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 $x^q - x$), 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 nth 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 $G \cong \prod \mathbb{Z}/p_i^{n_i}\mathbb{Z}$ for some integers n_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, $\mathbb{Z}/4\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z} = \mathbb{Z}/12\mathbb{Z}$ 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 $\mathbb{Z}/p^a\mathbb{Z} \times \mathbb{Z}/p^b\mathbb{Z}$. 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. □

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. □

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 $\mathbb{Q}$.

Finite Fields University Of Hertfordshire

Michael A. Lones,Stephen L. Smith,Sarah Teichmann,Felix Naef,Jonathan Oliver,Martin Albrecht Trefzer

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An Introduction to Computational Geometry for Curves and Surfaces Alan J. Davies,Philip Samuels,1996 This is an introductory textbook for undergraduates studying mathematics engineering or computer science and explains how differential and computational geometry are used to explain the mathematics of curves and surfaces It assumes only a basic knowledge of vector and matrix algebra andis filled with numerous exercises solutions and worked examples Ideal for those interested in computer graphics or computer aided design this book will be invaluable for those needing to understand the complex mathematics which lies behind these important areas of application **Security Protocols** Bruce Christianson,Bruno Crispo,James A. Malcom,Michael Roe,2007-11-15 This book constitutes the thoroughly refereed post proceedings of the 13th International Workshop on Security Protocols held in Cambridge UK in April 2005 There are 24 revised full papers presented together with edited transcriptions of some of the discussions following the presentations Among the topics addressed are authentication anonymity cryptographics and biometrics cryptographic protocols network security privacy SPKI user friendliness and access control *Quantum Communication, Measurement and Computing (QCMC)* Alexander Lvovsky,2009-05-13 The volume contains the proceedings of the 2008 International Conference on Quantum Communication Measurement and Computing This meeting has been the leading conference in the field for more than two decades The articles cover quantum information theory quantum optics quantum cryptography experimental tools for quantum information science and related subjects *Fourier Analysis on Finite Groups and Applications* Audrey Terras,1999-03-28 It examines the theory of finite groups in a manner that is both accessible to the beginner and suitable for graduate research Information Processing in Cells and Tissues Michael A. Lones,Stephen L. Smith,Sarah Teichmann,Felix Naef,Jonathan Oliver,Martin Albrecht Trefzer,2012-03-22 This book constitutes the refereed proceedings of the 9th International Conference on Information in Cells and Tissues IPCAT 2012 held in Cambridge UK in March April 2012 The 13 revised full papers presented together with 26 extended abstracts were carefully reviewed and selected from numerous submissions The papers cover a wide range of topics in disciplines related to genetic and epigenetic networks transcriptomics and gene regulation signalling pathways and responses protein structure and metabolic networks patterning and rhythm generation neural modelling and neural networks biomedical modelling and signal processing information processing and representation and algorithmic approaches in computational biology **Applications of Automata Theory and Algebra** John L. Rhodes,Chrystopher 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

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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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Urban Air Quality: Monitoring and Modelling Ranjeet S. Sokhi,1998-06-30 Proceedings of the First International Conference on Urban Air Quality   *Parallel Computational Fluid Dynamics 2000* C.B. Jenssen,T. Kvamdal,H.I. Andersson,B. Pettersen,P. Fox,N. Satofuka,A. Ecer,Jacques Periaux,2001-04-27 Parallel CFD 2000 the Twelfth in an International series of meetings featuring computational fluid dynamics research on parallel computers was held May 22 25 2000 in Trondheim Norway Following the trend of the past conferences areas such as numerical schemes and algorithms tools and environments load balancing as well as interdisciplinary topics and various kinds of industrial applications were all well represented in the work presented In addition for the first time in the Parallel CFD conference series the organizing committee chose to draw special attention to certain subject areas by organizing a number of special sessions We feel the emphasis of the papers presented at the conference reflect the direction of the research within parallel CFD at the beginning of the new millennium It seems to be a clear tendency towards increased industrial exploitation of parallel CFD Several presentations also demonstrated how new insight is being achieved from complex simulations and how powerful parallel computers now make it possible to use CFD within a broader interdisciplinary setting Obviously successful application of parallel CFD still rests on the underlying fundamental principles Therefore numerical algorithms development tools and parallelization techniques are still as important as when parallel CFD was in is infancy Furthermore the novel concepts of affordable parallel computing as well as metacomputing show that exciting developments are still taking place As is often pointed out however the real power of parallel CFD comes from the combination of all the disciplines involved Physics mathematics and computer science This is probably one of the principal reasons for the continued popularity of the Parallel CFD Conferences series as well as the inspiration behind much of the excellent work carried out on the subject We hope that the papers in this book both on an individual basis and as a whole will contribute to that inspiration Further details of Parallel CFD 99 as well as other conferences in this series are available at http www parcfd org   **British Reports, Translations and Theses** British Library. Document Supply Centre,British Library. Lending Division,1994 Issue for Mar 1981 contains index for Jan Mar 1981

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PCM-Enhanced Building Components Jan Kośny,2015-05-07 Presenting an overview of the use of Phase Change Materials PCMs within buildings this book discusses the performance of PCM enhanced building envelopes It reviews the most common PCMs suitable for building applications and discusses PCM encapsulation and packaging methods In addition to this it examines a range of PCM enhanced building products in the process of development as well as examples of whole building scale field demonstrations Further chapters discuss experimental and theoretical analyses including available software to determine dynamic thermal and energy performance characteristics of building enclosure components containing PCMs and present different laboratory and field testing methods Finally a wide range of PCM building products are presented which are commercially available worldwide This book is intended for students and researchers of mechanical architectural and civil engineering and postgraduate students of energy analysis dynamic design of building structures and dynamic testing procedures It also provides a useful resource for professionals involved in architectural and mechanical civil engineering design thermal testing and PCM manufacturing   **Reader's Guide to Literature in English** Mark Hawkins-Dady,2012-12-06 Reader s Guide Literature in English provides expert guidance to and critical analysis of the vast number of books available within the subject of English literature from Anglo Saxon times to the current American British and Commonwealth scene It is designed to help students teachers and librarians choose the most appropriate books for research and study   **Educational Times** ,1904

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