THE EVOLUTION OF SCIENTIFIC KNOWLEDGE

From Certainty to Uncertainty

THE EVOLUTION OF SCIENTIFIC KNOWLEDGE

From Certainty to Uncertainty

Edward R. Dougherty

SPIE PRESS
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Names: Dougherty, Edward R., author.
Title: The evolution of scientific knowledge : from certainty to uncertainty / Edward R. Dougherty.
Description: Bellingham, Washington : SPIE Press, [2016]
Identifiers: LCCN 2016045264 | ISBN 9781510607354 (softcover) | ISBN 1510607358 (softcover) | ISBN 9781510607361 (pdf) | ISBN 1510607366 (pdf)
Subjects: LCSH: Science--Philosophy. | Knowledge, Theory of.
Classification: LCC Q175 .D696 2016 | DDC 501--dc23 LC record available at https://lccn.loc.gov/2016045264

Published by
SPIE
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: +1 360.676.3290
Fax: +1 360.647.1445
Email: books@spie.org
Web: http://spie.org

Cover images of The Thinker by Rodin and an astrological clock courtesy of Shutterstock, Inc.

Printed in the United States of America.
Updated 4 May 2018.
For updates to this book, visit http://spie.org and type “PM275” in the search field.

SPIE.

To Jeffrey M. Trent

Who for twenty years gave me the opportunity
to freely consider fundamental problems of
translational genomics, where complexity
is manifest on an immense scale.

Contents

Acknowledgments

Let me first offer my appreciation to Frank Alexander and Ulisses Braga-Neto, both of whom carefully read the manuscript and made numerous suggestions regarding subtle, but important, points. I would also like to acknowledge Tim Lamkins and Dara Burrows for the book production and Sajad Sadeh for helping with the figures. Descriptions of certain issues relating to scientific epistemology have some overlap with my *Epistemology of the Cell* published by Wiley-IEEE Press (ISBN 978-1118027790). Any replications have been graciously permitted by the publisher. Finally, a book like this must by its nature represent thinking over many years and incorporate conceptual and technical contributions by numerous colleagues and students. With apologies to anyone omitted, let me mention some: Frank Alexander, Michael Bittner, Ulisses Brag-Neto, Lori Dalton, Roozbeh Dehghannasiri, Mohammad Shahrokh Esfahani, Ivan Ivanov, Xiaoning Qian, Ilya Shmulevich, Byung-Jun Yoon, and Amin Zollanvari.

Preface

This book aims to provide scientists and engineers, and those interested in scientific issues, with a concise account of how the nature of scientific knowledge evolved from antiquity to a seemingly final form in the Twentieth Century that now strongly limits the knowledge that people would like to gain in the Twenty-first Century. Some might think that such issues are only of interest to specialists in epistemology (the theory of knowledge); however, today's major scientific and engineering problems—in biology, medicine, environmental science, etc.—involve enormous complexity, and it is precisely this complexity that runs up against the limits of what is scientifically knowable.

To understand the issue, one must appreciate the radical break with antiquity that occurred with the birth of modern science in the Seventeenth Century, the problems of knowledge and truth engendered by modern science, and the evolution of scientific thinking through the Twentieth Century.

While originally aimed at practicing scientists and engineers, it is my hope that this book can provide a generally educated person with a basic understanding of how our perspective on scientific knowledge has evolved over the centuries to escape pre-Galilean commonsense thinking. Such an appreciation is not only beneficial for one's general education, but is important for non-scientists who must teach young students or make policy decisions in government or business. Physicist and historian Gerald Holton states the dilemma faced by many:

> By having let the intellectuals remain in terrified ignorance of modern science, we have forced them into a position of tragic impotence; they are, as it were, blindfolded in a maze through which they feel they cannot traverse. They are caught between their irrepressible desire to understand the universe and, on the other hand, their clearly recognized inability to make any sense out of modern science. [Holton, 1996]

Perhaps this small book can help some make sense of modern science and the crisis of complexity that will bedevil the Twenty-first Century. Except for the last chapter, mathematics has been avoided, and even in that chapter it has been kept minimal, the only exception being in Section 7.6, which requires some details of the Wiener filter, which are provided. Biological networks are used to illustrate complexity issues, but these are kept mainly at the descriptive level.

Beyond the general issues that have interested me since first encountering them in my genomic research, the immediate motivation behind the book comes from three sources.

First, for several years I have been giving lectures on the "Foundations of Translational Science," which as the name suggests concerns the translation of scientific knowledge into practice. It is a terminology popularly used in medicine. More generally, it refers to modern engineering. The lectures place the problems of computational biomedicine into the framework of classical scientific knowledge and consider the problems of large-scale modeling in medicine. The audience has consisted of Ph.D. students, post-doctoral candidates, and faculty. I have successively added more historical development of scientific epistemology because the audience always asks for more. This book provides it.

Second, in 2011, my colleague Michael Bittner and I published the book *Epistemology of the Cell: A Systems Perspective on Biological Knowledge*, which discusses epistemological problems relating to cellular biology, with emphasis on biomarkers and network models in genomic medicine [Dougherty and Bittner, 2011]. The book has some historical and philosophic background, but, as it has turned out, not a sufficient amount for the large number of contemporary students who have virtually no background in the philosophy of science. The current book rectifies that problem, is focused on science and engineering more generally than cellular biology, includes an extensive discussion of the emerging complexity problems, and puts forward ideas on how one might begin to address these problems in translational science.

Third, in the summer of 2015 I attended a small workshop in Hanover, Germany, entitled *How to Build Trust in Computer Simulations—Towards a General Epistemology of Validation*. The workshop brought together researchers from different fields who were interested in the emerging crisis of scientific knowledge. It was apparent that the issues that I had been grappling with were ubiquitous across science, economics, engineering, and social science. The discussions in Germany stimulated my thinking. This was accentuated because, upon giving a lecture at the University of Munich, I was asked to contribute a chapter to a forthcoming book on epistemology with the idea of speculating on how to deal with model complexity from the perspective of validation and data in the context of translational science [Dougherty, 2016]. Those speculations, which have developed since last summer and have reached a plateau, are discussed in the last chapter of the book, with applications to biomedicine, pattern recognition, and signal processing.

The book is short, a little over one hundred pages. This is intentional because the goal is to succinctly and cohesively hit the necessary points for one to grasp the meaning and structure of scientific thinking, and then engage the current crisis of validation. These are exciting times for a scientist (or anyone) who is interested in fundamental problems of complex systems. Just as physicists in the first half of the Twentieth Century had to squarely confront the unintelligibility of Nature, today's scientist must confront the virtual impossibility of reconciling the desire to model big systems with small data within the context of existing scientific epistemology. The profound question for scientists in the Twenty-first Century: Is it possible to weaken scientific epistemology and broaden the domain of science without destroying it?

Edward R. Dougherty
College Station, Texas
October 2016

Introduction
Challenging Times

Evolution of Galilean–Newtonian Scientific Thinking

Some people are sufficiently fortunate to have their most creative years coincide with great mysteries in human knowledge. One thinks of the magnificent Seventeenth Century. It began with Francis Bacon moving the study of Nature from haphazard experience to designed experiments, and Galileo placing scientific knowledge within the frame of mathematics, not requiring explanation in terms of human physical categories. It ended with Isaac Newton grounding scientific knowledge on mathematical laws applicable to a wide variety of phenomena. The human condition, that is, man's place in the world, changed radically in 1687 with Newton's publication of *Philosophiæ Naturalis Principia Mathematica*.

There was a profound enigma lurking in the thinking of Galileo and Newton. It was genius to declare that knowledge of Nature is constituted within mathematics, not within human categories of understanding; yet, as long as the mathematical laws were consistent with human cognition, the full implication of this thinking lay hidden. The advent of quantum mechanics in the first part of the Twentieth Century brought it to light: a theory may be preposterous from the perspective of human intelligibility but lead to predictions that agree with empirical observation—and therefore be scientifically valid. Man can possess knowledge beyond the limits of his physical understanding. There was excitement in the air. The human condition was changing again, and young scientists dove headlong into the maelstrom.

Today, slightly more than a century since Niels Bohr hypothesized that an electron can jump to a different level without continuously passing through space, and almost a century since Louis de Broglie argued that particles of matter exhibit wave–particle duality, once again science faces an epistemological conundrum, but this time it appears that the resolution does not lie implicitly within Newton's thinking.

Toward the end of the Twentieth Century, the emergence of high-performance computing allowed scientists to construct huge models consisting of thousands of variables and parameters. The complexity of these models prevents them from fulfilling the most basic requirement of science: validation by the successful prediction of future events. System complexity has resulted in data requirements that cannot be met. Model parameters cannot be accurately estimated, thereby resulting in model uncertainty. On the other hand, model simplification means that there can be many models aiming to describe the same complex phenomena, all being inherently partial and hence yielding different predictions. The desire to obtain scientific knowledge of complex systems runs up against the requirements for scientific knowledge. In addition to complexity, there is also an aspiration for systems covering large time scales, so that validating data cannot be obtained. The inability to validate theory via observations constitutes an existential crisis for science.

The first part of this book, comprising Chapters 1 through 5, tells perhaps the greatest saga of the human mind: the evolution of scientific knowledge from explanations of natural phenomena in terms of everyday physical understanding to mathematical models that possess no such understanding and require mathematical formulation of their experimental relation to Nature. The chapters are populated by many of history's greatest scientists and philosophers. Their struggle involves a most perplexing problem: How does mind characterize what mind can know? It is a story that should be known not only to every scientist and engineer, but also to every scholar and educator, for in a world so influenced by science, no discipline can be taken seriously if it does not account for itself in relation to science.

A Radical Shift in the Narrative

A radical shift in the narrative begins with Chapter 6. A chronicle that seemed to be complete runs abruptly into the quandary of complex systems. The issues are essentially mathematical and statistical. Thus, the presentation takes on a more mathematical tone. Many of the specifics are set in the context of biology, which some have proclaimed to be the key science of the Twenty-first Century. In fact, the underlying problems of system complexity and data paucity span the range of scientific investigation, from biology to economics to social science. While our computational ability continues to grow, thereby fueling the demand for modeling complex phenomena, limitations on human conceptualization and data appear to preclude the formation of valid scientific theory in many domains—at least insofar as scientific epistemology has thus far evolved. We are in the midst of a new epistemological crisis. What could be more exhilarating for a scientist, engineer, or philosopher? Yes, we are confused, but confusion is the norm when one is on the frontier–and where else would one want to be?

The last chapter of the book considers the impact of scientific uncertainty on the translation of scientific knowledge into means to alter the course of Nature—that is, the effect of uncertainty in engineering. It proposes a course of action based on integrating existing partial knowledge with limited data to arrive at an optimal operation on some system, where optimality is conditioned on the uncertainty regarding the system. It explains the classical paradigm of optimal operator design based on a scientific model, a class of potential operations, and a quantitative measure of performance, all of which presupposes a system description whose predictions are concordant with observations. It then postulates an alternative optimization paradigm grounded in a Bayesian framework to take advantage of existing partial knowledge pertaining to the physical system of interest. The ultimate scientific problem of model validation is not solved; rather, the thinking here is that of an engineer: find an optimization framework in which pragmatic goals can be achieved. As for a new scientific epistemology in which valid knowledge can be defined, that awaits the bold efforts of fertile minds enriched with the mathematical, scientific, and philosophic education required for such a quest.