

ALLEN HATCHER: ALGEBRAIC TOPOLOGY

MORTEN POULSEN

All references are to the 2002 printed edition.

CHAPTER 0

Ex. 0.2. Define $H: (\mathbf{R}^n - \{0\}) \times I \rightarrow \mathbf{R}^n - \{0\}$ by

$$H(x, t) = (1 - t)x + \frac{t}{\|x\|}x.$$

$x \in \mathbf{R}^n - \{0\}$, $t \in I$. It is easily verified that H is a homotopy between the identity map and a retraction onto S^{n-1} , i.e. a deformation retraction.

Ex. 0.3. First a few results which make things easier.

Lemma 1. Let f_0, f_1 and f_2 be maps $X \rightarrow Y$. If $f_0 \simeq f_1$ and $f_1 \simeq f_2$ then $f_0 \simeq f_2$.

Proof. Let $F_0: X \times I \rightarrow Y$ be a homotopy between f_0 and f_1 , and $F_1: X \times I \rightarrow Y$ a homotopy between f_1 and f_2 .

Define $F: X \times I \rightarrow Y$ by

$$F(x, t) = \begin{cases} F_0(x, 2t), & t \in [0, 1/2] \\ F_1(x, 2t - 1), & t \in [1/2, 1]. \end{cases}$$

If $t = 1/2$ then $F_0(x, 2t) = F_0(x, 1) = f_1(x) = F_1(x, 0) = F_1(x, 2t - 1)$, i.e. the map F is well-defined. By the pasting lemma, F is continuous. Since $F(x, 0) = F_0(x, 0) = f_0(x)$ and $F(x, 1) = F_1(x, 1) = f_2(x)$, F is a homotopy between f_0 and f_2 . $\square$

Lemma 2. If $f_0, f_1: X \rightarrow Y$ are homotopic and $g_0, g_1: Y \rightarrow Z$ are homotopic then $g_0 f_0, g_1 f_1: X \rightarrow Z$ are homotopic.

Proof. Let $F: X \times I \rightarrow Y$ be a homotopy between f_0 and f_1 , and let $G: Y \times I \rightarrow Z$ be a homotopy between g_0 and g_1 .

One proof: Now the composite $g_0 F: X \times I \rightarrow Z$ is a homotopy between $g_0 f_0$ and $g_0 f_1$, and the composite $G(f_1 \times \text{id}_I): X \times I \rightarrow Z$ is a homotopy between $g_0 f_1$ and $g_1 f_1$. By lemma 1, $g_0 f_0 \simeq g_1 f_1$.

Another proof: The map $G(F \times \text{id}_I)(\text{id}_X \times \Delta): X \times I \rightarrow Z$ is continuous, where $\Delta: I \rightarrow I \times I$ is the diagonal map, that is, $\Delta(t) = (t, t)$. Since

$$G(F \times \text{id}_I)(\text{id}_X \times \Delta)(x, 0) = G(F \times \text{id}_I)(x, 0, 0) = G(F(x, 0), 0) = g_0 f_0(x)$$

and

$$G(F \times \text{id}_I)(\text{id}_X \times \Delta)(x, 1) = G(F \times \text{id}_I)(x, 1, 1) = G(F(x, 1), 1) = g_1 f_1(x),$$

$g_0 f_0$ and $g_1 f_1$ are homotopic. $\square$

(a). Suppose $f_0: X \rightarrow Y$ is a homotopy equivalence with homotopy inverse $f_1: Y \rightarrow X$, and $g_0: Y \rightarrow Z$ is a homotopy equivalence with homotopy inverse $g_1: Z \rightarrow Y$.

Using lemma 2, $f_1 g_1 g_0 f_0 \simeq f_1 \text{id}_Y f_0 = f_1 f_0 \simeq \text{id}_X$ and $g_0 f_0 f_1 g_1 \simeq g_0 \text{id}_Y g_1 = g_0 g_1 \simeq \text{id}_Z$. In other words, $g_0 f_0: X \rightarrow Z$ is a homotopy equivalence.

Since being homotopy equivalent clearly is reflexive and symmetric, homotopy equivalence among spaces is an equivalence relation.

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Topology of Numbers Allen Hatcher, 2022-10-19 This book serves as an introduction to number theory at the undergraduate level emphasizing geometric aspects of the subject The geometric approach is exploited to explore in some depth the classical topic of quadratic forms with integer coefficients a central topic of the book Quadratic forms of this type in two variables have a very rich theory developed mostly by Euler Lagrange Legendre and Gauss during the period 1750 1800 In this book their approach is modernized by using the splendid visualization tool introduced by John Conway in the 1990s called the topograph of a quadratic form Besides the intrinsic interest of quadratic forms this theory has also served as a stepping stone for many later developments in algebra and number theory The book is accessible to students with a basic knowledge of linear algebra and arithmetic modulo n Some exposure to mathematical proofs will also be helpful The early chapters focus on examples rather than general theorems but theorems and their proofs play a larger role as the book progresses

Algorithmic Foundation of Robotics VII Srinivas Akella, Nancy M. Amato, Wesley Huang, Bud Mishra, 2008-08-27 Algorithms are a fundamental component of robotic systems they control or reason about motion and perception in the physical world They receive input from noisy sensors consider geometric and physical constraints and operate on the world through imprecise actuators The design and analysis of robot algorithms therefore raises a unique combination of questions in control theory computational and differential geometry and computer science This book contains the proceedings from the 2006 Workshop on the Algorithmic Foundations of Robotics This biannual workshop is a highly selective meeting of leading researchers in the field of algorithmic issues related to robotics The 32 papers in this book span a wide variety of topics from fundamental motion planning algorithms to applications in medicine and biology but they have in common a foundation in the algorithmic problems of robotic systems

An Introduction to Riemann Surfaces Terrence Napier, Mohan Ramachandran, 2011-09-08 This textbook presents a unified approach to compact and noncompact Riemann surfaces from the point of view of the so called L_2 bar delta method This method is a powerful technique from the theory of several complex variables and provides for a unique approach to the fundamentally different characteristics of compact and noncompact Riemann surfaces The inclusion of continuing exercises running throughout the book which lead to generalizations of the main theorems as well as the exercises included in each chapter make this text ideal for a one or two semester graduate course

Groups St Andrews 2017 in Birmingham C. M. Campbell, C. W. Parker, M. R. Quick, E. F. Robertson, C. M. Roney-Dougall, 2019-04-11 This volume arises from the 2017 edition of the long running Groups St Andrews conference series and consists of expository papers from leading researchers in all areas of group theory It provides a snapshot of the state of the art in the field and it will be a valuable resource for researchers and graduate students

Computational Psychiatry Rodrick Wallace, 2017-04-20 This book explores mental disorders from a uniquely evolutionary perspective Although there have been many attempts to mathematically model neural processes and to some extent their

dysfunction there is very little literature that models mental function within a sociocultural socioeconomic and environmental context Addressing this gap in the extant literature this book explores essential aspects of mental disorders recognizing the ubiquitous role played by the exaptation of crosstalk between cognitive modules at many different scales and levels of organization the missing heritability of complex diseases and cultural epigenetics Further it introduces readers to valuable control theory tools that permit the exploration of the environmental induction of neurodevelopmental disorders as well as the study of the synergism between culture psychopathology and sleep disorders offering a distinctively unique resource

Circle-valued Morse Theory Andrei V. Pajitnov, 2008-08-22 In the early 1920s M Morse discovered that the number of critical points of a smooth function on a manifold is closely related to the topology of the manifold This became a starting point of the Morse theory which is now one of the basic parts of differential topology Circle valued Morse theory originated from a problem in hydrodynamics studied by S P Novikov in the early 1980s Nowadays it is a constantly growing field of contemporary mathematics with applications and connections to many geometrical problems such as Arnold's conjecture in the theory of Lagrangian intersections fibrations of manifolds over the circle dynamical zeta functions and the theory of knots and links in the three dimensional sphere The aim of the book is to give a systematic treatment of geometric foundations of the subject and recent research results The book is accessible to first year graduate students specializing in geometry and topology

Spectral Flow Nora Doll, Hermann Schulz-Baldes, Nils Waterstraat, 2023-06-19 This is the first treatment entirely dedicated to an analytic study of spectral flow for paths of selfadjoint Fredholm operators possibly unbounded or understood in a semifinite sense The importance of spectral flow for homotopy and index theory is discussed in detail Applications concern eta invariants the Bott Maslov and Conley Zehnder indices Sturm Liouville oscillation theory the spectral localizer and bifurcation theory

Peterson's Guide to Graduate Programs in the Physical Sciences and Mathematics, 1990

Progress in Lorentzian Geometry Waldemar Barrera, Jónatan Herrera, Juan Pablo Navarrete, Matias Navarro, Oscar Palmas, Didier A. Solis, 2025-09-30 This proceedings volume gathers selected revised papers presented at the XI International Meeting on Lorentzian Geometry GeLoMer 2024 held at the Autonomous University of Yucatán Mexico from January 29 to February 2 2024 Lorentzian geometry provides the mathematical foundation for Einstein's theory of relativity It incorporates aspects from different branches of mathematics such as differential geometry partial differential equations and mathematical analysis to name a few This volume includes surveys describing the state of the art in specific areas and a selection of the most relevant results presented at the conference which is seen as a benchmark for those working in Lorentz geometry due to its relevance Given its scope the book will be of interest to both young and experienced mathematicians and physicists whose research involves general relativity and semi Riemannian geometry

Pattern Recognition on Oriented Matroids Andrey O. Matveev, 2017-09-11 Pattern Recognition on Oriented Matroids covers a range of innovative problems in combinatorics poset and graph theories optimization and number theory that constitute a far reaching extension of the

arsenal of committee methods in pattern recognition The groundwork for the modern committee theory was laid in the mid 1960s when it was shown that the familiar notion of solution to a feasible system of linear inequalities has ingenious analogues which can serve as collective solutions to infeasible systems A hierarchy of dialects in the language of mathematics for instance open cones in the context of linear inequality systems regions of hyperplane arrangements and maximal covectors or toposes of oriented matroids provides an excellent opportunity to take a fresh look at the infeasible system of homogeneous strict linear inequalities the standard working model for the contradictory two class pattern recognition problem in its geometric setting The universal language of oriented matroid theory considerably simplifies a structural and enumerative analysis of applied aspects of the infeasibility phenomenon The present book is devoted to several selected topics in the emerging theory of pattern recognition on oriented matroids the questions of existence and applicability of matroidal generalizations of committee decision rules and related graph theoretic constructions to oriented matroids with very weak restrictions on their structural properties a study in which in particular interesting subsequences of the Farey sequence appear naturally of the hierarchy of the corresponding tope committees a description of the three tope committees that are the most attractive approximation to the notion of solution to an infeasible system of linear constraints an application of convexity in oriented matroids as well as blocker constructions in combinatorial optimization and in poset theory to enumerative problems on tope committees an attempt to clarify how elementary changes one element reorientations in an oriented matroid affect the family of its tope committees a discrete Fourier analysis of the important family of critical tope committees through rank and distance relations in the tope poset and the tope graph the characterization of a key combinatorial role played by the symmetric cycles in hypercube graphs Contents Oriented Matroids the Pattern Recognition Problem and Tope Committees Boolean Intervals Dehn Sommerville Type Relations Farey Subsequences Blocking Sets of Set Families and Absolute Blocking Constructions in Posets Committees of Set Families and Relative Blocking Constructions in Posets Layers of Tope Committees Three Tope Committees Halfspaces Convex Sets and Tope Committees Tope Committees and Reorientations of Oriented Matroids Topes and Critical Committees Critical Committees and Distance Signals Symmetric Cycles in the Hypercube Graphs *Basic Algebraic Topology and its Applications* Mahima Ranjan Adhikari, 2016-09-16 This book provides an accessible introduction to algebraic topology a field at the intersection of topology geometry and algebra together with its applications Moreover it covers several related topics that are in fact important in the overall scheme of algebraic topology Comprising eighteen chapters and two appendices the book integrates various concepts of algebraic topology supported by examples exercises applications and historical notes Primarily intended as a textbook the book offers a valuable resource for undergraduate postgraduate and advanced mathematics students alike Focusing more on the geometric than on algebraic aspects of the subject as well as its natural development the book conveys the basic language of modern algebraic topology by exploring homotopy homology and

cohomology theories and examines a variety of spaces spheres projective spaces classical groups and their quotient spaces function spaces polyhedra topological groups Lie groups and cell complexes etc The book studies a variety of maps which are continuous functions between spaces It also reveals the importance of algebraic topology in contemporary mathematics theoretical physics computer science chemistry economics and the biological and medical sciences and encourages students to engage in further study

The Universal Coefficient Theorem and Quantum Field Theory Andrei-Tudor Patrascu, 2016-09-23 This thesis describes a new connection between algebraic geometry topology number theory and quantum field theory It offers a pedagogical introduction to algebraic topology allowing readers to rapidly develop basic skills and it also presents original ideas to inspire new research in the quest for dualities Its ambitious goal is to construct a method based on the universal coefficient theorem for identifying new dualities connecting different domains of quantum field theory This thesis opens a new area of research in the domain of non perturbative physics one in which the use of different coefficient structures in co homology may lead to previously unknown connections between different regimes of quantum field theories The origin of dualities is an issue in fundamental physics that continues to puzzle the research community with unexpected results like the AdS CFT duality or the ER EPR conjecture This thesis analyzes these observations from a novel and original point of view mainly based on a fundamental connection between number theory and topology Beyond its scientific qualities it also offers a pedagogical introduction to advanced mathematics and its connection with physics This makes it a valuable resource for students in mathematical physics and researchers wanting to gain insights into co homology theories with coefficients or the way in which Grothendieck's work may be connected with physics

Partial Differential Equations I Michael E. Taylor, 2023-12-06 The first of three volumes on partial differential equations this one introduces basic examples arising in continuum mechanics electromagnetism complex analysis and other areas and develops a number of tools for their solution in particular Fourier analysis distribution theory and Sobolev spaces These tools are then applied to the treatment of basic problems in linear PDE including the Laplace equation heat equation and wave equation as well as more general elliptic parabolic and hyperbolic equations The book is targeted at graduate students in mathematics and at professional mathematicians with an interest in partial differential equations mathematical physics differential geometry harmonic analysis and complex analysis The third edition further expands the material by incorporating new theorems and applications throughout the book and by deepening connections and relating concepts across chapters It includes new sections on rigid body motion on probabilistic results related to random walks on aspects of operator theory related to quantum mechanics on overdetermined systems and on the Euler equation for incompressible fluids The appendices have also been updated with additional results ranging from weak convergence of measures to the curvature of Kahler manifolds Michael E Taylor is a Professor of Mathematics at the University of North Carolina Chapel Hill NC Review of first edition These volumes will be read by several generations of readers eager to learn the modern theory of partial

differential equations of mathematical physics and the analysis in which this theory is rooted Peter Lax SIAM review June 1998

Understanding Topology Shaun V. Ault, 2018-01-30 A fresh approach to topology makes this complex topic easier for students to master Topology the branch of mathematics that studies the properties of spaces that remain unaffected by stretching and other distortions can present significant challenges for undergraduate students of mathematics and the sciences Understanding Topology aims to change that The perfect introductory topology textbook Understanding Topology requires only a knowledge of calculus and a general familiarity with set theory and logic Equally approachable and rigorous the book's clear organization worked examples and concise writing style support a thorough understanding of basic topological principles Professor Shaun V Ault's unique emphasis on fascinating applications from mapping DNA to determining the shape of the universe will engage students in a way traditional topology textbooks do not This groundbreaking new text presents Euclidean abstract and basic algebraic topology explains metric topology vector spaces and dynamics point set topology surfaces knot theory graphs and map coloring the fundamental group and homology includes worked example problems solutions and optional advanced sections for independent projects Following a path that will work with any standard syllabus the book is arranged to help students reach that Aha moment encouraging readers to use their intuition through local to global analysis and emphasizing topological invariants to lay the groundwork for algebraic topology

Mathematical Modelling of Physical Systems Michel Cessenat, 2018-10-26 Comprehensive and thorough this monograph emphasizes the main role differential geometry and convex analysis play in the understanding of physical chemical and mechanical notions Central focus is placed on specifying the agreement between the functional framework and its physical necessity and on making clear the intrinsic character of physical elements independent from specific charts or frames The book is divided into four sections covering thermostructure classical mechanics fluid mechanics modelling and behavior laws An extensive appendix provides notations and definitions as well as brief explanation of integral manifolds symplectic structure and contact structure Plenty of examples are provided throughout the book and reviews of basic principles in differential geometry and convex analysis are presented as needed This book is a useful resource for graduate students and researchers in the field

Navier-Stokes Turbulence Wolfgang Kollmann, 2024-05-24 This updated augmented second edition retains its class tested content and pedagogy as a core text for graduate courses in advanced fluid mechanics and applied science The new edition adds revised sections clarification problems and chapter extensions including a rewritten section on Schauder bases for turbulent pipe flow coverage of Cantwell's mixing length closure for turbulent pipe flow and a section on the variational Hessian Consisting of two parts the first provides an introduction and general theory of fully developed turbulence where treatment of turbulence is based on the linear functional equation derived by E Hopf governing the characteristic functional that determines the statistical properties of a turbulent flow In this section Professor Kollmann explains how the theory is built on divergence free Schauder bases for the phase space of the turbulent flow and

the space of argument vector fields for the characteristic functional The second segment presented over subsequent chapters is devoted to mapping methods homogeneous turbulence based upon the hypotheses of Kolmogorov and Onsager intermittency structural features of turbulent shear flows and their recognition Essays in Mathematics and its Applications Themistocles M. Rassias, Panos M. Pardalos, 2016-06-14 This volume dedicated to the eminent mathematician Vladimir Arnold presents a collection of research and survey papers written on a large spectrum of theories and problems that have been studied or introduced by Arnold himself Emphasis is given to topics relating to dynamical systems stability of integrable systems algebraic and differential topology global analysis singularity theory and classical mechanics A number of applications of Arnold's groundbreaking work are presented This publication will assist graduate students and research mathematicians in acquiring an in depth understanding and insight into a wide domain of research of an interdisciplinary nature **Analytic Combinatorics in Several Variables** Robin Pemantle, Mark C. Wilson, Stephen Melczer, 2024-02-15 Introduces the theory of multivariate generating functions with new exercises computational examples and a conceptual overview chapter **Immersion in Warped Product Spaces** Henrique Fernandes de Lima, Giovanni Molica Bisci, Marco Antonio Lázaro Velásquez, 2024-12-27 This book offers a detailed exploration of the intrinsic geometrical properties of warped product spaces through the lens of mathematical analysis and global differential geometry It touches upon key topics such as uniqueness results height estimates Riemannian immersions and the geometrical behavior of submanifolds while addressing complex phenomena that challenge traditional Euclidean assumptions Divided into five comprehensive parts the text provides clear refinements of recent findings with connections to General Relativity and semi Riemannian geometry Accessible yet thorough this monograph is ideal for post graduate students researchers and specialists across mathematics geometry and theoretical physics Geometrisation of 3-manifolds , 2010 The Geometrisation Conjecture was proposed by William Thurston in the mid 1970s in order to classify compact 3 manifolds by means of a canonical decomposition along essential embedded surfaces into pieces that possess geometric structures It contains the famous Poincaré Conjecture as a special case In 2002 Grigory Perelman announced a proof of the Geometrisation Conjecture based on Richard Hamilton's Ricci flow approach and presented it in a series of three celebrated arXiv preprints Since then there has been an ongoing effort to understand Perelman's work by giving more detailed and accessible presentations of his ideas or alternative arguments for various parts of the proof This book is a contribution to this endeavour Its two main innovations are first a simplified version of Perelman's Ricci flow with surgery which is called Ricci flow with bubbling off and secondly a completely different and original approach to the last step of the proof In addition special effort has been made to simplify and streamline the overall structure of the argument and make the various parts independent of one another A complete proof of the Geometrisation Conjecture is given modulo pre Perelman results on Ricci flow Perelman's results on the functional and solutions as well as the Colding Minicozzi extinction paper The book can be read by anyone already familiar

with these results or willing to accept them as black boxes The structure of the proof is presented in a lengthy introduction which does not require knowledge of geometric analysis The bulk of the proof is the existence theorem for Ricci flow with bubbling off which is treated in parts I and II Part III deals with the long time behaviour of Ricci flow with bubbling off Part IV finishes the proof of the Geometrisation Conjecture

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