points) What is the probability that the encryption of the message *cat* is the cipher text *dog*?

$$P(\text{cipher} = \text{"dog"} \mid \text{givenmessage} = \text{"cat"}) = P(\text{secretkey} = \text{"bon"}) = (1/26)^3 = 0.0000569$$

3. **Left Identity and Left Inverse.** Recall that when we defined a group (G, \circ) , we stated that there exists an element e such that for all $x \in G$ we have $x \circ e = x$. Note that e is “applied on x from the right.”

Similarly, for every $x \in G$, we are guaranteed that there exists $\text{inv}(x) \in G$ such that $x \circ \text{inv}(x) = e$. Note that $\text{inv}(x)$ is again “applied to x from the right.”

Intuitively, we shall explore the following questions: (a) Is there an “identity from the left?” and (b) Is there an “inverse from the left?”

We shall formalize and prove these results in this question.

- (10 points) Prove that $e \circ x = x$, for all $x \in G$.
- (10 points) Prove that if there exists an element $\alpha \in G$ such that for all $x \in G$ we have $\alpha \circ x = x$, then $\alpha = e$.

Note that these two steps prove that the “left identity” is identical to the right identity e .

- (10 points) Prove that $\text{inv}(x) \circ x = e$.
- (10 points) Prove that if there exists an element $\alpha \in G$ and $x \in G$ such that $\alpha \circ x = e$, then $\alpha = \text{inv}(x)$.

Note that these two steps prove that the “left inverse of x ” is identical to the left inverse $\text{inv}(x)$.

Finally, we can prove the following result crucial to the proof of security of one-time pad over the group (G, \circ) .

- (10 points) Suppose $m \in G$ is a message and $c \in G$ is a cipher text. Prove that there exists a unique $\text{sk} \in G$ such that $m \circ \text{sk} = c$.

Solution.

- **Prove that $e \circ x = x$, for all $x \in G$.**

Proof by contradiction. Suppose there exists x such that $e \circ x \neq x$

By performing the $\circ \text{inv}(x)$ function on both sides, we get $e \circ (x \circ \text{inv}(x)) \neq x \circ \text{inv}(x) \equiv e \circ e \neq e \equiv e \neq e$

Proof by contradiction, $e \circ x = x$

- **Prove that if there exists an element $\alpha \in G$ such that for all $x \in G$ we have $\alpha \circ x = x$, then $\alpha = e$.**

Suppose there exists α such that $\alpha \circ x = x$

Let $x = e$, such that $\alpha \circ e = e$ Given $\alpha \circ e = \alpha$, we can conclude $\alpha = e$

- **Prove that $\text{inv}(x) \circ x = e$.**

Given that $x \circ \text{inv}(x) = e$ and $x \circ e = x$

Then $\text{inv}(x) = \text{inv}(x) \circ e = \text{inv}(x) \circ (x \circ \text{inv}(x)) = (\text{inv}(x) \circ x) \circ \text{inv}(x)$

It follows that $e = \text{inv}(x) \circ \text{inv}(\text{inv}(x)) = (\text{inv}(x) \circ x) \circ \text{inv}(x) \circ \text{inv}(\text{inv}(x)) =$
 $(\text{inv}(x) \circ x) \circ e = \text{inv}(x) \circ x$

$\text{inv}(x) \circ x = e$

- **Prove that if there exists an element $\alpha \in G$ and $x \in G$ such that $\alpha \circ x = e$, then $\alpha = \text{inv}(x)$.**

Suppose $\alpha \circ x = e$

Then $\alpha \circ x = e \equiv \alpha \circ x \circ \text{inv}(x) = e \circ \text{inv}(x) \equiv \alpha \circ e = e \circ \text{inv}(x) \equiv \alpha = \text{inv}(x)$

- **Suppose $m \in G$ is a message and $c \in G$ is a cipher text. Prove that there exists a unique $\text{sk} \in G$ such that $m \circ \text{sk} = c$.**

Given $m, c \in G$, suppose $m \circ \text{sk} = c$

This would imply that $m \circ \text{sk} \circ \text{inv}(m) = c \circ \text{inv}(m) \equiv \text{sk} = c \circ \text{inv}(m)$

Therefor, there exists a $\text{sk} \in G$ for every $m, c \in G$ where $\text{sk} = c \circ \text{inv}(m)$

4. **One-time Pad with non-uniform secret key.** (25 points) Consider the one-time pad encryption scheme over a group $(G, +)$. Suppose the a priori distribution of messages is the uniform distribution over the set G . Suppose the generation algorithm samples the secret-key \mathbf{sk} according to the distribution \mathcal{D} over the sample space G such that \mathcal{D} is *not* the uniform distribution over G . Is this encryption scheme secure? (*Remark:* To prove that the scheme is secure, provide a proof that the a priori distribution of messages is same as the a posteriori distribution. To prove that the scheme is insecure, provide a proof that the a priori distribution of messages is different from the a posteriori distribution.)

5. **Designing Encryption Scheme.** We shall work over the field $(\mathbb{Z}_{11}, +, \times)$. Assume that there are ten people $\{1, 2, \dots, 10\}$. Design a private-key encryption scheme for the following scenario.

Alice meets the ten people $\{1, 2, \dots, 10\}$ today. She can provide each of them information $\{s_1, s_2, \dots, s_{10}\}$.

Tomorrow, Alice shall encrypt a message $m \in \mathbb{Z}_{11}$. The encryption has to ensure that decryption should be possible if and only if two people among $\{1, \dots, 5\}$ and three people among $\{6, \dots, 10\}$ get together.

- (15 points) Provide the (Gen, Enc, Dec) algorithms.
- (15 points) Proof of security of this scheme.

6. **A property of 2-wise Independence.** Let \mathcal{H} be a hash function family from the domain \mathcal{D} to the range \mathcal{R} .

- (20 points) Similar to the proof in the lectures for universal hash function family, prove the following. There exists distinct $x_1^*, x_2^* \in \mathcal{D}$ and $y_1^*, y_2^* \in \mathcal{R}$ such that

$$\mathbb{P} \left[h(x_1^*) = y_1^*, h(x_2^*) = y_2^* : h \xleftarrow{\$} \mathcal{H} \right] \geq \frac{1}{|\mathcal{R}|^2}$$

(*Remark:* Note that this result does not depend on whether $|\mathcal{R}| < |\mathcal{D}|$ or not.)

- (25 points) Now, suppose that $|\mathcal{R}| < |\mathcal{D}|$. Suppose that for all distinct $x_1, x_2 \in \mathcal{D}$ the following holds.

$$\mathbb{P} \left[h(x_1) = h(x_2) : h \xleftarrow{\$} \mathcal{H} \right] < \frac{1}{|\mathcal{R}|}$$

Prove that there exists distinct $x_1^*, x_2^* \in \mathcal{D}$ and $y_1^*, y_2^* \in \mathcal{R}$ such that

$$\mathbb{P} \left[h(x_1^*) = y_1^*, h(x_2^*) = y_2^* : h \xleftarrow{\$} \mathcal{H} \right] > \frac{1}{|\mathcal{R}|^2}$$

This result proves that if a universal hash-function family has collision probability $< \frac{1}{|\mathcal{R}|}$ then it is not pairwise independent.

7. **Extra Credit.** Suppose $\mathcal{D} = \{0, 1\}^n$ and $\mathcal{R} = \{0, 1\}^{n-1}$. Construct a hash function family such that for all distinct $x_1, x_2 \in \mathcal{D}$ we have

$$\mathbb{P} \left[h(x_1) = h(x_2) : h \xleftarrow{\$} \mathcal{H} \right] = \frac{1}{M} \cdot \left(\frac{N - M}{N - 1} \right),$$

where $N = 2^n$ and $M = 2^{n-1}$. Try to construct a hash function family such that each hash function can be efficiently evaluated.