

27 Finite Fields (continued)

Previously, we constructed the finite field \mathbb{F}_q for $q = p^n$, and showed that there is a unique such field. This construction had the unusual property that the field *consisted* of exactly the roots of a polynomial (where the polynomial was $x^n - x$), rather than just being *generated* by the roots of a polynomial.

There is more that we can say about the structure of finite fields.

27.1 The Multiplicative Group

Lemma 27.1

If F is any field and G is a finite subgroup of F^\times , then G is cyclic.

Example 27.2

If $F = \mathbb{C}$, then finite subgroups of F^\times are the n th roots of unity

$$\left\{ \exp \frac{2\pi i}{n} \right\} = \langle \zeta_n \rangle \cong \mathbb{Z}/n.$$

Proof of Lemma 27.1. By the classification of finite abelian groups, we know $G \cong \prod \mathbb{Z}/p_i^{a_i} \mathbb{Z}$ for some integers a_i . So it's enough to check that no prime appears twice (meaning that every prime appears in the list of p_i at most once). Then we can use the Chinese Remainder Theorem to show that the product is cyclic, as all the p_i are then coprime. For example, $\mathbb{Z}/4\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z} \cong \mathbb{Z}/12\mathbb{Z}$ is cyclic, while $\mathbb{Z}/4\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ is not.

But suppose p appears twice. Then G contains a subgroup $\mathbb{Z}/p^2\mathbb{Z} \times \mathbb{Z}/p^b\mathbb{Z}$. But then G has at least p^2 elements of order dividing p , since there's p choices for the coordinate in each. This would mean the polynomial $x^p - 1$ has at least p^2 roots; but it has degree p , so this is impossible. \square

Corollary 27.3

For any finite field \mathbb{F}_q , its multiplicative group \mathbb{F}_q^\times is cyclic, meaning $\mathbb{F}_q^\times \cong \mathbb{Z}/(q-1)$.

Note 27.4

Although we know in theory that $\mathbb{F}_q^\times \cong \mathbb{Z}/(q-1)$, in practice it's hard to compute how this isomorphism works — it is difficult to find a generator, or to figure out what power to raise the generator to in order to get a given element. Many cryptography and encryption protocols are based on this.

Corollary 27.5

We have $\mathbb{F}_q \cong \mathbb{F}_p(\alpha)$, and therefore, there exists an irreducible polynomial of any degree over \mathbb{F}_p .

Proof. There exists $\alpha \in \mathbb{F}_q$ which generates the multiplicative group; then α must generate \mathbb{F}_q as an extension of \mathbb{F}_p , since every element of \mathbb{F}_q is a power of α . (The converse is false — it is possible to find α which generates the extension but not the multiplicative group.)

Then $\mathbb{F}_q = \mathbb{F}_p(\alpha) \cong \mathbb{F}_p[x]/(Q)$ where Q is the minimal polynomial of α . So Q is an irreducible polynomial of degree n , where $q = p^n$. In particular, a procedure (in theory) to find an irreducible polynomial of degree n is to write down \mathbb{F}_{p^n} , find a multiplicative generator, and take its minimal polynomial. \square

27.2 Application to Number Theory

Finite fields arise in many areas of math and computer science — in particular, in number theory. One such example is $R/(p)$, where R is the ring of algebraic integers in a finite extension of \mathbb{Q} .

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Applications of Automata Theory and Algebra John L. Rhodes, Christopher L. Nehaniv, 2010 This book was originally written in 1969 by Berkeley mathematician John Rhodes It is the founding work in what is now called algebraic engineering an emerging field created by using the unifying scheme of finite state machine models and their complexity to tie together many fields finite group theory semigroup theory automata and sequential machine theory finite phase space physics metabolic and evolutionary biology epistemology mathematical theory of psychoanalysis philosophy and game theory The author thus introduced a completely original

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selected for inclusion in the book Among the topics addressed are ant colony optimization randomized algorithms for the intersection problem local search for constraint satisfaction problems randomized local search and combinatorial optimization simulated annealing probabilistic global search network communication complexity open shop scheduling aircraft routing traffic control randomized straight line programs and stochastic automata and probabilistic transformations

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Table of Contents **Finite Fields University Of Hertfordshire**

1. Understanding the eBook **Finite Fields University Of Hertfordshire**
 - The Rise of Digital Reading **Finite Fields University Of Hertfordshire**
 - Advantages of eBooks Over Traditional Books
2. Identifying **Finite Fields University Of Hertfordshire**
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an **Finite Fields University Of Hertfordshire**
 - User-Friendly Interface
4. Exploring eBook Recommendations from **Finite Fields University Of Hertfordshire**
 - Personalized Recommendations
 - **Finite Fields University Of Hertfordshire** User Reviews and Ratings
 - **Finite Fields University Of Hertfordshire** and Bestseller Lists

5. Accessing Finite Fields University Of Hertfordshire Free and Paid eBooks
 - Finite Fields University Of Hertfordshire Public Domain eBooks
 - Finite Fields University Of Hertfordshire eBook Subscription Services
 - Finite Fields University Of Hertfordshire Budget-Friendly Options
6. Navigating Finite Fields University Of Hertfordshire eBook Formats
 - ePub, PDF, MOBI, and More
 - Finite Fields University Of Hertfordshire Compatibility with Devices
 - Finite Fields University Of Hertfordshire Enhanced eBook Features
7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Finite Fields University Of Hertfordshire
 - Highlighting and Note-Taking Finite Fields University Of Hertfordshire
 - Interactive Elements Finite Fields University Of Hertfordshire
8. Staying Engaged with Finite Fields University Of Hertfordshire
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Finite Fields University Of Hertfordshire
9. Balancing eBooks and Physical Books Finite Fields University Of Hertfordshire
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Finite Fields University Of Hertfordshire
10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
11. Cultivating a Reading Routine Finite Fields University Of Hertfordshire
 - Setting Reading Goals Finite Fields University Of Hertfordshire
 - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Finite Fields University Of Hertfordshire
 - Fact-Checking eBook Content of Finite Fields University Of Hertfordshire
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning

- Utilizing eBooks for Skill Development
- Exploring Educational eBooks

14. Embracing eBook Trends

- Integration of Multimedia Elements
- Interactive and Gamified eBooks

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