

|          |                                                               |           |
|----------|---------------------------------------------------------------|-----------|
| <b>1</b> | <b>Physical Quantities and Measurements . . . . .</b>         | <b>1</b>  |
| 1.1      | Physical Quantities . . . . .                                 | 1         |
| 1.2      | Measurement Uncertainty . . . . .                             | 3         |
| 1.2.1    | Statistical Uncertainty . . . . .                             | 4         |
| 1.2.2    | Histograms and Distributions . . . . .                        | 5         |
| 1.2.3    | Gaussian Error Propagation . . . . .                          | 7         |
| 1.2.3.1  | Addition and Subtraction of Measured<br>Quantities . . . . .  | 7         |
| 1.2.3.2  | Multiplication of Measured Quantities . . . . .               | 8         |
| 1.2.3.3  | Division of Measured Quantities . . . . .                     | 8         |
| 1.2.4    | Linear Regression . . . . .                                   | 9         |
| 1.2.4.1  | Example: Disintegration of Beer Foam . . . . .                | 10        |
| 1.3      | Physical Measurements: Compact . . . . .                      | 12        |
| <b>2</b> | <b>Mechanics of Rigid Bodies . . . . .</b>                    | <b>13</b> |
| 2.1      | Kinematics . . . . .                                          | 13        |
| 2.1.1    | Position, Velocity and Acceleration . . . . .                 | 13        |
| 2.1.2    | Determination of the Position from the Acceleration . . . . . | 15        |
| 2.1.3    | Motion in Three Dimensions . . . . .                          | 17        |
| 2.1.3.1  | Oblique Projectile Motion . . . . .                           | 18        |
| 2.1.4    | Circular Motion . . . . .                                     | 20        |
| 2.2      | Forces . . . . .                                              | 23        |
| 2.2.1    | Newton's Axioms . . . . .                                     | 24        |
| 2.2.2    | Gravitational Force . . . . .                                 | 26        |
| 2.2.3    | Spring Force . . . . .                                        | 27        |
| 2.2.3.1  | Combination of Springs . . . . .                              | 29        |
| 2.2.4    | Pseudo Forces . . . . .                                       | 30        |
| 2.2.4.1  | Inertia Force . . . . .                                       | 30        |
| 2.2.4.2  | Centrifugal Force . . . . .                                   | 31        |
| 2.2.4.3  | Coriolis Force . . . . .                                      | 31        |
| 2.2.5    | Frictional Forces . . . . .                                   | 32        |
| 2.2.5.1  | Inclined Plane . . . . .                                      | 33        |
| 2.2.6    | Equation of Motion . . . . .                                  | 33        |

|          |                                                                         |           |
|----------|-------------------------------------------------------------------------|-----------|
| 2.3      | Conserved Quantities in Mechanics . . . . .                             | 35        |
| 2.3.1    | Work, Energy, Potential and Power . . . . .                             | 35        |
| 2.3.1.1  | Potential Energy . . . . .                                              | 36        |
| 2.3.1.2  | Elastic Energy . . . . .                                                | 36        |
| 2.3.1.3  | Kinetic Energy . . . . .                                                | 36        |
| 2.3.1.4  | Power . . . . .                                                         | 37        |
| 2.3.1.5  | Potential . . . . .                                                     | 38        |
| 2.3.1.6  | Outlook: General Definition of Work . . . . .                           | 39        |
| 2.3.2    | Straight Motion: Momentum and Collisions . . . . .                      | 40        |
| 2.3.2.1  | Central Collision . . . . .                                             | 42        |
| 2.3.3    | Circular Motion: Angular Momentum and Torque . . . . .                  | 44        |
| 2.4      | Statics and Equilibria . . . . .                                        | 46        |
| 2.4.1    | Statics of Translation . . . . .                                        | 46        |
| 2.4.1.1  | Suspension of a Lamp from the Suspension<br>Cable . . . . .             | 47        |
| 2.4.2    | Statics of Rotation . . . . .                                           | 48        |
| 2.4.2.1  | Leverage Law . . . . .                                                  | 49        |
| 2.4.2.2  | Equilibria of Extended Bodies . . . . .                                 | 49        |
| 2.4.2.3  | Centre of mass . . . . .                                                | 51        |
| 2.5      | Rotation of Extended Bodies . . . . .                                   | 52        |
| 2.5.1    | Moment of Inertia . . . . .                                             | 52        |
| 2.5.1.1  | Moments of Inertia of Special Bodies and<br>Steiner's Theorem . . . . . | 53        |
| 2.5.2    | Rotational Energy . . . . .                                             | 54        |
| 2.6      | Mechanics: Compact . . . . .                                            | 55        |
| <b>3</b> | <b>Continuum Mechanics . . . . .</b>                                    | <b>59</b> |
| 3.1      | Elastic Deformations of Solid Bodies . . . . .                          | 59        |
| 3.1.1    | Elongation and Compression . . . . .                                    | 60        |
| 3.1.2    | Bending . . . . .                                                       | 62        |
| 3.1.3    | Shear . . . . .                                                         | 63        |
| 3.1.4    | Torsion . . . . .                                                       | 64        |
| 3.1.5    | Beyond the Elastic Range: Fracture . . . . .                            | 64        |
| 3.2      | Hydrostatics . . . . .                                                  | 65        |
| 3.2.1    | Pressure in Liquids and Gases . . . . .                                 | 65        |
| 3.2.1.1  | Gravity Pressure . . . . .                                              | 66        |
| 3.2.1.2  | Plunger Pressure . . . . .                                              | 67        |
| 3.2.1.3  | Pressure Measurement with the U-Tube . . . . .                          | 67        |
| 3.2.1.4  | Compression of Liquids . . . . .                                        | 68        |
| 3.2.2    | Buoyancy Force: Swimming, Floating, Sinking . . . . .                   | 69        |
| 3.2.3    | Interfaces of Liquids . . . . .                                         | 72        |
| 3.2.3.1  | Force on Edge Lines and Overpressure . . . . .                          | 73        |
| 3.2.3.2  | Adhesion and Cohesion . . . . .                                         | 75        |
| 3.2.4    | Aerostatics . . . . .                                                   | 75        |
| 3.2.4.1  | Barometric Pressure Law . . . . .                                       | 76        |

|          |                                                          |            |
|----------|----------------------------------------------------------|------------|
| 3.3      | Hydrodynamics . . . . .                                  | 77         |
| 3.3.1    | Continuity Equation . . . . .                            | 78         |
| 3.3.2    | Bernoulli Effect . . . . .                               | 80         |
| 3.3.2.1  | Pitot Tube . . . . .                                     | 82         |
| 3.3.2.2  | Aerodynamic Lift Force on the Aircraft<br>Wing . . . . . | 82         |
| 3.3.2.3  | Magnus Effect . . . . .                                  | 83         |
| 3.3.2.4  | Hydrodynamic Paradox . . . . .                           | 83         |
| 3.3.2.5  | Torricelli's Law . . . . .                               | 84         |
| 3.3.3    | Flow of Real Fluids . . . . .                            | 84         |
| 3.3.3.1  | Application: Stokes Law of Friction . . . . .            | 86         |
| 3.3.3.2  | Flows in Tubes: Hagen-Poiseuille Law . . . . .           | 87         |
| 3.3.4    | Turbulence . . . . .                                     | 89         |
| 3.4      | Continuum Mechanics: Compact . . . . .                   | 91         |
| <b>4</b> | <b>Oscillations and Waves . . . . .</b>                  | <b>95</b>  |
| 4.1      | Harmonic Oscillation . . . . .                           | 95         |
| 4.1.1    | Examples of Harmonic Oscillations . . . . .              | 96         |
| 4.1.1.1  | Spring Pendulum . . . . .                                | 96         |
| 4.1.1.2  | Thread Pendulum . . . . .                                | 98         |
| 4.1.2    | Driven Harmonic Oscillator with Damping . . . . .        | 99         |
| 4.1.2.1  | Damped Harmonic Oscillator . . . . .                     | 99         |
| 4.1.2.2  | Driven Harmonic Oscillator . . . . .                     | 101        |
| 4.2      | Harmonic Wave . . . . .                                  | 104        |
| 4.2.1    | Interference . . . . .                                   | 106        |
| 4.2.1.1  | Standing Waves . . . . .                                 | 107        |
| 4.2.1.2  | Beatings . . . . .                                       | 109        |
| 4.2.2    | Sound Waves . . . . .                                    | 110        |
| 4.2.2.1  | Sound Perception . . . . .                               | 112        |
| 4.2.3    | Doppler Effect and Supersonic Speed . . . . .            | 113        |
| 4.3      | Oscillations and Waves: Compact . . . . .                | 115        |
| <b>5</b> | <b>Thermodynamics . . . . .</b>                          | <b>119</b> |
| 5.1      | Basic Concepts of Thermodynamics . . . . .               | 119        |
| 5.1.1    | Heat Transport . . . . .                                 | 121        |
| 5.1.2    | Thermal Expansion . . . . .                              | 123        |
| 5.2      | Ideal Gas . . . . .                                      | 124        |
| 5.2.1    | Molar Quantities . . . . .                               | 127        |
| 5.2.2    | Internal Energy . . . . .                                | 128        |
| 5.2.3    | First Law of Thermodynamics . . . . .                    | 130        |
| 5.2.4    | Changes of State in the Ideal Gas . . . . .              | 131        |
| 5.2.4.1  | Isochoric Change of State . . . . .                      | 132        |
| 5.2.4.2  | Isobaric Change of State . . . . .                       | 133        |
| 5.2.4.3  | Isothermal Change of State . . . . .                     | 133        |
| 5.2.4.4  | Adiabatic Change of State . . . . .                      | 134        |

|          |                                                                        |     |
|----------|------------------------------------------------------------------------|-----|
| 5.3      | Entropy and Reversibility . . . . .                                    | 136 |
| 5.3.1    | Example of Irreversible Expansion . . . . .                            | 136 |
| 5.3.2    | Entropy . . . . .                                                      | 138 |
| 5.3.3    | Heat Engines . . . . .                                                 | 141 |
| 5.3.3.1  | Carnot Cycle . . . . .                                                 | 142 |
| 5.4      | Phase Transitions . . . . .                                            | 144 |
| 5.5      | Thermodynamics – Compact . . . . .                                     | 146 |
| <b>6</b> | <b>Electrostatics</b> . . . . .                                        | 149 |
| 6.1      | Electric Charges, Forces and Fields . . . . .                          | 149 |
| 6.1.1    | Forces Between Charges: Coulomb's Law . . . . .                        | 150 |
| 6.1.2    | Electric Field and Electric Force on Charges . . . . .                 | 151 |
| 6.1.2.1  | Electric Field Lines . . . . .                                         | 151 |
| 6.2      | Gauss' Theorem Calculation of Electric Fields . . . . .                | 152 |
| 6.2.1    | Spherically Symmetrical Charge Distribution with Charge $Q$ . . . . .  | 154 |
| 6.2.2    | Long Straight Charged Wire . . . . .                                   | 155 |
| 6.2.3    | Infinitely Extended, Homogeneously Charged Plate . . . . .             | 156 |
| 6.2.4    | Plate Capacitor . . . . .                                              | 156 |
| 6.3      | Electrostatic Potential and Electric Voltage . . . . .                 | 157 |
| 6.3.1    | Examples of Electrical Potentials . . . . .                            | 158 |
| 6.3.1.1  | Potential of a Spherically Symmetrical Charge Distribution . . . . .   | 159 |
| 6.3.1.2  | Potential of an Infinitely Long Straight Charged Wire . . . . .        | 159 |
| 6.3.1.3  | Voltage in the Plate Capacitor . . . . .                               | 160 |
| 6.3.2    | Energy in the Electric Field . . . . .                                 | 160 |
| 6.4      | Matter in the Electric Field . . . . .                                 | 161 |
| 6.4.1    | Electrical Conductors and Currents . . . . .                           | 161 |
| 6.4.1.1  | Ohm's Law . . . . .                                                    | 163 |
| 6.4.1.2  | Electrical Power . . . . .                                             | 164 |
| 6.4.1.3  | Emission of Electrons from Metals . . . . .                            | 164 |
| 6.4.2    | Electrical Insulators and Dipoles . . . . .                            | 165 |
| 6.4.2.1  | Electric Dipole . . . . .                                              | 166 |
| 6.4.2.2  | Dielectricity . . . . .                                                | 167 |
| 6.5      | Electrostatics – Compact . . . . .                                     | 169 |
| <b>7</b> | <b>Magnetostatics</b> . . . . .                                        | 173 |
| 7.1      | Permanent Magnets and Magnetic Field Lines . . . . .                   | 173 |
| 7.2      | Lorentz Force and Definition of the B-Field . . . . .                  | 175 |
| 7.2.1    | Trajectories of Charged Particles in the Homogeneous B-Field . . . . . | 176 |
| 7.2.2    | Lorentz Forces on Electrical Conductors . . . . .                      | 178 |
| 7.2.3    | Hall Effect . . . . .                                                  | 179 |

|          |                                                                        |            |
|----------|------------------------------------------------------------------------|------------|
| 7.3      | Ampère's Law and Calculation of B-Fields . . . . .                     | 181        |
| 7.3.1    | Current-Carrying Straight Wire . . . . .                               | 182        |
| 7.3.2    | Circular Current – Magnetic Dipole Moment . . . . .                    | 183        |
| 7.3.3    | Long Thin Coil . . . . .                                               | 184        |
| 7.3.4    | Magnetic Flux . . . . .                                                | 185        |
| 7.3.5    | Energy in the Magnetic Field . . . . .                                 | 186        |
| 7.3.6    | Outlook: Vector Potential . . . . .                                    | 187        |
| 7.4      | Magnetism in Matter . . . . .                                          | 187        |
| 7.4.1    | Diamagnetism . . . . .                                                 | 188        |
| 7.4.2    | Paramagnetism . . . . .                                                | 188        |
| 7.4.3    | Ferromagnetism and Hysteresis . . . . .                                | 189        |
| 7.5      | Magnetostatics – Compact . . . . .                                     | 191        |
| <b>8</b> | <b>Electrodynamics . . . . .</b>                                       | <b>193</b> |
| 8.1      | Relationship Between Electric and Magnetic Fields . . . . .            | 193        |
| 8.2      | Induction Laws . . . . .                                               | 195        |
| 8.2.1    | Induction of Magnetic Fields . . . . .                                 | 196        |
| 8.2.2    | Induction of Electric Fields – Faraday's Law<br>of Induction . . . . . | 198        |
| 8.2.3    | Lenz's Rule . . . . .                                                  | 199        |
| 8.2.3.1  | Eddy Currents . . . . .                                                | 201        |
| 8.2.4    | Generation of Alternating Current – The Dynamo . . . .                 | 203        |
| 8.2.5    | Self-Induction . . . . .                                               | 204        |
| 8.3      | Maxwell Equations . . . . .                                            | 205        |
| 8.4      | Electrodynamics – Compact . . . . .                                    | 207        |
| <b>9</b> | <b>Electronics . . . . .</b>                                           | <b>209</b> |
| 9.1      | Passive Components and Alternating Current . . . . .                   | 209        |
| 9.1.1    | Alternating Current and Alternating Current<br>Resistance . . . . .    | 209        |
| 9.1.2    | Alternating Current in the Capacitor . . . . .                         | 211        |
| 9.1.3    | Alternating Current in the Coil . . . . .                              | 212        |
| 9.2      | Electrical Networks and Circuits . . . . .                             | 214        |
| 9.2.1    | Parallel and Series Connections . . . . .                              | 217        |
| 9.2.2    | Complex Impedance . . . . .                                            | 219        |
| 9.2.2.1  | Outlook: Calculating with Complex<br>Numbers . . . . .                 | 221        |
| 9.2.3    | Special Circuits . . . . .                                             | 223        |
| 9.2.3.1  | Voltage Divider . . . . .                                              | 223        |
| 9.2.3.2  | RC Filter . . . . .                                                    | 224        |
| 9.2.3.3  | RL Filter . . . . .                                                    | 225        |
| 9.2.3.4  | Transformer . . . . .                                                  | 226        |
| 9.2.4    | Switching On and Off in the RC and RL Circuits . . . .                 | 228        |
| 9.2.4.1  | RC Circuit . . . . .                                                   | 228        |
| 9.2.4.2  | RL Circuit . . . . .                                                   | 230        |

|           |                                                                   |            |
|-----------|-------------------------------------------------------------------|------------|
| 9.3       | Electric Resonant Circuit . . . . .                               | 233        |
| 9.3.1     | Electric Resonant Circuit with Damping . . . . .                  | 235        |
| 9.3.2     | RCL Bandpass Filter . . . . .                                     | 236        |
| 9.3.3     | Hertzian Dipole – Radiation of Electromagnetic<br>Waves . . . . . | 237        |
| 9.4       | Electronics – Compact . . . . .                                   | 239        |
| <b>10</b> | <b>Optics . . . . .</b>                                           | <b>243</b> |
| 10.1      | Electromagnetic Waves . . . . .                                   | 243        |
| 10.1.1    | Waves in Matter: Refractive Index . . . . .                       | 246        |
| 10.1.1.1  | Outlook: Superluminal Velocity in Media . . . . .                 | 247        |
| 10.1.1.2  | Dispersion . . . . .                                              | 247        |
| 10.1.2    | Absorption and Scattering . . . . .                               | 248        |
| 10.1.2.1  | Outlook: X-Ray Diagnostics . . . . .                              | 249        |
| 10.2      | Geometrical Optics . . . . .                                      | 250        |
| 10.2.1    | Refraction and Reflection at Interfaces . . . . .                 | 250        |
| 10.2.2    | Optical Imaging . . . . .                                         | 252        |
| 10.2.2.1  | Lenses . . . . .                                                  | 252        |
| 10.2.2.2  | Lens Equation . . . . .                                           | 254        |
| 10.2.2.3  | Imaging with the Eye . . . . .                                    | 256        |
| 10.3      | Polarization of Light . . . . .                                   | 256        |
| 10.3.1    | Linear Polarization . . . . .                                     | 257        |
| 10.3.2    | Circular Polarization . . . . .                                   | 258        |
| 10.3.3    | Elliptical Polarization . . . . .                                 | 258        |
| 10.3.4    | Unpolarized Light . . . . .                                       | 258        |
| 10.3.5    | Polarizing Elements and Effects . . . . .                         | 258        |
| 10.3.5.1  | Polarizers . . . . .                                              | 259        |
| 10.3.5.2  | Polarisation by Light Scattering . . . . .                        | 261        |
| 10.3.5.3  | Polarization by Brewster Reflection . . . . .                     | 262        |
| 10.3.6    | Birefringence . . . . .                                           | 263        |
| 10.3.6.1  | Outlook: Changing the Polarization with<br>Wave Plates . . . . .  | 265        |
| 10.3.7    | Optical Activity . . . . .                                        | 265        |
| 10.4      | Wave Optics . . . . .                                             | 267        |
| 10.4.1    | Interference of Light . . . . .                                   | 267        |
| 10.4.1.1  | Outlook: Light Rays as Interference<br>Patterns . . . . .         | 268        |
| 10.4.1.2  | Coherence . . . . .                                               | 268        |
| 10.4.1.3  | Mach-Zehnder Interferometer . . . . .                             | 270        |
| 10.4.1.4  | Thin Film Interference . . . . .                                  | 271        |
| 10.4.2    | Diffraction . . . . .                                             | 273        |
| 10.4.2.1  | Huygens' Principle . . . . .                                      | 273        |
| 10.4.2.2  | Diffraction at the Single Slit . . . . .                          | 274        |
| 10.4.2.3  | Diffraction at the Double Slit . . . . .                          | 275        |
| 10.4.2.4  | Diffraction at the Grating . . . . .                              | 276        |

|           |                                                                        |            |
|-----------|------------------------------------------------------------------------|------------|
| 10.4.3    | Resolving Power of Optical Images . . . . .                            | 277        |
| 10.4.3.1  | Rayleigh Criterion . . . . .                                           | 278        |
| 10.4.3.2  | Abbe Criterion . . . . .                                               | 278        |
| 10.5      | Quantum Optics . . . . .                                               | 280        |
| 10.5.1    | Properties of Photons . . . . .                                        | 280        |
| 10.5.2    | Experimental Detection of the Photon . . . . .                         | 282        |
| 10.5.2.1  | Black-Body Radiation . . . . .                                         | 282        |
| 10.5.2.2  | Photoelectric Effect . . . . .                                         | 284        |
| 10.5.2.3  | Compton Scattering . . . . .                                           | 286        |
| 10.5.2.4  | Photon Statistics in Parametric<br>Fluorescence . . . . .              | 288        |
| 10.6      | Optics: Compact . . . . .                                              | 289        |
| <b>11</b> | <b>Fundamentals of Quantum Physics . . . . .</b>                       | <b>293</b> |
| 11.1      | Properties of Quantum Objects . . . . .                                | 293        |
| 11.1.1    | Wave-Particle Duality . . . . .                                        | 294        |
| 11.1.2    | Copenhagen Interpretation . . . . .                                    | 295        |
| 11.1.2.1  | Electron Diffraction at the Double Slit<br>Experiment . . . . .        | 297        |
| 11.1.2.2  | Outlook: Alternative Interpretations of<br>Quantum Mechanics . . . . . | 299        |
| 11.1.3    | Heisenberg's Uncertainty Principle . . . . .                           | 300        |
| 11.1.4    | Superposition . . . . .                                                | 302        |
| 11.1.5    | Entanglement . . . . .                                                 | 304        |
| 11.1.5.1  | EPR Experiment . . . . .                                               | 305        |
| 11.1.5.2  | Schrödinger's Cat . . . . .                                            | 306        |
| 11.2      | Atomic Physics . . . . .                                               | 307        |
| 11.2.1    | Atomic Model According to Bohr . . . . .                               | 308        |
| 11.2.1.1  | Absorption and Emission . . . . .                                      | 310        |
| 11.2.2    | Atomic Model According to Schrödinger . . . . .                        | 312        |
| 11.2.2.1  | Principal Quantum Number $n$ . . . . .                                 | 313        |
| 11.2.2.2  | Angular Momentum Quantum Number $l$ . . . . .                          | 313        |
| 11.2.2.3  | Magnetic Quantum Number $m$ . . . . .                                  | 314        |
| 11.2.2.4  | Corrections to Schrödinger's Atomic<br>Model . . . . .                 | 316        |
| 11.2.3    | Elements and Periodic Table . . . . .                                  | 316        |
| 11.2.3.1  | Spin Quantum Number $m_s$ and Pauli<br>Principle . . . . .             | 317        |
| 11.2.3.2  | Occupation of the Orbitals . . . . .                                   | 317        |
| 11.2.3.3  | Periodic Table . . . . .                                               | 319        |
| 11.3      | Nuclear Physics . . . . .                                              | 321        |
| 11.3.1    | Structure of the Atomic Nucleus . . . . .                              | 321        |
| 11.3.2    | Decays of Atomic Nuclei . . . . .                                      | 325        |
| 11.3.2.1  | $\alpha$ -Decay . . . . .                                              | 325        |
| 11.3.2.2  | $\beta^-$ -Decay . . . . .                                             | 325        |

---

|              |                                               |            |
|--------------|-----------------------------------------------|------------|
| 11.3.2.3     | $\beta^+$ -Decay . . . . .                    | 326        |
| 11.3.2.4     | Proton and Neutron Emission . . . . .         | 327        |
| 11.3.2.5     | $\gamma$ -Decay . . . . .                     | 327        |
| 11.3.2.6     | Energy in Nuclear Decay . . . . .             | 328        |
| 11.3.2.7     | Decay Law and Activity . . . . .              | 328        |
| 11.3.2.8     | Biological Effects of Radioactivity . . . . . | 330        |
| 11.3.3       | Nuclear Fusion . . . . .                      | 331        |
| 11.4         | Quantum Physics: Compact . . . . .            | 332        |
| <b>12</b>    | <b>Appendix: Physical Constants . . . . .</b> | <b>335</b> |
| <b>Index</b> | <b>. . . . .</b>                              | <b>337</b> |