# The Nature of Life: Classical and Contemporary Perspectives from Philosophy and Science

Bringing together the latest scientific advances and some of the most enduring subtle philosophical puzzles and problems, this book collects original historical and contemporary sources to explore the wide range of issues surrounding the nature of life.

Selections ranging from Aristotle and Descartes to Sagan and Dawkins are organized around four broad themes covering classical discussions of life, the origins and extent of natural life, contemporary artificial life creations, and the definition and meaning of "life" in its most general form. Each section is preceded by an extensive introduction connecting the various ideas discussed in individual chapters and providing helpful background material for understanding them. With its interdisciplinary perspective, this fascinating collection is essential reading for scientists and philosophers interested in astrobiology, the origin of life, synthetic biology, and the philosophy of life.

Mark A. Bedau is Professor of Philosophy and Humanities at Reed College, Oregon, Director of the Initiative for Science, Society, and Policy in Denmark, and a regular Visiting Professor at the European School of Molecular Medicine in Milan, Italy. He is an internationally recognized leader in the philosophical and scientific study of living systems and has published and lectured extensively on issues concerning emergence, evolution, life, mind, and the social and ethical implications of creating life from nonliving materials.

Carol E. Cleland is Professor of Philosophy at the University of Colorado (Boulder). She is a central figure in the emerging science of astrobiology and has published in major science as well as philosophy journals. Her research focuses on issues in scientific methodology, historical science (especially earth and planetary science), biology (especially microbiology, origins of life, the nature of life, and astrobiology), and the theory of computation.

# The Nature of Life: Classical and Contemporary Perspectives from Philosophy and Science

Edited by
Mark A. Bedau
*Reed College, Oregon, USA*
Carol E. Cleland
*University of Colorado, Boulder, USA*

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Dubai, Tokyo, Mexico City

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521517751



First published 2010

Printed in the United Kingdom at the University Press, Cambridge

*A catalog record for this publication is available from the British Library*

*Library of Congress Cataloging-in-Publication Data*

The nature of life : classical and contemporary perspectives from philosophy and science / edited by Mark A. Bedau, Carol Cleland.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-521-51775-1 (Hardback)
1. Science–Philosophy. 2. Philosophy of nature. I. Bedau, Mark. II. Cleland, Carol. III. Title.
Q175.N333 2010
501–dc22

2010004399

ISBN 978-0-521-51775-1 Hardback

# Contents

# Preface

This book is a collection of readings about the nature of life. The idea for it was born when we first met and discovered our mutual interest in the nature of life, a shared background in philosophy of science and philosophy of biology, and a complementary scientific expertise in the origin of life and astrobiology (Cleland) and artificial life and synthetic biology (Bedau). We both wanted to have a book like this, so we decided to compile it together. Our interests and orientation led us to include material in four general areas: (i) classical philosophical and scientific discussions about the nature of life, (ii) contemporary scientific and philosophical discussions of the origins of life, and of chemical possibilities for unfamiliar forms of natural life, (iii) discussions of contemporary artificial life creations, including not just computer simulations but also self-reproducing robots, protocells, and other synthetic biology constructions created in the wet lab, and (iv) attempts by contemporary scientists and philosophers to describe and explain the nature of life in its most general, non-Earthcentric, form. Producing this book confirmed for us the value of combining multiple perspectives on life.

We hope that this book will inform philosophers about the latest scientific advances and introduce scientists to subtle philosophical puzzles and problems, and thereby foster new, well-informed and thoughtful philosophical and scientific reflection about the nature of life. In our opinion, genuine progress in understanding life crucially depends upon combining both scientific and philosophical perspectives on life.

Our book is aimed at a broad audience. Some of the chapters are quite accessible and others are fairly technical. Each section is preceded by an introduction connecting the various ideas discussed in individual chapters and providing helpful background material for understanding them. We hope that philosophers interested in life (including those working in philosophy of biology, philosophy of science, and philosophy of mind) will pay especially close attention to the scientific chapters, and that scientists interested in the nature of life (including biologists, chemists, physicists, astronomers, geologists, and astrobiologists) will pay especially close attention to the philosophical chapters. Graduate and undergraduate students in any of these areas will also find the book useful as a text in interdisciplinary courses on life. Anyone from the general public who is curious about up-to-date scientific and philosophical perspectives on life should enjoy the book as well.

Mark Bedau, Portland, Oregon
Carol Cleland, Boulder, Colorado

# Acknowledgments

The editors would like to thank the authors and publishers who gave us permission to collect their work in this anthology. We owe a special thanks to Chris Shields, for permitting us to publish part of his new translation of *De Anima*, forthcoming from Oxford University Press.

We would also like to thank many friends and colleagues who have shared and fostered our growing fascination with life and our attempts to understand it, and who helped us while developing this book. Thanks to Bob Hanna for help with the Kant selections, and to Meg Scharle for help on Aristotle. Thanks to Kellyn Bardeen for collecting permissions, copy-editing, and producing the final manuscript, and to Emily Parke for myriad crucial assistance. Thanks to Ben Pagelar and Michael Zerella at the Boulder campus of the University of Colorado for help with assembling the bibliography. We owe an important debt to the up and coming philosophers and scientists in Carol Cleland's 2006 graduate seminar on life for enthusiastically and industriously working through the articles in the original Table of Contents, helping us to decide which should be included as chapters in the final version. Thanks to the NASA Astrobiology Institute for providing partial funding for this project through a grant to the University of Colorado's Astrobiology Center, and to Reed College for a Stillman Drake grant that supported this project. Thanks also to the Center for Advanced Computation at Reed College, for hospitality during a crucial final stage in the preparation of the book.

# Sources

Grateful acknowledgment is made to the following publishers and authors:

1. Selections from *De Anima*, written by Aristotle with translation and commentary by Christopher Shields. Copyright © 2009, Oxford University Press (forthcoming). Reprinted by permission of Oxford University Press and Christopher Shields.
2. "Treatise on Man" by René Descartes, from *The Philosophical Writing of Descartes*, vol. 1, translated by John Cottingham, Robert Stoothoff, and Dugald Murdoch. Copyright © 1985, Cambridge University Press. Reprinted by permission of Cambridge University Press, John Cottingham, and Dugald Murdoch.
3. Selections from *Critique of the Teleological Power of Judgment*, written by Immanuel Kant and translated by Paul Guyer and Eric Matthews. Copyright © 2001, Cambridge University Press. Reprinted by permission of Cambridge University Press, Paul Guyer, and Eric Matthews.
4. Selections from *What is Life? The Physical Aspect of the Living Cell* by Erwin Schrödinger. Copyright © 1967, Cambridge University Press. Reprinted by permission of Cambridge University Press.
5. Excerpt from *Life: Its Nature, Origin, and Development*, written by A. I. Oparin and translated by Ann Synge. Copyright © 1964, Ann Synge. Reprinted by permission of Charlotte Synge and Liz Smith, Academic Press, and Oliver and Boyd Ltd., a subsidiary of Longman Publishing.
6. Chapter 1 from *This is Biology: The Science of the Living World* by Ernst Mayr. Copyright © 1997, Harvard University Press. Reprinted by permission of Harvard University Press.
7. Selections from *The Principles of Life*, written by Tibor Gánti, with commentary by James Griesemer and Eörs Szathmáry. Copyright © 2003, Oxford University Press. Reprinted by permission of Oxford University Press.
8. "The Origin of Life: A Review of Facts and Speculation" by Leslie E. Orgel, from *Trends in Biochemical Sciences 23 (1998)*. Copyright © 1998, Elsevier Science. Reprinted by permission of Elsevier Science and Alice Orgel.
9. Section "A Simpler Origin for Life" by Robert Shapiro, from *Scientific American (June 2007)*. Text copyright © 2007, Scientific American; figures copyright © 2007 Jennifer C. Christiansen. Reprinted by permission of Scientific American, Jennifer C. Christiansen, and Robert Shapiro.
10. "Are the Different Hypotheses on the Emergence of Life as Different as They Seem?" by Iris Fry, from *Biology and Philosophy 10(4) (1995)*. Copyright © 2004, Springer Science and Business Media. Reprinted by permission of Springer Science and Business Media, and by permission of Iris Fry.
11. "The Universal Nature of Biochemistry" by Norman Pace, from *Proceedings of the National Academy of Sciences 98(3) (2001)*. Text copyright © 2001, National Academy of Sciences; figure copyright © 1997, American Association for the Advancement of Science. Reprinted by permission of the National Academy of Sciences, the American Association for the Advancement of Science, and Norman Pace.
12. "Is There a Common Chemical Model for Life in the Universe?" by Steven A. Benner, Alonso Ricardo, and Matthew A. Carrigan, from *Current Opinion in Chemical Biology 8 (2004)*. Copyright © 2004, Elsevier Ltd. Reprinted by permission of Elsevier Ltd., Steven A. Benner, Alonso Ricardo, and Matthew A. Carrigan.
13. "Searching for Life in the Universe: Lessons from Earth" by Kenneth H. Nealson, from *Annals of the New York Academy of Sciences 950(1) (2001)*.

28. "Defining Life" by Kim Sterelny and Paul Griffiths, from *Sex and Death: An Introduction to Philosophy of Biology*, by Kim Sterelny and Paul Griffiths. Copyright © 1999, University of Chicago. Reprinted by permission of the University of Chicago Press, Kim Sterelny, and Paul Griffiths.
29. "Universal Darwinism" by Richard Dawkins, from *Evolution from Molecules to Man*, edited by D. S. Bendall. Copyright © 1983, Cambridge University Press. Reprinted by permission of Cambridge University Press and Richard Dawkins.
30. "What is Life? Was Schrödinger Right?" by Stuart A. Kauffman, from *What is Life? The Next Fifty Years: Speculations on the Future of Biology*. Copyright © 1995, Cambridge University Press. Reprinted by permission of Cambridge University Press and Stuart A. Kauffman.
31. "Four Puzzles About Life" by Mark A. Bedau, from *Artificial Life 4 (1998)*. Copyright © 1988, MIT Press. Reprinted by permission of the author.

# About the authors

ARISTOTLE (384 BC–322 BC), a student of Plato and teacher of Alexander the Great, was a prominent Greek philosopher and one of the most important founding figures in Western philosophy. With the scope of his work encompassing morality, science, logic, aesthetics, metaphysics and politics, he was the first to create a comprehensive system of Western philosophy. In addition, Aristotle is sometimes regarded as the originator of the scientific study of life, as he was among the first to articulate a systematic and comprehensive method for biological investigation. His own studies of animals were extensive, and several of his biological observations waited more than two millennia to be confirmed by modern science.

MARK A. BEDAU is a Professor of Philosophy and Humanities at Reed College, editor-in-chief of the MIT Press journal *Artificial Life*, co-founder of the European Center for Living Technology (Venice), Adjunct Professor of Systems Science at Portland State University, and Visiting Professor at the European School of Molecular Medicine (Milan). His areas of research include emergence, biological evolution and adaptation, the nature of life, artificial life and protocells, the evolution of technology, autonomous intelligent discovery and optimization processes, and the social and ethical implications of creating life in the laboratory.

STEVEN A. BENNER is a Distinguished Fellow at the Foundation for Applied Molecular Evolution and the Westheimer Institute for Science and Technology. He received his bachelor's degree and M.S. in Molecular Biophysics and Biochemistry from Yale University, and his Ph.D. in Chemistry from Harvard University. He co-founded several fields, including synthetic biology, paleogenetics, evolutionary bioinformatics, and dynamic combinatorial chemistry. His research combines the traditions of natural history with those of the physical sciences in order to gain a better understanding of life.

MARGARET A. BODEN is Research Professor of Cognitive Science at the University of Sussex. She is a Fellow of the British Academy, and of the American Association for Artificial Intelligence, along with its British and European equivalents. In 2002, she was awarded an Order of the British Empire "for services to cognitive science," and, in addition to her Cambridge Sc.D. and Harvard Ph.D., she has honorary doctorates from the Universities of Bristol and Sussex and the Open University. Her work is highly interdisciplinary, and has been translated into 20 languages. Her latest book is *Mind as Machine: A History of Cognitive Science* (2006).

MATTHEW A. CARRIGAN is a Research Fellow at the Foundation for Applied Molecular Evolution in Gainesville, Florida. His research centers on the origin of life and synthetic biology, with a particular focus on the synthesis and stability of the sugar backbone of RNA and the polymerization of ribonucleotides. Current efforts are directed toward isolating an RNA ribozyme capable of catalyzing RNA polymerization.

CHRISTOPHER CHYBA is a Professor of Astrophysical Sciences and International Affairs at Princeton University. He served on the White House staff from 1993 to 1995, working in the National Security Council and the National Security Division of the Office of Science and Technology Policy. His security-related research focuses on nuclear proliferation, nuclear weapons policy, and biological terrorism, while his planetary science and astrobiology research focuses on the search for life in the solar system. He received the Presidential Early Career Award in 1996 and was named a MacArthur Fellow in 2001. In addition to his Ph.D. in Astronomy, he holds an M.Phil. in History and Philosophy of Science from Cambridge University.

CAROL E. CLELAND is a Professor of Philosophy at the University of Colorado in Boulder. She is a member of the NASA Astrobiology Institute (NAI) and the Center for Astrobiology at the University of Colorado. Her research is in the areas of philosophy of science, logic,

and metaphysics. She has published articles on space and time, supervenience, events and causation, hypercomputation, the Church-Turing thesis, standards of evidence in science, the methodology of historical and experimental science, the problem of defining "life," and the possibility of alternative microbial life on Earth. She is currently finishing a book, *The Quest for a Universal Theory of Life: Searching for Life as We Don't Know it*.

SHELLEY D. COPLEY is a Professor of Molecular, Cellular and Developmental Biology at the University of Colorado in Boulder. Her research centers on the molecular evolution of catalysts and metabolic pathways throughout the history of life on Earth, from the emergence of proto-metabolic networks that supported the RNA world to the evolution of novel pathways for the degradation of toxic pollutants introduced into the environment in the last century.

JOHN COTTINGHAM is a Professor of Philosophy at the University of Reading in England. He is also the president of the British Society for the Philosophy of Religion, the director of the three-year research program Impartiality and Partiality in Ethics, and an editor for *Ratio*, an international journal of analytic philosophy. His main research interests include early modern philosophy (particularly Descartes), ethics, and philosophy of religion.

RICHARD DAWKINS is a British ethologist, evolutionary biologist, and popular science author well known for his criticism of religion, creationism, and intelligent design. He currently holds the position of Charles Simonyi Professor of the Public Understanding of Science at Oxford University. His influential first book, *The Selfish Gene* (1976), popularized the gene-centered view of evolution and introduced the term *meme* to the discourse on cultural evolution. He is a fellow of the Royal Society and has received the Faraday Award and the Kistler Prize. His most recent book is *The God Delusion* (2006).

DAVID DEAMER is a Research Professor of Biomolecular Engineering at the University of California, Santa Cruz. His research interests include nanopore analysis of nucleic acids and the biophysics behind processes of self-assembly, particularly those related to the structure and function of biological membranes. He is currently writing a book on the origin of cellular life to be published in 2009 by the University of California Press.

RENÉ DESCARTES (1596–1650) was a highly influential French philosopher who is generally regarded as the father of modern philosophy. In his pivotal work, *Meditations on First Philosophy*, he famously put forth the *cogito* argument as a step in his investigation into the rational foundations of philosophical inquiry and natural science. Descartes made significant contributions to mathematics and science during his lifetime, inventing the Cartesian coordinate system, founding analytic geometry, and discovering the law of refraction. As a strong proponent of the theory of mechanism, he was also a major player in the Scientific Revolution.

FRANCESCA FERRI is currently working at the Department of Neuroscience at the University of Parma. Her present research interests include self-identity, embodiment, coherence, and disorders involving the embodied self.

IRIS FRY teaches the history and philosophy of biology in the Department of Humanities and Arts at Technion at the Israel Institute of Technology. She was trained in chemistry and biochemistry at the Hebrew University in Jerusalem and studied the history and philosophy of science at the Universities of Haifa and Tel Aviv. Her publications discuss the concept of teleology in the philosophy of Kant, the history of evolutionary ideas, and the origin of life. Her first book, *The Origin of Life—Mystery or Scientific Problem?*, was published in Israel in 1997. Her second book, *The Emergence of Life on Earth: A Historical and Scientific Overview*, was published in 2000 by Rutgers University Press.

TIBOR GÁNTI is a chemical engineer, theoretical biologist and D.Sc. in biology. His main work is the creation of the chemoton theory, which contains the theory of fluid (chemical) automata and its application to living systems. This theory makes possible the precise separation of living entities from nonliving entities and the construction of an exact, quantitative model of the minimal living system (the chemoton model), while supplying the theoretical foundations for investigating the origin of life, biogenesis, and the artificial synthesis of living systems.

PAUL GRIFFITHS is a Philosopher of Science with a focus on biology and psychology. He received his education from Cambridge University and the Australian National University and is currently a University Professorial Research Fellow in Philosophy at the University of Sydney, Australia, and a Professor of Philosophy of Science at the ESRC Centre for Genomics in Society at the University of Exeter, UK. He is also a Fellow of the Australian Academy

of the Humanities, an adjunct member of the Pittsburgh HPS faculty, and a member of the Australian Health Ethics Committee of NHMRC.

PAUL GUYER is a Professor of Philosophy and a Florence R. C. Murray Professor in Humanities at the University of Pennsylvania. He is the author and editor of numerous books on the philosophy of Kant, and the general co-editor of the Cambridge Edition of the Works of Kant, in which he co-translated the *Critique of Pure Reason*, the *Critique of the Power of Judgment*, and Kant's *Notes and Fragments*. Guyer is a fellow of the American Academy of Arts and Sciences and has been awarded the Alexander von Humboldt-Stiftung Research Prize. He is currently writing a history of modern aesthetics.

IMMANUEL KANT (1724–1804) was a German philosopher who is widely regarded as one of the most influential thinkers of modern Europe and the late Enlightenment. Grappling with problems in philosophy of mind, Kant developed the doctrine of Transcendental Idealism, which he regarded as a compromise between the conflicting traditions of Rationalism and Empiricism. This doctrine was first set out in his epochal work, *The Critique of Pure Reason* (1781), which is now uniformly regarded as one of the greatest works in the history of philosophy. Kant also exerted a profound influence on moral philosophy with his contention that morality is required by reason itself.

STUART A. KAUFFMAN is a Professor of Biological Sciences, Physics, Astronomy, and Philosophy at the University of Calgary, in addition to being Director of the Institute for Biocomplexity and Informatics (IBI) and Chair of Informatics Circle of Research Excellence (iCORE). His interests include developmental genetics, theoretical biology, evolution, and the origin of life. He is a MacArthur Fellow and received the Accademia Nazionale dei Lincei Gold Medal in 1997, and the Herbert A. Simon Award in 2000.

EVELYN FOX KELLER received her Ph.D. in theoretical physics from Harvard University and worked for a number of years at the interface between physics and biology. She currently holds the position of Professor Emerita of History and Philosophy of Science in the MIT Program in Science, Technology and Society. She has authored many works, including: *Refiguring Life: Metaphors of Twentieth Century Biology* (1995), *The Century of the Gene* (2000), and *Making Sense of Life: Explaining Biological Development with Models, Metaphors, and Machines* (2002). Keller has received a number of awards and honorary doctorates, and is a MacArthur Fellow, a member of the American Philosophical Society, a member of the American Academy of Arts and Sciences, and, most recently, the recipient of the Blaise Pascal Research Chair in Paris.

DANIEL E. KOSHLAND, JR. (1920–2007) was a member of the National Academy of Sciences and the editor-in-chief of the leading science journal *Science* from 1985–1995. During World War II, he was one of the scientists working on the Manhattan Project purifying plutonium. In the early part of his career, his work with enzymes led him to propose the "induced fit" model of enzyme catalysis, overturning a century-old consensus on enzyme function. Later in his career, he spearheaded a major reorganization of the study of biology at the University of California at Berkeley, bringing departmental divisions into alignment with advances in genetics and other life sciences. In 1990, he won the National Medal of Science, and his more recent work focused on methane production in blue-green algae.

MARC LANGE is Bowman and Gordon Gray Distinguished Term Professor of Philosophy at the University of North Carolina at Chapel Hill. His interests include scientific explanation, inductive confirmation, natural kinds, disease, necessity and possibility. His most recent books are *Laws and Lawmakers* (2009), which concerns the concept of a law of nature, and *Locality, Fields, Energy, and Mass: An Introduction to the Philosophy of Physics* (2002). He is a member of the American Philosophical Association and the Philosophy of Science Society.

HOD LIPSON is an Associate Professor of Mechanical & Aerospace Engineering and Computing & Information Science at Cornell University in Ithaca, NY. He received his Ph.D. in 1998 from Technion at the Israel Institute of Technology, and continued on to a postdoctoral fellowship at Brandeis University and MIT. At present, Lipson directs the Computational Synthesis group, which focuses on novel ways of generating the automatic design, fabrication and adaptation of virtual and physical machines. He has led work in areas such as evolutionary robotics, multi-material functional rapid prototyping, machine self-replication, and programmable self-assembly.

PIER LUIGI LUISI is a Professor of Biophysics at the University of Rome (*Roma Tre*), and Emeritus Professor

of Macromolecular Chemistry at the Swiss Federal Institute of Technology (ETH) in Zurich. His scientific interests mainly concern the origins of life, and studying the macromolecular chemistry, enzymology, and self-assembly of structures such as micelles, reverse micelles, liposomes and giant vesicles. In the last few years, his research has included work on the chemical implementation of autopoiesis, the construction of minimal cells, and the origin of cellular complexity and self-reproduction in supramolecular structures.

LYNN MARGULIS is a Distinguished University Professor in the Department of Geosciences at the University of Massachusetts-Amherst. A member of the National Academy of Science, she investigates and publishes on evolution through symbiogenesis and the Gaia hypothesis (of J. E. Lovelock). She is best known for her endosymbiotic theory of the origin of certain eukaryotic organelles, a theory that is now generally accepted by the scientific community. In 1999, Lynn received the Presidential Medal of Science from William J. Clinton for her contributions to the understanding of living organisms.

ERIC MATTHEWS is Emeritus Professor of Philosophy and Honorary Research Professor of Medical and Psychiatric Ethics in the University of Aberdeen, Scotland. He has pursued an interest in the French philosophers Henri Bergson, Jean-Paul Sartre, and Maurice Merleau-Ponty and has translated a number of works of German philosophy for Cambridge University Press. His recent research concerns the ethics of communicating genetic information and the ethical and policy issues in the upcoming crisis of an aging population. His most recent book is *Body Subjects and Disordered Minds: Treating the Whole Person in Psychiatry* (2007).

ERNST MAYR (1904–2005) is widely regarded as one of the foremost evolutionary biologists of the twentieth century. His work contributed to the conceptual revolution that led to the modern evolutionary synthesis of Mendelian genetics, systematics, and Darwinian evolution. He also contributed to the development of the biological species concept that is currently in use. Among other honors, Mayr received the National Medal of Science in 1970, the Balzan Prize in 1983, the International Prize for Biology in 1994, and the Crafoord Prize in 1999.

ALVARO MORENO is a Professor of Philosophy of Science at the University of the Basque Country, in Spain, where he founded a research group specializing in complex systems, philosophy of biology, and artificial life. He has organized several international workshops and authored many publications on the relationship between artificial life and artificial intelligence.

DUGALD MUDOCH received his higher education at the Universities of Glasgow, Uppsala, and Oxford, and is currently a Professor of Philosophy at the University of Stockholm. His research interests lie in the areas of the philosophy of science, epistemology, and the history of modern philosophy, with a special interest in the philosophy of Descartes. At present, he is working on a project concerning the nature of reasons for belief.

KENNETH H. NEALSON is the Wrigley Professor of Environmental Sciences at the University of Southern California, and a Distinguished Investigator at the J. Craig Venter Institute of Environmental Genomics. His research focuses on the role of microbes in the biogeochemical cycle(s) of the elements, with special focus on iron and manganese. He has also pursued the definition of life and its detection, considering extreme environments on Earth and probing how to effectively search for life in extraterrestrial environments.

ALEKSANDR IVANOVICH OPARIN (1894–1980) pioneered the idea that life arose from inorganic matter through the spontaneous generation of simple organic compounds from inorganic molecules in the prebiotic environment. In his work, he formulated a number of pathways through which biologically important compounds such as amino acids, volatile fatty acids and carbohydrates could have formed in the chemically reductive atmosphere he hypothesized for early Earth. In 1979, he received the Lomonosov Gold Medal from the USSR Academy of Sciences for his work in biochemistry.

LESLIE E. ORGEL (1937–2007) was a distinguished biologist and one of the fathers of the RNA-world theory and the concept of panspermia. Born in London, he received his undergraduate degree and doctorate from Oxford University before pursuing research at Cambridge, the University of Chicago, and the California Institute of Technology. He assisted NASA in analyzing the findings of the Viking missions to Mars and was one of five principal investigators in the NASA-sponsored NSCORT program in exobiology. He was a fellow of the Royal Society and a member of both the National Academy of Sciences and the American Academy of Arts and Sciences.

NORMAN R. PACE is a Distinguished Professor at the University of Colorado in Boulder and an investigator for NASA's Astrobiology Institute. His research interests focus on RNA biochemistry, the application of molecular tools to problems in microbial ecology, and the development of methods for analyzing phylogenetic and quantitative aspects of natural microbial populations without the necessity for laboratory cultivation. He is a member of the National Academy of Sciences and a fellow of the American Association for the Advancement of Science. In 2008, he received Lifetime Achievement Awards from both the RNA Society and the International Society for Microbial Ecology.

JULI PERETÓ is a Professor of Biochemistry and Molecular Biology at the University of València, and researcher at the Cavanilles Institute for Biodiversity and Evolutionary Biology. From 2005 to 2008, Peretó served as the secretary of the International Society for the Study of the Origin of Life (ISSOL – The International Astrobiology Society). His research interests include the evolution of metabolic networks, the minimal genome concept, and the history of ideas concerning the artificial synthesis of life and its natural origin.

JORDAN P. POLLACK is a Professor at Brandeis University in the Computer Science Department as well as the Volen Center for Complex Systems. He directs a research laboratory seeking a fundamental and replicable understanding of how nature can "design" biologically complex machinery. In conjunction with Hod Lipson, Pollack led the Golem project (Genetically Organized Lifelike Electro Mechanics) to evolve simple electro-mechanical systems from scratch to yield physical locomoting machines.

ALONSO RICARDO is a postdoctoral fellow working at Szostak Lab, a research group aimed at creating the functional components of a protocell. He earned his Ph.D. from the University of Florida, working under Steven Benner for his doctorate. His research interests center on bioorganic chemistry, the origins of life, and using mRNA display as a tool for discovering new antibiotics.

KEPA RUIZ-MIRAZO is currently a Ramón y Cajal Research Fellow at the University of the Basque Country, Spain, working in the Department of Logic and Philosophy of Science in addition to the Biophysics Research Unit (CSIC-UPV/EHU). With a degree in Physics and a Ph.D. in Complex Systems, his present research activity cuts across several disciplines, centering on the definition of life, protocell models (*in vitro* and *in silico*), and major transitions in the origin of living systems.

CARL SAGAN (1934–1996) was an astronomer, astrochemist, and author who pioneered exobiology, promoted the search for extraterrestrial intelligence, and successfully popularized astronomy, astrophysics and other natural sciences. He played a leading role in the American space program from its inception, acting as an advisor to NASA and being directly involved in the *Apollo*, *Mariner*, *Viking*, and *Galileo* missions. A best-selling author and Pulitzer Prize winner, Sagan received twenty-two honorary degrees from American colleges and universities for his contributions to science, literature, education, and the preservation of the environment. As one of the first scientists to suggest the possibility of a nuclear winter, he also received multiple awards for his work on the long-term consequences of nuclear war and for his attempts to reverse the nuclear arms race.

DORION SAGAN is an American science writer and General Partner of Sciencewriters, an organization whose goal is to advance science through "enchantment in the form of the finest possible books, videos, and other media". He has written or co-authored many essays and more than fourteen books on evolution and other topics in biology, and is a recipient of an Ed-Press Award from the Educational Press Association of America for excellence in Educational Journalism. A recent book, *Death and Sex*, won first place at the 2010 New York Book Show in the general trade nonfiction category.

ERWIN SCHRÖDINGER (1887–1961) was an Austrian physicist best known for his contributions to the understanding of quantum mechanics, particularly the Schrödinger Equation, for which he received the Nobel Prize in 1933. He also devised the famous "Schrödinger's cat" thought experiment to illustrate what he saw as a problem with the Copenhagen interpretation of quantum physics. In 1944, he wrote *What is Life?* in which he derived the concept of a complex molecule as a carrier for genetic information. This book directly influenced James Watson and Francis Crick whose work eventually led to the discovery of DNA in 1953.

ROBERT SHAPIRO is Professor Emeritus and Senior Research Scientist in the Department of Chemistry at New York University. He is author or co-author of over 125 publications, primarily in the areas of DNA chemistry and the origin of life. In his research, he and his co-workers have studied the ways in which environmental

chemicals can damage hereditary material, causing changes that can lead to mutations and cancer. His research has been supported by numerous grants from the National Institute of Health, the Department of Energy, the National Science Foundation, and other organizations.

CHRISTOPHER SHIELDS is a Professor of Classical Philosophy at the University of Oxford and Tutorial Fellow at Lady Margaret Hall. His interests lie in classical philosophy, metaphysics, and philosophy of mind. He is the author of *Order in Multiplicity* (1999), *Classical Philosophy: A Contemporary Introduction* (2003), *Aristotle* (2007), and coauthor of *The Philosophy of Thomas Aquinas* (2004) along with Robert Pasnau. He also has a forthcoming translation (with commentary) of Aristotle's *De Anima* in the Clarendon Aristotle Series of Oxford University Press.

ELLIOTT SOBER is Hans Reichenbach Professor of Philosophy and William F. Vilas Research Professor at University of Wisconsin-Madison. His research is based in the philosophy of science, with a particular focus on the philosophy of evolutionary biology. Sober's books include *The Nature of Selection—Evolutionary Theory in Philosophical Focus* (1984), *Reconstructing the Past—Parsimony, Evolution, and Inference* (1988), *Unto Others—The Evolution and Psychology of Unselfish Behavior* (1998, coauthored with David Sloan Wilson), and *Evidence and Evolution—the Logic Behind the Science* (2008).

PASQUALE STANO is a research assistant to Professor Pier Luigi Luisi at the University of Rome (*Roma Tre*). His research interests concern the properties and reactivity of vesicles and other supramolecular assemblies, and the use of liposomes as cellular models. He is currently involved in the EU project "Synthcells."

KIM STERELNY is an Australian philosopher and Professor of Philosophy. He is affiliated with both the Philosophy Program in the Research School of Social Sciences (RSSS) at Australian National University and the Philosophy Program at the Victoria University of Wellington. He is the editor of *Biology and Philosophy*, the main specialist journal of the philosophy of biology, co-editor of the MIT Press series, *Life and Mind*, and the winner of several international prizes, including the Lakatos Award and the Jean-Nicod Prize, in the philosophy of science. In addition, he is a Fellow of the Australian Academy of the Humanities. His main research interests are philosophy of biology, philosophy of psychology, and philosophy of mind.

ROBERT STOOTHOFF is an Emeritus Professor in the School of Philosophy and Religious Studies at the University of Canterbury, New Zealand. His work, *The Philosophical Writings of Descartes*, co-edited with John Cottingham and Dugald Murdoch and published in three volumes by Cambridge University Press, has become the standard edition of Descartes' philosophical work. Stoothoff also coauthored the entry on theories of meaning in the *Encyclopedia of Philosophy* (1988) along with Jack Copeland.

ANN SYNGE (1916–1998) studied medicine in Cambridge and Dublin before marrying Nobel Prize winner Dr. Richard L. M. Synge, with whom she had eight children. She started translating from Russian in 1954 when she worked on A. I. Oparin's book, *Life: Its Nature, Origin, and Development*. She also translated *Protein Biosynthesis and Problems of Heredity Development and Aging* by Zhores A. Medvedev (1966). Later on, she taught biology and worked actively for nuclear disarmament and world peace.

# Introduction

This book is a collection of classic and contemporary readings by philosophers and scientists on the nature of life. Philosophers have pondered the question "what is life?" since at least the time of the ancient Greek philosopher Aristotle. In recent years the question has taken on increasing scientific importance. Molecular biologists and biochemists investigating the origin of life or trying to synthesize chemical life in the laboratory from basic molecular building blocks want to know at what stage an ensemble of nonliving molecules turns into a primitive living thing. Astrobiologists charged with designing instrument packages for spacecraft to detect extraterrestrial life struggle with the question of which characteristics of familiar Earth life (metabolism? reproduction? Darwinian evolution? carbon-based chemistry?) are universal indicators of life. Even computer scientists find themselves mired in questions about the nature of life when they speculate whether lifelike systems constructed of software (purely informational or digital structures) or hardware (metal, plastic, and silicon) could ever literally be alive. Many of these pressing questions are notable for their lack of obvious scientific solutions; one cannot answer them merely by performing more experiments or constructing additional lifelike systems. Although they arise out of science, these questions are deeply philosophical.

The twentieth-century American philosopher W. V. O. Quine proposed that epistemology could be viewed as an "enterprise within natural science" (Quine, 1975, p. 68). In a similar spirit, the editors of this volume believe that collaboration between scientists and philosophers provides the best hope for achieving a compelling answer to the question of the nature of life. Contemporary science has greatly expanded our understanding of the complexities of natural life, and it has provided many intriguing new examples of lifelike artificial systems. But an intellectually satisfying answer to the question "what is life?" requires more than this. It requires analyzing, evaluating, and systematizing disparate information emerging from a multiplicity of scientific disciplines. It is natural for philosophy to play a central role in this process. Philosophers are trained in logical and conceptual analysis. They have expertise in sorting out foundational issues, rooting out subtle inconsistencies, transforming vague generalizations into logically precise principles, tracing logical relations among concepts, principles, hypotheses, and empirical evidence, and evaluating the strength of arguments and theories. Philosophy brings conceptual clarity and logical rigor to scientific theorizing. At the same time, science grounds philosophical reflection on empirical evidence gleaned from careful observation and experiment. Together, contemporary philosophy and science hold forth the promise of finding a satisfactory answer to the age-old question of the nature of life.

The contents of this anthology are the outcome of many lively discussions among the editors and their scientific and philosophical colleagues concerning which issues about life matter most. The chapters selected represent only a small portion of a vast philosophical and scientific literature on life; readers are urged to consult the extensive Supplementary Bibliography at the end for many excellent and important additional writings on life. We tried to be representative, that is, to include classical writings that covered the historically most influential scientific and philosophical ideas, and the leading contemporary scientific and philosophical positions. Chapters were selected also on the basis of their promise for shedding light on central contemporary issues and controversies about life, such as how recent discoveries in microbiology have challenged traditional conceptions of the nature of life. We also made a point to include different approaches to methodology, such as whether the best answer to the question "what is life?" is a definition or a theory, or something else entirely.

We divided the anthology into four sections, corresponding to four central areas of contemporary philosophical and scientific research: Classical Discussions of Life (Section I), The Origin and Extent of Natural Life (Section II), Artificial Life and Synthetic Biology (Section III), and Defining and Explaining Life (Section IV). Each section is preceded by an introduction that conveys the current scientific and philosophical debate about the nature of life, underscoring lines of agreements and disagreements, and raising questions that, in our view, need greater attention. We hope that, taken together, the readings in this book will help inform and guide further scientific and philosophical investigations into the nature of life.

The father of classical physics, Issac Newton, famously observed in a letter to fellow English scientist Robert Hooke, "if I have seen further, it is by standing on the shoulders of giants." Newton's remark reflects the truism that most cutting-edge intellectual work builds upon earlier work. So, it is no surprise that many contemporary debates about life have deep historical roots. The chapters in Section I provide an historical context for the discussions in the rest of the book. We begin with the birth of philosophy in ancient Greece and the rise of modern philosophy and science in the sixteenth and seventeenth centuries, and continue with subsequent seminal scientific and philosophical developments up through the early twentieth century. These readings put contemporary thought about life into historical context and remind us of some great lessons from this history. They also reveal the extent to which contemporary perspectives and problems reflect their historical origins. Here is one illustration: A central theme running through the writings of the ancient Greek philosopher Aristotle up to the present is the idea that living things have functional characteristics, such as metabolism and development, which distinguish them from non-living things. As the chapters in Section I underscore, one of the great controversies about the nature of life bequeathed to us by Aristotle is whether these *prima facie* "teleological" (purposive, goal-directed or self-causing) characteristics are primitive or somehow "reducible to" nonteleological (structural or compositional) characteristics. Many different approaches (essentialist, mechanistic, vitalist, organismic, Darwinian, information-theoretic, thermodynamic, and chemical) to understanding the *prima facie* teleological characteristics of life are explored in the classic works included in Section I. Although sometimes disguised in innocuous-sounding contemporary scientific terminology, this debate reoccurs throughout this whole anthology.

Section II provides an overview of our current scientific understanding of the origin and extent of natural forms of life. Most of the authors are scientists who share the view that an understanding of life lies at the level of molecules and biochemical processes, as opposed to higher-level organizational and functional properties. This is reflected in the ways in which they interpret and articulate traditional questions about the nature of life. For example, what was "nutrition" for Aristotle and "metabolism" for early modern biologists becomes "chemical self-organization," and what was "reproduction" for Aristotle and "Darwinian evolution by natural selection" for nineteenth-century biologists becomes "replication" by means of "genetic [informational] structures." The reader is encouraged to consider whether this is the proper level of analysis for theorizing about life in general.

The authors in Section II discuss a variety of important issues about life within the context of recent scientific developments in molecular biology, biochemistry, microbiology, and astrobiology: Is the transition from a nonliving ensemble of molecules to a primitive living thing gradual or abrupt? Can an account of the nature of life be given independently of an account of the origin of life? Which came first, chemical self-organization or genetic structures? Was the original genetic molecule RNA or something else, e.g., a mineral surface? What are the alternative molecular and biochemical possibilities for life? How can we design methods and instruments for searching for truly "weird" forms of life elsewhere in the solar system, given that all known life on Earth is so similar at the molecular and biochemical level? Could the contemporary Earth contain undetected alternative forms of microbial life descended from a separate origin? A couple of chapters in this section are authored by philosophers who ferret out philosophical assumptions underlying scientific investigations into the origin and extent of life. They also evaluate the bearing of the results of these scientific investigations on some traditional and contemporary philosophical questions about life. Philosophers will want to know the material in this section, so that their discussions about life are scientifically informed.

Any contemporary attempt to understand the nature of life should be informed by important recent scientific developments. Artificial life and synthetic biology are motivating significant philosophical and scientific reflection about the nature of life. Section III concerns the implications of attempts in artificial life and synthetic biology to recreate life in the laboratory and to make lifelike systems out of hardware or software. The scientific state of the art in artificial life and synthetic biology is presented in some chapters. In other chapters philosophers and historians reflect on the larger implications of those scientific developments. The strong thesis of artificial life and synthetic biology is that we can construct new kinds of systems (using software, hardware, or wetware) that literally are alive—as alive as any other form of life we know. It contrasts with a weaker thesis that construes the lifelike systems constructed by artificial life researchers as useful theoretical tools for exploring properties of living systems, but not literally alive. Because research in artificial life aims to create novel kinds of lifelike systems, scientists must ask what really makes something alive. Is it the material stuff out of which it is composed (cytoplasm, flesh and bones, etc.)? Or is it the kinds of metabolic processes in which those materials are participating, in a transitory and fleeting way? Attempts to create lifelike systems or even life itself from nonliving materials also focus attention on a variety of foundational issues, such as whether there is a sharp distinction between life and non-life, or whether there is an open-ended array of alternative kinds of systems that are more or less alive. Artificial life and synthetic biology also raise a fundamental epistemological issue: What kind of evidence should we use when explaining why a given kind of chemical system is literally alive? For example, what weight should we give to generalizations derived only from all known forms of life on Earth?

Section IV illustrates the main philosophical and scientific approaches to answering the general question "what is life?" Achieving a satisfactory understanding of the nature of life involves explaining a range of familiar and striking phenomena. As these chapters illustrate, there is not a consensus about which characteristics of familiar life constitute the "signs," "hallmarks," or "puzzles" most in need of explanation. We need to figure out what evidential status to give to our current preconceptions about life. It is not obvious what epistemological authority they should have. Part of the problem is that our experience with natural life is limited to familiar Earth life. As the discussions in Section II reveal, we have compelling scientific reasons for believing that all known life on Earth descends from a common ancestor. We also have good scientific reasons for believing that life could have been at least modestly different, but we have very little idea how different it could have been. This makes it difficult to identify which characteristics of familiar Earth life are found universally in all actual examples of life. For all we know, familiar Earth life could constitute an unrepresentative example of all possible forms of life. However, not everyone views this problem as insurmountable. The development of artificial ("hard" and "soft") life systems and the creation of novel microorganisms in the laboratory by synthetic biologists give us powerful new tools for exploring and expanding our concept of life, and perhaps even increasing the sample size of kinds of life available to us for empirical investigation. The discussions in Section IV also address foundational theoretical issues about life such as the role of reduction and emergence in explanations of life and the question of whether life is a compositional, structural, or functional kind, or some combination thereof. The chapters in this section explore different perspectives on these and related issues within the context of recent scientific and philosophical advances.

The question of the proper methodology for constructing and evaluating views about the nature of life is a central concern of many of the chapters in Section IV written by philosophers. One issue is the evidential status of signs, hallmarks, and puzzles about life. What role should these play when investigating the nature of life? Are they test cases for evaluating accounts of life? A striking feature of investigations into the nature of life is the ambiguous and uncertain application of various methodologies. Another important question concerns the widespread use of definitions in explaining life. Definitions can be distinguished from criteria for life, and from life's signs and hallmarks. They can take different forms, including pragmatic and operational, although many scientists and philosophers prefer logically complete definitions providing necessary and sufficient conditions for life. Some authors in Section IV reject the project of defining life. They contend that definitions cannot provide satisfactory answers to "what

is" questions about natural kinds, such as water and life. On their view an empirically well-grounded, scientific theory of life is needed. But how does a theory of life differ from a highly complex definition of life? There is also the question of the status of computer simulations of complex living systems. Some authors argue that simulations can be fruitfully construed as distinctively *constructive* definitions or theories of life. Many of the chapters in Section IV address these issues. Scientists engaged in theorizing about life might find the material in this section especially useful.

The four sections of this anthology are knit together by three central open philosophical and scientific questions about the nature of life:

1. What are the central characteristic phenomena exhibited by all forms of life?
2. What are the best descriptions and explanations of the nature of life?
3. What is the proper way to construct and evaluate views about the nature of life?

In our view, attempting to answer any of these questions in isolation generates a tangle of thorny philosophical and scientific issues that can be resolved only by addressing the two other questions. In fact, we find it difficult to draw a bright red line separating scientific and philosophical questions about life. Fundamental progress in either discipline requires knowing and appreciating the other discipline. This book aims to foster mutual understanding and appreciation among philosophical and scientific perspectives on life. In the long run, a good measure of its success will be the advances in understanding of the nature of life that are eventually made by its readers.

## REFERENCES

Quine, W. V. O. (1975). The nature of empirical knowledge. In S. Guttenplan, S. (Ed.), *Mind and language* (pp. 57–81). Oxford: Oxford University Press.