THE QUEST FOR A UNIVERSAL THEORY OF LIFE
Searching for Life As We Don’t Know It

Integrating both scientific and philosophical perspectives, this book provides an informed analysis of the challenges of formulating a universal theory of life. Among the issues discussed are crucial differences between definitions and scientific theories and, in the context of examples from the history of science, how successful general theories develop. The central problem discussed is two-fold: First, our understanding of life is still tacitly wedded to an antiquated Aristotelian framework for biology; second, there are compelling reasons for considering that familiar Earth life, which descends from a last universal common ancestor, is unrepresentative. What is needed are examples of life as we don’t know it. Potential sources are evaluated, including artificial life, extraterrestrial life, and a shadow biosphere right here on Earth. A novel strategy for searching for unfamiliar life in the absence of a definition or general theory is developed. This book is a valuable resource for graduate students and researchers studying the nature, origins, and extent of life in the universe.

CAROL E. CLELAND is Professor of Philosophy at the University of Colorado, Boulder, USA, where she is also Director of the Center for the Study of Origins and a Co-Investigator at the Center for Astrobiology. She teaches advanced interdisciplinary courses in the philosophy of science, including graduate seminars on central issues in astrobiology. She publishes papers in major science and philosophy journals, and is co-editor of the anthology The Nature of Life (Cambridge University Press, 2010).
“An essential read for anyone interested in the nature of life and its origins. Cleland’s philosophical outlook means that she approaches the subject from a fresh perspective, framing important questions rarely discussed by scientists . . . and deliberating points in a provocative way that forces readers to examine some of their cherished beliefs that they thought were self-evident.”

Athel Cornish-Bowden,
French National Center for Scientific Research, Marseilles, France

“What is life? What universal principles apply to any biosphere? Our efforts to answer these deep questions are stymied because of our biased, Earth-bound perspective with only one kind of (known) life. In a book rich with original ideas and lucid insights, science philosopher Carol Cleland considers life from the perspective of what we don’t know – the limitations, hidden biases, sloppy definitions, and false assumptions that may lead us astray. From ‘shadow biospheres’ on Earth, to artificial life in the lab, to alien lifeforms in distant galaxies, Cleland expands our minds and leads us to rethink what we thought we knew.”

Robert Hazen,
Carnegie Institution for Science, Washington, USA

“Searching for life elsewhere in our solar system or beyond is at the forefront of science today due to recent discoveries about terrestrial life, planetary environments, and planets around other stars. We can’t extrapolate from our single example of life on Earth, which all share common biochemistry and are descended from a common ancestor, as to what the characteristics of life elsewhere in the universe might be. Given these uncertainties, how can we identify something as alive? What does it mean to be living? What is life? Carol Cleland takes a philosophy of science approach to what constitutes life, integrating it with biology in a planetary context. She has made a valuable contribution to our understanding of the nature of life and how to search for it, both on Earth and elsewhere.”

Bruce Jakosky,
University of Colorado, Boulder, USA
CAMBRIDGE ASTROBIOLOGY

Series Editors
Bruce Jakosky, Alan Boss, Frances Westall, Daniel Prieur, and Charles Cockell

Books in the Series:

1. *Planet Formation: Theory, Observations, and Experiments*
   Edited by Hubert Klahr and Wolfgang Brandner
   ISBN 978-0-521-18074-0

2. *Fitness of the Cosmos for Life: Biochemistry and Fine-Tuning*
   Edited by John D. Barrow, Simon Conway Morris, Stephen J. Freeland, Charles L. Harper, Jr
   ISBN 978-0-521-87102-0

   Edited by Ralph Pudritz, Paul Higgs, and Jonathan Stone
   ISBN 978-0-521-87548-6

4. *Exploring the Origin, Extent, and Future of Life: Philosophical, Ethical, and Theological Perspectives*
   Edited by Constance M. Bertka
   ISBN 978-0-521-86363-6

5. *Life in Antarctic Deserts and Other Cold Dry Environments*
   Edited by Peter T. Doran, W. Berry Lyons, and Diane M. McKnight

6. *Origins and Evolution of Life: An Astrobiological Perspective*
   Edited by Muriel Gargaud, Purificación Lopez-Garcia, and Hervé Martin
   ISBN 978 0521-76131-4

7. *The Astrobiological Landscape: Philosophical Foundations of the Study of Cosmic Life*
   Milan M. Čirković

8. *The Drake Equation: Estimating the Prevalence of Extraterrestrial Life through the Ages*
   Edited by Douglas A. Vakoch and Matthew F. Dowd
   ISBN 978-1-107-07365-4

9. *Astrobiology, Discovery, and Societal Impact*
   Steven J. Dick
10. *Solving Fermi’s Paradox*
   Duncan H. Forgan

11. *The Quest for a Universal Theory of Life: Searching for Life As We Don’t Know It*
    Carol E. Cleland
    ISBN 978-0-521-87324-6
THE QUEST FOR A UNIVERSAL THEORY
OF LIFE
Searching for Life As We Don’t Know It

CAROL E. CLELAND
University of Colorado, Boulder
For Leta and Elspeth
Contents

Acknowledgments

Introduction

1 The Enduring Legacy of Aristotle: The Battle over Life as Self-Organization or (Genetic-Based) Reproduction
1.1 Overview
1.2 Aristotle on the Nature of Life: Nutrition Versus Reproduction
1.3 Classical Mechanism about Life: From Optimism to Quiet Desperation
1.4 Darwin to the Rescue?
1.5 Here We Go Again: Aristotelian Roots of Contemporary Accounts of the Nature and Origin(s) of Life
1.5.1 Metabolism-Based Versus Evolution-Based Definitions of the Nature of Life
1.5.2 Metabolism-First Versus Genes-First Theories of the Origin(s) of Life
1.6 Concluding Thoughts

2 Why Life Cannot Be Defined
2.1 Overview
2.2 Popular Definitions of Life
2.2.1 Thermodynamic Definitions
2.2.2 Metabolic Definitions
2.2.3 Evolutionary Definitions
2.2.4 Defining Life as Self-Organized Complexity
2.3 The Problem with Definitions
2.3.1 Logical Character of Definition
2.3.2 Limits of Definition
2.3.3 Diagnosing the Problem: A Defective Theory of Meaning and Reference 53
2.3.4 Why Natural Kinds Cannot Be “Defined” 55
2.3.5 Is life an Exception to the Rule? 59
2.4 Concluding Thoughts 61
3 What is a Scientific Theory? 63
  3.1 Overview 63
  3.2 The Syntactic Conception of Scientific Theories 65
  3.3 The Semantic Conception of Scientific Theories 68
  3.4 Scientific Theories and Definitions 73
    3.4.1 Scientific Theories Do Not “Define” Natural Kinds 74
    3.4.2 Nonstandard Definitions Do Not “Define” Scientific Theories 76
  3.5 Concluding Thoughts 79
4 How Scientific Theories Develop 82
  4.1 Overview 82
  4.2 How Scientifically Fruitful Ontologies Develop: Content Matters 84
  4.3 The Goldilocks Level of Abstraction 88
  4.4 The Threat Posed by Premature Commitment to Ontologies 93
  4.5 The Monist (Versus Pluralist) Stance 98
  4.6 Concluding Thoughts 102
5 Challenges for a Universal Theory of Life 105
  5.1 Overview 105
  5.2 The Magnitude of the $N = 1$ Problem of Biology 107
  5.3 Microbes: The Most Representative and Least Well Understood Form of Earth Life 114
    5.3.1 Planet of the Microbes 115
    5.3.2 A Brief History of Misunderstandings and Surprises 118
  5.4 The Problem of Contingencies and the Origin(s) of Life 120
    5.4.1 A Plague of Contingencies (on Both the SM World and the RNA World) 123
    5.4.2 The Origin Versus Nature Problem 127
  5.5 Concluding Thoughts 130
6 Rethinking the Traditional Paradigm for Life: Lessons from the World of Microbes 132
  6.1 Overview 132
  6.2 Evolution Viewed Through the Lens of the Microbial World 133
    6.2.1 The Concept of a Biological Species and the Tree of Life 134
Contents

6.2.2 Is Lamarck Hiding in the Shadows? 138

6.3 The Living Individual Viewed Through the Lens of the Microbial World 143
  6.3.1 Is the Host–Microbiome Complex (Holobiont) a Living Thing? 146
  6.3.2 Biofilms: Aggregates of Cells or Living Individuals? 149
  6.3.3 Could Rock-Powered Ecosystems Be Living Things? 155

6.4 Concluding Thoughts 159

7 Artificial Life: Could ALife Solve the N = 1 Problem? 161
  7.1 Overview 161
  7.2 Soft ALife: Digital Organisms? 161
  7.3 Hard ALife: Living Robots? 164
  7.4 Synthetic Biology: Creating Novel Life in the Laboratory? 167
  7.5 Concluding Thoughts 170

8 Searching for Extraterrestrial Life Without a Definition or Universal Theory of Life 172
  8.1 Overview 172
  8.2 A Case Study: The Viking Missions to Mars 172
  8.3 The Role of Anomalies in Scientific Discovery 176
  8.4 Searching for Anomalies Using Tentative (Versus Defining) Criteria 184
  8.5 Concluding Thoughts 193

9 A Shadow Biosphere: Alien Microbes on Earth? 195
  9.1 Overview 195
  9.2 How Scientifically Plausible Is a Shadow Biosphere? 196
    9.2.1 Did Life Originate Only Once on Earth? 197
    9.2.2 Could the Present-Day Earth Be Host to a Shadow Biosphere? 201
  9.3 If They Exist, Why Have We Not Found Them? 206
    9.3.1 Limitations to Microscopy 206
    9.3.2 Limitations to Cultivation 207
    9.3.3 Limitations to Metagenomic Methods 208
  9.4 Potentially Biological Anomalies: Have We Already Encountered Them? 211
  9.5 Concluding Thoughts 215

Conclusion 217

References 220

Index 243
Acknowledgments

This book is an ambitious project. It has been in the works for a long time. During this time, I have had extensive and very helpful conversations with many friends and colleagues about issues covered in this book. I am very grateful to you all.

I would like to single out a few of you for special thanks. I cannot thank Athel Cornish-Bowden and Heather Demarest enough for reading through most of the chapters of this book and providing me with constructive criticism. Thanks to Mitzi Lee for her patience with my many questions and concerns about Aristotle’s biology; she saved me from several grave errors of interpretation. I am also grateful to Alexandra Laird, who engaged in the arduous task of putting together the references and index for the book. I am very grateful to Norm Pace for long phone conversations over the years about microbiology. Thanks to Lisa Lloyd for her enthusiasm for the project and lively discussions during our delightful “philosophical breakfasts” in the summers of 2014 and 2015. I would also like to thank Mark Bedau, Nick Byrd, Graeme Forbes, Jim Griesemer, Elizabeth Griffths, Bruce Jakosky, Mathew Kopec, Maureen O’Malley, Jessica Riskin, Julia Staffel, Mike Stuart, Brian Zaharatos, and Michael Zerella for reading individual chapters and providing me with thought provoking criticisms; their feedback has made the book much better than it would otherwise be.

I have given many talks on issues in this book to different groups of scientists and philosophers and would like to thank them all for helpful discussions and comments. I am especially grateful to John Norton and my fellow visiting scholars at the Center for Philosophy of Science (University of Pittsburgh) for extended discussions about artificial life, definitions, and the search for extraterrestrial life while I was on Sabbatical Leave during the spring of 2016. I also greatly benefited from discussions about natural kinds, definitions, and scientific theories with Lisa Lloyd’s energetic philosophy of biology reading group at Indiana University during my visit in 2015. Last but certainly not least, I owe an important debt to the up and coming philosophers (Alexander Beard, Christopher Dengler,
Acknowledgments

Alexandra Laird, Lorenzo Nericcio, Cristian Larroulet Philippi, and Erich Riesen) and scientists (Ellie Hara, Cara Lauria, and Michael Zawaski) in my Fall 2017 graduate seminar on life who enthusiastically worked through the penultimate version of this book, chapter by chapter, providing me with extensive and helpful feedback. I would also like to thank Eric Parrish for assisting with the figures in Chapter 5.

I am grateful to the NASA Astrobiology Institute (NAI) for providing partial funding (through a grant to the University of Colorado’s Astrobiology Center) for the early stages of this project. Thanks also to Sarah Warner who pressured me into getting started on what seemed an almost impossible task, and to the editors at Cambridge University Press for their patience, understanding, and encouragement.