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What, Why, and How

Lizhen Ji

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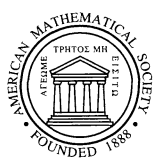

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To my wife Lan Wang
for her constant support and understanding

"What is... Symmetry?"
by Lena Min Ji

(showing both global and local symmetries)

Contents

Preface

In one guise or another, many mathematicians are familiar with certain arithmetic groups, such as $\mathbb{Z}$ and $\mathrm{SL}(n,\mathbb{Z})$. But their relatives, for example, S-arithmetic groups such as $\mathrm{SL}\left(n,\mathbb{Z}\left[\frac{1}{p_1},\ldots,\frac{1}{p_m}\right]\right)$, where $p_1,\ldots,p_m$ are prime numbers, and their analogues over function fields such as $\mathrm{SL}(n,\mathbb{F}_p[t])$, where $\mathbb{F}_p$ is a finite field and t is a variable, may not be so well-known. The purpose of this expository book is to explain through some brief and informal comments what these groups are, why they are important to study, and how they can be understood and applied to many fields such as analysis, geometry, topology, number theory, representation theory and algebraic geometry.

We try to emphasize the point of view that it is the group action on good spaces that makes the group interesting and understandable, and that it is also the group action which makes the spaces invloved more interesting and useful. In fact, problems naturally arise and are solved by such pairs of groups and spaces. For example, though symmetric spaces are important and interesting in themselves, their quotients by arithmetic groups, which are locally symmetric spaces of finite areas and sometimes called arithmetic locally symmetric spaces, are much richer in structures and have more applications. One obvious reason is that symmetric spaces of noncompact type have trivial topology, but cohomology groups of locally symmetric spaces are usually nontrivial and carry a lot of valuable information both for the arithmetic groups and other related objects, in particular when the locally symmetric spaces can be interpreted as moduli spaces in algebraic geometry and number theory. This point of view can be seen clearly in comparison between the Poincaré upper half plane $\mathbb{H}$ and its arithmetic quotients such as modular curves and Shimura curves.

Though Riemannian symmetric spaces and locally symmetric spaces are probably the most natural spaces associated with arithmetic subgroups of Lie groups, we also try to emphasize that it is natural and important to consider other related spaces such as pseudo-Riemannian symmetric and locally symmetric spaces, buildings (both spherical and Euclidean type) and Teichmüller spaces, which can feed back to symmetric and locally symmetric spaces, besides their own interests. In fact, for S-arithmetic groups such as $SL\left(n,\mathbb{Z}\left[\frac{1}{p_1},\ldots,\frac{1}{p_m}\right]\right)$, both symmetric spaces and buildings are needed simultaneously in order to understand them.

We also discuss some related groups such as tree lattices, building lattices, CAT(0)-groups, mapping class groups, and outer automorphism groups of free groups, and their related spaces such as Teichmüller spaces and moduli spaces of Riemann surfaces, outer spaces, by emphasizing their similarities to arithmetic groups and symmetric spaces, and also to S-arithmetic groups and Bruhat-Tits buildings. By putting all these related groups and spaces together at one place, results from one class can motivate and suggest results for another class.

Hopefully the reader will be convinced of and appreciate more the importance and ubiquity of arithmetic groups in mathematics, and consequently, learn some non-obvious connections between different subjects through them, by the snapshots on motivations, informal descriptions of basic objects and applications, and the many references included in this book, which might also serve as a partial guide to the huge literature on arithmetic groups and related topics.

Acknowledgements

The original motivation to write this book, or rather article, was to provide an informal guide to the students attending an instructional conference titled *Geometry, analysis and topology of discrete groups and locally symmetric spaces* held in Beijing from July 17 to August 4, 2006, at the Morningside Center of Mathematics. The introduction to the conference describes its purpose:

Locally symmetric spaces and discrete subgroups of Lie groups have played a fundamental role in many branches of modern mathematics. Various aspects of these important objects are often studied by different groups of people using different methods. It would be beneficial and fruitful to bring together experts in all these areas to exchange their results, techniques, to develop possible collaborations, and to show the power and beauty of locally symmetric spaces and discrete subgroups of Lie groups.

A shorter and incomplete version of this article was circulated at the conference. Encouragement from several people, including L. Carbone, R. Spatzier, T. Kobayashi, E. Leuzinger, and P. Gunnells, helped me not only to finish this article, but to turn it into a book. Although the work is still not as complete nor as detailed as I had planned it to be, or as it could be[1], I hope that it might still be of some interest to students and non-experts who would like to learn something informal about arithmetic groups and related topics (as one learns from a colleague over tea time or at colloquium dinners), and who wonder about where to look up relevant references.[2] [3]

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[1]Ideally, this book should give precise definitions of important concepts introduced, state significant theorems, explain their applications, and describe in some detail of interactions between various topics introduced below.

[2]I have always been wondering how and where arithmetic groups are used in some unexpected areas of mathematics, and how some other mathematical objects and methods are motivated by arithmetic subgroups and their associated symmetric and locally symmetric spaces. The above three weeks long conference on geometry, analysis and topology of discrete subgroups and locally symmetric spaces with talks by experts from different subjects around the world was very instructive to me. Writing this book has also been a very instructive and rewarding, though demanding and tiresome, experience to me.

[3]It should also be pointed out and emphasized right from the beginning that there are many subjects connected with arithmetic subgroups and related discrete subgroups, and a huge literature on many important topics in these subjects. Though efforts have been made and experts have been consulted to make the coverage of this book and its references comprehensive, I would like to apologize in advance to people whose important

I would like to thank R. Spatzier for very helpful references, discussions and comments on an earlier version (in particular about the Zimmer program), V. Jones for references and suggestions on rigidity in the theory of von Neumann algebras associated with countable groups (in particular lattices of semisimple Lie groups), K. Brown for suggesting to include outer automorphism groups of free groups and alerting me to their close relations with mapping class groups and arithmetic groups, S. Zelditch for some references on quantum chaos, R. Miatello for some references on automorphic forms, J. Schwermer for some references on cohomology of arithmetic groups, K. Vogtmann for some references on the outer automorphism groups of hyperbolic groups, G. Prasad for some references and conversations on automorphism groups of buildings, T. Januszkiewicz for conversations on CAT(0)-groups, L. Saper for comments and references on precise reduction theory and cohomology groups, S.T. Yau for comments and references on rigidity of Hermitian locally symmetric spaces, F. Luo for comments on the automorphism group of the curve complex of surfaces, A. Bloch for helpful conversations and references, J. Milne and S. Gelbart for very helpful comments, Peter Li and M. Olbrich for very helpful comments and references, S. Donkin, S. Friedberg and P. Igodt for helpful references, A. Deitmar for carefully reading an earlier version and many helpful comments, U. Bunke and Shihai Yang for many comments on the first preliminary version circulated at the conference and some references, and M. Goresky for some constructive suggestions. I would also like to thank A. Ranicki for suggesting to turn this article into book form, which greatly encouraged me to speed up the writing and revising process.

Especially, I would like to thank T. Kobayashi for many helpful comments and suggestions, in particular on unitary representations and discontinuous groups for pseudo-Riemannian cases, and for his substantial contributions to §4.8, §11.9, §15.5 and §15.6, E. Leuzinger for contributing to the subsections §3.3.13, §13.9 and §17.9, L. Carbone for contributing to the subsections §5.10, §12.14, §18.1 and §18.2, and S. Zelditch for contributing to the subsection §12.6.

I would also like to thank the Morningside Center of Mathematics in Beijing, in particular Lo Yang and Xiaoning Li, for making the conference mentioned above run smoothly, and thank the speakers of the conference for their interests and help in various ways. Otherwise this project would certainly not be finished since it is really beyond my ability and knowledge to give a comprehensive survey and guide on the vast and broad subjects of arithmetic groups and related topics, and the huge, still rapidly expanding, literature on them.

This long and non-standard article (or rather, short and unusual book) is closely related to the joint book with A. Borel [BoreJ]. The working

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contributions and papers are not mentioned (or not discussed adequately) in this little book due to the lack of knowledge and of ability of the author to describe them.

experience with him from 1997 to 2003 has had a lot of influence on both the writing and contents of this book. Besides doing mathematics proper, he shared with me many of his other insights. I would also like to thank M. Goresky and R. MacPherson for conversations over the years about arithmetic groups, their associated cohomology groups and compactifications, which instilled in me a desire to learn more about general arithmetic groups, locally symmetric spaces and related results.

Finally, I would like to thank S.T. Yau for his intensive student seminar during my graduate school years, where many papers in broad areas of geometry and analysis were lectured on and discussed. Those years opened up my appetite for learning more mathematics and understanding better relations between different parts of mathematics, and allowed me to be immersed in a very stimulating environment.[4] They also fully prepared me for attending multi-seminar talks and multi-conferences nonstop.

During the preparation of this book, I have been partially supported by NSF grant DMS 0604878. I also enjoyed the hospitality of the Morningside Center of Mathematics in Beijing and the Center of Mathematical Sciences in Hangzhou during a part of the summer of 2006.

Lizhen Ji
Ann Arbor, November 2007.

[4]Here I quote several pieces of simple and profound advice from S.T. Yau to his students:

(1) If you need something from a new subject or area, just learn it!
(2) Nothing is as simple as you may think, but not as hard as you might fear either.
(3) Study and learn mathematics for the joy and excitement of doing it.

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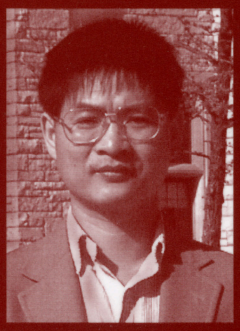

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In one guise or another, many mathematicians are familiar with certain arithmetic groups, such as $\mathbf{Z}$ or $\mathrm{SL}(n, \mathbf{Z})$. Yet, many applications of arithmetic groups and many connections to other subjects within mathematics are less well known. Indeed, arithmetic groups admit many natural and important generalizations.

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