

Bernd-Olaf Küppers

# The Language of Living Matter

How Molecules Acquire Meaning



Springer

Bernd-Olaf Küppers  
University of Jena  
Jena  
Germany

ISSN 1612-3018

The Frontiers Collection

ISBN 978-3-030-80318-6

<https://doi.org/10.1007/978-3-030-80319-3>

ISSN 2197-6619 (electronic)

ISBN 978-3-030-80319-3 (eBook)

© Springer Nature Switzerland AG 2022

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

*Thus, Nature speaks down to other senses,  
to known, misjudged, unknown senses;  
thus, she speaks to herself and to us  
through thousands of appearances.*

—*Johann Wolfgang von Goethe (Theory of Colors)*

# Acknowledgements

The ideas presented here emerged from discussions with scientists from quite different areas of research. Above all, I acknowledge a lasting debt of gratitude to Manfred Eigen, who in the early 1970s was my doctoral supervisor at the Max Planck Institute for Biophysical Chemistry in Göttingen. Manfred Eigen not only paved my way from physics to molecular biology, but also supported, over many years, my increasing interest in the information-theoretical foundations of biology.

Research at the interface of physics and biology inevitably leads to complex philosophical issues of science. In this respect, Erhard Scheibe and Carl Friedrich von Weizsäcker were my closest interlocutors in my early years as a scientist. Over time, many ideas in this book were also shaped in discussions with Gregory Chaitin, Günter Hotz, Jean-Marie Lehn, Juan Roederer and Peter Schuster, to mention but a few. My thanks go to all of them.

I also remember with gratitude a series of interdisciplinary meetings on frontier issues of science initiated by the John Templeton Foundation. Exchanges of ideas with Paul Davies, Christian de Duve, Freeman Dyson, George Ellis, John Lucas, Arthur Peacocke, John Polkinghorne, Martin Rees and others all influenced in one way or another my view on the scope and reach of science.

A long-lasting scientific friendship connects me with Koichiro Matsuno and Paul Woolley. Beside our scientific discussions, Koichiro sharpened my view on the differences between Far Eastern and Western culture, which are also reflected in these cultures' different attitudes to scientific and technological progress. Paul I thank for many valuable suggestions regarding the manuscript. His alert eye and constructive criticism were an enormous help for me. Finally, I would like to thank Springer Nature, and in particular Angela Lahee, for their support in publishing this book.

# Introduction: Bridging the Gap between Matter and Meaning

Until the middle of the twentieth century, it was a widely held view among leading physicists that life's phenomena elude a complete physical description. The characteristic features of living matter, such as self-maintenance, self-control and self-reproduction, seemed to have no explanation in physical terms. Moreover, living systems have a degree of ordered complexity that from the perspective of traditional physics is highly improbable. Altogether, this gave rise to a strong impression that living matter obeys its own laws.

An epoch-making turning point in our understanding of life was the elucidation of the molecular structure of DNA by Francis Crick and James D. Watson in the 1950s. In the years that followed, it became evident that living matter is not governed by life-specific laws, but only by the physical and chemical properties of biological molecules, among these above all two classes of macromolecules: the nucleic acids and the proteins. In living matter, these molecules operate together like the legislative and executive sides of government. The nucleic acids hold instructions for the formation of proteins, which for their part execute all the life functions that are encoded in the genetic script. This highly coordinated interplay is based exclusively on the known laws of physics and chemistry.

From the genetic instructions, everything about living matter can be explained, at least in principle, by the genome's interactions with its physical and chemical environment. The translation of the genetic script into proteins, which are the carriers of biological function, is mediated by the genetic code. It establishes the link between living matter's genotype and phenotype. To describe this interplay adequately, the concept of information has been

introduced into molecular biology. Through this, living matter has become accessible to a theoretical understanding based on the models of storage and processing of information.

Moreover, exploring the molecular basis of life has uncovered some striking parallels between the genetic script and a text written in human language. Thus, the genome's molecular building blocks ("nucleotides") have the property of letters that are organized hierarchically into functional units corresponding to words, sentences and paragraphs. Like a written text of human language, the genetic script has punctuation marks and a defined reading direction.

In the phase of molecular biology, theoreticians used the information concept of the then nascent communication technology. For example, this allowed one to measure the amount of information stored in the genetic script by the number of binary digits (bits) necessary to specify the precise sequence of the genome's building blocks ("letters"). This number, however, is only a measure of the complexity of the program resident in the genome, and it tells us nothing about the program's actual meaning, i.e., the operating instructions that it carries.

In fact, the communication engineer's concept of information is entirely detached from the meaning of a message. From a technical point of view, this is quite understandable. The communication engineer's task is merely to transfer a sequence of signals, symbols or binary digits with as few errors as possible to a receiver, so that the message's content, whatever its meaning may be, is not altered. From the point of view of technological communication, a randomly jumbled sequence of characters has the same information measure as a meaningful message of the same length. At the other extreme, it is precisely the meaning content of genetic information that constitutes the difference between living and non-living matter.

Theoretical biology, therefore, requires a comprehensive concept of information that also includes the semantic dimension of genetic information. However, to practitioners of the exact sciences, whose work is based on observation, measurement and mathematical formalization, semantic elements must seem highly foreign. The semantic aspects of reality would seem to be, at best, accessible to the humanities and their methods of interpretation, which in themselves are largely subjective. So, the question arises as to whether there is some hitherto unknown pathway between these two hemispheres of scholarly thinking that can guide us to grasping the semantic dimension of information in an objective and precise manner too.

In the 1980s, this question moved increasingly into the focus of theoretical biology, when the physical and chemical theory of molecular self-organization and evolution of life took shape (cf. my *Molecular Theory of Evolution* [1]). At

that time, it was becoming clear that an understanding of the generation of information in Nature will be the key to a deeper comprehension of living matter. I outlined this issue in *Information and the Origin of Life* [2]. In his foreword to that book, the physicist Carl Friedrich von Weizsäcker wrote: “Scientifically, this theory seems to me to close a gap that is perhaps comparable to the geographical discovery of the North-West Passage north of America: no one had reason to doubt that these waters existed, but it was uncertain whether our ships would be able to navigate them.” [2, p. xiv]

Where are we now? Has our voyage of discovery taken us to uncharted scientific territory? During the past three decades, rapid progress has been made in molecular biology (Chap. 6). The development of modern sequence analysis has led us to new and profound insights into the fine structure of genetic information (Sect. 6.2). The discovery that a particular class of nucleic acids (RNA) can catalyze their own reproduction, without the help of proteins, has jolted the RNA world into the center of research interest, opening new paths toward an experimental and theoretical understanding of life’s origin (Sect. 6.9). Moreover, within the frame of biological information theory, a “royal road” is today opening up that may lead us to modeling the semantics of genetic information (Sect. 6.8).

Given the huge amount of information that has accumulated from genetic research and which is deposited in more than a thousand databases worldwide, it is becoming clearer almost by the day that biology urgently needs a systematization frame that goes beyond the classical Darwinian theory of evolution. The theoretical concept we are looking for must be based on a natural principle that grasps the peculiarities of life’s processes within the framework of the known laws of physics and chemistry, without ascribing a special status to living matter. In this book, I posit that all molecular biological findings support the hypothesis that the principle sought is a molecular language.

It is evident that this idea not only has far-reaching consequences for the theoretical foundation of biology; it also bundles numerous issues of our scientific understanding of the world and brings them to a focus. This is the reason why the fundamentals of science occupy a large part of this book. Let me highlight here some points that lead directly to the core of the book. The conjecture that language might be relevant for understanding living matter, its origin and evolution, emerged long ago. No less a visionary than Charles Darwin wrote in his *Origin of Species* (1859): “If we possessed a perfect pedigree of mankind, a genealogical arrangement of the races of man would afford the best classification of the various languages now spoken throughout the world; and if all extinct languages, and all intermediate and slowly

changing dialects, were to be included, such an arrangement would be the only possible one.” [3, p. 410]

The physiologist Friedrich Miescher, who discovered nucleic acids at the end of the nineteenth century, saw no other way to explain the diversity of genetic dispositions than by comparing it to the unlimited richness of “words and expressions of all languages” [4, p. 117; author’s transl.]. In *Laws of the Game* [5] and other writings, Manfred Eigen also pointed to the obvious parallels between the organization of genetic information and that of human language. In his Nobel lecture on *The generative grammar of the immune system* [6], Niels Jerne compared the immune system’s “immense repertoire” to “a lexicon of sentences which is capable of responding to any sentence expressed by the multitude of antigens which the immune system may encounter” [6, p. 220]. He found it “astonishing that the immune system embodies a degree of complexity which suggests some more or less superficial though striking analogies with human language, and that this cognitive system has evolved and functions without assistance of the brain” [6, p. 223].

In this book, I will go a step further and claim that language is not merely a helpful analogy to describe the organization of living matter, but a principle of Nature that has its roots in the laws of physics and chemistry. This hypothesis breaks with our traditional view according to which language is a unique property of humans. Since language is mankind’s gateway to the world (Chap. 1), it is in the nature of things that we have, first and foremost, an anthropocentric idea of language. From this perspective, any talk about a language of living matter must inevitably seem to be metaphorical. To escape the constraints of a superficial analogy, one has to deepen the idea of language by abstracting from the complex and specific peculiarities of human language and uncovering its structural features. Afterward, one must demonstrate that these structures are already present at the molecular level of Nature. With this task, we are undoubtedly breaking new ground in the exact sciences.

Up to now, the most advanced approach to the structural aspects of human language has been developed by the linguist Noam Chomsky, in his book on *Syntactic Structures* [7]. His investigations uncovered an overarching aspect of human languages, termed “universal grammar,” comprising the rules according to which words and sentences are formed in all natural languages. The studies furthermore suggest that grammatical rules are recorded in innate structures of the brain. This, in turn, would mean that the universal grammar is genetically anchored.

A prerequisite for Chomsky’s analysis is the assumption that grammatical structures can be justified exclusively at the syntactic level of language, i.e., without reference to its semantic dimension. We will follow Chomsky’s argument by reconstructing the nucleation of language at the level of

prebiotic macromolecules (Sect. 6.9). The language itself we will denote as “molecular” language and its developed form as “genetic” language. Correspondingly, this book leads from the structures of human language to the language of living structures.

To justify our assertion of the existence of molecular language, we start from the well-grounded working hypothesis that all life processes are based exclusively on physical and chemical laws. These laws, however, may act together in a particular manner that we usually describe as a principle. An example of this is the principle of natural selection, which takes effect not only among living beings but also among molecules in non-living systems. The only requirements for this are self-reproduction and an overall growth limitation placed upon the population.

Self-reproducing nucleic acids are paradigmatic for selection in the Darwinian sense (Sect. 6.5). However, in the absence of any biosynthetic machinery, the molecules’ structural properties themselves are the target of selection. They determine the molecules’ reproduction dynamics and thereby their selection value. The greater a molecule’s reproduction rate, reproduction accuracy and inherent stability are, the higher is its selection value. Since nucleic acids’ structural properties depend on their nucleotide sequence, selection automatically favors sequence patterns that contribute to efficient reproduction. Moreover, in the interplay between random mutation and selection, these patterns will be strongly conserved. They can be considered as “proto-words” or “proto-sentences” of a molecular language, stabilizing the advantage acquired by the molecule’s structure (Sect. 6.8).

The folding of a nucleotide sequence to produce a three-dimensional autocatalytic structure is determined by physical and chemical forces only. At the same time, this is the most elementary relationship between structure and function in prebiotic molecules that one can imagine. At this level, the physical and chemical origin of molecular language lies before us, as it were, in a nutshell. It is fascinating that a relatively simple autocatalytic mechanism, combined with random mutation and natural selection, already leads to the formation of syntactic structures in non-living matter. This is the starting point for the development of a language that finally passes through numerous stages of evolution, from molecular language to genetic language up to the sophisticated forms of human language.

Detailed analysis verifies that living matter’s language shows all the structural features that we also associate with human language: Molecular language is based on a finite alphabet. Its words are hierarchically organized into sentences, paragraphs and so forth (Sect. 1.5). Its syntax is aperiodic (Sect. 5.4) and has a grammatical structure (Sect. 6.9). Finally, genetic information expression leads to a dynamization of information that shows all

the features of linguistic communication (Sect. 6.3). It breathes life, in the truest sense of the expression, into the abstract formula “Life = matter + information” (Sect. 5.7).

The concept of molecular language will significantly alter our traditional view of the origin and evolution of life. Beside natural selection, language must be considered the second decisive driving force of biological development. Thus, evolution theory becomes a matter of linguistic theorizing (Sect. 6.8). This shift in perspective suggests that life’s evolution should be viewed dualistically, i.e., as the evolution of the genetic language’s syntax and the evolution of its semantics. Both processes are based on natural selection, but they refer to different evolution processes, namely the non-Darwinian development of living matter’s genotype and the Darwinian development of its phenotype (Sect. 6.10).

The non-Darwinian development of syntax is non-adaptive. It is entirely restricted to the structural properties of the self-reproducing information carriers and their possible interactions. The later development of semantics is superimposed upon this process. It is the step at which genetic information is translated into proteins and obtains its relevance, i.e., its meaning regarding the outer world. The molecular language of living matter now becomes context-dependent, and Darwinian evolution by adaptation comes into play. This is also the point at which molecular language goes over into genetic language.

Language-driven evolution has several distinctive features. As described, the nucleation of molecular language’s grammar can be reduced entirely to physical and chemical processes combined with mutation and selection. At this level, nucleic acid molecules can already develop syntactic structures corresponding to words and sentences. However, by cooperative interactions, nucleic acid molecules can also form reaction cycles stabilizing and enlarging their structural information (Sect. 6.10). In this way, a reservoir of genetic “words” and “sentences” can build up, filling living matter’s linguistic toolbox. At this level, which is still the level of syntactic structures, a form of molecular organization begins to emerge. It is characterized by cooperation, compartmentation, self-regulation, hierarchy formation and other functional elements. Together, these constitute the proto-semantics of genetic information (Sect. 6.10) and thus represent a case study for the model of a semantic code (Sect. 6.8) that describes the emergence of the meaning of items of information.

By mutation and selection, numerous forms of organization may evolve, differing in both the kind and the weighting of their functional features. One can compare them with the myriads of possible ice crystals, each of which has an individual and unique form although all result from the same physical

mechanism (Sect. 5.7). Molecular organizations based on the chemical rules of living matter's proto-grammar show the same combinatorial richness of forms that is given by the unlimited diversity of linguistic expressions in human language. At first, however, molecular organizations were nothing more than linguistic pre-structures—blank forms for the further evolution of life. They were syntactic structures without semantics.

Language-driven evolution provides a plausible explanation for the genome's noncoding regions. These must be interpreted as the information structure on which the genetic organization of an organism is based. Obviously, only a minor part of the genome's information has a relation to the outside world at all, as expressed by the organism's phenotype. This information is located in the genes that are translated into proteins. The major part of the genotype, in contrast, seems to function only within the internal context, manifested in the organism's organization. In other words, the genome's noncoding information must be expected to serve the language mechanism, which causes and controls the genes' dynamization and establishes the genome's relation to the outside world. The same applies, by the way, to human language. In a written text, for example, many words do not relate to the actual subject matter at all. Instead, they are necessary to structure a sentence grammatically and logically. They only constitute the framework into which the minor fraction of words that are subject-matter-related is embedded (Sect. 6.9).

According to the Darwinian understanding of evolution, the semantic dimension of genetic information originates from organisms' evolutionary adaptation to their environment. Figuratively speaking, organisms gain information about their environment by mutation and selection, which becomes fixed in their genes. In this sense, genes are thought to map information about the organism's external world. They determine the organism's phenotype on which Darwinian selection operates. Given a sufficiently rich and varied environment, the evolution of the phenotype can be justified on the basis of Darwin's theory.

However, in the earliest stages of evolution, there was no information-rich environment (or context) that could serve as the reference frame for molecular evolution, directing the evolution of information toward increasing complexity. The generation of a sophisticated program complexity itself presupposes an external source of sufficiently complex information. Without it, evolution would be a kind of perpetual motion machine, creating information out of nothing—an idea, however, that can be shown to be impossible (Sect. 5.6).

Evidently, there is a blind spot in Darwin's theory of adaptation. The only way to put his idea onto a solid basis is provided by recourse to the language

of living matter. This leads directly to a highly significant aspect of language, namely the context-dependence of linguistic expressions (Sect. 1.8). To justify this significance, one has to reconsider the process of gene expression by which the relationship between genetic information and its environment, the “external” world, is established. This process requires a machinery for biosynthesis, to translate genetic information into the immense variety of biomolecules from which life processes emerge.

Moreover, gene expression also needs perpetual feedback between the genome and its gene products, to coordinate the myriads of molecular processes. This feedback takes the form of communication, even though molecules do not “talk” to each other in the literal sense. Communication does not presuppose consciousness; rather, it (only) requires the exchange of information between sender and receiver, in this case the genome and its physical and chemical environment. The environment suffices to give a meaning to the —*a priori* meaningless—nucleotide sequence of the genome.

The contextuality of information modifies the classical idea of genetic determinism without, however, abolishing it. Genetic determinism used to be based on the assumption that genetic information is necessary and sufficient for constructing the living organism. This idea must today be reinterpreted as a “generative” determinism (Sect. 6.3). According to this, the syntax of genetic information is still necessary and sufficient for the organism’s self-reproductive maintenance, but its semantics are constituted solely by the genome’s expression, i.e., through its “communicative” interaction with its molecular context. We know this very well from human language, where the meaning of linguistic expressions is sharpened in the dialog between communication partners.

The idea of genetic language leads to a new interpretation of Darwinian evolution. From the perspective of language-driven evolution, the source of evolutionary progress is not the environment, but the nearly unlimited number of linguistic expressions that can be generated at the genotypic level by molecular language. These expressions represent possible forms of functional organization. When translated into a phenotype, they are tested for fitness by natural selection. In other words, the actual motor of biological evolution is not the environment itself, but the change in use of living matter’s language in a continuously changing environment. Those forms of expression will survive that turn out to be meaningful under the prevailing conditions. By this mechanism, the biosphere emerged over time. Without the existence of genetic language, the genome would lose all its information when the environment changes. It would eliminate large parts as “junk”. Darwinian test-tube experiments demonstrate this clearly (Sect. 6.5).

The language paradigm can be expected to open up new questions and pathways in the exploration of the genome's structure and function. It may also have an impact on biotechnology and medical research. From the epistemological perspective, the language paradigm provides a systematic framework for biological theory. Quite different ideas on the mechanisms of evolution ("neutral selection", "selfish genes", "convergent evolution", "punctuated equilibria", "tinkering") no longer appear to contradict one another, but rather to be complementary features of a language-driven evolution.

The crux of the matter is the interface between physics and biology, where the language of living matter has its roots. However, this book goes far beyond that. It takes up the problem of how semantic information could arise in living matter—a problem intertwined with that of the genesis of meaning and with ramifications reaching into all areas of science. This broad issue is also reflected in the structure of this book. To justify the idea of living matter's language, one has to look in depth at our scientific and philosophical thinking, at language as such (Chap. 1), at science's claim to truth (Chap. 2) and its methods (Chap. 3), at the unity of science (Chap. 4), its limits (Chap. 5) and perspectives (Chap. 6). An epilog (Chap. 7) introduces Nature's semantics and considers some implications of this for our view of Nature. Accordingly, this book is also an account of how progress in the life sciences is transforming the whole edifice of science, from physics to biology and beyond.

## References

1. Küppers B-O (1983) *Molecular Theory of Evolution: Outline of a Physico-Chemical Theory of the Origin of Life*. Springer, Berlin/Heidelberg
2. Küppers B-O (1990) *Information and the Origin of Life* (transl: Woolley P) MIT Press. Cambridge/Mass [Original: *Der Ursprung biologischer Information*, 1986]
3. Darwin C (1859) *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*. Murray, London
4. Miescher F (1897) Letter to Wilhelm His, 17 Dec 1892. In: *Histochemische und physiologische Arbeiten*, Bd 1. Vogel, Leipzig
5. Eigen M, Winkler R (1993) *Laws of the Game: How the Principles of Nature Govern Chance*. Princeton University Press, Princeton [Original: *Das Spiel*, 1975]

6. Jerne NK (1984) The generative grammar of the immune system. Nobel lecture. Nobel Foundation
7. Chomsky N (1957) Syntactic Structures. Mouton, The Hague

# Contents

<b>1</b>	<b>Language: Gateway to the World</b>	<b>1</b>
1.1	Forms of Knowledge	1
1.2	Toward a New Atlantis	6
1.3	Language and the World	11
1.4	What is Information?	17
1.5	The Genetic Script	25
1.6	Symbolic Forms	34
1.7	Excursion into the Empire of Signs	39
1.8	Context-Dependence of Signs and Language	46
1.9	Contextual Aspects of Science	53
1.10	Context Principle and Quantum Physics	59
	References	68
<b>2</b>	<b>Truth: The Regulative Principle of Cognition</b>	<b>73</b>
2.1	What is Truth?	73
2.2	The Search for True Being	78
2.3	One or Two Worlds?	87
2.4	Empiricism Against Rationalism	91
2.5	The Copernican Revolution of Thought	96
2.6	Speculative Rank Growth	101
2.7	Knowledge and Pseudo-Knowledge	112
2.8	Approaching Truth by Evolution?	119
2.9	Practical Truth	124
2.10	Truths Without Truth?	128
	References	132

<b>3</b>	<b>Methods: Ways of Gaining Knowledge</b>	137
3.1	Implicit Knowledge	137
3.2	The Aesthetics of Cognition	141
3.3	Is “Understanding” a Method?	152
3.4	Fundamentalism of Understanding	156
3.5	Facets of Holism	163
3.6	The Problem of Non-separability	168
3.7	The Mechanistic Paradigm	175
3.8	The Reductionist Research Program	179
3.9	Misunderstandings	186
3.10	Anything Goes?	195
	References	199
<b>4</b>	<b>Unity: The Deep Structure of Science</b>	205
4.1	Toward the Unity of Science	205
4.2	The General and the Particular	210
4.3	The Structure of Scientific Explanations	217
4.4	Can History Become the Subject of Exact Science?	225
4.5	Mass Action and Cooperativity	229
4.6	Temporal Depth	235
4.7	The Double Nature of Causality	243
4.8	The Abstract World of Boundary Conditions	248
4.9	The Ascent of Structural Sciences	256
4.10	What Task Remains for the Human Sciences?	260
	References	262
<b>5</b>	<b>Limits: Insights into the Reach of Science</b>	267
5.1	The Enigmatic Reference to the “Self”	267
5.2	Incomplete and Undecidable	272
5.3	How Complicated is the Complex?	279
5.4	Limits of Objective Knowledge	286
5.5	Circular Reasoning	293
5.6	The Impossibility of a Perpetual Motion Machine	301
5.7	Fluid Boundaries	309
5.8	The World of “As-Well-As”	315
5.9	The Fuzziness of Truth	318
5.10	Limits of Conceptual Thinking	321
	References	325

<b>6</b>	<b>Perspectives: Designing Living Matter</b>	329
6.1	We Must Know, We Shall Know	329
6.2	How the “Impossible” Becomes Possible	333
6.3	Genetic Information and Communication	340
6.4	Reprogramming Gene Expression	345
6.5	Artificial Evolution	351
6.6	Pathways to Artificial Life	360
6.7	Toward Artificial Intelligence	369
6.8	Modeling Semantic Information	379
6.9	The Grammar of Genetic Language	387
6.10	Language-Driven Evolution	400
	References	412
<b>7</b>	<b>Epilog: Nature’s Semantics</b>	419
7.1	Unforeseen Progress	419
7.2	Future Visions: Organic Technology	424
7.3	Control by Renunciation?	430
7.4	The Phantom of Instrumental Reason	435
7.5	Only Knowledge Can Control Knowledge	443
7.6	The Nature of Ecological Balance	449
7.7	Does Nature Pursue Purposes?	454
7.8	Nature as a Cultural Task	458
7.9	Nature’s Intrinsic Proportions	461
7.10	Science in the Age of Global Change	468
	References	477
	<b>Author Index</b>	481
	<b>Subject Index</b>	487