

Exam Questions
Discrete Mathematics 2: Algebra

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Question 1: Let (S_5, \circ) be the group of permutations of $A = \{1, 2, 3, 4, 5\}$. Let f denote the permutation

$$f := \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 2 & 3 & 4 & 5 & 1 \end{pmatrix}$$

- Write f as a composition of disjoint cycles.
- What are the order and the cycle type of f ?
- What is the smallest natural number n such that S_n contains a permutation of order 10? Motivate your answer.
- Does S_9 contain a permutation of order 18? Motivate your answer.
- What is the maximal order a permutation of S_6 can have? Motivate your answer.

ANSWER

- The disjoint cycle decomposition of f is

$$f = c_1 \circ \dots \circ c_k$$

where c_i are disjoint cycles and $\text{ord}(c_i) = \ell_i = \text{number of elements in } c_i$.

- We're looking for the smallest integer $i \in \mathbb{Z}_{>0}$ such that $f^i = \text{id}_A$.

Because the disjoint cycle decomposition of f consists of k cycles c_i of length ℓ_i , it follows from Proposition 2.3.12 that

$$\text{ord}(f) = \text{lcm}(\ell_1, \dots, \ell_k)$$

To compute the cycle type, let t_1 be the number of elements in A that are fixed by f and for $i > 1$, let t_i be the number of t_i -cycles in the DCD of f . Then the cycle type of f is

$$(t_1, \dots, t_n)$$

- If $n = 7$ then a permutation $g \in S_n$ of order 10 can be found, for example

$$g = (12)(34567)$$

Now we show that such a permutation does not exist if $n \leq 6$, which proves that $n = 7$ is the smallest natural number such that S_n contains a permutation of order 10.

Assume that $n \leq 6$. Assume further that, by contradiction, $g \in S_n$ of order $\text{ord}(g) = 10$ exists. We know that, if $g = c_1 \circ c_2 \circ \dots \circ c_k$ is the disjoint cycles decomposition of g , and c_i is a cycle of length ℓ_i for $i = 1, \dots, k$, then

$$\text{ord}(g) = \text{lcm}(\ell_1, \dots, \ell_k)$$

This implies that every cycle length ℓ_i must divide 10. Thus, $\ell_i \in \{1, 2, 5, 10\}$. Since $n \leq 6$, a 10-cycle is impossible, so the lengths must be 1, 2, or 5. The cycles c_i thus need to be 5-cycles, 2-cycles or 1-cycles.

Now it holds that

$$n = 1 \cdot t_1 + 2 \cdot t_2 + \dots + n \cdot t_n = 1 \cdot t_1 + 2 \cdot t_2 + 5 \cdot t_5 \geq 2 \cdot t_2 + 5 \cdot t_5$$

Since $t_1 \geq 0$ and at least one of *each* needs to appear in the decomposition of f (i.e. $t_2 \geq 1$ and $t_5 \geq 1$), it follows that $n \geq 2 \cdot 1 + 5 \cdot 1 = 7$, a *contradiction*.

- (d) No. Indeed, if $f \in S_9$ and we write $f = c_1 \circ \dots \circ c_k$ as a disjoint cycle decomposition where c_i is a cycle of length ℓ_i , then $\text{ord}(f) = \text{lcm}(\ell_1, \dots, \ell_k)$.

To have $\text{ord}(f) = 18$, each ℓ_i must be a divisor of 18 and satisfy $\ell_i \leq 9$. Thus, the possible cycle lengths are:

$$\ell_i \in \{1, 2, 3, 6, 9\}$$

We distinguish two cases:

- **Case 1: No cycle of length 9 exists.**

In this case, all $\ell_i \in \{1, 2, 3, 6\}$. None of these numbers are divisible by 9 (they are either not divisible by 3, or divisible by 3 but not 9). Consequently, their least common multiple cannot be divisible by 9. Since 18 is divisible by 9, $\text{lcm}(\ell_1, \dots, \ell_k) \neq 18$.

- **Case 2: A cycle of length 9 exists.**

If there is a cycle of length $\ell_j = 9$, then because the cycles are disjoint and the total number of elements is 9 (i.e., $\sum \ell_i \leq 9$), no other non-trivial cycles can exist in the decomposition. Thus f is a 9-cycle, which implies $\text{ord}(f) = 9 \neq 18$.

Since both cases fail to produce an order of 18, such an element cannot exist in S_9 .

- (e) Let $f \in S_6$ and write $f = c_1 \circ c_2 \circ \dots \circ c_k$ as a disjoint cycles decomposition where c_i is a cycle of length ℓ_i for $i = 1, \dots, k$. To compute $\text{ord}(f) = \text{lcm}(\ell_1, \dots, \ell_k)$ we need to understand how the different cycle lengths ℓ_i can be. To do so, let m denote the maximum of the lengths ℓ_i of the cycles c_i with $i = 1, \dots, k$. Clearly $m \leq 6$. We divide some cases:

- $m = 6$. Then $k = 1$ and f is a 6-cycle. The order of f is 6 in this case.
- $m = 5$. Then f is a 5-cycle (recall that any 1-cycle is just the identity permutation). Hence the order of f is 5 in this case.
- $m = 4$. Hence either f is a 4-cycle, or the composition of a 4-cycle and a 2-cycle. In any case the order of f is 4 as $\text{lcm}(4, 2) = 4$.
- $m = 3$. Here either f is a 3-cycle, or the composition of 2 3-cycles or the composition of a 3-cycle and a 2-cycle. In the first 2 cases the order of f is 3 while in the last case $\text{ord}(f) = \text{lcm}(3, 2) = 6$.
- $m = 2$. Then f is composition of 2-cycles and hence its order is 2.

We conclude that the order of f is at most 6. We conclude that the order of f is at most 6.

Note that for any m -cycle $g = (a_0 a_1 \dots a_{m-1})$ of order $\text{ord}(g) = m$, we have that

$$g^m = \text{id}$$

and furthermore, we have that

$$g^i = g^{i \bmod m}$$

The above obviously holds if $0 \leq i < m$, as in this case $(i \bmod m) = i$.

In the general case, we can perform *division with remainder* to write

$$i = qm + r, \quad \text{with } 0 \leq r = (i \bmod m) < m \text{ and } q \text{ possibly negative}$$

and then we have that

$$g^i = g^{qm+r} = (g^m)^q \cdot g^r = \text{id}^q \cdot g^r = g^r,$$

and the result follows, as $r = i \bmod m$.

Question 2: Consider the group (G, \cdot) and consider the subgroup $H := \dots$

- (a) Show that H is a subgroup of G .
- (b) Show that $\varphi : \begin{cases} G \rightarrow V \\ g \mapsto \dots \end{cases}$ is a group homomorphism.
- (c) Determine whether (G_1, \cdot_1) is isomorphic to (G_2, \cdot_2) .

ANSWER

- (a) The identity element e_G is in H : ...

We can now use Lemma 4.1.2 (proven in an exercise), which says that any *non-empty* set $H \subseteq G$ is a subgroup of G if and only if

$$\forall f, g \in H : f^{-1} \cdot g \in H$$

- (b) We prove that the two axioms of a group homomorphism (Definition 6.1.1) hold:

- (a) $\varphi(e_G) = e_V$: ...
- (b) $\varphi(f \cdot g) = \varphi(f) \cdot \varphi(g)$: ...

(c) In order to be isomorphic, the cardinalities must match: $|G_1| = |G_2|$.

Furthermore, all elements in G_1 must have the same order as the corresponding elements in G_2 in case both groups are isomorphic.

To see this, assume that the groups are isomorphic ($G_1 \simeq G_2$) via the isomorphism $\psi : G_1 \rightarrow G_2$. Let $\text{ord}(g) = n$ for $g \in G_1$.

$$\psi(g)^n = \underbrace{\psi(g) \cdot_2 \dots \cdot_2 \psi(g)}_n \stackrel{(2)}{=} \psi(g \cdot_1 \dots \cdot_1 g) = \psi(g^n) \stackrel{\text{ord}(g)=n}{=} \psi(e_1) \stackrel{(1)}{=} e_2.$$

We conclude that $\psi(g)^n = e_2$, so because of Lemma 3.1.12, $\text{ord}(\psi(g))$ divides n . Now we show that n is the smallest such positive integer.

Assume there exists a positive integer $m < n$ such that $\psi(g)^m = e_2$. Then, by similar reasoning as above, we have $\psi(g^m) = e_2$.

Now we see that

$$\psi \text{ is bijective} \implies \psi \text{ is injective} \stackrel{\text{Lemma 6.1.8}}{\implies} \ker(\psi) = \{e_1\} \implies g^m = e_1$$

But we assumed that $\text{ord}(g) = n$ and that $m < n$. This gives a contradiction, since the order is by definition the smallest positive integer such that $g^{\text{ord}(g)} = e_1$. Therefore, no such m can exist and we conclude that $\text{ord}(\psi(g)) = n$.

Question 3: Consider the set $R = \dots$

- (a) Show that $(R, +, \cdot)$ is a ring.
- (b) Let $I := \dots \subseteq R$. Prove that I is an ideal of R .
- (c) Determine whether or not $I = R$.
- (d) Consider the map $\varphi : R \rightarrow S$. Show that φ is a ring homomorphism.
- (e) Compute the kernel and image of φ .
- (f) Prove that the quotient ring R/I is isomorphic to S .

ANSWER

- (a) We prove that $(R, +, \cdot)$ is a ring by showing that it satisfies all the ring axioms from Definition 7.1.1. The zero-element is $0_R = \dots$ and the one-element is $1_R = \dots$

- (1) $(R, +)$ is an abelian group.

- (i) There exists an identity element $0_R \in R$.

- (ii) The operation $+$ is **associative**. Take $a, b, c \in R$ arbitrarily.

(Associativity holds in the larger group G : for any $a', b', c' \in R$ we have $a' \cdot (b' \cdot c') = (a' \cdot b') \cdot c'$, so this particularly holds for $a = a', b = b', c = c'$)

- (iii) $(R, +)$ is **closed under inverses**. Take $a \in R$ arbitrarily.

Then, its additive inverse is a^{-1} is also in R .

- (iv) $(R, +)$ is **closed under addition**. Take $r, s \in R$ arbitrarily. Then, $r + s = \dots \in R$.

- (2) There exists an identity element $1_R \in R$ for the operation \cdot :

$$\forall f, g \in R : f \cdot 1_R = f = 1_R \cdot g$$

- (3) The operation \cdot is **associative**.

- (4) The operations $+$ and \cdot satisfy the **distributive laws**.

- (b) To prove that I is an ideal of R , we prove that (1) I is a subgroup of $(R, +)$ and (2) $\forall r \in R, \forall x \in I : rx \in I$.

- (1) I is a subgroup of $(R, +)$:

...

- (2) Take $r \in R$ and $x \in I$ arbitrarily. Then, $rx = \dots \in I$.

Because both conditions from Definition 8.1.7 are satisfied, we conclude that I is an ideal of R .

- (c) We now show that $I = R$.

Recall that $I = R$ if and only if I contains the one-element 1_R :

$$I = R \iff 1_R \in I$$

(Also recall that if a unit $u \in R^$ is in I , then $1_R \in I$ and thus $I = R$: $u \in I \Rightarrow 1_R \in I \Leftrightarrow I = R$)*

Our aim is thus to understand if I contains 1_R (or if I contains a unit $u \in R^*$).

(d) To show that φ is a ring homomorphism, we show that it satisfies all conditions in Definition 8.1.1:

(1) φ is a group homomorphism:

$$(i) \quad \varphi(0_R) = 0_S$$

$$(ii) \quad \varphi(r +_R s) = \varphi(r) +_S \varphi(s) \text{ for all } r, s \in R.$$

$$(2) \quad \varphi(1_R) = 1_S$$

$$(3) \quad \varphi(r \cdot_R s) = \varphi(r) \cdot_S \varphi(s) \text{ for all } r, s \in R.$$

(e) We compute that

$$\begin{aligned} \ker(\varphi) &\triangleq \{r \in R \mid \varphi(r) = 0_S\} \\ &= \dots \end{aligned}$$

$$\begin{aligned} \operatorname{im}(\varphi) &\triangleq \{\varphi(r) \mid r \in R\} \\ &= \dots \end{aligned}$$

(f) We show that $I = \ker(\varphi)$ by proving both inclusions.

\subseteq : Take $x \in I$ arbitrarily. Then, $\varphi(x) = \dots = 0_S$.

\supseteq : Take $x \in \ker(\varphi)$ arbitrarily. Then, $x \in I$.

Now we show that $\operatorname{im}(\varphi) = S$, i.e. φ is surjective. Take any $s \in S$ arbitrarily. Then, we can find a preimage $r \in R$ such that $\varphi(r) = s$. This shows that $\operatorname{im}(\varphi) = S$.

We now apply the *Isomorphism Theorem for Rings* (Theorem 8.3.5), which states that

$$\bar{\varphi} : \begin{cases} R / \ker(\varphi) & \rightarrow \operatorname{im}(\varphi) \\ r + \ker(\varphi) & \mapsto \varphi(r) \end{cases}$$

is a ring isomorphism. Because $\ker(\varphi) = I$ and $\operatorname{im}(\varphi) = S$, this proves that

$$(R/I, +, \cdot) \cong (S, +_S, \cdot_S)$$

Question 4: As usual, the finite field with 5 elements is denoted by $(\mathbb{F}_5, +, \cdot)$, while $(\mathbb{F}_5[X], +, \cdot)$ denotes the ring of polynomials with coefficients in \mathbb{F}_5 . Define the quotient ring $(R, +, \cdot)$, where

$$R := \mathbb{F}_5[X] / \langle X^4 + 2X^3 + X + 2 \rangle$$

- Compute the standard form of the coset $X^7 + X^6 + 2X^5 + X^4 + 2 + \langle X^4 + 2X^3 + X + 2 \rangle$.
- Write the polynomial $X^4 + 2X^3 + X + 2 \in \mathbb{F}_5[X]$ as the product of irreducible polynomials.
- Find z distinct zero-divisors in R .
(Only possible if $f(X)$ is **not** irreducible, otherwise R is a field and thus a domain!)
- Show that $X + 3 + \langle X^4 + 2X^3 + X + 2 \rangle$ is a unit of R and compute its multiplicative inverse.
- Which are the primitive elements in $\mathbb{F}_5[X] / \langle X^4 + 2X^3 + X + 2 \rangle$?
- Does R contain zero divisors? Motivate your answer.
- Determine how many units R contains.
- Compute the multiplicative order of the element $\alpha := X + \langle X^2 + X + 1 \rangle$ in the quotient ring $(\mathbb{F}_5[X] / \langle X^2 + X + 1 \rangle, +, \cdot)$.

ANSWER

- Because p is a prime, $\mathbb{Z}_p = \mathbb{F}_p$ is a *field* and we can apply Lemma 8.2.6, which says that any coset $g(X) + \langle f(X) \rangle$ of the ideal $I := \langle f(X) \rangle$ can be *uniquely* described in the standard form

$$r(X) + \langle f(X) \rangle \quad \text{where either} \quad \begin{cases} r(X) = 0 \Leftrightarrow \deg(r(X)) = -\infty \\ 0 \leq \deg(r(X)) < \deg(f(X)) \end{cases}$$

where $r(X) \in \mathbb{F}_p[X]$ is the *unique* remainder of long polynomial division of $g(X)$ by $f(X)$:

$$g(X) = q(X) \cdot f(X) + r(X)$$

- Denote the polynomial that generates the ideal $I := \langle f(X) \rangle$ as

$$f(X) := X^4 + 2X^3 + X + 2$$

Whenever $a \in \mathbb{F}_5$ is a root of $f(X)$, then $(X - a) \in \mathbb{F}_p[X]$ divides $f(X)$, providing a proper factor, as Proposition 7.4.3 states that in this case $f(X)$ can be factored as

$$f(X) = (X - a) \cdot q(X)$$

with $\deg(q(X)) = \deg(f(X)) - 1 = 3$. Because furthermore $(X - a)$ has degree 1, Lemma 9.2.4 says that it is our first *irreducible* factor of $f(X)$, which we will denote as $h_1(X) := X - a$. We check all $a \in \mathbb{F}_p$ to see if $f(a) \equiv 0 \pmod{p}$. Because $-1 \equiv 4 \pmod{5}$ and $-2 \equiv 3 \pmod{5}$, we have to check if $f(0), f(1), f(2), f(-1), f(-2) \equiv 0 \pmod{5}$ to check if $f(X)$ has any roots.

...

We see that $a \in \mathbb{F}_5$ is a root of $f(X)$. We now compute the factor $q(X)$ from above by performing long polynomial division of $f(X)$ by the factor $h_1 := (X - a)$.

...

We now apply the same principle to $q(X)$ to find the remaining factors of $f(X)$.

...

Because $\deg(h_k(X)) \in \{2, 3\}$, and $h_k(X)$ has no roots in \mathbb{F}_5 , it follows from Lemma 9.2.5 that $h_k(X)$ is irreducible. We conclude that the factorization of $f(X)$ into irreducible polynomials is

$$f(X) = h_1(X) \cdot \dots \cdot h_k(X)$$

- (c) To find k distinct zero-divisors in R , we first note that *any proper monic factor* $h(X)$ of $f(X)$ leads to a zero-divisor $h(X) + \langle f(X) \rangle$. In fact, for such polynomial

$$\deg(\gcd[h(X), f(X)]) = \deg(h(X)) \quad (1)$$

and since $h(X)$ is a *proper* factor of $f(X)$, it follows that

$$0 < \deg(h(X)) < \deg(f(X)) \xrightarrow{(1)} 0 < \deg(\gcd[h(X), f(X)]) < \deg(f(X))$$

Now we can apply Proposition 9.1.2 to conclude that $h(X) + \langle f(X) \rangle$ is a zero-divisor. Because in part (a) we found that

$$f(X) = h_1(X) \cdot \dots \cdot h_k(X)$$

a proper monic factor $h(X) \in \{h_1(X), \dots, h_k(X)\}$ leads to a zero-divisor. We thus already found k distinct zero-divisors in R .

To find more zero-divisors, we note that any multiple $a(X) \cdot h(X)$ of a proper monic factor $h(X)$ of $f(X)$ with degree

$$\begin{aligned} \deg(a(X) \cdot h(X)) &= \deg(a(X)) + \deg(h(X)) & (\mathbb{F}_p \text{ is a domain} \Rightarrow \mathbb{F}_p[X] \text{ is a domain}) \\ &< \deg(f(X)) \end{aligned}$$

strictly smaller than $\deg(f(X))$ leads to a zero-divisor $(a(X) \cdot h(X)) + \langle f(X) \rangle$ in the quotient ring $\mathbb{F}_q = \mathbb{F}_{p^q} = \mathbb{F}_5[X]/\langle f(X) \rangle$. Why? Because $h(X)$ divides both $f(X)$ and $a(X) \cdot h(X)$, it follows that $\deg(\gcd[f(X), a(X) \cdot h(X)]) \geq \deg(h(X))$. Furthermore, since $h(X)$ is a proper factor, it holds that $\deg(h(X)) < \deg(f(X))$. We conclude that

$$0 < \deg(\gcd[f(X), a(X) \cdot h(X)]) < \deg(f(X)),$$

so again by Proposition 9.1.2, $h(X) \cdot a(X) + \langle f(X) \rangle$ is a zero divisor in $\mathbb{F}_p[X]/\langle f(X) \rangle$.

We start with the $p-1$ constant multiples of each of the proper monic factors $h_i(X)$ ($i = 1, \dots, k$) of $f(X)$. We thereby find $(p-1) \cdot k$ more distinct zero-divisors in R on top of the k zero-divisors we found above.

Now consider the $p-1$ constant multiples of each of the proper monic factors $h_i(X)$ ($i = 1, \dots, k$) of $f(X)$.

- (d) The given coset $X+3+\langle f(X) \rangle =: g(X)+\langle f(X) \rangle$ is a unit of R if and only if $\deg(\gcd[f(X), g(X)]) = 0$ by Proposition 9.1.2. From the proof of this proposition, the inverse of this coset is given by

$$[g(X) + \langle f(X) \rangle]^{-1} = s(X) + \langle f(X) \rangle,$$

in this case, where $s(X)$ is obtained by performing the *Extended Euclidean algorithm* on $f(X)$ and $g(X)$ to obtain

$$\gcd[f(X), g(X)] = 1 = s(X) \cdot f(X) + r(X) \cdot g(X)$$

We now apply the Extended Euclidean algorithm to find $s(X)$ and $r(X)$:

$$\left[\begin{array}{c|cc} f(X) & 1 & 0 \\ g(X) & 0 & 1 \end{array} \right] \rightarrow \dots \rightarrow \left[\begin{array}{c|cc} c & s(X) & r(X) \\ \dots & \dots & \dots \end{array} \right]$$

The identity in row 1 is almost the one we are looking for. To ensure uniqueness, we now make the GCD monic by multiplying the identity in row 1 by c^{-1} .

- (e) Denote $\mathbb{F}_q = \mathbb{F}_{p^d} = \mathbb{F}_5[X]/\langle f(X) \rangle$. Because $f(X)$ is irreducible, by Theorem 9.3.2, \mathbb{F}_q is a field with $q = p^d$ elements.

Because of Theorem 9.4.1, we know that the finite field \mathbb{F}_q with $q = p^d$ for prime p and $d \geq 1$ has *at least one primitive element* $\alpha \in \mathbb{F}_q$. In this case, (\mathbb{F}_q^*, \cdot) is a *cyclic* group of order

$$\text{ord}(\mathbb{F}_q^*) = |\mathbb{F}_q^*| = \text{ord}(\alpha) = q - 1$$

generated by a primitive element α :

$$\mathbb{F}_q^* = \{\alpha^0, \alpha^1, \alpha^2, \dots, \alpha^{q-2}\}$$

Because of Lagrange's Theorem (more specifically Proposition 4.4.4), we know that

$$\forall g \in \mathbb{F}_q^* : \quad \text{ord}(g) \text{ divides } |\mathbb{F}_q^*| = q - 1$$

The possible orders of elements in \mathbb{F}_q^* are thus the divisors of $q - 1$:

$$D = \{d \in \mathbb{Z}_{>0} \mid d \text{ divides } (q - 1)\}$$

A primitive element is an element $\alpha \in \mathbb{F}_q^*$ with order $\text{ord}(\alpha) = q - 1$. We thus find a primitive element α by finding an element whose order is not any of the other divisors of $q - 1$:

$$\text{ord}(\alpha) \notin D \setminus \{q - 1\}$$

- (f) Yes, R contains zero divisors. From part (b), we know that $f(X) = X^4 + 2X^3 + X + 2$ is reducible in $\mathbb{F}_5[X]$, factoring as:

$$f(X) = (X + 1)(X + 2)(X^2 + 4X + 1)$$

Since $f(X)$ is not irreducible, the quotient ring $R = \mathbb{F}_5[X]/\langle f(X) \rangle$ is not a field and therefore contains zero divisors (for example, the coset $(X + 1) + \langle f(X) \rangle$), because $(X + 1)$ is a proper monic factor of $f(X)$.

- (g) *NOTE: In this exercise, we use a different f , namely $f(X) = X^3 + X - 2$.*

An element $g(X) + \langle f(X) \rangle \in R$ in this quotient group is either a zero-element, a unit, or a zero-divisor. Because we can write each coset in standard form, let's assume all these elements $g(X) + \langle f(X) \rangle$ are in standard form.

- The only zero-element is $0 + \langle f(X) \rangle = \langle f(X) \rangle$.
- Units are elements with $\deg(\gcd[f(X), g(X)]) = 0$.
- Zero-divisors are elements with $0 < \deg(\gcd[f(X), g(X)]) < \deg(f(X))$.

We conclude that a non-zero coset $u = g(X) + \langle f(X) \rangle$ in standard form (with thus $g(X) \neq 0$ and $\deg(g(X)) < \deg(f(X))$) is a zero-divisor if and only if $\deg(\gcd[g(X), f(X)]) > 0$.

We can thus calculate the number of units N_u by **first counting the number of zero-divisors** N_z . We know that the total number of elements in R is $|R| = p^d = 5^4 = 625$. The ring is partitioned into units, zero-divisors, and the zero element:

$$|R| = N_u + N_z + 1$$

To find N_z , we analyze the factorization of $f(X)$ in $\mathbb{Z}_5[X]$ to determine the conditions under which $\deg(\gcd[f(X), g(X)]) > 0$.

We find the following factorization into irreducible polynomials in $\mathbb{Z}_5[X]$:

$$X^3 + X + 3 = (X + 4)(X^2 + X + 2)$$

The quadratic factor $X^2 + X + 2$ is irreducible in \mathbb{Z}_5 because it has no roots (checking values $0, 1, 2, 3, 4$ yields no zeros). $(X + 4)$ is a factor of degree 1, which is always irreducible.

For a non-zero coset $g(X) + \langle f(X) \rangle$, $\gcd[f(X), g(X)]$ is either $X + 4$ or $X^2 + X + 2$, because the GCD is *unique* if it's monic. We count the possibilities for $g(X)$ in these two disjoint cases:

(a) **Case 1:** $\gcd[f(X), g(X)] = X + 4$

The polynomial $g(X)$ must be a multiple of $X + 4$. Further, since it is in standard form, $\deg(g(X)) < 3$. From these two conditions, we find that $g(X)$ must take the form:

$$g(X) = (X + 4)(aX + b)$$

where $a, b \in \mathbb{Z}_5$. There are $5 \cdot 5 = 25$ choices for the pair (a, b) . Excluding the zero-coset case where $(a, b) = (0, 0)$ (giving $g(X) = 0$), we have:

$$25 - 1 = 24 \text{ zero-divisors.}$$

(b) **Case 2:** $\gcd[f(X), g(X)] = X^2 + X + 2$

The polynomial $g(X)$ must be a multiple of $X^2 + X + 2$. Further, since it is in standard form, $\deg(g(X)) < 3$. From these two conditions, we find that $g(X)$ must take the form:

$$g(X) = a(X^2 + X + 2)$$

where $a \in \mathbb{Z}_5$. There are 5 choices for a . Excluding $a = 0$, we have:

$$5 - 1 = 4 \text{ zero-divisors.}$$

Summing these cases, the total number of zero-divisors is:

$$N_z = 24 + 4 = 28$$

Finally, we calculate the number of units N_u . Recalling that the total number of elements is $|R| = p^d = 5^3 = 125$:

$$N_u = |R| - 1 - N_z = 125 - 1 - 28 = 96$$

Thus, R contains **96 units**.

(h) Let's find the multiplicative order of α , i.e. the integer $i > 0$ such that $\alpha^i = 1_R = 1 + \langle f(X) \rangle$.

Note that $\deg(\alpha) < \deg(f(X))$, in other words, it is **already in standard form**. This means that $\alpha \neq 0 + \langle f(X) \rangle$. Furthermore, this also means that $\alpha \neq 1 + \langle f(X) \rangle$ and thus $\text{ord}(\alpha) \neq 1$.

We compute α^2 :

$$\alpha^2 = [X + \langle f(X) \rangle] \cdot [X + \langle f(X) \rangle] = X^2 + \langle f(X) \rangle$$

This is not in standard form, since $\deg(X^2) = 2 \not< \deg(f(X))$, so we perform long division of X^2 by $f(X)$! to find the standard form

$$\alpha^2 = -(X + 1) + \langle f(X) \rangle \neq 1 + \langle f(X) \rangle$$

For α^3 , note that $\alpha^3 = \alpha \cdot \alpha^2 = -(X^2 + X) + \langle f(X) \rangle = 1 + \langle f(X) \rangle$.