Transmission Electron Microscopy

A Textbook for Materials Science

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Springer

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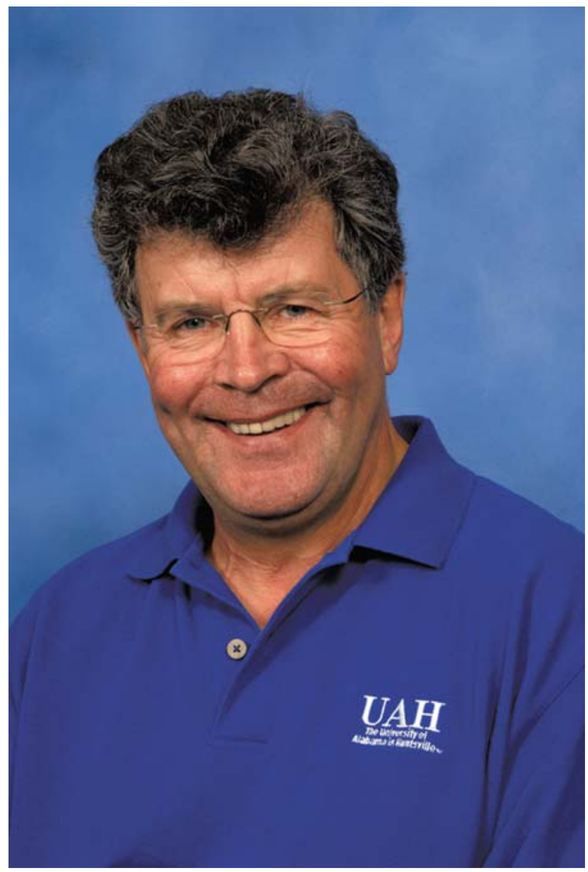
To our parents

Walter Dennis and Mary Isabel Carter
and
Joseph Edward and Catherine Williams,
who made everything possible.

About the Authors



David B. Williams

David B. Williams became the fifth President of the University of Alabama in Huntsville in July 2007. Before that he spent more than 30 years at Lehigh University where he was the Harold Chambers Senior Professor Emeritus of Materials Science and Engineering (MS&E). He obtained his BA (1970), MA (1974), PhD (1974) and ScD (2001) from Cambridge University, where he also earned four Blues in rugby and athletics. In 1976 he moved to Lehigh as Assistant Professor, becoming Associate Professor (1979) and Professor (1983). He directed the Electron Optical Laboratory (1980–1998) and led Lehigh's Microscopy School for over 20 years. He was Chair of the MS&E Department from 1992 to 2000 and Vice Provost for Research from 2000 to 2006, and has held visiting-scientist positions at the University of New South Wales, the University of Sydney, Chalmers University (Gothenburg), Los Alamos National

Laboratory, the Max Planck Institut für Metallforschung (Stuttgart), the Office National d'Etudes et Recherches Aérospatiales (Paris) and Harbin Institute of Technology.

He has co-authored and edited 11 textbooks and conference proceedings, published more than 220 refereed journal papers and 200 abstracts/conference proceedings, and given 275 invited presentations at universities, conferences and research laboratories in 28 countries.

Among numerous awards, he has received the Burton Medal of the Electron Microscopy Society of America (1984), the Heinrich Medal of the US Microbeam Analysis Society (MAS) (1988), the MAS Presidential Science Award (1997) and was the first recipient of the Duncumb award for excellence in microanalysis (2007). From Lehigh, he received the Robinson Award (1979), the Libsch Award (1993) and was the Founders Day commencement speaker (1995). He has organized many national and international microscopy and analysis meetings including the 2nd International MAS conference (2000), and was co-chair of the scientific program for the 12th International Conference on Electron Microscopy (1990). He was an Editor of *Acta Materialia* (2001–2007) and the *Journal of Microscopy* (1989–1995) and was President of MAS (1991–1992) and the International Union of Microbeam Analysis Societies (1994–2000). He is a Fellow of The Minerals Metals and Materials Society (TMS), the American Society for Materials (ASM) International, The Institute of Materials (UK) (1985–1996) and the Royal Microscopical Society (UK).

C. Barry Carter

C. Barry Carter became the Head of the Department of Chemical, Materials & Biomolecular Engineering at the University of Connecticut in Storrs in July 2007. Before that he spent 12 years (1979–1991) on the Faculty at Cornell University in the Department of Materials Science and Engineering (MS&E) and 16 years as the 3 M

Heltzer Multidisciplinary Chair in the Department of Chemical Engineering and Materials Science (CEMS) at the University of Minnesota. He obtained his BA (1970), MA (1974) and ScD (2001) from Cambridge University, his MSc (1971) and DIC from Imperial College, London and his DPhil (1976) from Oxford University. After a postdoc in Oxford with his thesis advisor, Peter Hirsch, in 1977 he moved to Cornell initially as a postdoctoral fellow, becoming an Assistant Professor (1979), Associate Professor (1983) and Professor (1988) and directing the Electron Microscopy Facility (1987–1991). At Minnesota, he was the Founding Director of the High-Resolution Microscopy Center and then the Associate Director of the Center for Interfacial Engineering; he created the Characterization Facility as a unified facility including many forms of microscopy and diffraction in one physical location. He has held numerous visiting scientist positions: in the United States at the Sandia National Laboratories, Los Alamos National Laboratory and Xerox PARC; in Sweden at Chalmers University (Gothenburg); in Germany at the Max Planck Institut für Metallforschung (Stuttgart), the Forschungszentrum Jülich, Hannover University and IFW (Dresden); in France at ONERA (Chatillon); in the UK at Bristol University and at Cambridge University (Peterhouse); and in Japan at the ICYS at NIMS (Tsukuba).

He is the co-author of two textbooks (the other is *Ceramic Materials; Science & Engineering* with Grant Norton) and co-editor of six conference proceedings, and has published more than 275 refereed journal papers and more than 400 extended abstracts/conference proceedings. Since 1990 he has given more than 120 invited presentations at universities, conferences and research laboratories. Among numerous awards, he has received the Simon Guggenheim Award (1985–1986), the Berndt Matthias Scholar Award (1997/1998) and the Alexander von Humboldt Senior Award (1997). He organized the 16th International Symposium on the Reactivity of Solids (ISRS-16 in 2007). He was an Editor of the *Journal of Microscopy* (1995–1999) and of *Microscopy and Microanalysis* (2000–2004), and became (co-)Editor-in-Chief of the *Journal of Materials Science* in 2004. He was the 1997 President of MSA, and served on the Executive Board of the International Federation of Societies for Electron Microscopy (IFSEM; 1999–2002). He is now the General Secretary of the International Federation of Societies for Microscopy (IFSM; 2003–2010). He is a Fellow of the American Ceramics Society (1996) the Royal Microscopical Society (UK), the Materials Research Society (2009) and the Microscopy Society of America (2009).

Preface

How is this book different from the many other TEM books? It has several unique features but what we think distinguishes it from all other such books is that it is truly a *textbook*. We wrote it to be read by, and taught to, senior undergraduates and starting graduate students, rather than studied in a research laboratory. We wrote it using the same style and sentence construction that we have used in countless classroom lectures, rather than how we have written our countless (and much-less read) formal scientific papers. In this respect particularly, we have been deliberate in *not* referencing the sources of every experimental fact or theoretical concept (although we do include some hints and clues in the chapters). However, at the end of each chapter we have included groups of references that should lead you to the best sources in the literature and help you go into more depth as you become more confident about what you are looking for. We are great believers in the value of history as the basis for understanding the present and so the history of the techniques and key historical references are threaded throughout the book. Just because a reference is dated in the previous century (or even the antepenultimate century) doesn't mean it isn't useful! Likewise, with the numerous figures drawn from across the fields of materials science and engineering and nanotechnology, we do not reference the source in each caption. But at the very end of the book each of our many generous colleagues whose work we have used is clearly acknowledged.

The book consists of 40 relatively small chapters (with a few notable Carter exceptions!). The contents of most of the chapters can be covered in a typical lecture of 50-75 minutes (especially if you talk as fast as Williams). Furthermore, each of the four softbound volumes is flexible enough to be usable at the TEM console so you can check what you are seeing against what you should be seeing. Most importantly perhaps, the softbound version is cheap enough for all serious students to buy. So we hope you won't have to try and work out the meaning of the many complex color diagrams from secondhand B&W copies that you acquired from a former student. We have deliberately used color where it is useful rather than simply for its own sake (since all electron signals are colorless anyhow). There are numerous boxes throughout the text, drawing your attention to key information (green), warnings about mistakes you might easily make (amber), and dangerous practices or common errors (red).

Our approach throughout this text is to answer two fundamental questions:

Why should we use a particular TEM technique?
How do we put the technique into practice?

In answering the first question we attempt to establish a sound theoretical basis where necessary although not always giving all the details. We use this knowledge to answer the second question by explaining operational details in a generic sense and showing many illustrative figures. In contrast, other TEM books tend to be either strongly theoretical or predominantly descriptive (often covering more than just TEM). We view our approach as a compromise between the two extremes, covering enough theory to be reasonably rigorous without incurring the wrath of electron physicists yet containing sufficient hands-on instructions and practical examples to be useful to the materials engineer/nanotechnologist who wants an answer to a materials problem rather than just a set of glorious images, spectra, and diffraction patterns. We acknowledge that, in attempting to seek this compromise, we often gloss over the details of much of the physics and math behind the many techniques but contend that the content is usually approximately right (even if on occasions, it might be precisely incorrect!).

Since this text covers the whole field of TEM we incorporate, to varying degrees, *all* the capabilities of the various kinds of current TEMs and we attempt to create a coherent view of the many aspects of these instruments. For instance, rather than separating out the broad-beam techniques of a traditional TEM from the focused-beam techniques of an analytical TEM, we treat these two approaches as different sides of the same coin. There is no reason to regard 'conventional' bright-field imaging in a parallel-beam TEM as being more fundamental (although it is certainly a more-established technique) than annular dark-field imaging in a focused-beam STEM. Convergent beam, scanning beam, and selected-area diffraction are likewise integral parts of the whole of TEM diffraction.

However, in the decade and more since the first edition was published, there has been a significant increase in the number of TEM and related techniques, greater sophistication in the microscope's experimental capabilities, astonishing improvements in computer control of the instrument, and new hardware designs and amazing developments in software to model the gigabytes of data generated by these almost-completely digital instruments. Much of this explosion of information has coincided with the worldwide drive to explore the nanoworld, and the still-ongoing effects of Moore's law. It is not possible to include all of this new knowledge in the second edition without transforming the already doorstop sized text into something capable of halting a large projectile in its tracks. It is still essential that this second edition teaches you to understand the essence of the TEM before you attempt to master the latest advances. But we personally cannot hope to understand fully all the new techniques, especially as we both descend into more administrative positions in our professional lives. Therefore, we have prevailed on almost 20 of our close friends and colleagues to put together with us a companion text (TEM; a companion text, Williams and Carter (Eds.) Springer 2010) to which we will refer throughout this second edition. The companion text is just as it says—it's a friend whose advice you should seek when the main text isn't enough. The companion is not necessarily more advanced but is certainly more detailed in dealing with key recent developments as well as some more traditional aspects of TEM that have seen a resurgence of interest. We have taken our colleagues' contributions and rewritten them in a similar conversational vein to this main text and we hope that this approach, combined with the in-depth cross-referencing between the two texts will guide you as you start down the rewarding path to becoming a transmission microscopist.

We each bring more than 35 years of teaching and research in all aspects of TEM. Our research into different materials includes metals, alloys, ceramics, semiconductors, glasses, composites, nano and other particles, atomic-level planar interfaces, and other crystal defects. (The lack of polymeric and biological materials in our own research is evident in their relative absence in this book.) We have contributed to the training of a generation of (we hope) skilled microscopists, several of whom have followed us as professors and researchers in the EM field. These students represent our legacy to our beloved research field and we are overtly proud of their accomplishments. But we also expect some combination of these (still relatively young) men and women to write the third edition. We know that they, like us, will find that writing such a text broadens their knowledge considerably and will also be the source of much joy, frustration, and enduring friendship. We hope you have as much fun reading this book as we had writing it, but we hope also that it takes you much less time. Lastly, we encourage you to send us any comments, both positive and negative. We can both be reached by e-mail: david.williams@uah.edu and cbcarter@engr.uconn.edu.

Foreword to First Edition

Electron microscopy has revolutionized our understanding of materials by completing the *processing-structure-properties* links down to atomistic levels. It is now even possible to tailor the microstructure (and mesostructure) of materials to achieve specific sets of properties; the extraordinary abilities of modern transmission electron microscopy—TEM—instruments to provide almost all the structural, phase, and crystallographic data allow us to accomplish this feat. Therefore, it is obvious that any curriculum in modern materials education must include suitable courses in electron microscopy. It is also essential that suitable texts be available for the preparation of the students and researchers who must carry out electron microscopy properly and quantitatively.

The 40 chapters of this new text by Barry Carter and David Williams (like many of us, well schooled in microscopy at Cambridge and Oxford) do just that. If you want to learn about electron microscopy from specimen preparation (the ultimate limitation); or via the instrument; or how to use the TEM correctly to perform imaging, diffraction, and spectroscopy—it's all there! This, to my knowledge, is the only complete text now available that includes all the remarkable advances made in the field of TEM in the past 30 to 40 years. The timing for this book is just right and, personally, it is exciting to have been part of the development it covers—developments that have impacted so heavily on materials science.

In case there are people out there who still think TEM is just taking pretty pictures to fill up one's bibliography, please stop, pause, take a look at this book, and digest the extraordinary intellectual demands required of the microscopist in order to do the job properly: crystallography, diffraction, image contrast, inelastic scattering events, and spectroscopy. Remember, these used to be fields in themselves. Today, one has to understand the fundamentals of *all* these areas before one can hope to tackle significant problems in materials science. TEM is a technique of characterizing materials down to the atomic limits. It must be used with care and attention, in many cases involving teams of experts from different venues. The fundamentals are, of course, based in physics, so aspiring materials scientists would be well advised to have prior exposure to, for example, solid-state physics, crystallography, and crystal defects, as well as a basic understanding of materials science, for without the latter, how can a person see where TEM can (or may) be put to best use?

So much for the philosophy. This fine new book definitely fills a gap. It provides a sound basis for research workers and graduate students interested in exploring those aspects of structure, especially defects, that control properties. Even undergraduates are now expected (and rightly) to know the basis for electron microscopy, and this book, or appropriate parts of it, can also be utilized for undergraduate curricula in science and engineering.

The authors can be proud of an enormous task, very well done.

G. Thomas
Berkeley, California

Foreword to Second Edition

This book is an exciting entry into the world of atomic structure and characterization in materials science, with very practical instruction on how you can see it and measure it, using an electron microscope. You will learn an immense amount from it, and probably want to keep it for the rest of your life (particularly if the problems cost you some effort!).

Is nanoscience "the next industrial revolution"? Perhaps that will be some combination of energy, environmental and nanoscience. Whatever it is, the new methods which now allow control of materials synthesis at the atomic level will be a large part of it, from the manufacture of jet engine turbine-blades to that of catalysts, polymers, ceramics and semiconductors. As an exercise, work out how much reduction would result in the transatlantic airfare if aircraft turbine blade temperatures could be increased by 200°C. Now calculate the reduction in CO_2 emission, and increased efficiency (reduced coal use for the same amount of electricity) resulting from this temperature increase for a coal-fired electrical generating turbine. Perhaps you will be the person to invent these urgently needed things! The US Department of Energy's Grand Challenge report on the web lists the remarkable advances in exotic nanomaterials useful for energy research, from separation media in fuel cells, to photovoltaics and nano-catalysts which might someday electrolyze water under sunlight alone. Beyond these functional and structural materials, we are now also starting to see for the first time the intentional fabrication of atomic structures in which atoms can be addressed individually, for example, as quantum computers based perhaps on quantum dots. 'Quantum control' has been demonstrated, and we have seen fluorescent nanodots which can be used to label proteins.

Increasingly, in order to find out exactly what new material we have made, and how perfect it is (and so to improve the synthesis), these new synthesis methods must be accompanied by atomic scale compositional and structural analysis. The transmission electron microscope (TEM) has emerged as the perfect tool for this purpose. It can now give us atomic-resolution images of materials and their defects, together with spectroscopic data and diffraction patterns from sub-nanometer regions. The field-emission electron gun it uses is still the brightest particle source in all of physics, so that electron microdiffraction produces the most intense signal from the smallest volume of matter in all of science. For the TEM electron beam probe, we have magnetic lenses (now aberration corrected) which are extremely difficult for our X-ray and neutron competitors to produce (even with much more limited performance) and, perhaps most important of all, our energy-loss spectroscopy provides unrivalled spatial resolution combined with parallel detection (not possible with X-ray absorption spectroscopy, where absorbed X-rays disappear, rather than losing some energy and continuing to the detector).

Much of the advance in synthesis is the legacy of half a century of research in the semiconductor industry, as we attempt to synthesize and fabricate with other materials what is now so easily done with silicon. Exotic oxides, for example, can now be laid down layer by layer to form artificial crystal structures with new, useful properties. But it is also a result of the spectacular advances in materials characterization, and our ability to see structures at the atomic level. Perhaps the best example of this is the discovery of the carbon nanotube, which was first identified by using an electron microscope. Any curious and observant electron microscopist can now discover new nanostructures just because they look interesting at the atomic scale. The important point is that if this is done in an environmental microscope, he or she will know how to make them, since the thermodynamic conditions will be recorded when using such a 'lab in a microscope'. There are efforts at materials discovery by just such combinatorial trial-and-error methods, which could perhaps be incorporated into our electron microscopes. This is needed because there are often just 'too many possibilities' in nature to explore in the computer — the number of possible structures rises very rapidly with the number of distinct types of atoms.

It was Richard Feynman who said that, "if, in some catastrophe, all scientific knowledge was lost, and only one sentence could be preserved, then the statement to be passed on, which contained the most information in the fewest words, would be that matter consists of atoms." But confidence that matter consists of atoms developed surprisingly recently and as late as 1900 many (including Kelvin) were unconvinced, despite Avagadro's work and Faraday's on electrodeposition. Einstein's Brownian motion paper of 1905 finally persuaded most, as did Rutherford's experiments. Muller was first to see atoms (in his field-ion microscope in the early 1950s), and Albert Crewe two decades later in Chicago, with his invention of the field-emission gun for his scanning transmission electron microscope (STEM). The Greek Atomists first suggested that a stone, cut repeatedly, would eventually lead to an indivisible smallest fragment, and indeed Democritus believed that "nothing exists except vacuum and atoms. All else is opinion." Marco Polo remarks on the use of spectacles by the Chinese, but it was van Leeuwenhoek (1632-1723) whose series of papers in *Phil. Trans.* brought the microworld to the general scientific community for the first time using his much improved optical microscope. Robert Hooke's 1665 Micrographica sketches what he saw through his new compound microscope, including fascinating images of facetted crystallites, whose facet angles he explained with drawings of piles of cannon balls. Perhaps this was the first resurrection of the atomistic theory of matter since the Greeks. Zernike's phase-plate in the 1930s brought phase contrast to previously invisible ultra-thin biological 'phase objects', and so is the forerunner for the corresponding theory in high-resolution electron microscopy.

The past fifty years has been a wonderfully exciting time for electron microscopists in materials science, with continuous rapid advances in all of its many modes and detectors. From the development of the theory of Bragg diffraction contrast and the column approximation, which enables us to understand TEM images of crystals and their defects, to the theory of high-resolution microscopy useful for atomic-scale imaging, and on into the theory of all the powerful analytic modes and associated detectors, such as X-rays, cathodoluminescence and energy-loss spectroscopy, we have seen steady advances. And we have always known that defect structure in most cases controls properties — the most common (first-order) phase transitions are initiated at special sites, and in the electronic oxides a whole zoo of charge-density excitations and defects waits to be fully understood by electron microscopy. The theory of phase-transformation toughening of ceramics, for example, is a wonderful story which combines TEM observations with theory, as does that of precipitate hardening in alloys, or the early stages of semiconductor-crystal growth. The study of diffuse scattering from defects as a function of temperature at phase transitions is in its infancy, yet we have a far stronger signal there than in competing X-ray methods. The mapping of strain-fields at the nanoscale in devices, by quantitative convergent-beam electron diffraction, was developed just in time to solve a problem listed on the Semiconductor Roadmap (the speed of your laptop depends on strain-induced mobility enhancement). In biology, where the quantification of TEM data is taken more seriously, we have seen three-dimensional image reconstructions of many large proteins, including the ribosome (the factory which makes proteins according to DNA instructions). Their work should be a model to the materials science community in the constant effort toward better quantification of data.

Like all the best textbooks, this one was distilled from lecture notes, debugged over many years and generations of students. The authors have extracted the heart from many difficult theory papers and a huge literature, to explain to you in the simplest, clearest manner (with many examples) the most important concepts and practices of modern transmission electron microscopy. This is a great service to the field and to its teaching worldwide. Your love affair with atoms begins!

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Acknowledgments

We have spent over 20 years conceiving and writing this text and the preceding first edition and such an endeavor can't be accomplished in isolation. Our first acknowledgment must be to our respective wives and children: Margie, Matthew, Bryn, and Stephen and Bryony, Ben, Adam, and Emily. Our families have borne the brunt of our absences from home (and occasionally the brunt of our presence). Neither edition would have been possible without the encouragement, advice, and persistence of (and the fine wines served by) Amelia McNamara, our first editor at Plenum Press, then Kluwer, and Springer.

We have both been fortunate to work in our respective universities with many more talented colleagues, post-doctoral associates, and graduate students, all of whom have taught us much and contributed significantly to the examples in both editions. We would like to thank a few of these colleagues directly: Dave Ackland, Faisal Alamgir, Arzu Altay, Ian Anderson, Ilke Arslan, Joysurya Basu, Steve Baumann, Charlie Betz, John Bruley, Derrick Carpenter, Helen Chan, Steve Claves, Dov Cohen, Ray Coles, Vinayak Dravid, Alwyn Eades, Shelley Gillis, Jeff Farrer, Joe Goldstein, Pradyumna Gupta, Brian Hebert, Jason Hefflefinger, John Hunt, Yasuo Ito, Matt Johnson, Vicki Keast, Chris Kiely, Paul Kotula, Chunfei Li, Ron Liu, Charlie Lyman, Mike Mallamaci, Stuart McKernan, Joe Michael, Julia Nowak, Grant Norton, Adam Papworth, Chris Perrey, Sundar Ramamurthy, René Rasmussen, Ravi Ravishankar, Kathy Repa, Kathy Reuter, Al Romig, Jag Sankar, David A. Smith, Kamal Soni, Changmo Sung, Caroline Swanson, Ken Vecchio, Masashi Watanabe, Jonathan Winterstein, Janet Wood, and Mike Zemyan.

In addition, many other colleagues and friends in the field of microscopy and analysis have helped with the book (even if they weren't aware of it). These include Ron Anderson, Raghavan Ayer, Jim Bentley, Gracie Burke, Jeff Campbell, Graham Cliff, David Cockayne, Peter Doig, the late Chuck Fiori, Peter Goodhew, Brendan Griffin, Ron Gronsky, Peter Hawkes, Tom Huber, Gilles Hug, David Joy, Mike Kersker, Roar Kilaas, Sasha Krajnikov, the late Riccardo Levi-Setti, Gordon Lorimer, Harald Müllejans, Dale Newbury, Mike O'Keefe, Peter Rez, Manfred Rühle, John-Henry Scott, John Steeds, Peter Swann, Gareth Thomas, Patrick Veyssière, Peter Williams, Nestor Zaluzec, and Elmar Zeitler. Many of these (and other) colleagues provided the figures that we acknowledge individually at the end of the book.

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Institut für Metallforschung, Stuttgart, with Manfred Rühle; Los Alamos National Laboratory with Terry Mitchell; Dartmouth College, Thayer School of Engineering, with Erland Schulson; and the Electron Microscope Unit at Sydney University with Simon Ringer. CBC wishes to acknowledge the Department of Energy, Basic Energy Sciences, the National Science Foundation, Division of Materials Research, the Center for Interfacial Engineering at the University of Minnesota, The Materials Science Center at Cornell University, and the SHaRE program at Oak Ridge National Laboratories. The first edition was started while CBC was with the Department of Materials Science and Engineering at Cornell University. This edition was started at the Department of Chemical Engineering and Materials Science at the University of Minnesota where the first edition was finished and was finalized while CBC was at the University of Connecticut. The second edition was partly written while CBC was on Sabbatical Leave at Chalmers University with Eva Olssen (thanks also to Anders Tholen at Chalmers), at NIMS in Tsukuba with Yoshio Bando (thanks also to Dmitri Golberg and Kazuo Furuya at NIMS at Yuichi Ikuhara at the University of Tokyo) and at Cambridge University with Paul Midgley. CBC also thanks the Master and Fellows of Peterhouse for their hospitality during the latter period.

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Despite our common scientific beginnings as undergraduates in Christ's College Cambridge, we learned our trade under different microscopists: DBW with Jeff Edington in Cambridge and CBC with Sir Peter Hirsch and Mike Whelan in Oxford. Not surprisingly, the classic texts by these renowned microscopists are referred to throughout this book. They influenced our own views of TEM tremendously, contributing to the undoubted bias in our opinions, notation, and approach to the whole subject.

List of Initials and Acronyms

The field of TEM is a rich source of initials and acronyms (these are words formed by the initials), behind which we hide both simple and esoteric concepts. While the generation of new initials and acronyms can be a source of original thinking (e.g., see ALCHEMl), it undoubtedly makes for easier communication in many cases and certainly reduces the length of voluminous textbooks. You have to master this strange language before being accepted into the community of microscopists, so we present a comprehensive listing that you should memorize.

ACF absorption-correction factor
ACT automated crystallography for TEM
A/D analog to digital (converter)
ADF annular dark field
AEM analytical electron microscope/microscopy
AES Auger electron spectrometer/spectroscopy
AFF aberration-free focus
AFM atomic force microscope/microscopy
ALCHEMI atom location by channeling-enhanced micro-analysis
ANL Argonne National Laboratory
APB anti-phase domain boundary
APFIM atom-probe field ion microscope/microscopy
APW augmented plane wave
ASW augmented spherical wave
ATW atmospheric thin window

BF bright field
BFP back-focal plane
BSE backscattered electron
BZB Brillouin-zone boundary

C1,2 condenser 1, 2, etc. lens
CASTEP electronic-potential calculation software
CAT computerized axial tomography
CB coherent bremsstrahlung
CBED convergent-beam electron diffraction
CBIM convergent beam imaging
CCD charge-coupled device
CCF cross-correlation function
CCM charge-collection microscopy
CDF centered dark field
CF coherent Fresnel/Foucault
CFE cold field emission
CL cathodoluminescence
cps counts per second
CRT cathode-ray tube
CS crystallographic shear
CSL coincident-site lattice
CVD chemical vapor deposition

DADF displaced-aperture dark field
DDF diffuse dark field
DF dark field
DFT density-functional theory
DOS density of states
DP diffraction pattern
DQE detection quantum efficiency
DSTEM dedicated scanning transmission electron microscope/microscopy
DTSA desktop spectrum analyzer

EBIC electron beam-induced current/conductivity
EBSD electron-backscatter diffraction
EELS electron energy-loss spectrometer/spectrometry
EFI energy-filtered imaging
EFTEM energy-filtered transmission electron microscope
ELNES energy-loss near-edge structure
ELP™ energy-loss program (Gatan)
EMMA electron microscope microanalyzer
EMS electron microscopy image simulation
(E)MSA (Electron) Microscopy Society of America
EPMA electron-probe microanalyzer
ESCA electron spectroscopy for chemical analysis
ESI electron-spectroscopic imaging
EXAFS extended X-ray-absorption fine structure
EXELFS extended energy-loss fine structure

FEFF ab-initio multiple-scattering software
FEG field-emission gun
FET field-effect transistor
FFP front-focal plane
FFT fast Fourier transform
FIB focused ion beam
FLAPW full-potential linearized augmented plane wave
FOLZ first-order Laue zone
FTP file-transfer protocol
FWHM full width at half maximum
FWTM full width at tenth maximum

GB grain boundary
GIF Gatan image filter™
GIGO garbage in garbage out
GOS generalized oscillator strength

HAADF high-angle annular dark field
HOLZ higher-order Laue zone
HPGe high-purity germanium
HREELS high-resolution electron energy-loss spectrometer/spectrometry
HRTEM high-resolution transmission electron microscope/microscopy
HV high vacuum
HVEM high-voltage electron microscope/microscopy

ICC incomplete charge collection
ICDD International Center for Diffraction Data
ID identification (of peaks in spectrum)
IDB inversion domain boundary
IEEE International Electronics and Electrical Engineering
IG intrinsic Ge
IVEM intermediate-voltage electron microscope/microscopy

K-M Kossel-Möllenstedt

LACBED large-angle convergent-beam electron diffraction
LCAO linear combination of atomic orbitals
LCD liquid-crystal display
LDA local-density approximation
LEED low-energy electron diffraction
LKKR layered Korringa-Kohn-Rostoker

MAS Microbeam Analysis Society
MBE molecular-beam epitaxy
MC minimum contrast
MCA multichannel analyzer
MDM minimum detectable mass
MLS multiple least-squares
MMF minimum mass fraction
MO molecular orbital
MRS Materials Research Society
MS multiple scattering
MSA multivariate statistical analysis
MSDS material safety data sheets
MT muffin tin
MV megavolt

NCEMSS National Center for Electron Microscopy simulation system
NIH National Institutes of Health
NIST National Institute of Standards and Technology
NPL National Physical Laboratory

OIM orientation-imaging microscopy
OR orientation relationship

PARODI parallel recording of dark-field images
PB phase boundary
P/B peak-to-background ratio
PEELS parallel electron energy-loss spectrometer/spectrometry
PIPS Precision Ion-Polishing System™
PIXE proton-induced X-ray emission
PM photomultiplier
POA phase-object approximation
ppb/m parts per billion/million
PDA photo-diode array
PSF point-spread function
PTS position-tagged spectrometry

QHRTEM quantitative high-resolution transmission electron microscopy

RB translation boundary (yes, it does!)
RDF radial distribution function
REM reflection electron microscope/microscopy
RHEED reflection high-energy electron diffraction

SACT small-angle cleaving technique
SAD(P) selected-area diffraction (pattern)
SCF self-consistent field
SDD silicon-drift detector
SE secondary electron
SEELS serial electron energy-loss spectrometer/spectrometry
SEM scanning electron microscope/microscopy
SESAMe sub-eV sub-Å microscope
SF stacking fault
SHRLI simulated high-resolution lattice images
SI spectrum imaging
SI Système Internationale
SIGMAK K-edge quantification software
SIGMAL L-edge quantification software
SIMS secondary-ion mass spectrometry
S/N signal-to-noise ratio
SOLZ second-order Laue zone
SRM standard reference material
STEM scanning transmission electron microscope/microscopy
STM scanning tunneling microscope/microscopy

TB twin boundary
TEM transmission electron microscope/microscopy
TFE thermal field emission
TMBA too many bloody acronyms

UHV ultrahigh vacuum
URL uniform resource locator
UTW ultra-thin window

V/F voltage to frequency (converter)
VLM visible-light microscope/microscopy
VUV vacuum ultra violet

WB weak beam
WBDF weak-beam dark field
WDS wavelength-dispersive spectrometer/spectrometry
WP whole pattern
WPOA weak-phase object approximation
WWW World Wide Web

XANES X-ray absorption near-edge structure
XEDS X-ray energy-dispersive spectrometer/spectrometry
XPS X-ray photoelectron spectrometer/spectrometry
XRD/F X-ray diffraction/fluorescence

YAG yttrium-aluminum garnet
YBCO yttrium-barium-copper oxide
YSZ yttria-stabilized zirconia

ZAF atomic number/absorption/fluorescence correction
ZAP zone-axis pattern
ZLP zero-loss peak
ZOLZ zero-order Laue zone

List of Symbols

We use a large number of symbols. Because we are constrained by the limits of our own and the Greek alphabets, we often use the same symbol for different terms, which can confuse the unwary. We have tried to be consistent where possible but undoubtedly we have not always succeeded. The following (not totally inclusive) list may help if you remain confused after reading the text.

a	interatomic spacing
a	relative transition probability
a	width of diffraction disk
a_0	Bohr radius
a_0	lattice parameter
a, b, c	lattice vectors
a*, b*, c*	reciprocal-lattice vectors
A	absorption-correction factor
A	active area of X-ray detector
A_0	amplitude
A	amplitude of scattered beam
A	amperes
A	atomic weight
A	Richardson's constant
Å	Ångstrom
$\mathcal{A}$	Bloch wave amplitude
$A(\mathbf{u})$	aperture function
A, B	fitting parameters for energy-loss background subtraction
b	beam-broadening parameter
b	separation of diffraction disks
$\mathbf{b}_e$	edge component of the Burgers vector
$\mathbf{b}_p$	Burgers vector of partial dislocation
$\mathbf{b}_T$	Burgers vector of total dislocation
B	beam direction
B	magnetic field strength
B	background intensity
$B(\mathbf{u})$	aberration function
c	centi
c	velocity of light
C	composition
C	contrast
C	coulomb
C_a	astigmatism-aberration coefficient
C_c	chromatic-aberration coefficient
$C_{\mathbf{g}}$	**g** component of Bloch wave
C_s	spherical-aberration coefficient
C_X	fraction of X atoms on specific sites
C_0	amplitude of direct beam
C_ε	combination of the elastic constants
$(C_s\lambda)^{1/2}$	scherzer
$(C_s\lambda^3)^{1/4}$	glaser
c/o	condenser /objective
d	beam (probe) diameter
d	diameter of spectrometer entrance aperture
d	interplanar spacing

d	spacing of moire fringes
d_c	effective source size
d_d	diffraction-limited beam diameter
d_{eff}	effective entrance-aperture diameter at recording plane
d_g	Gaussian beam diameter
d_{hkl}	*hkl* interplanar spacing
d_i	image distance
d_{im}	smallest resolvable image distance
d_o	object distance
d_{ob}	smallest resolvable object distance
d_s	spherical-aberration limited beam diameter
d_t	total beam diameter
dz	thickness of a diffracting slice
$d\sigma/d\Omega$	differential cross section of one atom
D	aperture diameter
D	change in focus
D	dimension (as in 1D, 2D...)
D	distance from projector crossover to recording plane
D	electron dose
D_A	distance from beam crossover to spectrometer entrance aperture
D_{im}	depth of focus
D_{ob}	depth of field
D_1, D_2	tie-line points on dispersion surfaces in presence of defect
e	charge on the electron
E	energy
$\mathbf{E}$	electric-field strength
E	Young's modulus
E	total energy
$\mathcal{E}$	energy loss
E_a	spatial-coherence envelope
E_c	chromatic-coherence envelope
E_c	critical ionization energy
E_d	displacement energy
E_F	Fermi energy/level
$E_{h/l}$	high/low energy for background-subtraction window
$E_{K/L/M}$	ionization energy for K/L/M-shell electron
$E_{K/L/M}$	energy of K/L/M X-ray
$\mathcal{E}_m$	average energy loss
E_P	plasmon energy
$\mathcal{E}_P$	plasmon energy loss
E_s	sputtering-threshold energy
E_t	threshold energy
E_0	beam energy
$E(\mathbf{u})$	envelope function
$E_c(\mathbf{u})$	envelope function for chromatic aberration
$E_d(\mathbf{u})$	envelope function for specimen drift
$E_D(\mathbf{u})$	envelope function for the detector
$E_s(\mathbf{u})$	envelope function for the source
$E_v(\mathbf{u})$	envelope function for specimen vibration
f	focal length
$f(\mathbf{r})$	strength of object at point (x,y)
$f(\theta)$	atomic-scattering factor
$f(\mathbf{k})$	atomic-scattering amplitude
f_x	scattering factor for X-rays
$f_i(x)$	residual of least-squares fit
F	Fano factor
F	fluorescence-correction factor
$\mathbf{F}$	Lorentz force
F	relativistic-correction factor
F	Fourier transform
F'	Fourier transform of edge intensity
F_B	fraction of alloying element B
$F_{\mathbf{g}}$	special value of $F(\theta)$ when θ is the Bragg angle
$F(P)$	Fourier transform of plasmon intensity
$F(\mathbf{u})$	Fourier transform of $f(\mathbf{r})$
$F(0)$	Fourier transform of elastic intensity
$F(1)$	Fourier transform of single-scattering intensity
$F(\theta)$	structure factor
$\mathbf{g}/\bar{\mathbf{g}}$	diffraction vector (magnitude of +/- $\mathbf{K}$ at the Bragg angle)
$\mathbf{g}_{hkl}$	diffraction vector for *hkl* plane
g	gram
$g(\mathbf{r})$	intensity of image at point (x,y)
G	Bragg reflection
G	radius of a HOLZ ring
G	giga
$G(\mathbf{u})$	Fourier transform of $g(\mathbf{r})$
Gy	gray (radiation unit)
h	Planck's constant
h	distance from specimen to the aperture
$h(\mathbf{r})$	contrast-transfer function
(hkl)	Miller indices of a crystal plane
hkl	indices of diffraction spots from *hkl* plane
H	spacing of the reciprocal-lattice planes parallel to beam
$H(\mathbf{u})$	Fourier transform of $h(\mathbf{r})$
i	beam current
i	imaginary number
i	number of atoms in unit cell
I	intensity
I	intrinsic line width of the XEDS detector
i_e	emission current

i_f	filament-heating current
I_g	intensity in the diffracted beam
$I_{K/L/M}$	K/L/M-shell intensity above background
$I(\mathbf{k})$	kinematical intensity
$I(1)$	single-scattering intensity
I_P	intensity in the first plasmon peak
I_T	total transmitted intensity
I_0	intensity in the zero-loss peak
$I_\mathbf{0}$	intensity in the direct beam
$I(t)$	low-loss spectrum intensity
J	current density
J	joule
J	sum of spin and angular quantum numbers
k	magnitude of the wave vector
k	Boltzmann's constant
k	kilo
$\mathbf{k}_I$	**k**-vector of the incident wave
$\mathbf{k}_D$	**k**-vector of the diffracted wave
k_{AB}	Cliff-Lorimer factor/sensitivity factor
K	bulk modulus
K	Kelvin
K	Kramers' constant
K	sensitivity factor
$K/L/M$	inner-shell/characteristic X-ray/ ionization edge
$\mathbf{K}$	change in **k** due to diffraction
$\mathbf{K}_B$	magnitude of **K** at the Bragg angle
K_o	kernel
l	angular quantum number
L	camera length
L	lattice spacing in beam direction
L	length of magnetic field
L_0	length of magnetic field along optic axis
L	path difference
L	width of composition line-profile
m	meters
m	milli
m	mirror plane
m	number of focal increments
m_0	rest mass of the electron
M	magnification
M	mega
M_A	angular magnification
M_T	transverse magnification
M_1, M_2	tie-line points on dispersion surfaces
n	integer
n	free-electron density
n	number of counts

n	number of scattered electrons
n_0	number of incident electrons
n	nano
n	principal quantum number
$\mathbf{n}$	vector normal to the surface
n_s	number of electrons in the ionized sub-shell
N	$h + k + l$
N	newton
N	noise
N	number of counts in ionization edge
N	number of atoms/unit area
N_V	number of atoms/unit volume
$N(E)$	number of bremsstrahlung photons of energy E
N_0	Avogadro's number
O	direct beam
p	integer
$\mathbf{p}$	momentum
p	pico
P	probability of scattering
P	peak intensity
P	FWHM of a randomized electronic-pulse generator
Pa	pascal
$P_{K/L/M}$	probability of K/L/M-shell ionization
$P(z)$	scattering matrix for a slice of thickness z
q	charge
Q	cross section
r	radius
r	distance a wave propagates
r	distance between contamination spots
r	minimum resolvable distance/resolution
r	power term to fit background in EEL spectrum
r_M	image-translation distance
$\mathbf{r}_n$	lattice vector
$\mathbf{r}^*$	reciprocal-lattice vector
r_{ast}	radius of astigmatism disk
r_{chr}	radius of chromatic-aberration disk
r_{sph}	radius of spherical-aberration disk
r_{min}	minimum disk radius
r_{th}	theoretical disk radius
$\mathbf{r}'_n$	lattice vector in strained crystal
r_0	maximum radius of DP in focal plane of spectrometer
R	ALCHEMI intensity ratio
R	count rate
$\mathbf{R}$	crystal-lattice vector

R	distance on screen between diffraction spots
R	radius of curvature of EEL spectrometer
R	resolution of XEDS detector
R	spatial resolution
R	reduction in partial cross section with increasing α
R_{MAX}	diameter of beam emerging from specimen
$\mathbf{R}_n$	lattice-displacement vector
$\mathbf{R}(\mathbf{r})$	displacement
$\mathbf{s}$	excitation error/deviation parameter
s	second
s	spin quantum number
$\mathbf{s}_\mathbf{R}$	excitation error due to defect
$\mathbf{s}_z(\mathbf{s}_\mathbf{g})$	excitation error
s_{eff}	effective excitation error
S	distance from specimen to detector
S	signal
S	standard deviation for n measurements
sr	steradians
$\mathbf{t}$	shift vector between the ZOLZ and HOLZ
t	student (t) distribution
t	thickness
t'	absorption path length
t_0	thickness at zero tilt
T	absolute temperature
T	tesla
T_c	period of rotation
$T(\mathbf{u})$	objective-lens transfer function
$T_{eff}(\mathbf{u})$	effective transfer function
$\mathbf{u}$	reciprocal lattice vector
$\mathbf{u}$	unit vector along the dislocation line
$\mathbf{u}^*$	vector normal to the ZOLZ
U	overvoltage
U_g	Fourier component of the perfect-crystal potential
$[UVW]$	indices of a crystal direction
UVW	indices of beam direction
v	velocity
V	accelerating voltage
$\mathcal{V}$	potential energy
V_c/V	volume of the unit cell
V_c	inner potential of cavity
V_t	projected potential through specimen thickness
$V(\mathbf{r})$	crystal inner potential
w	$s\xi_\mathbf{g}$ (excitation error multiplied by extinction distance)
w	projected width of planar defect
w	width
x	distance
$\times$	times (magnification)
x, y, z	atom coordinates
X	FWHM due to XEDS detector
X	rotation axis
y	displacement at the specimen
y	number of counts in channel
y	parallax shift in the image
z	distance within a specimen
z	distance along optic axis
z	specimen height
Z	atomic number/atomic-number correction factor

Greek symbols

α	phase shift due to defect
α	semi-angle of incidence/convergence
α	X-ray take-off angle
α_0	beam divergence semi-angle at gun crossover
α_{opt}	optimum convergence semi-angle
β	brightness
β	ratio of electron velocity to light velocity
β	semi-angle of collection
β_{opt}	optimum collection semi-angle
γ	degree of spatial coherence
γ	phase of direct beam
γ	relativistic-correction factor
γ	specimen tilt angle
Δ	change/difference
Δ	width of energy window
Δd	change in lattice parameter
$\Delta\phi$	phase difference
$\Delta\theta_i$	angle between Kossel–Möllenstedt fringes
Δ_{AB}	difference in mass-absorption coefficients
ΔE	energy width /spread
$\Delta\mathcal{E}_P$	plasmon-line width/change in plasmon energy
Δf	maximum difference in focus
Δf	defocus error due to chromatic aberration
Δf_{AFF}	aberration-free (de)focus
Δf_{MC}	minimum contrast defocus
Δf_{opt}	optimum defocus
Δ	change (in height)

Δh relative depth in specimen
ΔI change in intensity
Δp parallax shift
ΔV change in the inner potential
Δx path difference/image shift
Δx half-width of image of undissociated screw dislocation
Δx_{res} resolution at Scherzer defocus
Δf_{sch} Scherzer defocus

δ angle between XEDS detector normal and line from detector to specimen
δ angle between beam and plane of defect
δ diameter of disk image
δ diffuseness of interface
δ precipitate/matrix misfit
δ small increment
δ smallest resolvable distance (resolution)

ε deflection angle
ε detector efficiency
ε energy to create an electron-hole pair
ε specimen-tilt angle
ε strain
ε_0 permittivity of free space (dielectric constant)

η phase change
η angle between excess Kikuchi lines at $\mathbf{s} = 0$ and $\mathbf{s} > 0$
$\eta(\theta)$ phase of the atomic-scattering factor

Φ phase shift accompanying scattering
Φ work function
ϕ rotation angle between image and diffraction pattern
ϕ angle between Kikuchi line and diffraction spot
ϕ angle between two Kikuchi-line pairs
ϕ angle between two planes
ϕ angle between two plane normals
ϕ angle of tilt between stereo images
ϕ phase of a wave
ϕ^* complex conjugate of ϕ
$\phi_{\mathbf{g}}$ amplitude of the diffracted beam
ϕ_0 amplitude of the direct beam
ϕ_x angle of deflection of the beam
$\phi(\rho t)$ depth distribution of X-ray production

$\boldsymbol{\chi}$ wave vector outside the specimen
$\boldsymbol{\chi}_G$ wave vector terminating on the point G in reciprocal space
$\boldsymbol{\chi}_O$ wave vector terminating on the point O in reciprocal space

χ^2 goodness of fit (between standard and experimental spectra)
$\chi(\mathbf{u})$ phase-distortion function
$\chi(\mathbf{k})$ momentum transfer

κ thermal conductivity

$\xi_{\mathbf{g}}$ extinction distance for the diffracted beam
$\xi_{\mathbf{g}'}$ absorption parameter
ξ_0 extinction distance for the direct beam
ξ_{eff} effective extinction distance ($s \neq 0$)
$\xi_{\mathbf{g}}^{abs}$ absorption-modified $\xi_{\mathbf{g}}$

λ_c coherence length
λ mean-free path
λ wavelength
$\lambda_{K/L/M}$ mean-free path for K/L/M-shell ionization
λ_P plasmon mean-free path
λ_R relativistic wavelength
λ^{-1} radius of Ewald sphere

μ micro
μ refractive index
μ/ρ mass-absorption coefficient
$\mu^{(j)}(\mathbf{r})$ Bloch function

ν frequency
ν Poisson's ratio

ψ amplitude of a wave
ψ the wave function
ψ_{sph} amplitude of spherical wave
ψ_{tot} total wave function
ψ_0 amplitude

ρ angle between two directions
ρ density
$\rho_{c/s}$ information limit due to chromatic/spherical aberration
$\rho(\boldsymbol{r})$ radial distribution function
ρt mass thickness
ρ_i^2 area of a pixel

σ scattering cross section of one atom
σ standard deviation
σ stress
$\sigma_{K/L/M}$ ionization cross section for K/L/M-shell electron
σ_T total ionization cross section
$\sigma_{K/L/M}(\beta\Delta)$ partial ionization cross section for K/L/M-shell electron

θ scattering semi-angle

θ_B	Bragg angle
θ_C	cut-off semi-angle
θ_E	characteristic scattering semi-angle
θ_0	screening parameter
τ	XEDS detector time constant
τ	dwell time
τ	analysis time
ω	fluorescence yield
ω_c	cyclotron frequency
ω_p	plasmon frequency
Ω	filter for energy loss
Ω	solid angle of collection of XEDS
Ω	volume of unit cell
ζ	zeta factor
$\otimes$	convolution (multiply and integrate)

About the Companion Volume

As described in our Preface, the many years since the publication of the first edition have seen a significant increase in the number of TEM (and related) techniques and the sophistication of the microscope's experimental capabilities, as well as new hardware designs, astonishing improvements in computer control of the instrument and amazing developments in software to handle and model the gigabytes of data generated by these (now almost completely digital) instruments. Much of this explosion of information has coincided with the world-wide drive to explore the nanoworld, and the still-ongoing effects of Moore's law. It is not possible to include all of this new knowledge in a textbook, and the primary objective of the second edition is still to teach you to understand the essence of the TEM before you attempt to master the latest advances. We also personally cannot hope to comprehend fully all of the new techniques, especially as we both descend into more administrative positions in our professional lives.

Therefore, we have prevailed on almost 20 of our close friends and colleagues to put together with us a companion applications text (Carter and Williams, eds., Springer, 2010) to which we will refer throughout this second edition. The companion text is just as it says; it's a friend whose advice you should seek when the main text is not enough. The companion is not intended to be more advanced but it certainly provides much more detail on key recent developments and some more traditional aspects of TEM that have seen a resurgence of interest. We have taken our colleagues' contributions and worked with them to produce chapters that are in a similar conversational vein to this main text. While *Transmission Electron Microscopy, Second Edition*, is a completely stand-alone textbook, we think that you will find the cross-referencing between the two texts to be of great value as you continue along the rewarding path of becoming a transmission microscopist.

Contents

Figure Credits

TEM is a visual science, and any TEM text is heavily dependent on figures, halftones, and (more recently) full color images to transmit its message. We have been fortunate to work with many colleagues over the years who have generously given us fine examples of the art and science of TEM; we would like to acknowledge them here. We have also used our own work, and the work of others, whose permission has been sought as listed below.

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