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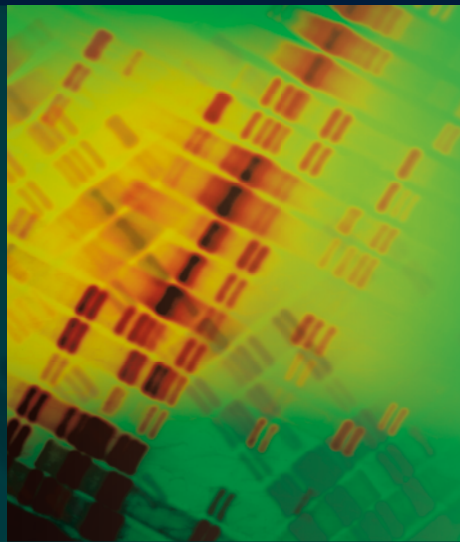

Bernd-Olaf Küppers

THE LANGUAGE OF LIVING MATTER

How Molecules Acquire Meaning

Springer

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The Language of Living Matter

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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)

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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.

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Contents

1

Language: Gateway to the World

1.1 Forms of Knowledge

"All men naturally desire knowledge. An indication of this is our esteem for the senses; for apart from their use we esteem them for their own sake, and most of all the sense of sight. Not only with a view to action, but even when no action is contemplated, we prefer sight, generally speaking, to all the other senses. The reason of this is that of all the senses sight best helps us to know things, and reveals many distinctions."

With these words Aristotle's *Metaphysics* begins [1, book 1, 980a]. In fact, the cultural history of man is marked by a steady increase in knowledge. However, only in our time has this knowledge grown to such a vast extent that it can hardly be surveyed anymore. An example of this is the enormous increase in knowledge that has accompanied recent developments in science. It has built up a virtually impenetrable jungle of information around us, in which only a few people are still able to find their way.

The almost explosive development of knowledge is undoubtedly a primary reason for the apprehension with which many people view science: when the complexity of scientific discoveries is no longer transparent and understandable, it becomes eerie and feels threatening. It is therefore not surprising that many people regard science as a destructive rather than a constructive element of our world. The increase in knowledge has been so great that, even among scientists, mutual understanding is often scarcely possible. More than that: our experience must be updated almost daily, which in turn requires a perpetual rearrangement of our stock of knowledge. The so-called expert controversy, in which everyone claims to possess real insight and to have the

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latest state of knowledge on his side, is the most clearly visible expression of this development.

Nevertheless, the widespread talk about a "flood of knowledge" is somewhat misleading. It conveys the impression that understanding in science accumulates continually, as new insights are found and integrated into our scientific view of the world. Yet is the mere increase in printed or electronically stored information really a significant indicator of progress in knowledge? Can knowledge be measured exclusively in digital bits? Are not, instead, content and quality the decisive hallmarks of advanced knowledge? How can we evaluate scientific progress in these terms? Such questions lead directly to the search for the essence of the human culture of knowledge. Before we set out on this path, however, let us briefly clarify some terms related to "knowledge".

The most elementary expression of cognition has always been sought in direct intuition and perception, in short: in the obviousness of things. Aristotle described it this way when, at the beginning of his *Metaphysics*, he emphasized the importance of our senses in satisfying man's thirst for knowledge. However, the bare experience of things is only a preliminary stage to a conceptually and methodically elaborated knowledge in which cognition is linked and theoretically substantiated by definitions, causal explanations and proofs.

Knowledge in the real sense is cognition of complex issues. For example, when one says that someone has particular cognition one is stating that the person concerned has not only perceived something, but also knows how the observed "something" is constituted and how it is related to other observations. In other words: It is only through insight into the causal interrelationships of reality that the bare experience of reality becomes a cognition of reality and thus constitutes theoretical knowledge.

There are other forms of knowledge. For example, if we say that we know how to achieve what we want to do, then we are talking about a kind of knowledge that guides our actions, and that is in the broadest sense relevant to our life pursuits. This knowledge is primarily a practical knowledge of specific skills by which we can cause or produce something.

Entirely different answers, on the other hand, are required by the questions of what we should do at all and whether what we intend to do is also morally justifiable. Answers to these questions need orientation guides that determine the goals, and the value yardsticks, of our actions. Such orientational knowledge is difficult to justify. It is mostly based on metaphysical or transcendental reasoning, including, last but not least, religious convictions and values.

The knowledge that can claim maximum validity is undoubtedly the knowledge of how to effect or to produce something, because this enables us to solve practical problems. On the other hand, practical knowledge is only possible because it is based on theoretical knowledge, which yields information about the interrelationships between causes and effects. These two forms of knowledge are, therefore, inseparably linked and document our rational approach to reality.

In current philosophy, there is much debate about the question of which knowledge form has priority in the development of science and technology. Does theoretical knowledge result from the understanding of life's practicalities, or is theoretical knowledge—conversely—an ultimate prerequisite for the development of practical knowledge? Would it have been possible to invent the scales without any concept of what weight is? Or, the other way around, could we have a notion of weight without ever having built a set of scales? We can ask the same questions in connection with other practical inventions, for example the technique of leverage and the lever laws.

Asked in the most general way: Are our scientific concepts and theories first and foremost cultural constructs that have emerged from dealing with the experimental technical issues of our living environment, or are they a distillate of objectively existing relationships that make it possible to deal with reality technically? The cultural history of mankind offers plenty of indications to support the one or the other explanatory variant. However, as we shall see later on, an absolute justification of human cognition is excluded, for a fundamental reason. This means, in turn, that the epistemological question, asking which of the two forms of knowledge has priority, cannot be answered finally.

The distinction between theoretical and practical knowledge goes back to Aristotle. He distinguished for the first time between an understanding of the universal principles of reality and knowledge focused on the demands of everyday life. This distinction was a remarkable step, in so far as in early antiquity the Greek word *theōria* had an ethical and religious connotation and thus a normative aspect.

The prescriptive function of *theōria* concerned both the understanding of Nature and the social organization of the human community. In other words: *theōria* was assumed to determine not only the movement of the stars but also the forms of reasonable coexistence in human society. Accordingly, theoretical and practical knowledge made up a unified whole. The related idea of *lógos* expresses clearly this line of thinking. In the antique understanding, *lógos* is the reasonable world law, which directs everything and mediates the unity of reality in the multiplicity, diversity and contradictoriness of its appearances.

Concerning practical knowledge, Aristotle further distinguished between knowledge that is focused explicitly on goodness and happiness, and knowledge that is aimed at the work to be done (*poiesis*). The latter is to be understood in the sense of skill (*téchne*) or creative production. Poietic actions include matters of everyday life as well as those of the world of arts. The latter aspect of *poiesis* is still reverberating today in the word "poetry".

Aristotle also argued that the "poietic" knowledge was the very basis of all knowledge, including in particular cognition about Nature. In fact, Nature appeared to him as an active subject that pursues goals and purposes. Through her "poietic" actions, Aristotle concluded, Nature creates and organizes herself.

In this connection, Aristotle's doctrine of the four causes played a central role. A simple example explains the basic idea behind this doctrine: If one wants to build a house, one needs specific materials ("material cause"); a building plan that determines the shape of the house ("formal cause"); craftsmen who fit together the material components ("efficient cause"); and a goal that describes the purpose which the building is ultimately to serve ("final cause"). In other words, Aristotle was saying: All things have been created, they consist of matter, they have a shape and they have a purpose. This applies not only to the things that have emerged from human activity but also to things of natural origin.

According to Aristotle, the four causes give a sufficient answer to the central question of why things exist and why things are the way they are. Aristotle furthermore assumed that the four causes are interrelated pairwise: the material cause with the formal cause and the efficient cause with the final cause. They behave as the determinable does to the determining: The material of a thing is in itself indeterminate and is given its characteristic shape only by the formal cause. The per se indefinite movement receives its direction only through the final cause.

Aristotle's notion of movement always raises the question of "where to". Since there is no motion without direction, every movement points inherently to a target (*télos*). However, in the antique understanding, "movement" means not only change in spatial position, but also any change in quantity or quality. Thus, the theory of movement, which Aristotle places at the center of his natural philosophy, inevitably leads to a teleological understanding of reality. Every process, whether artificial or natural, must be seen as a purposeful formation of things because the Aristotelian concept of movement necessarily implies a direction toward a goal.

For example, a seed becomes a plant because the state of being a plant is the seed's inherent target. Natural things differ from artificial things only in that they have the movement within themselves, while artificial things are moved from the outside. Since each movement, as Aristotle postulates, is induced by another movement, this raises the question of the "prime mover" of the world, who is himself unmoved. With the problem of the "unmoved mover" as the first cause for all things that exist, Aristotle finally enters the realm of speculative metaphysics.

It seems that Aristotle did not want to understand his theory of motion in the sense of cosmic teleology, in which the world is heading toward a universal goal or fulfilling a universal purpose. Although Aristotle regarded every natural process as targeted, he would have denied the existence of an overarching goal. Following this interpretation, one can say that Aristotle considered the dynamics of the world to be a network of purposeful processes, but not a goal-directed network serving an overall purpose. The latter interpretation is more likely to have stemmed from the over-interpretation of the Aristotelian world-view by medieval theology, which set out to justify the wisdom and perfection of a Creator God. For this reason, one must carefully distinguish between the Aristotelianism of medieval theology and the authentic ideas of Aristotle himself.

With the view that every movement, i.e. every change, is goal-directed, Aristotle gave the concept of Nature an interpretation that was definitive for more than two thousand years in the Western understanding of Nature. It was not until the beginning of the seventeenth century that the Aristotelian world-view collapsed when Galileo Galilei succeeded in proving the inconsistency, and thus the untenability, of the Aristotelian doctrine of motion. However, the path that ultimately led to a systematic reorientation and renewal of the sciences and thus to a modern, mechanistic concept of Nature was an arduous one, because the Aristotelian world-view had burned deep into occidental thinking, leaving many traces.

1.2 Toward a New Atlantis

Aristotle had dealt with almost all the philosophical and scientific questions accessible to the thinking of his time. They concerned, beside metaphysics, the philosophy of science and nature, physics, biology, ethics, political theory, logic and language. His scientific heritage is correspondingly extensive, so that Aristotle can rightly be considered the first universal scholar in the modern sense of the word. The influence of Aristotelian thinking on science was so strong that it took two thousand years before a new era of science could begin.

At first, the methodological redefinition of science became the focus of public interest. This step has been prepared by Francis Bacon and René Descartes. At the beginning of the seventeenth century, when science and technology were emerging, both had rediscovered the importance of practical knowledge, to which Aristotle had already turned his attention. Bacon and Descartes were inspired by the idea that the living conditions of humans can be improved with the help of science and technology. As a result, they focused on the question of which methods are best suited to increase scientific and technological knowledge.

While Descartes also had an epistemological interest in science, Bacon considered science and technology exclusively in terms of their usefulness to society. Bacon believed that social and political peace in a community could only be guaranteed if all people could live free of worry and conflict. According to Bacon, however, this is only possible if human society gains—with the help of science and technology—unlimited power over Nature.

Driven by his maxim "knowledge itself is power", Bacon was interested in the conditions under which scientific and technical progress can be organized as effectively as possible. This aim was served by his methodology, as he described it in his programmatic *Novum Organum Scientiarum* (Fig. 1.1). The title of this treatise, which announces the "renewal of science", alludes to the famous *Organon*, a collection of theoretical and logical writings by Aristotle that had influenced Western thought for centuries.

The Greek word *organon* means "tool". The new tools with which Bacon wanted to tackle Nature to elicit its secrets were observation and experiment. Bacon believed that from the generalization of observations he could finally derive the rules that Nature obeys and which, he thought, were the key to gaining power over Nature.

All in all, Bacon described the scientific method as the art of discovery (*inventio*) from experience. This approach, in which observation and experiment play a central role, seems to be so close to the idea of empirical science that one is immediately inclined to acknowledge Bacon as a mastermind of modern

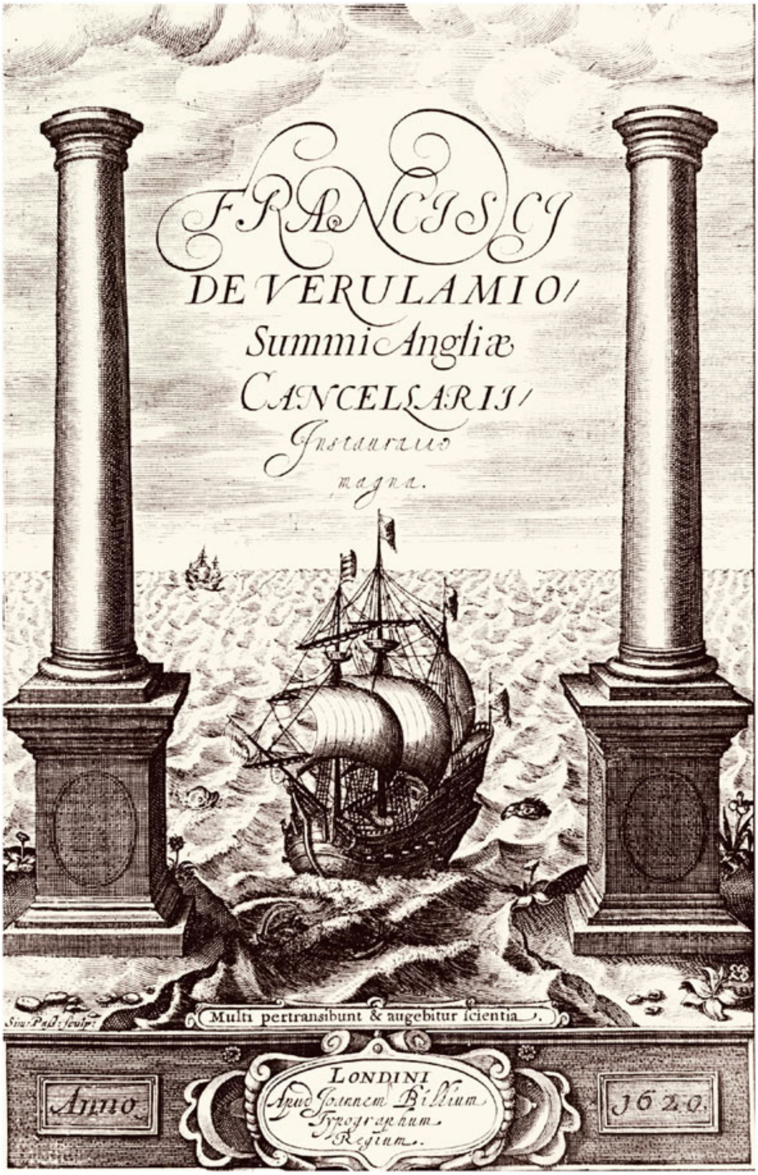

Fig. 1.1 Title page of Francis Bacon's major work *Instauratio Magna*. Bacon's book, published in 1620, is to a large extent a collection of aphorisms. Only the second part of the book, entitled *Novum Organum*, was completely worked out by Bacon. For this reason, later editions of the book were given the title of the dominant part, *Novum Organum Scientarium* [2]. Bacon's reflections have become eminently influential in modern scientific thinking, as they initiated the cultural transition from medieval science to modern science, even though Bacon's own thinking still seemed to be largely medieval. His program, which propagates the awakening of science and technology for the benefit of humanity, remains the guiding motive of contemporary science. [Image: Wikimedia Commons]

science. On closer inspection, however, it becomes clear that Bacon's understanding of science was not as revolutionary as it might seem at first glance.

The cultural philosopher Hans Blumenberg [3] has given a subtle and, as it would appear, conclusive interpretation of Bacon's actual intentions. According to this, all the methodological innovations that seem to emerge from Bacon's work are only aimed at providing man with the tools to enable him to transfer his creative will to Nature, according to the model of the divine act of creation. For this purpose, however, man must observe Nature as the work of the Creator without prejudice and with the utmost precision. Only in this way will man be able to elicit from Nature the rules—divine instructions—to which Nature adheres.

Following Blumenberg's interpretation, the method of observation, which Bacon emphasizes so strongly, has a background entirely different from that of the modern empirical sciences. As Blumenberg elaborates, Bacon was obviously recalling the creation story in the book of Genesis, which is nothing more than the sum of the commands given by God to the various beings when they were called by their names: to be.

Thus, the human in Paradise just repeats the names that had appeared in the creation commands of God. These are the actual names of the things. If these names are called out, the things obey in the same way as they did when they followed the divine act of creation, namely to come forth from nothing. According to Blumenberg, the task of Bacon's new science would have been "to extract from Nature the means by which power is exercised over her, just as Nature had been a product of power from the very beginning" [3, p. 87; author's transl.].

Blumenberg is probably right when he says that Bacon's conception of science was closer to the black art of magic than to the then nascent methods of modern science, which are devoid of any magic power. Bacon's idea that Nature will disclose its secrets if one only encounters it without prejudice, i.e., by merely observing, is in fact nothing more than a magical incantation, one in which mankind is supposed to gain control over Nature just by calling things by their names. Thus, Bacon's program proves to be deeply rooted in the biblical creation myth: science and technology are destined to regain the sovereignty and power over Nature that had been lost with the banishment of humans from Paradise. This thought is also supported by Bacon's utopia *New Atlantis* [4].

At the same time, it becomes clear that a renewal of science by critical thinking could not arise from an understanding of Nature that was still attached to the magical world of the Middle Ages. On the contrary, Bacon even believed that one has to put the creative mind into chains. Since he was convinced that the secrets of Nature could only be disclosed by encountering Nature without prejudice, he demanded that we temporarily prevent our restless intellect from jumping to premature conclusions. Therefore, Bacon advised that "understanding must not […] be supplied with wings, but rather hung with weights, to keep it from leaping and flying" [2, p. 97].

Following on from Bacon's "power of knowledge", none other than Descartes made a large-scale attempt to renew science. Descartes also advocated an ideal according to which he considered scientific knowledge would enable humans to appropriate Nature and to become her ruler for the good of humanity. In the foreword to his *Principles of Philosophy* published in 1644, Descartes compares science and its various disciplines to a tree [5]. Its fruits, however, as he points out, cannot be found at the roots (in metaphysics) or on the trunk (in theoretical physics), but rather in its branches, i.e., in mechanics, anatomy, physiology and psychology. According to Descartes, mechanics serves for technology, while anatomy and physiology are essential for medicine; finally, psychology allows the mental control of emotion, feelings and passions.

Like Bacon, Descartes emphasized the importance of science for the improvement of human living conditions. In this connection, he thought primarily of working conditions, the maintenance of health and the prolongation of life. However, while Bacon misconstrued the task of scientific mastery over Nature as "an excessive implementation of the basic idea of magic" [3, p. 88; author's transl.], Descartes had a completely different vision of science. He concluded that control of man's outer and inner nature could only be achieved on the basis of knowledge that was methodologically assured and subject to constant monitoring. Unlike Bacon, for whom scientific knowledge was just the means to an end, Descartes regarded scientific knowledge as a goal to be pursued for its own sake. In short, the essential difference between Descartes and Bacon is their different perspective on knowledge, which makes Descartes appear to us as the genuine pioneer of modern science.

In his *Discourse on Method* [6] of 1637, Descartes established four rules for the proper use of reason. First of all: one should never acknowledge something as being right that is not obviously true and does not appear indisputable. Secondly: one should divide every problem into partial problems as far as possible, in order to be better able to solve it. Thirdly: one should always start with the simplest and most easily understandable issues and then move step by step to the compound, complex ones. Finally: one should in all cases strive for generality and completeness of knowledge.

The first rule puts systematic doubt at the head of the process of scientific cognition. According to this rule, only knowledge that can withstand rigorous doubt can claim to be true. The idea of critical knowledge, which is formulated by this rule, is of such fundamental importance that it can rightly be described as the key principle of modern science.

The second and third rules set out the starting-direction for gaining knowledge in science: the problem to be investigated should first be broken down into sub-problems. Then one should proceed from simple issues to complex ones. This method, based as it is on the dissection of the object or problem under investigation, has been called since the eighteenth century the "analytical" research strategy.

The fourth rule takes account of the idea that only a general knowledge can provide information about the law-like character of the world. The far-reaching demand for the completeness of cognition is, however, a mere desideratum. It aims at the inner consistency and absence of contradictions of the system of cognition, and is intended to justify its claims to truth.

To sum up: Descartes' methodology represents the basis of modern science, the guiding principles of which are, beside systematic doubt: analytical access to reality, and the objectification and generalization of cognition. Only such a methodologically secured knowledge, placed under unrestricted testing by experience, can ensure the rationality of our world-cognition.

At the transition to modern times, it also became clear that man can only intervene in Nature if he has precise knowledge of its fabric of causes and effects. Only this causal knowledge allows man to make reliable predictions about natural events and thus to intervene in a direct manner in Nature. For this purpose, the search must be made for facts that can be represented as cases of mathematically formulated laws. The implementation of this idea by Johannes Kepler, Galileo Galilei, Christiaan Huygens, Robert Boyle, Isaac Newton and other natural scientists of the sixteenth and seventeenth centuries was the most crucial step on the way to today's exact science.