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Uri M. Ascher　Linda R. Petzold

Computer Methods for Ordinary Differential Equations and Differential-Algebraic Equations

常微分方程和微分代数方程的计算机方法

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《国外数学名著系列》(影印版)序

要使我国的数学事业更好地发展起来，需要数学家淡泊名利并付出更艰苦地努力。另一方面，我们也要从客观上为数学家创造更有利的发展数学事业的外部环境，这主要是加强对数学事业的支持与投资力度，使数学家有较好的工作与生活条件，其中也包括改善与加强数学的出版工作。

从出版方面来讲，除了较好较快地出版我们自己的成果外，引进国外的先进出版物无疑也是十分重要与必不可少的。从数学来说，施普林格(Springer)出版社至今仍然是世界上最具权威的出版社。科学出版社影印一批他们出版的好的新书，使我国广大数学家能以较低的价格购买，特别是在边远地区工作的数学家能普遍见到这些书，无疑是对推动我国数学的科研与教学十分有益的事。

这次科学出版社购买了版权，一次影印了 23 本施普林格出版社出版的数学书，就是一件好事，也是值得继续做下去的事情。大体上分一下，这 23 本书中，包括基础数学书 5 本，应用数学书 6 本与计算数学书 12 本，其中有些书也具有交叉性质。 这些书都是很新的，2000 年以后出版的占绝大部分，共计 16 本，其余的也是 1990 年以后出版的。这些书可以使读者较快地了解数学某方面的前沿，例如基础数学中的数论、代数与拓扑三本，都是由该领域大数学家编著的“数学百科全书”的分册。对从事这方面研究的数学家了解该领域的前沿与全貌很有帮助。按照学科的特点，基础数学类的书以“经典”为主，应用和计算数学类的书以“前沿”为主。这些书的作者多数是国际知名的大数学家，例如《拓扑学》一书的作者诺维科夫是俄罗斯科学院的院士，曾获“菲尔兹奖”和“沃尔夫数学奖”。这些大数学家的著作无疑将会对我国的科研人员起到非常好的指导作用。

当然，23 本书只能涵盖数学的一部分，所以，这项工作还应该继续做下去。更进一步，有些读者面较广的好书还应该翻译成中文出版，使之有更大的读者群。

总之，我对科学出版社影印施普林格出版社的部分数学著作这一举措表示热烈的支持，并盼望这一工作取得更大的成绩。

王　元

2005 年 12 月 3 日

Preface

This book was developed from course notes that we wrote, having repeatedly taught courses on the numerical solution of ordinary differential equations (ODEs) and related problems. We have taught such courses at a senior undergraduate level as well as at the level of a first graduate course on numerical methods for differential equations. The audience typically consists of students from mathematics, computer science, and a variety of disciplines in engineering and the sciences such as mechanical, electrical, and chemical engineering, physics, and earth sciences.

The material that this book covers can be viewed as a first course on the numerical solution of differential equations. It is designed for people who want to gain a practical knowledge of the techniques used today. The course aims to achieve a thorough understanding of the issues and methods involved and of the reasons for the successes and failures of existing software. On one hand, we avoid an extensive, thorough, theorem-proof–type exposition: we try to get to current methods, issues, and software as quickly as possible. On the other hand, this is not a quick recipe book, as we feel that a deeper understanding than can usually be gained by a recipe course is required to enable students or researchers to use their knowledge to design their own solution approaches for any nonstandard problems they may encounter in future work. The book covers initial value and boundary value problems, as well as differential-algebraic equations (DAEs). In a one-semester course, we have typically been covering over 75% of the material it contains.

We wrote this book partially as a result of frustration at not being able to assign a textbook adequate for the material that we have found ourselves covering. There is certainly excellent, in-depth literature around. In fact, we are making repeated references to exhaustive texts which, combined, cover almost all the material in this book. Those books contain the proofs and references which we omit. They span thousands of pages, though, and the time commitment required to study them in adequate depth may be more than many students and researchers can afford to invest. We have tried to stay within a 350-page limit and to address all three ODE-related areas mentioned above. A significant amount of additional material is covered in the exercises that conclude all but the first chapter. Other additional important topics are referred to in brief sections titled "Notes and References." Software is an important and well-developed part of this subject. We have attempted to cover the most fundamental software issues in the text. Much of the excellent and publicly available software is described in the "Software" sections at the end of the relevant chapters, and available codes are cross-referenced in the index. Review material is highlighted and presented in the text when needed, and it is also cross-referenced in the index.

Traditionally, numerical ODE texts have spent a great deal of time developing families of higher-order methods, e.g., Runge–Kutta and linear multistep methods, applied first to nonstiff problems and then to stiff problems. Initial value problems and boundary value problems have been treated in separate texts, although they have much in common. There have been fundamental differences in approach, notation, and even basic definitions between ODE initial value problems, ODE boundary value problems, and partial differential equations (PDEs).

We have chosen instead to focus on the classes of problems to be solved, mentioning wherever possible applications which can lend insight into the requirements and the potential sources of difficulty for numerical solution. We begin by outlining the relevant mathematical properties of each problem class, then carefully develop the lower-order numerical methods and fundamental concepts for the numerical analysis. Next we introduce the appropriate families of higher-order methods, and finally we describe in some detail how these methods are implemented in modern adaptive software. An important feature of this book is that it gives an integrated treatment of ODE initial value problems, ODE boundary value problems, and DAEs, emphasizing not only the differences between these types of problems but also the fundamental concepts, numerical methods, and analysis which they have in common. This approach is also closer to the typical presentation for PDEs, leading, we hope, to a more natural introduction to that important subject.

Knowledge of significant portions of the material in this book is essential for the rapidly emerging field of numerical dynamical systems. These are numerical methods employed in the study of the long-term, qualitative behavior of various nonlinear ODE systems. We have emphasized and developed in this work relevant problems, approaches, and solutions. But we avoided developing further methods which require deeper, or more specific, knowledge of dynamical systems, which we did not want to assume as a prerequisite.

The plan of the book is as follows. Chapter 1 is an introduction to the different types of mathematical models which are addressed in the book. We use simple examples to introduce and illustrate initial and boundary value problems for ODEs and DAEs. We then introduce some important applications where such problems arise in practice.

Each of the three parts of the book which follow starts with a chapter which summarizes essential theoretical or analytical issues (i.e., before applying any numerical method). This is followed by chapters which develop and analyze numerical techniques. For initial value ODEs, which comprise roughly half of this book, Chapter 2 summarizes the theory most relevant for computer methods, Chapter 3 introduces all the basic concepts and simple methods (relevant also for boundary value problems and for DAEs), Chapter 4 is devoted to one-step (Runge–Kutta) methods, and Chapter 5 discusses multistep methods.

Chapters 6–8 are devoted to boundary value problems for ODEs. Chapter 6 discusses the theory which is essential to understanding and making effective use of the numerical methods for these problems. Chapter 7 briefly considers shooting-type methods, and Chapter 8 is devoted to finite difference approximations and related techniques.

The remaining two chapters consider DAEs. This subject has been researched and solidified only very recently (in the past 15 years). Chapter 9 is concerned with background material and theory. It is much longer than Chapters 2 and 6 because understanding the relationship between ODEs and DAEs, and the questions regarding reformulation of DAEs, is essential and already suggests a lot regarding computer approaches. Chapter 10 discusses numerical methods for DAEs.

Various courses can be taught using this book. A 10-week course can be based on the first 5 chapters, with an addition from either one of the remaining two parts. In a 13-week course (or shorter in a more advanced graduate class) it is possible to comfortably cover Chapters 1–5 and either Chapters 6–8 or Chapters 9–10, with a more superficial coverage of the remaining material.

The exercises vary in scope and level of difficulty. We have provided some hints, or at least warnings, for those exercises that we (or our students) have found more demanding.

Many people helped us with the tasks of shaping up, correcting, filtering, and refining the material in this book. First and foremost are our students in the various classes we taught on this subject. They made us acutely aware of the difference between writing with the desire to explain and writing with the desire to impress. We note, in particular, G. Lakatos, D. Aruliah, P. Ziegler, H. Chin, R. Spiteri, P. Lin, P. Castillo, E. Johnson, D. Clancey, and D. Rasmussen. We have benefitted particularly from our earlier collaborations on other, related books with K. Brenan, S. Campbell, R. Mattheij, and R. Russell. Colleagues who have offered much insight, advice, and criticism include E. Biscaia, G. Bock, C. W. Gear, W. Hayes, C. Lubich, V. Murata, N. Nedialkov, D. Negrut, D. Pai, J. B. Rosen, L. Shampine, and A. Stuart. Larry Shampine, in particular, did an incredibly extensive refereeing job and offered many comments which have helped us to significantly improve this text. We have also benefitted from the comments of numerous anonymous referees.

U. M. Ascher
L. R. Petzold

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