

# The Numerical Integration of Ordinary Differential Equations†

By C. W. Gear

**Abstract.** Multistep methods for initial value problems are expressed in a matrix form. The application of such methods to higher-order equations is studied with the result that new techniques for both first- and higher-order equations are found. The direct approach to higher-order equations is believed to offer speed and accuracy advantages; some numerical evidence is presented. The new technique applied to first-order equations is a slight extension of the conventional multistep method and avoids the Dahlquist [2] stability theorem, that is, these new  $k$ -step methods are of order  $2k$  and yet convergent. The matrix formalism introduced provides an easy mechanism for examining the equivalence of methods as introduced by Descloix [3]. It is pointed out that the new first-order method on  $k$ -steps, Adams' method on  $(2k - 1)$ -steps and Nordsieck's [7] method with  $2k$  components are equivalent to each other. In fact, all methods discussed can be placed in equivalence classes so that theorems need only be proved for one member of each class. The choice between the members of a class can be made on the basis of round-off errors and amount of computation only. Arguments are given in favor of the extension of Nordsieck's method for general use because of its speed and applicability to higher order problems directly. The theorems ensuring convergence and giving the asymptotic form of the error are stated. The proofs can be found in a cited report.

**1. Introduction.** This paper is concerned with the integration of initial value problems for a system of ordinary differential equations of the form

$$(1.1) \quad y_i^{(p_i)} = f_i(x, y_1, \dots, y_1^{(p_1-1)}, y_2, \dots, y_s^{(p_s-1)}), \quad i = 1, 2, \dots, s,$$

where  $y^{(k)} = d^k y / dx^k$ . The motivation for the work was to try and integrate such equations directly rather than as a larger system of first-order equations. The study led to a matrix representation for multistep methods that is an extension of a similar representation due to Descloix [3]. This representation provides a unified approach to equations of all orders; it is sufficient and easier to study it in detail for first-order equations. The usual theorems of stability and convergence, etc. are stated for general higher-order systems in Section 5. The proofs can be found in Gear [5].

**2. Multistep Methods.** The equation  $y' = f(x, y)$  is frequently integrated numerically by a predictor-corrector algorithm of the following form:

Let  $x_n = x_0 + nh$  where  $h$  is the step size, and let  $y_n$  and  $y_n'$  be approximations to the values of  $y(x_n)$  and  $dy(x_n)/dx$  obtained in some manner. The values of  $y$  and  $y'$  at  $x_{n+1}$  are found by the sequence of steps: predictor formula

$$(2.1) \quad y_{n+1}^{(0)} = \sum_{j=1}^k (\alpha_j^* y_{n-j+1} + \beta_j^* h y'_{n-j+1}),$$

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# Numerical Integration Of Differential Equations

**National Research Council (U.S.).  
Committee on Numerical  
Integration, Albert Arnold Bennett**

## **Numerical Integration Of Differential Equations:**

Geometric Numerical Integration Ernst Hairer, Christian Lubich, Gerhard Wanner, 2006-05-18 This book covers numerical methods that preserve properties of Hamiltonian systems reversible systems differential equations on manifolds and problems with highly oscillatory solutions It presents a theory of symplectic and symmetric methods which include various specially designed integrators as well as discusses their construction and practical merits The long time behavior of the numerical solutions is studied using a backward error analysis combined with KAM theory

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Bennett, William Edmund Milne, Harry Bateman, 1933 *Numerical Methods for Differential Equations* J.R.

Dormand, 2018-05-04 With emphasis on modern techniques Numerical Methods for Differential Equations A Computational Approach covers the development and application of methods for the numerical solution of ordinary differential equations Some of the methods are extended to cover partial differential equations All techniques covered in the text are on a program disk included with the book and are written in Fortran 90 These programs are ideal for students researchers and practitioners because they allow for straightforward application of the numerical methods described in the text The code is easily modified to solve new systems of equations Numerical Methods for Differential Equations A Computational Approach also contains a reliable and inexpensive global error code for those interested in global error estimation This is a valuable text for students who will find the derivations of the numerical methods extremely helpful and the programs themselves easy to use It is also an excellent reference and source of software for researchers and practitioners who need computer solutions to differential equations *Numerical Integration of Differential Equations and Large Linear Systems* J. Hinze, 2006-11-15

**Numerical Methods for Ordinary Differential Equations** David F. Griffiths, Desmond J. Higham, 2010-11-11

Numerical Methods for Ordinary Differential Equations is a self contained introduction to a fundamental field of numerical analysis and scientific computation Written for undergraduate students with a mathematical background this book focuses on the analysis of numerical methods without losing sight of the practical nature of the subject It covers the topics traditionally treated in a first course but also highlights new and emerging themes Chapters are broken down into lecture sized pieces motivated and illustrated by numerous theoretical and computational examples Over 200 exercises are provided and these are starred according to their degree of difficulty Solutions to all exercises are available to authorized instructors The book covers key foundation topics o Taylor series methods o Runge Kutta methods o Linear multistep methods o Convergence o Stability and a range of modern themes o Adaptive stepsize selection o Long term dynamics o Modified equations o Geometric integration o Stochastic differential equations The prerequisite of a basic university level calculus class is assumed although appropriate background results are also summarized in appendices A dedicated website for the book containing extra information can be found via [www.springer.com](http://www.springer.com)

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**and Large Linear Systems**, 1980     *Numerical Integration of Differential Equations and Large Linear Systems* J.

Hinze, 2014-01-15     **Numerical Methods for Initial Value Problems in Ordinary Differential Equations** Simeon Ola

Fatunla, 2014-05-10 Numerical Method for Initial Value Problems in Ordinary Differential Equations deals with numerical treatment of special differential equations stiff stiff oscillatory singular and discontinuous initial value problems characterized by large Lipschitz constants The book reviews the difference operators the theory of interpolation first integral mean value theorem and numerical integration algorithms The text explains the theory of one step methods the Euler scheme the inverse Euler scheme and also Richardson s extrapolation The book discusses the general theory of Runge Kutta processes including the error estimation and stepsize selection of the R K process The text evaluates the different linear multistep methods such as the explicit linear multistep methods Adams Bashforth 1883 the implicit linear multistep methods Adams Moulton scheme 1926 and the general theory of linear multistep methods The book also reviews the existing stiff codes based on the implicit semi implicit singly diagonally implicit Runge Kutta schemes the backward differentiation formulas the second derivative formulas as well as the related extrapolation processes The text is intended for undergraduates in mathematics computer science or engineering courses and for postgraduate students or researchers in related disciplines     **Numerical Solution of Ordinary Differential Equations** Nik Pachis, 2016-04-01 Numerical

methods for ordinary differential equations are methods used to find numerical approximations to the solutions of ordinary differential equations ODEs Their use is also known as numerical integration although this term is sometimes taken to mean the computation of integrals An ordinary differential equation or ODE is a differential equation containing one or more functions of one independent variable and its derivatives The term ordinary is used in contrast with the term partial differential equation which may be with respect to more than one independent variable Ordinary differential equations are ubiquitous in science and engineering in geometry and mechanics from the first examples onwards Newton Leibniz Euler Lagrange in chemical reaction kinetics molecular dynamics electronic circuits population dynamics and many more application areas They also arise after semi discretization in space in the numerical treatment of time dependent partial differential equations which are even more impressively omnipresent in our technologically developed and financially controlled world The book Numerical Solution of Ordinary Differential Equations offers a complete and easy to follow introduction to classical topics in the numerical solution of ordinary differential equations The book s approach not only explains the presented mathematics but also helps readers understand how these numerical methods are used to solve real world problems     *Applying Integrals of Motion to the Numerical Solution of Differential Equations* Donald J. Jezewski, 1980

*Numerical integration of differential equations: report of Committee...* National Research Council (U.S.). Committee on Numerical Integration, Albert Arnold Bennett,     **Numerical Integration of Stochastic Differential Equations** G.N. Milstein, 2013-03-09 This book is devoted to mean square and weak approximations of solutions of stochastic differential

equations SDE These approximations represent two fundamental aspects in the contemporary theory of SDE Firstly the construction of numerical methods for such systems is important as the solutions provided serve as characteristics for a number of mathematical physics problems Secondly the employment of probability representations together with a Monte Carlo method allows us to reduce the solution of complex multidimensional problems of mathematical physics to the integration of stochastic equations Along with a general theory of numerical integrations of such systems both in the mean square and the weak sense a number of concrete and sufficiently constructive numerical schemes are considered Various applications and particularly the approximate calculation of Wiener integrals are also dealt with This book is of interest to graduate students in the mathematical physical and engineering sciences and to specialists whose work involves differential equations mathematical physics numerical mathematics the theory of random processes estimation and control theory

**A Concise Introduction to Geometric Numerical Integration** Sergio Blanes, Fernando Casas, 2017-11-22 Discover How Geometric Integrators Preserve the Main Qualitative Properties of Continuous Dynamical Systems A Concise Introduction to Geometric Numerical Integration presents the main themes techniques and applications of geometric integrators for researchers in mathematics physics astronomy and chemistry who are already familiar with numerical tools for solving differential equations It also offers a bridge from traditional training in the numerical analysis of differential equations to understanding recent advanced research literature on numerical geometric integration The book first examines high order classical integration methods from the structure preservation point of view It then illustrates how to construct high order integrators via the composition of basic low order methods and analyzes the idea of splitting It next reviews symplectic integrators constructed directly from the theory of generating functions as well as the important category of variational integrators The authors also explain the relationship between the preservation of the geometric properties of a numerical method and the observed favorable error propagation in long time integration The book concludes with an analysis of the applicability of splitting and composition methods to certain classes of partial differential equations such as the Schrödinger equation and other evolution equations The motivation of geometric numerical integration is not only to develop numerical methods with improved qualitative behavior but also to provide more accurate long time integration results than those obtained by general purpose algorithms Accessible to researchers and post graduate students from diverse backgrounds this introductory book gets readers up to speed on the ideas methods and applications of this field Readers can reproduce the figures and results given in the text using the MATLAB programs and model files available online

**Numerical Methods for Differential Equations and Applications** Liviu Gr. Ixaru, 1984-08-31

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partial differential equations finite difference method finite element approximations design of numerical approximations and analytical tools Includes review of linear algebra      **Numerical Methods for Engineers and Scientists, Second Edition**, Joe D. Hoffman, Steven Frankel, 2001-05-31 Emphasizing the finite difference approach for solving differential equations the second edition of Numerical Methods for Engineers and Scientists presents a methodology for systematically constructing individual computer programs Providing easy access to accurate solutions to complex scientific and engineering problems each chapter begins with objectives a discussion of a representative application and an outline of special features summing up with a list of tasks students should be able to complete after reading the chapter perfect for use as a study guide or for review The AIAA Journal calls the book a good solid instructional text on the basic tools of numerical analysis      **Numerical Methods for Partial Differential Equations** William F. Ames, 1969      **Methods of Numerical Integration** Philip J. Davis, Philip Rabinowitz, 2014-05-10 Methods of Numerical Integration Second Edition describes the theoretical and practical aspects of major methods of numerical integration Numerical integration is the study of how the numerical value of an integral can be found This book contains six chapters and begins with a discussion of the basic principles and limitations of numerical integration The succeeding chapters present the approximate integration rules and formulas over finite and infinite intervals These topics are followed by a review of error analysis and estimation as well as the application of functional analysis to numerical integration A chapter describes the approximate integration in two or more dimensions The final chapter looks into the goals and processes of automatic integration with particular attention to the application of Tschebyscheff polynomials This book will be of great value to theoreticians and computer programmers      **Numerical Methods for Delay Differential Equations** Alfredo Bellen, Marino Zennaro, 2013-01-10 This unique book describes analyses and improves various approaches and techniques for the numerical solution of delay differential equations It includes a list of available codes and also aids the reader in writing his or her own      **Numerical Methods for Ordinary Differential Equations** J. C. Butcher, 2016-08-05 A new edition of this classic work comprehensively revised to present exciting new developments in this important subject The study of numerical methods for solving ordinary differential equations is constantly developing and regenerating and this third edition of a popular classic volume written by one of the world's leading experts in the field presents an account of the subject which reflects both its historical and well established place in computational science and its vital role as a cornerstone of modern applied mathematics In addition to serving as a broad and comprehensive study of numerical methods for initial value problems this book contains a special emphasis on Runge Kutta methods by the mathematician who transformed the subject into its modern form dating from his classic 1963 and 1972 papers A second feature is general linear methods which have now matured and grown from being a framework for a unified theory of a wide range of diverse numerical schemes to a source of new and practical algorithms in their own right As the founder of general linear method research John Butcher has been a leading contributor to its development his special

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