Preface

Our intention in writing this book is threefold: to distill, to impart exciting new knowledge, and to predict. We have been impelled to delineate and recall the many remarkable achievements already accomplished using electron microscopy, and to focus on what we perceive to be key opportunities for the future exploration of the unique attributes that this powerful technique possesses — and this we do in an unorthodox manner so as to link the fundamentals of microscopy to emerging new concepts and developments.

First, we distill the basic principles involved in imaging and diffraction and in so doing illuminate the central role occupied by notions of coherence and interference. One of us first began using the electron microscope over 40 years ago, principally as an aid to elucidating certain enigmas in his main fields of study: solid-state chemistry, catalysis and surface and materials science. We devote two chapters to the diverse applications of static 2D and 3D imaging covering both organic and inorganic materials as well as biological extended structures, including proteins, viruses, and molecular machines.

The principal focus of the book, however, is on the new development at Caltech of 4D electron microscopy. Because more than a million million frames per second have to be taken in order to produce the picture of atomic motion, the time resolution achieved by stop-motion recording in "real time" far exceeds that of the human brain (milliseconds). Each of us passionately believes that the addition of the time domain to "static" imaging by conventional electron microscopy in its various modes of operation opens up an almost bewildering variety of exciting and important opportunities, especially in probing the intricacies of fundamental dynamic processes. It is well known that the electron microscope (EM) yields information in three distinct ways: in real space, in reciprocal space and, when used in a spectroscopic mode, in energy space. By introducing time resolution, we achieve a fourth domain. Here, our use of the term 4D EM also emphasizes the four fundamental dimensions of matter — three spatial and one temporal. These two notions of 4D EM are, however, inextricably interwoven as will become apparent in the ensuing text.

Time resolution in EM now exceeds by ten orders of magnitude that of conventional video cameras, making it feasible to follow the unfolding of various processes in their real length-time coordinates, from micrometer-subsecond down to angstrom-femtosecond. With such resolutions in both space and time, using "tabletop instruments," we believe that the modern 4D electron microscope in its numerous variants is unique (when compared, for example, with sources of synchrotron radiation) in the exploration of new phenomena and in the retrieval of new knowledge. For this reason, we devote several chapters to the principles of the 4D approach, emphasizing the concept and the merits of timed single-electron imaging in real space, Fourier space, and energy space. Besides the time resolution, there are consequential advantages which are discussed, with emphasis on the opportunities resulting from the spatial and temporal coherence, the brightness, and the degeneracy of (fermionic) electrons when generated as ultrafast packets and in the absence of space–charge repulsion. The applications span physical, mechanical, and some biological systems. We also discuss recent advances made possible in electron-energy-loss spectroscopy (EELS), in tomography and holography. We conclude with an outlook on the future.

This book is not a *vade mecum* — numerous other texts are available for the practitioner of 3D microscopy for that purpose. It is, instead, an in-depth exposé of new paradigms, new concepts and developed techniques, including the significant advances that can now be executed to retrieve new knowledge from the corpus of physical and biological sciences. We presuppose that the reader is acquainted with some introductory aspects of laser science and with the rudiments of basic knowledge of Fourier transformation and other crystallographic procedures, although we have made an effort didactically to present self-sufficient accounts in each chapter.

The first draft of the manuscript was written in Pasadena in August–September of 2008. During that period, we worked with frenetic zeal (up to 12 hours a day!) so as to do justice to the existing rich literature and numerous recent developments. Since then, and before sending the manuscript to the publisher, a variety of new and exciting results have emerged, the most important of which are incorporated herein.

We hope that the reader will share our enthusiasm for the book, and that we have succeeded in its execution to aim at a broad readership within the various disciplines of science, engineering, and medicine. Above all, we hope that we shall induce many young (and old!) readers to enter this field.

Ahmed H. Zewail
Pasadena

John M. Thomas
Cambridge