Contents

1 Introduction 1
Annick Lesne and Paul Bourgine
1.1 Fundamental Issues 1
1.1.1 The Notion of Shape 1
1.1.2 Some Paths to Explore the World of Shapes 2
1.1.3 Shapes and Their Causes 3
1.1.4 Modelling Morphogenesis 3
1.2 Morpho-Genesis 4
1.2.1 Shape-Generating Mechanisms 4
1.2.2 Equilibrium, Out-of-Equilibrium and Far-from-Equilibrium Shapes 4
1.2.3 Irreversibility 5
1.2.4 Self-Assembly and Self-Organisation 5
1.3 Instabilities, Phase Transitions and Symmetry Breaking 6
1.3.1 Phase Transitions, Bifurcations and Instabilities 6
1.3.2 Symmetry Breaking 7
1.3.3 Emergence 7
1.3.4 Fractal Shapes 8
1.4 Inanimate or Living Shapes 9
1.4.1 Some Questions 9
1.4.2 Are Living Shapes Special? 10
1.4.3 Functional Shapes 10
1.4.4 Genetic Programme, Self-Organisation and Epigenomics 11
1.4.5 The Robustness and Variability of Living Shapes 12
1.5 Book Overview 12
References 13

2 Ferrofluids: A Model System of Self-Organised Equilibrium 15
Jean-Claude Bacri and Florence Elias
2.1 Introduction: Situation with Regard to the Other Chapters 15
2.2 Physical Systems in Self-Organised Equilibrium 15
2.2.1 Examples of Self-Organised Physical Systems 16

2.2.2 The Origin of Order 19
2.2.3 The Bond Number 21
2.2.4 Domain Size and Choice of Pattern 21
2.2.5 Summary 22
2.3 Morphologies in Ferrofluids 22
2.3.1 Ferrofluids: A Model System for Studying Structures 22
2.3.2 Stripes and Bubbles, Foams and Rings in Ferrofluids 26
2.3.3 The Influence of History: Initial Conditions and Conditions of Formation 28
2.3.4 The Source of Patterns: Instabilities 31
2.4 Conclusion 37
References 38

3 Hierarchical Fracture Networks 41
Steffen Bohn
3.1 Introduction 41
3.2 The Formation of Hierarchical Fracture Networks 42
3.3 The Fracture Network as a Hierarchical Division of Space 44
3.4 A Characteristic Scale 45
3.5 Conclusion 47

4 Liquid Crystals and Morphogenesis 49
Yves Bouligand
4.1 Shells and Series of Arches 49
4.2 Helicoidal Plywood 51
4.3 Cholesteric Liquid Crystals and Stabilised Analogues 53
4.4 Specificity and Diversity of Liquid Crystals 54
4.4.1 Mesogenic Molecules 55
4.4.2 Structure of Liquid Crystals 56
4.4.3 Phase Transitions 57
4.5 Liquid Crystals and Stabilised Analogues in Biology: A Widespread Phenomenon 58
4.5.1 Muscles 58
4.5.2 Myelinic Figures and Fluid Cell Membranes 59
4.5.3 Stabilised Membranes 60
4.5.4 Nematic and Cholesteric Analogues 60
4.5.5 The Limits of a Widespread Phenomenon 60
4.6 Liquid Crystalline Self-Assemblies 61
4.7 Curvature and Structure 62
4.7.1 Diversity of Curvatures in Liquid Crystals and Their Analogues 62
4.7.2 Geometry of the Different Curvatures 64
4.7.3 Elastic Coefficients and Spontaneous Curvatures 68
4.8 Lyotropic Systems and Cell Fluidity 69

4.9 Liquids with Parallel Surfaces and the Geometrical Origin of Forms 72
4.9.1 Caps and Saddles: Elliptic or Hyperbolic Surfaces 73
4.9.2 Dupin Cyclides in Liquid Crystals 74
4.10 Germs and Textures of Liquid Crystals: Their Biological Analogues 77
4.11 Topological Nature of Liquid Crystalline Textures 81
4.11.1 Möbius Strips 81
4.11.2 Pairs of Interlocking Rings 82
4.12 Liquid Crystals and Mechanical Clock Movements 84
References 84

5 Biological Self-Organisation by Way of the Dynamics of Reactive Processes 87
James Tabony
5.1 Self-Organisation by Dynamic Processes in Physical Systems 90
5.2 Self-Organisation in Colonies of Living Organisms 92
5.3 Self-Organisation by Reaction and Diffusion: Stripes in a Test-Tube 93
5.4 Microtubule Self-Organisation 97
References 103

6 Dunes, the Collective Behaviour of Wind and Sand, or: Are Dunes Living Beings? 107
Stéphane Douady and Pascal Hersen
6.1 Discovery 107
6.2 The Wind Drives the Sand ... Which Steals the Wind's Force as It Flies 107
6.3 The Minimal Dune 108
6.4 The Wind Runs Over the Dune ... and Pushes It Along 109
6.5 Does the Wind Flow Make the Dune? 109
6.6 Understanding the Barchan Shape 111
6.7 The Paradox of Corridors ... or the Problem of Dunes Among Themselves 114
6.8 The Wind is Never Constant 114
6.9 Dunes are Not Isolated 115
6.10 The Grain of Sand, the Dune and the Corridor of Dunes ...What About the Individual, the Flows and the Form? 116
References 118

7 Morphodynamics of Secretory Endomembranes 119
François Képès
7.1 Some Preliminary Reminders 119
7.2 Introduction 120
7.2.1 Cell Membrane and Translocation 120
7.2.2 Eukaryotic Secretory Pathway 121
7.2.3 Other Eukaryotic Compartments 123

7.2.4 Cytoplasm, Cytoskeleton and Compartmentalisation 123
7.3 Morphodynamics of Membranes 123
7.3.1 Biological Membranes 123
7.3.2 Segregation 124
7.3.3 Fission 126
7.3.4 Fusion 131
7.4 Functional Models 133
7.5 Conclusions 136
7.5.1 Themes 136
7.5.2 Evolutionary Perspectives 136
7.5.3 Questions 137
7.5.4 Prospects 138
References 138

8 From Epigenomic to Morphogenetic Emergence 143
Caroline Smet-Nocca, Andràs Paldi, and Arndt Benecke
8.1 Genetic Inheritance, Regulation of Gene Expression, and Chromatin Dynamics 145
8.1.1 Gene Transcription and the Regulation of Gene Expression 145
8.1.2 Genomic Structure and its Impact on Transcriptional Regulation 146
8.2 Epigenetic Mechanisms, Epigenetic Inheritance and Cell Differentiation 149
8.2.1 DNA Methylation: Epigenetic Marker of Transcriptional Repression 149
8.2.2 Structural and Functional Organisation of Chromatin: Spatio-Temporal Regulation 152
8.3 The Link Between Epigenetic Information and the Regulation of Gene Expression 158
8.3.1 The Link Between DNA Repair and Transcription 158
8.3.2 CBP/p300, HATs Involved in Cell Growth, Differentiation and Development 160
8.3.3 Epigenetics and Oncogenesis 161
8.4 Morphogenomics 163
References 166

9 Animal Morphogenesis 167
Nadine Peyriéras
9.1 The Acquisition of Cell Diversity 169
9.1.1 Heterogeneity of the Egg: What Is Determined from the Moment of Fertilisation? 170
9.1.2 The Interaction Between Cells and Their Environment and the "Inside-Outside" Hypothesis 171

9.2 The Anatomical Tradition of Embryology, Identification of Symmetry Breaking and Characterisation of Morphogenetic Fields 171
9.2.1 Symmetry-Breaking in Early Embryogenesis 172
9.2.2 Formation of Boundaries and Compartments During Organogenesis 175
9.3 The "Bottom-Up" Approach of Developmental Biology 176
9.3.1 Dynamics of Molecular and Genetic Interactions in the Formation of Patterns 178
9.3.2 The Concept of Morphogen and Pattern Generation Through the Threshold Effect 179
9.3.3 The Formation of Somites in Vertebrates: A Model of Coupled Oscillators 181
9.4 The Reconstruction of Cell Morphodynamics and the Revival of the Anatomical Tradition of Embryology 184
9.4.1 Cell Movements and Deformations in Morphogenesis 184
9.4.2 Cell Adhesion and Biomechanical Constraints in the Embryo 185
9.4.3 The Tensegrity Model 185
References 187

10 Phyllotaxis, or How Plants Do Maths When they Grow 189
Stéphane Douady
10.1 Discovery 189
10.2 Why? 190
10.3 How? 192
10.4 Van Iterson's Tree ... Pruned! 194
10.5 Dynamics 196
10.6 Conclusion 197
References 198

11 The Logic of Forms in the Light of Developmental Biology and Palaeontology 199
Didier Marchand
11.1 Introduction 199
11.2 Palaeontology and Time 200
11.3 From the Cell to the Multicellular Organism: An Ever More Complex Game of "Lego" 201
11.4 The Major Body Plans: In the Early Cambrian, Quite Everything Was Already in Place 202
11.5 The Phylum of Vertebrates: A Fine Example of Peramorphosis 204
11.6 The Anomalies of Development: An Opening Towards New Morphologies 205
11.7 The Brain as the Last Space of Freedom 207

11.8 Conclusion 208
References 209

12 Forms Emerging from Collective Motion 211
Hugues Chaté and Guillaume Grégoire
12.1 Introduction 211
12.2 Towards a Minimal Model 213
12.2.1 The Ingredients 213
12.2.2 Formalisation 214
12.2.3 The Results of Vicsek et al. 216
12.3 Forms in the Absence of Cohesion 218
12.3.1 Moving in Self-Organised Groups 218
12.3.2 Microscopic Trajectories and Forms 219
12.4 When Cohesion Is Present: Droplets in Motion 220
12.4.1 Phase Diagrams and Form of Droplets 220
12.4.2 Cohesion Broken During the Onset of Motion 221
12.5 Back to Nature 222
References 223

13 Systems of Cities and Levels of Organisation 225
Denise Pumain
13.1 Three Levels of Observation of the Urban Fact 226
13.1.1 Emergent Properties at the City Level 226
13.1.2 The Structure of the System of Cities 228
13.2 A Functional Interpretation of the Hierarchical Ordering 231
13.2.1 Daily Life in the City 232
13.2.2 The Functions of the System of Cities 233
13.3 The Interactions that Construct the Levels 235
13.3.1 The Constituent Interactions of City Forms 237
13.3.2 The Constituent Interactions of Systems of Cities 239
13.4 Complex Systems Models for Urban Morphogenesis 242
13.4.1 Cities as Spatial Objects 243
13.4.2 Cities and Fractal Objects 244
13.4.3 From Support Space to Relational and Conforming Space . 245
References 246

14 Levels of Organisation and Morphogenesis from the Perspective of D'Arcy Thompson 251
Yves Bouligand
14.1 Games of Construction 252
14.1.1 Chemical Syntheses and Biosyntheses 252
14.1.2 Supramolecular Assemblies and their Lattices 254
14.1.3 Molecular and Supramolecular Models 256
14.2 Water Games 256

14.2.1 Hydrostatic Forms 257
14.2.2 Hydrodynamic Figures 258
14.2.3 Morphological Adaptations to the Hydrodynamics of the Environment 259
14.3 The Fragile Architectures of Diffusion 260
14.3.1 Hydrostatic Diffusion 260
14.3.2 Hydrodynamic Diffusion 261
14.4 Stabilisation and Reorganisation of Forms 262
14.5 The Problem of Strong Local Curvature and New Prospects 263
14.6 Particular and General Morphogenetic Theories 265
14.6.1 The Direct or Indirect Role of the Genome in Morphogenesis 265
14.6.2 Symmetry Breaking and Differentiation 267
14.6.3 New Prospects in Morphogenesis and the Concept of Viability 270
References 271

15 The Morphogenetic Models of René Thom 273
Jean Petitot
15.1 General Content of the Model 273
15.2 Morphodynamics and Structural Stability 275
15.3 The Theory of Dynamical Systems 276
15.4 The Theory of Singularities and "Elementary" Morphogenetic Models 279
15.5 The Principles of Morphodynamic Models 280
15.6 The Models of Morphogenesis 281
References 281

16 Morphogenesis, Structural Stability and Epigenetic Landscape 283
Sara Franceschelli
16.1 The Correspondence 283
16.2 Delbrück's Model 286
16.3 Structural Stability and Morphogenetic Field 287
16.4 Epigenetic Landscape: A Mental Picture, a Metaphor ... of What? . 288
16.5 Interpretations 292
References 292

17 Morphological and Mutational Analysis: Tools for the Study of Morphogenesis 295
Jean-Pierre Aubin and Annick Lesne
17.1 Objectives 295
17.2 Motivations 297
17.2.1 Problems of Co-Viability 297
17.2.2 Biological Morphogenesis 299

17.2.3 Image Processing 300
17.2.4 Shape Optimisation 300
17.2.5 Dynamic Economics 300
17.2.6 Front Propagation 301
17.2.7 Visual Robotics 301
17.2.8 Interval Analysis 301
17.3 The Genesis of Morphological Analysis 301
17.4 From Shape Optimisation to Set-Valued Analysis 302
17.5 Velocities of Tubes as Mutations 306
17.6 Mutational Analysis 306
17.7 Morphological Equations 308
17.8 Embryogenesis of the Zebrafish 311
References 312

18 Computer Morphogenesis 315
Jean-Louis Giavitto and Antoine Spicher
18.1 Explaining Living Matter by Understanding Development 315
18.1.1 The Animal-Machine 315
18.1.2 From Self-Reproduction to Development 317
18.1.3 Development as a Dynamical System 318
18.1.4 What Formalism for Dynamical Systems with Dynamical Structure? 321
18.2 Rewriting Systems 323
18.2.1 Introduction 323
18.2.2 Rewriting Systems and the Simulation of Dynamical Systems 325
18.3 Multiset Rewriting and Chemical Modelling 326
18.3.1 Some Examples of Application 328
18.3.2 Păun Systems and Compartmentalisation 329
18.3.3 In Parenthesis: The Application to Parallel Programming 331
18.4 Lindenmayer Systems and the Growth of Linear Structures 332
18.4.1 Growth of a Filamentous Structure 332
18.4.2 Development of a Branching Structure 334
18.5 Beyond Linear Structures: Calculating a Form in Order to Understand It 335
18.5.1 Simulation and Explanation 335
18.5.2 Giving Form to a Population of Autonomous Agents 336
References 337

Index 341