

# GROUPS AND GEOMETRY

JOUNI PARKKONEN

## 1. EUCLIDEAN AND SPHERICAL GEOMETRY

**1.1. Metric spaces.** A function  $d: X \times X \rightarrow [0, +\infty[$  is a *metric* in the nonempty set  $X$  if it satisfies the following properties

- (1)  $d(x, x) = 0$  for all  $x \in X$  and  $d(x, y) > 0$  if  $x \neq y$ ,
- (2)  $d(x, y) = d(y, x)$  for all  $x, y \in X$ , and
- (3)  $d(x, y) \leq d(x, z) + d(z, y)$  for all  $x, y, z \in X$  (the *triangle inequality*).

The pair  $(X, d)$  is a *metric space*. Open and closed balls in a metric space, continuity of maps between metric spaces and other “metric properties” are defined in the same way as in Euclidean space, using the metrics of  $X$  and  $Y$  instead of the Euclidean metric.

If  $(X_1, d_1)$  and  $(X_2, d_2)$  are metric spaces, then a map  $i: X \rightarrow Y$  is an *isometric embedding*, if

$$d_2(i(x), i(y)) = d_1(x, y)$$

for all  $x, y \in X_1$ . If the isometric embedding  $i$  is a bijection, then it is called an *isometry* between  $X$  and  $Y$ . An isometry  $i: X \rightarrow X$  is called an isometry of  $X$ .

The isometries of a metric space  $X$  form a group  $\text{Isom}(X)$ , the *isometry group* of  $X$ , with the composition of mappings as the group law.

A map  $i: X \rightarrow Y$  is a *locally isometric embedding* if each point  $x \in X$  has a neighbourhood  $U$  such that the restriction of  $i$  to  $U$  is an isometric embedding. A (locally) isometric embedding  $i: I \rightarrow X$  is

- (1) a *(locally) geodesic segment*, if  $I \subset \mathbb{R}$  is a (closed) bounded interval,
- (2) a *(locally) geodesic ray*, if  $I = [0, +\infty[$ , and
- (3) a *(locally) geodesic line*, if  $I = \mathbb{R}$ .

Note that in Riemannian geometry, the definition of a geodesic line is different from the above: in general a Riemannian geodesic line is only a locally geodesic line according to our definition.

**1.2. Euclidean space.** Let us denote the *Euclidean inner product* of  $\mathbb{R}^n$  by

$$(x|y) = \sum_{i=1}^n x_i y_i.$$

The *Euclidean norm*  $\|x\| = \sqrt{(x|x)}$  defines the *Euclidean metric*  $d(x, y) = \|x - y\|$ . The triple  $\mathbb{E}^n = (\mathbb{R}^n, (\cdot|\cdot), \|\cdot\|)$  is *n-dimensional Euclidean space*.

Euclidean space is a *geodesic metric space*: For any two distinct points  $x, y \in \mathbb{E}^n$ , the map  $j_{x,y}: \mathbb{R} \rightarrow \mathbb{E}^n$ ,

$$j_{x,y}(t) = x + t \frac{y - x}{\|y - x\|},$$

is a geodesic line that passes through the points  $x$  and  $y$ . The restriction  $j_{x,y}|_{[0, \|x-y\|]}$  is a geodesic segment that *connects*  $x$  to  $y$ :  $j(0) = x$  and  $j(\|x - y\|) = y$ . In fact, this is the only geodesic segment that connects  $x$  to  $y$  up to replacing the interval of

# Groups And Geometry

**Larry C. Grove**



## Groups And Geometry:

**Groups and Geometry** P. M. Neumann, Gabrielle A. Stoy, E. C. Thompson, 1994 This book is about the measurement of symmetry which is what groups are for Symmetry is visible in all parts of mathematics and the exercises provided give the reader an opportunity to obtain a fuller understanding of this area of mathematics *Geometry of Defining Relations in Groups* A.Yu. Ol'shanskii, 1991-10-31 The main feature of this book is a systematic application of elementary geometric and topological techniques for solving problems that arise naturally in algebra After an account of preliminary material there is a discussion of a geometrically intuitive interpretation of the derivation of consequences of defining relations of groups A study is made of planar and certain other two dimensional maps connected with well known problems in general group theory such as the problems of Burnside and O Yu Schmidt The method of cancellation diagrams developed here is applied to these and to a series of other problems This monograph is addressed to research workers and students in universities and may be used as a basis for a series of specialized lectures or seminars *Groups and Geometric Analysis* Sigurdur Helgason, 2022-03-17 Group theoretic methods have taken an increasingly prominent role in analysis Some of this change has been due to the writings of Sigurdur Helgason This book is an introduction to such methods on spaces with symmetry given by the action of a Lie group The introductory chapter is a self contained account of the analysis on surfaces of constant curvature Later chapters cover general cases of the Radon transform spherical functions invariant operators compact symmetric spaces and other topics This book together with its companion volume *Geometric Analysis on Symmetric Spaces* AMS Mathematical Surveys and Monographs series vol 39 1994 has become the standard text for this approach to geometric analysis Sigurdur Helgason was awarded the Steele Prize for outstanding mathematical exposition for *Groups and Geometric Analysis and Differential Geometry Lie Groups and Symmetric Spaces* *Groups* R. P. Burn, 1987-09-03 Following the same successful approach as Dr Burn's previous book on number theory this text consists of a carefully constructed sequence of questions that will enable the reader through participation to study all the group theory covered by a conventional first university course An introduction to vector spaces leading to the study of linear groups and an introduction to complex numbers leading to the study of Möbius transformations and stereographic projection are also included Quaternions and their relationships to 3 dimensional isometries are covered and the climax of the book is a study of the crystallographic groups with a complete analysis of these groups in two dimensions **From Groups to Geometry and Back** Vaughn Climenhaga, Anatole Katok, 2017-04-07 Groups arise naturally as symmetries of geometric objects and so groups can be used to understand geometry and topology Conversely one can study abstract groups by using geometric techniques and ultimately by treating groups themselves as geometric objects This book explores these connections between group theory and geometry introducing some of the main ideas of transformation groups algebraic topology and geometric group theory The first half of the book introduces basic notions of group theory and studies symmetry groups in various geometries including Euclidean

projective and hyperbolic The classification of Euclidean isometries leads to results on regular polyhedra and polytopes the study of symmetry groups using matrices leads to Lie groups and Lie algebras The second half of the book explores ideas from algebraic topology and geometric group theory The fundamental group appears as yet another group associated to a geometric object and turns out to be a symmetry group using covering spaces and deck transformations In the other direction Cayley graphs planar models and fundamental domains appear as geometric objects associated to groups The final chapter discusses groups themselves as geometric objects including a gentle introduction to Gromov's theorem on polynomial growth and Grigorchuk's example of intermediate growth The book is accessible to undergraduate students and anyone else with a background in calculus linear algebra and basic real analysis including topological notions of convergence and connectedness This book is a result of the MASS course in algebra at Penn State University in the fall semester of 2009

**Groups and Geometry** Roger C. Lyndon, 1985      **Topics in Groups and Geometry** Tullio Ceccherini-Silberstein, Michele D'Adderio, 2022-01-01 This book provides a detailed exposition of a wide range of topics in geometric group theory inspired by Gromov's pivotal work in the 1980s It includes classical theorems on nilpotent groups and solvable groups a fundamental study of the growth of groups a detailed look at asymptotic cones and a discussion of related subjects including filters and ultrafilters dimension theory hyperbolic geometry amenability the Burnside problem and random walks on groups The results are unified under the common theme of Gromov's theorem namely that finitely generated groups of polynomial growth are virtually nilpotent This beautiful result gave birth to a fascinating new area of research which is still active today The purpose of the book is to collect these naturally related results together in one place most of which are scattered throughout the literature some of them appearing here in book form for the first time In this way the connections between these topics are revealed providing a pleasant introduction to geometric group theory based on ideas surrounding Gromov's theorem The book will be of interest to mature undergraduate and graduate students in mathematics who are familiar with basic group theory and topology and who wish to learn more about geometric analytic and probabilistic aspects of infinite groups

**Groups and Geometry** P. M. Neumann, 1994      **Discrete Groups and Geometry** William J. Harvey, C. Maclachlan, 1992-07-30 This book constitutes the proceedings of a conference held at the University of Birmingham to mark the retirement of Professor A M Macbeath The papers represent up to date work on a broad spectrum of topics in the theory of discrete group actions ranging from presentations of finite groups through the detailed study of Fuchsian and crystallographic groups to applications of group actions in low dimensional topology complex analysis algebraic geometry and number theory For those wishing to pursue research in these areas this volume offers a valuable summary of contemporary thought and a source of fresh geometric insights      Geometric Group Theory Clara Löh, 2017-12-19 Inspired by classical geometry geometric group theory has in turn provided a variety of applications to geometry topology group theory number theory and graph theory This carefully written textbook provides a rigorous introduction to this rapidly

evolving field whose methods have proven to be powerful tools in neighbouring fields such as geometric topology Geometric group theory is the study of finitely generated groups via the geometry of their associated Cayley graphs It turns out that the essence of the geometry of such groups is captured in the key notion of quasi isometry a large scale version of isometry whose invariants include growth types curvature conditions boundary constructions and amenability This book covers the foundations of quasi geometry of groups at an advanced undergraduate level The subject is illustrated by many elementary examples outlooks on applications as well as an extensive collection of exercises *Topics in Geometric Group Theory*

Pierre de la Harpe, 2000-09-15 In this book Pierre de la Harpe provides a concise and engaging introduction to geometric group theory a new method for studying infinite groups via their intrinsic geometry that has played a major role in mathematics over the past two decades A recognized expert in the field de la Harpe adopts a hands on approach illustrating key concepts with numerous concrete examples The first five chapters present basic combinatorial and geometric group theory in a unique and refreshing way with an emphasis on finitely generated versus finitely presented groups In the final three chapters de la Harpe discusses new material on the growth of groups including a detailed treatment of the Grigorchuk group Most sections are followed by exercises and a list of problems and complements enhancing the book's value for students problems range from slightly more difficult exercises to open research problems in the field An extensive list of references directs readers to more advanced results as well as connections with other fields *Geometric Group Theory*

Mladen Bestvina, Michah Sageev, Karen Vogtmann, 2014-12-24 Geometric group theory refers to the study of discrete groups using tools from topology geometry dynamics and analysis The field is evolving very rapidly and the present volume provides an introduction to and overview of various topics which have played critical roles in this evolution The book contains lecture notes from courses given at the Park City Math Institute on Geometric Group Theory The institute consists of a set of intensive short courses offered by leaders in the field designed to introduce students to exciting current research in mathematics These lectures do not duplicate standard courses available elsewhere The courses begin at an introductory level suitable for graduate students and lead up to currently active topics of research The articles in this volume include introductions to CAT 0 cube complexes and groups to modern small cancellation theory to isometry groups of general CAT 0 spaces and a discussion of nilpotent genus in the context of mapping class groups and CAT 0 groups One course surveys quasi isometric rigidity others contain an exploration of the geometry of Outer space of actions of arithmetic groups lectures on lattices and locally symmetric spaces on marked length spectra and on expander graphs Property tau and approximate groups This book is a valuable resource for graduate students and researchers interested in geometric group theory Titles in this series are co published with the Institute for Advanced Study Park City Mathematics Institute Members of the Mathematical Association of America MAA and the National Council of Teachers of Mathematics NCTM receive a 20% discount from list price **The Geometry of the Word Problem for Finitely Generated Groups** Noel Brady, Tim

Riley, Hamish Short, 2007-05-11 The origins of the word problem are in group theory decidability and complexity But through the vision of M Gromov and the language of filling functions the topic now impacts the world of large scale geometry This book contains accounts of many recent developments in Geometric Group Theory and shows the interaction between the word problem and geometry continues to be a central theme It contains many figures numerous exercises and open questions

Groups and Geometry Roger C. Lyndon, 1985 This book which was originally published in 1985 and has been translated and revised by the author from notes of a course is an introduction to certain central ideas in group theory and geometry Professor Lyndon emphasises and exploits the well known connections between the two subjects and whilst keeping the presentation at a level that assumes only a basic background in mathematics leads the reader to the frontiers of current research at the time of publication The treatment is concrete and combinatorial with a minimal use of analytic geometry In the interest of the reader's intuition most of the geometry considered is two dimensional and there is an emphasis on examples both in the text and in the problems at the end of each chapter

*Classical Groups and Geometric Algebra* Larry C. Grove, Classical groups named so by Hermann Weyl are groups of matrices or quotients of matrix groups by small normal subgroups Thus the story begins as Weyl suggested with Her All embracing Majesty the general linear group  $GL(n, V)$  of all invertible linear transformations of a vector space  $V$  over a field  $F$  All further groups discussed are either subgroups of  $GL(n, V)$  or closely related quotient groups Most of the classical groups consist of invertible linear transformations that respect a bilinear form having some geometric significance e.g. a quadratic form a symplectic form etc Accordingly the author develops the required geometric notions albeit from an algebraic point of view as the end results should apply to vector spaces over more or less arbitrary fields finite or infinite The classical groups have proved to be important in a wide variety of venues ranging from physics to geometry and far beyond In recent years they have played a prominent role in the classification of the finite simple groups This text provides a single source for the basic facts about the classical groups and also includes the required geometrical background information from the first principles It is intended for graduate students who have completed standard courses in linear algebra and abstract algebra The author L C Grove is a well known expert who has published extensively in the subject area

The Geometry of the Classical Groups Donald E. Taylor, 1992

Geometry of Defining Relations in Groups A.Yu. Ol'shanskii, 2012-12-06

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**The Mathematical Legacy of Wilhelm Magnus: Groups, Geometry and Special Functions** William Abikoff, Joan S. Birman, Kathryn Kuiken, 1994 Wilhelm Magnus was an extraordinarily creative mathematician who made fundamental contributions to diverse areas including group theory geometry and special functions This book contains the proceedings of a conference held in May 1992 at Polytechnic University Brooklyn to honour the memory of Magnus The focus of the book is on active areas of research where Magnus influence can be seen The papers range from expository articles to major new research bringing together seemingly diverse

topics and providing entry points to a variety of areas of mathematics

**Ergodic Theory, Groups, and Geometry** Robert J. Zimmer, Dave Witte Morris, 2008 The study of group actions on manifolds is the meeting ground of a variety of mathematical areas In particular interesting geometric insights can be obtained by applying measure theoretic techniques This book provides an introduction to some of the important methods major developments and open problems in the subject It is slightly expanded from lectures given by Zimmer at the CBMS conference at the University of Minnesota The main text presents a perspective on the field as it was at that time Comments at the end of each chapter provide selected suggestions for further reading including references to recent developments

**BOOK JACKET**

**Conformal Groups in Geometry and Spin Structures** Pierre Anglès, 2007-10-16 Conformal groups play a key role in geometry and spin structures This book provides a self contained overview of this important area of mathematical physics beginning with its origins in the works of Cartan and Chevalley and progressing to recent research in spinors and conformal geometry Key topics and features Focuses initially on the basics of Clifford algebras Studies the spaces of spinors for some even Clifford algebras Examines conformal spin geometry beginning with an elementary study of the conformal group of the Euclidean plane Treats covering groups of the conformal group of a regular pseudo Euclidean space including a section on the complex conformal group Introduces conformal flat geometry and conformal spinoriality groups followed by a systematic development of riemannian or pseudo riemannian manifolds having a conformal spin structure Discusses links between classical spin structures and conformal spin structures in the context of conformal connections Examines pseudo unitary spin structures and pseudo unitary conformal spin structures using the Clifford algebra associated with the classical pseudo unitary space Ample exercises with many hints for solutions Comprehensive bibliography and index This text is suitable for a course in mathematical physics at the advanced undergraduate and graduate levels It will also benefit researchers as a reference text

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