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PREFACE TO THE SECOND EDITION

The text of the second edition, except for minor corrections, is identical with that of the first edition. A new bibliography and three appendices have been added in order to bring the material up to date. Appendix A indicates the present status of the problems which were noted as open in the first edition. Appendix B gives Goldie's theory of prime and semi-prime rings satisfying certain maximum conditions on one sided ideals. This theory is the most important contribution to the structure theory of rings which has appeared since the publication of the first edition. Appendix C gives a brief proof, due to Higgins, of a theorem of Nagata and Higman on nil rings.

I am indebted to Professors P. Cohn, C. Faith and E. Lazerson for lists of errata for the original text and to my assistant, D. Verma, for compiling the new bibliography. I am indebted also to the Air Force Offfice of Scientific Research for support during the preparation of the revised edition.

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PREFACE

Since the appearance of the author's *Theory of Rings* and Artin, Nesbitt and Thrall's *Rings with Minimum Condition*, a number of important developments have taken place in the theory of (non-commutative) rings. These are: the structure theory of rings without finiteness assumptions, cohomology of algebras, and structure and representation theory of non-semi-simple rings (Frobenius algebras, quasi-Frobenius rings). The main purpose of the present volume is to give an account of the first of these developments. The tools which have been devised for the study of general rings yield improved proofs of the older structure results on rings with minimum condition and of finite dimensional algebras. We have therefore considered the specialization of the general results and methods to these classical cases. Thus the present volume includes virtually all the results on semi-simple rings which can be found in the two books cited before. For example, the theory of centralizers of finite dimensional simple subalgebras of simple rings with minimum condition appears as a special case of the Galois theory of the complete ring of linear transformations of a vector space over a division ring. We believe that the passage to the more general case gives a better insight into these results.

The general structure theory is applicable also to a number of important new classes of rings. Of particular interest are the primitive rings with minimal ideals, algebraic algebras and algebras with a polynomial identity. The first class includes the rings of bounded operators in Banach spaces. Some of the results (e.g. the isomorphism theorem) were first obtained for this special case (Eidelheit's theorem). The study of algebraic algebras presents a number of interesting problems, one of the most interesting being Kurosch's analogue of Burnside's problem on periodic groups: Is every finitely generated algebraic algebra finite dimensional? In striking contrast with the situation in the group case, important positive results have been obtained for algebraic algebras. In particular, the analogue of the restricted Burnside problem has an affirmative answer for algebraic algebras. This fact is a corollary of a more general result on PI-algebras (algebras satisfying a polynomial identity).

The starting point in our considerations is the definition of a radical for an arbitrary ring. This is an ideal which measures the departure of a ring from semi-simplicity. A semi-simple ring is one which has enough irreducible representations to distinguish elements. A ring which has a faithful irreducible representation is called primitive. Chapter I is devoted to the basic properties of the radical, semi-simplicity and primitivity for rings and algebras. The considerations of Chapter II center around a density theorem for primitive rings. This is a special case of a more general result involving mappings of one vector space into a second one. The generalization and a lemma used in its proof are used in Chapter IV to derive all the elementary results on dual vector spaces. An extension of the density theorem for primitive rings to completely reducible modules is given in Chapter VI. Chapter III is concerned with rings satisfying the minimum condition for right ideals. In the first part we consider the theory of semi-simple rings with minimum condition. Next we collect a number of formal results on idempotents and matrix units. Finally we consider the notions of semi-primary and primary rings and we obtain structure theorems for these. Chapter IV is devoted to the structure theory of primitive rings with minimal ideals. We determine the isomorphisms, anti-isomorphisms and derivations for such rings. In Chapter V we define Kronecker products of modules and algebras and we reduce the problems of determining the structure of Kronecker products of simple algebras to the case of division algebras and fields. The notions of multiplication algebra and centroid play an important role in these considerations. Chapter VI is concerned with completely reducible modules and their centralizers. The last part of this chapter deals with the Galois theory of the complete ring of linear transformations of a vector space over a division ring. Chapter VII lays the foundations for the study of division rings which may be infinite dimensional over their centers. We consider the Galois theory of automorphisms for division rings, the structure of Kronecker products of division rings, and commutativity theorems (e.g. Wedderburn's theorem on finite division rings). In Chapter VIII we consider several types of nil radicals. One of these is the lower nil radical of Baer which coincides with the intersection of the prime ideals of a ring. We consider also nil subsystems of rings with maximum or minimum condition for right ideals. In Chapter IX we define a topology of the set of primitive ideals of a ring and we use this to obtain representations of rings as rings of continuous functions on topological spaces. The earliest result of this type is Stone's representation theorem for Boolean algebras. In Chapter X the structure theory is applied to commutativity theorems for general rings and to the study of PI-algebras and algebraic algebras. The main results on Kurosch's problem are derived here.

We have tried to make our presentation self-contained and to give complete proofs, particularly in the basic results. The only knowledge assumed is that of the rudiments of ring and module theory such as is found in any of the introductory texts to abstract algebra. Occasionally we have left proofs as exercises, but this has been done only in secondary results.

The principal contributors to the structure theory of rings without finiteness conditions have been Amitsur, Azumaya, Baer, Chevalley, Dieudonné, Kaplansky, Kurosch, Levitzki, McCoy, Nakayama and the present author. We had planned originally to write a series of notes indicating individual contributions. However, we had to abandon this project since it would have delayed still further the publication of this book which has been in process for several years. Instead we have substituted brief textual references to sources from time to time and we have listed the basic papers bearing on the subject of each chapter at the end of the chapter. We have also added a few references to papers which give further results on the topics considered. The bibliography at the end of the book is fairly complete for papers appearing since about 1943. For earlier references we refer to the bibliography of our *Theory of Rings* (Mathematical Surveys, No. 2, 1943).

We are greatly indebted to a number of friends for assistance in preparing this manuscript. The first version of this book was based on our lecture notes, which were prepared by M. Weisfeld. Later versions were read by Dieudonné, A. Rosenberg and Zelinsky who made a number of important suggestions for improvements. We are indebted also to Amitsur and to the late Professor Levitzki for communicating to us results prior to publication. Finally, we wish to express our hearty thanks to C. W. Curtis, F. Quigley, A. Rosenberg, G. Seligman and F. D. Jacobson for valuable help with the proofs.

New Haven, May 1, 1956.

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