Preface

The scientific method is based on the measurement of different physical quantities and the search for relations between their values. All measured values of physical quantities are, however, affected by uncertainty. Understanding the origin of uncertainty, evaluating its extent, and suitably taking it into account in data analysis, are fundamental steps for assessing the global accuracy of physical laws and the degree of reliability of their technological applications.

The introduction to uncertainty evaluation and data analysis procedures is generally made in laboratory courses for freshmen. During my long-lasting teaching experience, I had the feeling of some sort of gap between the available tutorial textbooks, and the specialized monographs. The present work aims at filling this gap, and has been tested and modified through a feedback interaction with my students for several years. I have tried to maintain as much as possible a tutorial approach, that, starting from a phenomenological introduction, progressively leads to an accurate definition of uncertainty and to some of the most common procedures of data analysis, facilitating the access to advanced monographs. This book is mainly addressed to undergraduate students, but can be a useful reference for researchers and for secondary school teachers.

The book is divided into three parts and a series of appendices.

Part I is devoted to a phenomenological introduction to measurement and uncertainty. In Chap. 1, the direct and indirect procedures for measuring physical quantities are distinguished, and the unavoidability of uncertainty in measurements is established from the beginning. Measuring physical quantities requires the choice of suitable standard units, and Chap. 2 is dedicated to the International System of units and to dimensional analysis. To perform measurements, suitable instruments are necessary; the basic properties of instruments are presented in Chap. 3, including the characteristics of static and dynamic performance. Chap. 4 plays a central role; here, the different possible causes of uncertainty are thoroughly explored and compared, and the methodologies for quantitatively evaluating and expressing the uncertainty are explained. The phenomenological introduction of the normal and uniform distributions naturally leads to the demand for a more formal probabilistic approach.

To such an approach, Part II is dedicated. In Chap. 5, the basic concepts of probability theory are presented: sample space, events, definitions of probability, sum and product of events. The theory of probability is further developed in Chap. 6, through the formalism of random variables; the general properties of the distributions of random variables are introduced, and attention is focused on the distributions most frequently encountered in physics: binomial, Poisson, normal, uniform, and Cauchy–Lorentz. Chap. 7 is devoted to some basic statistical concepts and tools: parent and sample populations, estimate of population parameters, and the maximum likelihood criterion.

In Part III, some common data analysis procedures are introduced. Chap. 8 is dedicated to the propagation of uncertainty in indirect measurements. Chap. 9 introduces the distinction between probability and confidence, and presents some relevant applications of the confidence level and the Student distribution. In Chap. 10, the correlation between physical quantities is quantitatively studied by introducing the linear correlation coefficient and the procedures of regression based on the least squares method. Finally, an introduction to the chi square statistical test is made in Chap. 11.

Part IV contains a set of appendices. A clever presentation of data increases the effectiveness of analysis procedures, and guarantees accuracy in communicating the results to other researchers. Appendix A is dedicated to the treatment of significant digits and the use of tables, graphs, and histograms. Appendix B is dedicated to the International System of Units (SI) and to other frequently used systems of units. Appendix C contains some useful tables: the Greek alphabet, a list of selected constants of physics, and the integrals of the probability distributions introduced in previous chapters. Mathematical technicalities have been avoided as much as possible in the main text of the book. Some useful demonstrations can, however, be found in Appendix D by interested readers. The comprehension of theoretical concepts is greatly facilitated by the possibility of practical applications. Several problems are proposed at the end of some chapters. Solving statistical problems is, however, much more effective if they refer to real experiments. Appendix E contains the description of some simple experiments, particularly suited to illustrate the data analysis procedures introduced in this book. The experiments are based on cheap and easily available instrumentation, and their effectiveness has been tested by many classes of students.

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