

Contents

1. Life: Information, Matter, and Energy	1
1.1 Physics and Life	1
1.2 The Hourglass of Change	5
1.2.1 Differences and Chemistry Make Things Happen	5
1.2.2 Life and Entropy	8
1.3 Energy, Metabolic Rate, and Allometry	10
1.3.1 Empirical Determination of Metabolic Rates	10
1.3.2 Allometry	13
1.3.3 The Benefits of Large Bodies	15
1.4 Zoological Physics Modeling	17
1.4.1 Where Zoological Physics Fits in	18
1.4.2 The Warp and Weft of Zoological Physics	19
1.4.3 Strength and Limits of Physical Models	20
Problems and Hints for Solutions	22
2. Energy and Temperature	25
2.1 Parameters of the Energy Chain	26
2.1.1 Temperature	27
2.1.2 Forms of Energy and Power	28
2.1.3 How Animals Do Work and Generate Mechanical Energy	29
2.1.4 Internal Energy, and Heat	30
2.2 The Conservation of Energy	33
2.2.1 The First Law of Thermodynamics	34
2.2.2 Energy Analysis	35
2.2.3 Compound Efficiency of the Energy Conversion Chain	36
2.2.4 Optimum Rates	39
2.3 Thermal Problems of Warm Blooded Animals	40
2.3.1 Temperature Control and Heat Fluxes	40
2.3.2 Heat Losses by Conduction	42
2.3.3 Surface Heat Transfer	45
2.3.4 Convection	46
2.3.5 How to Live with Permanently Cold Feet	47

2.3.6	Radiation	48
2.3.7	Phase Changes and Evaporation Cooling	50
2.3.8	Managing the Flow of Heat	51
2.4	How Thermodynamics Sets Limits for Life	52
2.4.1	A Place Called Home	53
2.4.2	Why Bigger is Better in a Cold Ocean	55
2.4.3	Why Birds Can't Be Smaller Than Bees	58
2.4.4	Water, the Magic Stuff	59
2.5	Other Physical Quantities	61
	Problems and Hints for Solutions	63
3.	Form and Forces	67
3.1	How to Deal with Forces	68
3.1.1	Forces in Static Equilibrium	68
3.1.2	Compression and Tension	69
3.1.3	The Free Body Diagram	70
3.2	Muscles and Tendons	71
3.2.1	Muscle Force	71
3.2.2	A Simple Model of the Muscle	73
3.2.3	The Muscle Cross Bridge Cycle	74
3.2.4	Muscle Efficiency	76
3.2.5	Cold and Warm Muscles	77
3.2.6	Muscle Connections	78
3.3	Static Forces That Animals May Encounter	78
3.3.1	Pressure	79
3.3.2	Buoyancy	81
3.3.3	Elastic Forces	82
3.3.4	Electrostatic Force	84
3.3.5	Capillary Forces, a Form of Surface Tension	85
3.3.6	The Maximum Size of Water Striders	87
3.3.7	Friction	87
3.4	Dynamic Forces	88
3.4.1	Bernoulli Force	89
3.4.2	Centrifugal Force	90
3.4.3	Drag	90
3.4.4	The Minimum Compound Drag	93
3.4.5	Ventilation Drag	95
3.4.6	Lift Force	96
3.4.7	Magnus Effect	97
3.4.8	Jet Thrust Force	97
3.5	Simple Body Forms from Skin Bags to Bones	97
3.5.1	Animals Without Bones – Giant Caterpillars?	98
3.5.2	Elephant Trunks and Octopus Arms	100
3.5.3	The Spiral Structure of Filaments in Nematodes	101
3.5.4	Hard Shell Critters	101

3.5.5	The Invention of Bones	102
3.6	Large Structures with Bones	103
3.6.1	Chewing: Pressure Amplification and Lethal Bananas	103
3.6.2	Triangular Elements in Large Structures	105
3.6.3	Vertebrae Construction, Bridges with Cable Support	105
3.6.4	Elastic Elements as Support Structures	106
3.6.5	The Secret of Posture	107
3.6.6	Impediment by Gravitation on Other Planets	109
3.7	Scaling Up	109
3.7.1	Geometric Scaling	110
3.7.2	Weakest Link Scaling	110
3.7.3	Maximum Tension Scaling	112
3.7.4	Elastic Similarity Scaling	113
3.8	Strong Materials in Biology	113
3.8.1	Surface Energy γ and Breaking Strength	114
3.8.2	The Strength of Real Materials	115
3.8.3	Why Are Spider Silk and Kevlar so Strong?	117
3.8.4	The Optimum Stretch of Spider Silk	118
3.8.5	The Dragline as Safety Line	120
	Problems and Hints for Solutions	122
4.	Fluids in the Body	127
4.1	Motion in Concentration Gradients	128
4.1.1	Diffusion	128
4.1.2	Osmosis	130
4.1.3	The Size of Body Cells	130
4.2	Convection and Pipe Flow	133
4.2.1	Pipe Flow and Bernoulli Equation	134
4.2.2	Laminar and Turbulent Flow	136
4.2.3	Pressure Drop in Blood Vessels	138
4.2.4	Flow Control in Blood Vessels	139
4.2.5	Strokes	140
4.2.6	Why Turbulent Flow Is Bad	140
4.3	The 'Highway System' of the Body	141
4.3.1	Pressure and Velocity in the Arteries	142
4.3.2	The Hemoglobin Connection	143
4.3.3	How Much Oxygen Does the Body Need?	144
4.3.4	How Many Capillaries?	147
4.3.5	Laminar Flow in the Aorta	147
4.3.6	The Power and Frequency of the Heart	148
4.3.7	The Ventilation System	149
4.3.8	Breathing	151
4.3.9	Blood Circulation Time	153
4.4	From Digestion to Propagation	153
	Problems and Hints for Solutions	154

5. Animals in Motion	159
5.1 Kinematics of the Motion	159
5.1.1 Translational and Rotational Motion	160
5.1.2 How to Manipulate Rotational Motion	162
5.1.3 How the Heron Starts Flying	163
5.1.4 Linear Motion: Predators Fast Food	164
5.1.5 Connection of Angular and Linear Velocities	165
5.1.6 Relative Motion	167
5.1.7 Lifetimes and Biological Periods	167
5.2 Dynamics of the Moving Animal	170
5.2.1 How Animals Get Going – the Resultant Force	171
5.2.2 Landing on Your Feet	172
5.2.3 The Jumping Flea	173
5.2.4 Forces in Angular Motion	174
5.2.5 Moving Through Fluids	175
5.2.6 Terminal Velocity of a Small Insect Falling in Still Air	176
5.2.7 Rocket Propulsion	177
5.2.8 Masters of Acceleration	178
5.3 Locomotion and Energy	179
5.3.1 Energy Analysis of Moving Objects	180
5.3.2 Cost of Transport and Resistive Force	180
5.3.3 Saving Mechanical Power by Slender Limbs	182
5.3.4 Spring Loaded Animals	183
5.3.5 Energy Storage in Elastic Body Components	184
5.4 Continuous Motion	186
Problems and Hints for Solutions	187
6. Locomotion	191
6.1 Periodic Motion and Resonance	191
6.1.1 Periodic Motion	192
6.1.2 Resonance, a Principle to Reduce Energy Consumption	194
6.2 Locomotion in the Water by Flippers and Tails	197
6.2.1 How Fast Are Swimmers?	198
6.2.2 Propulsion Strategies at Higher Speeds	199
6.2.3 Swimming at Slow Speeds	200
6.2.4 A Model for Fish Propulsion from Rest	201
6.3 On the Wing	205
6.3.1 Generation of Lift	206
6.3.2 The Minimum Flight Velocity	209
6.3.3 Why Big Birds Cannot Fly	211
6.3.4 The Hovering Flight of Insects and Humming Birds	212
6.3.5 Flapping Flight	214
6.4 Locomotion with Arms and Legs	216
6.4.1 The Arms Race of Tree Dwellers	217

6.4.2	Walking	218
6.4.3	Running	220
6.4.4	The Transition from Walking to Running	224
6.4.5	Why T-Rex Was No Endurance Runner	225
6.5	From Efficient Use of Energy to the Smarter Use of Information	226
	Problems and Hints for Solutions	228
7.	Waves, the Carriers of Information	231
7.1	External and Internal Information	232
7.1.1	From Genes to Brain and Senses	232
7.1.2	Organic and Technical Evolution	234
7.1.3	The Information and Material Hierarchies	234
7.2	Contact and Distant Senses	235
7.2.1	Signals and Sensor Sensitivities	235
7.2.2	What Is Extracted from the Background?	238
7.3	Wave Fields	239
7.3.1	Some Properties of Waves	240
7.3.2	Amplitudes, Wavelength, and How Things Move in Waves	241
7.3.3	The Inverse Square Law	243
7.3.4	Reduction of Intensity by Absorption ($\lambda \gg D$)	245
7.3.5	Scattering	247
7.4	How Waves Change Their Direction	248
7.4.1	The Phase Velocity	249
7.4.2	The Phase Velocity in a Compressible Medium	251
7.4.3	Refraction	252
7.4.4	Total Internal Reflection	252
7.4.5	Light Pipes and Wave Guides	253
7.4.6	Sound Pipes: The Sofar Channel and Ground Effect	254
7.4.7	The Lateral Spread of Wave Fronts	255
7.5	Information Background	257
	Problems and Hints for Solutions	258
8.	Light, Abundant Information	261
8.1	Facts of Light	261
8.1.1	Photons and Waves	262
8.1.2	Why Light Waves Can Produce Sharp Images	263
8.1.3	Intensity, Wavelength, and Photon Numbers	264
8.1.4	Biological Effects of Different Wavelengths	265
8.1.5	How Many Photons Make an Image?	266
8.2	Imaging Principles	267
8.2.1	Primitive Radiation Detectors	268
8.2.2	Pinhole Cameras	269

8.2.3	Imaging by Lenses	270
8.2.4	Eyes in Air and Under Water	271
8.2.5	The F-Number	274
8.2.6	The Diffraction Limit: How Sharp Are the Images of Lens Eyes?	275
8.2.7	Image Resolution of Lens Eyes	276
8.2.8	Why Imaging Cuts Down on Background Noise	277
8.3	The Human Eye	278
8.3.1	Geometry and Physiology	278
8.3.2	Receptors of the Eye, Sensitivities, and Field of View	279
8.3.3	Resolution of the Human Eye	281
8.3.4	Aging of Eye Components	281
8.4	Animal Eyes	282
8.4.1	Pinhole Camera Eyes for Heat Radiation	283
8.4.2	Spider Eyes	285
8.4.3	Fish Eyes	285
8.4.4	Big Eyes of the Deep	287
8.4.5	Non Spherical, Large Aperture Lens Eyes of Trilobites	289
8.5	Facet Eyes	290
8.5.1	The Principle of Light Pipes	290
8.5.2	Insect Eyes	292
8.5.3	Intensity Attenuation by Frustrated Internal Reflection	292
8.6	Unwanted and Wanted Visibility	294
8.6.1	How Animals Make Perfect Reflectors Using Interference	294
8.6.2	Improving the Contrast with Dielectric Mirrors	296
8.6.3	Hiding in the Water	296
8.6.4	Ghosts of the Deep with Anti Reflection Coatings	298
8.6.5	Unmasking the Ghosts with Polarized Light	299
8.6.6	More About Color	299
8.7	The Active Production of Light, and Limits of Seeing	300
8.7.1	Bioluminescence	300
8.7.2	Signal to Noise Reduction Through Binocular Seeing	301
8.7.3	Limitation of Seeing and How the Brain Sets You into the Picture	302
8.7.4	High Resolution of Optical Signals Is Not Always Good Enough	303
	Problems and Hints for Solutions	304
9.	Sound	309
9.1	Signals of Sound, Noise, and Language	310
9.1.1	Phenomena Associated with Sound	310
9.1.2	Parameters of Sound	311
9.1.3	Sound Quality	312
9.1.4	Fourier Analysis	314

9.2	Intensity and Impedance	315
9.2.1	Intensity and Particle Velocity	315
9.2.2	Pressure, Impedance, and Velocity Fluctuations	316
9.2.3	The Decibel Scale	319
9.2.4	Beats	320
9.2.5	Sound Absorption, Scattering and Refraction in Free Space ..	321
9.2.6	Impedance Mismatch Between Air and Water	323
9.2.7	Hearing and Voice Transmission in Air	325
9.3	Ears	326
9.3.1	Principles of Amplification in Mammal Ears	327
9.3.2	Pinna and Middle Ear Amplification	328
9.3.3	Inner Ear Frequency Analysis	329
9.3.4	The Ear of an Aquatic Mammal	331
9.3.5	Lateral Lines of Fish	332
9.3.6	The Sensitivity of Ears	333
9.4	Voices and Sound Production	334
9.4.1	How Sound Is Shed off a Sender	335
9.4.2	Resonators	336
9.4.3	Oscillations of Elastic Solids	337
9.4.4	Oscillations of Air Volumes	338
9.4.5	Frequencies of Periodically Interrupted Motion	340
9.5	Voices	342
9.5.1	The Human Voice	342
9.5.2	The Frequency Spectrum of Speech	344
9.5.3	The Sound of Frogs	346
9.5.4	The Sound of Snapping Shrimp: Cavitation	346
9.5.5	Insect Sounds	347
9.5.6	Sperm Whale Sound	347
9.6	Information Extracted from Ambient Sound	347
9.6.1	Direction, Echoes, and Shadows	348
9.6.2	Signal Spectrum Recognition – Who Is There?	349
9.6.3	Distance and Directions of Sound Sources	349
9.6.4	Delay Time Measurements	351
9.7	Sound Images	353
9.7.1	Little Energy Goes a Long Way Traveling as Information	353
9.7.2	Delphinid Acoustic Apparatus	354
9.7.3	Echo Location of Bats	355
9.7.4	How Bats Know the Speed of Their Prey	356
9.8	Sound, the Social Sense	359
9.8.1	Comparison of Light and Sound Images	359
9.8.2	Why Sound Images Are Not Always Good Enough	360
	Problems and Hints for Solutions	361

10. Body Electronics and Magnetic Senses	365
10.1 The Electrical Machinery of Life	365
10.1.1 Life Started in Leyden Jars	366
10.1.2 Forces Created by Electric Fields	367
10.1.3 Moving Charges into and out of Cells	368
10.2 Conduction of Nerve Pulses	371
10.2.1 Gates in Cells	371
10.2.2 Moving Charges by Mechanical Stresses: Piezo Effect	374
10.2.3 Electrical Signals of Muscle Activities	374
10.3 Passive Use of Electrical Fields	374
10.3.1 The 6th Sense: Electrical Detection of Prey	375
10.3.2 Electrical Detectors of Fish	376
10.3.3 Platypus	376
10.4 The Active Use of Electric Fields	377
10.4.1 Fields and Signals	377
10.4.2 Living Batteries and Voltage Sources	379
10.5 Navigation by Magnetic Fields	380
10.5.1 The Origin of Magnetic Fields	380
10.5.2 The Earth's Magnetic Field	381
10.5.3 The Magnetic Sense	382
10.5.4 Magneto-Tactic Bacteria with Ideal Compass Needles	383
10.5.5 Pigeons Trout, Turtles, and Dolphins	384
10.5.6 Life on Mars?	385
10.5.7 Orientation by $\mathbf{u} \times \mathbf{B}$ in the Earth Field	385
Problems and Hints for Solutions	387
11. Better Physics: The Trifle of Difference	389
11.1 Physics Enables Within the Framework of Biological Restrictions	391
11.1.1 Physics Concepts	391
11.1.2 Fitness Landscape Molded by Physics	394
11.1.3 Examples of How Physical Principles Are Utilized	395
11.1.4 Non-Dimensional Numbers and Scaling Relations	398
11.1.5 Co-Evolution	399
11.2 Optima and Limits	400
11.2.1 Size and Mass Ranges	400
11.2.2 Living Space Ranges	401
11.2.3 Information Limits	402
11.2.4 Energy Transfer Time Limits	402
11.2.5 Optima	403
11.2.6 The Phase Space Arena of Organisms	404
11.3 Overcoming Limitations: The Workshop of Evolution	405
11.3.1 Measures and Countermeasures	406
11.3.2 New Territory	406

11.4 The Open Door	407
11.4.1 Elements of Zoological Physics Modeling	408
11.4.2 Limitations of Modeling	409
11.4.3 Some Open Questions	409
Problems and Essays	411
Epilog	416
 List of Tables	417
 References	419
 Index	423