

# Contents

<i>Preface</i>	<i>page xv</i>
<i>List of Boxes</i>	xviii
<b>1 Evolution of materials science and engineering: from natural to bioinspired materials</b>	1
1.1 Early developments	1
1.2 Evolution of materials science and engineering	3
1.2.1 Traditional metallurgy	3
1.2.2 The structure–properties–performance triangle	6
1.2.3 Functional materials	7
1.3 Biological and bioinspired materials	8
Summary	12
Exercises	13
 <b>Part I Basic biology principles</b>	 17
<b>2 Self-assembly, hierarchy, and evolution</b>	19
Introduction	19
2.1 Hierarchical structures	19
2.2 Multifunctionality	29
2.3 Self-organization and self-assembly	30
2.4 Adaptation	31
2.5 Evolution and convergence	33
2.6 Ashby–Wegst performance plots	36
2.7 Viscoelasticity	40
2.8 Weibull distribution of failure strengths	45
Summary	47
Exercises	51
<b>3 Basic building blocks: biopolymers</b>	53
Introduction	53
3.1 Water	54
3.2 Nucleotides and nucleic acid	55
3.3 Amino acids, peptides, and proteins	57

3.3.1	Amino acids and peptides	57
3.3.2	Overview of protein structure	66
3.3.3	Collagen	69
3.3.4	Keratin	81
3.3.5	Elastin	83
3.3.6	Actin and myosin	84
3.3.7	Resilin and abductin	88
3.3.8	Other structural proteins	88
3.4	Polysaccharides	89
3.4.1	Chitin and chitosan	90
3.4.2	Cellulose	93
3.5	Lignin	95
3.6	Lipids	95
3.7	Formation of biopolymers	95
3.7.1	Collagen	95
3.7.2	Keratin	97
3.7.3	Chitin	97
	Summary	97
	Exercises	99
<b>4</b>	<b>Cells</b>	102
	Introduction	102
4.1	Structure	103
4.1.1	Cytoskeleton	107
4.1.2	Multifunctionality	110
4.2	Mechanical properties	110
4.3	Mechanical testing	110
4.4	Cell motility, locomotion, and adhesion	117
4.5	Flexure and compressive resistance of hollow and solid cylinders: application to microtubules	119
4.6	From cells to organisms	125
	Summary	126
	Exercises	127
<b>5</b>	<b>Biomineralization</b>	129
	Introduction	129
5.1	Nucleation	129
5.2	Growth and morphology of crystals	132
5.3	Structures	136
5.4	Origins and structures	144
	Summary	151
	Exercises	152

<b>Part II</b>	<b>Biological materials</b>	155
<b>6</b>	<b>Silicate- and calcium-carbonate-based composites</b>	157
	Introduction	157
6.1	Diatoms, sea sponges, and other silicate-based materials	157
6.1.1	Diatoms and radiolarians	157
6.1.2	Sponge spicules	160
6.2	Mollusc shells	164
6.2.1	Classification and structures	164
6.2.2	Nacreous shells	168
6.2.3	Conch shell	196
6.2.4	Giant clam	202
6.3	Teeth of marine organisms: chiton radula and marine worm	211
6.4	Sea urchin	213
6.5	Shrimp hammer	213
6.6	Egg shell	216
6.7	Fish otoliths	217
6.8	Multi-scale effects	217
	Summary	218
	Exercises	220
<b>7</b>	<b>Calcium-phosphate-based composites</b>	223
	Introduction	223
7.1	Bone	223
7.1.1	Structure	224
7.1.2	Bone cells and remodeling	226
7.1.3	Elastic properties	226
7.1.4	Strength	233
7.1.5	Fracture and fracture toughness of bone	239
7.1.6	Fatigue	254
7.2	Antler	255
7.2.1	Structure and functionality	255
7.2.2	Quasistatic and dynamic mechanical behavior	257
7.2.3	Exceptional fracture resistance	259
7.3	Teeth and tusks	262
7.3.1	Structure and properties	262
7.3.2	Fracture toughness and toughening mechanisms	263
7.4	Other mineralized biological materials	274
7.4.1	Armadillo	274
7.4.2	Testudine	278
7.4.3	Crocodilia	280
	Summary	283
	Exercises	285

<b>8 Biological polymers and polymer composites</b>	292
Introduction	292
8.1 Tendons and ligaments	293
8.2 Spider and other silks	296
8.2.1 Adhesive in spider web	301
8.2.2 Molecular dynamics predictions	301
8.3 Arthropod exoskeletons	304
8.3.1 Crustaceans	305
8.3.2 Hexapods	312
8.4 Keratin-based materials	318
8.4.1 Hoof	319
8.4.2 Horn	323
8.4.3 Beak	328
8.4.4 Pangolin scales	332
8.5 Fish scales	332
8.6 Squid beak	339
8.7 Invertebrate jaws and mandibles	342
8.8 Other natural fibers	346
Summary	348
Exercises	353
<b>9 Biological elastomers</b>	355
Introduction	355
9.1 Constitutive equations for soft biopolymers	355
9.1.1 Worm-like chain model	355
9.1.2 Power equation	358
9.1.3 Flory–Treloar equations	359
9.1.4 Mooney–Rivlin equation	359
9.1.5 Ogden equation	359
9.1.6 Fung equation	361
9.1.7 Molecular dynamics calculations	362
9.2 Skin	362
9.3 Muscle	375
9.4 Blood vessels	378
9.4.1 Nonlinear elasticity	381
9.4.2 Residual stresses	383
9.5 Mussel byssus	384
9.6 Whelk eggs	387
9.7 Extreme keratin: hagfish slime and wool	390
Summary	392
Exercises	395

<b>10 Biological foams (cellular solids)</b>	397
Introduction	397
10.1 Lightweight structures for bending and torsion resistance	397
10.2 Basic equations for foams	400
10.2.1 Elastic region	404
10.2.2 Plastic plateau	405
10.2.3 Densification	407
10.3 Wood	410
10.4 Bird bones	417
10.5 Bird beaks	420
10.5.1 Toucan and hornbill beaks	420
10.5.2 Modeling of interior foam (Gibson–Ashby constitutive equations)	425
10.6 Feather	435
10.7 Cuttlefish bone	443
Summary	446
Exercises	449
<b>11 Functional biological materials</b>	452
Introduction	452
11.1 Adhesion and attachment	452
11.2 Gecko feet	455
11.3 Beetles	461
11.4 Tree frog toe pad	461
11.5 Abalone foot: underwater adhesion	465
11.6 Surfaces and surface properties	472
11.6.1 Multifunctional surface structures of plants	472
11.6.2 Shark skin	477
11.7 Optical properties	478
11.7.1 Structural colors	478
11.7.2 Photonic crystal arrays	479
11.7.3 Thin film interference	481
11.7.4 Chameleon	482
11.7.5 Echinoderms	484
11.8 Cutting: sharp biological materials	486
11.8.1 Plants	486
11.8.2 Fish teeth	487
11.8.3 Rodent incisors	491
11.8.4 Wood wasp ovipositor	492
Summary	493
Exercises	495

<b>Part III</b>	<b>Bioinspired materials and biomimetics</b>	497
<b>12</b>	<b>Bioinspired materials: traditional biomimetics</b>	499
	Introduction	499
12.1	Structural and functional applications	501
12.1.1	VELCRO®	501
12.1.2	Aerospace materials	504
12.1.3	Building designs	506
12.1.4	Fiber optics and microlenses	508
12.1.5	Manufacturing	510
12.1.6	Water collection	511
12.1.7	Gecko feet	512
12.1.8	Nacre-inspired structures	514
12.1.9	Marine adhesives: mussel byssal attachment	524
12.1.10	Sonar-enabled cane inspired by bats	527
12.1.11	Butterfly wings	527
12.1.12	Origami structures	531
12.1.13	Self-healing composites	532
12.1.14	Sheep-horn-inspired composites	535
12.1.15	Shock absorbers based on woodpecker's head	536
12.1.16	Natural graded and sandwich structures (osteoderms)	537
12.1.17	Cutting edges	539
12.1.18	Ovipositor drill	541
12.1.19	Birds	541
12.1.20	Fish	543
12.1.21	Structures from diatoms	544
12.1.22	Structures based on echinoderms	545
12.1.23	Whale-fin-inspired turbine blades	546
12.2	Medical applications	547
12.2.1	Bioglass®	553
12.2.2	Tissue engineering scaffolds	553
12.2.3	Bioinspired scaffolds	554
12.2.4	Vesicles for drug delivery	555
12.2.5	The blue blood of the horseshoe crab	556
	Exercises	557
<b>13</b>	<b>Molecular-based biomimetics</b>	560
	Introduction	560
13.1	Self-assembly structures	561
13.2	Phage-enabled assembly	563
13.3	Genetically engineered peptides for inorganics (GEPIs)	566
13.4	Genetic engineering	568

13.4.1	General principles and methodology	568
13.4.2	Applications	569
13.5	Virus-assisted synthetic materials	571
13.6	Bioinspiration from the molecular level: the bottom-up approach	576
13.7	MEMS and NEMS	579
13.8	Bioinspired synthesis and processing of biopolymers	581
	Summary	582
	Exercises	583
	<i>References</i>	584
	<i>Index</i>	620