

Lecture Notes for Math 696

Coding Theory

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1 A few more things about finite fields

Definition 1.1. The *characteristic* of a field F is 0 if no finite sum of $1 \in F$ is 0. Otherwise, the characteristic is the smallest integer p such that

$$\underbrace{1 + 1 + 1 + \cdots + 1 + 1}_{p \text{ terms}} = 0$$

Definition 1.2. 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 $*_K$.

If F is a subfield of K , and $\alpha \in K$ we define $F[\alpha]$ to be the smallest subfield of K containing F and α .

Theorem 1.3. Let F be a subfield of K . Suppose that $\alpha \in K$ is the root of an irreducible monic polynomial $P(x) \in F[x]$. Then $F[x]/P(x)$ is isomorphic to $F[\alpha]$ under the map taking the conjugate class of x to α .

PROOF: Suppose that $P(x) = x^n + b_{n-1}x^{n-1} + \cdots + b_1x + b_0$. The field $F[x]/P(x)$ has $1, x, x^2, \dots, x^{n-1}$ as a basis (here I really mean the conjugate class of these elements). And the field $F[\alpha]$ has basis $1, \alpha, \dots, \alpha^{n-1}$. The map ϕ taking x^i to α^i is clearly an isomorphism of vector spaces. The multiplicative structure on $F[\alpha]$ is completely determined by $P(\alpha) = 0$, that is, $\alpha^n = -b_{n-1}\alpha^{n-1} + b_{n-2}\alpha^{n-2} + \cdots + b_1\alpha + b_0$. Likewise, the multiplicative structure on $F[x]/P(x)$ is determined by a similar formula with the conjugate class of x replacing α . Consequently, $\phi(f(x) + g(x)) = \phi(f(x)) + \phi(g(x))$ (again, conjugate classes of $f(x), g(x)$). \square

This theorem is of great use in showing isomorphisms between two different representations of \mathbb{F}_q over \mathbb{F}_p . It is sufficient to find an element in each representation which satisfies a particular irreducible polynomial, $P(x) \in \mathbb{F}_p[x]$. Then map these two elements to each other. This comment holds when p itself is a power of a prime.

Useful formulas

We assume $q = p^n$ with p prime. Recall that we showed that \mathbb{F}_q with is the splitting field of $x^{q-1} - 1$ over \mathbb{F}_p . Here are some simple consequences:

For any $\alpha \in \mathbb{F}_q$,

$$\alpha^q = \alpha \tag{1}$$

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

The final formula follows from the fact that $x^{q-1} - 1 = (x+1)(x^{q-2} + x^{q-3} + \cdots + x + 1)$. All elements of \mathbb{F}_q except 0 and 1 are therefore roots of $(x^{q-2} + x^{q-3} + \cdots + x + 1)$.

Conjugates

The Fourier transform

See Blahuts book [1, p. 169]

Vandermonde determinant

See Blahuts book [1, p. 169]

2 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 .

Objective: To compute the (positive) greatest common divisor of a and b .

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

While $r_i \neq 0$,

$$r_0 = a$$

$$r_1 = b$$

and r_{i+1}, q_i are the remainder and quotient when r_{i-1} is divided by r_i ,

$$r_{i-1} = q_i r_i + r_{i+1}$$

$$0 \leq r_{i+1} < r_i$$

Theorem 2.1. *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 [2]. □

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 .

Objective: To compute the a linear combination of a and b which gives the greatest common divisor of a and b .

Algorithm: Define inductively the remainders r_i and quotients q_i of the previous algorithm. We also define matrices $R^{(i)}$, and 2×2 matrix $T^{(i)}$ for $i \geq 0$:

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

While $r_i \neq 0$, define q_i as usual

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

Theorem 2.2. *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 2.3.

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.

2) Write a Maple procedure to find all irreducible polynomials of degree less than n over \mathbb{F}_2 . Extend to other finite fields.

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) 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} .

5) Let $n = 6$. Find all irreducible polynomials over \mathbb{F}_2 of degree d where $d|n$. Find the product of these polynomials.

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

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

Write Maple code to verify this result.

6) Prove that for any polynomial $f(x)$ of degree less than $q - 1$,

$$\sum_{\alpha \in \mathbb{F}_q} f(\alpha) = 0$$

. Hint: reduce to the case of a monomial, x^i . For i coprime to $q - 1$ use (2). For i not coprime to $q - 1$ you will need to think about the previous exercise and (2).

References

- [1] R. Blahut, *Theory and Practice of Error Control Codes*, Addison-Wesley, 1983.
- [2] K. Rosen, *Elementary Number Theory and Its Applications* 4th ed. Addison Wesley Longman, 2000.