

Lecture Notes for Math 696
Coding Theory

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January 12, 2004

Commutative Rings and Finite Fields

1 Introduction

To my students:

Since the birth of the subject roughly 50 years ago, coding theory has grown enormously and has become enriched by its relationship with many areas of mathematics. There are a number of excellent books on coding theory, but the challenge to write my own notes and cover the topics in the manner that made most sense to me proved irresistible. Here in this first installment we will cover the algebraic preliminaries: polynomial rings and finite fields being the essential topics. A later set of notes will cover Reed-Solomon codes and decoding by the Berlekamp-Massey algorithm. I hope to add some sections expanding beyond Reed-Solomon codes later in the semester.

I hope you will enjoy these notes, and enjoy being part of this project of mine to put them together. Please be patient with the typos and various problems that are certain to be encountered. Although I have revised and reread a number of times, there will still be mistakes. Please also inform me of any problems whether they be mundane errors, stylistic confusion or (heaven forbid) mathematical errors.

I will use the following notation.

- The positive integers: \mathbb{N} .
- The nonnegative integers: \mathbb{N}_0 .
- The integers greater than or equal to a : \mathbb{N}_a .
- All integers: \mathbb{Z} .
- The integers modulo n : \mathbb{Z}/n .
- The rationals: \mathbb{Q} .
- The real numbers: \mathbb{R} .
- The complex numbers: \mathbb{C} .
- The finite field of q elements: \mathbb{F}_q .

2 Review of Properties of the Integers

In this section we will review the main theorems that lead to the unique factorization of integers. We will establish analogous results for polynomials over a field in a later section. I recommend Rosen's Chapter 3 for a more detailed treatment of this material.

Theorem 2.1 (Division). *Given integers a, b with $b > 0$ there exist unique integers q, r such that*

1) $a = bq + r$, and

2) $0 \leq r < b$.

PROOF: (Sketch) Consider the set $S = \{a - bk : k \in \mathbb{Z}\}$. Let $r = a - bq$ be the smallest nonnegative integer in S , which exists by the well-ordering of the natural numbers. Then q and r satisfy item 1). Furthermore r must be less than b , for otherwise $r - b = a - (b+1)q$ would be in S and less than r , contradicting the choice of r . So item 2) is satisfied. For uniqueness, suppose that q' and r' also satisfy items 1) and 2). Take the difference and show $q = q'$ and $r = r'$. \square

Definition 2.2. Let a and b be integers, not both equal to 0. The *greatest common divisor* of a and b , denoted $\gcd(a, b)$, is the largest positive integer dividing both a and b . If the gcd is 1 we say a and b are coprime.

Theorem 2.3. Given integers a, b , not both 0, the greatest common divisor of a and b may be written as a linear combination of a and b .

PROOF: (Sketch) Choose the smallest positive element of $\{ra + sb : r, s \in \mathbb{Z}\}$, call it d . It is clear that any common divisor of a and b divides d . Show that the remainder when either a or b is divided by d must be 0, otherwise the definition of d is violated. Thus d must be $\gcd(a, b)$. \square

The preceding result simply says that the gcd of two integers can be written as a linear combination of the two. The next result—2000 years old—describes how to compute the gcd.

Theorem 2.4. The Euclidean algorithm may be used to find the greatest common divisor of two integers, and to find the linear combination that gives the greatest common divisor.

In Section 7, there is a matrix version of the Euclidean algorithm which computes the linear combination that gives the gcd. It very similar to a matrix version of the Berlekamp-Massey algorithm for decoding Reed-Solomon codes.

Definition 2.5. An integer p is *irreducible* if for any factorization $p = ab$ either a or b is ± 1 . An integer p is *prime* if whenever p divides ab , p divides either a or b .

In a first course in number theory one normally defines a prime as we have defined an irreducible. The reason for the switch here is to conform with the more modern usage in commutative algebra.

If you look for the following theorem in a number theory book it will say: “Suppose p is prime, then if p divides ab either p divides a or p divides b .”

Theorem 2.6. Let $p \in \mathbb{Z}$ be irreducible. Then p is prime.

PROOF: Suppose p is irreducible and $p|ab$. If $p \nmid a$ then the $\gcd(p, a) = 1$, so there are integers r and s such that $pr + as = 1$. Multiplying by b we have $prb + asb = b$. Now p divides the left hand side, so $p|b$. \square

Now we have unique factorization!

Theorem 2.7. Given any nonzero $n \in \mathbb{Z}$ there is a unique way to write n as a product

$$n = u \prod_{i=1}^r p_i$$

where $r \in \mathbb{N}_0$, the p_i are positive primes with $p_i \leq p_{i+1}$, and $u = \pm 1$.

PROOF: Clearly $u = -1$ for negative integers and $u = 1$ for positive integers, and it is sufficient to prove the result for positive integers. For $n = 1$ the result is trivial, r must be zero. Assuming that any integer less than n has a unique prime factorization, consider n . If n is prime then $n = 1n$ is a prime factorization. If n is composite then $n = ab$ for $a, b < n$. The product of the prime factorizations for a and b gives one for n . For uniqueness of the factorization, suppose that n has two factorizations $n = p_1 p_2 \cdots p_r$, and $n = q_1 q_2 \cdots q_s$ with the p_i and q_j in increasing order. By the previous theorem $p_1 | q_j$ for some j . But since q_j is a positive irreducible, $p_1 = q_j$. Since the q_j are in increasing order, $q_1 \leq p_1$. Similarly one shows that $p_1 \leq q_1$. So, in fact $p_1 = q_1$. Thus we have $p_2 p_3 \cdots p_r = q_2 q_3 \cdots q_s$. This integer is smaller than n so is factor-able in a unique way. Thus $r = s$ and $p_i = q_i$. \square

We sometimes consolidate multiple factors of a given prime to write

$$n = u \prod_{i=1}^r p_i^{a_i}$$

with the a_i positive integers and $p_i < p_{i+1}$.

Another important concept from number theory is modular arithmetic. I will skip the definition of \mathbb{Z}/n and the justification for the arithmetic in \mathbb{Z}/n , which you can read elsewhere [5, §4.1]. The main result we need is:

Theorem 2.8. *Let p be a prime number. Then \mathbb{Z}/p is a field.*

PROOF: Let a be an integer whose congruence class is nonzero mod p . Then a is not divisible by p , so in fact it must be coprime to p . By Theorem 2.3 there exist r and s such that $ar + ps = 1$. This means that $ar \equiv 1 \pmod{p}$, so a is a unit mod p . Thus every nonzero element of \mathbb{Z}/p is invertible, and \mathbb{Z}/p is a field. \square

Exercises 2.9.

1. Solve the linear equations.
 - (a) $3x + 7 \equiv 5 \pmod{17}$
 - (b) $3x + 7 \equiv 5 \pmod{15}$
 - (c) $3x + 7 \equiv 4 \pmod{15}$
2. Use the quadratic formula, or completing the square, to find solution(s) if they exist to
 - (a) $2x^2 + 7x + 5 \equiv 0 \pmod{17}$.
 - (b) $3x^2 + 16x + 4 \equiv 0 \pmod{17}$
 - (c) $5x^2 + 7x + 14 \equiv 0 \pmod{19}$
3. Use Maple to find solutions if they exist to
 - (a) $7x^4 + 3x^2 + x + 15 \equiv 0 \pmod{17}$.
 - (b) $7x^4 + 2x^2 + x + 15 \equiv 0 \pmod{19}$.
4. Give an example of a quartic polynomial with three distinct roots modulo 17.

3 Commutative Rings

The fundamental algebraic properties of the integers can be generalized to define a ring. Many of the notions of divisibility generalize as well. We give the formal definitions here and construct several examples.

Definition 3.1. A *ring* is a set R with two binary operations—addition, $+$, and multiplication, $*$ —such that

- both operations are commutative,
- both operations are associative,
- both operations have an identity (0 for $+$ and 1 for $*$),
- there is an additive inverse for each element of R , and
- multiplication distributes over addition.

A *field* is a ring with the extra property that there is a multiplicative inverse for each nonzero element.

Remark 3.2. Strictly speaking, the definition above is for a commutative ring with identity. Since that is a mouthful, and we will only use commutative rings with identity, I opt for a four letter term. Some authors allow fields to have noncommutative multiplication. Others call such a structure a skew field or division ring. We always assume multiplication is commutative.

Definition 3.3. Let R be a ring. An element $a \in R$ is called a *unit* if there is a multiplicative inverse for a . It is called a *zero-divisor* if it is nonzero itself and there is some nonzero $b \in R$ such that $a * b = 0$.

Elements $a, b \in R$ are called *associates* if there is a unit $u \in R$ such that $a = ub$.

Here are some quick exercises:

1. The zero element, 0, is unique.
2. For any $a \in R$, $0 * a = 0$
3. The unity element, 1, is unique.
4. The inverse of an element (additive or multiplicative) is unique.
5. Every nonzero element of a field is a unit.
6. No element can be both a zero-divisor and a unit.

Of particular interest are rings with no zero-divisors.

Definition 3.4. A ring R is called an *integral domain* if it has no zero-divisors.

Definition 3.5. Let A and R be rings. A *homomorphism* from A to R is a function f that preserves the operations of A and R . That is, $f(0_A) = 0_R$, $f(1_A) = 1_R$, and for $a, b \in A$, $f(a +_A b) = f(a) +_R f(b)$, and $f(a *_A b) = f(a) *_R f(b)$.

I used $+_A$ and $+_R$ to emphasize that the two operations take place in different rings. Normally we won't be so fussy since the context makes it clear. The more general ring theoretic approach does not require a homomorphism to satisfy $f(1_A) = 1_R$, but from a commutative algebra viewpoint it is natural to do so.

Example 3.6. The first ring that you should know about is the ring of integers, \mathbb{Z} . It is actually first in a very precise sense. There exists exactly one ring homomorphism from \mathbb{Z} to any other ring, R . It is defined by $1_{\mathbb{Z}} \rightarrow 1_R$. There is also a "last ring." See if you can find it!

There are three standard methods to construct new rings from old: 1) form a ring of fractions by adjoining inverses of some elements, 2) form a quotient ring modulo some element (or elements) 3) form a polynomial ring in an indeterminate. The first two methods are illustrated in the next two examples.

Example 3.7. If we adjoin to \mathbb{Z} the inverse of each nonzero integer we get the rational numbers: $\mathbb{Q} = \{a/b : a \in \mathbb{Z}, b \in \mathbb{N}, (a, b) = 1\}$. More formally, one defines an equivalence relation on the set of all fractions a/b with b nonzero: a/b is congruent to c/d whenever $ad = bc$. Then \mathbb{Q} is the set of equivalence classes.

There are numerous rings sandwiched between \mathbb{Z} and \mathbb{Q} that are very important in algebraic geometry and commutative algebra. They are constructed by inverting only certain integers. Here are two examples. In the first we invert 2, in the second we invert all primes except 2.

Let \mathbb{Z}_2 be the set of elements of \mathbb{Q} that can be expressed as a/b with b a power of 2. So $\mathbb{Z}_2 = \{a/2^i : a \in \mathbb{Z}, i \in \mathbb{Z}, \gcd(a, 2^i) = 1\}$. This ring is called the localization of \mathbb{Z} away from 2.

Let $\mathbb{Z}_{(2)}$ be the set of elements of \mathbb{Q} that can be expressed as a/b with b odd. So $\mathbb{Z}_{(2)} = \{a/b : a \in \mathbb{Z}, b \in \mathbb{N}, b \text{ odd}, \gcd(a, b) = 1\}$. This ring is called the localization of \mathbb{Z} at 2.

Example 3.8. You should already be familiar with the next standard family of examples, the integers modulo n , also called the quotient of \mathbb{Z} by n , which we will denote \mathbb{Z}/n . Suppose that the greatest common divisor of a and n satisfies $1 < (a, n) < n$. Let $b = n/(a, n)$. Then neither a nor b is congruent to 0 mod n , but $ab \equiv 0 \pmod{n}$. So a and b are both zero divisors. On the other hand, if $(a, n) = 1$ then there exist integers r and s such that $ra + sn = 1$. Since $ra \equiv 1 \pmod{n}$, we see that r is the multiplicative inverse of a in \mathbb{Z}/n .

The construction of rings of fractions, generalizing 3.7, and of quotient rings, generalizing 3.8 will be treated in Section 8.

Exercises 3.9.

1. Prove the cancellation law for integral domains. If a, b, c are elements of an integral domain with $a \neq 0$ and $ab = ac$ then $b = c$.
2. Show that every element in \mathbb{Z}/n is either 0, a zero-divisor, or a unit.
3. Show that \mathbb{Z}/p is a field when p is prime.
4. Show that the set of units in a ring forms a group under multiplication.

Polynomial Rings

We next want to introduce polynomial rings over a given ring R . This is actually a bit tricky. You can find an interesting discussion in [2, p.81]. We will give an informal definition and refer to [2, Appendix G] for one way to formally define polynomials. See also [3, pp. 248-]

Definition 3.10. Let R be a ring and let x be an indeterminate. For any $n \in \mathbb{Z}$ and $a_0, a_1, \dots, a_n \in R$ with $a_n \neq 0$, we will call an expression of the form $a_0 + a_1x + a_2x^2 + \dots + a_nx^n$ a *polynomial in x over R* . The *leading term* is a_nx^n , the *leading coefficient* is a_n and the *degree* is n . The *coefficient of x^k* is a_k , for $k \leq n$ and 0 for $k > n$. The polynomial is *monic* if the leading coefficient is 1. The *polynomial ring in x over R* , denoted $R[x]$ is the set of all such polynomials (along with 0) with addition and multiplication defined as you might expect using the operations in R .

Note that the zero element of $R[x]$ is the polynomial whose coefficients are all 0, its degree is undefined. The unity element is the polynomial such that $n = 0$ and $a_0 = 1$.

Some funny things can happen when the ring R has zero divisors. For example in $\mathbb{Z}/4[x]$, the product of $2x$ and $2x$ is 0. We will avoid this nuisance by only using polynomial rings over an integral domain.

Proposition 3.11. *If R is an integral domain then so is $R[x]$ and the degree of the product of two polynomials is the sum of the degrees.*

PROOF: [3][p. 251]. □

We can now add to our store of examples. We have the polynomial ring $\mathbb{Z}[x]$. We can also form polynomial rings over the rings constructed from \mathbb{Z} earlier. We can also adjoin inverses or take quotients of a polynomial ring.

Example 3.12. The ring $\mathbb{Z}/n[x]$ may be constructed by taking \mathbb{Z}/n and then forming the polynomial ring, or by forming $\mathbb{Z}[x]$ and then taking the quotient by n . Similarly one can form $\mathbb{Z}/n[x, y]$ and polynomial rings in an arbitrary number of variables.

Example 3.13. The ring $\mathbb{Q}[x]$ may be constructed as a polynomial ring over \mathbb{Q} or by adjoining to $\mathbb{Z}[x]$ the inverses of all primes in \mathbb{Z} . Similarly one can form the polynomial rings $\mathbb{Z}_2[x]$ and $\mathbb{Z}_{(2)}[x]$.

Example 3.14. If we adjoin to $\mathbb{Q}[x]$ the inverse of each nonzero polynomial, we get the field of rational polynomials, denoted $\mathbb{Q}(x)$. Formally one defines an equivalence relation on the set of all fractions $a(x)/b(x)$ with $b(x)$ nonzero: $a(x)/b(x)$ is congruent to $c(x)/d(x)$ whenever $a(x)d(x) = b(x)c(x)$. Then $\mathbb{Q}(x)$ is the set of equivalence classes.

Example 3.15. In number theory you may have seen the Gaussian integers, $\mathbb{Z}[i]$, or other quadratic extensions of \mathbb{Z} . The Gaussian integers is formed by taking the quotient of $\mathbb{Z}[x]$ by the polynomial $x^2 + 1$. More generally, if $F(x)$ is a polynomial, one may form $\mathbb{Z}[x]/F(x)$.

Primes and Irreducibles

The first step in analyzing many mathematical objects is to understand the elements that can't be broken down effectively.

Definition 3.16. Let R be an integral domain and let $r, s \in R$. We say r divides s if there is some $a \in R$ such that $ra = s$.

The units in R are those elements which divide 1. One can show, in the usual manner, that divides is transitive. If a and b are associates then each divides the other and any number divisible by a is also divisible by b .

Definition 3.17. A non-unit $p \in R$ is called *irreducible* if whenever p can be expressed as a product $p = a * b$, either a or b is a unit. A non-unit $p \in R$ is *prime* if, whenever p divides ab , either p divides a or p divides b .

There is a subtle difference between the two definitions. Note first of all that our usual definition of a prime integer corresponds to the definition for irreducible above, not the one for prime. Fortunately, as we showed in Section 2, for integers every irreducible is really prime.

Proposition 3.18. *Suppose r and s are associates in a ring R . If r is either prime or irreducible then so is s .*

PROOF: Let $r = us$ with u a unit. Suppose r is irreducible and that $s = ab$. Then $r = uab$. Since r is irreducible, one of ua or b must be a unit. If ua is a unit so is a . Thus one of a and b must be a unit. Therefore s is irreducible.

Suppose that r is prime and that s divides ab . Since r and s are associates, r also divides ab . But then r must divide one of a or b , say a . Since r and s are associates, s must divide a also. Thus s is prime. \square

Theorem 3.19. *In any integral domain R , any prime element is irreducible.*

PROOF: Let p be a prime element of R and suppose that $p = ab$. We wish to show that either a or b is a unit. Since p is prime we know that p either divides a or b . Suppose that it divides a , so $a = pr$. Then $p = prb$, so $p(1 - rb) = 0$. Since R is an integral domain, $1 - rb = 0$. This shows that b has an inverse, namely r . \square

The converse is not always true! An example can be found in $\mathbb{Z}[\sqrt{-5}]$ where $1 + \sqrt{-5}$, 2 , and 3 are all irreducible but not prime, [5, p. 105] Why are they not prime?

Example 3.20. The irreducible elements of \mathbb{Z}_2 are the ordinary odd prime integers (and their associates). For example, 3 is irreducible, for if $3 = (a/2^i) * (b/2^j)$ then $3 = ab/2^{i+j}$. But since a and b are odd (we may assume the original factors were in lowest terms) we must have $i + j = 0$ and $ab = 3$. Consequently, one of a or b is ± 1 . But then one of $a/2^i$ or $b/2^j$ is a unit in \mathbb{Z}_2 .

Since the only irreducibles of \mathbb{Z}_2 are the primes of \mathbb{Z} not equal to 2 (and associates), we say that \mathbb{Z}_2 is \mathbb{Z} localized away from 2.

The only irreducible element of $\mathbb{Z}_{(2)}$ is 2. It is clear that the odd prime integers are not irreducible in $\mathbb{Z}_{(2)}$ since they are in fact units! Since 2 is the only prime of \mathbb{Z} that remains prime in $\mathbb{Z}_{(2)}$ we say that $\mathbb{Z}_{(2)}$ is \mathbb{Z} localized at 2.

Exercises 3.21.

1. Define what we mean by \mathbb{Z}_n and by $\mathbb{Z}_{(n)}$ for a positive integer n .
2. Show that any element in \mathbb{Z}_n , or in $\mathbb{Z}_{(n)}$ is an integer times a unit. Conclude that after identifying all integers that are irreducible in \mathbb{Z}_n (or $\mathbb{Z}_{(n)}$) one can easily identify all irreducibles.
3. Show that any integer that is irreducible in \mathbb{Z}_n is also irreducible in \mathbb{Z} . Do the same thing for $\mathbb{Z}_{(n)}$.
4. Find the irreducibles in \mathbb{Z}_n and $\mathbb{Z}_{(n)}$.

4 Polynomials over a field

In Section 3, we discussed the basics of commutative rings. We defined what we mean by a field and we introduced polynomial rings. In this section we will show that the polynomial ring over a field F behaves very much like the integers. In particular, we establish unique factorization and show that $F[x]/p(x)$ is a field when $p(x)$ is irreducible. [The analogy is so strong that I wrote this section by pasting the previous one here and then editing a bit!]

Lemma 4.1. *Let $a(x)$, of degree r , and $b(x)$, of degree s , be two polynomials over a field F . Suppose $r \geq s$. Then*

$$\deg \left(a(x) - \frac{a_r}{b_s} x^{r-s} b(x) \right) < r$$

PROOF: Exercise. □

Theorem 4.2 (Division). *Given polynomials $a(x), b(x) \in F[x]$ with $b(x) \neq 0$ there exist unique polynomials $q(x), r(x)$ such that*

- 1) $a(x) = b(x)q(x) + r(x)$, and
- 2) $\deg r(x) < \deg b(x)$.

PROOF: For existence, consider the set $S = \{a(x) - b(x)k(x) : k(x) \in F[x]\}$. Let $r(x) = a(x) - b(x)q(x)$ be a monic polynomial of smallest degree in S . Then $q(x)$ and $r(x)$ satisfy item 1). Using the lemma above, one can show that if $\deg r(x) \geq \deg b(x)$ a polynomial of lower degree than $r(x)$ would be in S , contradicting the choice of $r(x)$. Thus item 2) is satisfied.

For uniqueness, suppose that $a(x) = b(x)q(x) + r(x)$ with $\deg r(x) < \deg b(x)$. Suppose also that $a(x) = b(x)q'(x) + r'(x)$ with $\deg r'(x) < \deg b(x)$. Taking the difference of the two equations, $0 = b(x)(q(x) - q'(x)) + r(x) - r'(x)$. Then $r'(x) - r(x) = b(x)(q(x) - q'(x))$. Now the degree of the left hand side is strictly less than $\deg b(x)$, but the right hand side has degree at least $\deg b(x)$ unless it is zero. Therefore both sides must be zero and we have $q(x) = q'(x)$ and $r(x) = r'(x)$. □

We say a polynomial $d(x)$ *divides* $f(x)$ when the remainder of $f(x)$ upon division by $d(x)$ is 0. We write $d(x)|f(x)$. Divisibility satisfies the following properties.

Proposition 4.3. Let $a(x), b(x), c(x) \in F[x]$.

- If $a(x)|b(x)$ and $a(x)|c(x)$ then $a(x)|(r(x)b(x) + s(x)c(x))$ for any $r(x), s(x) \in F[x]$.
- If $a(x)|b(x)$ and $b(x)|c(x)$ then $a(x)|c(x)$.

PROOF: Exercise. □

Theorem 4.4. Let $a(x), b(x) \in F[x]$ with not both equal to zero. The set $I = \{r(x)a(x) + s(x)b(x) : r(x), s(x) \in F[x]\}$ has a unique monic polynomial of minimal degree. This polynomial is also the unique monic polynomial of maximal degree that divides both $a(x)$ and $b(x)$.

PROOF: Let n be the maximal degree of polynomials in I . There is a monic polynomial of degree n in I , since we can multiply any polynomial in I by the inverse of its leading term to get a monic polynomial that is also in I . Suppose that there were two distinct monic polynomials $f(x)$ and $g(x) \in I$ of degree n . Then $f(x) - g(x)$ is in I , and of degree less than n . This contradicts the definition of n . Thus there can only be one monic polynomial of minimal degree in I . Let it be $d(x) = h(x)a(x) + k(x)b(x)$.

By Proposition 4.3, any common divisor of $a(x)$ and $b(x)$ also divides any element of I , in particular $d(x)$. If we can show that $d(x)$ divides both $a(x)$ and $b(x)$ then it must have maximal degree among all divisors of $a(x)$ and $b(x)$ as claimed. It must also be the unique common divisor of that degree since a monic polynomial can divide another monic polynomial of the same degree only if the two are equal.

From the Division Theorem, there are unique $q(x)$ and $r(x)$ such that

1. $a(x) = d(x)q(x) + r(x)$, and
2. $\deg r(x) < \deg d(x)$.

Substituting for $d(x)$ we get $r(x) = a(x) - d(x)q(x) = (1 - q(x)(h(x)))a(x) - q(x)k(x)b(x)$. If $r(x) \neq 0$, this contradicts our choice of $d(x)$ as the lowest degree element of I . Thus $d(x)$ divides $a(x)$, and by a similar argument $d(x)$ divides $b(x)$. □

The uniqueness in the proposition allows us to make the following definition of the greatest common divisor. It also says that the gcd of two polynomials can be written as a linear combination of the two. The next result says that the Euclidean algorithm can be extended to polynomials. You should implement it using Maple! In Section 7, there is a matrix version of the Euclidean algorithm which computes the linear combination that gives the gcd. It very similar to a matrix version of the Berlekamp-Massey algorithm for decoding Reed-Solomon codes.

Definition 4.5. Let $a(x)$ and $b(x)$ be two polynomials over a field F , not both equal to 0. The *greatest common divisor* of a and b , denoted $\gcd(a(x), b(x))$, is the largest degree monic polynomial dividing both $a(x)$ and $b(x)$. If the gcd is 1 we say $a(x)$ and $b(x)$ are coprime.

Theorem 4.6. The Euclidean algorithm may be used to find the greatest common divisor of two polynomials, and to find the combination that gives the greatest common divisor.

Exercises 4.7.

1. Find the greatest common divisor and express it as a combination of the given polynomials.

(a) $a(x) = x^3 + 2x^2 + 2x + 1$ and $b(x) = x^2 + 2x + 1$ over $\mathbb{Z}/3$.

(b) $f(x) = x^2 + 2$ and $g(x) = x^3 + x^2 + x + 2$ over $\mathbb{Z}/3$.

(c) $f(x) = 4x^2 + 9x$ and $g(x) = x^3 + 6x^2 + 6x + 2$ over $\mathbb{Z}/11$

2. Implement the Euclidean algorithm in Maple.

Definition 4.8. A positive polynomial $p(x) \in \mathbb{F}[x]$ is *irreducible* if for any factorization $p(x) = a(x)b(x)$ either $a(x)$ or $b(x)$ is an element of F . A polynomial $p(x)$ is *prime* if whenever $p(x)$ divides $a(x)b(x)$, $p(x)$ divides either $a(x)$ or $b(x)$.

Theorem 3.19 showed that any prime element of an integral domain is irreducible. As with the integers, the converse is true in the polynomial ring over a field.

Theorem 4.9. *Let $p(x) \in F[x]$ be irreducible. Then $p(x)$ is prime.*

PROOF: Suppose $p(x)$ is irreducible and $p(x)|a(x)b(x)$. Suppose that $p(x) \nmid a(x)$. Then $\gcd(p(x), a(x)) = 1$, so there are polynomials $r(x)$ and $s(x)$ such that $p(x)r(x) + a(x)s(x) = 1$. Multiplying by $b(x)$ we have $p(x)r(x)b(x) + a(x)s(x)b(x) = b(x)$. Now $p(x)$ divides the left hand side, so $p(x)|b(x)$. \square

Now we have unique factorization!

Theorem 4.10. *Given any nonzero $f(x) \in F[x]$ there exists an element $\alpha \in F$, a nonnegative integer r , and for each $i = 1, \dots, r$, distinct monic irreducibles $p_i(x)$ and integers $a_i > 0$ such that*

$$f(x) = \alpha \prod_{i=1}^r p_i(x)^{a_i}$$

The element α and the integer r are unique and the polynomials and their powers are unique, up to reordering.

PROOF: For polynomials of degree 0—that is, nonzero elements of F —unique factorization is clear since the number of polynomials, r , must be zero (Proposition 3.11). Suppose that all polynomials of degree less than n have a unique factorization as described in the statement of the theorem. Suppose that $f(x)$ has degree n . If $f(x)$ is irreducible with leading coefficient a_n then $a_n(f(x)/a_n)$ is a factorization as a product of monic irreducibles. If $f(x) = a(x)b(x)$ with both $a(x)$ and $b(x)$ having positive degree, then both $a(x)$ and $b(x)$ have degree less than n and so each has a factorization as a product of monic irreducibles. Then $a(x)b(x)$ also has a factorization as a product of monic irreducibles.

For uniqueness of the factorization, Suppose that $f(x)$ has two factorizations

$$\alpha p_1(x)^{a_1} p_2(x)^{a_2} \cdots p_r(x)^{a_r} = \beta q_1(x)^{b_1} q_2(x)^{b_2} \cdots q_s(x)^{b_s}$$

By the previous theorem $p_1(x)|q_k(x)$ for some k . By rearranging the q_j we may assume $k = 1$. Since q_1 is monic and irreducible we must have $p_1(x) = q_1(x)$. By the cancellation law in an integral domain we have

$$\alpha p_1(x)^{a_1-1} p_2(x)^{a_2} \cdots p_r(x)^{a_r} = \beta q_1(x)^{b_1-1} q_2(x)^{b_2} \cdots q_s(x)^{b_s}$$

This polynomial product has degree less than n so it can be factored in a unique way. Thus $r = s$ and after reordering $p_i = q_i$ and $a_i = b_i$. \square

Corollary 4.11. *If $p_1(x), p_2(x), \dots, p_r(x)$ are distinct monic irreducible polynomials dividing $f(x)$ then $\prod_{i=1}^r p_i(x)$ divides $f(x)$.*

Since the product of two polynomials over F has degree equal to the sum of the degrees of the factors we get the following.

Corollary 4.12. *Let $f(x)$ have the factorization in the Theorem. Then $\deg f(x) = \sum_{i=1}^r a_i \deg p_i(x)$.*

Roots of Polynomials

Another consequence of unique factorization is that a polynomial of degree d has at most d roots.

Definition 4.13. Let $f(x) \in F[x]$ and let $f(x) = \sum_{i=1}^n a_i x^i$ with $a_i \in F$. For $\alpha \in F$ we define $f(x)$ *evaluated at α* , written $f(\alpha)$, to be $\sum_{i=1}^n a_i \alpha^i$. This is an element of F . We say that α is a *root* of $f(x)$ if $f(\alpha) = 0$.

We leave it as an exercise to check that the evaluation of $f(x)+g(x)$ at α is $f(\alpha)+g(\alpha)$ and that the evaluation of $f(x)g(x)$ at α is $f(\alpha)g(\alpha)$.

From the division theorem we see that finding a root of $f(x)$ corresponds to finding a factor of f .

Proposition 4.14. *Let $f(x) \in F[x]$ and let $\alpha \in F$. Then α is a root of $f(x)$ if and only if $(x - \alpha)$ is a factor of $f(x)$.*

PROOF: Using the division theorem the remainder when $f(x)$ is divided by $x - \alpha$ has degree 0 and is therefore an element of F . Thus $f(x) = q(x)(x - \alpha) + r$ with $r \in F$. Evaluating at α , $f(\alpha) = q(\alpha)(\alpha - \alpha) + r = r$. Thus α is a root of $f(x)$ if and only if $r = 0$. That is, $x - \alpha$ divides $f(x)$. \square

Proposition 4.15. *If $\deg f(x) = d$ then $f(x)$ has at most d distinct roots.*

PROOF: Each root gives a factor of $f(x)$, so n distinct roots give n distinct linear factors of $f(x)$. By unique factorization the product of these roots, which has degree n , divides $f(x)$. Thus $n \leq d$. \square

Example 4.16. Suppose that F is the field \mathbb{Z}/p . Fermat's little theorem says that $1, 2, 3, \dots, p-1$ are all roots of $x^{p-1} - 1$. Therefore the unique factorization of $x^{p-1} - 1$ is $(x-1)(x-2)\cdots(x-(p-1))$.

Congruence Modulo a Polynomial

We now extend the concept of modular arithmetic to polynomial rings. We will only work modulo a prime polynomial. You will soon see why.

The first thing to do is to establish the equivalence relation to define the quotient ring $F[x]/p(x)$. Next one shows that arithmetic is well defined. I will just state the results. The proofs are exact analogues of those for integers.

Definition 4.17. Let $p(x) \in F[x]$ with F a field. We say $f(x), g(x)$ are *congruent modulo* $p(x)$, written $f(x) \equiv g(x) \pmod{p(x)}$, if $p(x)$ divides $f(x) - g(x)$.

We leave the following two important propositions as an exercise. The proofs follow with little change from the proofs for the analogous results for \mathbb{Z}/n .

Proposition 4.18. *Congruence modulo $p(x)$ is an equivalence relation.*

Proposition 4.19. *If $f(x) \equiv g(x) \pmod{p(x)}$ and $a(x) \equiv b(x) \pmod{p(x)}$ then*

- $a(x) + f(x) \equiv b(x) + g(x) \pmod{p(x)}$.
- $a(x)f(x) \equiv b(x)g(x) \pmod{p(x)}$.

If two unequal polynomials have degree less than $\deg p(x)$ then they cannot be congruent mod $p(x)$. Clearly, every polynomial is equivalent to its remainder when divided by $p(x)$, and the remainder has degree less than $\deg p(x)$. Thus the set of polynomials of degree less than $p(x)$ form a complete system of residues mod $p(x)$.

Suppose that $p(x)$ has degree d . Then a complete system of representatives for $F[x]/p(x)$ is $\{a_0 + a_1x + \cdots + a_{d-1}x^{d-1} : a_i \in F\}$. The addition of these polynomials is done component-wise. Multiplication by an element of F is also component-wise. Consequently, $F[x]/p(x)$ is a vector space of dimension d over F . Our next theorem concerns the multiplicative structure when $p(x)$ is irreducible.

Theorem 4.20. *Let $p(x)$ be an irreducible polynomial over a field F . Then $F[x]/p(x)$ is a field.*

PROOF: Let $a(x)$ be a polynomial whose congruence class is nonzero mod $p(x)$. Then $a(x)$ is not divisible by $p(x)$, so in fact it must be coprime to $p(x)$. Then by Theorem 4.4 there exist $r(x)$ and $s(x)$ such that $a(x)r(x) + p(x)s(x) = 1$. This means that $a(x)r(x) \equiv 1 \pmod{p(x)}$. Consequently $a(x)$ is a unit mod $p(x)$, and $F[x]/p(x)$ is a field. \square

Definition 4.21. A *subfield* of a field K is a subset F which contains 0_K and 1_K and is a field under the operations of K , $+_K$ and $*_K$. We also say that K is an *extension* of F .

If $\alpha \in K$ we define $F[\alpha]$ to be the smallest subfield of K containing F and α . (It is the intersection of all subfields of K containing F and α).

For $\alpha \in K$ consider all polynomials $f(x) \in F[x]$ that have α as a root. If this set is nonempty, we define the *minimal polynomial* of α over F to be the monic polynomial $M(x) \in F[x]$ of smallest degree such that $M(\alpha) = 0$.

The minimal polynomial is indeed unique, for if two monic polynomials have the same degree and both have α as a root then their difference also has α as a root and is of lower degree. Some multiple of this difference would be monic (and have α as a root) contradicting the minimal degree of the minimal polynomial.

Lemma 4.22. *Let F be a subfield of a field K . Suppose $\alpha \in K$ has minimal polynomial $M(x)$ over F .*

- 1) $M(x)$ is irreducible.
- 2) If α is a root of $f(x) \in F[x]$ then $M(x)$ divides $f(x)$.

PROOF: Exercise. Use the division theorem for item 2). □

I won't prove this but I will prove a simpler version in the context of finite fields.

Theorem 4.23. *Let F be a subfield of K . Suppose that $\alpha \in K$ has minimal polynomial $M(x)$. Then $F[x]/M(x)$ is isomorphic to $F[\alpha]$ under the map taking the conjugate class of x to α .*

Exercises 4.24.

1. Let $f(x) \in F[x]$ with $f(x) = x^n + \cdots + a_1x + a_0$. Let \bar{x} be the equivalence class of x in $F[x]/f(x)$. Show that $\bar{x}^n + \cdots + a_1\bar{x} + a_0$ is the 0 element of $F[x]/f(x)$.
2. What is $\mathbb{R}[x]/(x^2 + 1)$? Can you find any other extensions of the reals?
3. Describe the arithmetic for $\mathbb{Q}[x]/(x^2 + 1)$. Construct other extensions of \mathbb{Q} of degree 2. Give an example of an extension of degree 3. Does $x^3 + 1$ work?
4. Find an irreducible polynomial of degree 2, one of degree 3, and one of degree 4 over \mathbb{F}_2 . For each, find a system of representatives for $\mathbb{F}_2[x]/p(x)$.
5. Find a polynomial of degree 4 over \mathbb{F}_2 which has no roots but is not irreducible.

5 Finite Fields: Structure

The last section ended with the result that for a field F and irreducible polynomial $p(x)$ over F , $F[x]/p(x)$ is a field. We will be working with polynomials over this new field, so it will be useful to have simpler notation. We will use a Greek letter, say α , to denote the equivalence class of x . Notice that by an exercise in 4.24, α may be considered a root of $p(x)$. The field will then be identified as $F[\alpha]$ where $p(\alpha) = 0$. In coding, we are primarily interested in finite fields, for example \mathbb{Z}/p . The main result of this section is that for each prime power $q = p^n$, there is a unique field (up to isomorphism) with p^n elements. We denote this field \mathbb{F}_q . In particular, for a prime p , we use \mathbb{F}_p instead of \mathbb{Z}/p .

This section is devoted to proving the following theorem which we will do in stages.

Theorem 5.1. *Let F be a field with a finite number of elements.*

- 1) F has p^n elements where p is a prime.

- 2) There is an element $\alpha \in F$ whose powers $\alpha^1, \alpha^2, \dots, \alpha^{p^n-1}$ give all the nonzero elements of F .
- 3) F is isomorphic to $\mathbb{F}_p[x]/P(x)$ for some irreducible polynomial $P(x)$ over \mathbb{F}_p .

For any prime p and any positive integer n ,

- 4) There exists a field with p^n elements.
- 5) Any two fields with p^n elements are isomorphic.

As a first step we prove

Proposition 5.2. *A finite field is a vector space over \mathbb{F}_p for some prime p . Consequently, the number of elements of F is a power of p .*

PROOF: Suppose that F is a finite field. Consider the additive subgroup generated by 1, i.e. $1, 1+1, 1+1+1$. Let m be the smallest positive integer such that the sum of m 1's is 0. If m were composite, $m = ab$, then we would have

$$0 = \underbrace{1 + 1 + 1 + \cdots + 1 + 1}_{m \text{ terms}} = \underbrace{(1 + 1 + \cdots + 1)}_{a \text{ terms}} \underbrace{(1 + 1 + \cdots + 1)}_{b \text{ terms}}$$

The two factors on the right would then be zero-divisors, contradicting the assumption that F is a field. Thus m is in fact a prime, which we will now call p . We may think of F as containing a copy of \mathbb{F}_p . From the field axioms we see immediately that F is a vector space over \mathbb{F}_p . If its dimension over \mathbb{F}_p is n then F must have p^n elements. Thus any field has a prime power number of elements. \square

Definition 5.3. The prime p in the theorem is called the *characteristic* of the field.

Suppose that $q = p^n$ is the number of elements in F . By the field axioms, the set of nonzero elements of F is a group under multiplication. This group is denoted F^* . Recall that the *order* of an element α in a group G is the smallest positive integer r such that α^r is the identity, or infinity, if no such r exists. As an exercise, review the following properties:

Lemma 5.4. *Let α be an element of order r in a group G .*

- 1) $\alpha^i = \alpha^j$ iff $i \equiv j \pmod{r}$.
- 2) The order of α^i is r/d where $d = \gcd(i, r)$.
- 3) Let $\beta \in G$ have order s , coprime to r . Then $\text{ord}(\alpha\beta) = rs$.

Now we can establish item 2) of the Theorem.

Proposition 5.5. *The multiplicative group of a finite field is cyclic.*

PROOF: Let F have p^n elements and let the prime factorization of $p^n - 1$ be $\prod_{i=1}^r q_i^{a_i}$. We will show that for each $i = 1 \dots, r$ there is an element $b_i \in F^*$ of order $q_i^{a_i}$. By Lemma 5.4, the order of $b = \prod_{i=1}^r b_i$ is $\prod_{i=1}^r q_i^{a_i} = p^n - 1$. Thus b generates the multiplicative group of F .

Let $t = (p^n - 1)/q_i^{a_i}$ and consider the set $S = \{\alpha^t : \alpha \in F^*\}$. For any $\beta \in S$ the polynomial $x^t - \beta$ has at most t roots so there can be at most t elements of F whose t th power is β . Therefore the cardinality of S is at least $(p^n - 1)/t = q_i^{a_i}$. On the other hand, everything in S is a root of $x^{q_i^{a_i}} - 1$ since

$$(\alpha^t)^{q_i^{a_i}} = \alpha^{p^n - 1} = 1$$

There can be only $q_i^{a_i}$ roots so S has exactly $q_i^{a_i}$ elements. Only $q_i^{a_i - 1}$ of the elements in S can be roots of $x^{q_i^{a_i - 1}} - 1$ so there must be $q_i^{a_i} - q_i^{a_i - 1}$ elements of S whose order in F is $q_i^{a_i}$. This was what we wanted to show. \square

Definition 5.6. An element of a finite field whose powers generate the nonzero elements of the field is called *primitive*.

The theorem says that every finite field has a primitive element. Furthermore, from the lemma, if α is primitive in a field of p^n elements then α^k is also primitive whenever k is coprime to $p^n - 1$. Thus there are $\phi(p^n - 1)$ primitive elements, where ϕ is the Euler totient function ($\phi(n)$ is the number of positive integers less than n and coprime to n).

Corollary 5.7. If F is a field with p^n elements then

$$x^{p^n} - x = \prod_{\alpha \in F} (x - \alpha) x^{p^n - 1} - 1 = \prod_{\alpha \in F^*} (x - \alpha)$$

According to the following definition, the corollary shows that a field F of order p^n is a splitting field for $x^{p^n - 1} - 1$ and for $x^{p^n} - x$ over \mathbb{F}_p .

Definition 5.8. Let F be a field and let $f(x) \in F[x]$. A *splitting field* for $f(x)$ is a field K containing F such that

- $f(x)$ factors into linear factors in $K[x]$.
- Every element of K can be written as a polynomial in the roots of $f(x)$.

To prove item 3) of the Theorem we need to use the minimal polynomial of a primitive element (see Definition 4.21).

Proposition 5.9. Let F be a finite field of p^n elements. Let α be any primitive element of F and let $M(x)$ be its minimal polynomial over \mathbb{F}_p . Then F is isomorphic to $\mathbb{F}_p[x]/M(x)$. In particular $\deg M(x) = n$.

PROOF: Let $M(x) = x^r + a_{r-1}x^{r-1} + \dots + a_1x + a_0$ with $a_i \in \mathbb{F}_p$. We will show that $1, \alpha, \dots, \alpha^{r-1}$ is a basis for F over \mathbb{F}_p . We first observe that $1, \alpha, \dots, \alpha^{r-1}$ must be linearly independent over \mathbb{F}_p . Suppose on the contrary that some nontrivial linear

combination is 0, $b_{r-1}\alpha^{r-1} + \dots + b_1\alpha + b_0 = 0$. Let k be the largest positive integer such that $b_k \neq 0$. Then

$$\alpha^k + \frac{b_{k-1}}{b_k} \dots + \frac{b_1}{b_k} \alpha + \frac{b_0}{b_k} = 0$$

This shows that α is a root of a polynomial over \mathbb{F}_p of degree less than $\deg M(x)$, contradicting the minimality of $M(x)$.

Next we show that any power of α can be written as a linear combination of $1, \alpha, \alpha^2, \dots, \alpha^{r-1}$. This is true trivially for α^i for $i = 0, \dots, r-1$. Assume that for some $k \geq r$, each α^i for $i < k$ can be written as a linear combination as stated. Since $M(\alpha) = 0$, $\alpha^r = -a_{r-1}\alpha^{r-1} - \dots - a_1\alpha - a_0$. Multiplying by α^{k-r} we can write α^k as a linear combination of lower powers of α . By the induction hypothesis these are all linear combinations of $1, \alpha, \dots, \alpha^{r-1}$, so α^k is also. Since every nonzero element of F is a power of α , we have shown that $1, \alpha, \dots, \alpha^{n-1}$ span F as claimed.

Since F has p^n elements $r = n$. Furthermore the arithmetic on F is completely determined by its structure as a vector space and $\alpha^n = -a_{n-1}\alpha^{n-1} - \dots - a_1\alpha - a_0$. This is exactly the same structure that $\mathbb{F}_p[x]/M(x)$ has. In other words the map from F to $\mathbb{F}_p[x]/M(x)$ taking α to the class of x is an isomorphism. \square

We can now prove existence and uniqueness for fields of prime power order. We will need the ‘‘Freshman’s dream’’:

Proposition 5.10. *Let α, β be elements of a field of characteristic p . Then $(\alpha + \beta)^p = \alpha^p + \beta^p$.*

PROOF: Expand $(\alpha + \beta)^p$ using the binomial theorem and we get terms like

$$\binom{p}{k} \alpha^k \beta^{p-k}$$

The binomial coefficient really means 1 added to itself $\binom{p}{k}$ times. Since p divides the binomial coefficient when $1 < k < p$ the coefficient is 0 unless $k = 0$ or $k = p$. That gives the result. \square

Proposition 5.11. *For any prime power there exists a unique field of that order.*

PROOF: Uniqueness: Let F and F' be two fields with p^n elements. Let α be a primitive element in F and let $M(x)$ be its minimal polynomial over \mathbb{F}_p . Since α is a root of $x^{p^n} - x$, Lemma 4.22 says that $M(x)$ divides $x^{p^n} - x$. By Corollary 5.7, $x^{p^n} - x$ factors into distinct linear factors in F and F' so there must be a root of $M(x)$ in F' . By Proposition 5.9, both F and F' are isomorphic to $\mathbb{F}_p[x]/M(x)$ so they are isomorphic to each other.

Existence: By successively factoring $x^{p^n} - x$ and adjoining roots of a nonlinear irreducible factor, we can, after a finite number of steps, arrive at a field in which $x^{p^n} - x$ factors completely. I claim that the roots of $x^{p^n} - x$ form a field, which by Proposition 4.15 must have p^n elements.

We need to show that the sum of two roots is a root, that the additive inverse of a root is a root, that the product of two roots is a root and that the multiplicative inverse of a root is a root. These are all trivial except for the case of the sum of two roots, which can be proved using the ‘‘Freshman’s dream.’’ \square

The following example shows that there are many ways to construct a given field.

Example 5.12. Let $p = 3$. We can construct the field \mathbb{F}_{3^2} by adjoining to \mathbb{F}_3 a root α of the irreducible polynomial $x^2 + 2x + 2$. You can check by hand that α is primitive in this field. If we had used $x^2 + 1$, which is also irreducible, we would get still get a field with 9 elements. But the root of $x^2 + 1$ will only have order 4 since $\alpha^{-1} = -1$ implies $\alpha^4 = 1$.

Definition 5.13. Let F be a finite field and let $p(x)$ be a polynomial over F . If $p(x)$ is irreducible and the class of x is primitive in $F[x]/p(x)$, then we say $p(x)$ is a *primitive polynomial*.

Example 5.14. We can construct \mathbb{F}_{3^6} by adjoining to the field of the previous example a root β of the primitive polynomial (verified using Magma) $x^3 + \alpha x^2 + \alpha x + \alpha^3$ over \mathbb{F}_{3^2} . Elements of \mathbb{F}_{3^6} are uniquely represented as polynomials in α and β whose degree in α is at most 1, and whose degree in β is at most 2.

We could also construct \mathbb{F}_{3^6} by first constructing \mathbb{F}_{3^3} by adjoining a root α' of the primitive polynomial $x^3 + 2x + 1$ and then adjoining a root β' of the primitive polynomial (verified using Magma) $x^2 + x + (\alpha')^7$ over \mathbb{F}_{3^3} .

Finally we could construct \mathbb{F}_{3^6} directly by adjoining a root of the primitive polynomial $x^6 + 2x^4 + x^2 + 2x + 2$.

In each of these fields you can find a root of any one of the polynomials, and thereby define isomorphisms between the fields.

Exercises 5.15.

1. Construct \mathbb{F}_{2^6} in three ways:
 - a) by constructing \mathbb{F}_4 using an irreducible polynomial of degree 2 over \mathbb{F}_2 and then by constructing \mathbb{F}_6 using an irreducible polynomial of degree 3 over \mathbb{F}_4 .
 - b) by constructing \mathbb{F}_8 using an irreducible polynomial of degree 3 over \mathbb{F}_2 and then by constructing \mathbb{F}_6 using an irreducible polynomial of degree 2 over \mathbb{F}_8 .
 - c) by using an irreducible polynomial of degree 6 over \mathbb{F}_2 .
 Give isomorphisms between the three representations.
2. Construct \mathbb{F}_{81} in two ways. You may notice that $x^2 + 2x + 1$ and $x^2 + x + 2$ are both irreducible over \mathbb{F}_3 . Can you construct \mathbb{F}_{81} by using one of these polynomials and then the other?
3. Factor $x^{80} - 1$ over \mathbb{F}_3 and explain the relationship between the factors and the elements of \mathbb{F}_{81} . Factor $x^{80} - 1$ over \mathbb{F}_9 and explain the relationship between the factors and the elements of \mathbb{F}_{81} .
4. Factor $x^{15} - 1$ over \mathbb{F}_2 . Construct \mathbb{F}_{16} in three ways as a degree 4 extension of \mathbb{F}_2 and show isomorphisms between the three representations.
5. Make a table showing the possible orders and the number of elements of each order for \mathbb{F}_{64} , \mathbb{F}_{128} , and \mathbb{F}_{256} .
6. Prove that if $r|n$ then \mathbb{F}_{q^r} is a subfield of \mathbb{F}_{q^n} .
7. Let $n = 6$. Find all irreducible polynomials over \mathbb{F}_2 of deg d where $d|n$. Find the product of these polynomials.

8. For a given prime p , let $I(d)$ be the set of irreducible polynomials of degree d over \mathbb{F}_p . Show that for $n > 0$,

$$\prod_{d|n} \prod_{f \in I(d)} f = x^n - 1$$

9. Show that for any $\alpha \in \mathbb{F}_q$,

$$1 + \alpha + \alpha^2 + \alpha^3 + \cdots + \alpha^{q-2} = \begin{cases} 1 & \text{if } \alpha = 0 \\ -1 & \text{if } \alpha = 1 \\ 0 & \text{otherwise} \end{cases}$$

6 The Frobenius Map

Definition 6.1. The *Frobenius map* on \mathbb{F}_{p^n} is the map $\phi : \alpha \rightarrow \alpha^p$.

Theorem 6.2. *The Frobenius map satisfies the following*

- 1) *It is an automorphism of \mathbb{F}_{p^n} .*
- 2) *The set of elements which are fixed by the Frobenius map is exactly \mathbb{F}_p .*
- 3) *If $\alpha \in \mathbb{F}_{p^n}$ has minimal polynomial $M(x)$ over \mathbb{F}_p then $\alpha, \alpha^p, \alpha^{p^2}, \dots, \alpha^{p^{d-1}}$ are the roots of $M(x)$ where $d = \deg M(x)$.*
- 4) *For $d|n$ the set of elements fixed by ϕ^d is \mathbb{F}_{p^d} .*

Corollary 6.3. *For any $\alpha \in \mathbb{F}_{p^n}$, $\sum_{i=0}^{n-1} \phi^i(\alpha)$ and $\prod_{i=0}^{n-1} \phi^i(\alpha)$ are elements of \mathbb{F}_p*

Definition 6.4. The *trace map* from \mathbb{F}_{p^n} to \mathbb{F}_p is $\text{Tr}(\alpha) = \sum_{i=0}^{n-1} \phi^i(\alpha)$ The *norm map* from \mathbb{F}_{p^n} to \mathbb{F}_p is

$$N(\alpha) = \prod_{i=0}^{n-1} \phi^i(\alpha)$$

7 The Euclidean Algorithm

Let a, b be integers with $b > 0$. The following algorithm computes the greatest common divisor of a and b .

Input: Nonzero integers a, b .

Output: The (positive) greatest common divisor of a and b .

Algorithm: Define inductively r_i for $i \geq 0$ and q_i for $i \geq 1$:

$$\begin{aligned} r_0 &= a \\ r_1 &= b \end{aligned}$$

While $r_i \neq 0$, let r_{i+1}, q_i be the remainder and quotient when r_{i-1} is divided by r_i ,

$$\begin{aligned} r_{i+1} &= q_i r_i - r_{i-1} \\ 0 &\leq r_{i+1} < r_i \end{aligned}$$

Output r_{i-1} when $r_i = 0$.

Theorem 7.1. *The algorithm above terminates after a finite number of steps. If n is the smallest integer such that $r_{n+1} = 0$ then r_n is the greatest common divisor of a and b .*

The number of steps n is at most $1 + \log b / (\log(1 + \sqrt{5}) - 1)$, where \log is base 2.

PROOF: See Rosen [5]. □

We now consider a matrix version of the Euclidean algorithm that produces the linear combination of a and b that gives the gcd.

Input: Nonzero integers a, b .

Output: Integers d, r, s , such that $d = \gcd(a, b)$ and $d = ra + bs$.

Algorithm: Define inductively 2-vectors, $R^{(i)}$, and 2×2 matrices $T^{(i)}$ for $i \geq 0$:

$$\begin{aligned} R^{(0)} &= \begin{bmatrix} b \\ a \end{bmatrix} \\ T^{(0)} &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{aligned}$$

While $r_i \neq 0$, define $q_i = \lfloor R_2^{(i-1)} / R_1^{(i-1)} \rfloor$

$$\begin{aligned} Q^{(i)} &= \begin{bmatrix} -q_i & 1 \\ 1 & 0 \end{bmatrix} \\ R^{(i)} &= Q^{(i)} R^{(i-1)} \\ T^{(i)} &= Q^{(i)} T^{(i-1)} \end{aligned}$$

Theorem 7.2. *The matrix $R^{(i)}$ keeps track of the usual remainders.*

$$R^{(i)} = \begin{bmatrix} r_{i+1} \\ r_i \end{bmatrix}$$

The matrix $T^{(k)}$ is the product of the $Q^{(i)}$,

$$T^{(k)} = \prod_{i=1}^k Q^{(i)}$$

If the algorithm terminates after n steps then

$$\begin{bmatrix} r_{n+1} \\ r_n \end{bmatrix} = T^{(n)} \begin{bmatrix} b \\ a \end{bmatrix}$$

so the bottom row of $T^{(n)}$ gives a linear combination of a and b that produces the gcd, r_n .

Exercises 7.3.

1. Write a procedure implementing the matrix version of the Euclidean algorithm. Do it first for integers, then for polynomials over \mathbb{Q} , then generalize to polynomials over finite fields.

8 Ideals

Definition 8.1. An *ideal* of a ring R is a subset $I \subseteq R$ which is closed under addition and closed under multiplication by an arbitrary element of R :

$$a + b \in I \quad \text{if } a, b \in I \quad (1)$$

$$ar \in I \quad \text{if } a \in I \text{ and } r \in R \quad (2)$$

The ideal I is *principal* if there is some $a \in I$ such that $I = \{ar : r \in R\}$. We say I is *generated by* a_1, a_2, \dots, a_s if $I = \{r_1a_1 + r_2a_2 + \dots + r_sa_s : r_i \in R\}$. We write $I = \langle a_1, a_2, \dots, a_s \rangle$.

Example 8.2. The principal ideals of \mathbb{Z} are multiples of a particular integer.

- $\langle 2 \rangle$ is the set of even numbers.
- $\langle 3 \rangle$ is the set of multiples of 3.
- $\langle 1 \rangle$ is all integers.
- $\langle 0 \rangle$ is just the set 0.

Proposition 8.3. *Every ideal in \mathbb{Z} is principal.*

PROOF: Let I be an ideal of \mathbb{Z} . If $I = \{0\}$, there is nothing to prove. Otherwise, let a be the smallest positive integer in I . Let b be any other nonzero element of I . Then by the properties of ideals, any linear combination of a and b is in I . Therefore $\gcd(a, b) \in I$. But the gcd of a and b is positive and less than or equal to a . Since a is the smallest positive element of I , we must have $\gcd(a, b) = a$. In other words an arbitrary element of I is divisible by a , so $I = \langle a \rangle$ is principal. \square

You can prove this one.

Proposition 8.4. *If $u \in I$ is a unit then $I = R$.*

Definition 8.5. An ideal I in R is *prime* if whenever $ab \in I$ either $a \in I$ or $b \in I$. An ideal I is *maximal* if the only ideal properly containing I is R .

Proposition 8.6. *Let R be a subring of S and let J be an ideal of S . Then $J \cap R$ is an ideal in R .*

Exercises 8.7.

1. Identify all the ideals of \mathbb{Z}/n .
2. Let F be a field. Show that every ideal in $F[x]$ is principal.

3. Identify all the ideals of $F[x]/f(x)$.
4. Find ideals in $\mathbb{R}[x, y]$ that are not principal.
5. The Chinese Remainder theorem says that if $n = \prod_{i=1}^s p_i^{a_i}$ with p_i distinct primes and $a_i > 0$ then

$$\mathbb{Z}/n \cong \mathbb{Z}/p_1^{a_1} \times \mathbb{Z}/p_2^{a_2} \times \cdots \times \mathbb{Z}/p_s^{a_s}$$

State and prove a similar result for the polynomial ring $F[x]$.

Quotient Rings

Definition 8.8. Let I be an ideal in a ring R , we say $r, s \in R$ are *congruent modulo I* when $r - s \in I$. *congruent modulo*

We denote by R/I the set of equivalence classes modulo I .

Proposition 8.9. *The modulo I relation is an equivalence relation.*

The next propositions shows that R/I has the structure of a ring inherited from R .

Proposition 8.10. *Let I be an ideal of a ring R . Suppose that $r \equiv s \pmod{I}$ and $f \equiv g \pmod{I}$. Then*

- $r + f \equiv s + g \pmod{I}$
- $rf \equiv sg \pmod{I}$

Proposition 8.11. *The map $R \rightarrow R/I$ is a ring homomorphism. The image of an ideal in R which contains I is an ideal in R/I and this gives a one to one correspondence between the set of ideals in R which contain I and the set of ideals of R/I . Furthermore, prime ideals correspond to prime ideals and maximal ideals to maximal ideals.*

Proposition 8.12. *If I is a prime ideal then R/I is an integral domain.*

Proposition 8.13. *If I is a maximal ideal then R/I is a field.*

Rings of Fractions

We now generalize the process for forming the rational numbers from the integers. We will restrict to the case when the ring is an integral domain, but it is not difficult to extend the construction to rings with zero divisors.

Definition 8.14. Let R be an integral domain and let S be a subset of S which contains 1 and which is closed under multiplication. We will call S a *multiplicatively closed set*.

Example 8.15. Let R be an integral domain. Let f be an element of R and let $S = \{f^i : i \in \mathbb{N}_0\}$. Then S is multiplicatively closed.

Let \mathfrak{p} be a prime ideal in R . Let $S = R \setminus \mathfrak{p}$. Then S is multiplicatively closed. For if $a, b \in S$ then $ab \notin \mathfrak{p}$ from the definition of primality.

Let K be an index set and let \mathfrak{p}_k for $k \in K$ be prime ideals in R . Then $S = R \setminus (\cup_{k \in K} \mathfrak{p}_k)$ is multiplicatively closed.

Definition 8.16. Let R be a ring and let S be a multiplicatively closed subset of R . Define a relation on the Cartesian product $R \times S$ by $(a, s) \equiv (b, t)$ when $at = bs$ in R .

Proposition 8.17. *The relation described above is an equivalence relation.*

Proposition 8.18. *Let R be an integral domain and let S be a multiplicatively closed subset. Suppose that $(a, r) \equiv (a', r')$ and that $(b, s) \equiv (b', s')$. Then $(ab, rs) \equiv (a'b', r's')$ and $(as + br, rs) \equiv (a's' + b'r', r's')$.*

Definition 8.19. Let Q be the set of equivalence classes of the relation on $R \times S$ described above. We define 0_Q to be the equivalence class of $(0, 1)$ and 1_Q to be the equivalence class of $(1, 1)$. We define $+_Q$ and $*_Q$ for (a, r) and (b, s) in Q by $(a, r) + (b, s) = (as + br, rs)$ and $(a, r) *_Q (b, s) = (ab, rs)$. By the previous proposition, these operations are well defined. We call Q the *ring of fractions* of R with respect to S .

The reader should verify the the properties of 0_Q and 1_Q , the existence of an additive inverse and the commutative, associative, and distributive properties.

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