

Contents

<i>Preface</i>	v
1. Introduction	1
1.1 Where are the Atoms?	1
1.2 Brief Historical Overview	5
1.3 Scope of the Book	8
1.4 General Outline	8
Part I — Fundamentals	11
2. High-Resolution Transmission Electron Microscopy	13
2.1 Overview	14
2.2 The Exit-Plane Wave	16
2.2.1 The weak phase object approximation	16
2.2.2 Dynamic scattering theories	18
2.3 Image Formation	19
2.4 The Phase Contrast Transfer Function	21
2.4.1 The objective aperture	22
2.4.2 Lens effects	23
2.4.3 Partial spatial and partial temporal coherence	28
2.4.4 Point resolution and information limit	34
2.4.5 Other factors	36
2.5 Non-Linear Imaging	40
2.6 Summary	43
3. Scanning Transmission Electron Microscopy	45
3.1 Overview	45
3.2 Geometrical Considerations	49
3.2.1 The diffraction limit	49

3.2.2	Lens effects — spherical aberration	53
3.2.3	Partial temporal coherence — chromatic aberration	54
3.2.4	Partial spatial coherence — the effective source size	56
3.2.5	Stability	57
3.2.6	Small electron probes	58
3.3	Wave Optical Description of an Electron Probe	61
3.3.1	Diffraction	62
3.3.2	Defocus and spherical aberration	63
3.3.3	Geometrical source size	66
3.3.4	Energy spread of the electron beam	67
3.3.5	Concluding remarks	68
3.4	Summary	72
4.	Limits of Conventional Atomic-Resolution Electron Microscopy	73
4.1	The Case of Transmission Electron Microscopy	73
4.2	The Case of Scanning Transmission Electron Microscopy	80
4.3	Summary	87
Part II — Electron Optics		89
5.	Basic Principles of Electron Optics	91
5.1	The Electron Microscope	92
5.2	Newton's Second Law of Motion and Electron Optics	93
5.3	The Hamiltonian Analogy	95
5.4	Geometrical Electron Optics	96
5.5	Electrons in the Electrostatic Field	97
5.5.1	Snell's law of refraction	98
5.5.2	Snell's law of refraction for electrons	98
5.5.3	Fermat's principle: The shortest light optical path	103
5.5.4	The reduced principle of least action	107
5.5.5	The point eikonal	109
5.6	Electrons in the Stationary Electromagnetic Field	114
5.6.1	Principle of Maupertius	114
5.6.2	The refractive index of electrons	117
5.6.3	Geometrical wave surfaces	119
5.7	Summary	121
6.	Gaussian Dioptrics	123
6.1	Geometry and Coordinate Systems	123
6.2	Fields and Lenses	127
6.3	The Paraxial Approximation	129

6.4	Path Equation of an Electrostatic Field	130
6.5	Path Equation of a Stationary Magnetic Field	134
6.5.1	The homogeneous rotationally symmetric magnetic field .	134
6.5.2	The rotationally symmetric magnetic field	144
6.5.3	The rotationally symmetric electromagnetic field	152
6.6	Series Expansion of the Fields	159
6.7	Imaging Within the Paraxial Approximation	161
6.7.1	Theorem of optical imaging	161
6.7.2	Generalized theorem of Lippich	166
6.7.3	Real image and virtual image	168
6.7.4	Asymptotic cardinal elements	171
6.8	Summary	185
Part III — Aberration Correction		187
7.	Aberrations	189
7.1	Overview	190
7.2	Image Aberrations	192
7.3	Types of Aberrations	193
7.3.1	Axial aberrations vs. off-axial aberrations	193
7.3.2	Chromatic aberrations vs. geometrical aberrations	195
7.4	Geometrical Aberration of a Round Electron Lens	201
7.5	Wave Surface, Aberration Function and Image Aberrations	214
7.5.1	HRTEM and STEM	216
7.5.2	Non-ideal geometrical wave surfaces	218
7.5.3	The aberration function	218
7.5.4	Other notations for axial aperture aberrations	223
7.5.5	Aberration function and image aberrations	227
7.6	Summary	228
8.	Spherical Aberration Correctors	229
8.1	Overview	229
8.1.1	Strategies to deal with the spherical aberration	230
8.1.2	Strategies to correct the spherical aberration	231
8.2	Multi-Pole Lenses	234
8.2.1	Quadrupoles	235
8.2.2	Hexapoles	236
8.2.3	Octupoles	240
8.3	The Basic Principles of Spherical Aberration Correctors	240
8.3.1	Hexapole spherical aberration corrector	242
8.3.2	Quadrupole–octupole spherical aberration corrector	245

8.4	Beyond the Basic Principles — Parasitic Aberrations and Other Complications	252
8.4.1	The multitude of axial aberrations	252
8.4.2	Residual intrinsic axial aberrations	253
8.4.3	Balancing the effect of higher-order aberrations	253
8.4.4	Off-axial aberrations	254
8.4.5	The chromatic aberration	255
8.4.6	Dealing with the fifth-order spherical aberration	256
8.5	Improved Correctors	257
8.5.1	Fifth-order correction with hexapole fields	258
8.5.2	Fifth-order correction with quadrupole–octupole fields	259
8.5.3	Correction of geometrical and chromatic aberrations	260
8.6	Summary	264
9.	Aberration-Corrected Imaging	265
9.1	Aberration Diagnosis	265
9.1.1	Geometrical resolution limit	266
9.1.2	Zemlin-tableau method	267
9.1.3	Tilt tableaux for probe-forming microscopes	273
9.1.4	Ronchigram methods	276
9.1.5	Other methods	278
9.2	Aberration-Corrected HRTEM	279
9.2.1	The coherent phase contrast transfer function	280
9.2.2	Incoherent contributions	286
9.2.3	Summary	291
9.3	Aberration-Corrected STEM	291
9.3.1	Illumination aperture	291
9.3.2	Geometrical aberrations	293
9.3.3	Partial coherence	297
9.3.4	Considerations about small electron probes	300
9.4	New Possibilities and New Limits	306
Appendix A	Physical Constants, Abbreviations, Acronyms and Symbols	313
A.1	Physical Constants	313
A.2	Abbreviations and Acronyms	314
<i>Bibliography</i>		315
<i>Index</i>		329
<i>About the Author</i>		335