

Algebra Review

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1 Groups

Definition 1.1 A **semigroup** (G, \cdot) is a set G with a binary operation \cdot such that:

Axiom 1 $(\forall a, b \in G)(\exists! a \cdot b \in G)$

Axiom 2 $(\forall a, b, c \in G)((ab)c = a(bc))$

Definition 1.2 A **group** (G, \cdot) is a semigroup such that:

Axiom 3 (Identity element) $(\exists 1 \in G)(\forall a \in G)(1 \cdot a = a = a \cdot 1)$

Axiom 4 (Inverse) $(\forall a \in G)(\exists b \in G)(a \cdot b = b \cdot a = 1)$

Multiplicative Notation:

- $ab = a \cdot b$
- In Axiom 4, $b = a^{-1}$

Additive Notation:

- Binary operation ‘+’
- Identity becomes ‘0’
- Additive inverse ‘ $-a$ ’

The size of G as a set, which is denoted $|G|$, is called the **order** of G .

Definition 1.3 G is an **abelian group** if G is a group such that $(\forall a, b \in G)(ab = ba)$.

Definition 1.4 $H \subseteq G$ is a **subgroup** of G (denoted $H \leq G$) if

1. $1 \in H$
2. H is closed under the binary operation
3. H is closed under inverses

Definition 1.5 Let $H \leq G$. The sets of the form $a \cdot H := \{ah : h \in H\}$ for $a \in G$ are the **left cosets** of G . The left cosets partition G . **Right cosets** are defined analogously.

Definition 1.6 $|G : H| =$ number of left cosets of H in G is called the **index** of H in G .

Exercise 1.7 Prove that the number of left cosets is the same as the number of right cosets, even if G is infinite. (*Hint*: construct a bijection between the left and the right cosets.)

Exercise⁺ 1.8 Prove: if G is finite then the left and the right cosets have a common system of representatives, i. e., there exists a set T of size $|T| = |G : H|$ such that T contains exactly one element from every left coset as well as from every right coset.

Exercise 1.9 (Lagrange) If $H \leq G$ then $|G| = |H| \cdot |G : H|$. Therefore, if $|G| < \infty$ then $|H| \mid |G|$.

Exercise 1.10 Prove: the intersection of subgroups is a subgroup.

Definition 1.11 Let $S \subset G$. We define the subgroup of G **generated** by S by

$$\langle S \rangle = \bigcap_{\substack{H \leq G \\ H \supseteq S}} H.$$

A group is **cyclic** if it is generated by an element ($|S| = 1$).

Exercise 1.12 $\langle S \rangle$ is the set of all products of elements of S and inverses of elements of S .

Example 1.13 Let $S = \{a, b\}$. Then $aba^{-4}bab^6 \in \langle S \rangle$.

Example 1.14 If $|S| = 1$ and $S = \{g\}$ then $\langle S \rangle = \{g^n : n \in \mathbb{Z}\}$.

Exercise 1.15 If G is cyclic then

1. if $|G| = \infty$ then $G \cong (\mathbb{Z}, +)$
2. if $|G| = n$ then $G \cong (\mathbb{Z}/n\mathbb{Z}, +)$

Definition 1.16 The **order** of an element $g \in G$ is the order of the cyclic group generated by g : $|g| := |\langle g \rangle|$.

Exercise 1.17 $g^k = 1 \Leftrightarrow k \mid |g|$

Exercise 1.18 $g^{|G|} = 1$

Exercise 1.19 (Euler - Fermat) $(\forall a, n \in \mathbb{Z})(\text{g.c.d.}(a, n) = 1 \Rightarrow a^{\varphi(n)} \equiv 1 \pmod{n})$

Exercise 1.20 If G is an abelian group then

$$\frac{\text{l.c.m.} [|a|, |b|]}{\text{g.c.d.} [|a|, |b|]} \mid |ab| \mid \text{l.c.m.} [|a|, |b|].$$

This shows that if $\text{g.c.d.} [|a|, |b|] = 1$ then $|ab| = \text{l.c.m.} [|a|, |b|]$.

Definition 1.21 F_k is a **free group of rank k on free generators** $\{a_1, \dots, a_k\}$ if the products of the a_i and the a_i^{-1} give 1 only by explicit cancellation.

Example 1.22 $ab^{-3}a^4a^{-2}a^{-2}b^5b^{-2}a^{-1} = 1$

Exercise⁺ 1.23 $F_3 \leq F_2$. In fact, $F_\infty \leq F_2$.

Definition 1.24 For a commutative ring R , the **special linear group** $SL(n, R)$ is the group of those $n \times n$ matrices $A \in M_n(R)$ with $\det(A) = 1$. (More about rings below; we assume all rings have an identity element.)

Exercise* 1.25 (Sanov) $A = \begin{bmatrix} 1 & 2 \\ 0 & 1 \end{bmatrix}$ and A^T (A transpose) freely generate a free group $F_2 \leq SL(2, \mathbb{Z})$. (*Hint:* for $T = (t_{ij}) \in SL(2, \mathbb{Z})$, let $m(T) = \max |t_{ij}|$. Show that $\forall T$ there is at most one $X \in \{A, A^T, A^{-1}, A^{-T}\}$ such that $m(T) \geq m(TX)$.)

Definition 1.26 Let G be a group and $S \subseteq G \setminus 1$. The **Cayley graph** $\Gamma(G, S)$ has G for its vertex set; elements $g, h \in G$ are adjacent if $gh^{-1} \in S \cup S^{-1}$ (where $S^{-1} = \{s^{-1} : s \in S\}$).

Exercise 1.27 Prove: $\Gamma(G, S)$ is connected if and only if S generates G .

Exercise 1.28 Suppose $G = \langle S \rangle$. Then $\Gamma(G, S)$ is bipartite if and only if G has a subgroup N of index 2 such that $S \cap N = \emptyset$.

Exercise 1.29 Let S be a minimal set of generators of G , i. e., no proper subset of S generates G . Prove: $K_{3,5} \not\subseteq \Gamma(G, S)$.

A theorem of Erdős and Hajnal states that if an (infinite) graph X does not contain K_{m, \aleph_1} as a subgraph (for some $m \in \mathbb{N}$) then $\chi(X) \leq \aleph_0$. As a consequence of the preceding exercise, if S is a minimal set of generators then $\chi(\Gamma(G, S)) \leq \aleph_0$.

Exercise 1.30 Prove that every group G has a set S of generators such that $\chi(G, S) \leq \aleph_0$. *Hint.* Not every group has a minimal set of generators (e.g., $(\mathbb{Q}, +)$ does not). But every group has a *sequentially non-redundant* set of generators, $\{s_\alpha : \alpha \in I\}$, where I is a well-ordered set and $(\forall \alpha \in I)(s_\alpha \notin \langle s_\beta : \beta < \alpha \rangle)$. Prove that if S is sequentially non-redundant then $K_{5,17} \not\subset \Gamma(G, S)$.

Exercise 1.31 If a regular graph of degree r with n vertices has girth g then

$$n \geq 1 + r + r(r-1) + \dots + r(r-1)^{\lfloor (g-3)/2 \rfloor} > (r-1)^{g/2-1}.$$

Consequently, $g < 1 + 2 \log n / \log(r-1)$.

On the other hand, Erdős and Sachs proved for every $r \geq 3$ there exist r -regular graphs of girth $g \geq \log n / \log(r-1)$. The following problem addresses the question of **explicit construction** of a 4-regular graph with large girth. The girth will be optimal within a constant factor.

Exercise⁺ 1.32 (Margulis) Let $G = SL(2, p) := SL(2, \mathbb{Z}/p\mathbb{Z})$. Let $S = \{A, B\}$ where $A = \begin{bmatrix} 1 & 2 \\ 0 & 1 \end{bmatrix}$ and $B = A^T$ (A transpose). Note that $|G| < p^3$ and $\Gamma(G, S)$ has degree 4. Prove that the girth of $\Gamma(G, S)$ is $\Omega(\log p)$. (*Hint.* Use Sanov's Theorem and the submultiplicativity of matrix norm.)

2 Rings

Definition 2.1 A **ring** $(R, +, \cdot)$ is an abelian group $(R, +)$ and semigroup (R, \cdot) such that:

- (Distributivity) $(\forall a, b, c \in R)(a(b+c) = ab+ac)$ and $((b+c)a = ba+ca)$

Exercise 2.2 In a ring R , $(\forall a \in R)(a \cdot 0 = 0 = 0 \cdot a)$

Definition 2.3 $(R, +, \cdot)$ is a **commutative** if (R, \cdot) is abelian.

Definition 2.4 R is a **ring with identity** if (R, \cdot) satisfies Axiom 3 (semigroup with identity) and $1 \neq 0$.

CONVENTION. By “rings” we shall always mean **rings with identity**.

Definition 2.5 $a \in R$ is a **unit** if $\exists a^{-1} \in R$.

Exercise 2.6 The units of R form a multiplicative group denoted R^\times .

Example 2.7 Let R be a ring.

- $M_n(R) :=$ set of $n \times n$ matrices over R is a ring

Exercise 2.8 Let R be a commutative ring. $GL(n, R)$ denotes the group of units of $M_n(R)$. Prove: $A \in M_n(R)$ belongs to $GL(R)$ if and only if $\det(A) \in R^\times$.

Example 2.9 mod m residue classes form a ring, denoted $\mathbb{Z}/m\mathbb{Z}$.

Exercise 2.10 What is the order of the group of units of $\mathbb{Z}/m\mathbb{Z}$?

Definition 2.11 $a \in R$ is a **left zero divisor** if $a \neq 0$ and $(\exists b \in R, b \neq 0)(ab = 0)$. **Right zero divisors** are defined analogously.

Definition 2.12 $a \in R$ is a **zero-divisor** if a is a left OR a right zero-divisor.

Exercise 2.13 1. If $\exists a^{-1}$ then a is not a zero-divisor.

2. The converse is false.

3. The converse is true if R is finite.

4. The converse is true if $R = M_n(F)$ where F is a field. In this case, $A \in R$ is a zero-divisor if and only if $\det(A) = 0$.

Definition 2.14 An **integral domain** is a commutative ring with no zero-divisors.

Definition 2.15 A **division ring** is a ring where all nonzero elements are units, i. e., $R^\times = R \setminus \{0\}$.

3 Gaussian integers and quaternions; sums of two squares and four squares

Definition 3.1 The **Gaussian Integers** are complex numbers of the form $\{a + bi : a, b \in \mathbb{Z}\}$ where $i = \sqrt{-1}$. They form the ring $\mathbb{Z}[i]$. The *norm* of $z \in \mathbb{Z}[i]$ is $N(z) = a^2 + b^2 = z\bar{z}$.

Exercise 3.2 Define divisibility among Gaussian integers. Observe that $z | w \Rightarrow N(z) | N(w)$. Show that the units among the Gaussian integers are $\pm 1, \pm i$.

Exercise 3.3 Use Gaussian integers to show that $(a^2 + b^2)(c^2 + d^2) =$ sum of two squares. *Hint.* Observe that $N(zw) = N(z)N(w)$.

Exercise⁺ 3.4 Define division with remainder among Gaussian integers. Show the existence of g.c.d.'s. Use this to establish unique prime factorization in $\mathbb{Z}[i]$.

Exercise 3.5 Show: if z is a prime in $\mathbb{Z}[i]$ then $N(z)$ is either p or p^2 for some prime $p \in \mathbb{Z}$. In the former case $p = N(z) = a^2 + b^2$; in the latter case, $p = z$.

Exercise⁺ 3.6 Let $p \in \mathbb{Z}$ be a prime. Prove: p is a prime in $\mathbb{Z}[i]$ if and only if $p \equiv -1 \pmod{4}$. *Hint.* “If:” if $p \equiv -1 \pmod{4}$ then $p \neq a^2 + b^2$. “Only if:” if $p \equiv 1 \pmod{4}$ then $(\exists a \in \mathbb{Z})(p \mid a^2 + 1)$. Let $w = a + bi \in \mathbb{Z}[i]$. Let $z = \text{g.c.d.}(p, w)$.

Exercise 3.7 Infer from the preceding exercise: if p is a prime (in \mathbb{Z}) and $p \equiv 1 \pmod{4}$ then p can be written as $a^2 + b^2$.

Exercise⁺ 3.8 The positive integer $n = \prod p_i^{\alpha_i}$ can be written as a sum of two squares if and only if $(\forall i)(p_i \equiv -1 \pmod{4} \Rightarrow 2 \mid \alpha_i)$.

Exercise⁺ 3.9 Show that the number of ways to write n as $a^2 + b^2$ in \mathbb{Z} is

$$\epsilon + \prod_{i:p_i \equiv 1 \pmod{4}} (\alpha_i + 1)$$

where $\epsilon = 1$ if n is a square and 0 otherwise.

Exercise 3.10 Let n be a product of primes $\equiv 1 \pmod{4}$ and suppose n is not a square. Prove: the number of ways to write n as $a^2 + b^2$ is $d(n)$ (the number of positive divisors of n).

Definition 3.11 The **quaternions** form a 4-dimensional division algebra \mathbb{H} over \mathbb{R} , i.e., a division ring which is a 4-dimensional vector space over \mathbb{R} . The standard basis is denoted by $\mathbf{1}, \mathbf{i}, \mathbf{j}, \mathbf{k}$, so a quaternion is a formal expression of the form $z = a + b\mathbf{i} + c\mathbf{j} + d\mathbf{k}$. Multiplication is performed using distributivity and the following rules:

- $\mathbf{i}^2 = \mathbf{j}^2 = \mathbf{k}^2 = -1$;
- $\mathbf{ij} = -\mathbf{ji} = \mathbf{k}$;
- $\mathbf{jk} = -\mathbf{kj} = \mathbf{i}$;
- $\mathbf{ki} = -\mathbf{ik} = \mathbf{j}$.

It is clear that \mathbb{H} is a ring. We need to find inverses.

Exercise 3.12 For $z = a + b\mathbf{i} + c\mathbf{j} + d\mathbf{k}$, we define the **norm** of z by $N(z) = a^2 + b^2 + c^2 + d^2$. Prove: $N(z) = z\bar{z} = \bar{z}z$, where $\bar{z} = a - b\mathbf{i} - c\mathbf{j} - d\mathbf{k}$ is the **conjugate** quaternion.

Exercise 3.13 Let $z, w \in \mathbb{H}$. Prove: $N(zw) = N(z)N(w)$.

Exercise 3.14

$$(a^2 + b^2 + c^2 + d^2)(k^2 + l^2 + m^2 + n^2) = t^2 + u^2 + v^2 + w^2$$

where t, u, v, w are bilinear forms of (a, b, c, d) and (k, l, m, n) with integer coefficients. Calculate the coefficients.

Exercise* 3.15 (Lagrange) Every integer is a sum of 4 squares. *Hint.* By the preceding exercise, it suffices to prove for primes. First prove that for every prime p there exist $x_1, \dots, x_4 \in \mathbb{Z}$ such that $p \mid \sum x_i^2$ and $\text{g.c.d.}(x_1, \dots, x_4) = 1$. Let now $m > 0$ be minimal such that $mp = x_1^2 + \dots + x_4^2$; note that $m < p$. If $m \geq 2$, we shall reduce m and thereby obtain a contradiction (Fermat's method of infinite descent; Fermat used it to prove that if $p \equiv 1 \pmod{4}$ then p is the sum of 2 squares). If m is even, halve m by using $(x_1 \pm x_2)/2$ and $(x_3 \pm x_4)/2$ (after suitable renumbering). If m is odd, take $y_i = x_i - mt_i$ such that $|y_i| < m/2$. Observe that $0 < \sum y_i^2 < m^2$ and $m \mid \sum y_i^2$, so $\sum y_i^2 = md$ where $0 < d < m$. Now represent $m^2 dp = (\sum x_i^2)(\sum y_i^2)$ as a sum of four squares, $\sum z_i^2$, using the preceding exercise. Analyzing the coefficients, verify that $(\forall i)(m \mid z_i)$. Now $dp = \sum (z_i/m)^2$, the desired contradiction.

4 Fields

Definition 4.1 A **field** is a commutative division ring.

Example 4.2 Let F be a field.

- $M_n(F)$:= set of $n \times n$ matrices over F is a ring
- $GL_n(F)$:= group of units of $M_n(F)$ is called the "General Linear Group"

Exercise 4.3 A finite ring with no zero divisors is a division ring. (*Hint:* use Exercise 2.13.)

Theorem 4.4 (Wedderburn) A finite division ring is a field.

Exercise 4.5 If F is a field and $G \leq F^\times$ is a finite multiplicative subgroup then G is cyclic.

Definition 4.6 Let R be a ring and for $x \in R$ let n_x be the g.c.d. of all n such that $nx = 0$ where

$$\begin{aligned} nx &:= x + \dots + x \text{ when } n > 0 \\ nx &:= -x - \dots - x \text{ (} n \text{ times) when } n < 0 \\ nx &:= 0 \text{ (} n \text{ times) when } n = 0. \end{aligned}$$

Exercise 4.7 $n_x \cdot x = 0$

Exercise 4.8 If R has no zero divisors then $(\forall x, y \neq 0)(n_x = n_y)$.

Definition 4.9 The common value n_x is called the **characteristic** of R .

Exercise 4.10 If R has no zero divisors then $\text{char}(R) = 0$ or it is prime. In particular, every field has 0 or prime characteristic.

Exercise 4.11 If R is a ring without zero-divisors, of characteristic p , then $(a + b)^p = a^p + b^p$.

Exercise 4.12

1. If R has characteristic 0 then $R \supseteq \mathbb{Z}$
2. If R has characteristic p then $R \supseteq \mathbb{Z}/p\mathbb{Z}$.

Exercise 4.13 If F is a field of characteristic 0 then $F \supseteq \mathbb{Q}$.

Definition 4.14 A **subfield** of a ring is a subset which is a field under the same operations. If K is a subfield of L then we say that L is an extension of K ; the pair (K, L) is referred to as a **field extension** and for reasons of tradition is denoted L/K .

Definition 4.15 A **prime field** is a field without a proper subfield.

Exercise 4.16 The prime fields are \mathbb{Q} and $\mathbb{Z}/p\mathbb{Z}$ (p prime).

Definition 4.17 Observe: if L/K is a field extension then L is a vector space over K . The **degree** of the extension is $[L : K] := \dim_K L$. A **finite extension** is an extension of finite degree.

Exercise 4.18 The order of a finite field is a prime power. *Hint.* Let L be a finite field and K its prime field, so $|K| = p$; let $[L : K] = k$. Prove: $|L| = p^k$.

Exercise 4.19 The degree of the extension \mathbb{C}/\mathbb{R} is 2. The degree of the extension \mathbb{R}/\mathbb{Q} is uncountably infinite (continuum).

Exercise⁺ 4.20 Prove that $\sqrt{2}, \sqrt{3}, \sqrt{5}, \dots, \sqrt{p}$ are linearly independent over \mathbb{Q} .

Exercise 4.21 If $K \subset L \subset M$ are fields then $[M : L][L : K] = [M : K]$.

5 Polynomials over Rings and Fields

Definition 5.1 Let R be a commutative ring. (As always we assume R has an identity.) $R[x]$ denotes the ring of polynomials in the variable x with coefficients in R .

Exercise 5.2 If R is an integral domain then $R[x]$ is an integral domain.

Definition 5.3 A **unique factorization domain** (UFD) is an integral domain in which every element can be written uniquely as a product of irreducible elements. The factorization is unique up to the order of the factors and multiplying each factor by units.

Example 5.4 Every field is a UFD. The rings \mathbb{Z} and $\mathbb{Z}[i]$ are UFDs.

Exercise 5.5 Prove: if R is a UFD then $R[x]$ is a UFD.

Exercise 5.6 For an integral domain R , define the field of quotients (or field of fractions) $\left\{ \frac{a}{b} : a, b \in R, b \neq 0 \right\}$ by copying how \mathbb{Q} arises from \mathbb{Z} . (*Hint*: “rational numbers” are equivalence classes of fractions).

Definition 5.7 Let F be a field and $F(x)$ be the field of quotients of $F[x]$. $F(x)$ is called the **function field** over F .

Exercise 5.8 $\dim_{\mathbb{R}} \mathbb{R}[x]$ is countably infinite and $\dim_{\mathbb{R}} \mathbb{R}(x)$ is uncountably infinite. (*Hint*: Show $\left\{ \frac{1}{x - \alpha} : \alpha \in \mathbb{R} \right\}$ is linearly independent over \mathbb{R} .)

Definition 5.9 Let F be a field. $f \in F[x]$ is **irreducible** if f is not constant (i. e., $\deg f \geq 1$) and $(\forall g, h \in F[x])(f = gh \Rightarrow \deg g = 0 \text{ or } \deg h = 0)$.

Definition 5.10 Let L/K be a field extension; let $\alpha \in L$. We say that α is **algebraic** over K if $(\exists f \in K[x])(f \neq 0 \text{ and } f(\alpha) = 0)$. We define $m_{\alpha}(x)$ as the g.c.d. of all such polynomials. $m_{\alpha}(x)$ and we call it the **minimal polynomial** of α (over K). If all elements of L are algebraic over K then we call L/K an algebraic extension.

Exercise 5.11 $m_{\alpha}(\alpha) = 0$.

Exercise 5.12 m_{α} is irreducible over K .

Exercise 5.13 Every finite extension is algebraic.

Definition 5.14 Let R be a ring. $I \subseteq R$ is a **left ideal** of R if I is an additive subgroup of R and $(\forall r \in R)(rI \subseteq I)$. Right ideals are defined analogously. I is an **ideal** if it is both a left- and a right-ideal.

Definition 5.15 Let R be a ring and I an ideal of R . The additive quotient group R/I with elements $a + I$ is a ring under the multiplication rule $(a + I)(b + I) = ab + I$. It is called the **quotient ring**.

Exercise 5.16 Let F be a field and $f \in K[x]$. The ring $K[x]/(f)$ is a field if and only if f is irreducible.

Definition 5.17 A **simple extension** $K(\alpha)$ is the smallest field containing K and α .

Exercise 5.18 If α is algebraic over K then $K(\alpha) = K[\alpha] = \{f(\alpha) : f \in K[x]\} \simeq K[x]/(m_\alpha)$.

Exercise 5.19 Let \mathbb{F}_q be a finite field of order q . Then

$$x^q - x = \prod_{\alpha \in \mathbb{F}_q} (x - \alpha)$$

$$x^{q-1} - 1 = \prod_{\alpha \in \mathbb{F}_q^\times} (x - \alpha)$$

Exercise⁺ 5.20 Let $q = p^n$ be a prime power. Let $F_d(x)$ be the product of all monic irreducible polynomials of degree d over \mathbb{F}_p . Prove that $x^q - 1 = \prod_{d|n} F_d(x)$. (For this exercise, do not assume the existence of \mathbb{F}_q . The field $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$ of course exists.)

Exercise⁺ 5.21 Let N_d be the number of monic irreducible polynomials of degree d over \mathbb{F}_p . Observe from the preceding exercise that $p^k = \sum_{d|k} dN_d$. Infer:

$$N_n = (1/n) \sum_{d|n} \mu(n/d) p^d.$$

Conclude that $N_n \neq 0$.

Exercise 5.22 Prove that there exists a field of order p^n . *Hint.* The preceding exercise shows that there exists an irreducible polynomial f of degree n over \mathbb{F}_p . Take the field $\mathbb{F}_p[x]/(f)$.

Exercise 5.23 Prove: the field of order p^k is unique (up to isomorphism).

6 Irreducibility over \mathbb{Z} , Gauss lemma, cyclotomic polynomials

Exercise 6.1 (Gauss Lemma) A polynomial $f \in \mathbb{Z}[x]$ is **primitive** if the g.c.d. of its coefficients is 1. Prove: the product of primitive polynomials is primitive. (*Hint.* Assume $fg = ph$ where $f, g, h \in \mathbb{Z}[x]$ and p is a prime. Look at this equation modulo p and use the fact that $\mathbb{F}_p[x]$ is an integral domain.)

Exercise 6.2 If $f \in \mathbb{Z}[x]$ splits into factors of lower degree over $\mathbb{Q}[x]$ then such a split occurs over $\mathbb{Z}[x]$. In fact, if $f = gh$ where $g, h \in \mathbb{Q}[x]$ then $(\exists r \in \mathbb{Q})(rg \in \mathbb{Z}[x] \text{ and } h/r \in \mathbb{Z}[x])$.

Exercise 6.3 Let $f(x) = \prod_{i=1}^n (x - a_i) - 1$ where the a_i are distinct integers. Then $f(x)$ is irreducible over \mathbb{Q} . *Hint.* Let $f = gh$ where $g, h \in \mathbb{Z}[x]$. Observe that $(\forall i)(g(a_i) + h(a_i) = 0)$.

Exercise 6.4 Let $f(x) = \left(\prod_{i=1}^n (x - a_i) \right)^2 + 1$ where the a_i are distinct integers. Then $f(x)$ is irreducible over \mathbb{Q} . *Hint.* Let $f = gh$ where $g, h \in \mathbb{Z}[x]$. Observe that $(\forall i)(g(a_i) = h(a_i) = \pm 1)$. Observe further that g never changes sign; nor does h .

Exercise 6.5 Let $f(x) = \sum_{i=0}^n a_i x^i \in \mathbb{Z}[x]$. If p is a prime and $p \nmid a_n, p \mid a_0, \dots, p \mid a_{n-1}, p^2 \nmid a_0$, then f is irreducible over \mathbb{Q} . (*Hint:* Unique factorization in $\mathbb{F}_p[x]$).

Exercise 6.6 If p is a prime then $\Phi_p(x) := x^{p-1} + x^{p-2} + \dots + x + 1$ is irreducible over \mathbb{Q} . (*Hint:* Introduce the variable $z = x - 1$.)

Exercise 6.7 $\text{g.c.d.}(x^k - 1, x^\ell - 1) = x^d - 1$ where $d = \text{g.c.d.}(k, \ell)$.

Definition 6.8 The **n -th cyclotomic polynomial** is defined as

$$\Phi_n(x) = \prod_{\omega} (x - \omega) \in \mathbb{C}[x]$$

where the product extends over all complex primitive n -th roots of unity.

Exercise 6.9

$$\prod_{d|n} \Phi_d(x) = x^n - 1$$

Exercise 6.10 Let $f, g \in \mathbb{Z}[x]$ with the leading coefficient of g equal to 1. If $\frac{f}{g} \in \mathbb{Q}[x]$ then $\frac{f}{g} \in \mathbb{Z}[x]$.

Exercise 6.11

$$\Phi_n(x) \in \mathbb{Z}[x]$$

Exercise 6.12

$$\Phi_n(x) = \prod_{d|n} (x^d - 1)^{\mu(n/d)}$$

Exercise 6.13 Let f, g be polynomials over the field F . Prove: if $g^2 \mid f$ then $g \mid f'$, where f' is the (formal) derivative of f .

Exercise 6.14 Prove: if $p \nmid n$ then $x^n - 1$ has no multiple factors over \mathbb{F}_p .

Exercise⁺ 6.15 Let $a \neq b$ and n be positive integers. Let p be a prime. Assume $p \mid \text{g.c.d.}(\Phi_a(n), \Phi_b(n))$. Prove: $p \mid \text{g.c.d.}(a, b)$.

Exercise 6.16 Prove: if f is a polynomial over any field of characteristic p , then $f(x^p) = (f(x))^p$.

Exercise⁺ 6.17 Let ω be a complex primitive n -th root of unity. Prove: if p is a prime and $p \nmid n$ then the minimal polynomials of ω and ω^p (over \mathbb{Q}) coincide. (*Hint.* Let f and g be the minimal polynomials of ω and ω^p , respectively. Assume $f \neq g$; then $fg \mid x^n - 1$. Observe that $f(x) \mid g(x^p)$. Look at this equation over \mathbb{F}_p and conclude that $x^n - 1$ has a multiple factor over \mathbb{F}_p , a contradiction.)

Exercise 6.18 A major result is now immediate: Φ_n is irreducible over \mathbb{Q} .